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ORIGINAL PAPER

Weather elements, chemical air pollutants and airborne pollen influencing asthma emergency room visits in Szeged, Hungary: performance of two objective weather classifications

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Abstract Weather classification approaches may be useful tools in modelling the occurrence of respiratory diseases. The aim of the study is to compare the performance of an objectively defined weather classification and the Spatial Synoptic Classification (SSC) in classifying emergency department (ED) visits for acute asthma depending from weather, air pollutants, and airborne pollen variables for Szeged, Hungary, for the 9-year period 1999–2007. The research is performed for three different pollen-related periods of the year and the annual data set. According to age and gender, nine patient categories, eight meteorological variables, seven chemical air pollutants, and two pollen categories were used. In general, partly dry and cold air and partly warm and humid air aggravate substantially the symptoms of asthmatics. Our major findings are consistent with this establishment. Namely, for the objectively defined weather types favourable conditions for asthma ER visits occur when an anticyclonic ridge weather situation happens with near extreme temperature and humidity parameters. Accordingly, the SSC weather types facilitate aggravating asthmatic conditions if warm or cool weather occur with high humidity in both cases. Favourable conditions for asthma attacks are confirmed in the extreme seasons when atmospheric stability contributes to enrichment of air pollutants. The total efficiency of the two classification approaches is similar in spite of the fact that the methodology for derivation of the individual types within the two classification approaches is completely different.

Keywords Objective weather types · Spatial Synoptic Classification (SSC) weather types · Air pollution · Pollen allergy · Forecasting · Asthma emergency visits

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Introduction

Since the last century, air pollution has become a major environmental problem, mostly over large cities and industrial areas (Cassiani et al. 2013). For instance, the global mean per capita mortality caused by air pollution is about 0.1 % per year. The highest premature mortality rates are found in the Southeast Asia and Western Pacific regions where more than a dozen of the most highly polluted megacities are located (Lelieveld et al. 2013).

In Hungary, air pollution is one of the highest in Europe. Around 16,000 annual premature deaths attributable to exposure to ambient PM_{10} concentrations are estimated in the country (Barrett et al. 2008). Furthermore, the Pannonian Plain involving Hungary (Fig. 1) is heavily polluted with airborne pollen and most polluted with airborne ragweed *(Ambrosia)* pollen in Europe (Makra et al. 2005). About 30 % of the Hungarian population has some type of allergy, 65 % of them have pollen sensitivity, and at least 60 % of this pollen sensitivity is caused by *Ambrosia* (Makra et al. 2004).

The substantial increase of respiratory diseases in industrialized countries is partly attributable to a combination of chemical air pollutants and allergenic airborne pollen in big cities. Several papers have analysed separately the effects of either chemical air pollutants (Alves et al. 2010) or allergenic pollen (Díaz et al. 2007) to hospital admissions of respiratory diseases. However, only very few studies have yet examined the effect of these two kinds of variables together (Andersen et al. 2007).

The impact of weather on asthma has been known for centuries. For instance, prevalence of emergency department (ED) visits for acute asthma significantly increases by low minimum temperature (Abe et al. 2009), low temperatures (Abe et al. 2009) and by either a sudden and substantial decrease (Makie et al. 2002) or increase of temperature (Anderson et al. 2013). It was found that in an urban population, the highest (smallest) number of acute asthma ED visits occurs in the fall (in the summer; Silverman et al. 2003).

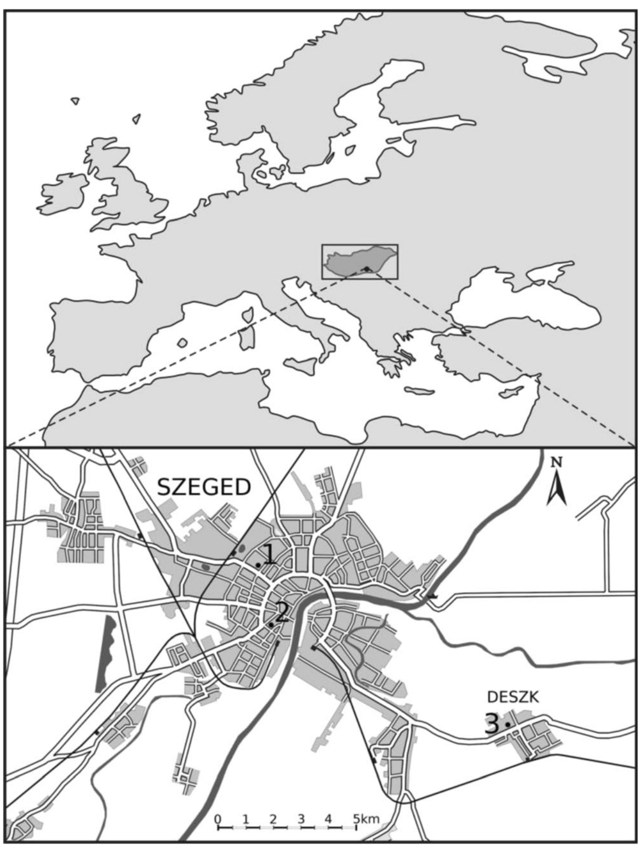

Fig. 1 Location of Europe with Hungary (*upper panel*) and the urban web of Szeged with the positions of the data sources (*lower panel*). *1*: air quality and meteorological monitoring station; *2*: aerobiological station; *3*: Hospital of Chest Diseases in Deszk

Association between the number of ED visits for acute asthma was examined for PM_{10} (Scarinzi et al. 2013), $PM_{2.5}$ (Scarinzi et al. 2013), coarse PM (Qiu et al. 2012), NO_2 (Scarinzi et al. 2013), SO_2 (Sousa et al. 2012), CO (Sousa et al. 2012) and O_3 (Yeh et al. 2011), as well as for pollen grains of different taxa (Makra et al. 2012). The importance of the area is stressed by the extreme high expenses of the treatment of asthma ED patients.

Instead of using one or more meteorological variables in order to detect relationships between weather and a given type of morbidity as resultant variable, some researchers applied indices or developed objective air mass types combining several meteorological parameters to assess their effect in classifying different diseases (Kassomenos 2003a, b; Kassomenos et al. 2003a). An objective classification approach of air mass types developed by Makra et al. (2006a, b) was used to separate concentrations of chemical (Makra et al. 2006a) and biological (Makra et al. 2006b) air pollutants and to determine their efficiency in separating the prevalence of respiratory diseases (Makra et al. 2008). They found that low levels of pollutants occurred when zonal currents passed through Hungary. During the summer months, anticyclones and anticyclone ridge weather situations were characteristic over the Carpathian Basin. Furthermore, secondary pollutants were highly enriched due to high irradiance (Makra et al. 2006a). Saaroni et al. (2010) found that not the cyclonic or anticyclonic synoptic systems were the key factor for the pollution potential in their study region, but rather the ambient atmospheric conditions they induce, static stability and weak easterly offshore flow. Local processes were the direct cause of the pollution and the role of the synoptic conditions was to support meso-scale processes. Note that their (Saaroni et al. 2010) study area was the eastern Mediterranean, a region with different climate. Sindosi et al. (2003) defined characteristic air mass types in order to reveal the association of atmospheric circulation with air pollution levels. McGregor and Bamzelis (1995) derived objective air mass types on surface meteorological data and analysed them in terms of their climatological, meteorological and air pollution characteristics. Further papers developing objective air mass types and meteorological indices in the subject are Kassomenos et al. (2003b, 2007, 2008, 2010) and Katsoulis and Kassomenos (2004).

Synoptic weather types characterizing the prevailing weather systems over an area have been associated with human health effects. Several papers have been published both on the association of weather-types-related air pollution on one hand and respiratory morbidity (Monsalve et al. 2013) and respiratory mortality (Rainham et al. 2005; Vanos et al. 2013) on the other. Nevertheless, very few papers have been appeared on asthma ED visits—weather-type dependence (Lee et al. 2013).

The daily number of ED visits for asthma by ambulance has been studied by several authors. Atkinson and Strachan (2004) surveyed the special literature on the incidences of asthma ED visits in conjunction with its environmental components, namely meteorological elements, aerobiological parameters (pollen grains and spores), as well as chemical air pollutants. Some authors analysed the occurrence of asthma ED visits in the function of chemical air pollutants (Bedeschi et al. 2007; Stieb et al. 2009); others studied the interrelationship between the prevalence of emergency room (ER) visits for asthma on the one hand, as well as aeroallergen levels and the concentrations of chemical air pollutants on the other (Stieb et al. 2000; Villeneuve et al. 2007); whilst, again others examined the incidence of asthma emergency room visits in the function of meteorological elements and chemical air pollutants (Wilson et al. 2005; Abe et al. 2009). At the same time, the remaining authors investigated the association of the occurrence of asthma ED visits with airborne allergens (airborne pollen grains and spores), meteorological elements and chemical air pollutants (Garty et al. 1998; Rosas et al. 1998; Orazzo et al. 2009).

Analysis of the environmental factors for asthma ED visits were partly limited to either children (Garty et al. 1998; Bedeschi et al. 2007; Orazzo et al. 2009) or adults (Wilson et al. 2005); however, it was jointly performed both for children and adults (Villeneuve et al. 2007; Abe et al. 2009) and for children, adults and elderly (Rosas et al. 1998), respectively.

