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Application of the FAPPS system based on the CALPUFF model in short-term air pollution forecasting in Krakow and Lesser Poland

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Abstract: The aim of the study is to present the FAPPS (Forecasting of Air Pollution Propagation System) based on the CALPUFF puff dispersion model, used for short-term air quality forecasting in Krakow and Lesser Poland. The article presents two methods of operational air quality forecasting in Krakow. The quality of forecasts was assessed on the basis of PM_{10} concentrations measured at eight air quality monitoring stations in 2019 in Krakow. Apart from the standard quantitative forecast, a qualitative forecast was presented, specifying the percentage shares of the city area with PM_{10} concentrations in six concentration classes. For both methods, it was shown how the adjustment of the emissions in the FAPPS system to changes in emissions related to the systemic elimination of coal furnaces in Krakow influenced the quality of forecasts. For standard forecasts, after the emission change on June 7, 2019, the average RMSE value decreased from 23.9 $\mu g/m^3$ to 14.9 $\mu g/m^3$, the average FB value changed from -0.200 to -0.063, and the share of correct forecasts increased from 0.74 to 0.91. For qualitative forecasts, for the entire year 2019 and separately for the periods from January to March and October to December, Hit Rate values of 5.43, 2.18 and 3.48 were obtained, the False Alarm Ratios were 0.28, 0.24 and 0,26, and the Probability of Detection values were 0.66, 0.75, and 0.74. The presented results show that the FAPPS system is a useful tool for modelling air pollution in urbanized and industrialized areas with complex terrain.

Introduction

Human activities and natural processes lead to the emission of gaseous substances and particulate compounds, which have a large impact on air quality. Despite efforts by national and city authorities, air pollution remains a significant problem in Europe (WHO 2021) and polluted air in 2019 caused the premature death of several hundred thousand Europeans (Juginowić et al. 2021). Therefore, it is still necessary to take measures to reduce the presence of harmful substances in the air and to warn the public about the possible occurrence of concentrations exceeding the permissible standards.

The article presents the possibilities offered by Forecasting of Air Pollution Propagation System (FAPPS), based on the CALPUFF meteorological and air quality modelling system (Scire et al. 2000a, Scire et al. 2000b). The aim of the study is to present the applications of the FAPPS system in supporting local governments in forecasting air quality in Lesser Poland and Krakow. In addition to standard air quality forecasts for Krakow and Lesser Poland, the FAPPS system is used to prepare qualitative forecasts determining the probability of high concentrations of 8-hour PM_{10} in Krakow. Based on these forecasts, a decision on free transport in the city is issued. The presented FAPPS applications concern the most polluted area of Poland and one of the most polluted areas in Europe, where air quality standards have been exceeded many times (EEA 2021). The large variety of emission sources and the diverse topography make it difficult to model the dispersion of pollutants.

In the FAPPS, the transport of pollutants is controlled by the meteorological models AROME (Termonia et al. 2018, Yessad 2019) and MM5 (PSU/NCAR 2004) and the meteorological pre-processor CALMET (Scire et al. 2000a), which is part of CALPUFF system. The CALMET meteorological pre-processor is equipped with parametrizations describing the behavior of the wind in the presence of hills and roughness elements, as well as determining the stability class and the mixing height. These features enhance the possibility of a correct description of the transport of pollutants near the emission source. Another part of the CALPUFF system – the California Puff Model (Scire et al. 2000b) is responsible for taking into account chemical transformations, dry and wet deposition, the behavior of pollutants in the presence of terrain obstacles and close to the source of emission.

The studies based on the experimental model evaluation databases (Dresser & Huizer 2011, Rood 2014, Rzeszutek 2019) showed that the CALPUFF model may be successfully applied to conduct air pollutant dispersion simulations on a local scale, in complex terrain and around the buildings. The validation of the system conducted for industrial emitters located in urbanized areas (Ghannam & El-Fadel 2013; Oleniacz & Rzeszutek 2018) showed its usefulness also in such applications. The CALPUFF model was also used to identify the most polluted districts and pollutants and to check where the concentration limits of individual pollutants in Warsaw are exceeded (Holnicki et al. 2017).

The basis for the performance of all air quality modelling systems is a good quality emission input. Until recently, in Poland, activities in this area were scattered and largely inconsistent. The considerable effort made in recent years by the National Balancing and Emission Management Centre KOBIZE, operating within the framework of the Institute of Environmental Protection – State Research Institute, has contributed to the development of a methodically uniform emission database covering the whole of Poland and verified on an ongoing basis (Gawuc et al. 2021). In the future, the data from this database should be an enormous support in air quality modelling dedicated to local and regional needs, strengthening the credibility and comparability of the obtained results.

In this article, based on the example of the FAPPS system, it is shown that the CALPUFF system is a useful tool for short-term forecasting and for use in warning systems for cities located in areas with varying altitude and with heterogeneous distribution of emission sources. Moreover, the main causes of forecast errors in such areas are identified.

