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ORIGINAL PAPER

Estimation of the dispersion of an accidental release of radionuclides and toxic materials based on weather type classification

Róbert Mészáros · Ádám Leelőssy · Csilla Vincze · Mihály Szűcs · Tibor Kovács · István Lagzi

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Abstract We investigate the influence of the regional-scale weather types on the atmospheric dispersion processes of the air pollutants originated from point sources. Hypothetical accidents were simulated with two different dispersion models. During a year's test period, the 6-h emission of a radionuclide from the Paks Nuclear Power Plant (Paks NPP, Hungary) was assumed every day and the transport and deposition of the radionuclide was simulated by the Eulerian TREX dispersion model over the Central European region. In addition, the ALOHA Gaussian air dispersion model was also used for the local environment of the Paks NPP to simulate hypothetical hourly releases of ammonia during a 10-year period. During both types of model simulations, the dispersion of the plume for each time was analysed and tested with consideration of 13 circulation types corresponding to daily weather patterns over the Carpathian Basin. There are significant correlations between circulation types and plume directions and structures both in local and regional scales. The daily circulation pattern can be easily obtained from weather analyses; the expected size and direction of polluted area after an accidental release can be quickly estimated even before an accident occurs. However, this fast method cannot replace or neglect dispersion model simulations. It gives a 'first guess' and a fast estimation on the direction of the plume and can provide sufficient information for decision-making strategies.

1 Introduction

Harmful effects of any accidental release should be diminished by an appropriate decision-making strategy based on a fast and accurate estimation of the air pollutant dispersion. Therefore, progressive model developments and extensive test simulations of dispersion are essential. In this study, an Eulerian and a Gaussian model were used to estimate the dispersion of different air pollutants. The ALOHA (areal locations of hazardous atmospheres) Gaussian air dispersion model developed by the National Oceanic and Atmospheric Administration (NOAA; NOAA and EPA 2007) was used for the local environment of the Paks Nuclear Power Plant (Hungary) for non-radioactive chemicals. Based on the experience during our former investigations (Lagzi et al. 2001, 2004, 2006; Lovas et al. 2006; Mészáros et al. 2006; Dombovári et al. 2008), an Eulerian dispersion model called TREX (TRansport-EXchange) has also been developed and applied for estimating the atmospheric transport processes of radionuclides from nuclear power plants. In the frame of detailed statistical examinations, the influence of weather situations in Hungary on the simulated transport and deposition of air pollutants emitted hypothetically from a point source was analysed.

The main aim of this investigation was to present a new fast evaluation method to predict the dispersion of chemical species from an accidental release using the daily circulation pattern. This can demonstrate a new possible application of the atmospheric circulation classification in environmental problems. We must emphasize that we do not advise to use only this method instead of detailed model

R. Mészáros · Á. Leelőssy · C. Vincze · I. Lagzi (✉)
Department of Meteorology, Eötvös Loránd University,
H-1518 Budapest P.O. Box 32, Hungary
e-mail: lagzi@vuk.chem.elte.hu

M. Szűcs
Hungarian Meteorological Service,
H-1525 Budapest P.O. Box 38, Hungary

T. Kovács
Institute of Radiochemistry and Radioecology,
University of Pannonia,
H-8200 Veszprém P.O. Box 158, Hungary

simulations after an accident, but besides them, due to its very fast results (there is no computational time); as a primary rough estimation, it could be an appropriate tool for decision makers.

Weather situations are often typified by circulation classifications. After some early subjective classification methods, one of them proposed by Hess and Brezowszky (1952) for Europe, Péczely (1955) for Hungary, Brádka et al. (1961) for Bohemia and Moravia, or Lamb (1972) for the British Isles, several other subjective, objective, or mixed, semi-automated methodological approaches have been developed.

The subjective classification methods are based on a visual interpretation of the surface weather maps. Their advantage is that the long-term experience and knowledge of meteorologists can be fully used in the classification. However, a major disadvantage is that the results can only be applied for a given region. In contrast to the 'manual' methods, objective classifications are based on different multivariate statistical methods. In the past decades, increasing computer resources have led to the development of a variety of automated algorithms operating on selected meteorological datasets to allow fast and reproducible classification. Some mixed methods can combine the advantages of both subjective and objective classifications. For a review of the classification methods, see, e.g. Huth et al. (2008).

Some new classifications have been presented or former types have also been developed in the last few years (e.g. Enke et al. 2005; Esteban et al. 2006; Anagnostopoulou et al. 2009; Casado et al. 2009; Michailidou et al. 2009a, b; Philipp 2009; Wetterhall et al. 2009). Each of the classifications defines its own characteristics for which the classification is carried out (Babolcsai and Hirsch 2006; Bednorz 2009). Comparative analyses of different classification types can be found in some papers (Stehlík and Bárdossy 2003; Cahynová and Huth 2009a, b; Philipp 2009). The macro-synoptic classifications are widely used and the influences of circulation types are analysed in numerous meteorological, climatological and environmental studies (in the last decade: Trigo and DaCamara 2000; Hirsch and Babolcsai 2006; Milionis and Davies 2008; Bartholy et al. 2009; Cahynová and Huth 2009a, b; Niedźwiedź et al. 2009). Among them, some air pollution-related investigations have also been carried out (Buchanan et al. 2002; Helmis et al. 2003; Keim et al. 2005; Demuzere et al. 2009; Flocas et al. 2009).

In this study, the traditional Péczely's weather type categories (Péczely 1955) were used because this classification is more suitable to characterize the atmospheric situations over the Carpathian Basin considering the geographical and climatological feature of this region. It has been shown that there are significant differences in the air pollutant concentrations (pollution pattern) in different atmospheric conditions at regional scale (Péczely 1959). Péczely's classification is still very useful and is widely applied in local and regional environmental impact studies. Influences of Péczely's circulation patterns have been analysed among others on airborne pollen concentration (Fehér and Járai-Komlódi 1996), surface radiation components (Rimóczi-Paál et al. 1997), bird migration dynamics (Gyurácz et al. 2003), local climate and its anomalies (Mika 1993; Mika et al. 2005), local air pollution (Makra et al. 2007, 2009) and severe thunderstorm occurrences (Horváth et al. 2008). During the present investigation, the impact of Péczely's macroscale weather types on the dispersion of air pollutants from a single point source was analysed on local and regional scales. The same hypothetical accident (using the same emission rate) was simulated under different meteorological conditions. Model results corresponding to the same weather types were collected and spatially averaged. Extensive analyses of these results are presented in this study.