The purpose of the present study is to compare an objectively defined weather classification and the Spatial Synoptic Classification (SSC; Kalkstein et al. 1996; Sheridan 2002, 2003) for determining their performance in (1) classifying the prevalence of the different categories of asthma ER visits, (2) estimating the role of the weather elements, air pollutants and airborne pollen in inducing the occurrence of asthma attacks, (3) assessing the relative risks of ED visits within the weather types for clarifying as to which incoming weather type presents the greatest asthma risk and the relative usefulness of both classification approaches, furthermore (4) assessing and comparing the metrics (character, efficiency) of these weather classification approaches for Szeged, Hungary. The reason for using the possible dependence of emergency department visits for acute asthma on meteorological variables, chemical air pollutants and airborne pollen is that asthma emergency cases can alone be directly associated to the given daily values of the influencing variables. Therefore, an objective weather classification approach is developed and compared with the Spatial Synoptic Classification (SSC) weather types (Kalkstein et al. 1996; Sheridan 2002, 2003) in regard to classifying weather variables and air pollutant related emergency department visits for acute asthma for Szeged, Hungary, for the 9-year period 1999–2007. The research is performed for three different pollen-related periods of the year.

Materials and methods

The city of Szeged (46.25°N; 20.10°E) being the largest town in SE Hungary is located at the confluence of the Tisza and Maros Rivers characterized by an extensive flat landscape of the Hungarian Great Plain with the lowest elevation (79 m above mean sea level) in the Carpathian Basin (Fig. 1). The built-up area covers a region of about 46 km^2. The city is the centre of the Szeged region with 203,000 inhabitants. The climate of Szeged belongs to Köppen's Ca type (warm temperate climate) with relatively mild and short winters and hot summers (Köppen 1931). According to the climate classification of Trewartha (1968), Szeged is associated with class D1 (continental climate with a long warm season).

Data

Meteorological parameters, chemical and biological air pollutants

Daily values of the meteorological variables used are mean temperature (T_{mean}, in degree Celsius), maximum temperature (T_{max}, in degree Celsius), minimum temperature (T_{min}, in degree Celsius), temperature range ($T_{max}-T_{min}=\Delta T$, in degree Celsius), mean global solar flux (GSF, in watts per square meter), mean relative humidity (RH, in percent), mean sea-level air pressure (P, in hectopascal) and mean wind speed (WS, in meter per second). Chemical air pollutants include the daily average mass concentrations of CO (in milligram per cubic meter), NO, NO_2, SO_2, O_3, and PM_{10}, furthermore daily O_{3max} (all in microgram per cubic meter).

When selecting biological air pollutants, special emphasis is put on *Ambrosia* due to extreme high concentrations of its most allergenic pollen during its pollen season in Hungary. Two pollen variables were formed for our analysis: daily pollen counts of *Ambrosia* and daily total pollen count (the pollen counts of each of the 24 taxa measured in Szeged) excluding the pollen of *Ambrosia*. The remaining 23 taxa with their Latin (English) names are as follows. *Acer* (maple), *Alnus* (alder), *Artemisia* (mugwort), *Betula* (birch), *Cannabis* (hemp), *Carpinus* (hornbeam), *Chenopodium* (goosefoot), *Corylus* (hazel), *Fraxinus* (ash), *Juglans* (walnut), *Morus* (mulberry), *Pinus* (pine), *Plantago* (plantain), *Platanus* (platan), *Poaceae* (grasses), *Populus* (poplar), *Quercus* (oak), *Rumex* (dock), *Salix* (willow), *Taxus* (yew), *Tilia* (linden), *Ulmus* (elm) and *Urtica* (nettle).

Meteorological variables and chemical air pollutants were collected in a monitoring station located in the inner city area of Szeged, at a distance of about 10 m from the busiest main road (Fig. 1). The pollen content of the air was measured using a 7-day recording "Hirst-type" volumetric trap (Hirst 1952). The air sampler is located about 20 m above the ground (Fig. 1, lower panel).

Asthma ED visits

Daily number of ED visits registered with asthma comes from the Hospital of Chest Diseases, Deszk, Csongrád County, located about 10 km from the monitoring station in Szeged downtown (Fig. 1, lower panel). Age, gender, date of admission and disease type were available for each patient. Asthma ED diseases were categorized using the International Classification of Diseases, Tenth Revision (ICD-10; WHO 1999) as follows: allergic asthma (J4500), mixed asthma (J4580) and asthma without specification (J4590). Allergy was defined in all here-mentioned disease categories. Generally, three age groups can be considered in the research: young patients (0–14 years), adult patients (15–64 years) and elderly patients (equals to or older than 65 years) because the diagnostic category of asthma may include different syndromes in children, adults and elderly people (Ko et al. 2007). Due to the very small patient number in younger age group, only categories of adults and the elderly people were analysed. For these latter two categories, ED visits of male and female patients were considered. Altogether, 936 ED visits were recorded due to asthma consisting of 497 females and 439 males, respectively.

Daily sea-level pressure fields

Daily sea-level pressure fields measured at 00 UTC (Coordinated Universal Time) come from the ECMWF (European Centre for Medium-Range Weather Forecasts) Re-Analysis ERA 40 project, in the frame of which daily data have been re-analysed since September 1, 1957. The procedure has been performed with a uniform method from the data being available in the investigated period. Data for the ECMWF Re-Analysis ERA 40 project are verified, dynamically correct, the pressure field is real even over the Atlantic Ocean and there is no lack of data. When using the method, the measured false input data are omitted. At the same time, if original station data are used, false data can frequently be accounted.

The investigated area is in the North-Atlantic–European region between 30°N–70.5°N latitudes and 30°W–45°E longitudes. The grid network is selected with a density of 1.5°× 1.5°, which indicates 28°×51=1428 grid points for the region.

Study periods

The analysis was performed for the 9-year period 1999–2007 with two pollen variable data sets, namely the daily *Ambrosia* pollen counts for the pollen season of *Ambrosia* (July 15–October 16) and the daily total pollen counts excluding the pollen season of *Ambrosia* (January 14–July 14); furthermore, the pollen-free season (October 17–January 13) were considered. Though the total pollen excluding the pollen season of *Ambrosia* comprises several allergens, this separation permits studying asthma ED cases that can be originated in the two pollen variables separately as *Ambrosia* dominates the pollen counts during the main part of its pollen season.

The pollen season is defined by its start and end dates. For the start (end) of the season we used the first (last) date on which at least one pollen grain per cubic meter of air is recorded and at least five consecutive (preceding) days also show one or more pollen grains per cubic meter (Galán et al. 2001). Evidently, the pollen season varies from year to year. Here, the longest pollen season observed during the 9-year period was assigned to each year.

Methods

Spatial Synoptic Classification (SSC) weather types

The Spatial Synoptic Classification (SSC) system was originally developed by Kalkstein et al. (1996) for USA and later it was redeveloped (Sheridan 2002, 2003) and then expanded for Canada and Western Europe (Bower et al. 2007), as well as for Asia. The SSC is based solely on four-time daily station based observations of temperature, dew point, wind speed, air pressure and cloud cover. Hence, the SSC is properly called a weather-type classification.

The SSC is a hybrid classification scheme. Initially, weather-type identification was made manually for each weather type, based on climatological knowledge. Then, using algorithms, for each type hypothetical "seed days", namely typical days were determined for each day of the year. Once this process is complete, actual conditions on each day were compared to the seed days, and the day was classified as the one it most closely resembles. Hence, when the process is complete, each day is classified into one of the weather types. SSC has a wide application in the area of climate–health associations (Sheridan et al. 2009; Sheridan and Kalkstein 2010; Hondula et al. 2014).

The SSC calendar for Europe, including Budapest (http://sheridan.geog.kent.edu/ssc.html), is continuously prepared (recently it is available for the period 1974–2013) that comprise the study period (1999–2007). Since the distance of Szeged from Budapest is 161 km as the crow flies, the weather types determined for Budapest can be considered valid for Szeged, as well.

The number codes of the weather types developed are as follows: 1=dry moderate (DM), 2=dry polar (DP), 3=dry tropical (DT), 4=moist moderate (MM), 5=moist polar (MP), 6=moist tropical (MT), 7=transition (T), 8=day is missing, 66=moist tropical plus (MT+) and 67=moist tropical double plus (MT++). Note that MT+ and MT++ (66 and 67) are subsets of the MT weather type. They were developed for the assessment of heat-related mortality (Kalkstein et al. 1996; Sheridan 2002, 2003; Bower et al. 2007).

Objectively defined weather types

Classification of weather types objectively can be performed using multivariate statistical methods such as factor analysis (FA) and cluster analysis (CA). Kalkstein and Corrigan (1986) used a combination of principal component analysis (PCA) and cluster analysis in order to demonstrate the application of objective synoptic climatological classification schemes to air pollution climatology. FA and PCA are similar methods since both aim at reducing the dimensionality of a set of correlated variables to a smaller number of manageable and physically interpretable new dimensions that can be referred to as components or factors, as well. However, the two procedures are not identical (McGregor and Bamzelis 1995; Sindosi et al. 2003).

Factor analysis

Factor analysis reduces the dimensionality of a large data set of p-correlated variables, expressing them in terms of m ($m < p$) new uncorrelated variables, the so-called components or factors. Calculation was based on PCA combined with varimax rotation keeping the factors uncorrelated (Sindosi et al. 2003). The number of components produced is equivalent to the number of original input variables and account for 100 % of the total variance of all original variables. Since only a few components may account for the majority of the total variance, it may be unnecessary to retain all components. Several methods are available for determining the number of components to be retained (Jolliffe 1990, 1993; McGregor and Bamzelis 1995). One of the most known component selection techniques selects components with eigenvalues >1. This is based on the idea that all new variables should have greater explanatory power than the original variables, which have an eigenvalue of 1. Some papers have established that selecting components with eigenvalues <1 can result in an increase of the explanatory power and thus suggested retaining the number of components with the largest explained cumulative variance that account for at least 80 % of the total variance of the original variables that has to be explained by the factors (Jolliffe 1990). Note that these methods are considered subjective (McGregor and Bamzelis 1995). We applied the latter procedure, as perhaps the most common method, for calculating the number of components to be retained (Sindosi et al. 2003; Liu 2009).