Data and methods

Study area

Lesser Poland with an area of over 15000 km² is located in southern Poland. This region is characterized by greatly diversified terrain and is inhabited by over three million people. Many houses in this area are heated with solid fuels (mostly coal), that is why emissions of pollutants remain a major problem. The level of pollution in the region is also affected by the inflow of pollutants from the neighboring Silesia region with its numerous industrial plants connected with power engineering, coal mining and heavy industry. The region's capital – Krakow with the area of 327 km² is inhabited by almost eight hundred thousand people, which makes it the second largest city in Poland both in terms of population and territorial spread. Krakow lies in the valley of the Vistula River. The hills in the north and south of the city, located 150 m above the river valley, force the air to flow in the west-east axis. However, this flow is largely obstructed by the Sowiniec Ridge dominating in the central part of the riverside depression in the west of the city, which significantly limits the ventilation potential of Krakow (Fig. 1). The city authorities, struggling with the problem caused by air pollution, decided to ban solid fuel heating. However, many houses in the Lesser Poland area are still heated by solid fuels, which means that pollutants reach Krakow from nearby towns, mainly from municipalities located west and southeast of the city (i.e. Skawina, Czernichow, Liszki, Zabierzow, Wieliczka, Niepolomice). Traffic emissions also have an influence on the level of pollution observed in the city (Chlebowska-Styś et al. 2019, Samek et al. 2021).

Modelling system

Various types of regional-scale air quality management applications presented in this paper are based on the set of models AROME/MM5/CALMET/CALPUFF making up the FAPPS system. AROME (Termonia et al. 2018, Yessad 2019) is a non-hydrostatic spatially constrained model powered by a global model ARPEGE. Currently, it is being used for operational preparation of forecasts of meteorological conditions for the area of Poland in Institute of Meteorology and Water Management – National Research Institute (IMWM-NRI). For the needs of the FAPPS system, the operational domain of the AROME model is converted into the POL1 domain with a resolution of 13.5 km at 180×180 grid points and 70 vertical levels, which allows to shorten the forecast preparation time while maintaining good data quality. The MM5 (PSU/NCAR 2004) is a mesoscale, regional, three-dimensional prognostic model. The version of model used is non-hydrostatic. The applied physical options are: Grell cumulus scheme, MRF PBL, cloud radiation scheme, as well as Schultz moisture scheme. Five-Layer Soil model is used. In the case of FAPPS, the calculations are performed at 34 levels and in two domains using two-way nesting technique. The bigger domain, which is adjusted to resolution of POL1 domain (60×65 grid cells), covers entire territory of Poland, while the second domain (82x82 grid cells, 4.5 km grid size) covers central and southern parts of the country.

Results of modelling of wind are highly dependent on the parametrization used in CALMET model. In the CALMET meteorological preprocessor (Scire et al. 2000a), wind speed and direction are adjusted to the orography by taking into account the kinematic effects of the terrain. Thus, CALMET can be used to model at the high grid resolution, which allows for more precise reproduction of the wind field of the modelled area than it is possible while using only MM5. The terrain obstacles increase the wind speed and create its vertical component. Moreover, blocking effects, based on the Froude number, are also modelled. They cause change in the wind direction because of terrain obstacle and thermodynamically driven flows in sloping terrain. This results in additional wind components in steady equilibrium directed downslope and, to a lesser extent, in unstable equilibrium directed upslope. The influence of urban fabric is taken into account in CALMET by assigning different land use categories to different values of physical parameters responsible for controlling energy and momentum exchange in the boundary layer. In Krakow, based on laser scanning data (GMES 2010) for the city area, nine urban categories were recognized. The roughness parameter z_0 which is responsible for wind behavior was determined from morphometric terrain features based on the average for every category height of roughness elements and building density (Grimmond & Oke 1999). Stability and mixing height, necessary for description of behavior of pollution in atmospheric boundary layer, were adjusted by comparison of modelled values with the results obtained from Sodar data for Krakow (Godłowska et al. 2012).

Lagrangian Gaussian puff modelling system CALPUFF (Scire et al. 2000b) used to model dispersion of pollution has the ability to simulate influence of meteorological fields prepared by meteorological part of the system on transport, transformation and removal of air pollutants. FAPPS uses algorithms describing the behavior of pollutants close to their source (buildings downwash, elongated puff formula), a pseudo-first-order

MESOPUFF II chemical mechanism to account for chemical transformations, and procedures describing the processes of dry deposition and wet removal of pollution.

