GEOGRAPHY AND TOURISM, Vol. 9, No. 1 (2021), 71-81, Semi-Annual Journal
eISSN 2449-9706, ISSN 2353-4524, DOI: 10.34767/GAT.2021.09.06

Paweł Druet[1], Paweł Wiśniewski[2]

[1] University of Gdansk, Students' Research Group of Geographers

[2] University of Gdansk, Department of Landscape Research and Environmental Management

ORCID: [1] https://orcid.org/0000-0002-5541-4572, [2] https://orcid.org/0000-0002-3445-2000

Corresponding author: Paweł Druet, email: paweldruet@gmail.com

Foehn wind as a factor affecting the air quality in the town of Zakopane

Abstract: Zakopane, the largest town in the Tatra County, located at the foot of the northern slope of the Tatra Mountains, i.e. the highest mountains in Poland, is characterised by the frequent occurrence of high atmospheric air pollutant concentrations, and the resulting poor aerosanitary conditions, particularly in winter months. The aim of this study is to demonstrate the relationship between the occurrence of a foehn-type wind, which is called *halny* in the area of the Tatra Mountains and the Podhale region, and changes in concentrations of pollutants found in the atmospheric air in Zakopane, based on the example of PM2.5 and PM10 particulate matter. The concentrations of the analysed substances in the town of Zakopane were compared on the days when foehn wind occurred on the Kasprowy Wierch peak and on the days when the foehn wind did not occur on the above-mentioned peak. The study initially showed the existence of a relationship between *halny* velocity on the Kasprowy Wierch peak (1987 m a.s.l) and its effects on the air quality in the town of Zakopane. Decreases in concentrations of PM2.5 and PM10 particulate matter were noted on the days when foehn wind velocity on the Kasprowy Wierch peak was equal to or exceeded 20 $m \cdot s^{-1}$.

Keywords: foehn wind, *halny* wind, Zakopane, Sub-Tatra Depression, Zakopane Depression, air pollution, PM2.5, PM10, ventilation

1. Introduction

Poor aerosanitary conditions are among major environmental problems faced by many urbanised and rural areas in numerous places in the world, *inter alia*, in Poland. It is a cause of many health problems, including death, to people living in the areas with polluted air. A 2018 report of the Supreme Audit Office indicated that air pollution-related diseases contributed to the deaths of 46.000 people in Poland *per annum* (Ochrona powietrza przed zanieczyszczeniami, 2018). One of such places is Zakopane, the largest town located at the foot of the northern slope of the Tatra, the highest Polish mountains and the only ones featuring Alpine character (https://tpn.pl/poznaj). It is one of the most important and popular points on the tourist map of Poland as well as Central Europe, both in summer and in winter. It is characterised by frequently occurring high concentrations of harmful substances in the atmospheric air, particularly in winter months. This is due to geomorphological and climatic factors in parallel with the high intensity of activities which are the sources of air pollution. At the same time, one of the features characterising the climate of the study area is the occurrence of a foehn-type wind, which in the Tatra Mountains and in the Podhale region is called *halny*. It is a gusty wind which reaches high velocities (Trepińska, 2002). This wind is characterized by a wide spectrum of impact on the entire geographical environment of the Tatra Mountains and the Podhale region. One of the best known effects of its occurrence in the above-mentioned areas are large-scale windfalls and windthrows in the Tatra forests. This wind has been a subject of many studies in Poland, but only one of them concerned the foehn wind's impact on air quality. Sekuła et al. (2021) studied this problem for the city of Cracow. The impact of foehn winds on air quality is more commonly studied in other regions of the world, *inter alia*, in the Alpes (Natale et al., 1999; Seibert et al., 2000; Weber and Prévôt, 2002; Bo et al., 2020) or in China (Li et al., 2015, 2020; Ning et al., 2019). There is no research concerning the impact of the foehn wind on the air quality in the town of Zakopane.

The purpose of this study is to demonstrate the relationship between the occurrence of foehn wind and changes in pollutant levels, based on the example of PM2.5 and PM10 particulate matter found in the atmospheric air in the town of Zakopane.

2. Geographical background and research methodology

2.1. Study area

The study area is Zakopane, the largest town in the region and the seat of Tatra County authorities, located in the southern part of the Małopolskie Voivodeship. Its main part is located within the physico-geographical microregion of Zakopane Depression, which is part of the Sub-Tatra Depression mesoregion (514.14) (Krąż and Wójcik, 2015; Solon et al., 2018). This is an area characterised by the location on lower absolute heights and terrain concavity as compared to the Fore-Tatra Foothills (514.13) surrounding it from the North, and to the Tatra Mountains surrounding it from the South, divided into three mesoregions: Reglowe Tatra Mountains (514.54), High Tatra Mountains (514.53), and Western Tatra Mountains (514.52), which together form the macroregion of the Tatra Range (514.5) (Fig. 1) (Solon et al., 2018).

In 2019, the population of Zakopane municipality was 27.010 (https://krakow.stat.gov.pl/vademecum/vademecum_malopolskie/portrety_gmin/powiat_tatrzanski/zakopane.pdf). There is no precise data indicating the number of tourists visiting the town every year, but the exceptional and constantly growing popularity of Zakopane among tourists makes this number the highest in Poland. The scale of this phenomenon is shown by the Tatra National Park

