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اثرات تغییر اقلیم و عوامل هواشناختی بر شاخص‌های فصل گرده‌ای آرایه‌های گیاهی آلرژی‌زا

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چکیده. آلرژی های تنفسی در دو دهه گذشته تا حدی در نتیجه تغییر اقلیم در حال افزایش هستند. برای بسیاری از گونه های درختی، گراس و علف هرز افزایش تولید گرده و طول مدت گرده افشانی، منجر به افزایش طولانی مدت آلرژن های گرده ای در جو؛ جابجایی های زودهنگام دانه های گرده هوابرد و تماس طولانی مدت با آلرژن های تنفسی با اثرات مهم سلامتی بر روی افراد آلرژیک می گردد. هدف از این مقاله بررسی اثر تغییر اقلیم و عوامل هواشناختی بر روی شاخص های فصل گرده ای با یک تمرکز ویژه بر روی تاکسون های اصلی آلرژی زا در سرتاسر جهان است. متغیرهای اصلی تاثیرگذار بر فنولوژی گلدهی مانند موقعیت مکانی، عوامل اقلیمی و هواشناختی، شناسایی، مورد بحث و اثبات قرار گرفتند. دما، تشعشع خورشیدی، رطوبت، سرعت و جهت باد، از جمله مهمترین عوامل هواشناسی اثرگذار بر نوسانات غلظت سالانه گرده های هوابرد آلرژی زا هستند. اگرچه تغییرات قابل توجهی مطابق با گونه های آلرژی زا و ناحیه چغرافیایی مورد مطالعه مشاهده شد، اما به نظر می رسد دما مهمترین عامل اقلیمی اثرگذار بر فنولوژی گلدهی و شاخص های فصل گرده ای به ویژه در گونه های درختی باشد. افزایش سطوح دی اکسیدکربن همچنین منجر به افزایش زیست توده گیاهی، افزایش شدت گلدهی و تولید گرده در چندین گونه آلرژی زای درختی ، گراس و علف هرز می گردد. در پرتو این بررسی شواهد فزاینده ای وجود دارد که از تاثیر تغییر اقلیم بر فنولوژی گلدهی و شاخص های فصل گرده ای تعداد قابل توجهی از گونه های گیاهی مهاجم و زینتی آلرژی زا حمایت می کند.

واژه‌های کلیدی. آئروبیولوژی، آلرژی، هوابرد، تغییر اقلیم، عوامل هواشناختی، فنولوژی گلدهی

The impacts of climate change and meteorological factors on pollen season indicators of allergenic plant taxa

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Abstract. Pollen respiratory allergies have been increasing in prevalence over the last two decades, partly as the result of the impact of climate change. For many allergenic trees, grass and weed species, increased pollen production and prolonged pollination period result in long-term increased abundance of pollen allergens in the atmosphere; earlier shifts of airborne pollen grains and prolonged exposure to respiratory allergens with important health effects on allergic individuals. The aim of this review paper was to investigate the impact of climate change and meteorological factors on pollen season indicators with a special focus on the main allergenic taxa worldwide. Main variables influencing flowering

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phenology such as location, climatic and meteorological parameters were identified, discussed and substantiated by published literature. Temperature, solar radiation, humidity, rainfall, wind speed and direction were identified among the most important meteorological parameters affecting the fluctuations of annual concentrations of allergenic airborne pollen grains. Although notable variations were observed according to allergenic species and studied geographical areas, temperature appeared to be the most important climatic parameter affecting flowering phenology and pollen season indicators, especially in tree species. Rising carbon dioxide levels also result in increased plant biomass, increased flowering intensity and pollen production in several tree, grass and weed allergenic species. In the light of this review, there is a growing body of evidence supporting the effect of climate change on the flowering phenology and pollen season indicators of a substantial number of allergenic ornamental and invasive plant species.

Key words. aerobiology, allergy, airborne, climate change, meteorological factors, flowering phenology

Introduction

The issue of climate change, and particularly global warming resulting from anthropogenic activities, is one of the major environmental concerns that have attracted the attention of scientists and policy makers in the last two decades. This phenomenon is considered as one of the ten main factors that can endanger the life of living organisms (Doran & Zimmerman, 2009). Climate change means stable and long-term change in the Earth's climate patterns (caused by changes in climate components and the relationships between them) which is triggered by natural events and human activities (Ghahremaninejad et al., 2021; Solomon et al., 2007).

Airborne particles are all particles that are passively transferred by air. These particles may originate from biological source (bioaerosol) or non-biological (aerosol). Bioaerosols represent particles of biological origins with variable sizes ranging from 0.001 to 100 μm (Georgakopoulos et al., 2008). They include bacteria, viruses, pollen, fungi spores, bacterial endotoxins, antigens, allergens, toxins, mycotoxins, glucans, and plant fibers (Rogoff, 2013). The prevalence of bioaerosols in the environment is associated with many risks to human health such as pneumonia, influenza, allergies, SARS-CoV-2, etc. (Srikanth et al., 2008) .Pollen grains are large biological aerosol particles with a diameter of 10-100 µm constituting the major source of respiratory allergy worldwide (Cariñanos & Casares-Porcel, 2011; Charpin et al., 2019; Sénéchal et al., 2015). Anemophilous plant species release huge quantities of pollen grains into the atmosphere that are able to interact with other atmospheric components such as air pollutants, impacting their allergenic properties (Chassard et al., 2015; Duque et al., 2013; Frank & Ernst, 2016; Okuyama et al., 2007; Sénéchal et al., 2015). Aerobiology is the science studying airborne biological particles including pollen; it also examines the impact of climate modifications on bioaerosols. Aeropalynology specifically examines the behavior, interactions and biology of pollen grains released in the atmosphere (Cecchi et al., 2010; Corden & Millington, 2001).

Many airborne pollen grains released by tree, grass and weed species can cause pollinosis in susceptible individuals with symptoms such as watery eyes, eye irritation, runny nose, skin irritations, dry cough and sneezing (Mousavi et al., 2016; Mousavi et al., 2019). Several studies also reported a significant association between short-term exposure to pollen and asthmatic manifestations (Caillaud et al., 2014; Häfner et al., 2011; Kitinoja et al., 2020; Roberts et al., 2005). Therefore, the monitoring of airborne allergenic pollen grains can be helpful in predicting the severity of allergy seasons and appeared to be crucial for people suffering from pollinosis, estimated at 10-30% of the global population (Pawankar et al., 2011). By collecting and identifying pollen grains via appropriate methods and determining the time of their distribution in the air, a schedule could be applied and correlated to the date of allergy symptoms attack in sensitive people. This could help to determine the types of allergenic pollen grains occurring in each regions and to estimate the allergenic potential of different pollen species (Cariñanos González & Casares Porcel, 2019; Mansouritorghabeh et al., 2019).