2 Methodology

2.1 Location, data and a macro-synoptic classification

Dispersion of a radionuclide (^{131}I) and ammonia from hypothetical accidents at the Paks NPP (φ=46.617° N, λ= 18.850° E, Hungary) was simulated by the TREX (Eulerian model) and the ALOHA (Gaussian model) model, respectively. All meteorological data necessary for Eulerian model simulations were obtained from the ALADIN mesoscale numerical weather prediction model used by the Hungarian Meteorological Service (Horányi et al. 2006), whereas meteorological data for the Gaussian model were obtained from weather reports of a weather station operated by the Hungarian Meteorological Service at the Paks NPP.

Considering weather patterns over Hungary, Péczely defined a subjective macro-synoptic classification (Péczely 1955, 1957) based on the position of cyclones and anticyclones on the sea level pressure maps and on the large-scale motions. In this classification, 13 circulation types over the Carpathian Basin are separated (Table 1). According to the direction of the prevailing current, five groups can be separated: types connected with northerly and southerly currents (meridional types), types connected with westerly and easterly currents (zonal types) and types of pressure centres. In Fig. 1, the relative frequencies of each weather type based on Pécely's classification over Carpathian Basin are presented for the two periods, where model simulations were applied. Thirteen categories are separated for cyclonic and anticyclonic situations. Generally,

Table 1 Weather types of the Péczely macro-synoptic classification

Meridional types	
Types connected with northerly current	
P1 (mCc)	Hungary is in the rear of a West European cyclone
P2 (AB)	Anticyclone over the British Isles
P3 (CMc)	Hungary lies in the rear of a Mediterranean cyclone
Types connected with southerly current	
P4 (mCw)	Hungary lies in the fore part of a West European cyclone
P5 (AE)	Anticyclone in the east from Hungary
P6 (CMw)	Hungary lies in the fore part of a Mediterranean cyclone
Zonal and central types	
Types connected with westerly current	
P7 (zC)	Zonal, cyclonic
P8 (Aw)	Anticyclone extending from the west
P9 (As)	Anticyclone in the south from Hungary
Types connected with easterly current	
P10 (An)	Anticyclone in the north from Hungary
P11 (Af)	Anticyclone over the Fenno-Scandinavian region
Types of pressure centres	
P12 (A)	Anticyclone over the Carpathian Basin
P13 (C)	Cyclone over the Carpathian Basin

compared with cyclonic situations, the anticyclonic ones are more frequent in the Carpathian Basin, 68% and 65% for the 1-year and the 10-year examined periods, respectively. These weather patterns represent not only the specific wind fields but also the frequency of precipitation, which can modify the value of concentration through the wet deposition. In this region, in general, the highest precipitation is connected to Mediterranean cyclones, especially in the autumn and winter.

Péczely codes were defined for each day based on the 0000 UTC sea level weather maps created by the Hungarian Meteorological Service, and these codes were corresponded to the whole day period.

2.2 The TREX Eulerian model

The TREX is a multi-layered Eulerian passive tracer dispersion model (Mészáros et al. 2010) developed at Eötvös University. The simulation of the dispersion (advection, diffusion as well as source and sinks of the radionuclides) is described in the model by the atmospheric diffusion equation:

$$\frac{\partial c_i}{\partial t} = -\underline{V}\nabla c_i + \nabla\underline{\underline{\mathbf{K}}}\nabla c_i - (k_{ci} + k_{di} + k_{wi})c_i + E_i \qquad (1)$$

where c_i is the concentration of the ith species, V is the three-dimensional velocity vector, $\underline{\underline{\mathbf{K}}}$ is the tensor of

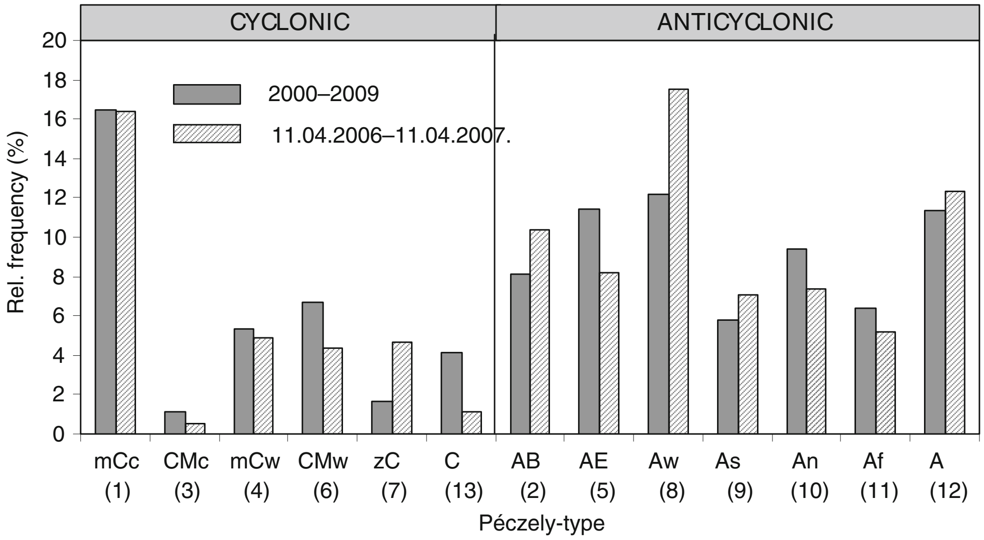


Fig. 1 Relative frequencies of 13 circulation types (for details, see Table 1) during the two test periods

turbulent diffusion coefficients, k_{ci} is the coefficient of the radioactive decay, k_{di} and k_{wi} are the dry and wet deposition coefficients, and E_i is the emission of species, respectively. This equation has been solved by a 'method of lines' technique. The two main components of the method of lines are the application of the spatial discretization followed by time integration. A second-order central difference stencil and an upwind approximation are used for the spatial discretization of the turbulent diffusion and advection.

The model domain covers a Central European region (φ=43.10–52.00° N, λ=10.85–25.10° E), which means 90×96 grid points with a horizontal resolution of 0.1×0.15° (~10×10 km) and contains 32 levels vertically. Each vertical level was determined with the barometric formula (assuming isotherm stratification) in a fictive air column, where the surface pressure is equal to 1,013.25 hPa. Below 200 m above the surface, the column was divided into 12 levels with equidistant pressure difference (197 Pa in the isotherm atmosphere), whilst below 3,000 m, it was parcelled out with higher pressure difference (1,514 Pa) and these two resolutions were joined together.

