



Immunol Allergy Clin N Am
23 (2003) 411–422

IMMUNOLOGY
AND ALLERGY
CLINICS OF
NORTH AMERICA

Meteorologic variables in aerobiology

Richard W. Weber, MD^{a,b,*}

^a*National Jewish Medical and Research Center, 1400 Jackson Street, Room J326,
Denver, CO 80206, USA*

^b*University of Colorado Health Sciences Center, 4200 E. 9th Avenue, Denver, CO 80262, USA*

It is unassailable that climate and weather have a huge impact on the presence of pollen and mold spores in the atmosphere. Climate, as it defines vegetative diversity, is dealt with in another article by the author in this issue. Although prevalent weather helps define climate, individual weather conditions, such as rain, humidity, wind speed and direction, temperature, or amount of sunshine, may have direct and indirect effects on bioaerosols. How specific meteorologic parameters affect aeroallergen burden is addressed in this article.

Numerous studies from around the globe have tabulated regional pollen counts, and many reports have attempted to correlate those counts with a number of meteorologic variables. With the uniform exception of temperature, humidity, and precipitation, it is difficult to show any reproducible correlations. Interactions between variables frequently are complicated. Solomon has stated that “pollen emission, dispersion and transport displays a variety of distinctive and often inconsistent effects when they are examined in relation to complex weather patterns” [1]. As has been pointed out previously, weather is the prototypic demonstration of chaos theory: Although present, it is difficult to discern order within the disorder [2]. Weather is an inherently unpredictable chaotic system of numerous variables that interact in an additive or synergistic fashion. It seems likely that from year to year, different variables may have a more central role in determining pollen counts. Older studies were hampered by the limited ability to perform sophisticated statistical analysis: As recently as 10 years ago, large mainframe computers were required to assess interactions between more than a few parameters. Meteorologic parameters are collected continually and are reported for a 24-hour period from midnight to midnight. Pollen and mold spores traditionally are sampled for a 24-hour period, from early morning to the next morning. Results must be lagged appropriately. Use of a 24-hour rotating drum

* National Jewish Medical and Research Center, 1400 Jackson Street, Room J326, Denver, CO 80206.

E-mail address: weberr@njc.org

device, such as the Burkard (Burkard Manufacturing Co., Ltd., Rickmansworth, Hertfordshire, England, UK), can allow for accurate comparison of pollen or mold counts with the weather conditions during any given hour, whereas gravimetric samplers or a rotating impaction device, such as the Roto-Rod (Multidata Sampling Technologies, St. Louis Park, MN), cannot. Weather conditions can have immediate effects, such as the scrubbing effect (cleansing of the air of particulates with rain) or delayed effects, such as the accumulated warmth necessary to induce the onset of anthesis.

The following sections address general affects on pollen counts of individual factors, such as temperature, humidity, precipitation, wind speed, wind direction, and sunshine. Spore-release mechanisms and the primary effects of humidity and precipitation also are discussed. Major factors are summarized in Table 1. Special circumstances, such as the release of submicronic particles and the clinical impact of thunderstorms and mechanisms, are addressed.

Definition of season

The strength of correlations is frequently dependent on the number of observation days included in the analysis for each pollen type, and this factor is dependent on the definition of season or peak pollination period. The definition of season, and which days to include in a statistical analysis, is not intuitive. Several studies have not mentioned season criteria, and some only have investigated days with the highest counts (eg, grass >50 grains/m³) [3,4]. Most pollens demonstrate long tails of trace or very low levels at the onset and the end of the pollination period. Inclusion of these tails in the observation days could dilute out any correlations. Meteorologic parameters are expected to be operant, with lower producing periods and peaks. Glassheim et al used four definitions of the season [2]. The most restrictive definition was inclusive of the first and last days,

Table 1
Meteorologic factors affecting pollen and mold spore counts

Factor	Pollen		Mold spore	
	Immediate effect	Delayed effect	Immediate effect	Delayed effect
Rainfall	↓ [2,6,7] ↑ [44,48]	↑ [10–13]	± [7,37]	↑ [36]
Humidity	↓ [2,8,9]	—	↑ [36]	↑ [38]
High temperature	↑ [14,15] ± [2]	↑ [11,20,23,25]	↑ [39]	—
Low temperature	↓ [17,34]	↑ [21,22]	—	—
Moderate wind speed	↑ [26]	—	↑ [36]	—
High wind speed	↓ [2,3]	—	—	—
Inversion	↑ [34]	—	—	—
Outflow	↑ [48]	—	—	—
Barometric pressure	± [2]	—	↑ [39]	—