Pollen calendars are used for graphic expression, timing, and pollen concentrations of different species in specific locations (Katotomichelakis et al., 2015). In Europe, long-term monitoring of pollen season of plant species is being carried out using a regular collection of relevant data, and many pollen monitoring stations in European countries are conducting regular and periodic surveys on airborne pollen grains (Sofiev et al., 2013). More than half of worldwide pollen monitoring stations are placed in this continent (598 out of 1013 active stations worldwide) (Buters et al., 2018). Most of them based on the Hirst pollen monitoring method (Hirst, 1952). The top European countries in terms of the number of active pollen monitoring stations are Italy (90 active stations), Spain (89 active stations), France (88 active stations) and Germany (58 active stations) (Buters et al., 2018); (https://www.zaum-online.de/pollen/pollen-monitoring-map-of-the-world.html, accessed12-08-2020). However, only a few countries in Europe, such as Switzerland, have government surveillance networks, and the majority of pollen and spore surveillance networks belong to the private sector, and in some cases their data are not freely available (Buters et al., 2018). In Asia, we can highlight the Japanese aerobiological network by its unique density (147 active stations). Although, historically the pollen time series are longer in other countries as India and Turkey. In Africa, most of the efforts to record airborne pollen are in the North African Mediterranean countries of Tunisia, Morocco and Algeria as well as in South Africa. In Oceania, a growing number of active stations are available in Australia since 2016 (21 active stations), following the dramatic thunderstorm event driven by airborne pollen causing 10 deaths (Thien et al., 2018). In America, pollen monitoring is performed routinely in most of the countries but the USA network shows the highest number (105 active stations) of recording stations (Fig. 1) (Buters et al., 2018; Hirst, 1952).

Pollen concentrations in an area are closely related to the distribution of plants in the area and are strongly influenced by climatic and meteorological factors (Lo et al., 2019). This review aimed at presenting relevant data that have been published on the influence of climate change and meteorological factors on pollen season indicators (main pollen season, pollen production, pollen concentration, annual pollen integral, and pollination peak value) of main allergenic plant taxa. This article also provides insights on climate parameters influencing pollen production in main allergenic plant species and their possible impacts on human health. We performed a literature search of google scholar using the 150 key words and summarized more than 100 scientific articles related to pollen season indicators, meteorological parameters, and climate change. Given that the present article is not a systematic review, we may not have identified all studies, and we must acknowledge a certain publication bias.

2. Flowering phenology and pollen season indicators

Phenology is the timing of repetitive events in the life cycle of plants and animals in response to seasonal and climatic changes, therefore, it is one of the most important indicators of climate change (Schwartz, 2003). In relation to plants and health impacts, one of the most important phenological events is the emergence of the first flowers and the spread of pollen. Therefore, the concentration of pollen in the air is strongly regulated by phenology and flowering intensity, and data related to airborne pollen are widely used as phenological indicators (Aguilera et al., 2015; Cecchi et al., 2010; Chuine et al., 1998; García-Mozo et al., 2009; García-Mozo et al., 2016).

Figure. 1. Overview of the total number of active pollen monitoring stations worldwide. (Buters et al., 2018; https://www.zaum-online.de/pollen/pollen-monitoring-map-of-the-world.html, checked 12-08-2020).

The production and distribution of pollen grains are strongly regulated by internal and environmental factors such as regional climate, age and size of the plant, phenology and genotype. Thus, phenological studies represent an efficient tool to differentiate airborne pollen concentrations both temporally and spatially (Aguilera & Valenzuela, 2012; Branzi & Zanotti, 1992; García-Mozo et al., 2016; Scheifinger et al., 2013; Walther et al., 2002).

In aeropalynology, various indicators are used to describe the pollen season; mainly depending on their suspected use, being for aerobiologists or medical uses in the context of preventive programs (Pfaar et al., 2017). These indicators include main pollen season (duration of time when a specific pollen is present in the atmosphere in significant concentrations at a location), pollen production (quantity of pollen produced per anther in angiosperms), pollen concentrations (the number of airborne pollen grains per unit volume of air), annual pollen integral (the sum of daily pollen concentrations for a specific taxon over the pollen year), and pollination peak value (the maximum daily count recorded during a pollen season) (Galán et al., 2017; Ruiz-Valenzuela & Aguilera, 2018; Zhang et al., 2015). These pollen season indicators are the consequence of a combination of processes as pollen production, emission, and dispersion. Each one depends on a combination of plant endogenous factors, the environmental conditions, or the analyzed parameter. Annual pollen integral of allergenic pollen grains correlated with the severity of pollinosis symptoms among sensitized individuals and could be used to present inter-annual variations (Bastl et al., 2016).

3. The effect of climate change on flowering phenology and pollen season indicators

Climate, and especially the prevailing weather during the plant growth season, is the most important factor influencing plant phenology (Schwartz, 2003). The impacts of climate change on reproductive phenology and pollen season have been extensively studied by the analysis of long-term trends of pollen time series. Most of the analyses are based on simple linear regression between the parameters and the time, or decomposing the time series components (García-Mozo et al., 2014). So far, the short-term and long-term effects of environmental and meteorological factors such as light, temperature, rainfall, relative humidity, snow cover, hours of sunlight, and wind speed on the pollination period and the concentration of airborne pollen grains have been well-documented. These effects vary depending on the type of taxon and different climates (Dąbrowska-Zapart et al., 2018; Donders et al., 2014; Emberlin et al., 2002; Galán et al., 2005). The pollen concentration is strongly influenced in hot and dry climates by average and maximum temperatures and water availability, while in semi-arid climates, it mainly relies on relative humidity, rainfall, hours of sunlight and daily temperature fluctuations (Rodriguez-Rajo et al., 2004). In the Mediterranean climate, pollen concentration is mainly impacted by rainfall and ambient temperature (Aboulaich et al., 2013; Uguz et al., 2017), in the semi-tropical climates by maximum temperature (Green et al., 2004) and in areas with temperate climates by relative humidity and maximum air temperatures (Puc, 2012).

Climate can affect the pollen production and pollination period, and consequently, the pollen concentration in the air. Several variations in the phenological behavior of plants over time, as a consequence of climate change have been reported. These changes are especially relevant for pollen exposure, especially those related to flowering phenology of anemophilous plants. For example, the International Phenological Gardens Network reported a six-day advance of the onset of spring events over a thirty-year period, with the highest rates of change in the Baltic region and Western Europe (Menzel & Fabian, 1999). It was found that climate change caused an up to six-day advance of phenological events in early spring and an up to five-day delay of autumn events in comparison with the early 1960s (Walther et al., 2002). Menzel (2000)reported a six-day advance for the flowering of some flowers over a 45-year period (1951-1996) in Europe (Menzel, 2000), and Fitter and Fitter (2002) have reported early flowering onset (about 4 to 5 days) for Great Britain over 10 years (Fitter & Fitter, 2002). In another study, Spieksma et al. (2003) analyzed several allergenic plant species to define their annual pollen integral in five cities located in Western Europe (Spieksma et al., 2003). Worryingly, data related to the highly allergenic birch pollen showed a rising trend in all studied stations and countries, although only two of the five rising trends were significant over time. A phenological study preformed in Switzerland between 1951 and 1998 showed a tendency towards earlier onset of the main pollen season in the spring and a weak tendency to start the main pollen season later in the fall (Defila & Clot, 2001). Bortenschlager and Bortenschlager (2005) reported that the flowering period of six taxa began earlier in Austria, thereby increasing the duration of the main pollen season of these species (Bortenschlager & Bortenschlager, 2005). In addition, pollination peak values and total pollen production showed an increasing trend. In contrast, in Eastern Europe, phenological trends sometimes showed a delay of one to two weeks at the onset of spring events, mainly due to colder winters observed in these areas (Ahas et al., 2002).