Cluster analysis

The relationship between the original variables and the components is expressed by component loadings. When squared, the loadings are equivalent to the correlation between the component and the original variable. The component loadings are therefore used to physically interpret the components. Calculation of the component scores is the next step of the classification process in developing weather element categories. The days involved are classified into groups of days with the most similar component score structure, using a clustering technique (McGregor and Bamzelis 1995). The aim of the method is to maximize the homogeneity of objects within the clusters and also to maximize the heterogeneity between the clusters. Each day corresponds to a point in the m-dimensional space and each cluster consists of those observations, which are "close" to each other in this space. Here, a non-hierarchical cluster analysis with the k-means method (Anderberg 1973) was applied using the Mahalanobis metric (Mahalanobis 1936) available in MATLAB 7.5.0.

A further decision concerning cluster analysis is the selection of the optimum number of clusters. Our decision on selecting the optimum cluster number is associated with the within cluster homogeneity. The homogeneity within clusters was measured by RMSD defined as the sum of the root mean square deviations of cluster elements from the corresponding cluster centre over clusters. As the RMSD will usually decrease with an increasing number of clusters, this quantity is not very useful for deciding about the optimal number of clusters. However, the change of RMSD (CRMSD) versus the change of cluster numbers, or rather the change of CRMSD (CCRMSD) is much more informative. Here, working with cluster numbers from 15 to 1, an optimal cluster number was selected so as to maximize the change in CRMSD. The rationale behind this approach is that the number of clusters producing the largest improvement in cluster performance compared to that for a smaller number of clusters is considered optimal (Makra et al. 2010).

We stress that clustering of the days considered was based exclusively on meteorological data. In order to characterise the clusters retained, in terms of their meteorology, mean values of the original meteorological variables for the days comprising each cluster were calculated. In this way, each group will represent a specific weather type.

After producing the meteorology based clusters of the days considered, mean daily values of the air pollutants and airborne pollen variables, as well as mean daily number of asthma ED admissions are calculated for each cluster.

Hence, cluster-related associations between the mean daily values of air pollutants and airborne pollen variables on one hand and the corresponding mean daily number of asthma ER admissions on the other hand are revealed.

Analysis of variance (ANOVA) and Tukey test

When determining the synoptic types, only meteorological parameters are taken into account, excluding emergency admissions, pollen data and the chemical air pollutants. Hence, the differences of the mean number of ED visits, the mean concentrations of pollen data and the mean levels of the chemical air pollutants calculated for each synoptic type need a further statistical evaluation. This is performed by the method of one-way analysis of variance (ANOVA) for the means of all the three variables mentioned above. By using the method, significant differences in the mean number of asthma ED visits, furthermore the mean levels of both the pollen variables and the chemical air pollutants of the different synoptic types (clusters) can be determined. If ANOVA, based on the F test, detects significant differences among these means then another test is applied to determine that specifically which cluster pairs differ significantly from each other. Significant differences among cluster related mean numbers of emergency admissions may inform us about the dependence of asthma ED visits from the ensembles of the influencing variables. There are several versions available for comparing means calculated from subsamples of a sample. A relatively simple but effective way is to use the Tukey test. It performs well in terms of both the accumulation of first order errors of the test and the test power (Tukey 1985). In this way, the Tukey's honestly significant difference test is applied in order to quantitatively compare the mean number of asthma ED visits and the mean levels of the above air pollutants between each pair of synoptic types (pairwise multiple comparisons; Tukey 1985; Sindosi et al. 2003).

All statistical computations were performed with MATLAB software.

Comparability of the test statistics

The two objective classifications have different number of weather types for the three different periods examined. In order to take the results of ANOVA and Tukey tests comparable, the average of numbers of days classified into different types (total number of days divided by the number of types) should be the same for the two classification approaches. This task is solved as follows. Since the objectively defined weather classification consists of substantially smaller number of types, it comprises considerably higher average number of days per types (y) compared to that of the Spatial Synoptic Classification (SSC) weather types (x). Hence, $(y-x)/y$ portion of days are excluded randomly from the original data set when classifying days into the objectively defined weather types. Due to the different number of clusters for the objectively defined weather types, the task should be implemented for each pollen-related period, respectively.

Results

Mean sea-level pressure fields of the objectively defined weather types

For the yearly period, altogether, six weather types were classified. These types and the corresponding pressure patterns with the associated mean daily air pollution and airborne pollen levels, as well as mean daily asthma ED cases are described as follows (Fig. 2).

Cluster 1: During its occurrence, an anticyclone extends from the region of Azores over Central Europe. This weather type is most frequent in the winter months between November and February. Due to its predominance in winter, when this type occurs, the temperature parameters and global solar flux are low, whilst relative humidity and air pressure are high. Among the air pollutants, NO concentration is high, whilst levels of O_3 and O_{3max}, as well as the remaining pollen are low. Prevalence of all asthma ER categories for adults is low and for elderly is high, respectively. At the same time, it is around average for each category of all cases (Fig. 2).

Cluster 2: The frequency of this weather type is little. It mostly occurs in the first half of the year. This cluster is characterized by undisturbed weather conditions with high global solar flux and daily temperature range, furthermore low wind speed. The levels of CO, ozone parameters and SO_2 are high, whilst those of NO and NO_2 are the lowest of all clusters. Mean values of asthma ER categories, except for female and elderly female patients are very high (Fig. 2).

Cluster 3: This is the third most frequent weather type. Its sea-level pressure field is very similar to that of cluster 1. Though the values of the global solar flux and the temperature parameters are slightly higher for cluster 3 than for cluster 1; unsurprisingly, those of the remaining meteorological elements, air pollutants and airborne pollen are very similar. Furthermore, the prevalence of female, total, adult female and adult total patients are very low (Fig. 2).

Cluster 4: The weather type featured by this cluster occurs only on 15 days (0.5 %) from the 9-year period examined. Hence, this cluster is not important in classifying the environmental parameters and the different patient categories (Fig. 2).

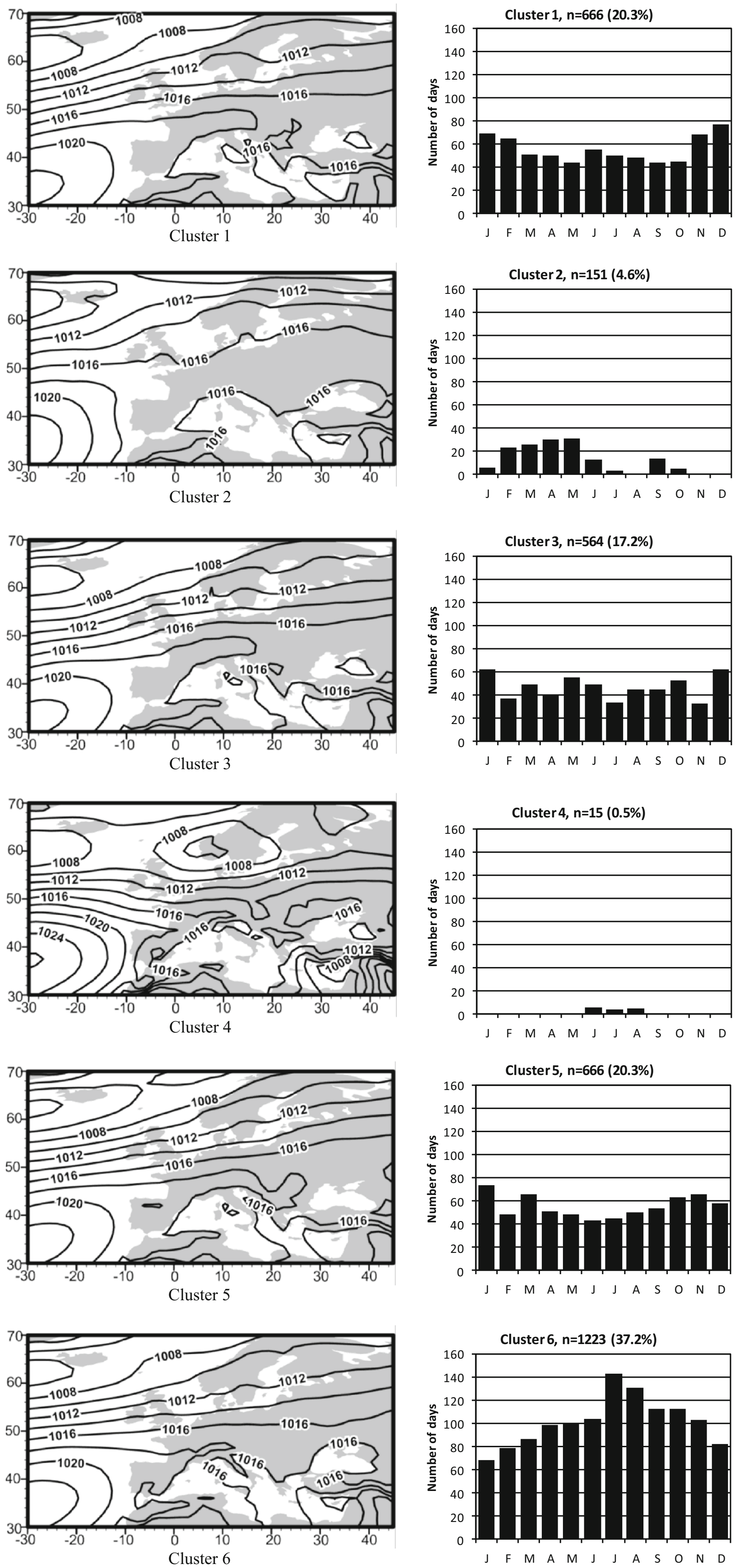

Fig. 2 Mean sea-level pressure fields for each objectively defined weather type (cluster) and monthly frequency of their number of days, North-Atlantic—European region, year, 1999–2007

Cluster 5: This type has an anticyclonic character with an undisturbed weather. It happens with almost equal frequency in each month of the year and is characterized by low temperature parameters and low global solar flux. During its occurrence, CO and NO concentration are the highest of all clusters, whilst ozone parameters are low. At the same time, the frequency of the asthma ED categories are slightly above average (Fig. 2).