During model simulations, the dispersion of ^{131}I was considered. The emission was assumed from the Paks NPP as a point source. The radioactive decay and the change of activity of ^{131}I were simulated. The deposition is handled as a first-order reaction, which decreases the amount of the substance in the atmosphere. Dry deposition of radionuclides from the bottom layer is parameterized by a constant deposition coefficient (3×10^{-6} s^{-1} for ^{131}I) based on Baklanov and Sørensen (2001). The wet deposition velocity was parameterized using a simple scheme to calculate the wet deposition based on the parameterisation of Pudykiewicz (1989). The radioactive decay is calculated by a constant rate: $k_c = \log 2 / t_{1/2}$, where the radioactive half-life ($t_{1/2}$) of ^{131}I is 6.948×10^5 s. During the model computations, each process—horizontal spreading (advection and diffusion); vertical dispersion; source and sink terms (deposition, radioactive decay and emission processes)—was calculated separately using an operator splitting approach. Both the concentration values at each grid point and the cumulative amount of deposited values to the surface are determined.

2.3 The ALOHA Gaussian model

Besides regional-scale model simulations with the TREX Eulerian model, a simpler Gaussian model was also applied on local scale for the statistical analyses of dispersion properties in the case of different weather situations. The ALOHA Gaussian air dispersion model developed by the NOAA has the advantages of extremely short runtime and simplicity. Its main purpose is to provide the authorities an easy-to-use tool for the estimation of the consequences of an accidental release within 1 h and 10 km from the source (Jakala 2007). Although the two-dimensional Gaussian model cannot handle complex terrain and the spatial variability of meteorological fields, its fast runtime and simple algorithm makes ALOHA an effective tool for sensitivity and statistical studies (Bubbico and Mazzarotta 2008). The following input data and parameters are required for simulations with ALOHA model: time and location; atmospheric data (wind speed and wind direction, air temperature, relative humidity, cloud cover, inversion height); stability category of the atmosphere (proposed by the model based on meteorological data); roughness length (z_0); and information about the release (air pollutant, duration of release, amount of released material, source height).

3 Results and discussions

3.1 Regional-scale study

With a large number of model simulations, the influence of atmospheric circulation types over Central Europe on dispersion processes both in local and regional scales was analysed and a statistical examination of the results of dispersion models carried out. In the first step, during a 1-year test period (11 April 2006–11 April 2007), an accidental release (10^{10} cm^{-3} s^{-1} ^{131}I emission) was assumed every day from 0000 to 0600 UTC in the Paks Nuclear Power Plant, and after each hypothetical accident, a 48-h model simulation was performed by TREX Eulerian dispersion model using meteorological fields of the ALADIN mesoscale limited area numerical weather prediction model. After the simulations, the average distribution of the plume was determined for every hour after the hypothetical nuclear accident for each Péczely code.

Figures 2 and 3 present the average fields of the plume 24 h after the accident for cyclonic and anticyclone conditions, respectively. These average fields show the specialties of pollution transport by the different weather conditions. The patterns generally represent the specific current (see Table 1), but in some cases (e.g. P1 in Fig. 2, northerly current), this is not seen obviously. In P1 case (rear part of a cyclone), when the weather is variable, windy and rainy, the average plume spreads around the source.

Fig. 2 Average fields of plumes 24 h after the accident in the surface layer (at 2-m height), assuming a 6-h hypothetical emission of I^{131} from Paks NPP (denoted with a *white circle* in the maps) every day in the case of each cyclonic weather condition during a 1-year period (11 April 2006–11 April 2007). Weather types were defined based on Péczely's classification. Model simulations were performed by TREX Eulerian model ▶

