

# The impact of a foehn wind on PM<sub>10</sub> concentrations and the urban boundary layer in complex terrain: a case study from Kraków, Poland

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## ABSTRACT

Kraków, Poland, is a city with poor air quality, located in the large Wisła (Vistula) valley, and affected by a foehn wind from the Tatra Mountains. We analyzed 14 long episodes of the foehn from the periods Sep 2017 - Apr 2018 and Sep 2018 - Apr 2019. Data used included measurements of PM<sub>10</sub> (i.e. particulate matter with an aerodynamic diameter up to 10 µm) concentrations, air temperature and relative humidity, wind speed and direction from ground stations and mast measurements up to 100 m a.g.l., along with model analysis results. A non-operational configuration of the AROME CMC (the Application of Research to Operations at Mesoscale canonical model configuration) 1 km x 1 km was applied. A conceptual model concerning the impact of a foehn on urban air pollution was developed. The occurrence of a particular effect of a foehn on the PM<sub>10</sub> spatial-temporal pattern depends on its mode of transfer through the city: a. a foehn flows above the valley where a strong cold air pool and a return flow can be found; b. a foehn enters the valley from the eastern, wider part or from the valley top and destroys the cold air pool; c. gravity waves generated by a foehn are strong enough to enter the western narrower part of the valley and cause large spatial differences in turbulence parameters within the city. The first transfer mode worsens air pollution dispersion conditions throughout the city and leads to large increases in PM<sub>10</sub> levels (from below 50 to 150–200 µg·m<sup>-3</sup>), the second mode improves dispersion and leads to large decreases in PM<sub>10</sub> levels (from 150–200 to below 50 µg·m<sup>-3</sup>) throughout the city, and the third generates large spatial differences in PM<sub>10</sub> levels (50–70 µg·m<sup>-3</sup>) within the city. There is no single effect of a foehn on air pollution dispersion conditions.

*Keywords:* foehn wind, UBL dynamics, PM10, cold air pool, AROME model

## 1. Introduction

Abundant air pollution with particulate matter (PM) is still a serious environmental and social problem in many cities all over the world, for instance Santiago (Muñoz and Corral 2017), Beijing (Liu et al. 2019), Grenoble (Largerion and Staquet 2016) and Los Angeles (Wang et al. 2017), and PM is currently considered the best indicator for the health effects of ambient air pollution (Burnett et al. 2014; WHO 2016). High PM concentrations are caused by emissions from various stationary

and mobile sources, and from chemical reactions between primary and secondary pollutants, but atmospheric conditions are equally important and can significantly modify air pollution dispersion and/or removal (e.g. Seinfeld and Pandis 1998; Prtenjak et al. 2009; Toro A et al. 2019). For example, precipitation has a great impact on concentrations of particulate matter, but it mainly washes out coarse particles while having little effect on fine particles (Li Y. et al., 2015). Foehns are among weather phenomena with great potential for modifying the urban boundary layer (UBL) and thus the atmospheric conditions for air pollution dispersion.

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The impact of foehns on concentrations of air pollution has been studied mainly at a regional scale (e.g. Mira-Salama et al. 2008; Turton et al. 2018; Álvarez and Noel Carbajal 2019); studies at a city scale are rather rare (e.g. Corsmeier et al. 2006; Li X. et al., 2015). However, Vicente et al. (2018) point out that urban air quality is characterized by high spatial and temporal variability, as the factors controlling it (e.g. chemical and physical processes that deliver PM, traffic intensity and the location of buildings and other obstacles) usually vary spatially, too. Therefore, studies on intra-city spatial variations of air pollution levels become crucial from the point of view of habitability and health risk. The present paper has focussed on concentrations of PM<sub>10</sub>, i.e. particulate matter with an aerodynamic diameter up to 10 µm.

The aim of the paper is to evaluate the importance of a foehn on spatial and temporal changes to PM<sub>10</sub> concentration in Kraków, southern Poland. Kraków is a large city located in a valley (but outside a mountainous area), with very diversified environmental conditions (described in detail in Section 2), and has very poor natural ventilation. In spite of a significant improvement in aerosanitary conditions after 1989 (e.g. Bokwa 2008), Kraków is still one of the most polluted cities in Europe concerning PM<sub>10</sub> as it is in the 6% of all European measurement sites where the mean annual limit value of PM<sub>10</sub> (i.e. 40 µg·m<sup>-3</sup>) was exceeded in 2016 (European Environment Agency 2018). The city is located in the Wisła (Vistula) valley, which is parallel to the Carpathian Mountains to the south, and the Wyżyny Polskie (Polish Uplands) to the north (Fig. 1). About 100 km south of Kraków, is the highest ridge of the Carpathians, the Tatra. In a certain synoptic situation, a foehn known as ‘*halny*’ occurs there and brings significant weather changes to the region (Ustrnul 1992b). Ambient air pollution in Kraków has been the subject of numerous studies (e.g. Niedźwiedź and Olecki 1995; Walczewski et al. 1996; Bokwa 2007) and a strong dependence of high PM concentrations on weather conditions has been shown (e.g. Niedźwiedź and Olecki 1994; Tomaszewska 1994; Bokwa 2011). However, little is known about the impact of a foehn on spatial and temporal patterns of PM<sub>10</sub> pollution in the city. Interactions between foehns and air pollution determined for other world regions or cities show a large variety of effects due to the different atmospheric processes generated, and the strong primary dependence of those effects on local topography. The atmospheric processes linked to foehns which have a significant impact on air quality in urbanized areas include:

1. Intensification of an air temperature inversion in the valley in which a city is located; it can be linked to the occurrence of a so-called ‘sandwich’ foehn (Vergeiner 2004), or to the formation of an effective lid that traps pollutants in the cold air pool (CAP) below, by reducing the available mixing volume (Drechsel and Mayr 2008); these processes are linked to a high increase in air pollution
2. Removal of the CAP and the penetration of the foehn flow to the valley floor, due to the diurnal heating of the cold pool by solar radiation which may diminish stability and allow vertical mixing, turbulent erosion at the top of the cold pool, or interaction with orographic gravity waves (Drobinski et al. 2007; Flamant et al. 2006); these processes improve air pollution dispersion conditions and decrease its concentration.

Foehn/CAP interaction still poses a major challenge to understanding and predicting local weather and air pollution dispersion conditions, and in Kraków the CAP forms often in areas of the Wisła valley surrounding the city (see Section 2). Therefore, the present study on the role of the foehn on PM<sub>10</sub> concentrations contributes to general research on the mechanisms of interaction between foehns and local-scale meteorological phenomena, including air pollution dispersion conditions.

## 2. Study area

Kraków is the second largest city in Poland, located in the Małopolska (Lesser Poland) region, with an area of 326.8 km<sup>2</sup> and 771 000 inhabitants (data from Dec 2018; Statistical Yearbook of Kraków 2019). Kraków agglomeration consists of the city itself and the highly populated towns and villages which surround it; the total number of inhabitants is estimated to exceed one million. The city’s area belongs to three different geographical regions and geological structures, i.e. the Polish Uplands, the Western Carpathians, with the basin of the Carpathian Foredeep in between. The central part of the city is located in the Wisła valley at an altitude of about 200 m a.s.l. In the western part of Kraków, the valley is as narrow as one km wide. However, in the eastern part of the city, the valley broadens to about 10 km and there is a system of river terraces. East of the city’s borders, the Raba enters the Wisła via a valley cutting through the Carpathian Foothills from south to north. The hilltops bordering the city to the north and south reach about 100 m above the valley floor, similar to the hilltops in the western part of the valley which means that the city is located in a semi-concave basin open to the east, and sheltered from the prevailing westerly winds (Fig. 1). The local-scale processes linked to the impact of relief include katabatic flows, CAP formation, frequent air temperature inversions and a much lower wind speed in the valley floor

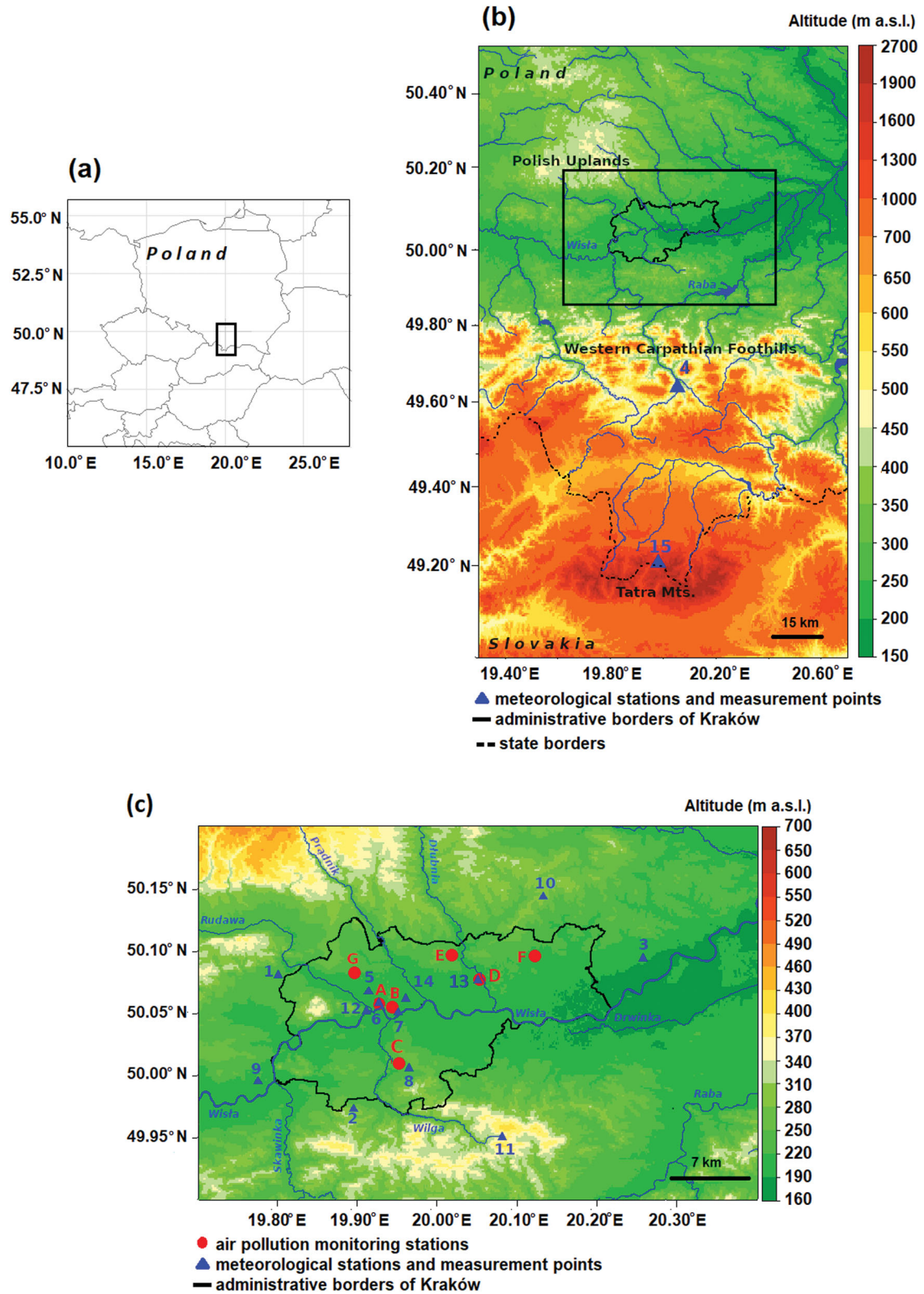


Fig. 1. Location of the region studied: a. in Central Europe, b. in southern Poland, c. at the junction of the Wisła valley, Polish Uplands and the Western Carpathian Foothills.

Key: numbers and letters as in Tables 1 and 2. Topographic data used in Fig. 1 comes from the Shuttle Radar Topography Mission database provided by National Aeronautics and Space Administration (<https://www2.jpl.nasa.gov/srtm/>).