Cluster 6: This is the equally most frequent weather type with cluster 1. During its occurrence, global solar flux and relative humidity are very low, whilst the wind speed is the highest. All chemical air pollutants indicate low values except for NO. Since average concentrations of NO in clusters 1 and 6 are the same, higher enrichment of ozone in cluster 6 compared to cluster 1 can be explained with the lower cloudiness (in this case advection is supposed to be neglected; Fig. 2).

For the pollen season of total pollen excluding *Ambrosia* (January 14–July 14, 1999–2007), altogether, three weather types were received. These types and their pressure patterns with the associated mean daily values of air pollution and airborne pollen parameters; furthermore, mean daily asthma ED cases are shown below (Fig. 3).

Cluster 1: This type is very calm; it is free of weather fronts and occurs rather rarely. This cluster is characterized by high temperature parameters and global solar flux, whilst relative humidity and wind speed are the lowest. Furthermore, the mean values of NO and NO_2 are the lowest, at the same time the mean daily concentrations of the remaining pollutants and pollen are the highest of all clusters. In addition, female and adult female patients show above average values, whilst the frequency of the remaining asthma ED categories is the highest of all clusters (Fig. 3).

Cluster 2: This is the most frequent weather type. Azores high-pressure ridge advances deeply into the European continent involving even Eastern Europe. Air pressure is the highest during this type, whilst temperature parameters and global solar flux are well below the average. Mean daily values of all air pollutants are low, whilst the pollen level is high. Mean values of female and adult female asthma ER visits are the highest of all clusters, whilst the prevalence of the remaining categories is below average (Fig. 3).

Cluster 3: Sea-level pressure field of this type is very similar to that of cluster 2. As it is expected, mean daily values of both the meteorological elements and the air pollutants are also very similar for these clusters. At the same time, pollen levels are the smallest. In addition, mean daily occurrences of all asthma ER categories are the smallest for this cluster (Fig. 3).

For the pollen season of *Ambrosia* (July 15–October 16, 1999–2007), altogether, four weather types were received. Sea-level pressure fields of these types and mean daily values of air pollution and airborne pollen parameters, as well as mean daily number of asthma ER visits are shown below (Fig. 4).

Cluster 1: This type occurs most frequently. Its pressure system assumes a calm weather type. Mean daily values of the daily temperature range and sea-level pressure are the highest, whilst those of CO, PM_{10} and the remaining pollen are the lowest of all clusters. The occurrence of elderly male patient is the highest of all clusters, whilst the remaining patient categories show very low values (Fig. 4).

Cluster 2: This weather type involves only 7 days (0.8 %) during the 9-year period examined. Hence, it is practically negligible and is omitted from further analysis (Fig. 4).

Cluster 3: Its occurrence is very small. The pressure system of this type shows a fragmented picture. Its temperature parameters and global solar flux show the lowest values of all clusters in this period, whilst relative humidity and wind speed is the highest in this cluster. NO indicates the highest value, whilst NO_2, the ozone parameters and the remaining pollen the lowest values in this cluster. In addition, the occurrence of male and adult male patients is the highest, whilst the remaining patient categories show very low values (Fig. 4).

Cluster 4: This is the second most important weather type for this period. A well-developed high-pressure ridge stretches far to the east over Europe through the East European Plain, reaching the area of Moscow. Mean daily values of the meteorological parameters are around average, those of the chemical air pollutants are low except for CO, *Ambrosia* pollen level is the highest, whilst mean daily values of all asthma ED categories, except for elderly males are well below (Fig. 4).

For the pollen-free season (October 17–January 13, 1999–2007), three weather types were classified. Their sea-level pressure fields, occurrences and mean daily values of the air pollutants and mean daily number of asthma ER visits according to their categories are as follows (Fig. 5).

Cluster 1: This weather type is the most important for this period with its highest frequency. Strong western air currents occur through the northern part of Europe. At the same time, an anticyclone centre can be observed over the central Mediterranean and South-Eastern Europe. Temperature parameters are above average, the sea-level pressure is low and the air pollutants take values around average. The prevalence of asthma ER cases for male and

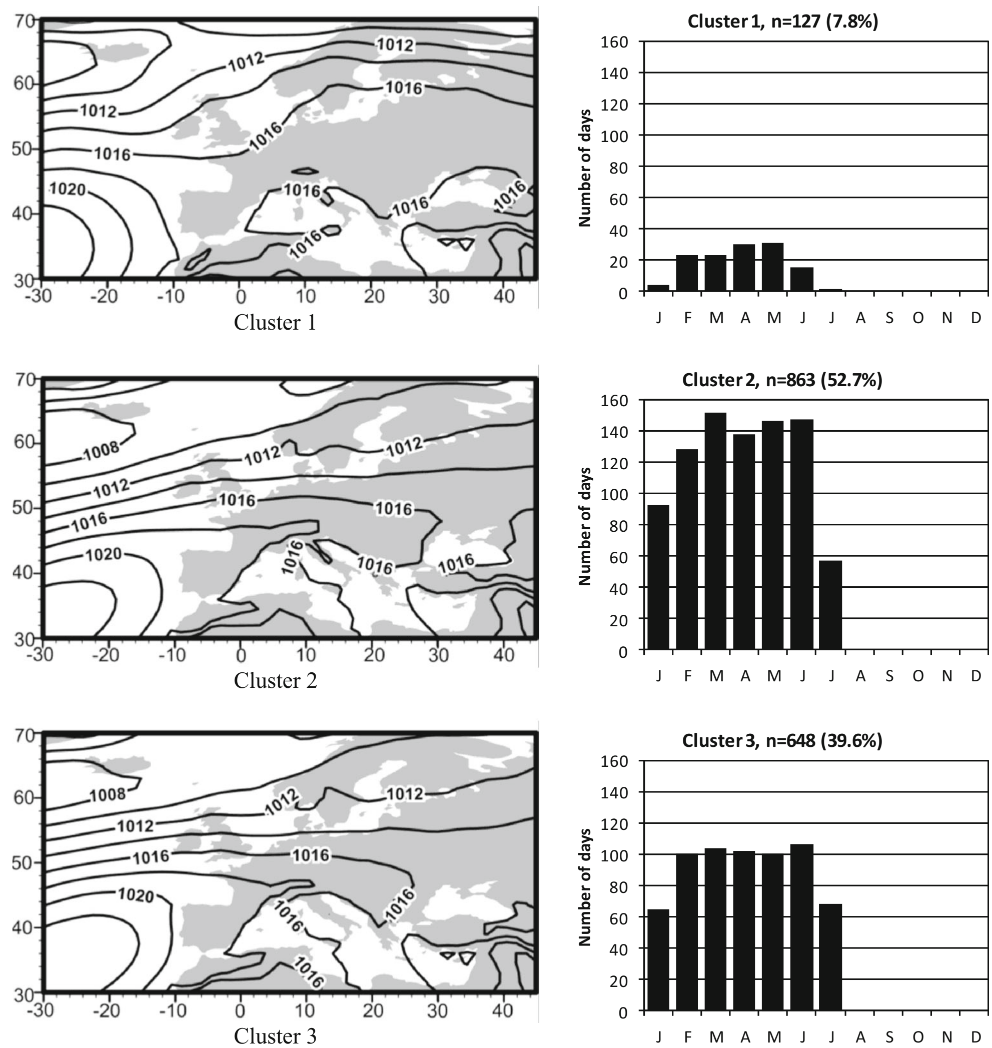

Fig. 3 Mean sea-level pressure fields for each objectively defined weather type (cluster) and monthly frequency of their number of days, North-Atlantic—European region, pollen season of total pollen excluding *Ambrosia* (January 14–July 14), 1999–2007

adult male patients is the highest, whilst for all the elderly categories is the lowest (Fig. 5).

Cluster 2: The sea-level pressure system of this type is very similar to that of cluster 1. Accordingly, mean daily values of the meteorological parameters are also very similar in these clusters, with their somewhat higher values in cluster 2: Mean daily values of NO, NO_2 and the ozone parameters are the highest, whilst those of CO and PM_{10} are the lowest in this cluster. Mean daily number of all asthma ER categories is the lowest in this cluster, however, elderly male patients are the most frequent here (Fig. 5).

Cluster 3: The similarity of this weather type is not so remarkable with clusters 1 or 2 than between clusters 1 and 2. Definitely stronger western air currents can be observed over northern Europe than for clusters 1 or 2. At the same time, the high-level pressure formation in the central Mediterranean migrates over Central Europe and, simultaneously, gets substantially stronger. Since this is a winter type with a highly developed anticyclone, temperature parameters, global solar flux and wind speed should be low, whilst relative humidity and sea-level pressure should be high as they are in reality, as well. Among air pollutants only, CO level is the highest, whilst concentrations of the remaining air pollutants are the lowest, except for PM_{10}. Furthermore, according to our expectations, mean daily number of asthma ER patients is the highest or above their average practically for each patient category (Fig. 5).