FAPPS in providing short-term forecasts for Krakow and Lesser Poland

FAPPS developed in IMWM-NRI is used to forecast air quality for the city of Krakow and Lesser Poland region. The FAPPS is based on three modelling domains (Fig. 1): (i) external (EMEP), which takes into account inflow from outside of the region with a computational resolution of 50 km, fed by EMEP data, (ii) central (MP) with a computational resolution of 5 km, and (iii) internal (KR) with a computational resolution of 1 km. The MP and KR domains use data from the 2015 Emission Inventory for Lesser Poland, prepared for the needs of the Air Protection Program. Data on emission from heating sources, which is the input to the modelling system, was modified on June 7, 2019 to the state as of the end of December 2018 by including information on the liquidation of solid fuel furnaces in Krakow between 2015 and 2018. The final configuration of the system is a compromise between the quality and the level of detail of forecast and the speed of obtaining it and the convenience of operating the system. In the presented forecasting system, generalization of emission sources (except emission from point emitters) to the size of modelling grids was applied. All emission sources except high point emitters are treated as volume sources, with parameters depending on the type of emission source. Emission sources were assigned daily or on annual emission variability characteristic to them: for traffic sources it was a daily variability determined by available traffic studies, and for heating sources it was a forecast temperature-dependent variability based on the number of heating degree-hours (CIBSE TM41 2006). MEZOPUFF II chemical transformations were included in the modelling.

The FAPPS system is run once per day on AROME data from 0 UTC with a forecast horizon of 50 hours. Modelling results are sent daily to the website http://smog.imgw.pl as maps of predicted hourly and daily concentrations of SO_2, NO_2, PM_{10} and $PM_{2.5}$ for two consecutive days, separately for Lesser Poland and Krakow, as well as maps of predicted ventilation index (VI) for Krakow. VI maps provide a comprehensive assessment of pollutant transport conditions, both in the horizontal direction, for which the horizontal wind components are responsible, and in the vertical direction, for which the thermal stratification of the atmosphere and the mixing layer height are responsible. In addition to modelling results, the website also includes a package of information materials, describing health impacts of pollutants and the relationship between pollutant immission and meteorology, and a list of laws, regulations and other Polish and European documents providing the legal framework for air protection in Poland. In addition, the manner of preparing forecasts presented on the website is described and applicable air quality standards are listed.

Qualitative forecasts for the warning system

FAPPS has become the basis for providing information for Krakow on the probability of exceeding the PM_{10} concentration thresholds, which is important for warning system. Forecasts have been published since 2016, currently only in the heating season, which covers the months of January–March and October–December. They are validated every year. The qualitative forecast provided for the Krakow City Hall is prepared on the basis of hourly PM_{10} immission calculations with a spatial resolution of 1 km for the city area. For each grid point inside the city, an appropriate average PM_{10} is calculated from the hourly forecasts obtained from the FAPPS system (8-hour, daily). Assuming the city's administrative area as 100%, it is calculated in what percentage of the city the given concentration thresholds will be exceeded. The set of information on the forecasted air quality and the forecasted pollution dispersion conditions is automatically sent by e-mail to the Crisis Management Team of the Krakow City Hall.

The following are shared:

- information about the possibility of exceeding the value of 50 $\mu g/m^3$ by the area-averaged daily average PM_{10} for

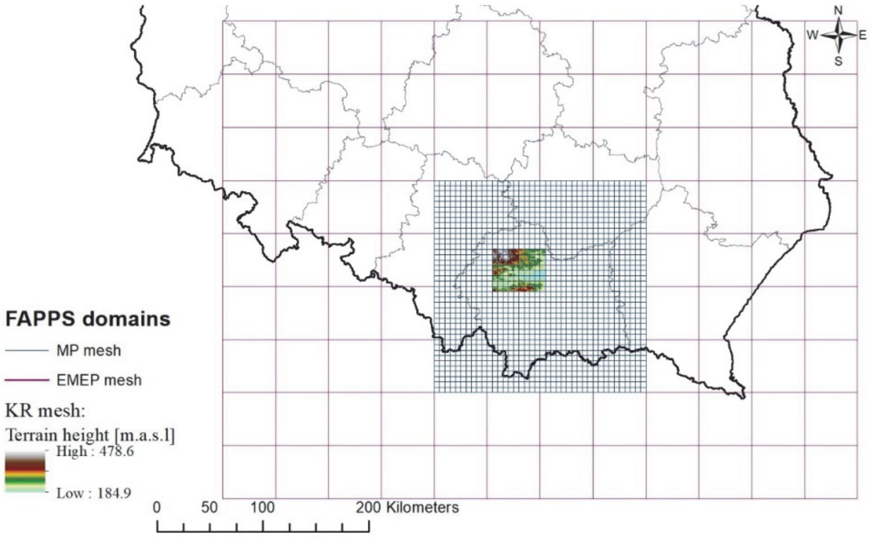

Fig. 1. Domains of the CALMET/CALPUFF models used in forecasting air pollution by the FAPPS system in Lesser Poland. External domain (EMEP), 12×9 grid, 50 km resolution, middle domain (MP) 40×40 grid, 5 km resolution, inner domain (KR) 50×40 grid, 1 km resolution, with terrain data

the districts of Krakow, with the names of the districts in which such exceedances are expected,

- forecast of the percentage share F_n of the city area in 6 concentration classes (<50; 50–100; 100–150; 150–200; 200–300; ≥ 300 μg/m^3) for three 8-hour periods of the day,
- forecasts of the ventilation index (VI) and meteorological parameters responsible for the dispersion of pollutants for the city area.