Table 1. Location of meteorological stations in Kraków and nearby, Kasprowy Wierch and the meteorological elements used in the research.

| No. | Station                         | Lat N | Lon E | Altitude (m a.s.l.) | Manager of the station | Land form                | Elements used           |
|-----|---------------------------------|-------|-------|---------------------|------------------------|--------------------------|-------------------------|
| 1   | Balice                          | 50.08 | 19.80 | 237                 | IMWM-NRI               | Valley bottom            | V, D, T, RH             |
| 2   | Libertów                        | 49.97 | 19.90 | 314                 | IMWM-NRI               | Hill top                 | V, D, T, RH             |
| 3   | Igołomia                        | 50.09 | 20.26 | 202                 | IMWM-NRI               | Valley bottom            | V, D, T, RH             |
| 4   | Mszana Dolna                    | 49.66 | 20.05 | 440                 | IMWM-NRI               | Valley slope             | V, D, T, RH             |
| 5   | Reymonta St.                    | 50.07 | 19.91 | 220                 | AGH UST                | Valley bottom            | V, D, T, RH             |
| 6   | Kraśińskiego St.                | 50.06 | 19.93 | 204                 | JU                     | Valley bottom            | T                       |
| 7   | Słowackiego Theatre             | 50.05 | 19.95 | 215                 | JU                     | Valley bottom            | T, RH                   |
| 8   | Bojki St.                       | 50.01 | 19.96 | 252                 | JU                     | 50 m above valley bottom | T                       |
| 9   | Jeziorzany                      | 49.99 | 19.77 | 211                 | JU                     | Valley bottom            | T, RH                   |
| 10  | Kocmyrzów                       | 50.14 | 20.13 | 299                 | JU                     | Hill top                 | T                       |
| 11  | Chorągiewa                      | 49.95 | 20.08 | 436                 | JU                     | Hill top                 | T                       |
| 12  | Telecommunication mast (Tower): | 50.05 | 19.91 | 222                 | JU                     | Valley bottom            | T, RH                   |
|     | 2 m a.g.l.                      |       |       | 272                 |                        |                          |                         |
|     | 50 m a.g.l.                     |       |       | 322                 |                        |                          |                         |
|     | 100 m a.g.l.                    |       |       |                     |                        |                          |                         |
| 13  | Szkolne district                | 50.08 | 20.05 | 205                 | JU                     | Valley bottom            | T                       |
| 14  | Botanical Garden                | 50.05 | 19.95 | 206                 | JU                     | Valley bottom            | V, D, T, RH, cloudiness |
| 15  | Kasprowy Wierch                 | 49.23 | 19.98 | 1998                | IMWM-NRI               | Mountain peak            | V, D, T, RH             |

Explanations: AGH UST – AGH University of Science and Technology, JU – Jagiellonian University. More information about the measurement points administered by JU can be found in Bokwa (2010). V – wind speed, D – wind direction, T – air temperature, RH – relative humidity.

than on the hilltops (e.g. Hess 1974). According to Hajto and Rozwoda (2010), who studied sodar data from Kraków at an hourly resolution in the months from October to March, the mean monthly frequency of stable atmospheric conditions varies from 58.1% in March to 74.0% in December. All the factors mentioned contribute to the poor natural ventilation of the city and the occurrence of high  $PM_{10}$  levels, especially in the heating season. Analysis of the data on wind speed and direction from three meteorological stations in the Wisła valley (Balice, Reymonta St, Igołomia) and one station on a nearby hilltop (Libertów) for the two cold seasons (Sep 2017 to Apr 2018 and from Sep 2018 to Apr 2019) indicated significant spatial variability due to the complexity of the landforms and the presence of urban structures (Table 1, Appendix 1). In terms of spatial variability, the average frequency of weak winds (up to  $2\text{ m}\cdot\text{s}^{-1}$ ) varied from 36% in Balice to 59% in Reymonta St; in Libertów and Igołomia the values reached 50%. For a wind speed  $\geq 5\text{ m}\cdot\text{s}^{-1}$ , the highest average frequency was measured in Igołomia (12%) and Balice (20%), while in Libertów and Reymonta St it did not exceed 3%. A wind speed  $\geq 10\text{ m}\cdot\text{s}^{-1}$  was noted in Igołomia (26 hourly cases) and Balice (122 hourly cases) – 1% for both analyzed periods only. Dominant wind directions are strongly linked to the

impact of relief. In Balice they are SW and NE, in Igołomia and Reymonta St, W and E, while in Libertów, SSW to WNW.

### 3. Data and methods

The research is based on various data from two sub-periods: Sep 2017 - Apr 2018 and Sep 2018 - Apr 2019. Such sub-periods were chosen because 1. They include the heating season when  $PM_{10}$  concentration in Kraków is highest; 2. They include the cold half of the year when foehns occur most often; 3. At the end of 2016, the number of  $PM_{10}$  measurement points in Kraków, administered by the National Inspectorate for Environmental Protection, was increased from 3 to 8 which allowed data sufficient for the present research to be obtained.

The delimitation of foehn episodes was carried out using criteria from Ustrnul (1992a). Periods of *potential foehn* were determined based on an analysis of measurement data from the meteorological mountain observatory of the Institute of Meteorology and Water Management - National Research Institute (Pol: IMGW-PIB) on Kasprowy Wierch in the Tatra Mountains (1991 m a.s.l.) (Fig. 1b); a potential foehn event was defined as a period

Table 2. Location of air pollution stations in Kraków.

| Symbol | Station            | Lat N | Lon E | Altitude (m a.s.l.) | Land form                   |
|--------|--------------------|-------|-------|---------------------|-----------------------------|
| A      | Kraśińskiego St    | 50.06 | 19.93 | 207                 | Valley bottom               |
| B      | Dietla St.         | 50.05 | 19.94 | 209                 | Valley bottom               |
| C      | Kurdwanów district | 50.01 | 19.95 | 223                 | 50 m above<br>valley bottom |
| D      | Bulwarowa St.      | 50.08 | 20.05 | 195                 | Valley bottom               |
| E      | Piastów district   | 50.10 | 20.02 | 239                 | Valley slope                |
| F      | Wadów district     | 50.10 | 20.12 | 218                 | Valley bottom               |
| G      | Złoty Róg St.      | 50.08 | 19.90 | 218                 | Valley slope                |

when wind speed was  $\geq 10 \text{ m s}^{-1}$  and wind direction was in a range from SE to SW (i.e. 140–220°).

The next step was the verification of *foehn occurrence* in the area of Kraków and nearby. The foehn episodes included in the present study are classical cases according to Hann's theory (1901), however, foehns are complex atmospheric phenomena in both genesis and occurrence (e.g. Brinkmann 1971, Hoinka 2007, Seibert 1990, Gohm and Mayr 2004, Drobinski et al. 2007, Cetti et. al. 2015). In particular, this complexity concerns the assessment of foehn occurrence at weather station level and at particular points or areas. The research area used in the present study has diversified relief and land use/land cover which has a significant impact on climatic conditions at a local scale. In Kraków for periods of potential foehn occurrence they were confirmed if at least one of the following criteria sets was fulfilled (according to measurements in Balice, and/or Libertów and/or Igołomia):

- wind direction: 90–270°, wind speed:  $\geq 5 \text{ m s}^{-1}$ , presence of altocumulus lenticularis clouds;
- wind direction: 90–270°, wind speed:  $\geq 5 \text{ m s}^{-1}$ , relative humidity  $\leq 70\%$ ;
- relative humidity  $\leq 70\%$  and the presence of altocumulus lenticularis clouds.

The criteria were established by Ustrnul (1992a,b) for the area of southern Poland from an analysis of synoptic maps and measurement data from the period 1966–1985. Such an approach allowed situations when a foehn occurred somewhere in the whole area from the Tatra Mts to Kraków to be identified. However, it should be mentioned that most probably a foehn impact was not observed at all measurement points of that area as for instance valley floors quite often experience air temperature inversions, and that prevents the entrance of a foehn to such areas.

The duration of a foehn in the Kraków area was defined as the number of consecutive hours when these criteria were fulfilled. The conditions were checked by analysis of measurement data from meteorological stations and measurement points located around Kraków

and within the city, as presented in Table 1. Observations of altocumulus lenticularis clouds were obtained from the climatological station of the Jagiellonian University in the Botanical Garden in Kraków. Fig. 1 shows the location of the meteorological stations and measurement points.

Potential foehn episodes were divided into long ( $>24 \text{ h}$ ) and short ( $\leq 24 \text{ h}$ ), and only the long ones were included in further analyses.

There were 14 long episodes which all together lasted for 591 hours and occurred on 40 days (Appendix 2). Altocumulus lenticularis clouds were found during 13 out of 14 long foehn episodes and provided a visible proof of foehn occurrence in the study area even if at the station level the foehn impact was not detectable for example due to the impact of the relief. The episodes studied can be considered 'deep' foehn cases, following the criteria of Zängl (2003) and Gohm and Mayr (2004) from an analysis of synoptic maps for long foehn episodes.

Data on PM<sub>10</sub> concentrations come from the data bases of the National Inspectorate of Environmental Protection (<https://powietrze.gios.gov.pl/pjp/archives>). Mean hourly and daily concentrations for the sub-periods Sep 2017 - Apr 2018 and Sep 2018 - Apr 2019 from seven measurement points located in Kraków were used (Fig. 1, Table 2). The measurement points represent several parts of the city, located on various types of landform and land use/land cover (see Fig. 1 for the location of the measurement points):

- A. Kraśińskiego St: street canyon in the city center on the floor of the Wisła valley, with a very busy municipal transportation route and intensive traffic;
- B. Dietla St: a busy inner ring road in the city center on the floor of the Wisła valley, with intensive tram, bus and vehicular traffic;
- C. Kurdwanów district: suburban area in a large district of blocks of flats in the southern part of the city, about 50m above the valley floor;
- D. Bulwarowa St: suburban area in a large district of blocks of flats, located close to the steelworks in the eastern part of the city, on a terrace of the Wisła;

- E. Piastów district: suburban area in a large district of blocks of flats in the eastern part of the city, on the slopes of the Wyżyny Polskie (Polish Uplands), about 50m above the valley floor;
- F. Wadów district: suburban area with agriculture activity and scattered residential buildings located close to the steelworks, on a river terrace in the eastern part of the Wisła valley;
- G. Złoty Róg St: suburban area in a large district of blocks of flats and residential buildings, on the slope of the Wyżyny Polskie (Polish Uplands) in the western part of the city.

The other measurement point operated by the National Inspectorate of Environmental Protection, i.e. in Swoszowice district, was not taken into consideration due to large gaps in its data base. The general features of the spatial variability of  $PM_{10}$  concentrations, shown below with daily data, give the background for an analysis of hourly data in the context of foehn impact. The  $PM_{10}$  levels in the study periods were not only relatively high but they also showed significant spatial variability within the area of Kraków. The number of days with a mean daily  $PM_{10}$  level  $\geq 50 \mu\text{g}\cdot\text{m}^{-3}$  (i.e. exceeding the allowed value), was highest in Krasińskiego St at 275 days, which is 57% of all days in the periods analyzed (i.e. Sep 2017 - Apr 2018 and Sep 2018 - Apr 2019). For other measurement points, the percentage of such days varied from 38% in Dietla St to 24% in the Wadów district (Appendix 2). Additionally, the only case of a mean daily concentration above  $200 \mu\text{g}\cdot\text{m}^{-3}$  was noted in Krasińskiego St at  $224 \mu\text{g}\cdot\text{m}^{-3}$  on 5<sup>th</sup> Mar 2018.

Spatial variability of  $PM_{10}$  concentrations can also be shown as the difference between the lowest and the highest concentrations noted at measurement points at specific times. On 47 days in total (i.e. 10% of the study period), differences of mean daily  $PM_{10}$  concentration exceeded  $50 \mu\text{g}\cdot\text{m}^{-3}$ , and the greatest difference was  $136 \mu\text{g}\cdot\text{m}^{-3}$  on 5<sup>th</sup> Mar 2018 between Krasińskiego St ( $224 \mu\text{g}\cdot\text{m}^{-3}$ ) and Wadów district ( $88 \mu\text{g}\cdot\text{m}^{-3}$ ). On 181 days (37%) differences in mean daily  $PM_{10}$  concentration were from 25 to  $49 \mu\text{g}\cdot\text{m}^{-3}$ . These data additionally demonstrate a high spatial variability of  $PM_{10}$  levels within the city. The comparison of data on foehn occurrence and  $PM_{10}$  indices shows that differences of mean daily  $PM_{10}$  concentrations in the ranges of  $25\text{--}50 \mu\text{g}\cdot\text{m}^{-3}$  and  $51\text{--}75 \mu\text{g}\cdot\text{m}^{-3}$  are much more frequent during foehn episodes (43% and 16%) than for non-foehn periods (35% and 5%). During the study period, there were 56 days with potential conditions for a foehn based on data from Kasprowy Wierch. For 67% of them, the mean daily  $PM_{10}$  concentration allowed (i.e.  $50 \mu\text{g}\cdot\text{m}^{-3}$ ) was exceeded at one measurement point at least in Kraków; and for

14% of days, the maximum difference in  $PM_{10}$  mean daily concentrations between measurement points exceeded  $50 \mu\text{g}\cdot\text{m}^{-3}$ . The figures for the whole period (i.e. both foehn conditions and non-foehn) were 57% and 10% respectively. During foehn periods, the share of the mean daily concentration above  $50 \mu\text{g}\cdot\text{m}^{-3}$  is larger at stations in the western part of the city than during non-foehn periods: in Krasińskiego St by +8%, in Dietla St by +18%, and in Złoty Róg St by +3%; while at other stations the share is smaller than during non-foehn periods. Therefore, a foehn can be considered as one of the factors which determine elevated PM levels in the western part of Kraków. On the other hand, mean daily concentrations of  $PM_{10}$  for days with foehn conditions and for all other days of the study period do not differ very much; the values for days with a foehn vary from  $64 \mu\text{g}\cdot\text{m}^{-3}$  in Krasińskiego St to  $35 \mu\text{g}\cdot\text{m}^{-3}$  in the Wadów district, while for the whole study period from  $61 \mu\text{g}\cdot\text{m}^{-3}$  in Krasińskiego St to  $38 \mu\text{g}\cdot\text{m}^{-3}$  in the Wadów district.

In order to analyze the impact of the foehn on the UBL and  $PM_{10}$  dispersion conditions in Kraków during long foehn episodes, model analysis outcomes were used, in addition to the measurement data described above, so as to obtain three-dimensional information for the area of the whole city and surrounding areas. *Aire Limitée Adaptation Dynamique Développement International* (ALADIN) is a numerical weather prediction (NWP) system developed by the international ALADIN consortium for operational weather forecasting and research purposes (Termonia et al. 2018). Part of the consortium's development work is to provide several configurations of a limited-area model (LAM), precisely validated to be used for operational weather forecasting at the 16 partner institutes. These are called the ALADIN canonical model configurations (CMCs).