↓, decreased; ↑, increased; ±, variable effects.

bracketing 99% of the sum total of the specific pollen produced that year [5]. The most lenient definition was of 3 consecutive days with pollen counts of greater than 1 grains/m³. The number of observation days for cottonwood in 1991 for each of the progressively more stringent criteria was 49, 44, 40 and 36. The investigators tabulated correlations for the most lenient and most stringent definitions. Such definitions are important because of the differences seen in the study between a broader and a narrower set of criteria. Which definition is more correct than the others is difficult to answer: Correlation trends were in opposite directions for trees and weeds, emphasizing the impact that differences in pollen-release mechanics between these two types of plants will have on such associations.

Factors affecting pollen counts in general

Humidity and precipitation

Rainfall is considered to cleanse the air with the capture of pollens or spores by raindrops [6]. The efficiency with which this is achieved is dependent on several factors, as described by McDonald [7]. Entrapment of pollen grains of typical size (diameter, 20–60 µm) is less dependent on the size of the grain than on the character of the rain droplets and the duration of the rainfall. Even a light shower (0.1 cm of rainfall) is 99% efficient in removing pollen with drizzle-sized raindrops (diameter, 0.2 mm) and is about 75% efficient with average-sized droplets (diameter, 1.0 mm). In contrast, a flurry of large drops (diameter, 4.0 mm) from a thunderstorm only removes a quarter to a third of the pollen grains. A more sustained rainfall of 1.0 cm is 80% to 99% effective in removing pollens, regardless of the raindrop diameter. Smaller mold spores, such as *Penicillium* (diameter, 3.5 µm) are not removed by lighter rain of any size droplet (0%–10% effective) or heavier rainfall if the droplets are large or drizzle-sized. Sustained rainfall of medium-sized droplets removes about two thirds of *Penicillium* spores.

This scrubbing effect is most pronounced when rainfall is sudden and heavy, such as during severe thunderstorms. This type of rainfall is common in the midwestern United States during the spring, summer, and autumn. Glassheim et al observed that severe storms seasons in the Front Range of the Colorado Rocky Mountain occurs during May and June, with only widely scattered and isolated brief thundershowers during July, August, and early September. The study demonstrated significant negative correlations between spring and early summer pollinating plants' (trees and grasses) pollens and occurrence of precipitation and showed weaker correlations with weeds. The scrubbing effect on pollen counts also was demonstrated after a snowfall, affecting trees in early spring and weeds in early autumn [2].

Negative correlations between relative humidity and pollen count have been observed for most pollens in a number of reports [2,8]. Grass anthers close with increased humidity, limiting pollen release during moist situations [9]. With drying, anthers reopen. A similar observation has been made with other plants.

Another possible mechanism for lower counts is hygroscopic pollen weight gain, which occurs with more rapid settling [2].

Cumulative rainfall has opposite effects from the scouring action during actual rainfall. Soil moisture is crucial for adequate plant and fungal growth. Subiza et al examined total grass counts in Madrid from April through July and found a strong correlation with total rainfall from the previous October to March [10]. Antépara et al found that the intensity of the grass pollen season was related to the rainfall in the months preceding the onset of the season [11]. Fairley and Batchelder reported that the oak pollen counts in the Bay area of California strongly correlated with the total rainfall during the previous year [12]. Counts of *Artemisia* in the summer and fall were correlated with precipitation that occurred 6 to 8 weeks before the start of the season [13].

Temperature

Temperature affects pollen counts in complex ways. There are immediate effects: Drops in temperature correlate with drops in pollen counts. In some cases, however, these temperature drops may be indicative of other events that are the primary effectors, such as precipitation. Urticaceae counts obtained in southwestern Spain during the nonrainy season showed the strongest correlation with temperature [14]. Effects are not uniform across plant species and peak pollination periods: Puc and Wolski found a positive correlation between average temperature and birch pollen, but also found a negative correlation between temperature and poplar pollen [15]. They attributed this difference to the impact of cumulative temperature before the poplar season, as discussed later in this article. In a report by Glassheim et al, none of the tree pollens studied during a 5-year period, with the exception of pine (a late pollinating tree), seemed to be affected by temperature [2]. The lack of correlation was consistent with earlier observations of tree-pollen discharge during snowfall [16].

