TEMPERATURE INVERSIONS IN THE POLISH CARPATHIANS AND THEIR INFLUENCE ON AIR POLLUTION (CASE STUDY)

ANGELIKA PALARZ, ZBIGNIEW USTRNUL, AGNIESZKA WYPYCH
Jagiellonian University, 7 Gronostajowa Str., 30-387 Krakow, Poland

Temperature inversion, which is defined as a phenomenon of increasing air temperature with altitude, seems to be an important element of mountain climates and a critical factor affecting air quality. The primary goal of this study is to clarify the causes of high concentration of air pollutants occurring in the period 2005-2014 in the selected cities located in the Polish Carpathians. In order to fulfill this main objective, the detailed synoptic situation was analyzed and the relationship between meteorological factors and air pollution was determined. The study is based on data collected from the air quality monitoring network as well as the high resolution gridded data sets – CARPATCLIM and ERA-Interim reanalysis. The data consist of the daily mean concentration of particulate matter PM 10 and sulfur dioxide as well as daily the air temperature, relative humidity, cloud cover and wind characteristics. The results confirmed that the extremely high concentration of air pollutants was associated both with the local relief and the extremely unfavorable dispersion condition – a strong inversion layer occurred in the lower and the middle troposphere.

Keywords: air pollution, meteorological data, temperature inversion, Polish Carpathians

INTRODUCTION

Temperature inversions, which is defined as an increase in temperature with height, is commonly considered a negative phenomenon as it contributes to the incidence of frost, fog and mist generation as well as an increase in the concentration of air pollution (Jacobson, 2002). Areas particularly predisposed to the formation of surface-based inversion are mountain areas, in particular valleys and basins. Considering the impact of air pollution on the human health, leading to an increase in the incidence of respiratory infections as well as cardiovascular and oncological diseases (Pascal et al. 2013 Dholakia et al. 2014, Kim et al. 2015, Lu et.al. 2015), it seems to make sense to conduct research on the determinants of the occurrence of extremely high concentrations.

The issue of temporal and spatial variability in the occurrence of high concentrations of air pollutants and their synoptic conditions has been studied in different parts of the world. Among the most recent publications discussing this issue, works on urban areas of North America (Whiteman et al., 2014) and Europe (Unal et al. 2011; Knozová, 2012, Russo et al. 2014) as well as the quickly developing cities most affected by poor air quality in China (Wang et al. 2014) and India (Trivedi et al. 2014) deserve special attention. Regardless of the location, distribution of concentrations of suspended dusts - PM 10 and PM 2.5, they were characterized by distinct seasonal peaking in winter (December-February) when the atmosphere was more stable. In Poland, similar studies were conducted in relation to the industrialized areas of the Upper Silesian Industrial District (Niedźwiedź, Ustrnul, 1989, Leśniok et al. 2010; Radomski, Widawski, 2011) and Krakow (Bokwa, 2011, Bielec-Bąkowska et al. 2011). As should have been expected, even in these cases, concentrations of PM 10 and sulfur dioxide reached the highest levels in the period from December to February, which was associated with reduced insolation, low temperatures and increased air emissions from home furnaces. The maximum standards were exceeded mostly in low-gradient anticyclonic situations – central anticyclonic situation, anticyclonic wedges and circulation types with the air-flow from south (Leśniok et al. 2010; Bielec-Bąkowska et al. 2011).

Another group of studies constitute a detailed analysis of severe pollution episodes, whose aim was to determine the relationship of air quality with synoptic conditions and selected meteorological elements (Kukkonen et al., 2005; Malek et al. 2006, Fu et al. 2008). In addition, parts of articles attempt to identify potential sources of inflow of undesirable dusts and gases (Ji et al., 2012; Lee et al., 2013; Segura et al., 2013). Despite widespread interest in the topic discussed, to date research on air quality has focused almost exclusively on large cities. The exception is the work of Malek et al. (2006), which discussed the meteorological and environmental conditions of the occurrence of one of the worst air pollution episodes in the United States. Extremely high concentrations of PM 2.5, which were recorded in January 2004 in Logan with a population of about 100,000 people, were associated with both the location of the town in the form of a highly concave area, and weather conditions hindering the dispersion of air pollutants – the occurrence of air temperature inversion enhanced by a strong high pressure system and persistence of snow cover.