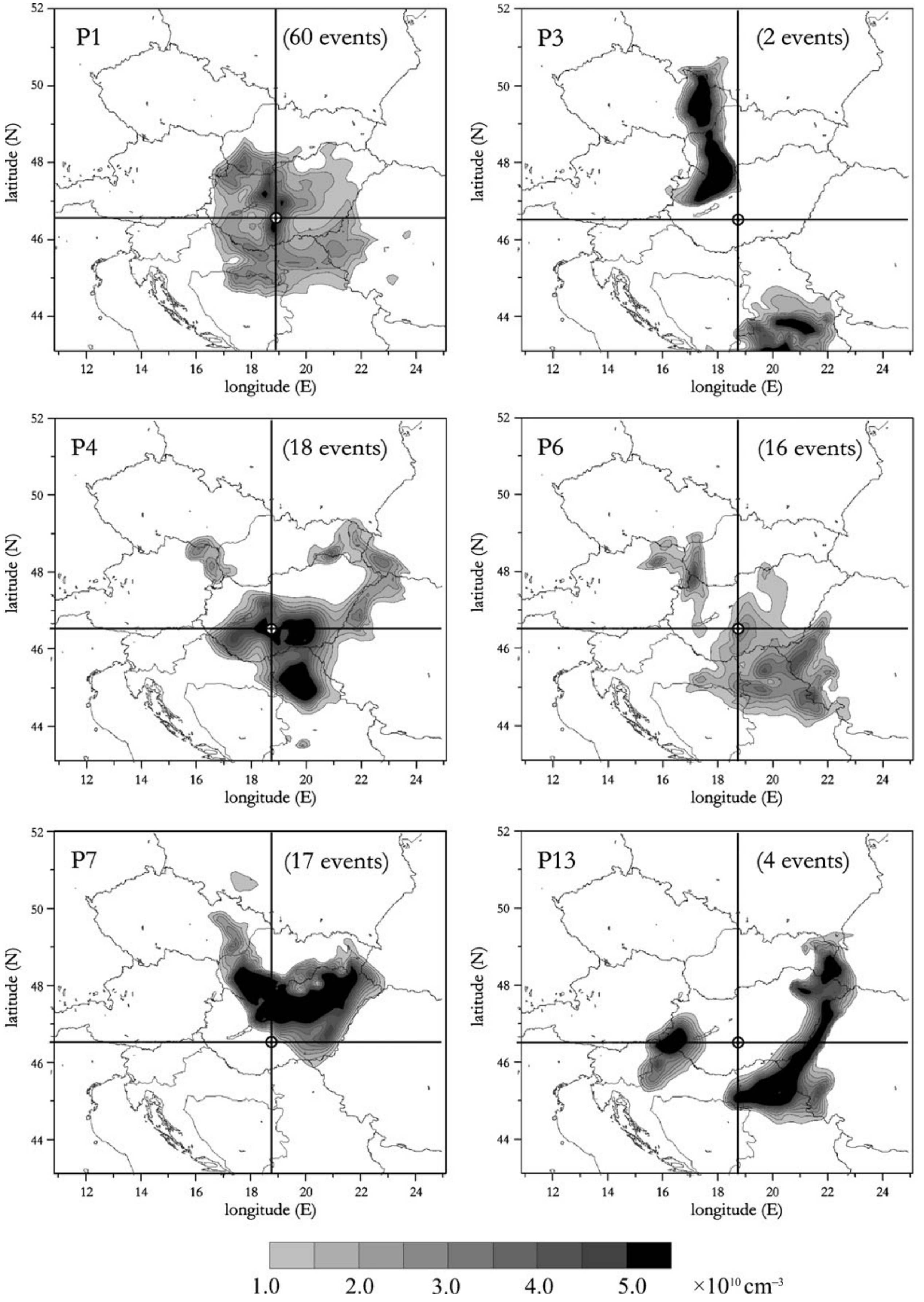
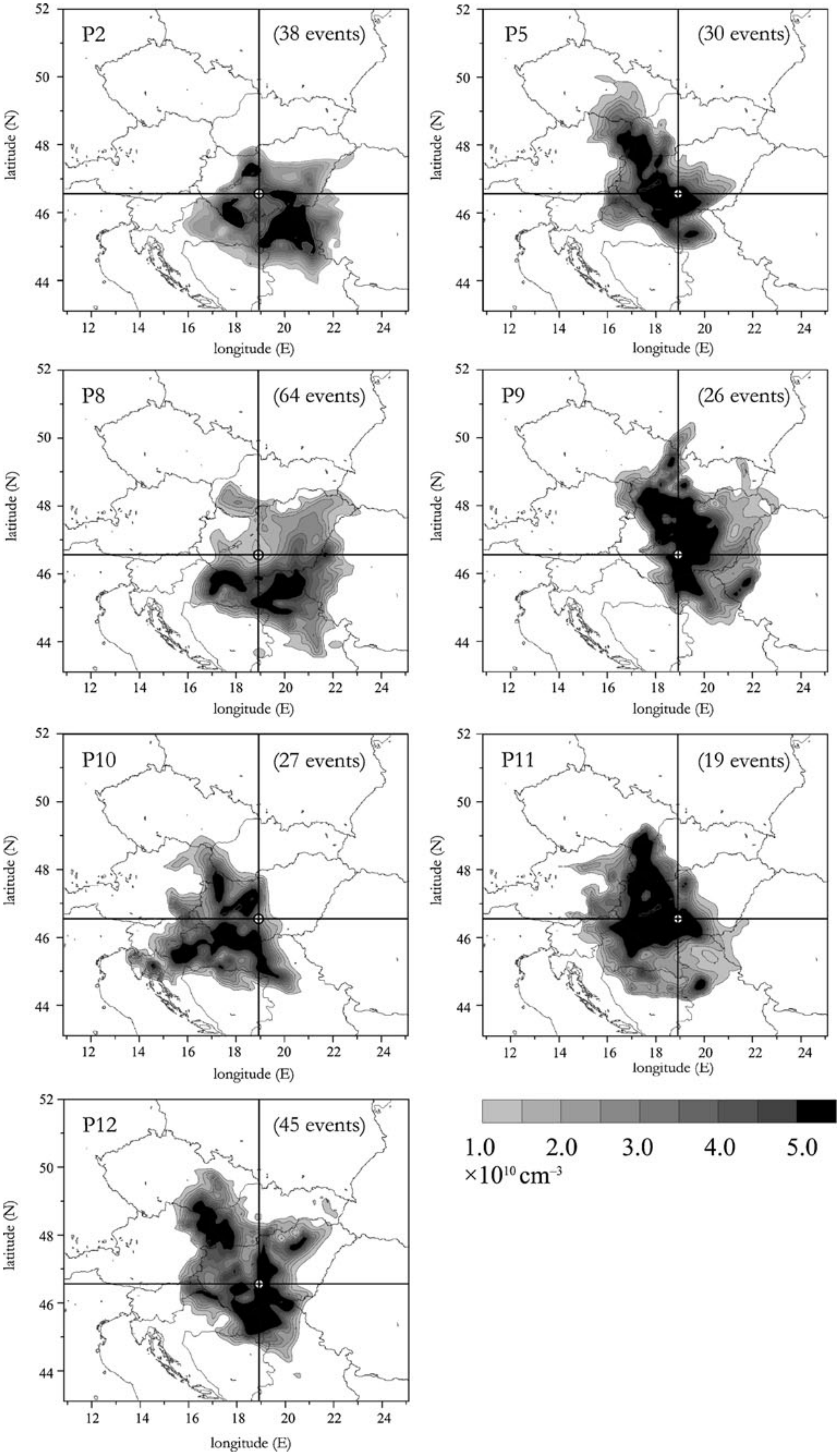

P1
(60 events)
P3
(2 events)
P4
(18 events)
P6
(16 events)
P7
(17 events)
P13
(4 events)
latitude (N)
52
50
48
46
44
longitude (E)
12
14
16
18
20
22
24
1.0
2.0
3.0
4.0
5.0
$\times 10^{10}$ cm^{-3}

Fig. 3 Same as Fig. 2, but for anticyclonic situations



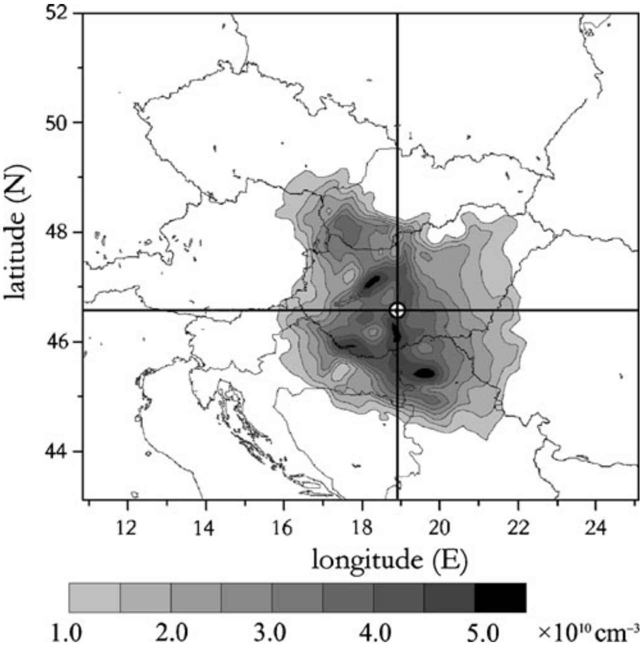


Fig. 4 Average field of plumes 24 h after the accident, assuming a 6-h hypothetical emission of ^{131}I from Paks NPP (denoted with a *white circle* in the map) every day during a 1-year period (11 April 2006–11 April 2007). Model simulations were performed by TREX Eulerian model