It is a widely held belief that patients with seasonal allergic rhinitis can expect their weed-induced symptoms to abate on the arrival of the first frost or freeze in autumn [17]. Few studies other than that by Glassheim et al have addressed whether this phenomenon is limited to the ragweed or also pertains to other fall pollens [2]. Frost is defined by the National Weather Service as “the formation of thin ice crystals in the form of scales, needles, feathers, or fans, which develop under conditions similar to dew (high relative humidity, low wind velocity, clear skies) except for the minimum temperature required—less than or equal to 32°F/0°C.” A freeze “describes conditions when the temperature at or near the surface is 32°F/0°C or below” (usually this term is used only during the growing season). Adjectives such as killing (28°F [−2°C]), hard (24°F [−4°C]), or severe (20°F [−7°C]) are used when appropriate upper-bound temperatures are recorded [2]. That study showed a definitive tendency toward a re-emergence of small amounts of ragweed and chenopod-amaranth pollen in the air, even after the official date of first frost. The relative cold hardiness of sage (*Artemisia* sp) was documented, in which

somewhat higher counts were noted compared with the counts of other fall weeds.

In addition to acute effects, cumulative temperature is important for the onset of pollination and impacts the seasonal pollen load. These issues are addressed in greater detail in an article by Levetin and Van de Water elsewhere in this issue. Fitter and Fitter reported that the average onset of pollination of 385 British plants has advanced by 4.5 days during the past 10 years compared with the pollination onset of the previous 4 decades [18]. They attributed this finding to global warming. Flowering was sensitive to the temperatures in the preceding months of pollination onset, and plants flowering in spring were the most affected. Sixteen percent of the species flowered more than 15 days sooner than during the previous decade. Emberlin et al, however, found contrasting grass anthesis onsets, beginning earlier in Wales and Derby, but later in London [19]. Antépara et al found that the onset and duration of the grass pollen season were related to cumulative average temperatures [11]. Adding cumulative temperature greater than 9°C, grass pollination began with a sum greater than 300°C and terminated between 800°C to 900°C. In France, Laaidi found that grass-pollen onset could be predicted using sum of temperatures or Q10, an agrometeorologic coefficient that incorporates temperature [20].

Many trees require a chilling period to break dormancy and a warming period to induce flowering [21]. In a study of European hazel (*Corylus avellana*), Frenguelli et al found that the start of catkin elongation in late winter signaled that the chilling requirement had been fulfilled, and this marker could be used as the beginning point of the heat accumulation that is necessary for pollination [22]. Total annual output of olive pollen has been predicted based on preseason rainfall and the 5-day moving average of the temperature of the preceding months [23]. These investigators reported that the onset of the olive season could be predicted by the heat accumulation that is greater than the threshold of 209.9°C [24]. Tree buds frequently mature during the fall of the preceding season. A study from San Remo, Italy, demonstrated the higher the average temperature in the previous July and the greater the presence of Palmaceae, Cupressaceae, and *Parietaria* pollen during the following year [25].

Wind speed and direction

Wind speed affects the efficiency of impaction and suction samplers (see article by Muilenberg elsewhere in this issue). Brisk winds resuspend settled pollen particles, and Laaidi has reported that brisk winds are associated with greater eye and asthma symptoms in patients with birch-pollen sensitivities [26]. Singh and Babu reported that wind speeds of 5 to 15 km/h were most conducive for increasing pollen counts [27]. Raynor et al found little impact of wind speed on local ragweed counts, but commented that speeds were not high during the study periods [28]. Davies and Smith found that grass pollen counts were correlated negatively with wind speeds, although Glassheim et al did not find such a relationship [2,3]. Wind speed showed a moderate negative correlation for

combined weed pollen counts only, implying that a wind scrubbing effect occurred with higher wind velocities in the late summer.