The decision on free transport in Krakow is made when the concentrations of PM$_{10}$ in selected concentration classes are occurring in an area greater than half of the city's area: for at least one 8-hour average, the threshold in the forecast is exceeding 150 μg/m^3, and additionally for another 8-hour average it is exceeding the threshold of 100 μg/m^3.

For alert systems, it is important to validate the forecast for periods with high concentrations of pollutants. In the case of the FAPPS, the quality of forecasts is verified using methods which take into account the periods of high concentration. In this method, assuming that the area of the city of Krakow is 100%, for each 8-hour average of PM10, the percentages of the area of the city of Krakow are calculated in six concentration classes with the concentration ranges of PM$_{10}$ particulate matter as described above. The percentage values are calculated for the forecast concentrations of PM$_{10}$ suspended dust (F_n was calculated on the basis of data from 327 grid points) and for the concentrations of PM$_{10}$ suspended dust measured at air quality monitoring stations located in Krakow (M_n was calculated based on data from 8 stations). The method developed at the Krakow City Hall compares the percentages of the city area within individual concentration classes F_n for the forecast with the percentages of measurements of stations in these classes M_n, summing up the common parts of both percentages for all n classes.

$$FC = \sum_{n=1}^{6} (\min(F_n, M_n)) \qquad (1)$$

where $\sum_{n=1}^{6} F_n = \sum_{n=1}^{6} M_n = 100\%$

For time periods when for two consecutive days forecast compliance FC is less than 50%, a detailed analysis of the causes of forecast errors is carried out. Measurements from all air quality monitoring stations of the Chief Inspectorate of Environmental Protection (CIEP) within the city are compared with the forecast of concentrations averaged for the grid cells in which these stations are located. Additionally, the forecasted and measured wind speed and direction are compared.

Results

Short-term forecasts for Lesser Poland

Quality assessment of the FAPPS forecasts is presented on the example of PM$_{10}$ concentrations measured at eight air quality monitoring stations of the Chief Inspectorate of Environmental Protection in Krakow.

Basic characteristics of measurement stations are presented in Table 1. The forecast of the quality of the FAPPS system was assessed for PM$_{10}$ concentrations in 2019 by comparing the results of operational modelling with the results of measurements at air quality monitoring stations in Krakow, separately for two periods, 1.01–6.06 and 7.06–31.12. To quantify the difference between observed and modelled values, Normalized Bias (NMB), Fractional Bias (FB), Normalized Mean Square Error and Root Mean Square Error (RMSE) were calculated as well as FAC2 index (Holnicki et al., 2017, Juda-Rezler 2010, ETC/ACM 2013). They are defined as:

$$NMB = \sum_{k=1}^{n}(C_{ok} - C_{mk}) / \sum_{k=1}^{n} C_{ok} \qquad (2)$$

$$FB = 2(\bar{C}_o - \bar{C}_m)/(\bar{C}_o + \bar{C}_m) \qquad (3)$$

$$NMSE = \sum_{K=1}^{n}(C_{ok} - C_{mk})^2 / n\bar{C}_o\bar{C}_m \qquad (4)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{k=1}^{n}(C_{ok} - C_{mk})^2} \qquad (5)$$

$$\text{FAC2 = fraction of data for which:} \quad 0.5 \leq C_{mk}/C_{ok} \leq 2 \qquad (6)$$

where C_{ok} and C_{mk} are observed and modelled concentrations, $\bar{C}_o$ and $\bar{C}_m$ are the mean values and n is the number of observations.

The presented results (Table 1) show the size of the variation in the observed and modelled PM$_{10}$ concentrations in the city. Concentrations much higher than at other stations are observed at the PL0012A traffic station located in a street canyon. All forecast quality indicators show a general improvement in forecast quality after the introduction of changes in emission. The average RMSE value for the entire city decreased from 23.9 μg/m^3 to 14.9 μg/m^3. The sign of FB and NMB shows that for most stations the forecasted average concentrations are slightly higher than the observed ones. The exception is the PL0012A traffic station. After introducing the emission changes, the FB values approached the optimal value of 0.00 at all stations except PL0012A and PL0735A and the share of correct forecasts described by the FAC2 index increased on average from 0.74 to 0.91.