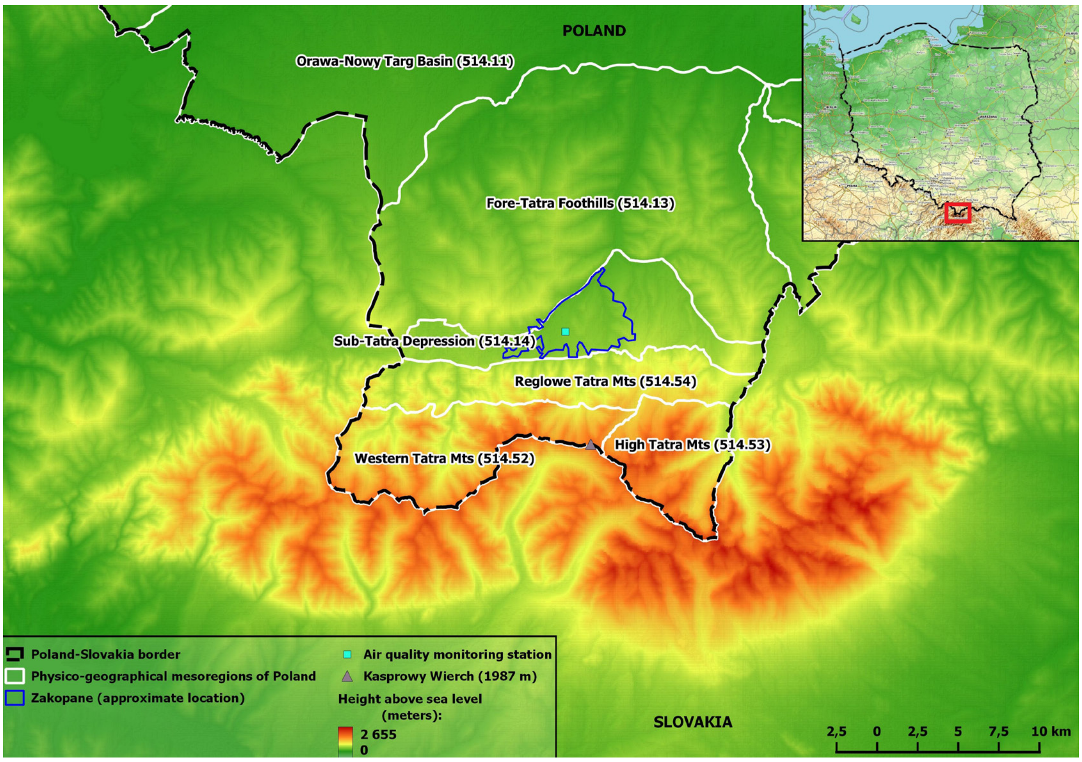

Figure 1. Hypsometry of the study area (Authors' own study based on Digital Terrain Model of the Head Office of Geodesy and Cartography)

statistics concerning the number of entrance tickets to the park sold. In 2017, it amounted to approx. 3.500.000, while in 2018, to more than 3.700.000 (https://tpn.pl/zwiedzaj/turystyka/statystyka). A particularly great influx of tourists to Zakopane is noted during summer holidays (July, August), school winter holidays (January, February), and the Christmas and New Year periods. Due to the popularity with tourists in winter, the town is called the "winter capital of Poland".

The study area is characterised by the occurrence of two climatic phenomena that are specific to mountainous regions. The first one is the air temperature inversion which involves an increase in the air temperature with altitude. Cold, heavy air falls down from higher altitudes and settles in depressions, such as basins or valleys, where low temperatures prevail. The second one is the foehn wind called *halny* in the area of the Tatra Mountains and the Podhale region (Trepińska, 2002).

2.2. Selected atmospheric aspects in the town of Zakopane

In the cool half of the year, particularly during winter months, Zakopane often experiences poor air quality caused by high concentrations of pollutants of anthropogenic origin, including PM2.5 and PM10 particulate matter. These are atmospheric aerosols comprising particles of, *inter alia*, heavy metals, sulphur, polycyclic hydrocarbons, and toxic dioxins, with a diameter less than or equal to 2.5 μm (for PM2.5), and less than or equal to 10 μm (for PM10). They are characterised by a very negative effect on human health, as they increase the risk of respiratory, nervous system, and cardiovascular diseases, cancer, and other health conditions. Moreover, they have an adverse effect on the fauna, flora, buildings, and works of art (Malec and Borowski, 2016). Their concentration values in the town area often exceed the acceptable limits of 25 $\mu g \cdot m^{-3} \cdot day^{-1}$ for PM2.5 and 50 $\mu g \cdot m^{-3} \cdot day^{-1}$ for PM10, sometimes even several fold (http://powietrze.gios.gov.pl/pjp/current/station_details/archive/459).

The main source of PM2.5 and PM10 particulate matter and other air pollutants in Zakopane, as in most Polish towns and cities, is the so-called near-ground emission, i.e. emissions of harmful substances at heights of no more than 40 metres (Graboś et al., 2014). Its main sources include the household and municipal sector through fuel combustion in heating systems, both in individual buildings and in municipal district heating plants, and road traffic (Krajowy Program Ochrony powietrza do roku 2020, z perspektywą do 2030, 2015). The majority of buildings in Zakopane are single-family houses which use high-emission coal or wood-burning stoves. Their use intensifies during the heating season, i.e. in winter months. On the other hand, car traffic in the area is exacerbated for a considerable part of the year, including in winter, due to the high popularity of the town with tourists (Aktualizacja Programu Ochrony Środowiska dla powiatu tatrzańskiego na lata 2010-2013 z perspektywą na lata 2014-2017, 2010; Strategia Rozwoju Miasta Zakopane na lata 2017-2026, 2018).

The terrain in the town and surrounding areas is conducive to the accumulation and retention of atmospheric pollutants in the air in Zakopane. As already mentioned above, the main part of the town is located in the Zakopane Depression, a part of the Sub-Tatra Depression, which is characterised by lower absolute heights and terrain concavity as compared to the Fore-Tatra Foothills surrounding it from the North, and the Tatra Mountains surrounding it from the South (Krąż and Wójcik, 2015). These geomorphological factors are conducive to the accumulation and deposition of heavy air, which retains harmful compounds, in these depressions. They also impede the free movement of air masses and ventilation, and thus the removal and dispersion of harmful substances. Moreover, the accumulation of pollutants in the air is supported by the occurrence of wind calms and low-strength winds in the town area, and by the phenomenon of air temperature inversion that is determined by the immediate vicinity of the Tatra Mountains, which results in the flow of cold air down from higher altitudes in the mountains, and its retention in the Sub-Tatra Depression (Trepińska, 2002; Strategia Rozwoju Miasta Zakopane na lata 2017-2026, 2018).