Wind direction has little effect on pollen counts if the sampling station is surrounded by fairly uniform vegetative conditions, as seen in Denver, Colorado, or Cardiff, Wales, UK [2,4]. Davies and Smith found a positive correlation between grass pollen counts and wind direction in London, which verified the directions in which the greatest open ground was located [3]. Similarly, a study from Spain showed that wind direction was important for pollen counts from plants occupying specific niches, but widely distributed species, such as grass, oak, and olive, were unaffected by wind direction [29]. McDonald and O'Driscoll explained a mild allergy season in Galway, Ireland, UK in 1978, which resulted from the occurrence of a persistent sea breeze between May and September that lowered pollen and spore catches [30].

Other factors

Generally, other weather conditions have little impact on airborne counts, only as those variables are associated with factors such as precipitation and temperature. In a study of nine different pollens, Glassheim et al found no consistent effects of wind speed or direction, sunshine, or barometric pressure [2]. Sunshine had erratic effects on pollen counts, suggesting that this variable probably reflected linkage with other factors, such as relative humidity. Hours of daylight are important in triggering anthesis in late summer weeds such as ragweed, however [31–33]. Carinanos et al reported that winter inversions, associated with low temperatures, cloudless skies, and atmospheric calms, were associated with higher levels of solid particles, including pollens of winter-pollinating plants, such as Cupressaceae [34]. Seasonal conditions that are likely to increase pollen or mold spore counts are depicted in Figure 1.

Factors affecting mold counts

Spore-release mechanisms

Numerous members of Deuteromycetes (Fungi Imperfecta) have simple spore structures, with tenuous attachments between spores and hyphae. Spore dispersion is accomplished by scouring of air currents, and outdoor counts are highest on hot, dry, windy days. Characteristic of such molds are *Alternaria*, *Cladosporium*, *Epicoccum*, and many *Penicillium* species [35]. Other Deuteromycetes, of the subclass Sphaeropsidales, have spores develop in mucinous slime-spore masses that require humidity, dew, or raindrops for dispersal. Representative molds are *Phoma*, *Fusarium*, and *Cephalosporium*. The classes Ascomycetes and Basidiomycetes have release mechanisms that require increased moisture or rainfall. Spores of these classes are more prevalent in damper areas or after periods of greater rainfall or humidity. Outdoor molds may be considered to be

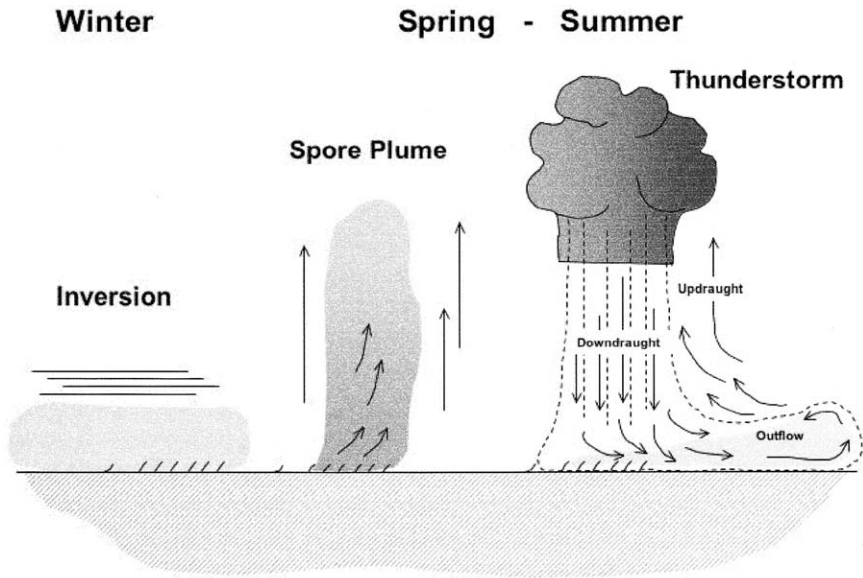


Fig. 1. Seasonal meteorologic factors that may increase pollen or mold spore counts. Inversions during winter act to trap particulates in a smaller volume of air. Up-drafts associated with higher temperature and decreased humidity may result in mold plumes before storms. Down-drafts and outflows resuspend pollen and disrupt grains, increasing allergenic exposure. See text for further details. (Data from Refs. [34,39,48])