Qualitative forecasts for Krakow

A big problem when verifying the quality of the forecasts is that the forecast value averaged in the mesh of the modelling grid is compared with the measured value characteristic for the location of the measuring station. The measured value is most influenced by the stations immediate surroundings and when there are many unevenly distributed emission sources, the station indications may not be consistent with the averaged concentration level for the entire mesh size (in FAPPS – 1 km^2). Especially, great care should be taken when analyzing data from monitoring station focused on traffic pollution, because they are located in close proximity to emission sources and as a result of that they are not representative for larger area

For each individual 8-hour averages, the FC values are calculated using Eq. 1. Table 2 present monthly averaged FC values for forecasts prepared operationally in 2019.

The method of validating the forecasts concerning the correctness of issued warnings was based on the indicators using the contingency table (Table 3) (Schlünzen and Sokhi 2008).

Table 1. Modelled $\overline{C}_m$ vs observed $\overline{C}_o$ [µg/m^3] PM$_{10}$ concentration, FAC2 index and RMSE calculated for eight GIOŚ monitoring stations in Krakow for two periods of the 2019 forecast with different emission input (1.01–6.06 in white, 7.06–31.12 in grey). Type station: T – Traffic, B – Background, I – Industrial.

Site	Site coordinates [^{0}]	Type	$\overline{C}_m/\overline{C}_o$	FAC2	RMSE [µg/m^3]	NMB	FB	NMSE
PL0012A MpKrakAlKras	50.058, 19.926	T	48.6/54.9	0.85	27.3	0.115	0.121	0.279
			33.8/44.9	0.89	21.9	0.245	0.279	0.316
PL0501A MpKrakBujaka	50.011, 19.949	B	45.7/39.9	0.76	20.9	-0.147	-0.136	0.238
			31.4/30.6	0.92	14.1	-0.021	-0.021	0.208
PL0641A MpKrakDietla	50.057, 19.946	T	51.1/40.5	0.79	27.4	-0.269	-0.236	0.363
			35.7/30.6	0.92	16.3	-0.169	-0.155	0.245
PL0642A MpKrakOsPias	50.099, 20.018	B	47.8/34.9	0.66	24.3	-0.381	-0.318	0.354
			33.5/28.1	0.90	12.6	-0.198	-0.179	0.173
PL0735A MpKrakSwoszo	49.991, 19.937	B	46.6/37.1	0.71	19.7	-0.270	-0.236	0.224
			33.2/25.3	0.88	14.9	-0.311	-0.268	0.266
PL0670A MpKrakWadow	50.101, 20.123	I	41.7/33.1	0.70	18.1	-0.259	-0.228	0.237
			29.5/25.8	0.94	10.7	-0.143	-0.133	0.152
PL0643A MpKrakZloRog	50.081, 19.895	B	47.2/39.4	0.74	24.8	-0.212	-0.191	0.330
			31.7/31.9	0.93	14.9	-0.001	-0.001	0.223
PL0039A MpKrakBulwa	50.069, 20.053	I	48.4/33.0	0.68	28.9	-0.473	-0.380	0.522
			31.3/30.6	0.92	14.0	-0.023	-0.022	0.207

Table 2. Monthly air pollution forecast compliance FC for 2019

Month	FC [%]				Monthly average PM$_{10}$ concentration from all measuring stations [µg/m^3]
	00:00–08:00	08:00–16:00	16:00–24:00	00:00–24:00	
January	69.8	79.3	65.2	71.5	47
February	60.9	65.6	52.3	**59.6**	56
March	69.7	84.3	82.8	78.9	38
April	67.8	92.9	76.4	79.0	36
May	61.6	96.9	85.3	81.3	23
June	76.6	96.1	96.8	89.8	26
July	95.7	97.3	95.9	96.3	23
August	94.7	97.2	96.3	96.0	24
September	88.5	94.4	91.7	91.5	24
October	79.8	84.1	69.1	77.7	38
November	67.9	80.5	67.5	72.0	40
December	74.3	78.6	67.9	73.6	41

Table 3. Contingency table (yes means daily $\overline{\mathrm{PM10}}$ >50 µg/m^3: for observations $\overline{\mathrm{PM10}}$ is daily PM$_{10}$ averaged for all monitoring stations, for forecast $\overline{\mathrm{PM10}}$ is daily PM$_{10}$ averaged in Krakow districts and the condition must be met for more than half of them)

	observed event yes	observed event no
forecast event yes	a	b
forecast event no	c	d

The indicators applied to access the model's capability of simulating extreme events are Hit Ratio (HR, optimal score is 1.00), False Alarm Ratio (FAR, optimal score is 0.00) and Probability of Detection (POD, optimal score is 1.00). They are defined as:

$$HR = \frac{a+d}{a+b} \tag{7}$$

$$FAR = \frac{b}{a+b} \tag{8}$$

$$POD = \frac{a}{a+c} \tag{9}$$

Table 4 presents the values of a, b, c and d from the contingency table as well as HR, FAR and POD values for individual months of 2019, for Krakow. In the months of May–August 2019 in Krakow, due to the lack of exceeding the threshold of 50 µg/m³ by the daily PM_{10} concentrations averaged for all measuring stations in the city, it was not possible to calculate the POD value. In the months of April, July–September, it was also not possible to determine the HR and FAR values. Therefore, in order to assess the quality of the forecast, the values of the HR, FAR and POD indicators were determined for the entire year and for the two periods of the heating season – from January to March and from October to December. For 2019 and separately for both heating season periods, Hit Rate values of 5.43, 2.18, and 3.48 were obtained, False Alarm Ratio FAR were 0.28, 0.24, and 0.26, and Probability of Detection POD values were 0.66, 0.75, and 0.74.