Regarding pollen concentrations, an Italian study performed in Genova, found that the annual pollen concentration of *Parietaria* L. considerably increased from 1981 to 1997, while no significant increase in the pollen concentrations of *Artemisia* L. and Poaceae Barnhart were reported. (Voltolini et al., 2000). A longer duration of the pollen season has been also evidenced in Italy, peculiarly in summer (Beggs, 2004) as in the case of the Urticaceae Juss. (Frenguelli, 2002). In a grassy area in North America using simulated warming, rising temperatures led to the advance of main pollen season for species that flowered naturally before the peak of summer temperatures, and also delayed the start of the main pollen season for species such as ragweed in which their flowering occurs after the peak of summer temperatures (Sherry et al., 2007). Based on a new method using dynamic systems, the effects of climate change on the concentration of airborne pollen grains can be predicted. Accordingly, de León et al. (de León et al., 2015) were able to predict an increase in the pollen concentration by 2070 from 28.5 to 44.3%, by examining the airborne pollen fluctuations of grass species from 1982 to 2012 in the city of Córdoba in southern Spain. The results of the studies investigating the effect of climate and meteorological parameters on flowering phenology and pollen season indicators of allergenic herbaceous taxa (grasses and weeds) are summarized in Table 1 and 2. Correlating data on aerobiological factors such as the onset, peak and main pollen season of allergenic species with pollen

Table 1. Studies investigating the effect of climate change and metrological factors on flowering phenology and pollen season indicators of allergenic herbaceous taxa (grasses).

Pollen Taxon	**Parameter (s)**	**Location & time period**	**Phenology/ pollen season indicators**	**Reference (s)**
Bromus japonicus, Dichanthelium oligosanthes, Panicum virgatum	Temperature	McClain (US) (2003-2004)	Main pollen season (Earlier flowering)	(Sherry et al., 2007)
Andropogon gerardii, Schizachyrium scoparium	Temperature	McClain (US) (2003-2004)	Main pollen season (Delayed flowering)	(Sherry et al., 2007)
Poaceae	Temperature	Liguria (Italy) (1981-2007)	Main pollen season (Increased duration, advanced onset date)	(Ariano et al., 2010)
Poaceae	North Atlantic Oscillation (NAO)	Iberian Peninsula (Spain and Portugal) (1994-2013)	Annual Pollen integral (Decreased)	(Galán et al., 2016)
Poaceae	Wind direction	Guadalajara (Spain) (2008-2013)	Pollen concentration (Concentration fluctuations)	(Rojo et al., 2015)
Poaceae	Temperature, Relative humidity, Wind speed, Radiation, Rainfall, Wind calm frequency	Brussels (Belgium) (1982-2015)	Pollen concentration (Decreased diurnally)	(Bruffaerts et al., 2018)
Poaceae	Temperature, Relative humidity, Wind speed, Radiation, Rainfall, Wind calm frequency	Brussels (Belgium) (1982-2015)	Main pollen season (Earlier flowering)	(Bruffaerts et al., 2018)
Poaceae	Temperature, Relative humidity	Šiauliai (Lithuania) (2010-2018)	Pollen concentration (Effected concentration)	(Sauliene et al., 2019)
Poaceae	Temperature, Solar irradiance, Sunlight	Guadalajara (Spain) (2008-2013)	Pollen concentration (Increased)	(Rojo et al., 2015)
Poaceae	Rainfall, Relative humidity	Guadalajara (Spain) (2008-2013)	Pollen concentration (Decreased)	(Rojo et al., 2015)

Table 2. Studies investigating the effect of climate change and metrological factors on flowering phenology and pollen season indicators of allergenic herbaceous taxa (weeds).

Pollen Taxon	**Parameter (s)**	**Location & time period**	**Phenology/ pollen season indicators**	**Reference (s)**
Ambrosia psilostachya	Temperature	Norman (Oklahoma) (1999-2001)	Pollen concentration (Increased)	(Wan et al., 2002)
Viola bicolor, *Veronica arvensis*, *Cerastium glomeratum*, *Plantago virginica*, *Achillea millefolium*, *Erigeron strigosus*	Temperature	McClain (US) (2003-2004)	Main pollen season (Earlier flowering)	(Sherry et al., 2007)
Ambrosia psilostachya	Temperature	McClain (US) (2003- 2004)	Main pollen season (Delayed flowering)	(Sherry et al., 2007)
Parietaria	Temperature	Liguria (Italy) (1981-2007)	Main pollen season (Increased duration, advanced onset date) Pollen concentration (Increased)	(Ariano et al., 2010)
Plantago major, Urticaceae	Temperature	Jaen (Spain) (1994-2016)	Pollen concentration (Decreased)	(Ruiz-Valenzuela & Aguilera, 2018)
Artemisia	Temperature	Poznan (Poland) (1995-2004)	Pollen concentration (Increased daily)	(Stach et al., 2007)
Artemisia	Relative humidity	Poznan (Poland) (1995-2004)	Pollen concentration (Decreased daily)	(Stach et al., 2007)
Ambrosia	Latitude	Maryland (US) (1995-2009)	Main pollen season (Increased duration)	(Ziska et al., 2003)
Artemisia	Rainfall	Córdoba (Spain) (1991-2011)	Main pollen season (Earlier flowering, Increased duration)	(Cariñanos et al., 2014)
Amaranthaceae	Rainfall	Iberian Peninsula (Spain and Portugal) (1994-2013)	Annual pollen integral (Increased)	(Galán et al., 2016)
Urticaeae, *Plantago*, *Rumex*, Amaranthaceae, *Artemisia*	North Atlantic Oscillation (NAO)	Iberian Peninsula (Spain and Portugal) (1994-2013)	Annual pollen integral (Decreased)	(Galán et al., 2016)
Chenopodiaceae–Amaranthaceae, Urticaceae, *Plantago*, *Rumex*	Wind direction	Guadalajara (Spain) (2008-2013)	Pollen concentration (Concentration fluctuations)	(Rojo et al., 2015)
Artemisia vulgaris	Temperature, Relative humidity, Wind speed, Radiation, Rainfall, Wind calm frequency	Brussels (Belgium) (1982-2015)	Pollen concentration (Decreased diurnally)	(Bruffaerts et al., 2018)
Urticaceae	Temperature, Relative humidity, Wind speed, Radiation, Rainfall, Wind calm frequency	Brussels (Belgium) (1982-2015)	Main pollen season (Earlier flowering)	(Bruffaerts et al., 2018)
Artemisia	Temperature, Relative humidity	Šiauliai (Lithuania) (2010-2018)	Pollen concentration (Effected concentration)	(Sauliene et al., 2019)
Chenopodiaceae–Amaranthaceae, Urticaceae, *Plantago*, *Rumex*	Temperature, Solar irradiance, Sunlight	Guadalajara (Spain) (2008-2013)	Pollen concentration (Increased)	(Rojo et al., 2015)
Chenopodiaceae–Amaranthaceae, Urticaceae, *Plantago*, *Rumex*	Rainfall, Relative humidity	Guadalajara (Spain) (2008-2013)	Pollen concentration (Decreased)	(Rojo et al., 2015)