dry-weather or wet-weather types. Not all molds peak in humid conditions. In 1972, Long and Kramer compared mold profiles from a wooded ravine site and a grassy hilltop and demonstrated marked differences in mold prevalence and a response to dry and wet conditions [36]. *Cladosporium* and *Alternaria* were prevalent on the grassy open area and were most prominent on dry, windy days. *Epicoccum*, although not commented on in this article, shows a similar dry pattern. The wooded, more humid site showed greater amounts of Ascospores and Basidiospores, molds whose spore release is facilitated by moisture. Although mold spores generally are found in the air unless the ground is frozen or there is snow cover, molds such as *Alternaria*, *Cladosporium*, and the smuts have distinct seasonality, being prevalent in the late summer and fall. *Alternaria* peak about the same time as does ragweed, and smuts and rusts are abundant during fall harvesting.

The impact of precipitation on the diversity of airborne spores on an orchard was well demonstrated by Pady et al [37]. Rain removed *Cladosporium* spores, *Alternaria* spores, and hyphal fragments from the air. Simultaneously, thousands of other spores, primarily puffball basidiospores and fusoid ascospores, reached levels of 6000 and 20,000 spores/ft³. Within a day of the end of the rainfall, numerous species, including *Alternaria*, *Cladosporium*, *Sporobolomyces*, *Cercospora*, and *Helminthosporium*, released spores in the air because of the favorable

impact of moisture on spore formation. Adams et al reported persistently higher-than-normal mold spore levels in Wales in October following a wetter and more humid season from July through September [38]. The investigators attributed this finding to greater persistent soil humidity following the increased rainfall.

Burch and Levetin, presenting data from Tulsa, Oklahoma, reported on meteorologic parameters on 4 days containing spore plumes [39], which are defined as dramatic increases in concentrations over a short period of time, usually occurring around midday. Total spore counts may increase from lows of about 20,000 p/m³ to greater than 170,000 particles/m³. Multiple regression analysis showed that increases in temperature, air pressure, and dew point were correlated, but no single factor predicted the occurrence of a spore plume. Thunderstorms occurred later on 3 of 4 plume days (see Fig. 1).

Special circumstances

Release of submicronic allergenic particles

Persistence of ragweed hay fever symptoms has been known to persist for days after intact pollen is no longer collected from the air. This observation spurred studies that then demonstrated airborne allergens in submicronic particles [40,41]. It was assumed that such particles represented fragmented pollen grains. Airborne birch antigenic activity has been demonstrated on particles smaller than 2.4 μm [8]. Starch granules are prominent in the cytoplasm of certain pollens, such as the grasses (Poaceae) and docks (*Rumex*, Polygonaceae) [42]. One study found that grass starch granules have heavy concentrations of group 5 allergens [43]. It has been postulated that the force of storm-driven raindrops disrupts grass pollen grains, releasing large amounts of respirable allergen-laden starch granules [44]. Taylor et al have demonstrated that a moisture-drying cycle of grass pollen results in starch granules that emanate through the aperture [9].

Thunderstorms

There have been reports of dramatic epidemics of asthma-related emergency department visits after thunderstorms. During a midsummer, 2-day interval in Calgary, Canada, in 2000, there was a near 10-fold rise in asthmatic urgent care complaints associated with a thunderstorm [45]. Patients who were outside before the storm were particularly affected. A stagnant air mass during the previous day resulted in low pollen and spore counts, followed by high winds with the storm and a marked elevation of pollen and spore counts. In England, a number of severe thunderstorms (those with a large number of lightning discharges, or sferics) were associated with increased emergency department visits among child and adult asthmatics, especially if these storms occurred after days of high grass pollen counts [46]. Spring epidemic asthma had been linked to grass pollen sensitivity at a large Air Force Base outside of Sacramento, California [47].

Another study demonstrated that cold air downdrafts and outflows from thunderclouds tend to concentrate grass pollen grains near to the ground (Fig. 1) [48]. Several studies showed associations between asthma flares, thunderstorms, and rises in grass pollen counts [46,48–53]. It seems that several factors are responsible for this phenomenon of increased grass allergen concentration: resuspension of settled grains because of the wind, concentration of grains within outflow bands low to the ground, and increased airborne grass allergens on starch granules from disrupted grains. Irritation of asthmatic airways from cold air and airborne grit also probably contribute.