The significant source of errors are changes in emissions. Recently, there have been rapid changes in the method of heating apartments in Poland. In the case of Krakow, this process was accelerated by the resolution of the Krakow City Council on a total ban on burning coal and wood in the city after September 1, 2019. How important it is to use the most up-to-date emission inventory in air quality forecasts is shown, for example, for forecasts from the period of high PM_{10} concentrations between November 9 and 12, 2018 (Fig. 2). The results of two variants of 8-hour average PM_{10} forecasts presented as a percentage of the city area in subsequent concentration classes, prepared on the publicly available emission inventory (Fig. 2a) and the inventory supplemented with information on the decommissioning of some solid fuel furnaces (Fig. 2b), were compared with 8-hour PM_{10} concentrations measured at the CIEP air quality stations.

On November 11, 2018, based on the forecasts prepared on the basis of the emission inventory for the Lesser Poland region, a decision was issued on free urban transport in Krakow (Fig. 2a). This forecast significantly overestimated the PM_{10} concentration for the third 8-hour mean, which was decisive factor for the issuance of this decision. The introduction of changes to the emission inventory on the basis of the data provided by the Krakow City Hall on the number of active coal furnaces at the end of 2018 significantly improved the quality of forecasts for that day (Fig. 2b). The 8-hour concentrations of PM_{10} obtained on the basis of measurements at air quality monitoring stations presented in Fig. 2 show how large the variation in the concentration of pollutants in the city area can be. Particularly noteworthy are the concentrations of PM_{10} from the PL0012 station located in street canyon, focused on measuring traffic pollution, clearly different from the indications of other stations.

In the case of air quality forecasts, the most common causes of incorrect forecasts, apart from emission inventory, is the occurrence of inconsistencies in the forecast of the course of meteorological elements with the actual course of the weather and incorrect consideration of local conditions. The verification of the quality of forecasts for Krakow shows that the error in the forecast of wind speed and direction is responsible for the majority of errors in the forecast of immission. As indicated by the research carried out under the MONITAIR project (Bajorek-Zydroń et al. 2016), the impact of the wind speed value on the ability to remove pollutants outside the city, and thus on the level of pollutant concentrations in Krakow, is not linear. The minimum wind speed to ventilate the city is about 3 m/s measured outside the city. A relatively small error in the forecast of wind speed at wind speeds close to this threshold value usually results in large consequences for the forecast of concentrations. In Krakow, situated in the valley of the Vistula River flowing from the west to the east, and additionally blocked by hills on the west side, there are situations of a delayed reaction of the system to the increase in wind speed, resulting from obstructed air exchange from the city area. Moreover, because of the large size of the city and the characteristic height of convection in winter of about 200 m and a ground inversion height of about 300 m (Godłowska 2019), the space available for the accumulation of pollutants is so

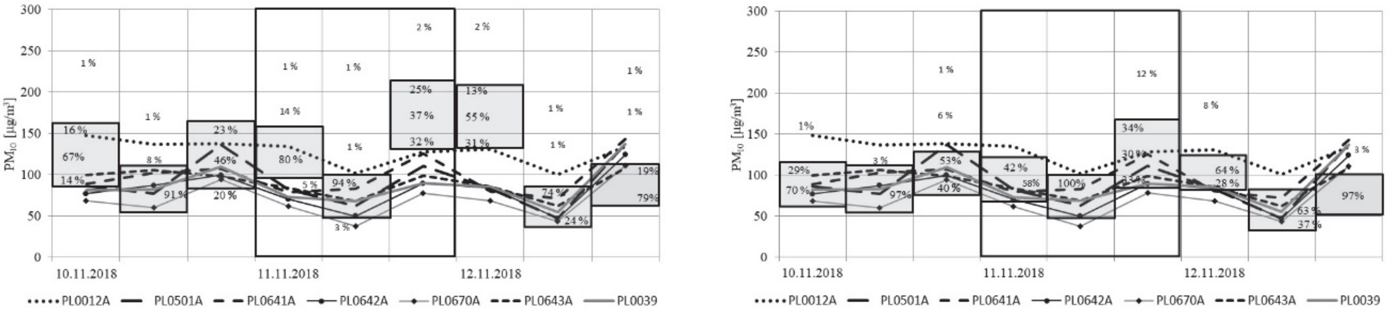

Fig. 2. Comparison of the percentages of the city area obtained from the forecast in individual concentration classes (boxes), with the average 8-hour PM_{10} measured at the CIEP air quality stations (continuous lines) in the period of 9–12 November 2018. Standard emission input (a) and updated number of active coal furnaces at the end of 2018 (b).

large that the increase in PM_{10} concentrations resulting from the reduction of wind speed is usually delayed in relation to the forecast. Both these processes can be seen in a detailed analysis of incorrect forecasts for the period of 11–15 December 2021 (Fig. 3).