This paper refers to the study of air quality in relatively small cities located in areas of concave terrain forms. Its main objective is to clarify the causes of high concentrations of air pollutants in selected cities located in the Polish Carpathians - Nowy Sącz, Zakopane and Żywiec, as well as comparatively in Krakow. This work is a case study and includes an analysis of the period from 23 January to 2 February 2006, i.e. the strongest episode of pollution recorded in southern Poland in the years 2005-2014. The main objective of the research paper will be reached through a detailed assessment of the synoptic situation and an analysis of the relationship between the air quality and selected meteorological elements.

Location of the study area

The spatial extent of the study covers an area of four mesoregions located in the western part of the Polish Carpathians - Valley of the Vistula River, Sądecka Basin, Podtatrzańska Valley and Żywiecka Basin (Kondracki, 2002). They represent concave forms surrounded by hills and mountain peaks. Their bottoms are located at altitudes of 180-300 m above sea level in the Vistula Valley, 280-300 m above sea level in the Sądecka Basin, 340-500 m above sea level in the Żywiecka Basin to 750-1000 m above sea level in the Podtatrzańska Valley and the height differences oscillate in the range of 500 to 1600 m (Fig. 1). The topography of the areas in question is a very favorable factor for the stagnation of cool air in the basins and in the formation of so-called 'cold air pools', as well as the occurrence of inversion layers that inhibit the mixing of air.

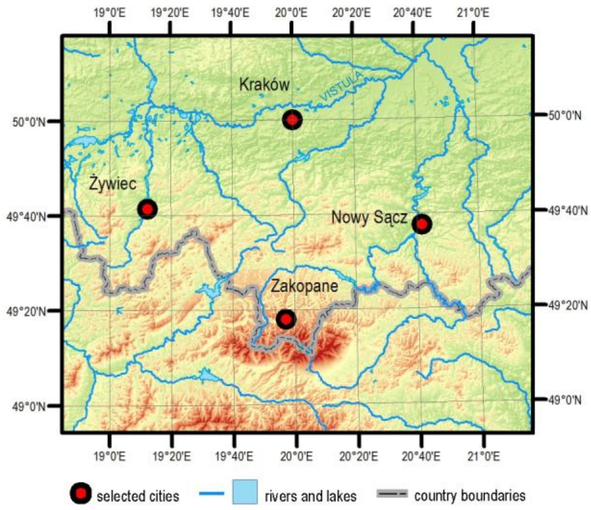

Fig. 1. Location of the study area

Moreover, with the exception of the Żywiecka Vallley, there are no significant bodies of water in the areas concerned. Such conditions reduce the likelihood of air circulation associated with differential heating and cooling rates for land and water. The number of inhabitants of the cities selected for analysis amounts to 760,000 for Krakow, 85,000 for Nowy Sącz and about 30,000 each for Zakopane and Żywiec.

MATERIALS AND METHODS

The research was conducted on the basis of average daily concentrations of PM 10 and sulfur dioxide obtained from the information portals Voivodship Inspectorates for Environmental Protection in Krakow and Katowice for the stations of Nowy Sacz, Zakopane, Żywiec and for comparison the station located along the communication lanes in Krakow (http://monitoring.krakow.pios.gov.pl/; http://monitoring.krakow.pios.gov.pl/).

The synoptic conditions were marked using the lower synoptic maps (http://www.knmi.nl/) and ERA-Interim reanalysis with a spatial resolution of 0.125×0.125º (http://www.ecmwf.int/en/research/climate-reanalysis/era-interim). The temporal and spatial values of selected meteorological elements were developed based on the high resolution gridded data sets - CARPATCLIM with a spatial resolution of 0.1×0.1º (http://www.carpatclim-eu.org/). In addition, for the purposes of verifying the obtained results, the data from the stations Krakow (Botanical Garden), Nowy Sącz, Zakopane and Kasprowy Wierch, as well as the results of aerological soundings of Poprad-Gánovce (http://weather.uwyo.edu/) and upper air charts (http://www1.wetter3.de/) were analyzed.