Currently there are three canonical model configurations: 1. ALADIN baseline CMC, 2. Application of Research to Operations at Mesoscale (AROME) CMC, and 3. ALADIN-AROME (ALARO) CMC. AROME 2 km x 2 km grid spacing and ALARO 4 km x 4 km grid spacing, both with 60 vertical levels, are operationally used in IMGW-PIB. Non-operational configuration of AROME with 1 km x 1 km grid spacing and 87 vertical levels (AROME CMC 1 km) was applied in the present study as a better solution for the determination of the foehn effect on the UBL in Kraków, using lateral boundary data from ALARO 4 km x 4 km grid spacing. The size of the AROME CMC km domain was  $810 \times 810$  points centered on  $20^\circ\text{E } 50^\circ\text{N}$ . The location of the lowest model level is 9 m a.g.l., and the highest is at 50 km a.g.l. Details concerning the height of the lowest model levels up to 3 km altitude, information about the parametrization schemes used in the AROME model and a

topographic map of the model domain are included in Appendices 4, 5 and 6. Due to ongoing work on the assimilation of surface data in the ALARO model in the ALADIN Poland group, data assimilation was not used in this research, and models were run in dynamical adaptation mode. The data obtained with the model were used to provide vertical profiles of wind speed and direction, air temperature and relative humidity, with a one-hour temporal resolution, in points representative for the western, central and eastern parts of the city, corresponding to measurements in Balice, Krasieńskiego St and Bulwarowa St, respectively (see Fig. 1 and Tables 1 and 2 for their location). Additionally, N-S cross-sections through the valley at those points were obtained for the same elements. For selected cases, wind and air temperature fields at selected levels were obtained for Kraków and surrounding areas.

Verification of forecast results was performed for 24-h periods (beginning from the 7<sup>th</sup> hour of the forecast) for 40 selected days in the period during which the 14 long foehn episodes occurred. Data obtained from four meteorological stations (Balice, Libertów, Igołomia and Reymonta St) were used to verify the model forecast for air temperature, relative humidity and wind components on the valley floor and at the hill top nearby. The value of root mean square error (RMSE), difference (bias), and forecast accuracy were determined on the basis of differences between observation and forecast for each hour. Forecast accuracy was calculated for three difference ranges for all meteorological components (air temperature – 826 cases of one-hour observations; relative humidity – 826 cases; and wind components – 772 cases). For air temperature and wind speed the ranges were set to  $\pm 1$ ,  $\pm 2$ , and  $\pm 5^\circ\text{C}$  or  $\text{m}\cdot\text{s}^{-1}$ , and for relative humidity and wind direction they were set to  $\pm 10$ ,  $\pm 20$ ,  $\pm 30\%$  and  $\pm 20$ ,  $\pm 50$ ,  $\pm 90^\circ$ , respectively. The accuracy for a given range specified the percentage of forecast hours when the difference between forecast and observation was below a specified range. Detailed information of model verification with meteorological stations measurements are included in Appendices 7 and 8. Appendix 8 presents wind roses based on forecast and measurements for two stations: one in the Wisła valley and one on a hill top.

Air temperature and relative humidity measurements (747 cases of one-hour observations) at 50 and 100 m a.g.l. from a telecommunication mast were used to verify the model forecast of atmosphere stratification in the western part of the Wisła valley. Values of RMSE and bias for air temperature and relative humidity for both altitudes (i.e. 50 and 100 m a.g.l.) are similar. Accuracy of air temperature in the range  $\pm 2^\circ\text{C}$  was equal to 87%, and for relative humidity accuracy in the range  $\pm 10\%$  was higher than 80%. Differences between the forecast and

observed air temperature gradients between 50 and 100 m a.g.l. were in the range  $\pm 1^\circ\text{C}/100\text{m}$  for 65% of cases. Differences between forecast and measured relative humidity gradients were in the range  $\pm 5\%/100\text{m}$  for 69% of cases. The verification procedure confirmed the convergence of model forecast results with observations, i.e. the AROME model properly presented spatial and vertical variations of meteorological conditions in the Wisła valley.

The first step of data analysis in a particular foehn episode was to distinguish the phases of PM<sub>10</sub> concentration changes. Four spatial-temporal patterns of PM<sub>10</sub> concentration, found in various episodes, were defined (Fig. 2): 1. a sudden large increase of PM<sub>10</sub> concentrations at all measurement points; 2. a sudden large decrease of PM<sub>10</sub> concentrations at all measurement points; 3. short-term peaks or long-term periods of high PM<sub>10</sub> concentrations in the western part of the city only; 4. long-term periods of high PM<sub>10</sub> concentrations at all measurement points.

For each phase of each episode, all measurement and model data were analyzed in order to define the mechanisms responsible for a certain type of PM<sub>10</sub> pattern. All available data on air temperature and relative humidity, from both measurements and the model, were used above all to determine whether a CAP was formed in the valley or not, and what its vertical extent was. Then the data were used to observe changes of UBL properties in the valley. To study the dynamics of turbulence, vertical Turbulent Kinetic Energy (TKE) fields from the AROME model were used (Termonia et al. 2018), as this type provides information about mechanical turbulence and convection potential. All available data on wind speed and direction were used to trace the occurrence of a foehn in the study area, its impact on the CAP, the parallel occurrence of katabatic flows and local winds modified by the relief. The next section presents the characteristics of each PM<sub>10</sub> pattern, together with the mechanisms which modified the UBL and PM<sub>10</sub> dispersion conditions.

#### 4. Foehn-linked mechanisms generating spatial-temporal patterns of PM<sub>10</sub> concentrations in Kraków

Within the 14 foehn episodes, for PM<sub>10</sub> spatial-temporal Pattern no. 1 there were 8 cases; for Pattern no. 2 – 11 cases; for Pattern no. 3 – 15 cases; and for Pattern no. 4 – 3 cases. Usually, there were different patterns and cases of each pattern during each episode. The processes decisive for PM<sub>10</sub> level changes were different in each pattern, and that is why no single index could be used to characterize all situations.

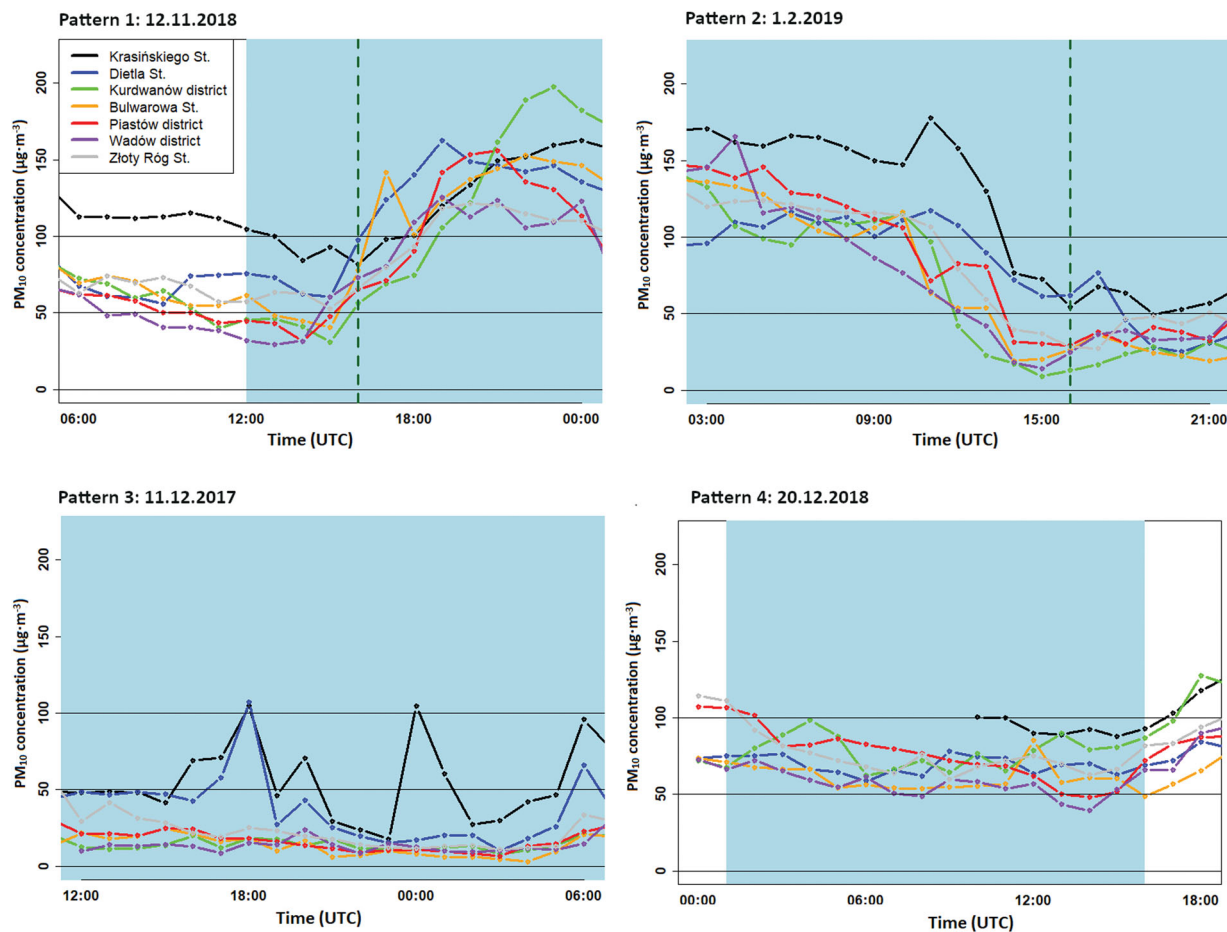


Fig. 2. Examples of the four spatial-temporal patterns of PM<sub>10</sub> concentration.

Key: blue background: foehn period; green dashed line: occurrence of altocumulus lenticularis cloud.

#### 4.1. Pattern 1: a sudden large increase of PM<sub>10</sub> concentration at all measurement points

A PM<sub>10</sub> increase case was considered a sudden and a large one if the concentration changed from allowed levels (i.e. below  $50 \mu\text{g}\cdot\text{m}^{-3}$ ) to about  $150\text{--}200 \mu\text{g}\cdot\text{m}^{-3}$  within 3–5 hours (see example on 12/13.11.2018 - Fig. 3e). In all cases, PM<sub>10</sub> increase was linked to the development of an air temperature inversion in the Wisła valley. The air temperature difference between a level of 2 m a.g.l. and 100 m a.g.l. in the western part of the valley (at the telecommunication mast) reached from about  $4^\circ\text{C}$  to as much as over  $10^\circ\text{C}$ . At the same time, relative humidity reached 80–90% on the valley floor in rural areas which indicates fog occurrence, as the values were decreasing quickly with height. Wind speed inside the valley was below  $3 \text{ m}\cdot\text{s}^{-1}$  while at about 100 m higher (i.e. above the valley) it increased to  $6\text{--}8 \text{ m}\cdot\text{s}^{-1}$  (situation for the city centre - Fig. 3c). Warm and dry air streams, generated by the foehn, did not enter the valley but went above it to the north which contributed to the increase of the air

temperature inversion (Fig. 3a–b - situation for the city centre). Additionally, in the western part of the valley, a weak northerly wind was observed but at station level only. The data indicate that there was a CAP on the valley floor which formed a stable air layer. The stability was further strengthened by katabatic flows from the slope of the Uplands presented in Fig. 4. Winds from the southern sector were forecast only on hill tops and selected parts of the valley, while in many lower parts of the valleys located on north-facing slopes, NW–NE light winds were predicted. They did not exceed  $2 \text{ m}\cdot\text{s}^{-1}$  and they resulted from the orographic reflection of air streams coming from the south. This is an example of a phenomenon described for instance by Sheridan (2019), i.e. a dense current-like return flow of air within and beneath an inversion (katabatic flows from the slope of the Uplands). It is worth mentioning that such a change of wind direction due to reflection can be seen in many parts of the Western Carpathians during foehn episodes and also that areas north of Kraków, are highly

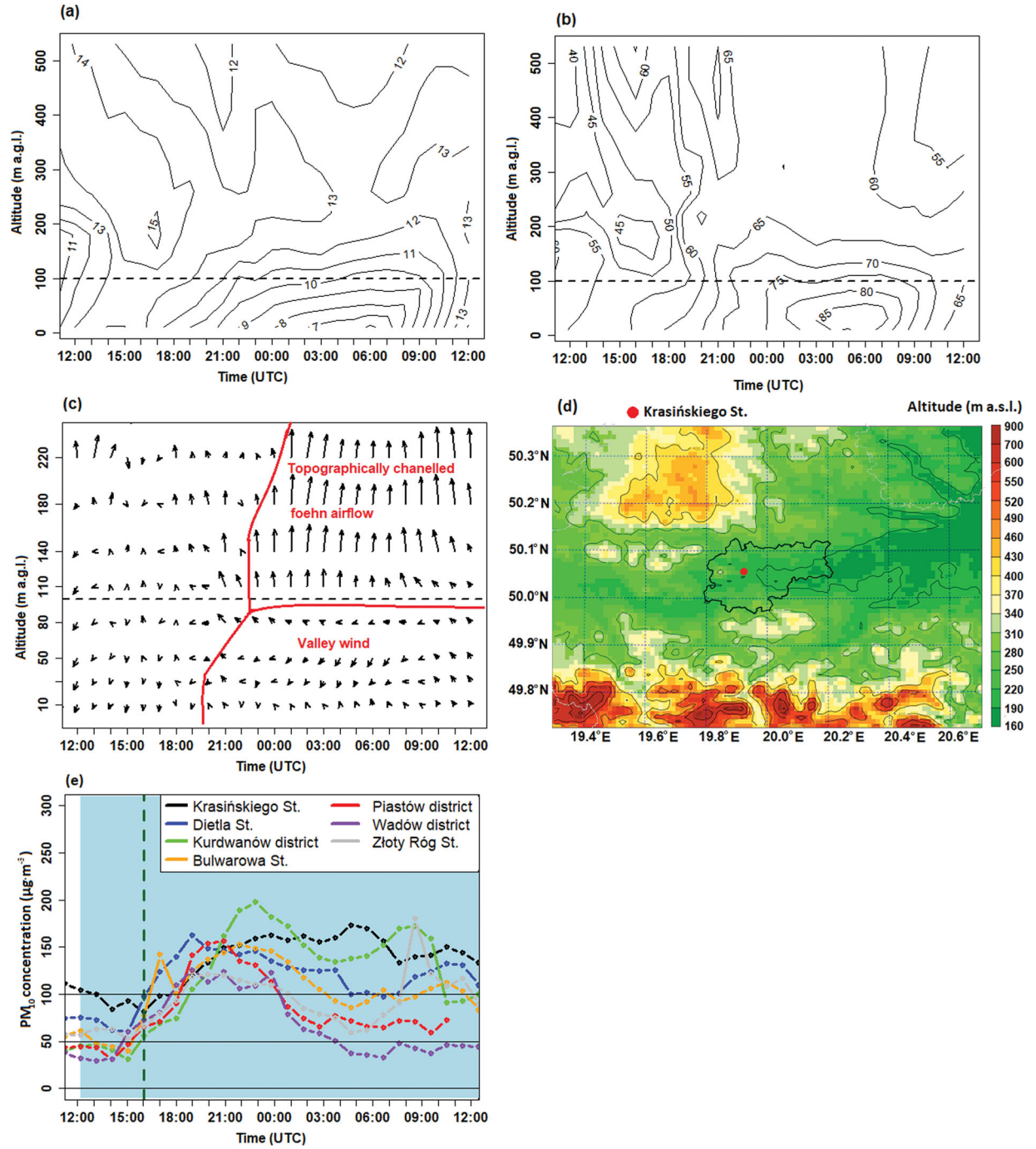


Fig. 3. Vertical profiles of a. air temperature (°C); b. relative humidity (%); c. wind components for the location of PM<sub>10</sub> monitoring station in Krasieńskiego St; d. location of station in Krasieńskiego St on a topographic map from the AROME model; e. spatial-temporal patterns of PM<sub>10</sub> concentration on 12/13.11.2018.