Summary

Although prevalent weather helps define climate, individual weather conditions, such as rain, humidity, wind speed and direction, temperature, or amount of sunshine, may have direct and indirect effects on bioaerosols. Effects may be immediate or cumulative. Precipitation and humidity acutely decrease particle air burden, but sufficient preseason moisture is necessary to assure proper growth of flower buds on perennials and trees and growth of annuals in general. Ambient temperature increase is necessary for anthesis in many plants, and cumulative heat above a threshold value has been linked to onset and intensity of pollination in grasses, weeds, and trees.

Wind direction only impacts if there is lack of uniformity in the pollen sources that surround sampling sites. Wind speed may factor in re-entrainment of settled particles or may act to scour the air. Thunderstorms provide a unique sum of factors that greatly may increase aeroallergen burden.

Dispersal of mold spores is linked intimately to precipitation and humidity. The effects may be opposed diametrically, however, depending on the type of fungi. Certain ascospores and basidiospores require active rainfall for release of spores, whereas other Deuteromycetes are suppressed by precipitation.

References

- [1] Solomon WR. Aerobiology of pollinosis. *J Allergy Clin Immunol* 1984;74:449–61.
- [2] Glassheim JW, Ledoux RA, Vaughan TR, Damiano MA, Goodman DL, Nelson HS, et al. Analysis of meteorologic variables and seasonal aeroallergen pollen counts in Denver, Colorado. *Ann Allergy Asthma Immunol* 1995;75:149–56.
- [3] Davies RR, Smith LP. Weather and the grass pollen content of air. *Clin Allergy* 1973;3:95–108.
- [4] Mullins J, White J, Davies BH. Circadian periodicity of grass pollen. *Ann Allergy* 1986;57:371–4.
- [5] Rantio-Lehtimäki A, Koivikko A, Kupias R, Mäkinen Y, Pohjola A. Significance of sampling height of airborne particles for aerobiological information. *Allergy* 1991;46:68–76.
- [6] Buck P, Levetin E. Weather patterns and ragweed pollen production in Tulsa, Oklahoma. *Ann Allergy* 1982;49:272–5.
- [7] McDonald JE. Collection and washout of airborne pollens and spores by raindrops. *Science* 1962;135:435–7.