RESULTS

Concentration of particulate matter PM 10 and sulfur dioxide

Based on the analysis of mean daily concentrations of PM 10 and sulfur dioxide from the years 2005 to 2014, it has been determined that the acceptable standards – 50 μg.m^{-3} and 125 μg.m^{-3}, respectively – were often exceeded, especially in the case of PM 10. These situations most often occured during the winter season i.e. from December to February, which is the subject of the separate analysis. Given the importance of the issues, focus was placed on a detailed examination of the heavy pollution episodes in the studied multiplicity, which occurred in the period from 13 January to 2 February 2006. As shown in Fig. 4., at all stations the concentration of PM 10 exceeded the accepted limit permanently at all measuring stations. However, the maximum concentration values for PM 10 did not appear simultaneously at all the analyzed stations. They were accordingly recorded in Nowy Sącz on 24 and 29 January (519 μg.m^{-3} and 500 μg.m^{-3}), in Zakopane on 25 and 27 January (171 μg.m^{-3} and 162 μg.m^{-3}), and in Żywiec on 29 January (505 μg.m^{-3}). It is worth noting that the average daily value of the concentration of PM 10 exceeded the value of the analyzed episode listed at the communication station in Krakow for 9 days in the case of Nowy Sącz and 7 days for Żywiec, respectively. A similar situation did not occur in Zakopane.

The concentration of sulfur dioxide was characterized by a high spatial differentiation between the stations selected for analysis. Throughout the entire period broken down in Fig. 3, significantly higher levels of the characteristics mentioned were recorded in Żywiec, which may be related to local emissions. The accepted standard of daily average concentration was exceeded on January 24 in Nowy Sącz and throughout the entire measurement period in Żywiec.

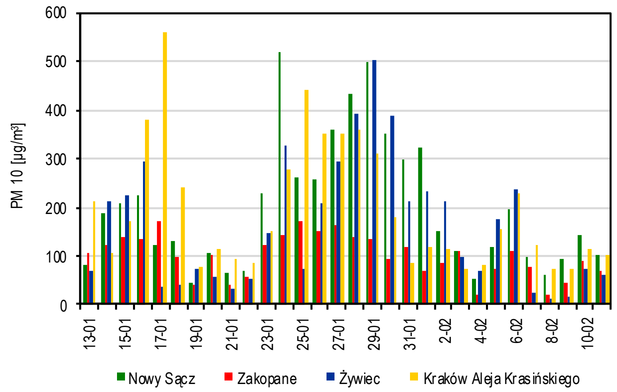

Fig. 2. The daily average particulate matter PM 10 concentration in selected cities from 13.01. to 11.02.2006

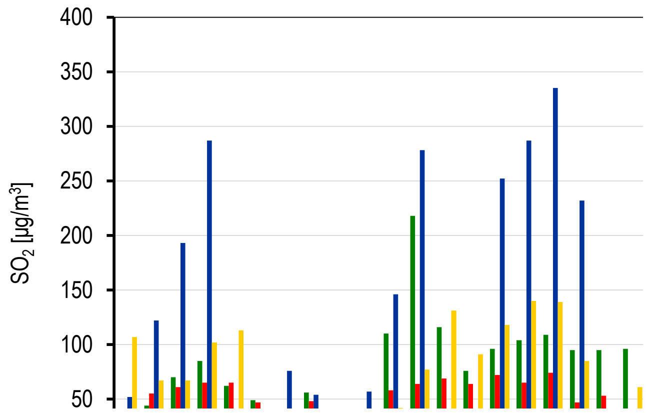

Fig. 3. The daily average sulfur dioxide concentration in selected cities from 13.01. to 11.02.2006

Synoptic situation

The occurrence of extremely high concentrations of air pollutants in the period from January 22 to February 2, 2006 was conditioned by the retention of a high pressure systems over a vast area of Central Europe. The high-pressure area originally discussed was on the Kola Peninsula, moved relatively quickly to the south, systematically increasing its spatial reach. On January 22 its center was located in the Gulf of Riga, on January 23 over northern Poland, and January 24 over western Ukraine. The atmospheric pressure in its center at the time was over 1,045 hPa (Fig. 4). Starting on January 25, the anticyclonic center mentioned began to move towards the east starting on January 28 leaving Central Europe under the influence of a vast anticyclonic wedge genetically related to the high-pressure zone from the British Isles, in the center of which atmospheric pressure exceeded 1,035 hPa (Fig. 4.). Despite the low pressure systems developing over the Scandinavian Peninsula, southern Poland remained within the impact region of the British high-pressure zone until 3 February, which eventually gave way to a furrow of low pressure associated with a shallow cyclonic center hovering over eastern Ukraine.