Key: horizontal dashed black line for Fig. 3a-c: the Wisła valley height; blue background for Fig. 3e: foehn period; green dashed line for Fig. 3e: occurrence of altocumulus lenticularis cloud.

populated and deliver a lot of air pollution. Therefore, katabatic flows which enter the city from the north, contain a lot of PM<sub>10</sub> and significantly worsen aero-sanitary

conditions of Kraków. The foehn reduced available mixing volume and trapped the pollutants emitted inside the valley within a CAP, a mechanism described for instance

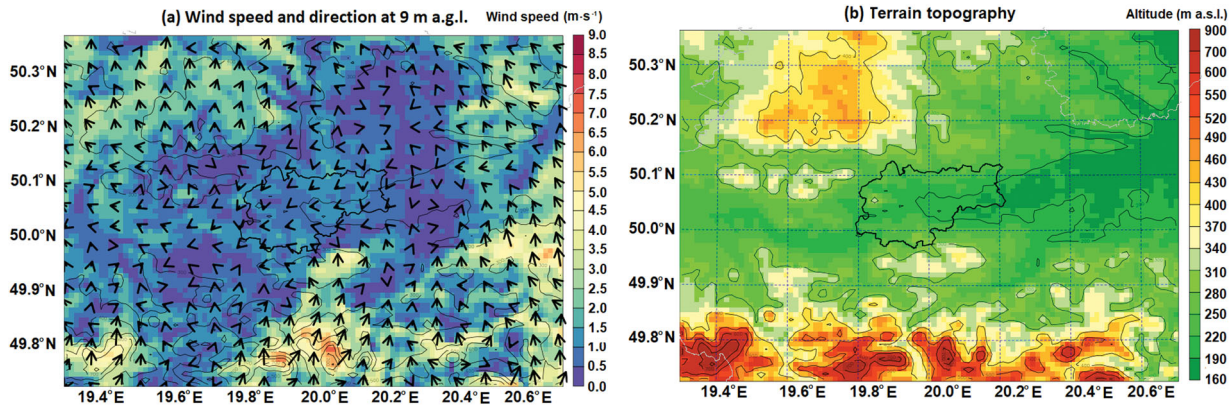


Fig. 4. Predicted wind speed and wind direction at 9 m a.g.l. from the AROME model at 19 UTC (a) (12.11.2018), and topographic map of terrain (b).

Key: thin lines: elevation; thick line: administrative borders of Kraków.

by Drechsel and Mayr (2008) or Kishcha et al. (2017). Sheridan (2019) summarized research showing that a CAP inhibits the penetration of a cross-mountain flow which is also the case in the present study.

#### 4.2. Pattern 2: a sudden large decrease of $PM_{10}$ concentration at all measurement points

A  $PM_{10}$  decrease was considered a sudden and a large one if the concentration changed from about  $150\text{--}200\mu\text{g}\cdot\text{m}^{-3}$  to values below allowed levels within 3–5 hours (see example on 25.11.2017 - Fig. 5g).  $PM_{10}$  decreases were linked to the intrusion of a foehn into the valley, destruction of the CAP and an increase in wind speed. However, two different modes of that process were observed. In the first, the foehn, moving from the south, entered the Raba valley first (a right tributary of the Wisła) east of Kraków and then moved into the area of Kraków from the east where the Wisła valley is much wider than in the western part of the city (Fig. 5a–e). Therefore, the wind speed within the valley increased gradually from east to west, the air temperature inversion and CAP were destroyed (Fig. 5f), and dispersion conditions improved significantly which led to a quick and large decrease in  $PM_{10}$  concentration.

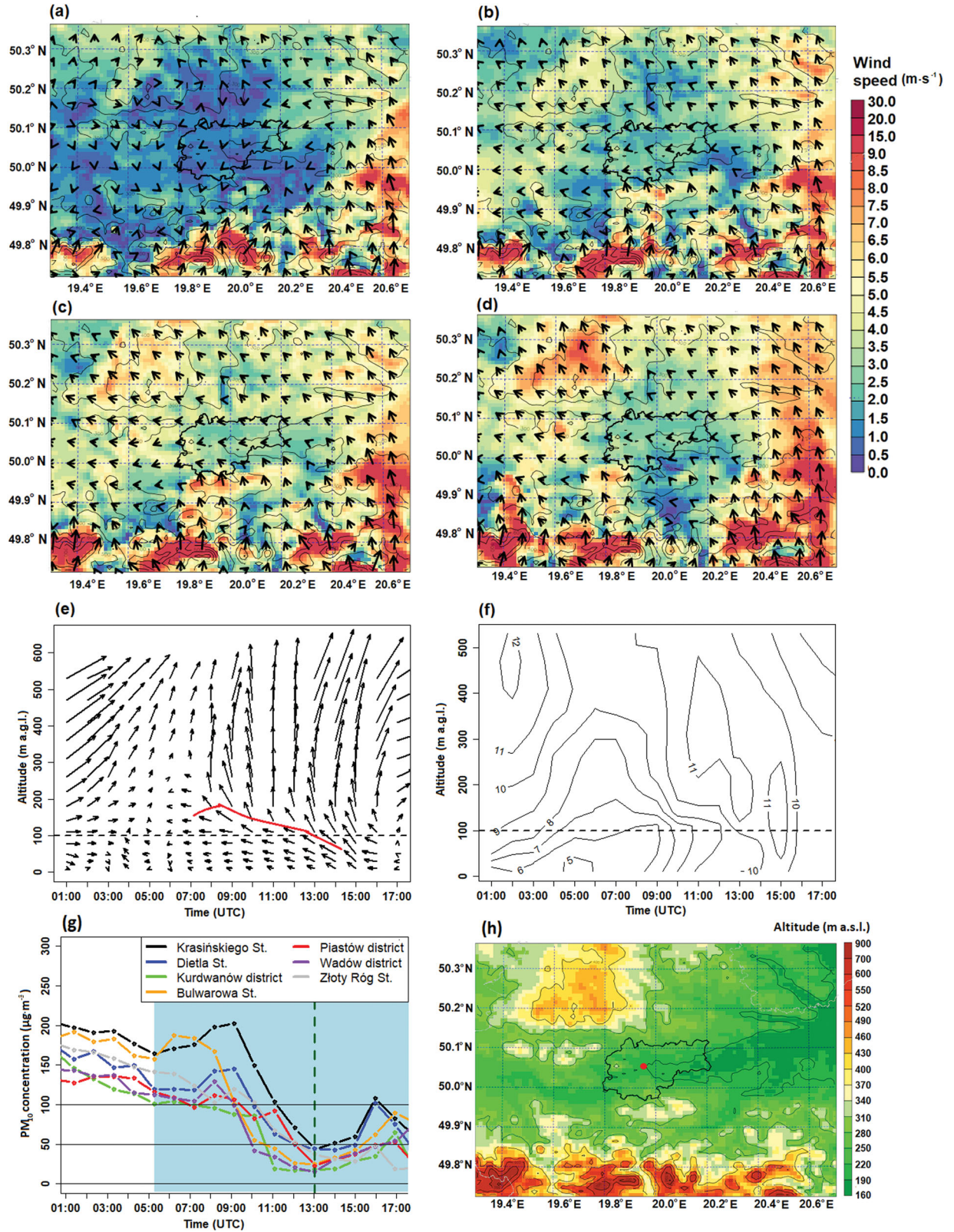
The second is based on the intrusion of a foehn into the Wisła valley from the top of the CAP, an example of such situation was observed on 6/7.03.2019, see Fig. 6. In that case, first the wind speed increases gradually from the top of the CAP downward, while air temperature does too. Usually, the air temperature inversion in the 2–100 m a.g.l. stratum is still present and becoming more intense (due to warming of the upper strata - see air temperature measurements from the telecommunication mast- Fig. 6d) while  $PM_{10}$  concentrations are already decreasing, as there is the exchange of air between the

CAP and the strata above. Additionally, as the CAP is decreasing, tall chimneys begin to deliver their emissions of  $PM_{10}$  into a well-mixed stratum above the CAP which contributes to a  $PM_{10}$  concentration decrease. Later in the day, the delivery of solar radiation triggers surface warming and the destruction of the CAP from the bottom (not shown). The CAP forming within the valley, and the topographically channelled foehn flow from the east, were predicted in the Wisła valley during that period.

The mechanisms described above correspond well to those defined for the removal of the cold pool in the Rhine valley during a foehn event (Flamant et al. 2006). Convection within the cold pool seems to have the least significance due to low incoming solar radiation in the cold half year and shade from the valley. Turbulent erosion at the top of the cold pool, linked to a strong wind shear between the foehn air and the cold pool leading to the mixing necessary to deplete it, seems to be decisive in the second case described above. In the case of the Rhine valley, dynamic displacement of the cold pool by foehn air was attributed to an orographic wave effect while in case of the Wisła valley it should rather be linked to the channelling of the foehn flow first into the Raba valley and then to the Wisła.

#### 4.3. Pattern 3: Short-term peaks or long-term periods of high $PM_{10}$ concentration in the Western part of the city only

The differences in relief between the western and eastern part of the Wisła valley in Kraków contribute to the occurrence of Pattern 3, see example on 11/12.12.2017 (Fig. 7). The western part is much narrower and more closed than the eastern one, and as shown by Sheridan (2019), valley width is an important parameter affecting



interactions between the CAP and air flow above the valley. In all cases of Pattern 3, much larger  $PM_{10}$  concentrations were observed in the western than in the eastern part of the valley and were either long-lasting or occurred as concentration peaks. The wind speed in the eastern part was much higher than in the western, likewise the relative stability of the air layer within the valley. Such conditions show a significant impact of the relief on the foehn effect at a local scale which included closed eddies which in turn lead to the accumulation of air pollution locally. Fig. 7 shows air temperature, relative humidity, wind speed and direction, and vertical velocity in an SW-NE cross section, with Krasieńskiego St as a central, reference point. The fluctuations of air temperature and vertical velocity presented in the SW-NE cross section (Fig. 7) correspond well to the spatial pattern of wind and TKE at a regional scale shown in Fig. 8.

Drobinski et al. (2007) studied orographic waves linked to foehns in the Rhine Valley. They have shown that occasional intensification of an orographic wave at higher levels may force the foehn down to ground level and flush the cold pool downstream, for instance in the case of a breaking wave above. However, they also concluded that the sensitivity of amplitude, phase and temporal evolution of orographic gravity waves to ambient flow are still poorly understood. The study for Kraków shows that the gravity waves contributing to vertically trapped lee waves can cause a local and significant increase of  $PM_{10}$ .

Another case that shows the impact of gravity waves on the CAP is presented with data from 9/10.2.2019 (Fig. 9). Very strong vertical movements can be seen in mountain areas south of Kraków while in the Wisła valley the phenomenon is much weaker (Fig. 9f). This is shown by the measurements at the tower in the 50-100 m stratum in the western part of the valley, where there were isothermal conditions from 18 UTC on 9.02.2019 to 8 UTC on 10.02.2019. Gravity waves increased turbulence in the southern part of the city while in the northern part TKE was close to zero. The southern part of the city was warmer by about 2-3 K than the northern. According to additional measurements from other stations, in the 2-50 m stratum after 00 UTC, a strong temperature decrease occurred (Fig. 9d.). The temperature in the western part of valley floor was similar (e.g. in

Jeziorzany, Krasieńskiego St tower station at 2 m a.g.l.) and dropped below zero, while in the eastern part of valley floor (Igołomia) and in locations at 50 and 100 m above the valley floor (Libertów, Bojki St telecommunication mast at 50 and 100 m a.g.l.), the temperature remained constant and was about 5 °C.

Later, from 9 to 11 UTC, the western part of the valley was sheltered by the upland areas to the north, as shown in Fig. 10, for 30 m and 110 m a.g.l. levels. A large wind speed difference can be seen between the western and eastern parts of the valley, accompanied by similar differences in TKE. Towards the south and south-west of Balice meteorological station (red point on Fig. 11e-f), strong ridge-parallel up-draughts downstream of the relief can be observed with S-N and SW-NE cross sections of vertical velocity (25-30 km from reference point) which were identified as hydraulic jumps (marked by HJ on Fig. 11c-d). Spatial patterns of air temperature, relative humidity and wind components on the S-N and SW-NE cross sections (Fig. 11a-b) indicate significant fluctuations in the region of the hydraulic jump. Its occurrence resulted in the weakening of the wind in the valley and strong wind shear above the valley marked by a horizontal red line (Fig. 11a-b). The spatial map of vertical velocity at 800 m a.g.l (Fig. 11e), with arrows presenting horizontal wind at this altitude, shows the location of strong up-draughts with blue circles marking places of hydraulic jumps visible in S-N and SW-NE cross sections. The results of a numerical simulation of a real case study (Elvidge et al. 2016) and under idealized conditions (Sheridan and Vosper 2005) coincided with these observations.