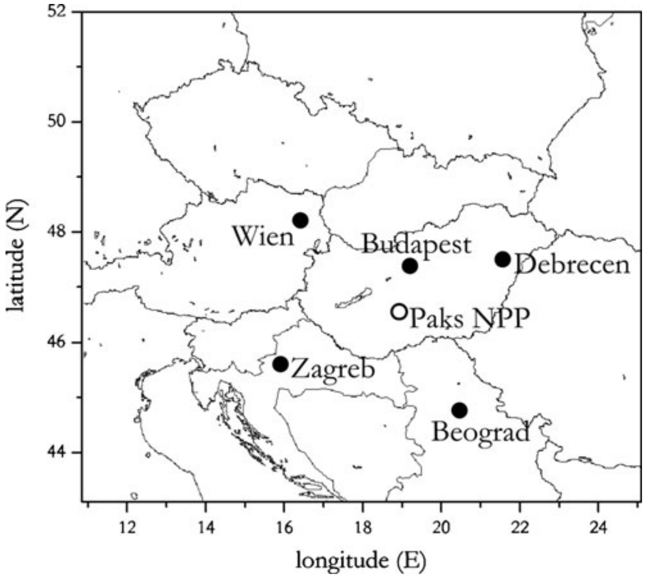


Fig. 6 Location of cities: Budapest (φ=47.51° N, λ=19.04° E); Beograd (φ=44.81° N, λ=20.46° E); Debrecen (φ=47.54° N, λ=21.64° E); Zagreb (φ=45.83° N, λ=15.98° E); and Wien (φ=48.22° N, λ=16.37° E)

Likewise, there is no featured direction of the average plume in the case of P12, when an anticyclone is situated just over the Carpathian Basin. However, the probability of the most polluted regions could also be predicted in these uncertain weather situations. In some other cases, when only a small number of events occurred during the examined 1-year period (P3, two cases; P13, four cases),

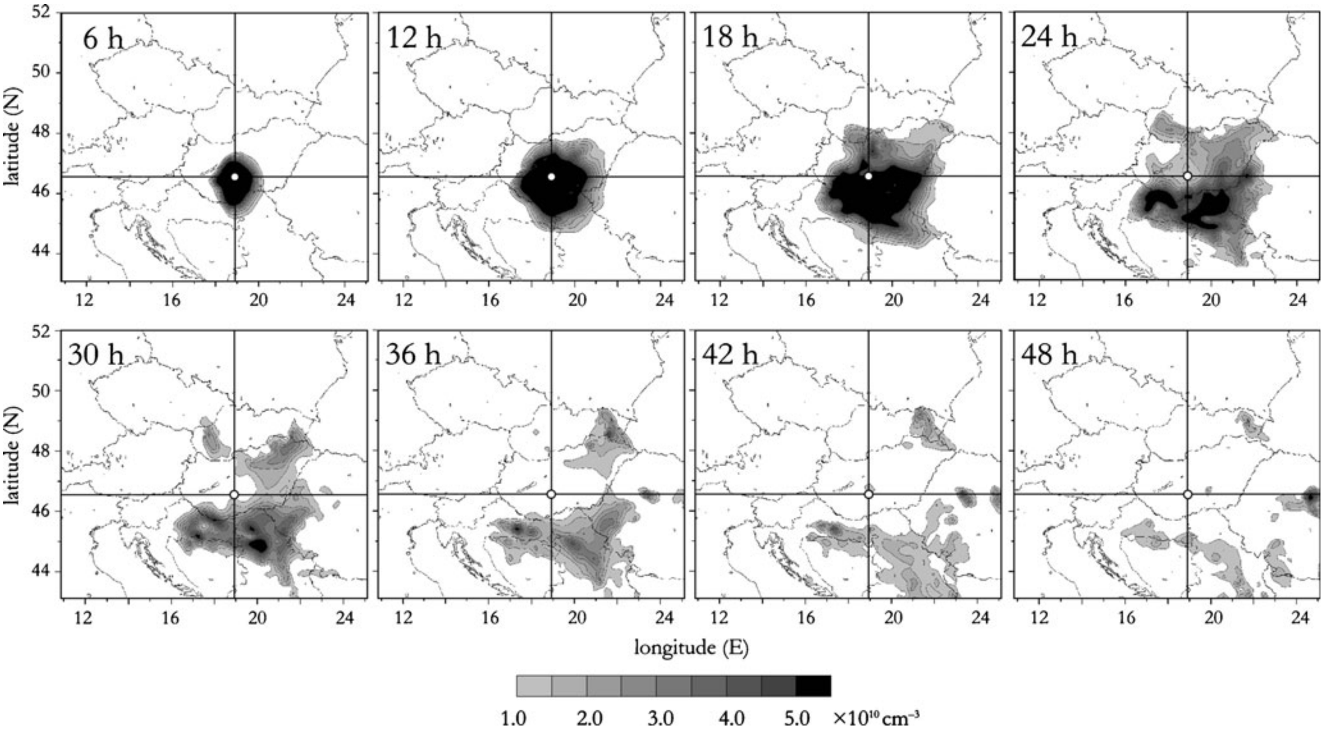


Fig. 5 Average fields of plumes during a 2-day period with 6-h time step hours after the accident, assuming a 6-h hypothetical accident of ^{131}I from Paks NPP (denoted with a *white circle* in the maps) every day in the case of P8 weather type (anticyclone extending from the west) during a 1-year period (11 April 2006–11 April 2007)

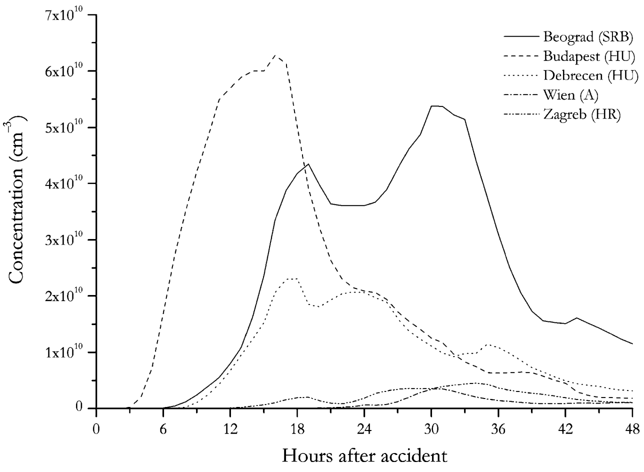


Fig. 7 Average time series of surface concentration of ^{131}I in the case of P8 weather type (based on 64 hypothetical events)

the prediction is very uncertain. This uncertainty could be reduced with the use of a larger statistical dataset. Aside from the aforementioned uncertainties, in most cases, it could be easily determined, in which area the highest concentrations of air pollutants are expected. Based on the results of the statistical analyses, it seems that there is a high probability that 24 h after an accidental release, the greatest part of the most polluted area is located to the south–southeast (P2, P4, P8), southeast (P6), west–northwest (P5), west (P10, P11), north–northeast (P9) and north (P7) from the nuclear power plant.