Inter-weather-type comparison of the air pollutants and pollen variables for the two weather classification approaches

In order to determine the influence of the weather types on the concentrations of the air pollutants (seven variables) and the pollen types (two variables), as well as the prevalence of acute asthma ED visits (nine variables), ANOVA was performed on the here-mentioned variables (altogether 18 variables). Calculations were implemented for both weather

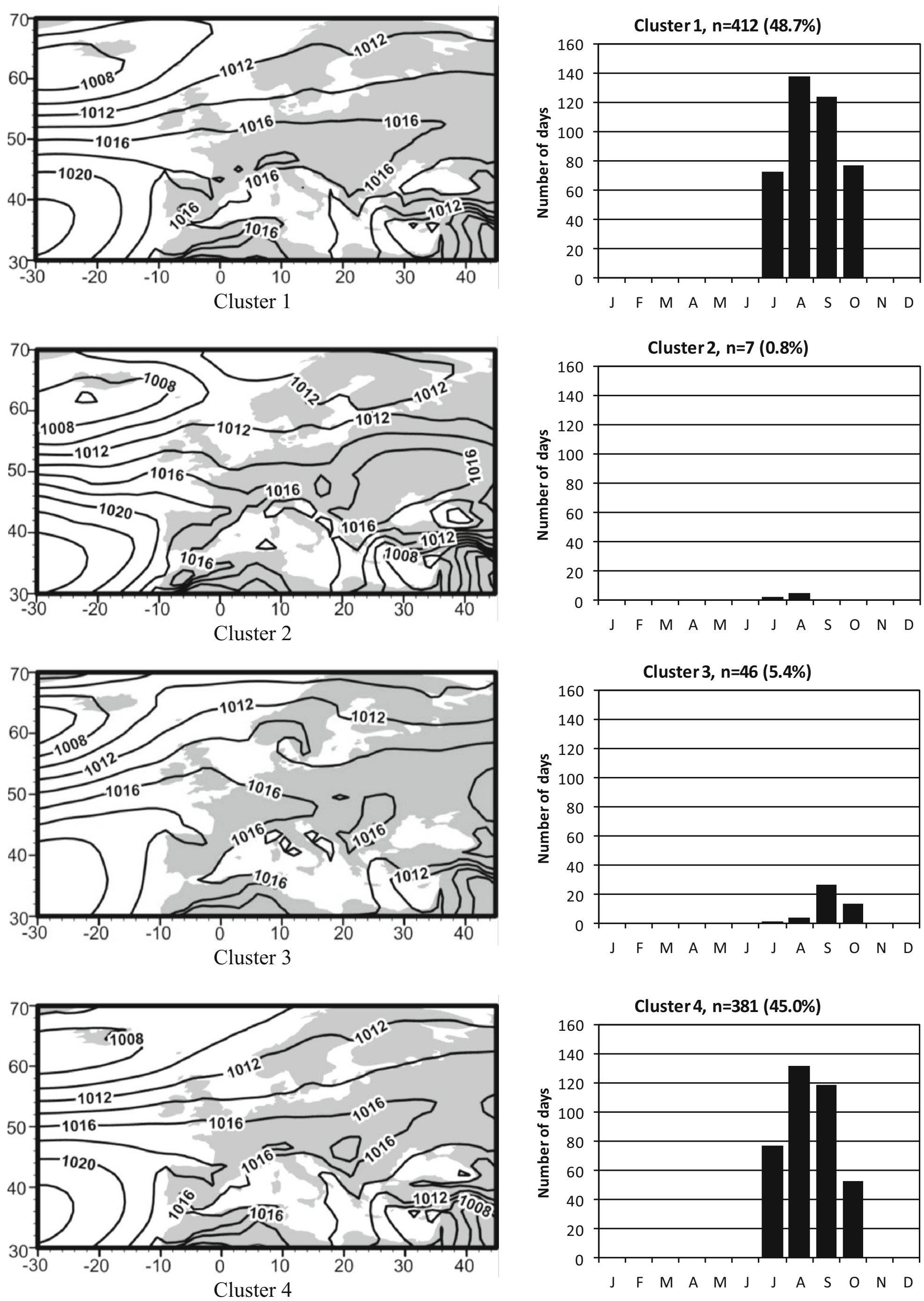

Fig. 4 Mean sea-level pressure fields for each objectively defined weather type (cluster) and monthly frequency of their number of days, North-Atlantic—European region, pollen season of *Ambrosia* (July 15–October 16), 1999–2007

classification approaches, as well as for all the three within-year periods and the annual data sets. It was found that cluster averaged mean daily values of the above variables indicated significant inter-weather-type differences at least at the 95 % probability level.

For the objectively defined weather types, no significant inter-weather-type differences can be observed in the mean daily number of the patient categories in the annual data set (six weather types, Fig. 2). Nevertheless, significant differences for mean daily values of O_3 between types 1 and 2, furthermore for those of O_3 and O_{3max} between types 1, 2, 3 and4, as well as O_{3max} between types 1, 2, 3, 4, 5 and 6 can be observed, respectively.

At the same time, in the pollen season of total pollen excluding *Ambrosia* (three weather types, Fig. 3), total adult (T_{ad}) and total elderly (T_{eld}) patients show significant differences in their cluster averaged prevalence between types 1 and 2, furthermore mean daily values of these patient variables

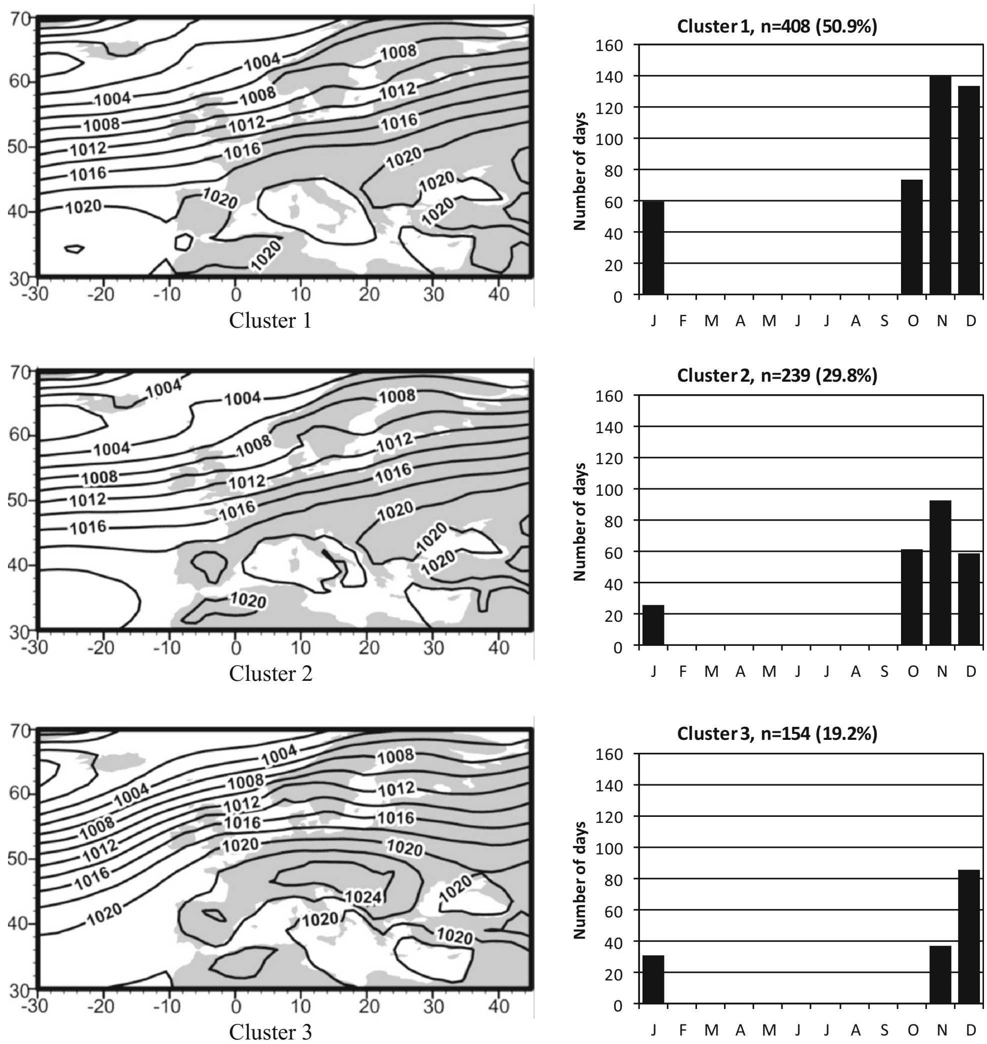

Fig. 5 Mean sea-level pressure fields for each objectively defined weather type (cluster) and monthly frequency of their number of days, North-Atlantic–European region, pollen-free season (October 17–January 13), 1999–2007

completed with that of the female patients (*F*) also indicate remarkable differences between types 1, 2 and 3 (Fig. 3). For type 1, temperature parameters and global solar flux are substantially higher, whilst sea-level pressure and wind speed are lower than for types 2 and 3. Calm weather and high global solar flux in type 1 may contribute to enrichment of SO_2 and the remaining pollen (T-Amb) and, in this way, indirectly may facilitate to increase the patient numbers (Fig. 3). However, NO and NO_2 affect inversely, whilst T-Amb values proportionally the number of asthmatic patients both for types 1 and 2 and 1 and 3.

For the pollen season of *Ambrosia* (four weather types, Fig. 4), only types 1 and 2 indicate significant differences in patient numbers, namely in the mean daily values of asthma ED occurrences of female (*F*), total (*T*) and female elderly (F_{eld}) patients, respectively. In addition, O_3, O_{3max} and *T*-Amb show significant differences in their daily means when compared types 1 and 2. All the three pollutants indicate significant positive association with the prevalence of the above patient categories, respectively. However, since altogether 7 days belong to type 2, the here-mentioned comparison of types 1 and 2 concerns very few cases (Fig. 4).