The characteristic phenomenon occurring in the study area is referred to as the foehn wind. This type of wind occurs in mountain areas all over the world. It has many regional names, e.g. *megas* in Greece, *zonda* in the Andes, or *chinook* on the eastern Rocky Mountain foreland. In the Tatra Mountains and in the Podhale region it is called *halny* (Trepińska, 2002). In the Tatra Mountains, this wind occurs mainly in the cooler half of the year and blows from southerly directions. It is characterised by high velocities, gustiness, warmth, and low relative humidity. Foehn situation manifests itself as a decrease in atmospheric pressure and relative humidity as well as an increase in air temperature. This wind is formed as a result of the difference between the pressures on the southern and northern side of the mountain range. High-pressure air masses come from the south, while low-pressure air masses prevail on the northern side. The air moving from the high-pressure area to the low encounters an orographic barrier which, in this case, is the Tatra Mountains. Having dropped its humidity on the southern mountain slopes, it falls down rapidly while warming up in accordance with the dry adiabatic lapse rate (1°C·100 m^{-1}) on the northern side, mainly in the Tatra County area, including Zakopane (Niedźwiedź, 1984; Trepińska, 2002). What is characteristic during a foehn situation is the formation of a "foehn cloud bank" at the height of mountain ridges, and the occurrence of *Altocumulus lenticularis* clouds (Niedźwiedź, 1984). Foehn wind features a wide spectrum of impact on the entire geographical environment. Examples of foehn wind consequences are, *inter alia*, large-scale windfalls and windthrows in the area of the northern Tatra Mountains slope; blockages on tourist trails due to broken and windfallen trees in the Tatra National Park area, and on roads in the Tatra County; blowing off building roofs or their covering in the area of the Tatra County; or mental deterioration in people suffering from mental illnesses (Przybyła, 1994; Grodzki and Guzik, 2009; http://osp-koscielisko.pl/category/aktualnosci/wyjazdy).

2.3. Research methodology

The days on which the foehn-type wind occurred were determined in the study periods. This was done on the basis of the criteria for identifying foehn wind in the Polish Carpathian Mountains according to Ustrnul (1992): on the Kasprowy Wierch peak, the wind velocity had to be equal to or higher than 10 m·s^{-1}, and the wind direction had to fall within the range of 140°–220° (SE-SW). Moreover, it was assumed that a wind with such parameters had to be blowing for a minimum of 6 hours, in order to rule out short-term increases in the wind velocities caused by local factors (Ustrnul, 1992). The meteorological measurement and observation data needed for this purpose originated from the High-Mountain Meteorological Observatory of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) on Kasprowy Wierch (1987 m ASL) and were obtained from the IMGW website (https://danepubliczne.imgw.pl). This was followed by a comparison of concentrations of PM2.5 and PM10 particulate matter on specific days of the four adopted periods, and by an analysis of their changes, which compared them with the absence or presence of foehn wind, and with its velocities on the Kasprowy Wierch peak. The values of PM2.5 and PM10 particulate matter concentrations were provided by the only measuring station in Zakopane. It has a national code "MpZakopaSien" and is located at the weather station of the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB) at the address of ul. Sienkiewicza 26c (Fig. 1), at an altitude of 844 m a.s.l. (http://powietrze.gios.gov.pl/pjp/current/station_details/info/459). The study took into account the manually measured daily concentrations of these substances, which were obtained from the measurement data bank (http://powietrze.gios.gov.pl/pjp/current/station_details/archive/459).

The time span of the study included four two-week periods in different years and months: from 19 December 2013 to 1 January 2014; from 3 February 2016 to 16 February 2016; from 7 December 2017 to 20 December 2017; and from 29 January 2019 to 7 February 2019. The hypsometric map of the study area and adjacent areas (Fig. 1) was created using QGIS software.

3. Results

The first fourteen-day period under analysis lasted from 19 December 2013 to 1 January 2014 (Fig. 2). During the period, 11 days on which foehn wind occurred on the Kasprowy Wierch peak were determined. These included 19, 21, 22, 24, 25, 26, 27, 28, 29 and 31 December 2013, and 1 January 2014. The day of 25 December should be particularly highlighted, as on that day, *halny* gustiness velocity on the Kasprowy Wierch peak exceeded 40 m·s^{-1}. The strongest gust reached a velocity of 49 m·s^{-1} (176.4 km·h^{-1}). In turn, in the Zakopane area, the velocity of the strongest wind gust was 33 m·s^{-1} (118.8 km·h^{-1}).

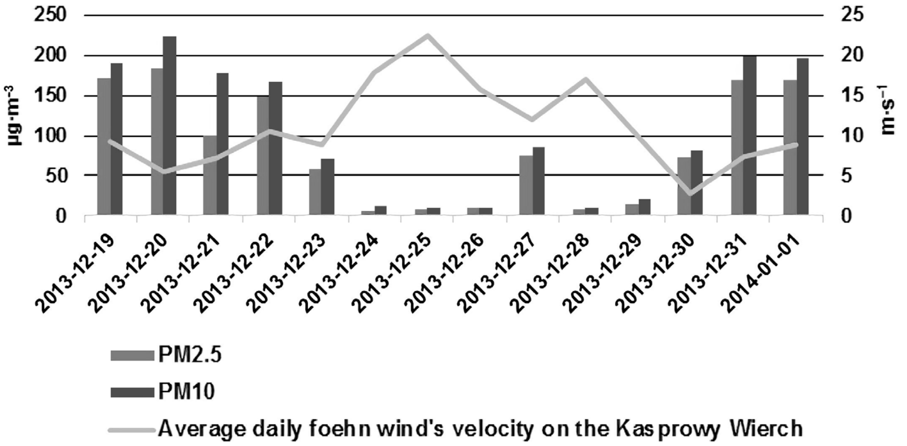

Figure 2. PM2.5 and PM10 particulate matter concentrations in Zakopane from 19 December 2013 to 1 January 2014 (Authors' own study based on the data obtained from the Inspectorate of Environmental Protection, http://powietrze.gios.gov.pl/pjp/current/station_details/info/459)