Besides the specific wind directions, deposition processes could also influence the magnitude of concentration fields. In this case, only the effect of the wet deposition can be noticeable because dry deposition was assumed to be constant. The wet removal of air pollutants from the atmosphere is the most significant in the Carpathian Basin, when a warm front of a Mediterranean cyclone causes high precipitation (P6), but also considerable in a rear part of a West European cyclone (P1).

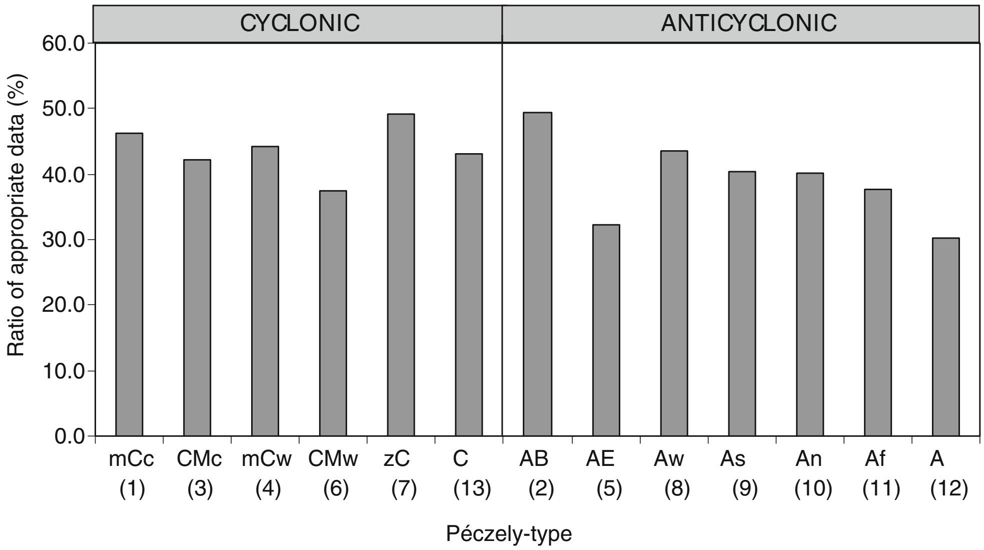
Generally, in the case of cyclonic situations due to more precipitation and more intense mixing of air pollutants caused by stronger wind, the concentration values are lower and the most polluted areas are limited to a smaller region than in the case of anticyclonic situations.

The average concentration field in all cases (Fig. 4) shows that there is a northwestern–southeastern axis where the highest concentrations are more frequent. This information could also be useful for the analysis of the long-term effects of continuous releases.

Figures 2, 3 and 4 present the distributions of the average plumes, 24 h after the start of the release at 0000 UTC, but after an accident, the expected development of the plume could be the most important information for decision makers. In Fig. 5, the average spatial distributions of the plume are presented in the case of P8 code (average of 64 events) for a 48-h period for a 6-h time step. In the first 12 h, the average plume spreads around the source, but later extends in a southerly direction.

Not only these maps with the average concentration fields can be presented with this method, but the expected variation of the concentration at arbitrary locations can also be estimated. Five cities around the Paks NPP have been chosen (Fig. 6), and the time-averaged series of ^{131}I concentrations after the hypothetical accidents in the case of P8 code are illustrated (Fig. 7). Based on the average of 64 events, 3 h after the accident, the plume appears in Budapest (around 100 km north from the Paks NPP), and the concentration increases rapidly, until 16 h after the accident. Whereas the average plume moves south, southeastward, a high concentration can be found for a longer time in Beograd. This means that in the case of P8

Fig. 8 Ratio of all appropriate input meteorological datasets for ALOHA model simulations in the case of each weather type