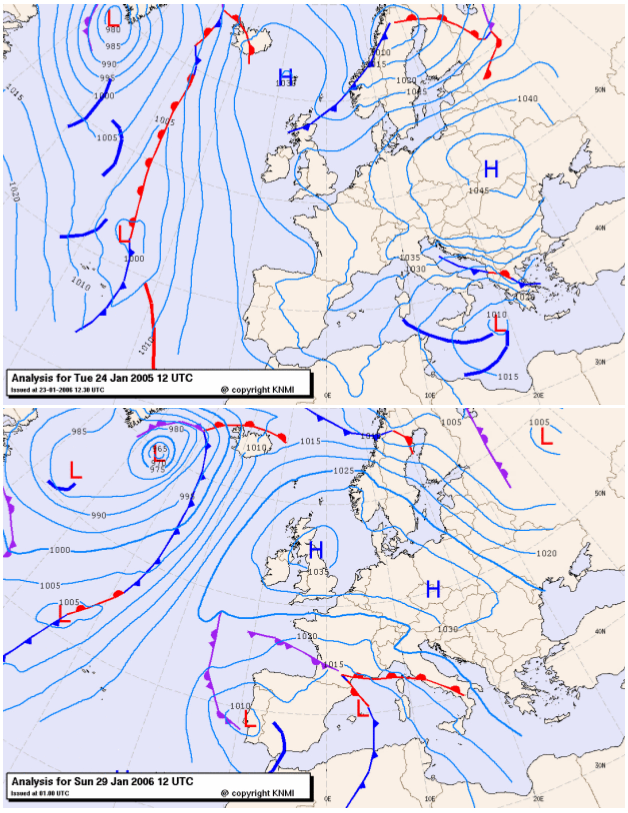

Fig. 4. Distribution of atmospheric pressure at sea level at 00 UTC 24 January (upper map) and 29 January (lower map) (http://www.knmi.nl/)

The center of high pressure that shaped the weather conditions on January 24 over Central Europe was noted mainly in the lower layers of the troposphere - at isobaric levels of 925 hPa and 850 hPa, while in the middle troposphere - at isobaric levels of 700 hPa and 500 hPa the vast anticyclonic wedge associated with the zone of high atmospheric pressure occurring over northern Africa played an important role. At isobaric levels of 700 hPa and 500 hPa, said anticylonic wedge was accompanied by a low-pressure system from the center of the Balkan Peninsula, which in the middle troposphere resulted in the confluence of relatively warm air masses over central Europe. The British high-pressure zone, which affected the weather situation in Europe starting on January 28 was characterized by a similar vertical range. It made its mark mainly in the lower troposphere - at isobaric levels of 925 and 850 hPa, and in the middle troposphere - at levels of 700 hPa and 500 hPa - the region of the British Isles was under the influence of the anticyclonic wedge genetically linked with the Azores high-pressure zone, which was accompanied by the low-pressure zone from the Iberian Peninsula. At isobaric levels of 700 hPa and 500 hPa, Central Europe remained at the time in the border zone between the above-surging surface of geopotential over the British Isles and its rapidly declining height zone heading northeast. The consequence of the occurrence of relatively warm air masses in the middle troposphere during the period of analysis was the slow subsidence of its particles and an increase in their temperature, thereby generating inversion layers in the lower and middle troposphere. According to the data acquired from ERA-Interim reanalysis and aerological soundings at the Poprad-Gánovce station, on January 24 they reached the levels of 675 hPa and on 29 January a level of 700 hPa (Fig. 5.).

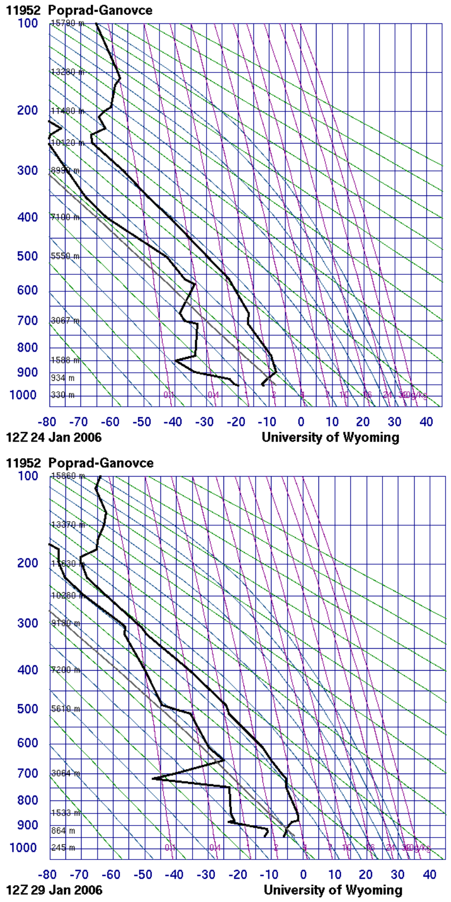

Fig. 5. Atmospheric sounding from Poprad-Gánovce station at 12 UTC on 24 January (top figure) and 29 January (bottom figure) (http://weather.uwyo.edu/)