For December 11, 2021, higher concentrations of PM_{10} were forecasted than was measured. The obvious reason for this were (for most of the day) higher than forecasted wind speeds. The absolute difference between forecasted and measured wind speeds was not large, but very significant considering its very low values. On 14 and 15 December, the predicted concentrations were lower than the measured ones. On December 15, the reason for the lowering of PM_{10} concentrations by the forecasts was a significant overestimation of the forecast wind speed, while the incorrect forecasts of concentrations on December 14 were probably caused by difficulties in removing pollutants from the city area at low speeds and changing wind direction.

Summary and conclusions

The article presents the possibilities of providing short-term forecasts with the use of the FAPPS air quality forecasting system. The paper presents an assessment of the quality of operational forecasts of PM_{10} concentrations from the FAPPS system for two forecast versions – a quantitative forecast of PM_{10} concentrations for Krakow and Lesser Poland (http://smog.imgw.pl) and a qualitative area forecast for PM_{10} concentrations developed for the support of the Crisis Management Center in Krakow.

The example of the quantitative forecasts from 2019 shows how the quality of the FAPPS system forecasts changes after taking into account the changes in emissions, resulting from the systemic decommissioning process of solid fuel stoves in Krakow. As a result of the emission changes introduced to the FAPPS on June 7, 2019 the forecast error values for NMB indicator decreased three times and for NMSE almost one

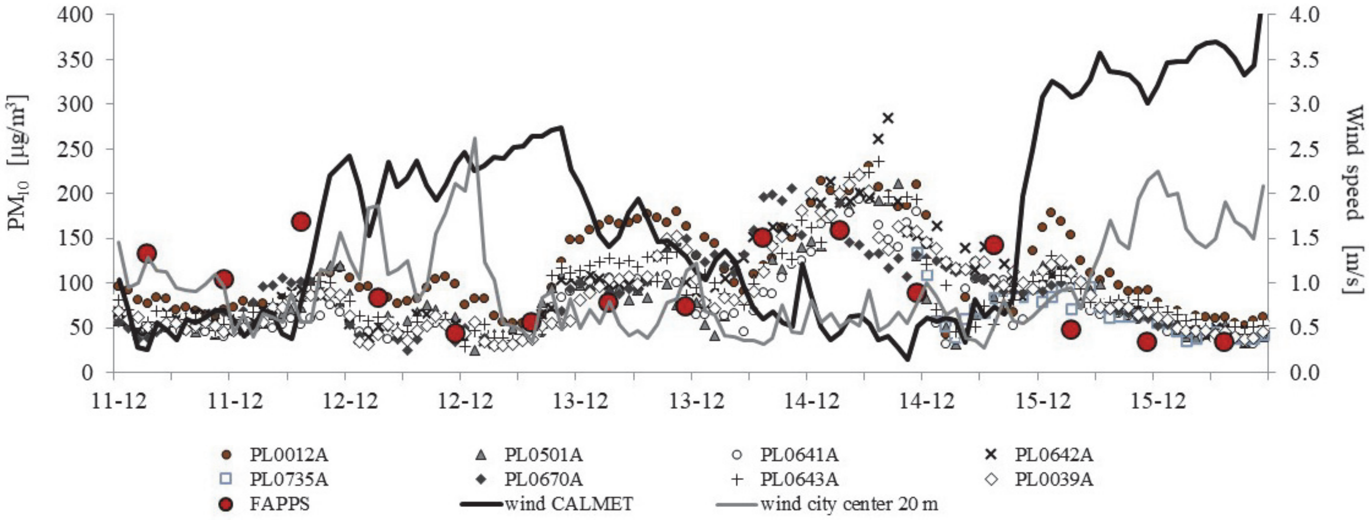

Fig. 3. Comparison of modelled (AROME/MM5/CALMET) and measured (on the roof of the AGH University of Science and Technology building in the city centre, approx. 20 m above ground) wind velocity against the measured hourly average PM_{10} (8 CIEP stations in the city area) and modelled averages 8-hour PM_{10} (averaged for the grid cells in which the measuring stations are located) on 11–15 December 2021

Table 4. Values of contingency table as well as Hit Rate HR, False of Alarm Ratio FAR and Probability of Detection POD on a monthly basis for 2019