concentration data can be used as evidence for changes in the flowering and onsets of main pollen season as well as for the prediction of pollen season of the species of interest (Clot, 2003; Emberlin et al., 2002; Galán et al., 2005; Huynen, 2003; Rasmussen, 2002; Van Vliet et al., 2002). In this regard, the majority of studies have focused on allergenic plants such as *Betula* L. (Emberlin et al., 2002; Van Vliet et al., 2002), *Artemisia vulgaris* L. (Stach et al., 2007), Urticaceae Juss. (Frenguelli, 2002), grasses (Burr, 1999; Emberlin et al., 1999), *Quercus* L. (García-Mozo et al., 2006; Van Vliet et al., 2002), *Cedrus* Mill. (Tosunoglu et al., 2015) and *Platanus* L. (Tedeschini et al., 2006). Some studies have predicted the advance of the onset of the main pollen season from one to three weeks for *Olea europea* L. (Galán et al., 2005) and one month for oak by the end of the century (García-Mozo et al., 2006). Also, the increase in spring temperature in the Mediterranean region leads to earlier flowering of olive trees (Garcia-Mozo et al., 2009; Orlandi et al., 2010). Likewise, in Italy, prediction models point towards a prolonged pollination period for olive trees throughout the 21st century (Avolio et al., 2012). Spieksma et al. (1995) examined the birch pollen concentration in the European atmosphere and reported quantitative annual fluctuations and changes in onset dates of the main pollen season (Spieksma et al., 1995). This study revealed that the main pollen season of the birch tree shows a tendency towards an earlier onset, which has nothing to do with the observed weather trends. Likewise, Emberlin et al.'s research (1997) on the onset of the main pollen season of birch in three regions of the United Kingdom over a 42-year period showed a tendency for the main pollen season to onset earlier (Emberlin et al., 1997). However, in this latter study, this trend was closely related to higher temperature records (more than 5.5 degrees centigrade) from January to March with 3-month cumulative temperatures ranging from 25 to 30 degrees centigrade for the study sites. Interestingly, the main pollen seasons of birch have advanced in the studied areas by about Five days per decade. In another study, Emberlin et al. (2002) investigated over a 20-year period the correlation between the temporal patterns of change in spring temperatures and changes in the onset of the main pollen season of birch in several selected areas in Europe (Brussels, Kevo, London, Turku, Vienna and Zurich), in order to predict these patterns for the next ten years. Accordingly, the city of Kevo showed a six-day delay, the cities of London, Brussels, Zurich, and Vienna showed about a six-day advance, and the city of Turku showed a cyclical pattern (Emberlin et al., 2002). Early flowering of *Bromus rubens* Delile. and *Hordeum leporinum* Link., that routinely bloom in in start of spring, in years with higher mean winter temperatures and *Trisetaria panicea* (Lam.) Paunero and *Dactylis glomerata* subsp. *hispanica* (Roth) Nyman, that routinely bloom in mid to late spring in years with higher cumulative rainfall in spring and winter has been reported in city of Toledo, Spain (Romero-Morte et al., 2020).

Some studies have examined simultaneously a wide range of pollen flora in a specific area. For example, Clot's study showed that 71% of the main pollen season onset or end dates show a significant advance, and for the majority of pollen species, the main pollen season does not last longer but changes over time(Clot, 2003). Both Damialis et al. (2007) and Cristofori et al. (2010) reported a trend towards a significant increase of pollen concentrations for the majority of plant taxa. In these studies, tree species showed a significant increase in their pollen production compared to herbaceous plants (Damialis et al., 2007) (Cristofori et al., 2010) . Table 3 provides a summary of studies investigating the effect of climate and meteorological parameters on flowering phenology and pollen season indicators of allergenic tree taxa.

Investigation of the main pollen season changes in allergenic species of birch (*Betula*), oak (*Quercus*), mugwort (*Artemisia*), and grass (Poaceae) using registered data related to daily airborne pollen grains and climatic factors from 1994 to 2010 across the contiguous USA has shown that the main pollen season of trees, grasses, and weeds during the 2001-2010 decade has advanced three days on average when compared to the previous decade (1994-2000). Also, the average peak value and the total number of annual airborne pollen recorded daily were 42.2% and 46% higher, respectively (Zhang et al., 2015).

During an 18-year study, Scevkova et al. (2021) examined the duration and intensity of the pollen season in three allergenic taxa (*Alnus* Mill., Poaceae, *Artemisia*). During this period, the flowering period was shorter for Poaceae and *Artemisia*. The pollination peak reached earlier for *Alnus* and *Artemisia*. *Alnus* peak value showed a significant rising trend and the duration of pollen season and peak values of *Artemisia* and Poaceae had a declining trend (Ščevková et al., 2021).

Seasonal variations of airborne pollen concentrations can be related to phenological and/or meteorological factors. In this regards, a quantitative evaluation of airborne pollen in during 2018 to 2020 showed that the highest concentration of airborne pollen is related to spring and autumn. This could be due to the favorable phenological and meteorological factors for plant growth, dispersion and pollen transfer in these seasons (Ravindra et al., 2021).

Table 3. Studies investigating the effect of climate change and metrological factors on flowering phenology and pollen season indicators of allergenic arboreal taxa (trees).