The presented synoptic conditions are a common situation conducive to the presence of very high concentrations of air pollutants in the Polish Carpathians, especially during the winter season (Palarz, 2014). The long-term persistence of high pressure centers is conducive to the occurrence of temperature inversions associated with intensive air subsidence and its stagnation in concave terrain forms - valleys and basins. At the same time, the analysis of the full series of measurements shows that the cause of inverion layers may be more complex. For example, very high concentrations of PM 10 occurring on 21 January 2013 in Zakopane were conditional upon the occurrence of an advection inversion. The then incoming warmer air masses, while colder and heavily polluted masses simultaneously remained in the Podtatrzańska Valley, they halted the mixing process leading to higher concentrations of air pollutants in Zakopane (244 $\mu g.m^{-3}$) than in Krakow (88 $\mu g.m^{-3}$).

Meteorological factors

Temperature conditions accompanying such high concentrations of air pollutants were analyzed in relation to the average daily temperature and daily maximum and minimum temperatures obtained through the CARPATCLIM database. From 23 January until 2 February, the average daily temperature ranged from -23.3 °C to -4.1 °C in Nowy Sącz, from -19.9 °C to 1.1 °C in Zakopane and from -21.3 °C to -3.2 °C in Żywiec. Significantly lower values of the discussed characteristic were listed in the initial phase of the pollution episode, i.e. from 22 to 25 January. Similar dependences was observed for both the minimum and maximum temperature. The absolute air temperature minima during the analyzed period occurred on January 23 in Zakopane (-25.7 °C) and January 24 in Nowy Sącz (-29.1 °C) and Żywiec (-27.2 °C) respectively (Fig. 6.). A comparison of PM 10 and sulfur dioxide with the time distribution of all these characteristics suggests a relationship between the temperature conditions and air quality – the occurrence of days of high concentrations of selected pollutants coincided with the lowest values of the analyzed temperature characteristics.

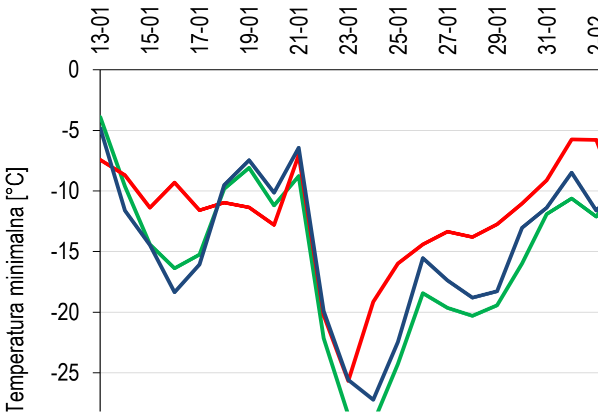

Fig. 6. The temporal variability of the minimum temperature on 13.01-11.02.2006 – according to the CARPATCLIM database

The spatial distribution of the minimum temperature during the analyzed episode pointed to the presence of specific "cold pools" located in concave formations in the Western Carpathians. In extreme cases – on 24 and 29 January – the recorded minimum temperature at the peaks of the Tatras was over 10 °C higher than in the studied basins. The presence of surface-based inversions - defined as negative temperature gradient between the selected grid point and a representative point for Kasprowy Wierch - was observed in the period from January 23 to February 1 (Fig. 7.). The evaluation of the lapse rate relationship with the concentration of air pollutants revealed the existence of statistically significant negative relationship between the analyzed variables at 0.01. The persistence of inversion layers was conducive to the deterioration of the air quality favored in the basins and the growth intensity of temperature inversion significantly influenced the increase in concentration of all air pollution taken into account. Depending on the measuring station, the value of Pearson's correlation coefficient oscillated in the range appropriate for PM 10 from -0.78 to -0.81, and for sulfur dioxide from -0.76 to -0.82.