On 19, 21, and 22 December, *halny* occurred on Kasprowy Wierch with velocities exceeding 20 m·s^{-1}. High concentrations of the analysed substances persisted in Zakopane at that time. On 19 December, these reached the values of 172 µg·m^{-3} for PM2.5 and 189 µg·m^{-3} for PM10. On 21 December, they amounted to 101 µg·m^{-3} for PM2.5 and 178 µg·m^{-3} for PM10, while on 22 December, the values noted were 149 µg·m^{-3} for PM2.5, and 167 µg·m^{-3} for PM10. On 23 December, these amounted to 59 µg·m^{-3} for PM2.5 and 71 µg·m^{-3} for PM10. During the period from 24 to 26 December, *halny* was blowing with velocities on the Kasprowy Wierch peak exceeding 20 m·s^{-1}. On these days, the particulate matter content in the air in Zakopane dropped dramatically. For PM2.5, it amounted to 6 µg·m^{-3} (30.5 times less than on 22 December), 8 µg·m^{-3}, and 10 µg·m^{-3}, respectively. As regards PM10, these values amounted to 12 µg·m^{-3} (over eighteen times less than on 22 December), 10 µg·m^{-3}, and 11 µg·m^{-3}, respectively. On 27 December, foehn wind also occurred, but its velocities on the Kasprowy Wierch peak were on that day lower than 20 m·s^{-1}. In was at that time that a sudden increase in concentrations of both analysed pollutants to 76 µg·m^{-3} for PM2.5 and 86 µg·m^{-3} for PM10 was noted. The values of particulate matter concentration dropped significantly again with the re-emergence of *halny* blowing on the Kasprowy Wierch peak with velocities exceeding 20 m·s^{-1} on 28 and 29 December. On 28 December, the values of 8 µg·m^{-3} for PM2.5 and 10 µg·m^{-3} for PM10 were noted, while on 29 December, the recorded values were 15 µg·m^{-3} for PM2.5, and 21 µg·m^{-3} for PM10. On 30 December, no foehn wind was noted, and the particulate matter content in the atmosphere increased to reach a value of 73 µg·m^{-3} for PM2.5 and 82 µg·m^{-3} for PM10. On 31 December and 1 January, *halny* was blowing again with velocities on the Kasprowy Wierch peak dropping below 20 m·s^{-1}. The concentrations of analysed substances on these days were very high and amounted, on 31 December, to 168 µg·m^{-3}for PM2.5 and 199 µg·m^{-3} for PM10, and on 1 January, to 169 µg·m^{-3} for PM2.5 and 196 µg·m^{-3} for PM10. These are values over twofold higher than those on 30 December, while in comparison with the concentrations noted on 29 December, they were over eleven times higher for PM2.5, and approx. nine times higher for PM10 (Fig. 2).

The second analysed fourteen-day period included days from 3 February 2016 to 16 February 2016 (Fig. 3). During this period there were 9 days when foehn wind on the Kasprowy Wierch peak was noted, namely: 6, 7, 8, 9, 10, 12, 13, 14, and 15 February.

On 6 February, *halny* occurred on the Kasprowy Wierch peak with velocities lower than 20 m·s^{-1}. On that day, concentrations of the analysed substances reached the values of 96 µg·m^{-3} for PM2.5 and 104.2 µg·m^{-3} for PM10, which were significantly higher than those on the previous days when no foehn wind occurred. For example, on 5 February, these amounted to 36.1 µg·m^{-3} for PM2.5 and 37.7 µg·m^{-3} for PM10. On the other hand, on 7 February, the emergence of foehn wind with velocities on the Kasprowy Wierch peak exceeding 20 m·s^{-1} was accompanied by an almost three-fold drop in these values to a level of 28.1 µg·m^{-3} for PM2.5 and 33.1 µg·m^{-3} for PM10. During the following 3 days on which *halny* velocities on the Kasprowy Wierch peak exceeded 20 m·s^{-1}, these values were even lower. On 9 February, these amounted to 8.9 µg·m^{-3} for PM2.5 and 11 µg·m^{-3} for PM10, on 7 February, to 6.5 µg·m^{-3} for PM2.5 and 8 µg·m^{-3} for PM10, and on 10 February, to 6.4 µg·m^{-3} for PM2.5 (fifteen times less than on 6 February) and 7.9 µg·m^{-3} for PM10 (over thirteen times less than on 6 February). On 11 February, no foehn wind was noted. On that day, there was an increase in the particulate matter concentration to levels of 23.8 µg·m^{-3} for PM2.5 and 24.4 µg·m^{-3} for PM10. On 12, 13, 14. On 15 February *halny* occurred again, with velocities on the Kasprowy Wierch peak below 20 m·s^{-1}. On these days, a further increase in the concentrations of the analysed pollutants took place. On 13 February, their content in the air in Zakopane reached levels of 45.2 µg·m^{-3} for PM2.5 and 49.2 µg·m^{-3} for PM10, i.e. was over seven times higher than that on 10 February. On 14 February, there was a decrease in their concentrations to the values of 32.7 µg·m^{-3} for PM2.5 and 35.8 µg·m^{-3} for PM10, respectively. In turn, on 15 February, these increased again and amounted to 45.9 µg·m^{-3} for PM2.5 and 49.9 µg·m^{-3} for PM10.