Pollen Taxon	Parameter (s)	Location & time period	Phenology/ pollen season indicators	Reference (s)
Betula	Temperature	Basel (Switzerland) (1969-2006)	Main pollen season (Earlier flowering) Annual pollen integral (Increased) Pollination peak value (Increased)	(Frei & Gassner, 2008)
Betula, *Cedrus*, *Olea*	Temperature	Liguria (Italy) (1981-2007)	Main pollen season (Increased duration, advanced onset date) Pollen concentration (Increased)	(Ariano et al., 2010)
Betula	Temperature	(Finland) (1974-2004)	Pollen concentration (Increased)	(Yli-Panula et al., 2009)
Cupressaceae, *Olea*, *Pinus*, *Platanus*, *Quercus*	Temperature	Jaen (Spain) (1994-2016)	Main pollen season (Increased duration) Pollen concentration (Increased)	(Ruiz-Valenzuela & Aguilera, 2018)
Betula	Altitude	Zugspitze (Germany) (2009-2010)	Pollen concentration (Decreased)	(Jochner et al., 2015)
Pinus taeda	Carbon Dioxide	North Carolina (US) (1996-2004)	Main pollen season (Advanced onset date, prolonged pollen season) Pollen concentration (Increased)	(LaDeau & Clark, 2006)
Cupressaceae, *Quercus*, *Platanus*, *Olea*, *Populus*, *Pinus*, *Ulmus*, Moraceae, *Fraxinus*	Wind direction	Guadalajara (Spain) (2008-2013)	Pollen concentration (Concentration fluctuations)	(Rojo et al., 2015)
Alnus, *Corylus*, *Betula*, *Carpinus*, *Quercus*, *Fraxinus*, *Platanus*	Temperature, Relative humidity, Wind speed, Radiation, Rainfall, Wind calm frequency	Brussels (Belgium) (1982-2015)	Pollen concentration (Increased diurnally)	(Bruffaerts et al., 2018)
Betula, *Quercus*, *Fraxinus*, *Platanus*	Temperature, Relative humidity, Wind speed, Radiation, Rainfall, Wind calm frequency	Brussels (Belgium) (1982-2015)	Main pollen season (Earlier flowering)	(Bruffaerts et al., 2018)
Quercus	Temperature, Radiation, Wind speed, Wind frequency	Malaga (Spain) (1992-2015)	Pollen concentration (Increased diurnally and weekly)	(Recio et al., 2018)
Quercus	Rainfall, Relative humidity	Malaga (Spain) (1992-2015)	Pollen concentration (Decreased diurnally and weekly)	(Recio et al., 2018)
Alnus, *Betula*, *Corylus*	Temperature, Relative humidity	Šiauliai (Lithuania) (2010-2018)	Pollen concentration (Effected concentration)	(Sauliene et al., 2019)
Cupressaceae, *Quercus*, *Platanus*, *Olea*, *Populus*, *Pinus*, *Ulmus*, Moraceae, *Fraxinus*	Temperature, Solar irradiance, Sunlight	Guadalajara (Spain) (2008-2013)	Pollen concentration (Increased)	(Rojo et al., 2015)
Cupressaceae, *Quercus*, *Platanus*, *Olea*, *Populus*, *Pinus*, *Ulmus*, Moraceae, *Fraxinus*	Rainfall, Relative humidity	Guadalajara (Spain) (2008-2013)	Pollen concentration (Decreased)	(Rojo et al., 2015)

3.1 Effect of temperature

Flowering phenology in many plant species appeared to be closely related to temperature when compared to other metrological parameters (Moore & Lauenroth, 2017). The impact of temperature on plants reproductive behavior depends on the exposure time along the reproductive cycle (Rojo et al., 2020). Also, it is essential to take into account that the impact of weather conditions depends on the state of the plants and the range of values (Oteros et al., 2013a; Oteros et al., 2013b). In tree species, flowering phenology is specifically regulated by temperature and in herbaceous species, it is regulated by temperature and water availability (García-Mozo et al., 2016). Flowering phenology of plants pollinating in spring and early summer is strongly influenced by temperature, while the photoperiod was found to be more important for plants flowering from late summer to autumn (Beaubien & Freeland, 2000). In addition to the variation of temperatures in spring and increased global temperatures leading to milder winters and warmer springs may result to the early flowering of many spring species in different regions (Fitter & Fitter, 2002; Linderholm, 2006; Menzel, 2000). Based on the Marsham family phenological data record (1736), Margary suggested that if spring average temperatures increased by one degree centigrade, a 5- to 7-day advance in spring events would be expected (Menzel, 2000).

Studies on ragweed (*Ambrosia psilostachya* DC.) showed that, when plants are exposed to high temperatures, the number of their stems increased by 88%, which increases the pollen production rate in each pot by 84% (Wan et al., 2002). In another study, Sherry et al. (2007) looked at the effects of rising ambient temperatures on the flowering of a number of species and reported early flowering in species that flower in spring and early summer (Sherry et al., 2007). However, species that flowered naturally in late summer and autumn showed a delay in flowering.

Frei and Gassner (2008) used data from long-term airborne pollen data in Basel, Switzerland, for a period of 38 years and reported that flowering season in birch occurs 15 days earlier due to the increase in the temperature and also, there was a tendency to increase the annual pollen integral and the daily peak value (Frei & Gassner, 2008).

Ariano et al., in a 27-year long-term study (between 1981 and 2007), studied the effect of climate changes, especially rising temperatures, on the pollen season of 5 major allergenic pollen (birch, olive, cedar, *Parietaria* and grass) in Liguria (Italy) (Ariano et al., 2010). The results showed that duration of the main pollen season increased for *Parietaria* spp. (85 days), cedar and olive (18 days each). In all mentioned species, a general advance of the main pollen season was also observed. The pollen concentrations of all intended species other than grasses also increased by an average of about 25 percent. These behaviors were parallel to the increase in the continuity of direct radiation, temperature, and the number of days with temperatures above 30 degrees centigrade. A long-term study performed by Yli-Panula et al. (2009) demonstrated that high temperatures promote early phenological advance and increase concentrations of birch airborne pollen during a 31-year period in the Turku region of Finland. However, no changes were reported in the main pollen season (Yli-Panula et al., 2009).

According to the Intergovernmental Panel on Climate Change, the increase in temperatures is closely associated with the latitude. Ziska et al. (2003) investigated and compared the main pollen season of the ragweed from 1995 to 2009 in North America. Their data showed a significant increase in the main pollen season of ragweed from 13 to 27 days at latitude above 44 ° N (Ziska et al., 2003).

A study investigating changes in the pollen spectrum of twelve types of allergenic airborne pollens from southern Spain over a 23-year period by Ruiz-Valenzuela and Aguilera (2018) that, with increasing temperature, the pollen concentration of wood species increases, while the pollen concentrations in grass and weed taxon's especially *Plantago major* L., shows a decreasing trend (Ruiz-Valenzuela & Aguilera, 2018). Therefore, the main pollen season of tree species appears to be more affected by temperature fluctuations and showed significant changes in response to climate change. The main pollen season of these tree species also shows a tendency to become longer. The results of several researches suggested that *Quercus*, *Platanus*, *Pinus* L. and Cupressaceae Gray pollen grains, along with *Plantago* L. pollen grains could be used as efficient biological indicators for identifying local climate change (Ziska et al., 2019). In various geographic locations across the northern hemisphere, most recent investigations demonstrated that an increase in temperature (minimum and maximum temperatures) significantly contributed to increased pollen concentrations and extended the main pollen season for numerous airborne allergic pollen species (Ziska et al., 2019). Some studies also point other factors closely related to temperature, like slope orientation or altitude, as relevant driver of flowering phenology e.g. (Oteros et al., 2013c)