Month	a	b	c	d	HR	FAR	POD
January	9	5	1	16	1.79	0.36	0.90
February	10	2	5	11	1.75	0.17	0.67
March	7	1	2	21	3.50	0.13	0.78
April	0	0	6	24	NA	NA	0.00
May	0	1	0	30	30.00	1.00	NA
June	0	2	0	28	14.00	1.00	NA
July	0	0	0	31	NA	NA	NA
August	0	0	0	31	NA	NA	NA
September	0	0	2	28	NA	NA	0.00
October	6	2	2	21	3.38	0.25	0.75
November	3	0	3	24	9.00	0.00	0.50
December	8	4	1	18	2.17	0.33	0.89

and a half times in the period June 7–December 31, 2019, in comparison to the period January 1–June 6, 2019. The share of correct forecasts defined by the FAC2 indicator changed in the same time on average from 0.74 to 0.91. The average RMSE value for the entire city decreased from 23.9 μg/m^3 to 14.9 μg/m^3 and the average FB value changed from -0.200 to -0.063.

In this paper the concept of a qualitative forecast of PM_{10} concentration level is also presented. In this forecast, the percentage share of the city area with PM_{10} concentrations in 6 concentration classes is given for three 8-hour periods of a day. The method of assessing the quality of such qualitative forecasts and the method of determining the causes of poor forecast quality are also shown. Basing on 8-hour period forecasts and taking into account the variability of PM_{10} concentrations in the area of the city allows us to assess their temporal and spatial variability during the day. It is also helpful in the process of issuing warnings. The information in which neighborhoods the predicted intra-district averaged daily PM_{10} concentrations are greater than 50 ug/m^3 allows us to assess the scale of the city populations exposure to elevated concentrations. It is also useful in analyzing the causes of forecast misses. Such an analysis carried out for several years of publishing the forecasts showed that the most common cause of misses in PM_{10} forecasts in Krakow are difficulties in forecasting wind speed in the city and a delay of several hours in response to changing wind conditions. As shown by the research carried out in Krakow (Godłowska & Kaszowski 2019), if in the FAPSS system one applies the parameterization of wind within canopy layer developed with the use of large-eddy simulation (Kanda et al. 2013), it will enable a better description of the behavior of meteorological parameters important for the transport of pollutants in the city. Due to the widespread availability of data from laser scanning, it is possible to determine the morphometric parameters of cities necessary for this parameterization.

The presented results of the forecast quality indicate that FAPPS system based on CALPUFF modelling system, performs well in short-term forecasting in cities where high spatial resolution of the results is required.

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Zastosowanie systemu FAPPS opartego na modelu CALPUFF w prognozowaniu krótkoterminowym jakości powietrza w Krakowie i Małopolsce

Streszczenie. Celem opracowania jest zaprezentowanie systemu FAPPS opartego o model dyspersji obłoku CALPUFF, wykorzystywanego do prognozowania krótkoterminowego jakości powietrza w Krakowie i Małopolsce. W artykule opisano system modelowania oraz przedstawiono dwie metody operacyjnego prognozowania jakości powietrza w Krakowie. Dla każdej z metod przedstawiono sposób przeprowadzenia oceny sprawdzalności prognoz. Jakość prognoz oceniano na podstawie stężeń pyłu zawieszonego PM_{10} mierzonych w ośmiu stacjach monitoringu jakości powietrza w 2019 roku w Krakowie. Oprócz standardowej prognozy ilościowej zaprezentowano jakościową prognozę obszarową, określającą udziały procentowe powierzchni miasta ze stężeniami PM_{10} w sześciu klasach stężeń. Dla obu metod pokazano jak dostosowanie emisji w systemie FAPPS do zmian emisji związanych z systemową eliminacją palenisk węglowych w Krakowie wpłynęło na jakość prognoz. Po zmianie emisji w dniu 7 czerwca 2019 średnia wartość RMSE spadła z 23,9 $\mu g/m^3$ do 14,9 $\mu g/m^3$, średnia wartość FB zmieniła się z -0,200 do -0,063, a udział poprawnych prognoz wzrósł średnio z 0,74 do 0,91. Jakość prognoz obszarowych oceniono dla całego roku 2019 i dwóch okresów sezonu grzewczego od stycznia do marca i od października do grudnia. Dla całego roku i obu okresów grzewczych uzyskano odpowiednio wartości Hit Rate równe 5.43, 2.18 i 3.48, wartości współczynnika fałszywych alarmów FAR równe 0.28, 0.24 i 0.26, a wartości prawdopodobieństwa wykrycia POD równe 0,66, 0.75 i 0.74. Przedstawione wyniki pokazują, że system FAPPS jest użytecznym narzędziem do modelowania zanieczyszczenia powietrza w zurbanizowanym i uprzemysłowionym terenie o skomplikowanej rzeźbie terenu.