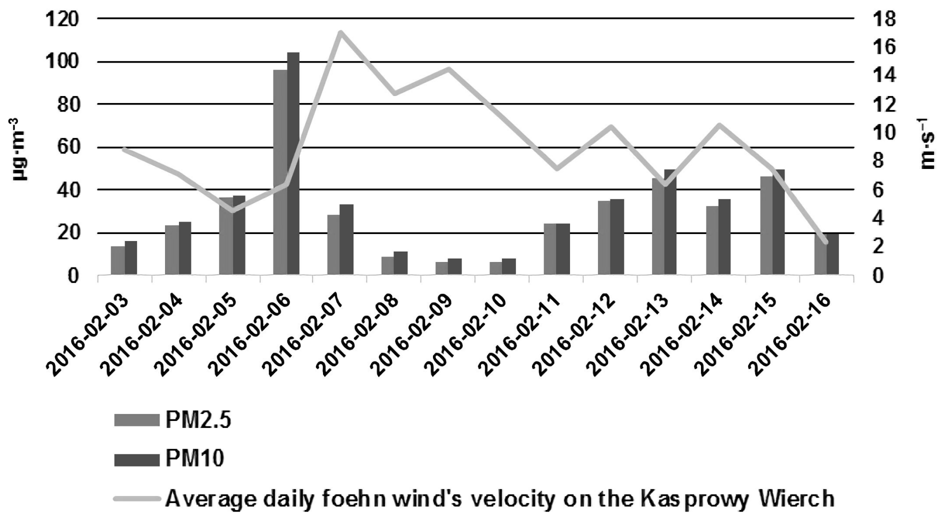

Figure 3. PM2.5 and PM10 particulate matter concentrations in Zakopane from 3 February 2016 to 16 February 2016 (Authors' own study based on the data obtained from the Inspectorate of Environmental Protection, http://powietrze.gios.gov.pl/pjp/current/station_details/info/459)

Another time interval under study was the period from 7 December 2017 to 20 December 2017 (Fig. 4). During this period there were 8 days when a wind of the foehn type occurred on the Kasprowy Wierch peak, namely: 7, 8, 10, 11, 12, 13, 14, and 15 December.

However, the observations for this period were not as unambiguous as those for the other intervals. On 7 and 8 December, during the occurrence of *halny* with velocities lower than 20 m·s^{-1}, concentrations of the analysed substances amounted to 74.8 µg·m^{-3} for PM2.5 and

81.5 μg·m^{-3} for PM10 on 7 December, and 66.9 μg·m^{-3} for PM2.5 and 73.3 μg·m^{-3} for PM10 on 8 December. On 9 December, when no foehn wind occurred, these were significantly lower and amounted to 26.2 μg·m^{-3} for PM2.5 and 26.5 μg·m^{-3} for PM10. What is more, these were even lower than on 10 December i.e. on the first day when *halny* occurred on the Kasprowy Wierch peak with velocities exceeding 20 m·s^{-1}, when they amounted to 28.8 μg·m^{-3} for PM2.5 and 29.5 μg·m^{-3} for PM10. On the second day with foehn wind blowing with such velocities on the Kasprowy Wierch peak, i.e. on 11 December, the PM2.5 and PM10 particulate matter content in the air in Zakopane dropped to levels of 5.1 μg·m^{-3} for PM2.5 and 5.6 μg·m^{-3} for PM10. On the other hand, on the last day of *halny* blowing with the above-mentioned velocities, i.e. on 12 December, higher concentrations of the analysed substances were again noted, namely 21.7 μg·m^{-3} for PM2.5 and 24.1 μg·m^{-3} for PM10. On 13, 14, and 15 December, *halny* continued to blow, yet with velocities lower than 20 m·s^{-1}. On 13 December there was an increase in the PM2.5 and PM10 particulate matter content in the air in Zakopane to levels of 44 μg·m^{-3} for PM2.5 and 46.5 μg·m^{-3} for PM10. On 14 December these were lower and amounted to 30.7 μg·m^{-3} for PM2.5 and 35.6 μg·m^{-3} for PM10 (Fig. 4). On the other hand, on 15 February, these increased again to reach the values of 34.9 μg·m^{-3} for PM2.5 and 39.3 μg·m^{-3} for PM10.

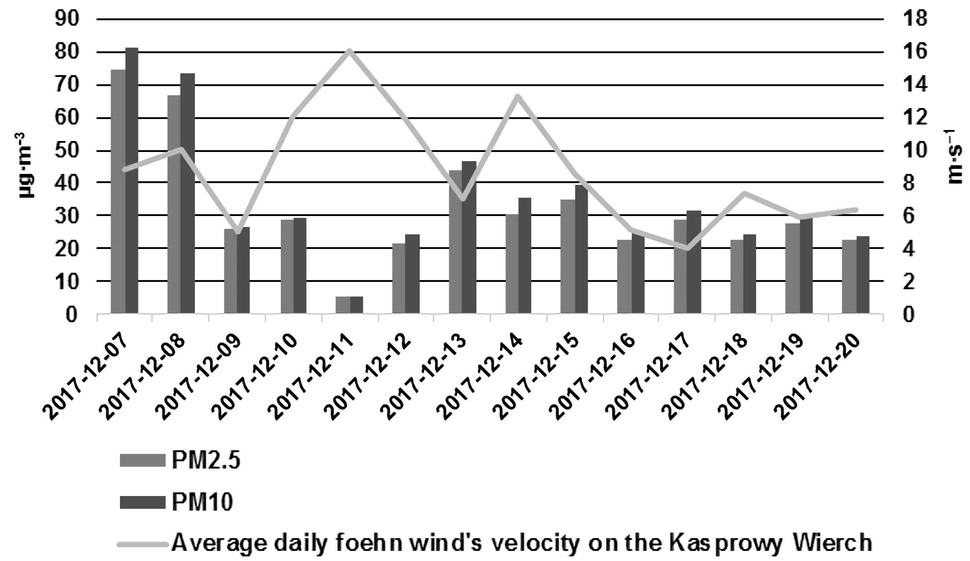

Figure 4. PM2.5 and PM10 particulate matter concentrations in Zakopane from 7 December 2017 to 20 December 2017 (Authors' own study based on the data obtained from the Inspectorate of Environmental Protection, http://powietrze.gios.gov.pl/pjp/current/station_details/info/459)

The fourth analysed fourteen-day period included days from 28 January 2019 to 10 February 2019 (Fig. 5). 7 days were determined on which foehn wind occurred on the Kasprowy Wierch peak: 28 January, and 1, 2, 3, 7, 9, and 10 February.