The relative air humidity was characterized by a strong variation in time and space in the analyzed period ranging between 50 to 95 % (Fig. 8). Zakopane was characterized by its relatively low values. During the period of highest concentration of air pollutants, relative humidity ranged from 60 to 80 % depending measuring station - the lower values were observed in Zakopane and the higher values in Nowy Sącz. However, no clear relation has been identified between relative humidity and its air quality.

Cloudiness was also characterized by significant differences across time and space. According to the CARPATCLIM database, days with high levels of PM 10 and sulfur dioxide were accompanied by low cloudiness. The data of weather stations indicate the presence of fog and mist during this period, especially intense in the morning. Considering the anemological conditions, the accompanied analyzed pollution episode was accompanied by mainly weak wind from the south-western sector (Fig. 9.). The flow of air from the south and south-west from the hills surrounding the concave formations was expected to further increase the stability of persistent inversion layers located there.

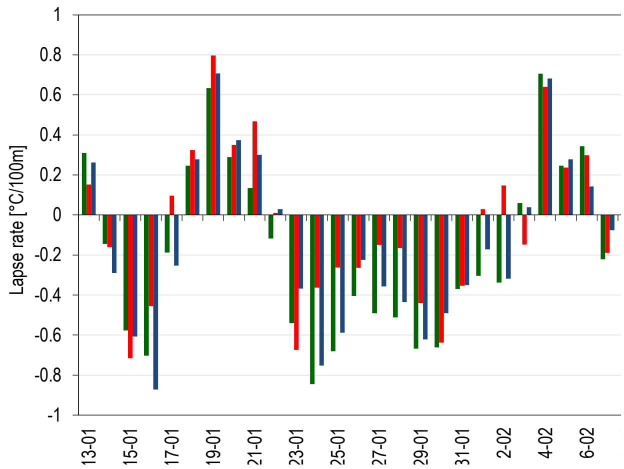

Fig. 7. The temporal variability of the temperature gradient between the selected measurement station and grids representative of Kasprowy Wierch on 13.01-11.02.2006 – according to the CARPATCLIM database

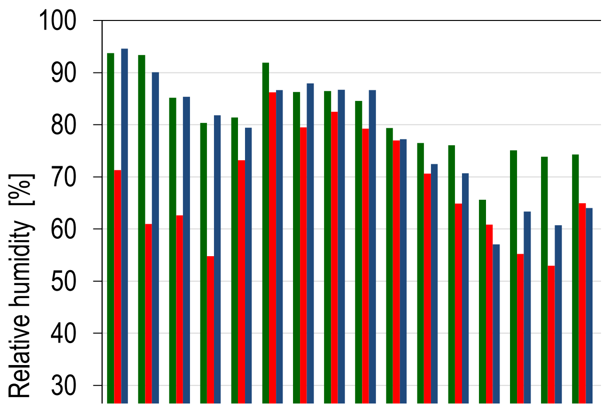

Fig. 8. The temporal variation in relative humidity in days 13.01-11.02.2006 – according to CARPATCLIM database

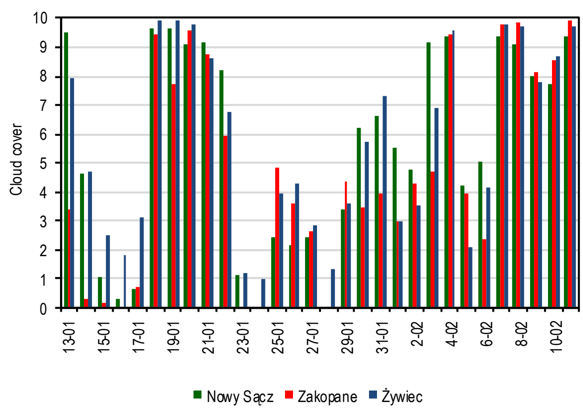

Fig. 8. The temporal variability of cloudiness on 13.01-11.02.2006 – according to CARPATCLIM database

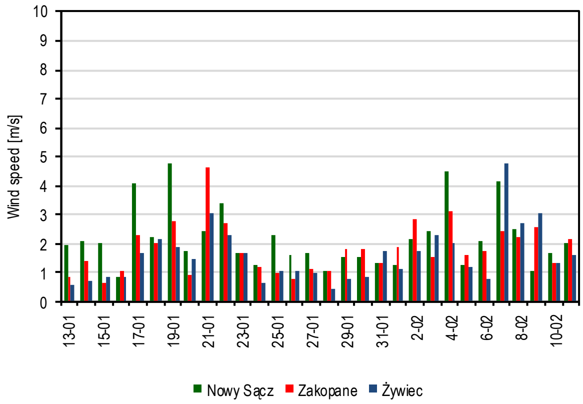

Fig. 9. The temporal variability of wind speed on 13.01-11.02.2006 – according to CARPATCLIM database