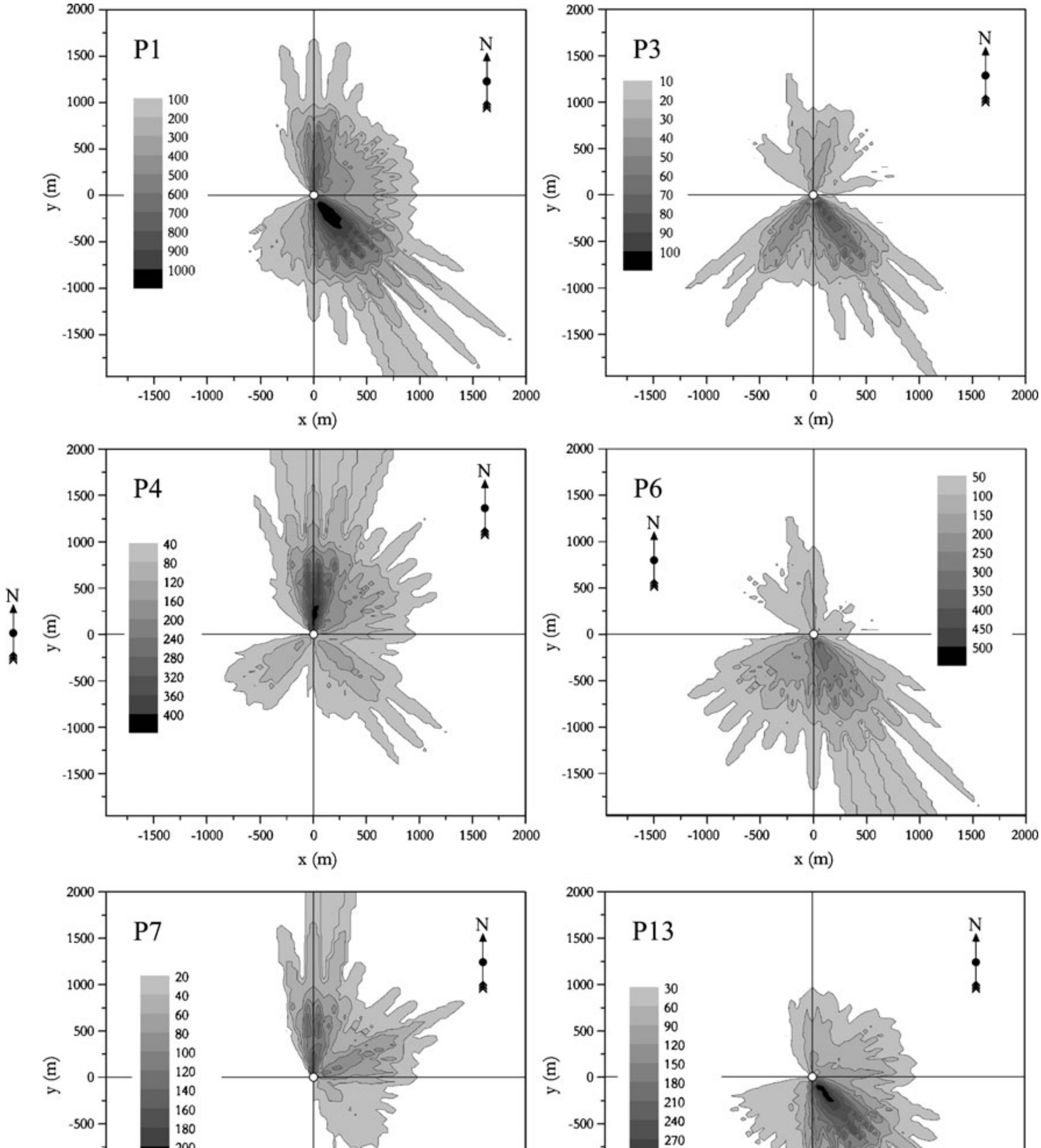
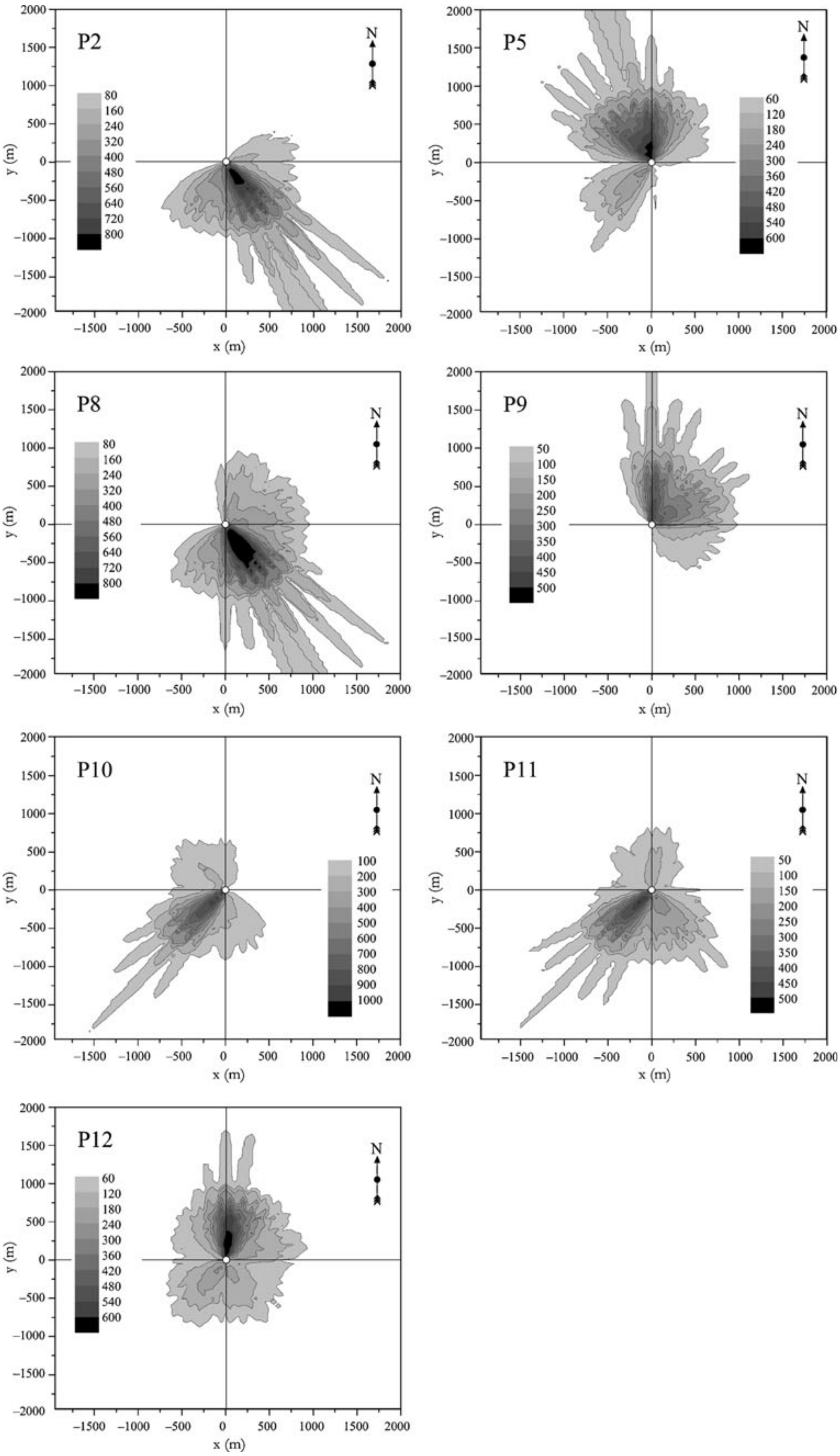


Fig. 9 Distribution of plume occurrence over a 50×50-m resolution grid in the ground level where concentrations over 25 ppm occurred, assuming 100 kg of hypothetical emission of ammonia from the Paks NPP (denoted with a *white circle* in the maps) every hour in the case of each cyclonic weather conditions during a 10-year period (01 January 2000–31 December 2009). Weather types were defined based on Péczely's classification. Model simulations were performed by ALOHA Gaussian model

situation, these cities are more endangered than others which are situated in other directions, and it is especially unlikely to develop a high concentration in the westerly or southwesterly directions (e.g. Wien or Zagreb).

Although only a 1-year period was simulated with the Eulerian model because of the large computational time and huge dataset, the statistical results show significant differences among plume distributions in the case of each

Fig. 10 Same as Fig. 9, but for anticyclonic situations



weather type. After an accident, if the weather type—represented by only one number—is known for the actual day, the probability of expected dispersion on regional scale can be predicted immediately.