On 28 January, *halny* was blowing on the Kasprowy Wierch peak with velocities not exceeding 20 m·s^{-1}. On that day, PM2.5 and PM10 particulate matter concentrations in the air in Zakopane amounted to 46.2 μg·m^{-3} for PM2.5 and 47.6 μg·m^{-3} for PM10. On 30 and 31 January, i.e. on the days directly preceding the three-day period of foehn wind occurrence, PM2.5 concentrations were 62 and 40 μg·m^{-3}, respectively, and for PM10, these amounted to 54.1 and 34.2 μg·m^{-3}, respectively. On the day of the emergence of *halny* with velocities on the Kasprowy Wierch peak exceeding 20 m·s^{-1}, i.e. on 1 February, these values dropped to 22.7 μg·m^{-3} for PM2.5 and 18.7 μg·m^{-3} for PM10. On 2 February, when foehn wind was also blowing with such velocities, the following concentrations of the analysed substances were noted, and proved to be even lower than those on the previous day: 5.9 μg·m^{-3} for PM2.5 (over nine times less than on 31 January) and 5.2 μg·m^{-3} for PM10 (over six times less than on 31 January). On 3 February, *halny* was blowing, but its velocities were lower than 20 m·s^{-1}. It was then that the PM2.5 and PM10 particulate matter content in the air in Zakopane increased by over six times as compared to the previous day. On that day, concentrations at levels of 40 μg·m^{-3} for PM2.5 and 31.9 μg·m^{-3} for PM10 were noted. Foehn wind with velocities on the Kasprowy Wierch peak not exceeding 20 m·s^{-1} was also recorded on 7 and 9 February. On 7 February, concentrations of the analysed particulate matter in Zakopane amounted to 54.9 μg·m^{-3} for PM2.5 and 65 μg·m^{-3} for PM10, while on 9 February, to 43.2 μg·m^{-3} for PM2.5 and 51.2 μg·m^{-3} for PM10. On 10 December, *halny* with velocities on the Kasprowy Wierch peak exceeding 20 m·s^{-1} was blowing again. It was then that a drop was noted in the particulate matter content in the air in Zakopane to a level of 27 μg·m^{-3} for PM2.5 (37.5% less than on 9 February, and 59% less than on 8 February), and 21.7 μg·m^{-3} for PM10 (approx. 58% less than on 9 February, and approx. 72% less than on 8 February).

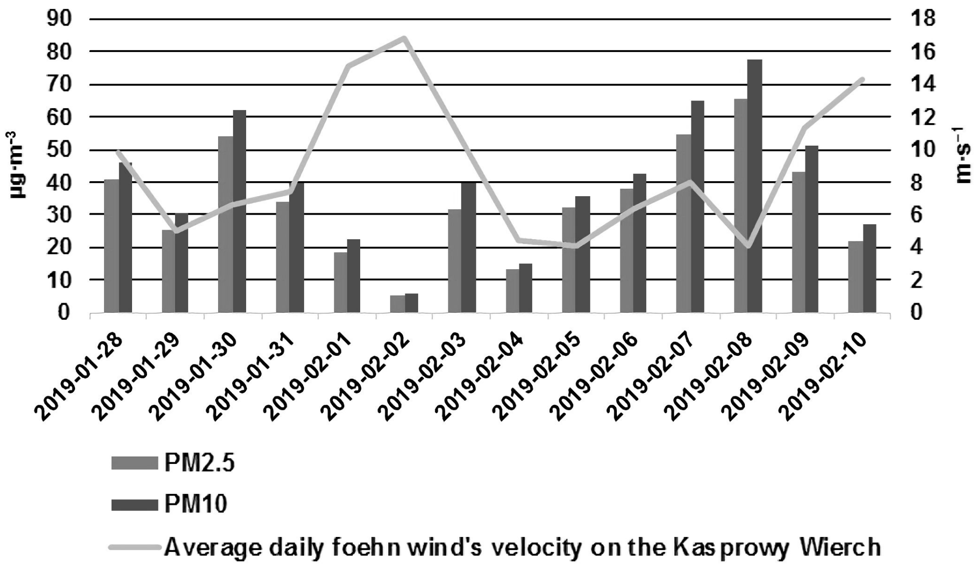

Figure 5. PM2.5 and PM10 particulate matter concentrations in Zakopane from 28 January 2019 to 10 February 2019 (Authors' own study based on the data obtained from the Inspectorate of Environmental Protection, http://powietrze.gios.gov.pl/pjp/current/station_details/info/459)

To sum up, during all four fourteen-day periods under analysis, a total of 35 days with foehn wind on the Kasprowy Wierch peak were determined. On 14 out of 15 days with *halny* featuring velocities on the Kasprowy Wierch peak exceeding 20 m·s^{-1}, a drop was noted in the PM2.5 and PM10 particulate matter content in the air in Zakopane, and their values were lower as compared to the days preceding the periods of its occurrence and following them. An exception was the day of 10 December 2017, when despite foehn wind with such velocities on the Kasprowy Wierch peak, concentrations of the analysed substance proved to be higher than on the previous day, when no *halny* occurred. On 10 out of 15 days with foehn wind featuring velocities exceeding 20 m·s^{-1} on the Kasprowy Wierch peak, the PM2.5 and PM10 values dropped to a very low level, lower than 10 μg·m^{-3} or only slightly exceeding this value.

4. Discussion and conclusions

The analysis and comparison of both meteorological conditions prevailing on the Kasprowy Wierch peak and the changes in concentrations of PM2.5 and PM10 particulate matter in the air in Zakopane showed that not every foehn wind occurring on the Kasprowy Wierch peak affected the air quality in Zakopane. Decreases in the PM2.5 and PM10 particulate matter content occurred on the vast majority of days on which *halny* velocities on the Kasprowy Wierch peak exceeded 20 $m \cdot s^{-1}$ (only one out of fifteen days was an exception to this rule). Also on these days, the lowest concentrations of the analysed substances in each of the four periods under analysis were noted. In none of the analysed period did a situation occur, based on which it could be determined as to whether the above-mentioned relationship would also apply to the days on which foehn wind velocities equal to 20 $m \cdot s^{-1}$, but do not exceed that value on the Kasprowy Wierch peak. On the days when *halny* velocities on the Kasprowy Wierch peak were lower than 20 $m \cdot s^{-1}$, no correlation was found between the occurrence of a wind of this type and the drop in the amounts of the analysed substances in the air in Zakopane.