3.2. The Effect of carbon dioxide

High levels of CO2 may increase the concentration of airborne pollen grains in large cities and thus increase respiratory allergies. Carbon dioxide from human activities, as a major factor implicated in climate change, has direct (stimulating photosynthesis and plant growth) and indirect (increasing the average surface temperature of the Earth) effects on plants (Ziska et al., 2012). Pioneer researches showed an increase in the atmospheric concentrations of carbon dioxide, about 200 ppm above the ambient atmosphere values (600 ppm), highly stimulated photosynthesis by up to 60% in some C3 plants (Curtis & Wang, 1998; Jablonski et al., 2002; Norby et al., 1999). This change in carbon adsorption may directly or indirectly impact the physiology, phenology the reproductive behavior and the geographical distribution of plant species. As a result, the plant's biomass, the number of flowers and pollen production significantly increased, and subsequently, the concentration of allergenic airborne pollen is affected (Jablonski et al., 2002). For example, some studies performed on the invasive and highly allergenic ragweed plant have reported a significant increase in the number of flower spikes per bush and a 60 to 90 percent increase in pollen production under an approximate doubling of carbon dioxide concentrations (Rogers et al., 2006; Singer et al., 2005; Wayne et al., 2002). A study on one of the fastest-growing pine species (*Pinus taeda* L.), extensively planted worldwide has shown that increasing concentrations of carbon dioxide led to an elevated pollen production as well as to the early onset and prolongation of the main pollen season (LaDeau & Clark, 2006). Likewise, rising temperatures and carbon dioxide appeared to significantly increase pollen production in many common species (Blando et al., 2012).

Other studies showed that an enrichment with 500 to 800 ppm carbon dioxide of plant reproductive organs led to a 31% increase of the total plant mass and the intensity of flowering was 19% higher in treated crop and wild plant species in comparison with controls (Curtis & Wang, 1998; Jablonski et al., 2002). In one study, Knapp and Soulé (1998) studied the spread of *Juniperus occidentalis* Hook. populations under increased amounts of atmospheric carbon dioxide over a 23-year period in Oregon (Knapp & Soulé, 1998). Their results showed that increasing atmospheric carbon dioxide would preferably increase the growth and spread of young trees. In addition, similar studies have suggested that ragweed quantitative and qualitative spread during the twentieth century has been due to increased concentrations of atmospheric carbon dioxide (Singer et al., 2005; Ziska & Caulfield, 2000).

3.3. The effect of rainfall

Rainfall can have a dual effect on the concentration of airborne pollen. Like temperature, the impact of rainfall depends directly on the exposure time along the reproductive cycle. In some studies, the rain during the main pollen season has reduced the pollen concentration in the atmosphere, thereby reducing the allergy symptoms caused by herbaceous pollen grains (Ursu, 2012). In contrast, after heavy rains, increased concentrations of pollen, other bio-aerosols and free allergen molecules binding airborne particles have been reported (Huffman et al., 2013; Müller-Germann et al., 2015; Schäppi et al., 1997; Taylor et al., 2007). It appeared that in a warmer climate, heavy rains will increase and tend to fewer but more intense events. In this respect, it comes that heavy rainfalls and strong winds increased asthma attacks among pollen allergic individuals, a phenomenon repeatedly reported and known as thunderstorm asthma in many regions worldwide (Girgis et al., 2000; Suárez-Varela et al., 2008).

In Poland, the flowering phenology of *Artemisia* pollen as one of the most important causes of respiratory allergies appeared to be affected by climate change, especially rainfall. In a study on the concentration of *Artemisia* airborne pollen grains between 1995 and 2004 in southern Poland (Poznan), Stach et al. (2007) reported that the main pollen season of *Artemisia* is greatly affected by rainfall in weeks preceding the pollen season, which the main pollen season starts earlier and lasts longer. The authors also reported a direct effect of the temperature on the daily pollen concentration in this genus, while relative humidity has the opposite effect on its pollen concentration (Stach et al., 2007).

Cariñanos et al. (2014) investigated a 21-year data set (1991-2011) related to airborne pollen grains of Amaranthaceae Juss. in Córdoba, in the southern Iberian Peninsula, to assess the impact of climatic conditions on pollen season indicators. This study revealed the very long persistence (from early spring to early autumn) of Amaranthaceae pollen in the atmosphere. The annual pollen integral showed a significant increase (from approximately 200 pollen grains to about 2,000 pollen grains) which was strongly affected by rainfall during the flowering period, causing the growth of new plants and thus increased pollen production (Cariñanos et al., 2014).

In southern Europe, lack of access to water may lead to a decline in flowering, especially in herbaceous species (Alcázar et al., 2009; Recio et al., 2009). As North Atlantic Oscillation (NAO) also affects rainfall (Gallego et al., 2005), Galán et al. (2016) examined over two decades (1994-2013) the effect of NAO on the flowering intensity of 12 inflated taxa at 12 locations of the Iberian Peninsula by analyzing and comparing their annual pollen index (API). Their results showed a negative relationship between the pollen concentration in the atmosphere and the NAO index averages during winter(Galán et al., 2016). These results suggested that the phenology of many Mediterranean species is influenced by variations in rainfall, partly driven by climate change.

3.4. The effect of atmospheric pollutants

Among the factors that may affect the concentration of airborne pollen grains are atmospheric pollutants in urban areas such as suspended particles in the atmosphere (PM, coarse and fine), ozone (O3), carbon monoxide (CO), dioxide nitrogen (NO2) and sulfur dioxide (SO2) (Sauliene et al., 2019). Orby et al. (2015) showed that there was a significant association between pollen concentrations and atmospheric ozone (Ørby et al., 2015). Sauliene et al. (Sauliene et al., 2019) also showed that the concentrations of O3 and PM10 pollutants were significantly associated with the concentration of airborne pollen grains during the main pollen season. The SO2 pollutant showed a positive correlation with Betulaceae Gray pollen concentrations and a negative correlation with grasses pollen concentrations. Recently, Oduber et al. (2019) studied the effect of air pollutants concentration on airborne pollen grains concentration. The researchers looked at the association of pollen concentration trends of allergenic species i.e *Fraxinus* Tourn. ex L., Poaceae, and *Populus* L. with the concentration trends of O3, NO2, NO, CO, SO2 and, PM10 atmospheric pollutants over the past two decades in the city of Leon. In this study, a significant decreasing trend was observed in the concentration of air pollutants, while the concentration of *Fraxinus* airborne pollens a significantly decreased. No tendency was reported for the advance or delay of the main pollen season of any of the three taxa. Analysis of their data using the Spearman correlation method showed that the duration of flowering and pollination is highly dependent on the weather conditions before these periods and is affected by the concentrations of atmospheric pollutants. However, they were unable to find any statistically significant relationship between airborne pollen concentrations and air pollution during pollination periods (Oduber et al., 2019). Therefore, although the effect of air pollutants on the allergen content of pollen grains is well documented (Chassard et al., 2015; Frank & Ernst, 2016; Mousavi et al., 2019; Sénéchal et al., 2015 (Shahali et al., 2009), it does not appear to be a clear relationship between air pollution parameters and the concentration of airborne pollutants, although further research is needed.