For the pollen-free season, mean daily prevalence of female elderly (F_{eld}) and total elderly (T_{eld}) patients differ significantly between types 1 and 2, and types 1 and 3. In addition, mean daily NO_2 levels also show substantial difference between types 1 and 3 (Fig. 5). For types 1 and 2 significant differences in patient numbers cannot be associated with air pollutants and pollen variables. Concerning the meteorological elements, temperature parameters and global solar flux are substantially higher in type 2 compared to type 1. However, possibly high wind speed in type 2 restricts enrichment of air pollutants. Significant difference of NO_2 concentration between types 1 and 3 is in an inverse connection with female elderly (F_{eld}) and total elderly (T_{eld}) patients.

For Spatial Synoptic Classification (SSC) weather types, no significant inter-weather-type differences occur in mean daily number of the patient categories in the pollen season of total pollen excluding *Ambrosia*. Whilst, only one patient variable differs substantially both for the annual data set (female patients, types 1–4) and for the pollen-free season (male patients, types 4–6), respectively. In the former case, CO, NO_2, O_3, O_{3max} and SO_2 serve as significant influential variables for female patients. CO and SO_2 are in a proportional association with female patient numbers, whilst NO_2, O_3 and O_{3max} are inversely associated with the occurrences of female asthma admissions. For the pollen-free season, male (*M*) asthma occurrences are proportionally associated with O_3, O_{3max} and PM_{10} levels, respectively.

At the same time, the pollen season of *Ambrosia* seems to most heavily influence the prevalence of asthmatic diseases. Namely, for most of its categories their daily cluster-averages differ significantly in the pairwise comparisons of the weather types, compared to those of the remaining seasons. Surprisingly, influential variables are only chemical air pollutants and the remaining pollen, at the same time *Ambrosia* pollen cannot be associated with asthma ER admissions.

Metrics of the two weather classification approaches (character, efficiency)

The character of the associations between the number of asthmatic patients on one hand and the air pollutants and the pollen variables on the other is not clear. For the objectively defined weather types, asthma ED occurrences indicate proportional association with O_3, O_{3max}, T-Amb and SO_2 levels, whilst they are in inverse relationship with NO and NO_2 concentrations. At the same time, for the SSC weather types, patient numbers change proportionally with CO and SO_2 concentrations and inversely with NO_2 and T-Amb levels. However, the role of O_3, O_{3max} and PM_{10} is complex; namely, they show both negative and positive relationships with the number of asthmatic patients. If the two classification approaches are compared, NO_2 shows negative, whilst SO_2 positive association with the patient numbers for both classifications. At the same time, the remaining pollen (T-Amb) level changes proportionally with the patient numbers for the objectively defined types, whilst inversely for the SSC types. O_3 and O_{3max} are in positive association with the asthma ER visits for the objectively defined types, whilst they show both positive and negative relationship with the patient numbers for the SSC types. The role of PM_{10} in the latter case is also ambivalent.

The efficiency of the individual weather types were calculated and compared for both weather classification approaches in each period. The efficiency of the classifications was defined 100 % (0 %) if mean values of all (none of) the variables (16–18 influencing variables depending on the pollen-related periods considered) differ significantly for all pairwise comparisons. For the objectively defined categories, weather type 1 (an anticyclonic ridge weather type for each pollen-related season with near extreme values of temperature and humidity parameters) is the most effective in each period, especially in the pollen season of total pollen excluding *Ambrosia* (41.2 %; Table 1). The efficiency of the Spatial Synoptic Classification (SSC) weather types is the highest for type 5 [MP (moist polar) with humid and cool air], except for the pollen-free season (type 4). Whilst, the lowest efficacy changes according to the periods (pollen season of total pollen excluding *Ambrosia*: type 1; pollen season of *Ambrosia*: type 2, pollen-free season: type 3; Table 2). When comparing the total efficiency of the two classification approaches, the objectively defined types stand out in the pollen season of total pollen excluding *Ambrosia*, whilst this is the case for the SSC weather types in the pollen season of *Ambrosia*. As a conclusion, the total efficiency of the two classification approaches is similar (Table 3).

Discussion

Studying asthma ER admissions due to pollutant concentrations is a very important public health issue. This paper analyses a large dataset, namely a 9-year daily database. Relatively few papers (e.g. Anderson et al. 1998; Lierl and Hornung 2003; Carracedo-Martínez et al. 2008; Makra et al. 2012) involve two categories of air pollutants, namely chemical air pollutants and airborne pollen for studying their influence on the prevalence of asthma ER visits. This paper concurrently includes two categories of influencing variables with seven chemical air pollutants and two pollen parameters, furthermore altogether nine age and gender categories of asthma ER cases as resultant variables. The above-mentioned associations are examined for three seasons and the annual data set. There are very few papers in the literature analysing weather-type-related association of different diseases with meteorological parameters and air pollutants (weather elements and air pollutants, Kassomenos et al. 2007; weather elements, Kassomenos et al. 2010). However, to our best knowledge, only one paper has yet been published

Table 1 Efficiency of each objectively defined weather type in separating significantly different cluster average values of the chemical air pollutants and the airborne pollen types in the inter-weather-type comparisons, in percent

Period	Objectively defined weather types					
	1	2	3	4	5	6
Pollen season of total pollen excluding *Ambrosia*	**41.2**	*17.6*	23.5			
Pollen season of *Ambrosia*	**13.0**	11.1	1.9	*0.0*		
Pollen-free season	**15.6**	*6.3*	9.4			
Year	**4.4**	1.1	*0.0*	2.2	*0.0*	1.1

Bold: maximum, italic: minimum

Table 2 Efficiency of each SSC weather type in separating significantly different cluster average values of the chemical air pollutants and the airborne pollen types in the inter-weather-type comparisons, in percent

Period	Spatial Synoptic Classification (SSC) weather types						
	1	2	3	4	5	6	7
Pollen season of total pollen excluding *Ambrosia*	*10.8*	12.7	11.8	20.6	**27.5**	14.7	15.7
Pollen season of *Ambrosia*	20.4	*10.2*	23.1	20.4	**25.0**	20.4	12.0
Pollen-free season	15.6	10.4	*3.1*	**16.7**	11.5	11.5	8.3
Year	22.2	*15.7*	19.4	27.8	**30.6**	23.1	16.7

Bold: maximum, italic: minimum

(Makra et al. 2008) studying the dependence of meteorological elements, air pollutants and pollen variables (13, 8 and again 8 parameters, respectively) on nine symptom groups of respiratory diseases for different weather types. To our knowledge, the present paper can be considered the first study analysing weather-type-related association of two categories of pollutant variables (chemical air pollutants and pollen variables) on the occurrence of a wide scale of age and gender categories of asthmatic diseases.

Weather-type-related impact of environmental parameters on asthma occurrences

Meteorological conditions

Objectively defined weather types 1 for the pollen season of total pollen excluding *Ambrosia* and the pollen-free season are low-pressure formations (Figs. 3 and 5). At the same time, the SSC weather type 5 is described as an MP (moist polar) formation with cloudy, humid and cool weather (Kalkstein et al. 1996; Sheridan 2002, 2003; Bower et al. 2007). Accordingly, favourable conditions for asthma ER visits occur during low-pressure formations in both weather classification approaches.

Table 3 Total efficiency of the two weather classifications in separating significantly different cluster average values of the chemical air pollutants and the airborne pollen types in the inter-weather type comparisons, in percent

Period	Weather types	
	Objectively defined types	SSC weather types
Pollen season of total pollen excluding *Ambrosia*	27.4	16.3
Pollen season of *Ambrosia*	6.5	18.8
Pollen-free season	10.4	11.0
Mean performance	14.8	15.4

Meteorological parameters influence asthma ER visits; however, this association is generally not clear. Namely, both air temperature and relative humidity were found positively correlated with acute pediatric (Fauroux et al. 2000) and adult (May et al. 2011; Hayes et al. 2013) asthma ED admissions. Kassomenos et al. (2010) also associated increased hospital admissions with high relative humidity. Furthermore, highest daily mortality was observed on days with southerly flow conditions for the Athens Basin, indicating that high relative humidity, though indirectly, may substantially influence weather-related asthmatic diseases, as well (Kassomenos et al. 2007). At the same time, according to others, high asthma ED admissions occurred on days with low levels of humidity (Celenza et al. 1996; Dales et al. 2000). Furthermore, a significant negative association was reported between minimum temperature and asthma exacerbation in adults (Celenza et al. 1996; Abe et al. 2009). The evidence regarding the effect of rainfall is also mixed (Jamason et al. 1997; Rosas et al. 1998). For instance, heavy rain during the pollen season was thought to have suppressed both the size of the pollen peaks and their duration. At the same time, thunderstorms have been associated with asthma epidemics (Celenza et al. 1996; Marks et al. 2001). One possible explanation is that the humidity preceding a thunderstorm, or rainfall during a thunderstorm, leads to the break up of pollen grains releasing starch granules comprising allergens that are then circulated by the exceptional meteorological conditions (Atkinson and Strachan 2004).

Physiological effects of the meteorological elements explaining the above contradictory associations are as follows. (1) Temperature. Inhalation of cold air in hyper-reactive bronchia induces inflammation of the mucous membrane. Furthermore, the inhalation of dry and cold air also activates the so-called cold receptors on the nasal mucous membrane, which contributes to the development of the respiratory hyper-reactivity (Strausz 2003). (2) Relative humidity. (2a) After inhaling dry air, increased neutrofil, eosinophil and leukotrien content of bronchial lavatory fluid was detected. In general, if the relative humidity is less than 15 %, this may trigger an excessive cough for asthmatics (http://www.aaaai.org). From the above, we can conclude that repeated exposition to dry air produces inflammation, obstruction and hyper-reactivity of the small respiratory tracts. (2b) When breathing humid air, due to the fact that water vapour molecules displace a part of oxygen molecules, asthmatics feel difficult inhaling it. Furthermore, high humidity levels provide favourable conditions for reproduction of fungus and moulds that exacerbate the symptoms of asthmatics. In addition, when the humidity is greater than 50 %, the amount of dust mites in the air is increased. For these reasons, high relative humidity is contraindicated for asthmatics by physicians. Note that air conditioners can be of benefit for asthmatics, since they remove the humidity and air pollution, as well as particles of biological origin from the air and, as a result, make it cleaner and easier to breath. Nevertheless, low humidity in itself helps to control mould and dust mites in the air (http://www.lung.org/site/pp.asp?c=dvLUK9O0E&b=22591). On the whole, a medium relative humidity between 35 and 50 % is recommended for asthmatic patients to keep in their homes (http://www.cdc.gov/asthma/faqs.htm). (3) Wind directions. Winds partly influence air pollution and partly desiccate and cool the air (see: hyper-reactivity occurring by the influence of cold and dry air).