CONCLUSIONS

Similarly to the paper by Fu et al. (2008) mentioned in the introduction, the persistence of air pollution episodes were associated with the occurrence of extensive high pressure centers in the case of the Carpathian Mountains as well. They were conducive to the subsidence of air particles and the increase in stability of the atmosphere, which in turn led to the subsidence inversion in the lower and middle troposphere.

In addition, similarly to Logan (Malek et al. 2006), slight cloudiness and low wind speed, as well as snow cover increasing the reflected solar radiation contributed to intense heat radiation from the substrate and the formation of radiation inversion enhanced probably by katabatic run-off from the surrounding mountain areas.

As previously mentioned, the causes of air temperature inversion shown above that contribute to high levels of air pollution are the most common in the Western Carpathians. Occasionally, however, they can also appear in situations of abrupt atmospheric front transition. The influx of warmer air masses in the middle troposphere often inhibits the dissipation of remaining inversion layers in the basins leading to the further stagnation of air pollution.

Comparing PM 10 and sulfur dioxide in Nowy Sącz, Zakopane, Żywiec and Krakow proves that air quality is not only conditioned by the degree of urbanization and local emissions. The greatest significance should be attributed to the current synoptic situation and local relief. In addition, the lower the concentration of these pollutants in Krakow during the reported episode could be determined by, among others, the development of an urban heat island effect and the associated increased heat emission layers for the easy dissipation of inversion layers. However, this problem requires attention in the course of further research.

In conclusion, it must be stated that occasionally addressing the air quality problem in relatively small cities and towns located in the concave formations of land in the scientific literature indicates that the seriousness of the problem is underestimated. According to the authors, due to the negative impact of air pollution on human health and life, this issue requires increased attention so as to broaden the operation of the air quality monitoring network, as well as scientific studies that discuss the situations conducive to the presence of high concentrations of air pollutants.

Acknowledgement

This research was partially made thanks to the Jagiellonian University grants – K/ZDS/004855 and K/DSC/003024.

LITERATURE

Bielec-Bąkowska Z., Knozová G., Leśniok M., Matuszko D., Piotrowicz K., 2011, High suspended dust concetration in Brno, Sosnowiec and Krakow (the year 2009 as an example), Prace Geograficzne UJ, 126, 67-84.

Bokwa A., 2011, Influence of the air temperature inversions on the air pollution dispersion conditions in Krakow, Prace Geograficzne UJ, 126, 41-51.

CARPATCLIM: http://www.carpatclim-eu.org/ (access March 2015).

Deutscher Wetterdienst: http://www1.wetter3.de/ (access December 2014).

Dholakia H. H., Bhadra D., Garg A., 2014, Short term association between ambient air pollution and mortality and modification by temperature in five Indian cities, Atmospheric Environment, 99, 168-174.

ERA-Interim reanalysis: http://www.ecmwf.int/en/research/climate-reanalysis/era-interim (access January 2015).

Fu Q., Zhuang G., Wang J., Xu Ch., Huang K., Li J., Hou B., Lu T., Street D. G., 2008, Mechanism of formation of the heaviest pollution episode ever recorded in the Yangtze River Delta, China, Atmospheric Environment, 42, 2023-2036.

Jacobson M. Z., 2002, Atmospheric pollution: History, science and regulation, Cambridge University Press, New York.

Ji D., Wang Y., Wang L., Chen L., Hu B., Tang G., Xin J., Song T., Wen T., Sun Y., Pan Y., Liu Z., 2012, Analysis of heavy pollution episodes in selected cities of northern China, Atmospheric Environment, 50, 338-348.

Kim K. H., Kabir E., Kabir S., 2015, A review on the human health impact of airborne particulate matter, Environment International, 74, 136–143.

Knozová G,. 2012, Zanieczyszczenie pyłem zawieszonym na Morawach południowych przy różnych typach cyrkulacji [in:] Z Bielec-Bąkowska., E. Łupikasza, A.Widawski (eds.) Rola cyrkulacji atmosfery w kształtowaniu klimatu. Kat. Klimat., Wydz.Nauk o Ziemi, Uniw. Śl., Sosnowiec: 287–297.