#### 4.4. Pattern 4: long-term periods of high $PM_{10}$ concentration at all measurement points

In the case of Pattern 4, the mechanisms responsible for long-lasting high  $PM_{10}$  concentrations are similar to Pattern 1, but their duration is longer. An example of such a situation was presented by data from 20.12.2018 (Fig. 12). The decisive factor is the sheltering effect, i.e. warm air streams generated by the foehn flow above the valley which runs W-E, and that shelters a much cooler and stable air layer, often with fog, and increases the air temperature inversion (Fig. 12e). The situation can persist

Fig. 5. Spatial patterns of wind speed and direction at 50 m a.g.l. at 6 UTC (a), 8 UTC (b) 9 UTC (c), and 11 UTC (d) in Kraków and nearby, and changes of wind components (e) and air temperature (°C) (f) in vertical profiles for the location of  $PM_{10}$  monitoring station in Krasieńskiego St, from the AROME model on 25.11.2017, spatial-temporal patterns of  $PM_{10}$  concentrations on 25.11.2017 (g), and the location of the station in Krasieńskiego St on a topographic map from the AROME model (h).

Key: black dashed line in Fig. 5e-f: Wisła valley height; red line in Fig. 5e: topographically channeled foehn flow in the valley; blue background in Fig. 5g: foehn period; green dashed line in Fig. 5g: occurrence of altocumulus lenticularis cloud.

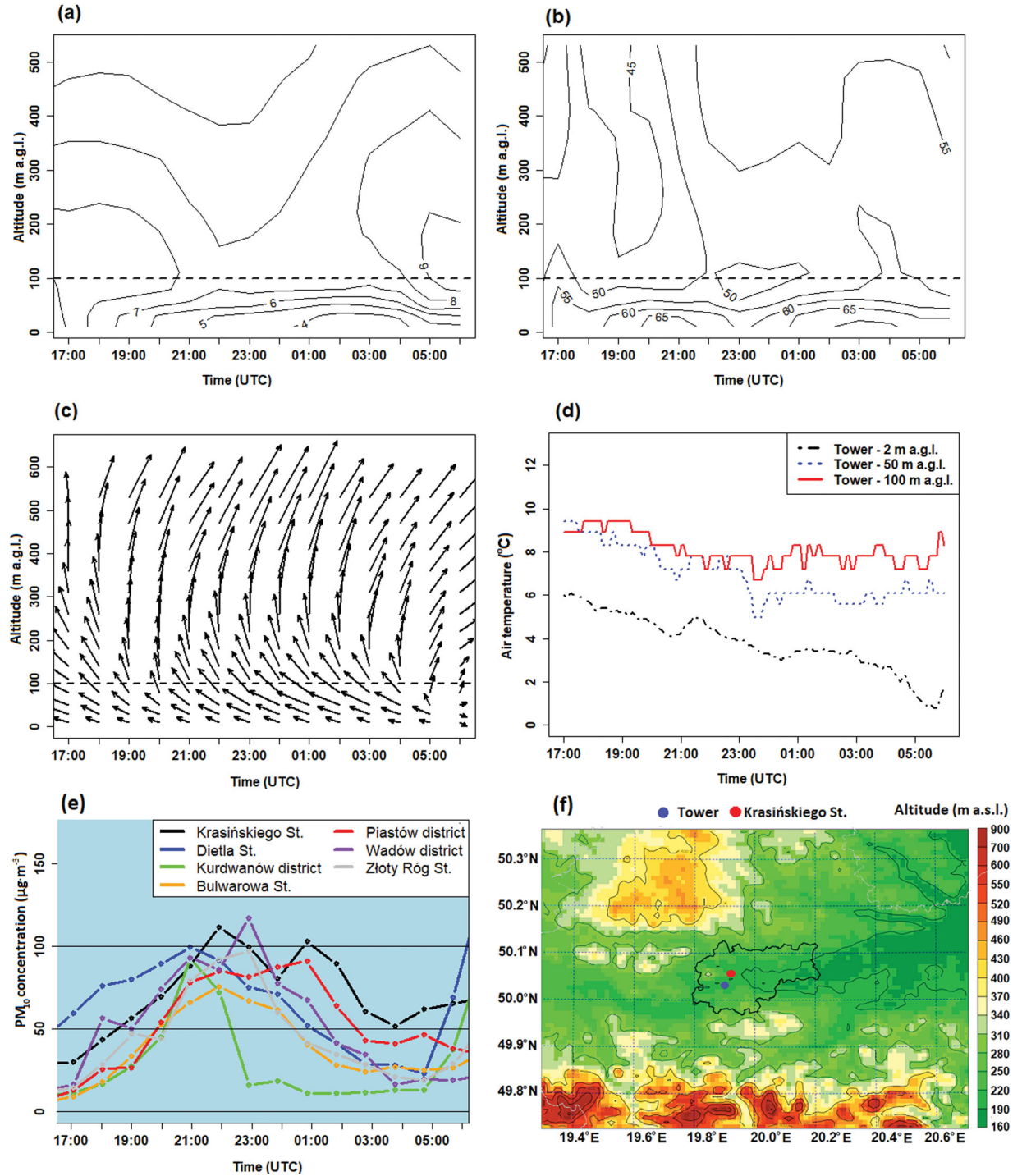


Fig. 6. Vertical profiles of a. air temperature (°C), b. relative humidity (%), and c. wind components for the PM<sub>10</sub> monitoring station in Krasieńskiego St, from the AROME model on 6/7.3.2019, and d. air temperature measurements from the telecommunication mast at three altitudes. Spatial-temporal patterns of PM<sub>10</sub> concentration on 6/7.3.2019 (e). Location of the station in Krasieńskiego St and the telecommunication mast (marked Tower) on a topographic map, from the AROME model (f).

Key: dashed line in Fig 6a-c: Wisła valley height; blue background in Fig. 6e: foehn period.

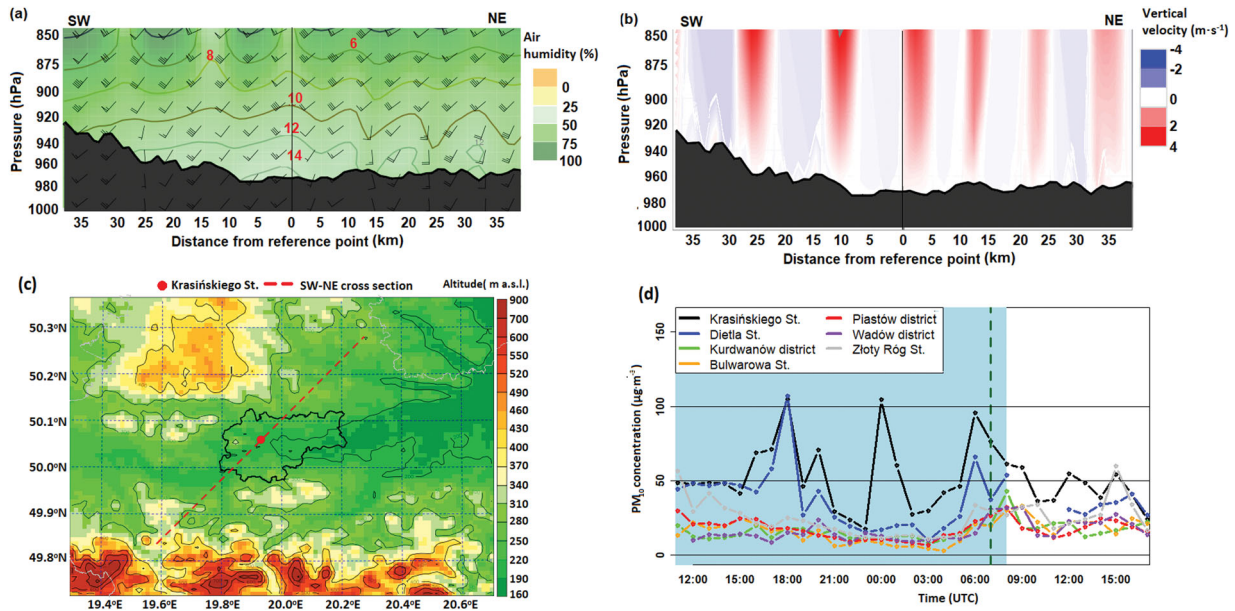


Fig. 7. Spatial pattern of a. air temperature (contour lines), relative humidity (background) and wind speed (in knots) and direction (graphical symbols) in the SW-NE cross section through Kraków and nearby, and b. vertical velocity at 7 UTC on 12.12.2017. Location of the station in Krasińskiego St (reference point at Fig. 7a-b) and the extent of the cross section presented on Fig. 7a-b on a topographic map, from the AROME model (c). Spatial-temporal patterns of PM<sub>10</sub> concentrations on 11/12.12.2017 (d). Key: reference point with distance 0: Krasińskiego St; the red and blue colour scales at cross section of vertical velocity in Fig. 7b indicates upward and downward movements, respectively; blue background in Fig. 7d: foehn period; green dashed line in Fig. 7d: occurrence of altocumulus lenticularis cloud.

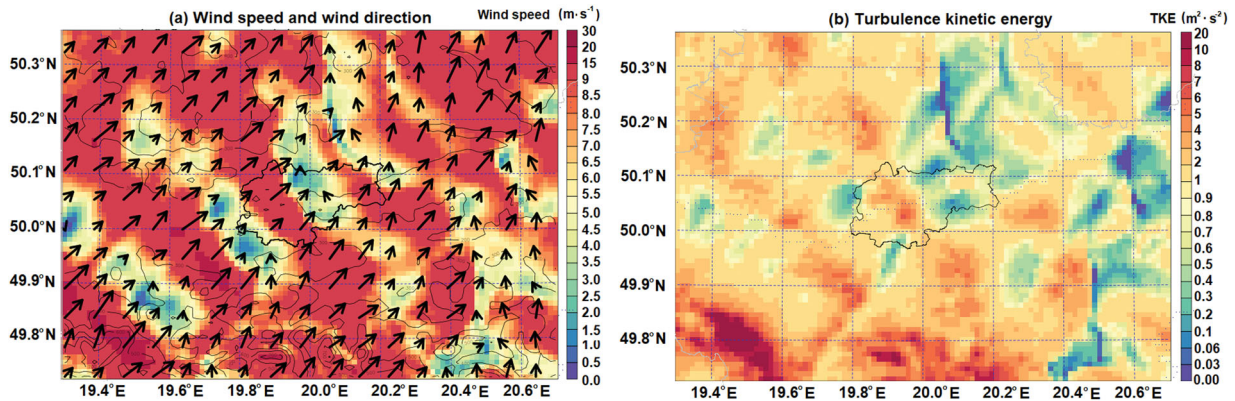


Fig. 8. Spatial patterns of a. wind components, and b. turbulent kinetic energy (TKE) at 30 m a.g.l. at 7 UTC on 12.12.2017.

even during daytime. Within the valley, wind speed is close to zero and so is turbulence which reduces available mixing volume and traps emitted pollutants, while in the areas located above the values are much higher (Pattern 1, Fig. 3; Fig. 12a-c).

This situation can also be observed in other mountainous areas, and the determination of the factors influencing foehn intrusion into a valley is not simple. For example, studies on foehns in the Dead Sea valley using a high resolution WRF model (Kunin et al. 2019) point out

that foehn intrusion depends on synoptic and mesoscale conditions which affect the vertical structure of the lower troposphere generating different heights of stable layers. During a high stable layer over the Dead Sea Valley, the foehn reached the valley floor, while during a low stable layer, it did not. On the other hand, studies of valley CAPs presented by Sheridan (2019) point out that for valleys whose depth exceeds that of the nocturnal stable boundary layer, processes related to daytime insolation may be not strong enough to break the CAP. Persistent