Significant influence of air pollution on acute human respiratory mortality is overall greater than influences from weather, and varies with season and the entire weather situation. According to Vanos et al. (2014), the spring season presents the overall greatest risk of respiratory-related death. In particular, the risks due to air pollution exposure are the highest on dry tropical (DT) and moist tropical (MT) days with CO and NO_2, the most harmful air pollutants.

The interaction between temperature and specific air pollutants during extreme hot days works synergistically to negatively affect respiratory mortality (Sheridan and Kalkstein 2010; Vanos et al. (2014). At the same time, Anderson and Bell (2009) found respiratory mortality effects to be greater in both cold and heat. The mortality effects of PM_{10} were also significantly higher on warmer days. Extreme heat days in Australia significantly increased respiratory mortality risk with O_3 (Vaneckova et al. 2008). Alternatively, Keatinge and Donaldson (2001) found that excess deaths were associated with cold weather patterns more so than ambient SO_2 and CO concentrations in the Greater London area (1976–1995).

Cai et al. (2014) established a stronger association between air pollution and asthma hospitalization in the cool season, compared to the warm season. This finding is consistent with prior studies in Shanghai (Chen et al. 2010) and Hong Kong (Wong et al. 2002). In both cities, air pollution levels were higher and more variable in the cool season than in the warm season. During the warm season, Shanghai and Hong Kong residents use air conditioning more frequently due to the relatively higher temperature and humidity, thus reducing their indoor exposure. In addition, frequent rain in the warm season partly wash out air pollutants reducing their concentration in ambient air, partly may reduce time spent outdoors and thus personal exposure. In contrast, the cool season in these cities is drier and less variable, so people are more likely to go outdoors and/or open the windows.

Vanos et al. (2014) reported that the temperature effect on respiratory mortality was greater when pollutant levels were higher, commonly referring to O_3 and emphasized the synergism between air pollution and heat or cold. Cheng et al. (2009) also found elevated respiratory mortality associated with heat and air pollution in five major Canadian cities, with 80 % attributable to air pollution, and 20 % to temperature. It is suggested that such temperature effects are likely to persist even after controlling for multiple air pollutants in modelling, particularly O_3 and $PM_{2.5}$ (O'Neill et al. 2005; Gasparrini and Armstrong 2010).

Chemical air pollutants

Several examples are available indicating significant positive association between NO_2 (in children, Bedeschi et al. 2007; Villeneuve et al. 2007; in adults, Cirera et al. 2012; in elderly, Anderson et al. 1998; Villeneuve et al. 2007), SO_2 (in children, Anderson et al. 1998; in adults, Wilson et al. 2005; Cirera et al. 2012), CO (in children and elderly, Villeneuve et al. 2007), TSP (in children, Bedeschi et al. 2007), PM_{10} (in children, Ostro et al. 2001; Bedeschi et al. 2007; Villeneuve et al. 2007; in elderly, Villeneuve et al. 2007) and black smoke (in elderly, Anderson et al. 1998) on one hand and asthma ER admissions, on the other. Furthermore, according to Vanos et al. (2014), all relative risk estimates for respiratory disease are significantly above 1.0 for all combinations of season, pollutant and weather type.

However, these relationships are rather complex.

We did not receive significant association between the occurrence of asthma ER admissions and CO levels. However, CO has been associated with respiratory hospital admissions in several studies. Freitas et al. (2010) did not find any statistically significant relationship between respiratory hospital admissions and CO. Makra et al. (2012) detected both positive and negative relationships between asthma attacks and CO concentration, respectively. Whilst, others (Fusco et al. 2001; Kassomenos et al. 2008; Giovannini et al. 2010; Darrow et al. 2011; Tramuto et al. 2011) confirmed the positive role of CO on respiratory health effects. The impact of a long-lasting but low-level exposure to CO on respiratory system is therefore still unclear.

When using SSC weather types, we received significant inverse (for males, elderly males and elderly females in the pollen season of *Ambrosia*) and proportional (for males in the pollen-free season) association between PM_{10} levels and asthma ER admissions, respectively. Kassomenos et al. (2008) found that elevated PM_{10} levels indicate a dominant role among the main air pollutants. Fusco et al. (2001) and Alves et al. (2010) found that the association between particulate matter and health conditions was not significant, whilst others (Ko et al. 2007; Meng et al. 2007; Freitas et al. 2010; Namdeo et al. 2011; Tramuto et al. 2011; Makra et al. 2012) detected that the number of admissions for respiratory causes rose significantly with increased exposure to particulate matter. It should be added that the health impact of particulates is complex as their biological effect can be influenced by the particle size and composition (Alves et al. 2010). Cakmak et al. (2014) associated aluminium, nickel and titanium with an increased risk of respiratory hospitalizations. Several metals, in particular cadmium, were associated with increased blood pressure and with reductions in lung functions. Cadmium has been found to bind and deplete antioxidant defences, reducing the capacity to scavenge reactive oxygen species such as OH radicals (Liu et al. 2009).

Asthma ER visits indicated significant negative associations for both weather classifications and all the three within-year seasons between asthma occurrences on the one hand and NO and NO_2 levels on the other. Although NO and NO_2 are thought to increase the predisposition to respiratory diseases, there is still a disparity between the results of different studies (Makra et al. 2012). For example, high levels of NO_2 partly indicate no significant association with respiratory admissions (Alves et al. 2010) and partly increase the susceptibility for respiratory diseases (Freitas et al. 2010). Other examples of the significant positive impact of NO_2 levels on respiratory causes are given in Fusco et al. (2001), Kassomenos et al. (2008), Patel et al. (2010), Chiusolo et al. (2011) and Tramuto et al. (2011). In urban areas, anthropogenic NO_2 in the ambient air mainly comes from combustion processes in mobile sources (e.g. traffic). After inhaling NO_2, inflammation of mucous membrane in the bronchia, depending on the quality of the irritative substances, will develop by the transmission of different mediators. As a result of this, plentiful and stagnant bronchus secretion will arise, which is an excellent substrate for pathogens and, in this way, for respiratory infections (Braman 2006).

Both the objectively defined and the SSC weather types showed relevant associations of O_3 and O_{3max} of both signs with asthma ER cases for the pollen season of *Ambrosia* and the pollen-free season. Ozone proved to be a significant trigger for asthma attacks both in children (Fauroux et al. 2000; Ostro et al. 2001; Villeneuve et al. 2007), in adults (Anderson et al. 1998; Wilson et al. 2005) and in elderly (Villeneuve et al. 2007). However, this association may be rather complex. Namely, significant seasonal differences were observed for ozone in children and adults; furthermore in children, there were negative associations with ozone in the cool season (Anderson et al. 1998). Even, Lierl and Hornung (2003) found no significant relationship between asthma ER visits and the ozone concentration. The interpretation of these findings is not straightforward. However, it has been found that O_3 and NO_2, with or without SO_2, can enhance the airway allergic response in susceptible individuals such as those with asthma and rhinitis. Investigating cellular and sub-cellular mechanisms suggest that pollutants are likely to influence the actions and interactions of a variety of cells, and lead to the synthesis of pro-inflammatory mediators that modulate the activity and functions of inflammatory cells (Davies et al. 1998). As there is no evidence that low levels of ozone are harmful, this association seems paradoxical. The phenomenon called Paradoxical Ozone Association, i.e. POA (Joseph 2007), could be due to methyl nitrite from some combustion of methyl ethers or esters in engine fuels. Methyl nitrite is known to be highly toxic and closely related alkyl nitrites are known to induce respiratory sensitivity in humans (Joseph and Weiner 2002). Since sunlight is essential for ozone formation by photochemical oxidation, a probable explanation for POA is the existence of this nitrite pollutant that is rapidly destroyed by solar radiation. Hence, methyl nitrite is negatively correlated with O_3. Since sunlight has the opposite effect on methyl nitrite, one would expect the most acute methyl nitrite effect in winter and its smallest effects in summer (Joseph 2007). A negative association between O_3 levels and asthma ER visits in the summer period (pollen season of *Ambrosia*, can be explained by the fact that our monitoring station is situated at a junction with a high traffic volume).

In the last two decades, contrary to the sharp decrease in NO concentrations, only a moderate, insignificant decrease in NO_2 occurred because catalytic filters in vehicles support emissions of NO_2 as a primary pollutant. This procedure, with a decrease in NO/NO_2 and higher temperature favours an increase in ozone concentrations, which appears to be the indicator of summer smog. Smaller NO/NO_2 ratios and the increased frequency of high pressure global circulation regimes and increased temperatures as a consequence of global climate change (Jacob and Winner 2009; Jeong and Park 2013) favoured ozone formation in the last two decades (Melkonyan and Kuttler 2012). Therefore, an increase in ozone-related asthmatic cases is expected.