3.5. The effect of land use

One of the important reasons for the difference in flowering phenology and pollen season indicators among plant species and in different parts of the world is the difference in land use (Scheifinger et al., 2013). Land use determines the number of individuals of a plant species in a given area (García-Mozo et al., 2016). As the airborne pollen grains identified in a given area is directly related to local land uses, this factor can strongly influence changes in the pollen spectrum and the concentration of airborne pollen grains (Galán et al., 2016). García-Mozo et al. (2016) investigated the common influence of climate variables and land use change on airborne pollen concentrations fluctuations in the city of Cordoba (southern Spain) over a 15-year period. A significant increase in some pollen types such as olives and grasses was found, while the airborne pollen concentration of some invasive taxa such as Amaranthaceae, *Rumex* L., *Plantago*, Urticaceae decreased, which could be related to fluctuations in vegetation, climate or land use change (García-Mozo et al., 2006). In another study, using comprehensive modeling methods, Hamaoui-Laguel et al. (2015) estimated that by 2050, the concentration of ragweed airborne pollen grains, an allergenic invasive species in Europe (Kazinczi et al., 2008), would be four times higher (Hamaoui-Laguel et al., 2015). This prediction largely depends on the hypotheses of the pollen distribution rate. About two-thirds of the ragweed airborne pollen concentration is related to land use change and climate change. Therefore, land use change and climate change could lead to the expansion of ragweed habitats in northern and eastern Europe, thereby increasing ragweed pollen production levels in these areas in the coming years (Kazinczi et al., 2008).

3.6. The effect of urbanization

The physical properties of the lower layers of the atmosphere could be modified both horizontally and vertically by urban environments. This leads to a change in the equilibrium of solar radiation and creates an urban heat island which is the term used to describe the dome of warm air covering large cities (Cecchi et al., 2010). This phenomenon, which is characterized by higher temperatures, lower air humidity levels, and warm winds t, causes pollen deposition and changes in pollen distribution patterns in cities and prolonged plant growing periods and thus increases airborne pollen grains concentration (Mimet et al., 2009; Unger, 1999). This phenomenon leads to the pollen season advance in urban areas compared to rural areas in about 2 to 4 days (D'Amato, 2011). Also, in cities, the increase in turbulence caused by specific thermal wind patterns can transfer pollen grains from suburban areas to urban centers (Emberlin & Norris-Hill, 1991). In urban areas, earlier flowering and pollination have been reported for *Ambrosia* L. compared to rural areas (Ziska et al., 2003). The same observations have been reported for some allergenic tree species such as *Platanus acerifolia* (Aiton) Willd. (Emberlin & Norris-Hill, 1991) and a number of non-allergenic plants. However, in the case of *Ambrosia* spp., rising temperatures and high concentrations of carbon dioxide in urban areas have led to a significant reduction in the urban population of this invasive species (Ziska et al., 2007). There is evidence that urbanization can significantly reduce herbaceous pollen grains such as grasses (Cecchi et al., 2010). The declining trend in the number of grass annual pollen related to urbanization in Leiden (Netherlands) (Jäger et al., 1991), London and Derby (UK) (Emberlin et al., 1999; Frenguelli, 2002), Parma (Italy) (Ridolo et al., 2007), and even lower pollen peaks and fewer pollination days have been reported in other studies (Jato et al., 2009; Minero et al., 1998).

3.7. Combined effect of several parameters

Some studies have studied the simultaneous effect of several meteorological parameters on the concentration of airborne pollen grains. For example, a study performed between 1982 and 2015 in Brussels (Bruffaerts et al., 2018) examined the relationship between pollen concentrations and meteorological parameters. Using daily data obtained from 11 pollen types (8 tree species and 3 herbaceous species) and 10 meteorological parameters, a general increasing trend in daily airborne pollen grains of tree species (except for European beech species) and a general decreasing trend in daily airborne pollen grains for herbaceous species (except Urticaceae) were reported. Early flowering was also observed for birch, oak, ash, plane tree, grass, and Urticaceae trees. The rate of change in the annual cycle of several meteorological parameters such as rainfall, humidity temperature and radiation, was significantly associated with the rate of change in the annual cycle of airborne pollen grains (Bruffaerts et al., 2018).

In oak, the formation of flower buds is very sensitive to temperature. In this regard, a 25-year aerobiological study of the effect of climate variables on oak pollen atmospheric concentrations in the coastal city of Malaga (southwestern Mediterranean basin) showed that fluctuations in oak pollen atmospheric concentrations (daily and weekly values) are significant and has a positive relationship with temperature, changes in solar radiation, wind speed, and northwest wind frequency, and a negative relationship with precipitation and relative humidity. The peak of oak pollen production was observed almost every four years, which corresponds to periods of drought. These results suggest that the reason for the observed trend in oak pollen production is probably the increase in atmospheric temperature and drought, which is increasing in the western Mediterranean region (Recio et al., 2018). Sauliene et al. (2019) examined the relationship between the airborne pollen concentration of three taxa of the birch genus (*Alnus*, *Betula* and *Corylus* L.), grasses, and *Artemisia* genus with a set of meteorological factors and air pollution levels in Lithuania between 2010 and 2018. The results showed that the relative humidity and air temperature parameters had a significant effect on the airborne pollen concentrations of *Alnus*, *Artemisia*, *Betula*, *Corylus* and Poaceae. However, wind speed has little to do with the concentration of these airborne pollutants. Temperature conditions had the greatest impact on the concentration of *Corylus* and *Alnus* pollen grains (both early in flowering). There was no statistically significant relationship between *Corylus* pollen concentrations and air pollution. *Betula* and grasses pollen concentrations also had a positive correlation with ozone pollution (Sauliene et al., 2019).

Wind speed and direction (Damialis et al., 2005; Palacios et al., 2000) is one of the most important determinants of the distribution and transmission of airborne pollen grains. Small pollen grains are able to reach the upper layers of the atmosphere and travel long distances (Hernández-Ceballos et al., 2011; Rojo & Pérez-Badia, 2015; Smith et al., 2008). Most pollen grains do not travel a long distance from the emission area and are often distributed locally (Lavee & Datt, 1978). Therefore, the pollen spectrum provides important indications regarding the vegetation in/close to the area (Hamaoui-Laguel et al., 2015; González Minero & Candau, 1997). Rojo et al. (Rojo et al., 2015) examined and analyzed the pollen spectrum of the city of Guadalajara (central Spain) up to a radius of 20 km from the perspective of vegetation and land use in order to identify the source of pollen in the air and further explore the potential effect of meteorological parameters on pollen propagation. This study revealed that the local wind direction was one of the most important variables influencing the concentration of different types of airborne pollen grains, and land use played a key role in airborne pollen counts and distribution in urban green spaces. The propagation of pollen grains from ornamental species was strongly influenced by eastern winds (plane tree), southern winds (cedar), western winds (cedar and plane tree) of the areas where the largest parks and gardens of the city were located. Cedar pollen is basically transmitted by the wind from the eastern edge of the city. Most pollen counts of *Populus* were related to western and eastern winds in environments containing rivers and streams. Temperatures, hours of solar irradiance and sunlight had a positive effect on the number of pollen grains in the air, while rainfall and relative humidity had a negative effect.