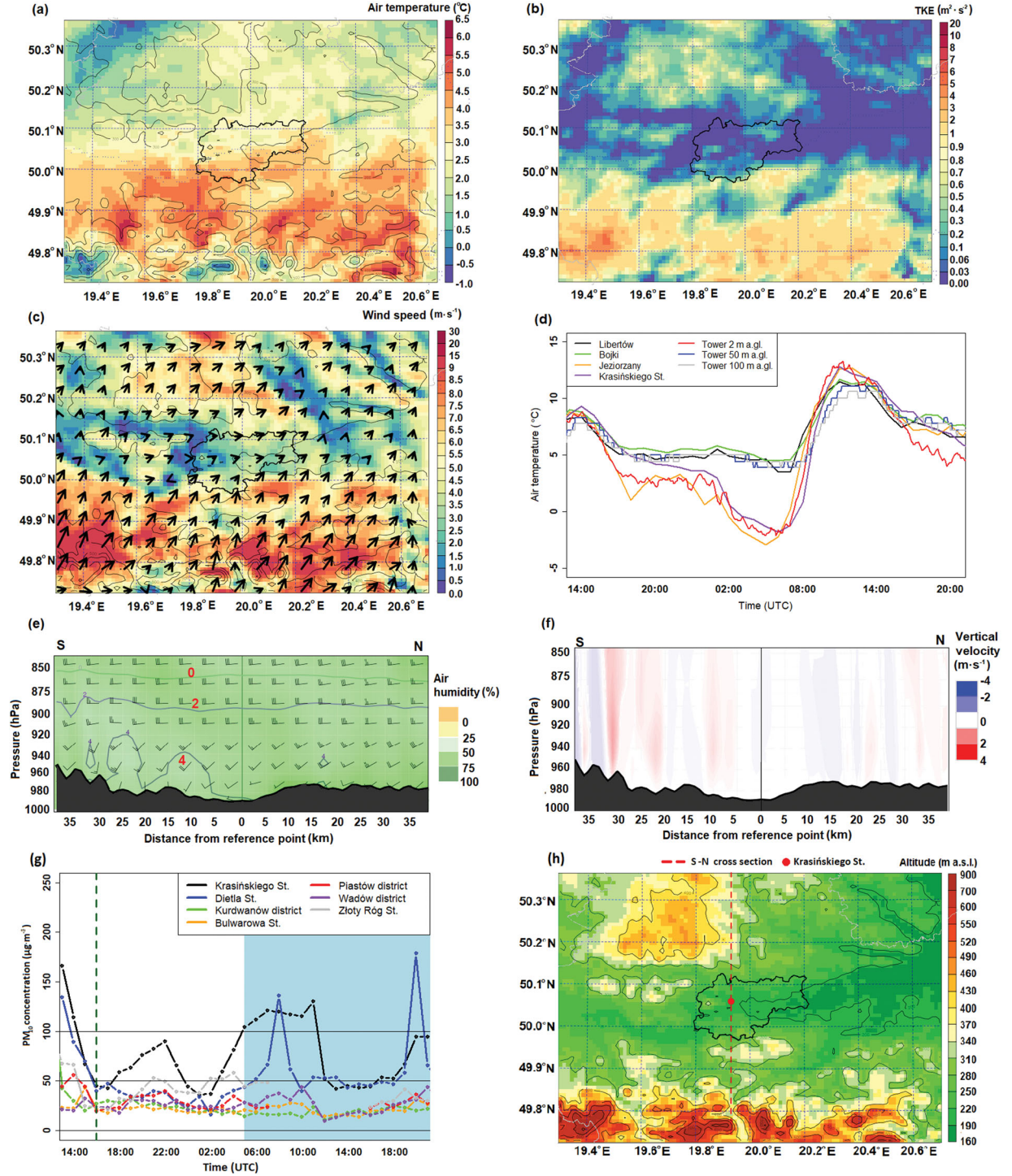


Fig. 9. Spatial pattern of a. air temperature; b. turbulent kinetic energy parameter (TKE), and c. wind components at altitude 30 m a.g.l. at 4 UTC (10.02.2019), in Kraków and nearby; d. air temperature measurements from ground stations on 9-10.02.2019; S-N cross sections of e. air temperature (contour lines), relative humidity (background), and wind speed (in knots) and direction (graphical symbols), and f. vertical velocity, at 4 UTC (10.02.2019). Spatial-temporal patterns of PM<sub>10</sub> concentrations on 9/10.02.2019 (g). Location of station in Krasieńskiego St (reference point at Fig. 9e-f) and cross section S-N presented at Fig. 9e-f on a topographic map, from the AROME model (h).

Key: reference point with distance 0 in Fig. 9e and f: Krasieńskiego St; the red and blue colour scales at cross section of vertical velocity at Fig. 9f indicates upward and downward movements, respectively; blue background in Fig. 9g: foehn period; green dashed line in Fig. 9g: occurrence of altocumulus lenticularis cloud.

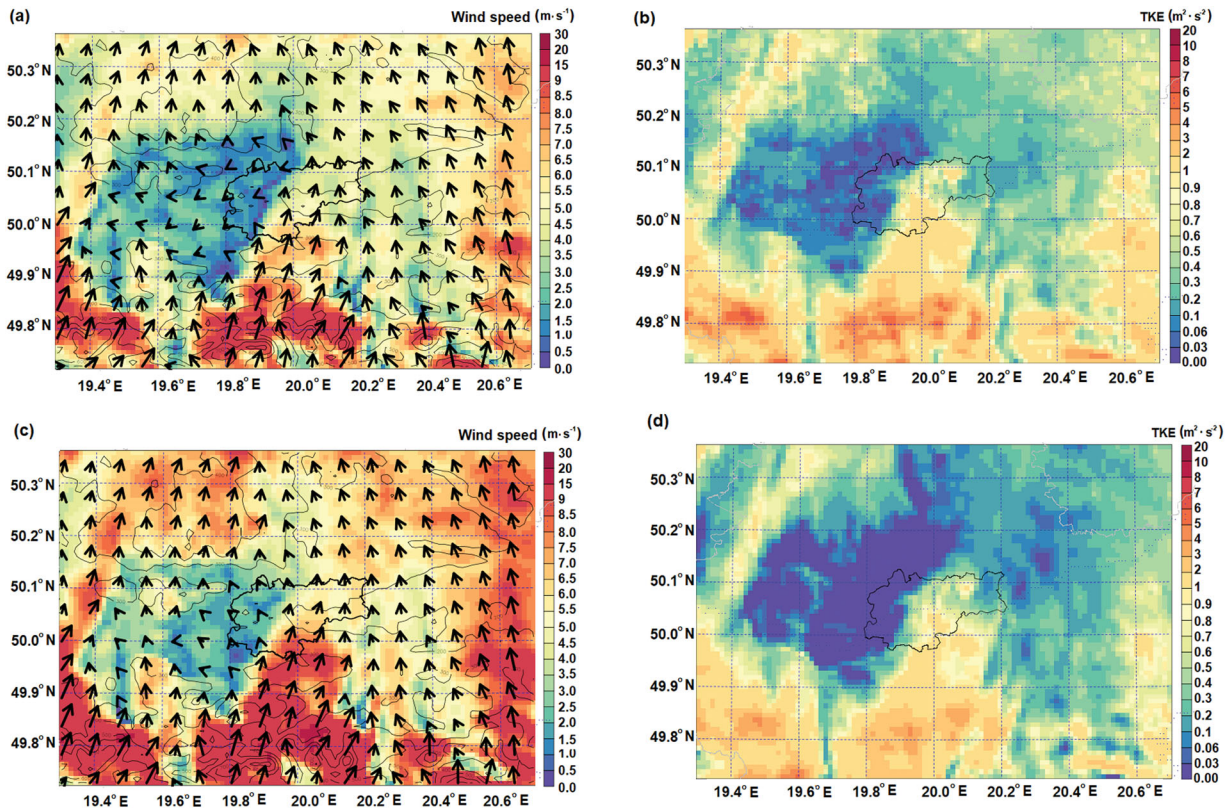


Fig. 10. Spatial patterns of wind speed and direction a. at 30 m a.g.l. and c. 110 m a.g.l.; turbulent kinetic energy parameter (TKE) at b. 30 m a.g.l. and d. 110 m a.g.l. at 11 UTC on 10.2.2019.

CAPs in deep basins represent a combination of a stable boundary layer near the surface (at night), residual stability at the top of the nocturnal stable layer which is not much eroded during the day, and any stability above this is due to air mass stratification.

## 5. Discussion

A foehn blowing from the Carpathian Mountains, can significantly modify the UBL in the areas it reaches, which in turn has a significant impact on air pollution dispersion conditions and pollution levels in ambient air. The main mechanisms involved in that process, and known from other mountain areas, are:

1. Intensification of air temperature inversion and the CAP, and reduction in the available air volume for mixing pollutants (e.g. Li X. et al., 2015; Drechsel and Mayr 2008);
2. Occurrence of gravity waves (Zängl 2003), hydraulic jump (Gohm and Mayr 2004; Kishcha et al. 2017), trapped lee waves (Nance and Durran 1998) or shear-induced gravity waves which occur at the top of CAPs (Richner and Hächler 2013);

3. Intrusion of foehns into a valley and mixing local air parcels into a larger volume (Drechsel and Mayr 2008).

Research on the intra-urban spatial variability of PM is not very common (e.g. Moore et al. 2009; Vicente et al. 2018), and the impact of a foehn on intra-urban air quality has been studied in detail even less (e.g. Li X. et al., 2015). An important aspect of the present work is to evaluate the role of a foehn in the modification of PM<sub>10</sub> dispersion conditions in relation to other factors which regularly impact UBL in Kraków. On the one hand, as already mentioned, the allowed mean daily level of PM<sub>10</sub> (i.e. 50 µg·m<sup>-3</sup>) was exceeded at one measurement point in Kraków at least on 57% of days in the study period, and a foehn occurred on only 12% of those days, but on the other hand, the allowed limit was exceeded on 69% of days with a foehn. In the case of mean hourly PM<sub>10</sub> concentrations, values ≥50 µg·m<sup>-3</sup> for all days of the study period constitute from 50.2% to 23.6%, and there is no spatial order in their distribution, while on days with a foehn, a clear difference can be seen between the western part of the valley (represented by Krasińskiego St, Dietla St and Złoty Róg St) and the eastern one. In the western

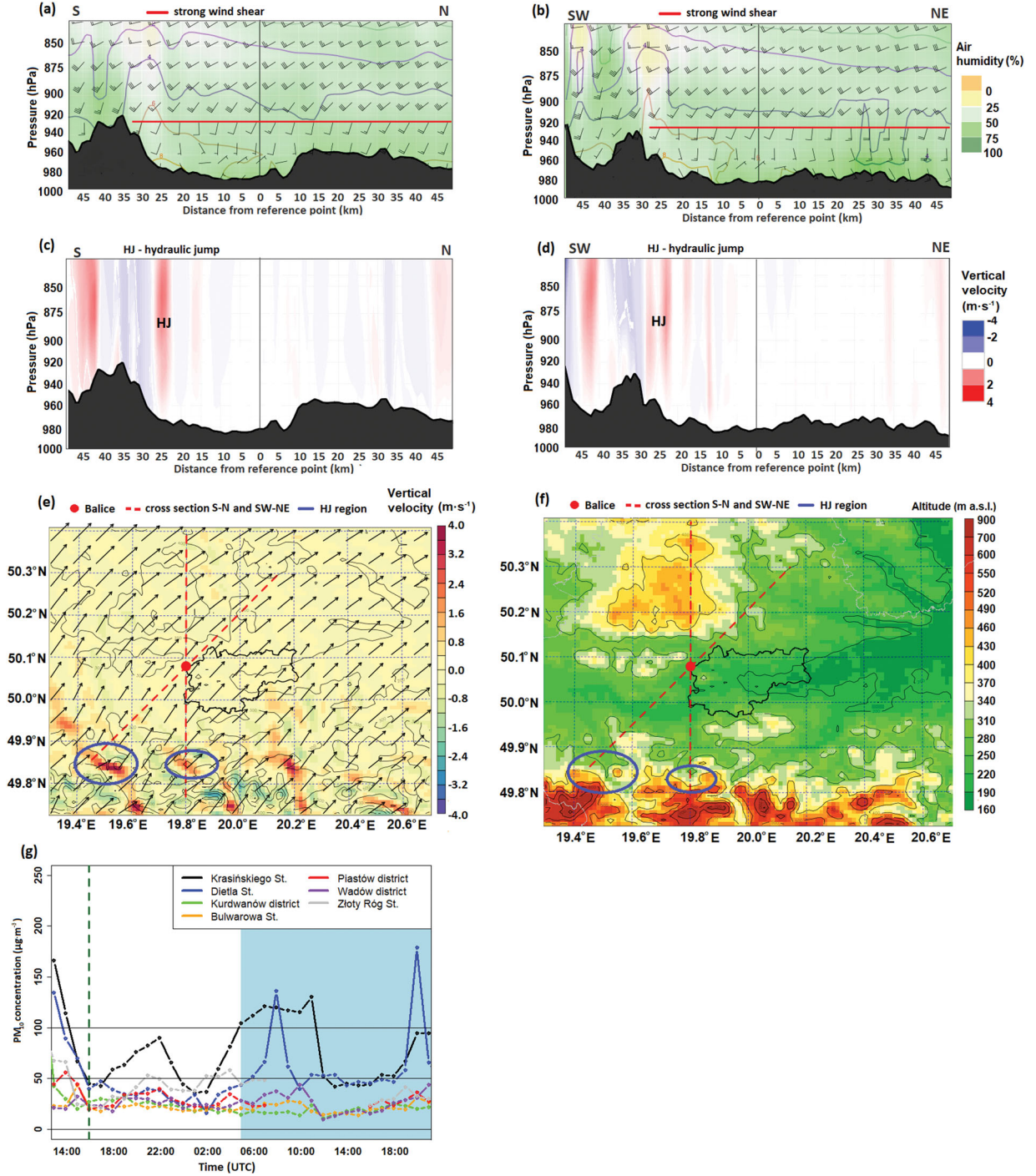


Fig. 11. Spatial pattern of a. air temperature (contour lines), relative humidity (background) and wind speed (in knots) and direction (graphical symbols) in the S-N cross section through Kraków and nearby, and c. vertical velocity at 11 UTC on 10.02.2019; SW-NE cross section of b. air temperature (contour lines), relative humidity (background) and wind speed (in knots) and direction (graphical symbols), and d. vertical velocity at 11 UTC (10.02.2019). Spatial map of vertical velocity at 800m a.g.l. with arrows presenting horizontal wind at this altitude (e). Blue circles in Fig. 11e-f present location of hydraulic jumps identified at S-N and SW-NE cross sections (Fig. 11c and d). Location of Balice station (reference point in Fig. 11a-d) and cross sections presented in Fig. 11a-d at topographic map, from the AROME model (f). Spatial-temporal patterns of PM<sub>10</sub> concentrations on 10.02.2019 (g).

Key: reference point with distance 0 in Fig. 11a-d: Balice; the red and blue colour scales at cross section of vertical velocity in Fig. 11c-d indicates upward and downward movements, respectively; blue background in Fig. 11g: foehn period.