Decreases in concentrations of PM2.5 and PM10 particulate matter due to the effects of *halny* with velocities on the Kasprowy Wierch peak exceeding 20 $m \cdot s^{-1}$ were short-term, and coincided with days when foehn wind with such velocities occurred. After its disappearance or a decrease in its velocity on the Kasprowy Wierch peak to values lower than 20 $m \cdot s^{-1}$, a re-increase in concentrations of the analysed substances was observed on subsequent days, and in certain cases even their sharp increase was recorded as early as on the first day with no *halny,* or with *halny* featuring velocities on the Kasprowy Wierch peak lower than 20 $m \cdot s^{-1}$.

A limitation in this study and for future similar studies is the presence of only one air quality monitoring station in Zakopane, which means that it is possible to determine air quality only in one place in the city, while its topography is varied.

There are studies whose conclusions are similar to the ones drawn here. The study by Furger et al. (2005) shows that foehn winds reduce aerosol concentrations in the Rhine Valley. The study by Bo et al. (2020) points out that the occurrence of foehn wind in Northern Italy causes the reduction of aerosol concentrations in the city of Turin.

There are also studies related to the analysed issue presenting results that contradict the above-mentioned indications. Seibert et al. (2000) noted that South Foehn's occurrence entails an increase in ozone concentrations in the Eastern Alps, especially in valleys and during night-time. The study by Gunia et al. (2008) points out that the foehn situations cause an increase in concentrations of NO_x in the Colchian Lowland in southwest Caucasus and the Akhangaran Valley in Western Tien Shan. There are similar conclusions in the study by Li et al. (2015) – air mass movements during the foehn situation lead to the cumulations of air pollution (PM10, SO_2, NO_2) in Urumqi, which is located at the northern lee side of Tien Shan Mountains in China. Kishcha et al. (2018) noted that foehn winds affect the occurrence of local dust pollution in the Dead Sea Valley. The negative impact of foehn situations on the air quality is also showed by studies for Calgary (near the Rocky Mountains, Canada) by Nkemdirim and Leggat (1978) or Mintz et al. (2003), for Turin by Natale et al. (1999) and for Sichuan Basin (China) by Ning et al. (2019).

Results of some studies concerning the discussed issue are ambiguous. Research by Weber and Prévôt (2002) showed the relationship between seasons and the North Foehn's influence on the concentrations of ozone in the South Alps. The occurrence of North Foehn causes a decrease in ozone concentrations in the summer months and an increase of ozone concentrations in winter. Li et al. (2020) points out that gusty foehn winds could reduce air pollutants but, on the other hand, the authors take notice of seldom-studied indirect impact of foehn winds on the air quality – foehn-related meteorological conditions cause a weak pressure gradient between air masses, which allows the polluted air mass to invade the clean air mass. The only Polish study related to the discussed issue shows that some of foehn-related air mass movements in the city of Cracow are favourable for cumulations of polluted air, but some of them contribute to dispersions of air pollution (Sekuła et al., 2021).

To sum up, this study demonstrates that foehn wind is a factor affecting the air quality, which is observed in many regions of the world. In some cases foehn wind results in reduction of air pollution, as in the case of this study, but in other cases foehn situations are conductive to the cumulations of air pollution and its increases. This study shows that not every foehn wind affects the air quality in the town of Zakopane, and only *halny* with velocities exceeding 20 $m \cdot s^{-1}$ on the Kasprowy Wierch peak is a factor that has an impact on the improvement of atmospheric air quality in Zakopane. When foehn wind reached the above-mentioned velocities, it triggered ventilation of the Zakopane Depression, and thus, removal of the polluted air retained in it despite unfavourable terrain topography.

References

Aktualizacja Programu Ochrony Środowiska dla powiatu tatrzańskiego na lata 2010-2013 z perspektywą na lata 2014-2017, 2010. Zakopane, 83 [In Polish].

Bo M., Mercalli L., Pognant F., Cat Berro D., Clerico M., 2020. Urban air pollution, climate change and wildfires: The case study of an extended forest fire episode in northern Italy favoured by drought and warm weather conditions. Energy Reports 6(1), 781-786.

Furger M., Werner R., Mitev R., Frioud M., Neininger B., Prévôt A.S.H., 2005. Aerosol Measurements in the Rhine Valley During Foehn – Another Form Perspective. Hrvatski meteorološki časopis 40(40), 272-275.

Grodzki W., Guzik M., 2009. Wiatro- i śniegołomy oraz gradacje kornika drukarza w Tatrzańskim Parku Narodowym na przestrzeni ostatnich 100 lat. Próba charakterystyki przestrzennej. [In:] Guzik M. (Ed.), 2009, Długookresowe zmiany w przyrodzie i użytkowaniu TPN. Wydawnictwa Tatrzańskiego Parku Narodowego, Zakopane, 33-46 [In Polish].

Gunia G., Tskvitinidze Z., Kholmatjanov B., Fatkhullaeva Z., 2008. Influence of Foehn Phenomena on the Processes of Atmospheric Air Pollution. Bulletin of the Georgian National Academy of Sciences 2(3), 65-69.

Kishcha P., Starobinets B., Alpert P., 2018. Modeling of Foehn-Induced Extreme Local Dust Pollution in the Dead Sea Valley. (In:) Mensink C., Kallos G. (Eds.), Air Pollution Modeling and its Application 25. Springer International Publishing, 433-437.

Krajowy Program Ochrony Powietrza do roku 2020, z perspektywą do 2030, 2015. Ministerstwo Środowiska – Departament Ochrony Powietrza, Warszawa [In Polish].