A study performed by Alan et al. (2018) tried to determine over a two-year period the relationship between airborne concentrations of grass pollen grains and Phl p 5 concentrations (group 5 of grass pollen allergens) in two cities with different climatic and geographical characteristics (Ankara and Zongledok). It was found that the index of the total number of grass pollen and the total concentration of Phl p 5 allergen in these two regions was different. The temperature appeared to be the main meteorological factor that affects the airborne pollen concentration and the Phl p 5 allergen concentration at both stations. Rainfall was also important for Zonguldak because of its geographical and climatic characteristics. Finally, the researchers suggested the term "drift effect" to describe the critical impact of the initial wind direction on the propagation of airborne allergens. Therefore, the distribution of allergen and pollen grains is highly influenced by wind direction, especially in areas with elevated topography (Alan et al., 2018). In this regard, Jochner et al. (2015) showed that pollen and allergen concentrations were significantly lower at higher altitudes (Jochner et al., 2015).

Conclusion

Phenological monitoring is a useful tool for assessing the effects of climate change on plants behavior. In recent decades, climate change has led to the advance of spring events and the delay of autumn phenological events. Considering reproductive phenology, most of the impacts are related to the advance of the flowering. This can affect the pollen season indicators of the species and, consequently, the airborne pollen concentrations and risk of pollen exposure. Flowering phenology and pollen season indicators vary for allergic plant species according to their geographical location and is strongly influenced by climatic and meteorological parameters. Temperature, wind speed and direction, humidity, and rainfall are among the most important meteorological parameters affecting the fluctuations of annual concentrations of airborne pollens. Interestingly, tree species appeared to be particularly sensitive to temperature fluctuations and temperature is the most important climatic parameter affecting the flowering phenology and pollen season indicators of anemophilous trees releasing abundant concentrations of allergenic pollen grains. The most important pollen season indicators that are affected by temperature include annual pollen integral, main pollen season and pollen production (Fig. 2). Flowering phenology of plant species that flower in spring and early summer is strongly affected by temperature, while species that flower in late summer and fall are generally more significantly impacted by photoperiod or lighting. Rainfall can affect some indicators of the pollen season, such as annual pollen integral, main pollen season and pollen concentration. However, elevated CO2 has an enhancing impact on pollen production, pollen concentration and main pollen season (Fig. 2).

The change in the main pollen season and airborne pollen concentration also depends on latitude, which is directly linked to temperature changes and rainfall during plant growth. For allergenic tree, grass and weed species, the main pollen season can be predicted by combining long-term data of pollen concentrations with onset time and pollination peak value. It is now well-documented that increasing global temperature due to climate change could lead to warmer winters and springs, resulting in the early flowering of many plant species in different parts of the world. There is also a growing body of scientific evidence supporting the fact that carbon dioxide from human activities results in increased plant biomass, increased flowering intensity, and pollen production by stimulating photosynthesis and plant growth and through its influence on the average temperature of the Earth's surface (Fig. 2). However, so far, no statistically significant relationship has been observed between the concentration of airborne pollen grains and the concentration of industrial/ urban air pollutants and further studies are still required to draw any conclusion regarding the exceedingly complex interactions between air pollution and the concentration of allergic pollen grains in different areas. The present review provides a global view of the effects of climate change and meteorological factors on flowering phenology and pollen season indicators of allergenic plant taxa worldwide, paving the way for comprehensive studies in this area of major environmental and public health importance.

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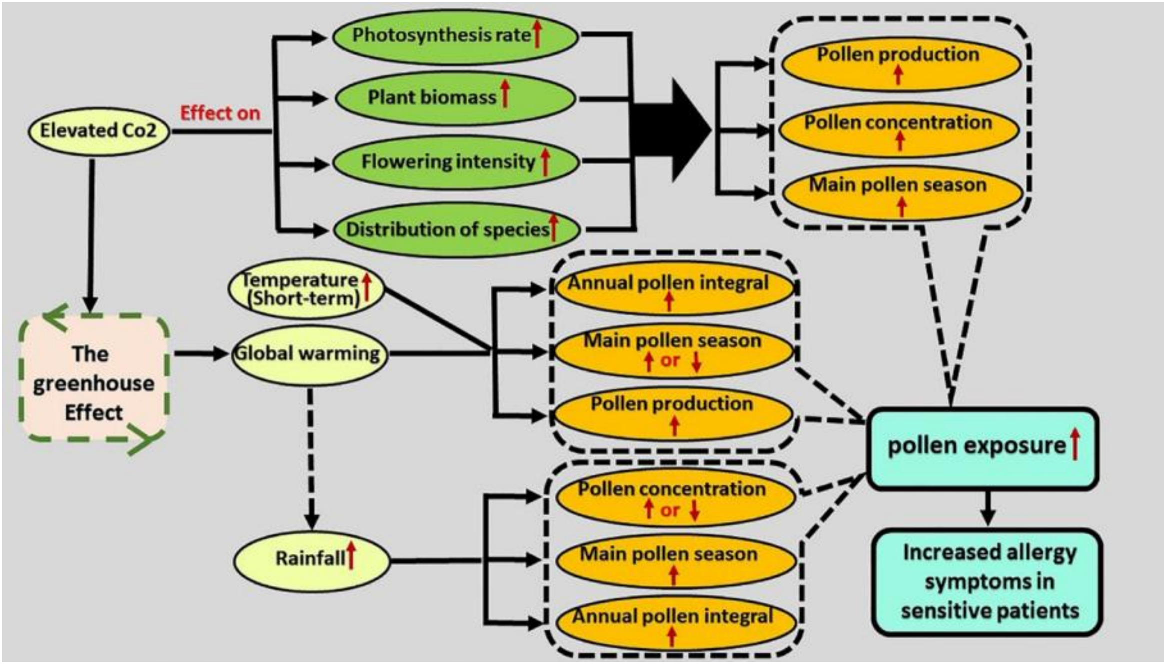

Figure. 2. A Schematic outline of climate change and meteorological factors affecting pollen season indicators and pollen exposure. The long term and short-term effects of temperature, carbon dioxide, and rainfall on flowering phenology, pollen season indicator and pollen exposure are depicted. Pollen season indicators that have been studied include pollen production (quantity of pollen produced per anther in angiosperms), pollen concentration (the number of airborne pollen grains per unit volume of air), main pollen season (the presence of a specific pollen in the atmosphere in significant concentrations at a location) and annual pollen integral (the daily pollen concentration for a specific taxon over the pollen year). Increasing these indices, especially annual pollen integral, can increase the risk of pollen exposure in sensitized individuals. The increase in atmospheric carbon dioxide concentrations emitted through anthropogenic activities can amplify greenhouse effects, which elevate the Earth's surface temperature (global warming). This abnormal rise in global temperature could lead to climate change and increased heavy precipitation events. The up and down arrows indicate enhancing and lowering impacts, respectively and dashed arrows shows the potential impact.

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