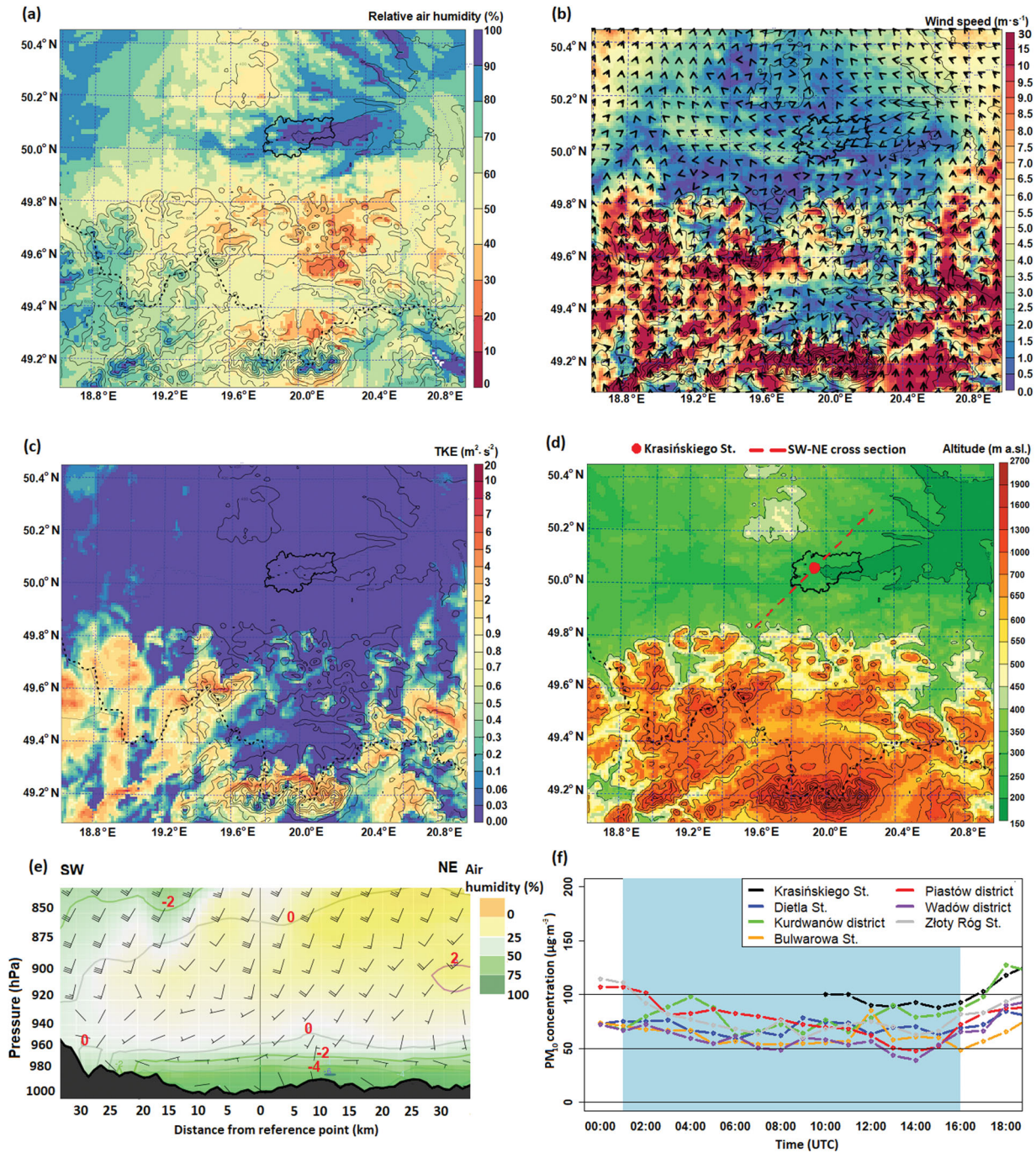


Fig. 12. Spatial pattern of relative air humidity (a), wind speed and direction (b) and turbulence kinetic energy at 110m a.g.l. (c), topographic map of this terrain (d) and cross section of air temperature (temperature isolines), relative humidity (background) and wind (in knots) (e) for station Krasieńskiego St at 6 UTC (20.12.2018). Spatial-temporal patterns of PM<sub>10</sub> concentrations on 20.12.2018 (f). Key: blue background in Fig. 12f: foehn period.

part, the share of time with PM<sub>10</sub> concentrations above  $50 \mu\text{g}\cdot\text{m}^{-3}$  is from 33.1% to 52.9% while in other points it reaches from 19.2% to 28.7%. Therefore, the foehn can be considered an important factor which contributes both

to an increase in PM<sub>10</sub> concentration in Kraków, and to its large spatial variability. However, that impact has a different background than for instance in the case of the Santa Ana (Álvarez and Noel Carbajal 2019) which

shows the importance of local conditions for the evaluation of foehn impacts on air quality.

In the case of Kraków, the main factor which modifies weather conditions at a local scale is the relief, as described in Section 2. That factor is decisive for the interactions between the foehn and UBL too. The city is located in a valley which is generally perpendicular to southerly winds, it is much wider in the eastern than in the western part, and during the cold half year stable atmospheric conditions occur in the UBL most of the time. The foehn can either blow above the valley or enter it in various modes. As shown in Section 4, it can either worsen or improve air pollution dispersion conditions, and increase or decrease PM<sub>10</sub> levels, but it also contributes to large differences in PM<sub>10</sub> concentrations within the city. The mode of interaction depends to a large extent on the exact direction from which the foehn reaches the city, which is an effect of general circulation conditions; SE winds have a much larger potential to enter the valley.

The mechanisms of interaction between the UBL and a foehn described in Section 4 were modified by local-scale processes. As shown for Urumqi (Li X. et al. 2015) or for Dead Sea valley (Vüllers et al. 2018), the impact of foehns on the UBL and on air pollution depends strongly on its modification by local relief which further suggests that it is possible to construct conceptual models concerning its impact on spatial patterns of urban air pollution but for a certain type of city location only. In the case of Kraków, such a model consists of the following elements:

1. The foehn from the Tatra Mountains is often strong enough to reach the area of the city of Kraków. It can affect air pollution dispersion conditions in the city and contribute both to a sudden and a large decrease or increase of PM<sub>10</sub> levels all over the city, or to the occurrence of PM<sub>10</sub> peaks in the western part of the city only, or to long-lasting high PM<sub>10</sub> levels throughout the city. The occurrence of a particular effect depends on the mode of foehn transfer through the area of the city and nearby.
2. The following transfer modes were identified: a. the foehn flows above the valley where a strong CAP and return flow can be found; b. the foehn enters the valley from the east or from the valley top and destroys the CAP; c. gravity waves generated by the foehn are strong enough to enter the western, narrower part of the valley and cause large spatial differences in turbulence parameters within the city.
3. The first transfer mode worsens air pollution dispersion conditions for the whole city and leads to large increases in PM<sub>10</sub> levels, the second transfer mode improves the dispersion conditions and leads to

large decreases in PM<sub>10</sub> levels throughout whole city, and the third mode generates large spatial differences in PM<sub>10</sub> levels within the city.

## 6. Conclusions

Analysis of PM<sub>10</sub> concentration changes in Kraków during foehn episodes showed that there is no single effect on air pollution dispersion conditions. Several mechanisms of foehn impact on the UBL were identified and a conceptual model of the foehn effect on PM<sub>10</sub> spatial pattern was formulated. The model might be useful in research on other cities located in similar relief conditions to Kraków, i.e. in large valleys located at the foothills of mountain ranges with a special focus on those perpendicular to the foehn direction. An important issue is valley width; in the western narrower part of the valley, the PM<sub>10</sub> levels are higher than in the wider eastern part. This is due to limited natural ventilation and the katabatic flows which intensify the CAP. The latter factor shows that the mechanisms of foehn impact on the UBL and air pollution dispersion conditions, well known from research in various mountain areas, might be significantly modified by specific local-scale processes.

The present study is an attempt at a climatological approach to the issue of foehn impact on UBL properties, air pollution dispersion conditions and intra-urban PM<sub>10</sub> patterns, in spite of the limited research period length. The four patterns of PM<sub>10</sub> spatial-temporal changes, described in Section 4, were defined by analysis of several cases for each pattern and accompanying processes. These analyses were possible due to the combination of observational and model data, including long-term mesoclimatic measurements. Such an approach allows results to be obtained which are useful for municipal management including spatial planning and air protection policy. As urban air pollution is a problem for many cities, a better understanding of the various mechanisms controlling UBL features and air pollution dispersion is needed.

## Disclosure statement

The authors declare that they have no conflict of interest.

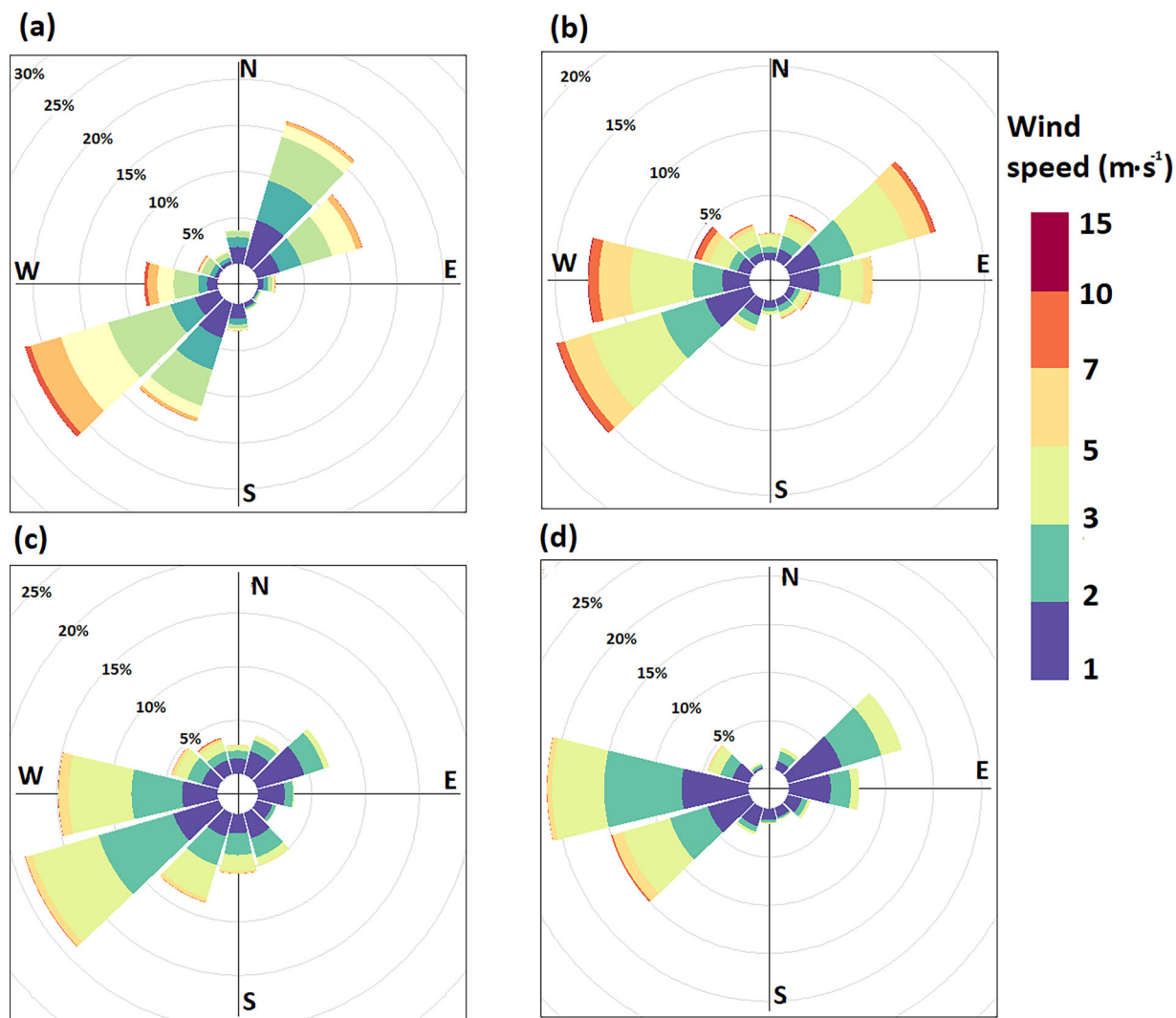
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### Appendix 1. Wind rose at two Sub-periods for (a) Balice, (b) Igołomia, (c) Libertów and (d) Reymonta St



### Appendix 2. List of foehn wind episodes studied

| No. of episode | Foehn start at Kasprowy Wierch (UTC) | Foehn end at Kasprowy Wierch (UTC) | Duration (h) | PM10 pattern type observed |
|----------------|--------------------------------------|------------------------------------|--------------|----------------------------|
| 1              | 08.09.2017 17:00                     | 10.09.2017 00:00                   | 31           | 2                          |
| 2              | 25.11.2017 05:00                     | 25.11.2017 21:00                   | 16           | 1–2                        |
| 3              | 10.12.2017 10:00                     | 12.12.2017 08:00                   | 46           | 3                          |
| 4              | 13.12.2017 18:00                     | 15.12.2017 13:00                   | 43           | 1–3                        |
| 5              | 15.01.2018 18:00                     | 16.01.2018 19:00                   | 25           | 1–3                        |
| 6              | 11.03.2018 16:00                     | 13.03.2018 00:00                   | 32           | 3                          |
| 7              | 02.04.2018 17:00                     | 05.04.2018 00:00                   | 55           | 2–3                        |
| 8              | 28.04.2018 19:00                     | 01.05.2018 08:00                   | 61           | 3                          |
| 9              | 29.10.2018 08:00                     | 31.10.2018 00:00                   | 40           | 3                          |

(Continued)

(Continued).