3.2 Local-scale study

After the formerly presented regional-scale analyses, the effects of a macro-synoptic weather pattern on local-scale dispersion were also investigated. A hypothetical release of 100 kg ammonia in each hour from the area of the Paks NPP was simulated with the ALOHA Gaussian model during a 10-year period (2000–2009). One hour after a release, the distribution and the direction of the polluted area over the ERPG-1 (Emergency Response Planning Guidelines, 25 ppm threshold concentration) were estimated for 13 different atmospheric situations. Hourly weather reports of the nearby weather station operated by the Hungarian Meteorological Service were used as an input dataset for ALOHA. These reports were processed automatically to filter and convert meteorological data into the required input format. ALOHA's graphic input was driven through a SendKey method based on Jakala (2007), which enabled ALOHA's continuous run for a large amount of observation data.

In some cases, ALOHA's assumptions lead to false results. Gaussian approximation is not applicable in situations with low wind speed due to its uncertain direction and weak effect on the dispersion. On the other hand, ALOHA cannot handle wet deposition. According to the user's manual (NOAA and EPA 2007), we excluded from the study all observations that reported either wind speed lower than 2 m/s or present weather with fog or precipitation (SYNOP data vv≥30). Data for all necessary input parameters were available in 93% of the hourly observation data during the 10 years in Paks. Wind speed lower than 2 m/s occurred in 50% of the observations, which warns of the frequent occurrence of stable atmospheric situations where air dispersion of toxic materials can be extremely dangerous. However, during daytime, low wind speeds occurred in <40% of the observations in each month, whilst this rate reached 70% at summer nights. Fog or precipitation occurred in 12% of the observations during the 10 years, with a maximum above 20% in the winter and rate under 10% between March and October. After excluding all missing data and situations with low wind speed and/or wet deposition, ALOHA can handle around 40% of the hourly timeline between 2000 and 2009, but this ratio also depends on the weather situations (Fig. 8). This means that approximately 35,000 runs of the model allow a statistical study, especially for daytime situations where the ratio of applicable observations is above 50% for each month, except December with 46%.

Model simulations were performed with this filtered dataset, and the results were processed automatically for all events to study the maximum distance from the source and the total area where a ground concentration level over 25 ppm occurred. Over a 50×50-m resolution grid, the frequency of plume occurrence was summarized in each of the 13 typical atmospheric situations (Figures 9 and 10 for cyclonic and anticyclonic situations, respectively). The major effect of prevailing wind direction in each weather type is conspicuous regardless of the cyclonic or anticyclone situations. The effects of the cyclonic and anticyclonic situations on local-scale transport would be more expressed using a more detailed temporal (e.g. monthly) resolution.

A radial structure can be seen in the figures because the resolution of wind direction data in weather reports is 10°. Although the spreading is mainly controlled by the specific wind direction in local scale, the characteristic directions of plume dispersion are outlined in each weather type. The results show a good agreement with regional-scale patterns (see Figs. 2 and 3). Even though in two cases different input meteorological datasets were used and the dispersion was analysed in different spatial and temporal scales, the effects of large-scale weather types on the dispersion processes in both local and regional scales are imposing. We can conclude that similarly to the regional-scale study, the probabilities of more or less polluted areas after an accidental release can be well defined in the case of each weather type in local scale as well.

Analysing all of the possible events together (Fig. 11), it can be stated that in almost all weather situations, the area

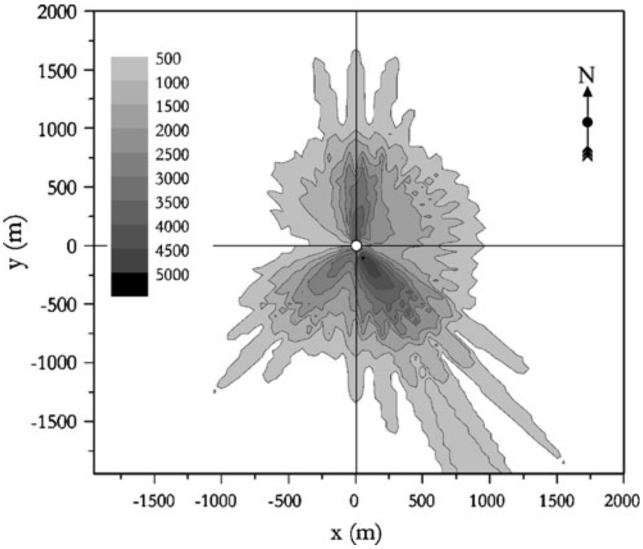


Fig. 11 Distribution of plume occurrence over a 50×50-m resolution grid where ground level concentration over 25 ppm occurred, assuming 100 kg of hypothetical emission of ammonia from the Paks NPP (denoted with a *white circle* in the maps) every hour during a 10-year period (01 January 2000–31 December 2009). Model simulations were performed by ALOHA Gaussian model

to the west from the NPP is very rarely affected by the plume, whilst directions to the southeast and north are the most endangered areas. This general picture is tuneable using a macro-synoptic classification for each weather type (Figs. 9 and 10).

4 Conclusions

The main goal of our investigation was to determine how the different atmospheric conditions affect the air pollution processes originated from a point source and how these statistical results can be valuable to predict the dispersion of an accidental release. The atmospheric conditions can be represented by different macro-synoptic patterns corresponding to the related area. For this task, several subjective, objective or mixed classifications are available from the literature. Here, we used the Péczely type classification which was created specifically for the Carpathian Basin and which is widely used for different kinds of environmental problems. In our study, the effects of macroscale weather patterns on local- and regional-scale dispersions were investigated. The results show that there are significant differences among plume dispersions of the 13 Péczely's weather categories. Using this statistical–climatological method, a first guess approximation of the dispersion of toxic substances can be made to support decision makers before the results of detailed dynamic model simulations are available. These estimations are not as reliable as the results of a numerical model, but there are several advantages:

- Easy-to-use for decision-making strategy;
- Pollution statistics (inventory) for an arbitrary point or region could be available at the moment of an accident;
- Immediate preparation of the possible consequences of an accident;
- Can be applied both on local and regional scales; and
- Can be applied both for an accidental release and continuous emissions from a point source.

This method does not dispute the role and the importance of numerical models; it is only an additional possibility for decision makers. Similar statistical analyses can be made for other point sources using an appropriate dispersion model and an adequate meteorological database.

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