When using objectively defined weather types, we found significant positive associations between SO_2 levels and asthma ER visits in adult male, adult female, elderly male and elderly female patients for the pollen season of total pollen excluding *Ambrosia*. Previous findings concerning the role of SO_2 seem inconsistent. This pollutant was not significantly associated with respiratory diseases by Katsouyanni et al. (1995) or Ko et al. (2007), but other studies reported positive relationships (Kassomenos et al. 2008; Alves et al. 2010). SO_2 is able induce bronchospasm in asthmatics at low level and non-asthmatics at much higher level (Tunnicliffe et al. 2001).

Pollen conditions

Surprisingly, *Ambrosia* pollen did not show significant dependence with the patient numbers for either classification approaches. However, Makra et al. (2012) found a significant positive association of *Ambrosia* pollen levels with adult male patients. At the same time, total pollen excluding *Ambrosia* pollen has an important positive role in the occurrence of asthmatic diseases regarding both classification approaches and its both seasons. Significant positive associations between pollen levels (excluding *Ambrosia* pollen) and the patient numbers are similar to those found e.g. in Carracedo-Martínez et al. (2008) and Erkara et al. (2009). However, this association is negative for male, elderly male and elderly female patients in the pollen season of *Ambrosia* that is hard to explain. Probably, the case is that several variables influence this dependence and some variable(s) being beyond our scope may destroy the effect of the total pollen excluding *Ambrosia* pollen. Another point is that some of the elderly habits, as social factors, tend to underestimate chronic diseases and consider them as a natural attendant of age. Hence, the elderly often do not turn to physician and seek medical treatment in time (Johnson 2005).

The association of asthma ED visits with pollen concentrations is not unequivocal in the special literature. Carracedo-Martínez et al. (2008) established that whilst elevations in particulate air pollution increase medical emergency calls because of cardiac or respiratory causes or both combined, elevations in pollen levels raise the number of medical emergency calls due to respiratory causes. However, Cirera et al. (2012) found that pollen levels of Poaceae and Urticaceae did not alter the risk of asthma ER visits. Furthermore, in Villeneuve et al. (2007) air pollution risk estimates were largely unchanged after adjustment for aeroallergen levels. Contrarily, an increased risk of asthma hospitalization was found to be associated with ambient aeroallergens on days of higher air pollution (Cakmak et al. 2012).

Pollen-related asthmatic symptoms depend on the pollen levels influenced by, among other things, meteorological parameters. Note that still rather low pollen concentrations may induce asthmatic symptoms depending on individual sensitivity (Kosman et al. 1994; Goldberg et al. 1998). DellaValle et al. (2012) detected that even very low-level pollen exposure ($\geq$2 grass pollen grains per cubic meter) can be associated with daily asthmatic symptoms. During a severe pollen episode, an inflammation mediated by IgE will develop in the respiratory tracts of the individuals sensitive to the given pollen. After antigen–antibody linkage, mediator substances (histamine, serotonin, prostaglandins, leukotriens, etc.) will multiply, which generate inflammation of the bronchial mucous membrane and the cramp of bronchia. As a result of this, stricture of bronchiolus (bronchoconstriction) will also develop, which is reversible in the case of asthma (Millqvist 1999; Strausz 2003; Parsons and Mastronarde 2005).

Difficulties in determining the interrelationships

The size of asthmatic effects and the existence of a threshold in the level of air pollutants and pollen concentrations at which these effects are triggered are not clear. Thresholds mainly depend on individual sensitivity that moves on a rather wide scale. Furthermore, the possible role of meteorological conditions and other environmental factors in modifying the nature of asthmatic symptoms due to air pollutants are neither fully understood. Another point, the synergy among the possible factors further complicates the association between the environmental components and asthma ER admissions. Further studies are required to clarify details of this rather complex interrelationship, and hence to determine that which environmental components and by which weight influence the development of asthmatic symptoms.

Conclusions

This paper compared an objectively defined weather classification and the Spatial Synoptic Classification (SSC) system in order to determine their performance in (1) classifying the prevalence of the different categories of emergency department (ED) visits for acute asthma, (2) estimating weather-type-related role of environmental parameters (weather elements, air pollutants and airborne pollen) in inducing the occurrence of asthma attacks, (3) determining those components which are the most prone to exacerbate asthma, furthermore (4) assessing and comparing the metrics (character, efficiency) of these weather classifications for Szeged, Hungary.

Among meteorological elements, temperature and relative humidity are most concerned in exacerbating asthma attacks. The inhalation of dry and cold air contributes to the development of the respiratory hyper-reactivity. At the same time, high humidity levels provide favourable conditions for reproduction of fungus and moulds that exacerbate the symptoms of asthmatics.

For the objectively defined weather types, the most efficient type in separating categories of asthma ER visits is weather type 1 (an anticyclonic ridge weather type for each pollen-related season with near extreme values of temperature and humidity parameters). At the same time, for the Spatial Synoptic Classification (SSC) weather types, type 5 [MP (moist polar) with humid and cool air] is the most efficient except for the pollen-free season. In general, partly dry and cold air (Strausz 2003; Anderson and Bell 2009; http://www.aaaai.org), partly warm and humid air (Anderson and Bell 2009; http://www.lung.org/site/pp.asp?c=dvLUK9O0E&b=22591) aggravate substantially the symptoms of asthmatics. We should stress that our major findings are consistent with this establishment. Namely, for the objectively defined weather types favourable conditions for asthma ER visits occur when an anticyclonic ridge weather situation happens with near extreme temperature and humidity parameters. In accordance with this, the SSC weather types facilitate aggravating asthmatic conditions if warm or cool weather occur with high humidity in both cases. Accordingly, favourable conditions for asthma attacks happen with greater chance in the extreme seasons when, in addition to near-extreme values of temperature and humidity parameters, atmospheric stability contributes to enrichment of air pollutants.

The character of the associations between the number of asthmatic patients on one hand and the air pollutants and the pollen variables on the other is not clear. Namely, they can be associated both proportionally (SO_2 for both classifications) and inversely (NO and NO_2 for both classifications) with asthma ER occurrences both for the objectively defined and the SSC weather types. This result is not surprising, since the relationship of any individual pollutant with asthma ER cases is complex and beyond the rather different individual sensitivity, different degrees of synergisms, include also unknown environmental and social factors that make rather difficult to clarify real associations.

Efficiency analysis makes it possible to select the appropriate weather classification approaches for indirectly forecasting of specific environmental conditions for asthma exacerbation, providing in this way more precise information on environmental risk factors of asthma conditions. For the objectively defined categories, weather type 1 (an anticyclonic ridge weather type with near extreme values of temperature and humidity parameters) is the most effective in each pollen-related season, especially in the pollen season of total pollen excluding *Ambrosia* (41.2 %). The efficiency of the Spatial Synoptic Classification (SSC) weather types is the highest for type 5 [MP (moist polar) with humid and cool air], except for the pollen-free season. When comparing the total efficiency of the two classification approaches, the objectively defined types stand out in the pollen season of total pollen excluding *Ambrosia*, whilst this is the case for the SSC weather types in the pollen season of *Ambrosia*. As a conclusion, the total efficiency of the two classification approaches is similar in spite of the fact that the methodology for derivation of the individual types within the two classification approaches is completely different.

Note that considerable evidence is available to suggest that recent warming has already had impacts on pollen amount and all pollen-related characteristics, as well (Beggs 2004; Beggs and Bambrick 2005). Hence, pollen induced asthma attacks aggravated by the ever-increasing air pollution are of major concern, worldwide.

Prediction of weather types 2 or 3 days in advance can be a useful tool for providing valuable information to public health authorities. Improvement of the performance of weather classification approaches may substantially refine the prediction and, hence, may prepare for and/or prevent from risk situations concerning asthma ED visits.

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Appendix

Spatial Synoptic Classification (SSC) weather types

DP (dry polar; type 2) is synonymous with the traditional cP air mass classification. This air mass is generally advected from polar regions around a cold-core anticyclone and is usually associated with the lowest temperatures observed in a region for a particular time of year, as well as clear, dry conditions.

DM (dry moderate; type 1) air is mild and dry. It has no traditional analogy, but is often found with zonal flow in the middle latitudes, especially in the lee of mountain ranges. It also arises when a traditional air mass such as cP or mT has been advected far from its source region and has thus modified considerably.

The DT (dry tropical; type 3) weather type is similar to the cT air mass; it represents the hottest and driest conditions found at any location. There are two primary sources of DT: either it is advected from the desert regions, such as the Sonoran or Sahara Desert, or it is produced by rapidly descending air, whether via orography (such as the chinook) or strong subsidence.

MP (moist polar; type 5) air is a large subset of the mP air mass, weather conditions are typically cloudy, humid, and cool. MP air appears either by inland transport from a cool ocean, or as a result of frontal overrunning well to the south of the region. It can also arise in situ as a modified cP air mass, especially downwind of the Great Lakes.

MM (moist moderate; type 4) is considerably warmer and more humid than MP. The MM air mass typically appears in a zone south of MP air, still in an area of overrunning but with the responsible front much nearer. It can also arise within an mT air mass on days when high cloud cover suppresses the temperature.

MT (moist tropical; type 6), analogous to the traditional mT air mass, is warm and very humid. It is typically found in warm sectors of mid-latitude cyclones or in a return flow on the western side of an anticyclone; as one approaches the tropics this weather type dominates. MT+ (moist tropical plus) is a subset of MT that was derived after the initial classification, to account for the lack of utility of a weather-type scheme in the warm subtropics when one weather type dominates most of the year. It is defined as an MT day where both morning and afternoon temperatures are above seed day means, and thus captures the most "oppressive" subset of MT days.

TR (transitional; type 7) days are defined as days in which one weather type yields to another, based on large shifts in air pressure, dew point, and wind speed over the course of the day (Kalkstein et al. 1996; Sheridan 2002, 2003; Bower et al. 2007).

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