| No. of episode | Foehn start at Kasprowy Wierch (UTC) | Foehn end at Kasprowy Wierch (UTC) | Duration (h) | PM10 pattern type observed |
|----------------|--------------------------------------|------------------------------------|--------------|----------------------------|
| 10             | 12.11.2018 12:00                     | 13.11.2018 15:00                   | 27           | 1,4                        |
| 11             | 20.12.2018 01:00                     | 20.12.2018 16:00                   | 43           | 2,4                        |
|                | 21.12.2018 00:00                     | 21.12.2018 20:00                   |              |                            |
| 12             | 01.02.2019 00:00                     | 03.02.2019 12:00                   | 60           | 2–4                        |
| 13             | 06.03.2019 13:00                     | 07.03.2019 21:00                   | 32           | 1–3                        |
| 14             | 23.04.2019 07:00                     | 26.04.2019 15:00                   | 80           | 1–2                        |

Explanations: pattern 1 - increase of PM10 concentration at all stations, pattern 2 - decrease of PM10 concentration at all stations; pattern 3 - short-term peaks or long-term periods of high PM10 at western stations; pattern 4 - long-term periods of high PM10 concentrations at all measurement points

### Appendix 3. Number of days with mean daily PM concentrations $\geq 50, 100, 150$ and $200 \mu\text{g}\cdot\text{m}^{-3}$ at measurement points in Kraków in the study periods (two cold seasons)

| PM concentrations                    | Krasińskiego St | Piastów district | Wadów district | Złoty Róg St. | Kurdwanów district | Dietla St. | Bulwarowa St. |
|--------------------------------------|-----------------|------------------|----------------|---------------|--------------------|------------|---------------|
| $>50 \mu\text{g}\cdot\text{m}^{-3}$  | 275             | 127              | 115            | 176           | 163                | 185        | 151           |
| $>100 \mu\text{g}\cdot\text{m}^{-3}$ | 64              | 12               | 9              | 27            | 26                 | 28         | 14            |
| $>150 \mu\text{g}\cdot\text{m}^{-3}$ | 6               | 1                | 1              | 3             | 3                  | 4          | 4             |
| $>200 \mu\text{g}\cdot\text{m}^{-3}$ | 1               | 0                | 0              | 0             | 0                  | 0          | 0             |

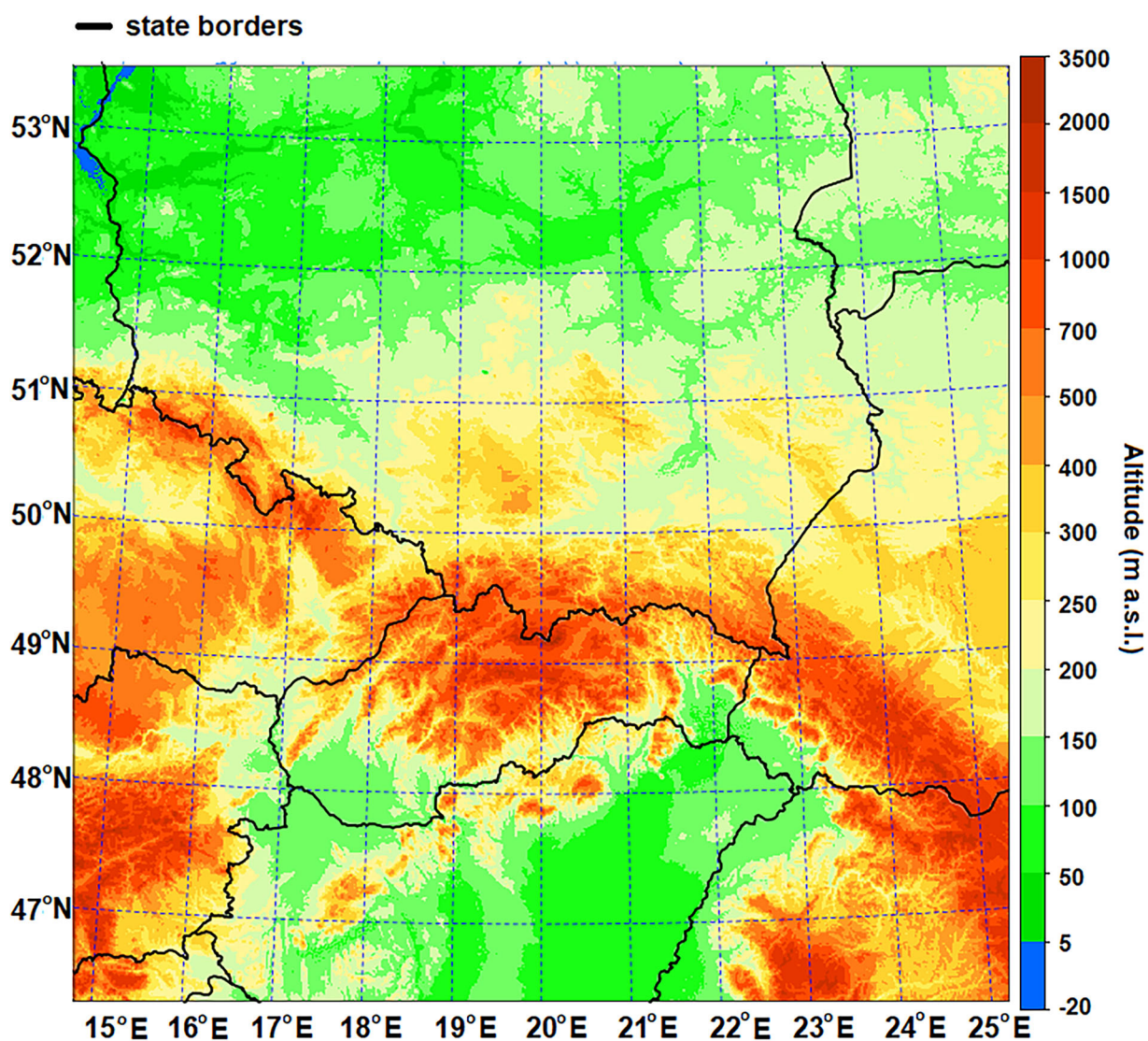
### Appendix 4. Height of the lowest 87 vertical levels (v.l.) from the model up to 3 km of altitude, used in forecast

| No. of v.l. | Height of v.l. (km a.g.l.) | No. of v.l. (cont.) | Height of v.l. (km a.g.l.) |
|-------------|----------------------------|---------------------|----------------------------|
| 1           | 0.009                      | 20                  | 0.969                      |
| 2           | 0.030                      | 21                  | 1.055                      |
| 3           | 0.053                      | 22                  | 1.144                      |
| 4           | 0.079                      | 23                  | 1.237                      |
| 5           | 0.110                      | 24                  | 1.334                      |
| 6           | 0.143                      | 25                  | 1.435                      |
| 7           | 0.180                      | 26                  | 1.537                      |
| 8           | 0.221                      | 27                  | 1.640                      |
| 9           | 0.264                      | 28                  | 1.744                      |
| 10          | 0.311                      | 29                  | 1.849                      |
| 11          | 0.362                      | 30                  | 1.957                      |
| 12          | 0.415                      | 31                  | 2.066                      |
| 13          | 0.472                      | 32                  | 2.178                      |
| 14          | 0.533                      | 33                  | 2.292                      |
| 15          | 0.597                      | 34                  | 2.408                      |
| 16          | 0.664                      | 35                  | 2.527                      |
| 17          | 0.735                      | 36                  | 2.649                      |
| 18          | 0.809                      | 37                  | 2.773                      |
| 19          | 0.887                      | 38                  | 2.900                      |

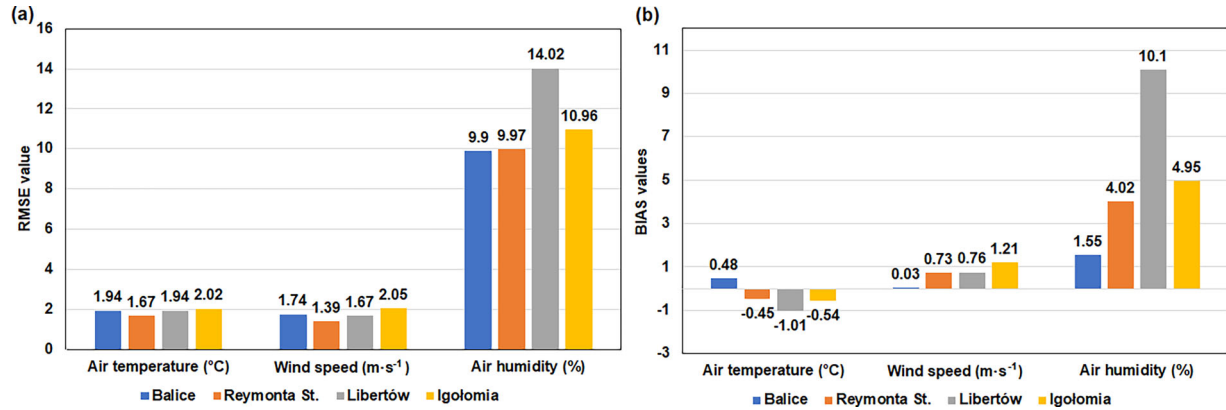
## Appendix 5. Physical processes' schemes used in AROME CMC 1-km model

|                    |                                                                                                                                                                       |
|--------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Dynamics           | Nonhydrostatic ALADIN (21.20.Bénard et al. 2010)                                                                                                                      |
| Turbulence         | Prognostic turbulent kinetic energy (TKE) combined with diagnostic mixing length (Cuxart et al. 2000; Bougeault and Lacarrere, 1989)                                  |
| Radiation          | Longwave Rapid Radiative Transfer Model (RRTM) radiation scheme, Morcrette shortwave radiation scheme from European Centre for Medium-Range Weather Forecasts (ECMWF) |
| Microphysics       | Three-class parameterization (ICE3)                                                                                                                                   |
| Shallow convection | Pergaud, J., Masson, V., Malardel, S., and Couvreux, F., 2009 (PMMC09) (Pergaud et al. 2009)                                                                          |
| Deep Convection    | —                                                                                                                                                                     |
| Clouds             | Statistical cloud scheme                                                                                                                                              |
| Surface scheme     | SURFEX (Masson et al. 2013)                                                                                                                                           |

## Appendix 6. Orographic map of the AROME model domain with 1km x 1km grid spacing



**Appendix 7. Verification of the AROME model forecast with data from meteorological stations: a) RMSE value; b) BIAS value**

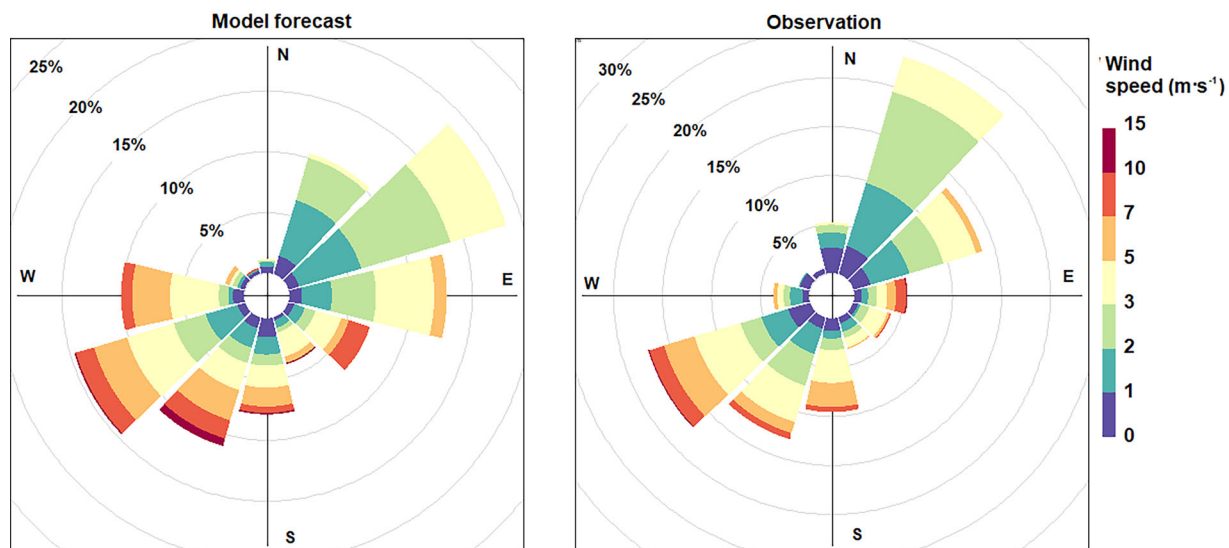


**Appendix 8. Accuracy of the AROME forecast (%) in comparison with data from meteorological stations**

| Parameter                                     | Balice | Reymonta St. | Libertów | Igołomia |
|-----------------------------------------------|--------|--------------|----------|----------|
| Air temp. $\pm 1^{\circ}\text{C}$             | 41     | 46           | 39       | 44       |
| Air temp. $\pm 2^{\circ}\text{C}$             | 71     | 78           | 71       | 70       |
| Air temp. $\pm 5^{\circ}\text{C}$             | 98     | 99           | 98       | 97       |
| Air hum. $\pm 10\%$                           | 66     | 68           | 47       | 64       |
| Air hum. $\pm 20\%$                           | 96     | 96           | 84       | 92       |
| Air hum. $\pm 30\%$                           | 100    | 100          | 98       | 99       |
| Wind speed $\pm 1\text{ m}\cdot\text{s}^{-1}$ | 58     | 60           | 48       | 42       |
| Wind speed $\pm 2\text{ m}\cdot\text{s}^{-1}$ | 83     | 88           | 80       | 74       |
| Wind speed $\pm 5\text{ m}\cdot\text{s}^{-1}$ | 98     | 100          | 99       | 98       |

**Appendix 9. Comparison of wind roses obtained from model forecast and measurements for Balice (i.e. a station on the valley bottom; a), and Libertów (i.e. a station on a hilltop; b)**

**(a)**



**(b)**