Krąż P., Wójcik S., 2015. Physicogeographical regions of the polish part of the Bruzda Podtatrzańska and Pogórza Przedtatrzańskie. [In:] Liro J., Liro M., Krąż P., Współczesne problemy i kierunki badawcze w geografii 3. Instytut Geografii i Gospodarki Przestrzennej, Uniwersytet Jagielloński, Kraków, 131–147 [In Polish with English abstract].

Li X., Xia X., Wang L., Cai R., Zhao L., Feng Z., Ren Q., Zhao K., 2015, The role of foehn in the formation of heavy air pollution events in Uruqi, China. Journal of Geophysical Research: Atmospheres 120(11), 5295-5720.

Li X., Xia X., Zhong S., Luo L., Yu X., Jia J., Zhao K., Li N., Liu Y., Ren Q., 2020. Shallow foehn on the northern leeside of Tianshan Mountains and its influence on atmospheric boundary layer over Urumqi, China — A climatological study. Atmospheric Research 240, 104940, DOI: 10.1016/j.atmosres.2020.104940.

Malec A., Borowski G., 2016. The hazards of dusting and monitoring of atmospheric air. Inżynieria Ekologiczna 50, 161-170 [In Polish with English abstract].

Mintz R., Young B.R., Svrcek W.Y., 2003. Fuzzy Logic Modelling Of Air Pollution During Chinook Winds. [In:] Brebbia C.A., Patania F. (Eds.), Air Pollution 11. WIT Transactions on Ecology and the Environment 66, Witt Press, 33-41.

Natale P., Anfossi D., Cassardo C., 1999. Analysis of an anomalous case of high air pollution concentration in Turin after a foehn event. International Journal of Environment and Pollution 11(2), 147-164.

Niedźwiedź T., 1984. O pogodzie i klimacie gór polskich. Wydawnictwo PTTK Kraj, Warszawa – Kraków [In Polish].

Ning G., Yim S.H.L., Wang S., Duan B., Nie C., Yang X., Wang J., Shang K., 2019. Synergistic effects of synoptic weather patterns and topography on air quality: a case of the Sichuan Basin of China. Climate Dynamics 53(11), 6729–6744.

Nkemdirim L.C., Leggat K., 1978. The effect of Chinook weather on urban heat islands and air pollution. Water, Air, and Soil Pollution 9, 53-67.

Ochrona powietrza przed zanieczyszczeniami, 2018. Najwyższa Izba Kontroli, Warszawa, 280 [In Polish].

Przybyła R., 1994. An Approach At The Determination Of The Meteorotropic Effects In Mental Diseases Of The Patients In Zakopane. Zeszyty IGiPZ PAN 24, Wybrane zagadnienia z klimatologii i bioklimatologii, 31-48 [In Polish with English abstract].

Graboś A., Żymankowska-Kumon S., Sadlok J., Sadlok R., 2014. Przeciwdziałanie niskiej emisji na terenach zwartej zabudowy mieszkalnej. Stowarzyszenie na rzecz efektywności energetycznej i rozwoju odnawialnych źródeł energii „HELIOS", Bochnia [In Polish].

Seibert P., Feldmann H., Neininger B., Bäumle M., Trickl T., 2000. South foehn and ozone in the Eastern Alps – case study and climatological aspects. Atmospheric Environment 34(9), 1379-1394.

Sekuła P., Bokwa A., Ustrnul Z., Zimnoch M., Bochenek B., 2021. The influence of a foehn wind on air quality in Kraków. (In:) Drzeniecka-Osiadacz A., Korzystka-Muskała M., Sawiński T., Bilińska D., Kubicka J. (Eds.), Book of Abstracts, 3rd Symposium Air Quality and Health – online conference 12–14.05.2021. University of Wrocław, 28.

Solon J., Borzyszkowski J., Bidłasik M., Richling A., Badora K., Balon J., Brzezińska-Wójcik T., Chabudziński Ł., Dobrowolski R., Grzegorczyk I., Jodłowski M., Kistowski M., Kot R., Krąż P., Lechnio J., Macias A., Majchrowska A., Malinowska E., Migoń P., Myga-Piątek U., Nita J., Papińska E., Rodzik J., Strzyż M., Terpiłowski S., Ziaja W., 2018. Physico-geographical mesoregions of Poland: Verification and adjustment of boundaries on the basis of contemporary spatial data. Geographia Polonica 91(2), 143-170.

Strategia Rozwoju Miasta Zakopane na lata 2017-2026, 2018. Zakopane, 57-58 [In Polish].

Trepińska J., 2002. Górskie klimaty. Instytut Geografii i Gospodarki Przestrzennej, Uniwersytet Jagielloński, Kraków, 90-96 [In Polish].

Ustrnul Z., 1992. Potencjalne warunki występowania wiatrów fenowych w Karpatach polskich. Zeszyty Naukowe UJ, Prace Geograficzne 90, 97-111 [In Polish].

Weber R.O., Prévôt A.S.H., 2002. Climatology of ozone transport from the free troposphere into the boundary layer south of the Alps during North Foehn. Journal Of Geophysical Research: Atmospheres 107, D3, 4030,10.1029/2001JD000987.

Internet sources

https://danepubliczne.imgw.pl (Date of access: 8.04.2021)

https://krakow.stat.gov.pl/vademecum/vademecum_malopolskie/portrety_gmin/powiat_tatrzanski/zakopane.pdf (Date of access: 8.04.2021)

http://osp-koscielisko.pl/category/aktualnosci/wyjazdy (Date of access: 8.04.2021)

http://powietrze.gios.gov.pl/pjp/current/station_details/archive/459 (Date of access: 8.04.2021)

http://powietrze.gios.gov.pl/pjp/current/station_details/info/459 (Date of access: 8.04.2021)

https://tpn.pl/poznaj (Date of access: 8.04.2021)

https://tpn.pl/zwiedzaj/turystyka/statystyka (Date of access: 8.04.2021)