Kondracki J., 2002, Geografia regionalna Polski, Wydawnictwo Naukowe PWN, Warszawa.

Kukkonen J., Pohjola M., Sokhi R. S., Luhana L., Kitwiroon N., Fragkou L., Rantamäki M., Berge E., Ødegaard V., Slørdal L. H., Denby B., Finardi S., 2005, Analysis and evaluation of selected local-scale PM10 air pollution episodes in four European cities: Helsinki, London, Milan and Oslo, Atmospheric Environment 39, 2759–2773.

Lee S., Ho Ch., Lee Y.G., Choi H., Song Ch., 2013, Influence of transboundary air pollutants from China on the high PM10 episode in Seoul, Korea for the period October 16-20, 2008, Atmospheric Environment, 77, 430-439.

Leśniok M., Małarzewski Ł., Niedźwiedź T., 2010, Classification of circulation types for Southern Poland with an application to air pollution concentration in Upper Silesia, Physics and Chemistry of the Earth, 35, 516-522.

Lu F., Xu D., Cheng Y., Dong S., Guo Ch., Jiang X., 2015, Systematic review and meta-analysis of the adverse health effects of ambient PM 2.5 and PM 10 pollution in the Chinese population, Environmental Research, 136, 196-2004.

Niedźwiedź T., Ustrnul Z., 1989, Wpływ sytuacji synoptycznych na występowanie nad Górnośląskim Okręgiem Przemysłowym typów pogody sprzyjającej koncentracji lub rozpraszaniu zanieczyszczeń powietrza, Wiadomości IMGW, 12,1-2, 31-39.

Malek E., Davis T., Martin R. S., Silva P. J., 2006, *Meteorological and environmental aspects of one of the worst national air pollution episodes (January, 2004) in Logan, Cache Valley, Utah, USA, Atmospheric Research, 79, 108-122.*

Palarz A., 2014, Variability of air temperature inversions over Cracow in relation to the atmospheric circulation, Prace Geografoczne UJ, 138, 29-43.

Pascal M., Corso M., Chanel O., Declercq C., Badaloni C., Cesaroni G., Henschel S., Meister K., Haluza D., Martin-Olmedo P., Medina S., 2013, Assessing the public health impacts of urban air pollution in 25 European cities: Results of the Aphekom project, Science of the Total Environment 449, 390–400.

Radomski J., Widawski A., 2011, Influence of circulation types on the SO2 concentraation in the Silesian Upland, Prace Geograficzne UJ, 126, 53-65.

Royal Netherlands Meteorological Institute Ministry of Infrastructure and the Environment: http://www.knmi.nl/ (access June 2015).

Russo A., Trigo R. M., Martins H., Mendes M., 2014, NO2, PM10 and O3 urban concentrations and its association with circulation weather types in Portugal, Atmospheric Environment, 89, 768-785.

Segura S., Estellés V., Esteve A. R., Utrillas M. P., Martínez-Lozano J. A., 2013, Analysis of a severe pollution episode in Valencia (Spain) and its effect on ground level particulate matter, Journal of Aerosol Science, 5641–52.

Trivedi D. K., Ali K., Beig G., 2014, Impact of meteorological parameters on the development of fine and coarse particles over Delhi, Science of the Total Environment, 478, 175-183.

Unal Y. S., Toros H., Deniz A., Incecik S., 2011, Influence of meteorological factors and emission sources on spatial and temporal variations of PM10 concentrations in Istanbul metropolitan area, Atmospheric Environment, 45, 5504-5513.

University of Wyoming, Department of Atmospheric Science: http://weather.uwyo.edu (access December 2014).

Voivodship Inspectorate for Environmental Protection in Katowice: http://monitoring.katowice.wios.gov.pl/ (access October 2014).

Voivodship Inspectorate for Environmental Protection in Krakow: http://monitoring.krakow.pios.gov.pl/ (access October 2014).

Wang Y., Ying Q., Hu J., Zhang H., 2014, Spatial and temporal variations of six criteria air pollutants in 31 provincial capital cities in China during 2013 – 2014, Environment International 73, 413–422.

Whiteman C. D., Hoch S. W., Horel J. D., Charland A., 2014, Relationship between particulate air pollution and meteorological variables in Utah's Salt Lake Valley, Atmospheric Environment, 94,742-753.