- [8] Pehkonen E, Rantio-Lehtimäki A. Variations in airborne pollen antigenic particles caused by meteorological factors. *Allergy* 1994;49:472–7.
- [9] Taylor PE, Flagan RC, Valenta R, Glovsky MM. Release of allergens as respirable aerosols: a link between grass pollen and asthma. *J Allergy Clin Immunol* 2002;109:51–6.
- [10] Subiza J, Masiello JM, Subiza JL, Jerez M, Hinojosa M, Subiza E. Prediction of annual variations in atmospheric concentration of grass pollen: a method based on meteorological factors and grain crop estimates. *Clin Exp Allergy* 1992;22:540–6.
- [11] Antépara I, Fernández JC, Gamboa P, Jauregui I, Miguel F. Pollen allergy in the Bilbao area (European Atlantic seaboard climate): pollination forecasting methods. *Clin Exp Allergy* 1995; 25:133–40.
- [12] Fairley D, Batchelder GL. A study of oak-pollen production and phenology in northern California: prediction of annual variation in pollen counts based on geographic and meteorologic factors. *J Allergy Clin Immunol* 1986;78:300–7.
- [13] Munuera Giner M, Carrion Garcia JS, Garcia Selles J. Aerobiology of *Artemisia* airborne pollen in Murcia (SE Spain) and its relationship with weather variables: annual and intradiurnal variations for three different species. Wind vectors as a tool in determining pollen origin. *Int J Biometeorol* 1999;43:51–63.
- [14] Galan C, Alcazar P, Carinanos P, Garcia H, Dominguez-Vilches E. Meteorological factors affecting daily urticaceae pollen counts in southwest Spain. *Int J Biometeorol* 2000;43:191–5.
- [15] Puc M, Wolski T. *Betula* and *Populus* pollen counts and meteorological conditions in Szczecin, Poland. *Ann Agric Environ Med* 2002;9:65–9.
- [16] Silvers WS, Ledoux RA, Dolen WK, Morrison MR, Nelson HS, Weber RW. Aerobiology of the Colorado Rockies: pollen count comparisons between Vail and Denver, Colorado. *Ann Allergy* 1992;69:421–6.
- [17] Vander Veer A. Allergic rhinitis: seasonal (hay fever-pollinosis). In: Cooke RA, editor. *Allergy in theory and practice*. Philadelphia: WB Saunders; 1947. p. 183–219.
- [18] Fitter AH, Fitter RSR. Rapid changes in flowering time in British plants. *Science* 2002;296: 1689–91.
- [19] Emberlin J, Mullins J, Corden J, Jones S, Millington W, Brooke M, et al. Regional variations in grass pollen seasons in the UK: long-term trends and forecast models. *Clin Exp Allergy* 1999; 29:347–56.
- [20] Laaidi M. Forecasting the start of the pollen season of Poaceae: evaluation of some methods based on meteorological factors. *Int J Biometeorol* 2001;45:1–7.
- [21] Emberlin J, Detandt M, Gehrig R, Jaeger S, Noland N, Rantio-Lehtimäki A. Responses in the start of *Betula* (birch) pollen seasons to recent changes in spring temperatures across Europe. *Int J Biometeorol* 2002;46:159–70.
- [22] Frenguelli G, Ferranti F, Romano B, Bricchi E, Mincigrucci G, Fornaciari M, et al. Temperature influence on differentiation and release of hazel pollen. *Allergol Immunol (Paris)* 1993;25:147–9.
- [23] Galan C, Carinanos P, Garcia-Mazo H, Alcazar P, Dominguez-Vilches EL. Model for forecasting *Olea europaea* L. airborne pollen in South-West Andalusia, Spain. *Int J Biometeorol* 2001;45: 59–63.
- [24] Galan C, Garcia-Mazo H, Carinanos P, Alcazar P, Dominguez-Vilches E. The role of temperature in the onset of the *Olea europaea* L. pollen season in southwestern Spain. *Int J Biometeorol* 2001;45:8–12.
- [25] Ariano R, Panzani RC, Chiapella M, Augeri G. Pollinosis in a Mediterranean area (Riviera Ligure, Italy): ten years of pollen counts, correlation with clinical sensitization and meteorological data. *J Investig Allergol Clin Immunol* 1994;4:81–6.
- [26] Laaidi K. Predicting days of high allergenic risk during *Betula* pollination using weather types. *Int J Biometeorol* 2001;45:124–32.
- [27] Singh AB, Babu CR. Studies on pollen allergy in Delhi: diurnal periodicity of common allergenic pollen. *Allergy* 1980;35:311–7.
- [28] Raynor GS, Ogden EC, Hayes JV. Effect of a local source on ragweed pollen concentrations from background sources. *J Allergy* 1968;41:217–25.

- [29] Silva Palacios I, Tormo Molina R, Nunoz Rodriguez AF. Influence of wind direction on pollen concentration in the atmosphere. *Int J Biometeorol* 2000;44:128–33.
- [30] McDonald MS, O'Driscoll BJ. Aerobiological studies based in Galway: a comparison of pollen and spore counts over two seasons of widely differing weather conditions. *Clin Allergy* 1980; 10:211–5.
- [31] Bianchi DE, Schwemmin DJ, Wagner Jr WH. Pollen release in the common ragweed (*Ambrosia artemisiifolia*). *Botanical Gazette* 1959;4:235–43.
- [32] Raynor GS, Hayes JV. Experimental prediction of daily ragweed concentration. *Ann Allergy* 1970; 28:580–5.
- [33] Dingle AN, Gill GC, Wagner Jr WH, Hewson EW. The emission, dispersion, and deposition of ragweed pollen. In: Landsberg HE, Van Mieghen J, editors. *Advances in geophysics*, vol. 6. New York: Academic Press; 1959. p. 367–87.
- [34] Carinanos P, Galan C, Alcazar P, Dominguez E. Meteorological phenomena affecting the presence of solid particles suspended in the air during winter. *Int J Biometeorol* 2000;44:6–10.
- [35] Solomon WR, Weber RW, Dolen WK. Common allergenic pollen and fungi. In: Bierman CW, Pearlman DS, Shapiro GG, Busse WW, editors. *Allergy, asthma, and immunology from infancy to adulthood*. 3rd edition. Philadelphia: WB Saunders; 1996. p. 93–114.
- [36] Long DL, Kramer CL. Air spora of two contrasting ecological sites in Kansas. *J Allergy Clin Immunol* 1972;49:255–66.
- [37] Pady SM, Kramer CL, Clary R. Diurnal periodicity in airborne fungi in an orchard. *J Allergy* 1967;39:302–10.
- [38] Adams KF, Hyde HA, Williams DA. Woodlands as a source of allergens, with special reference to basidiospores. *Acta Allergol* 1968;23:265–81.
- [39] Burch M, Levetin E. Effects of meteorological conditions on spore plumes. *Int J Biometeorol* 2002;46:107–17.
- [40] Busse W, Reed C, Hoehne J. Where is the allergic reaction in ragweed asthma? II. Demonstration of ragweed antigen in airborne particles smaller than pollen. *J Allergy Clin Immunol* 1972; 50:289–93.
- [41] Habenicht HA, Burge HA, Muilenberg ML, Solomon WR. Allergen carriage by atmospheric aerosol. II. Ragweed-pollen determinants in submicronic atmospheric fractions. *J Allergy Clin Immunol* 1984;74:64–7.
- [42] Weber RW. Pollen identification. *Ann Allergy Asthma Immunol* 1998;80:141–7.
- [43] Schäppi GF, Taylor PE, Pain MCF, Cameron PA, Dent AW, Staff IA, et al. Concentrations of major grass group 5 allergens in pollen grains and atmospheric particles: implications for hay fever and allergic asthma sufferers sensitized to grass pollen allergens. *Clin Exp Allergy* 1999; 29:633–41.
- [44] Suphioglu C, Singh MB, Taylor PE, Bellomo R, Holmes P, Puy R, et al. Mechanism of grass-pollen-induced asthma. *Lancet* 1992;399:569–72.
- [45] Wardman AE, Stefani D, MacDonald JC. Thunderstorm-associated asthma or shortness of breath epidemic: a Canadian case report. *Can Respir J* 2002;9:267–70.
- [46] Newson R, Strachan D, Archibald E, Emberlin J, Hardaker P, Collier C. Effect of thunderstorms and airborne grass pollen on the incidence of acute asthma in England, 1990–94. *Thorax* 1997; 52:680–5.
- [47] Pollart SM, Reid MJ, Fling JA, Chapman MD, Platts-Mills TA. Epidemiology of emergency room asthma in northern California: association with IgE antibody to ryegrass pollen. *J Allergy Clin Immunol* 1988;82:224–30.
- [48] Marks GB, Colquhoun JR, Girgis ST, et al. Thunderstorm outflows preceding epidemics of asthma during spring and summer. *Thorax* 2001;56:468–71.
- [49] Bellomo R, Giglotti P, Treloar A, Holmes P, Suphioglu C, Singh MB, et al. Two consecutive thunderstorm associated epidemics of asthma in the city of Melbourne: the possible role of rye grass pollen. *Med J Aust* 1992;156:834–7.
- [50] Celenza A, Fothergill J, Kupek E, Shaw RJ. Thunderstorm associated asthma: a detailed analysis of environmental factors. *BMJ* 1996;312:604–7.

- [51] Venables KM, Allitt U, Collier CG, Emberlin J, Greig JB, Hardaker PJ, et al. Thunderstorm-related asthma—the epidemic of 24/25 June 1994. *Clin Exp Allergy* 1997;27:725–36.
- [52] Girgis ST, Marks GB, Downs SH, Kolbe A, Car GN, Paton R. Thunderstorm-associated asthma in an inland town in southeastern Australia: who is at risk? *Eur Respir J* 2000;16:3–8.
- [53] Anderson W, Prescott GJ, Packham S, Mullins J, Brookes M, Seaton A. Asthma admissions and thunderstorms: a study of pollen, fungal spores, rainfall, and ozone. *QJM* 2001;94: 429–33.