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Analysis of the Applied Flight Trajectory Influence on the Air Pollution in the Area of Warsaw Chopin Airport

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ABSTRACT

One of the adverse effects of airport activity is the deterioration of local air quality. Aircraft operations are among the main airport-related emission sources of harmful compounds into the atmosphere. Breathing polluted air by residents of areas adjacent to airports causes numerous illnesses and can even lead to death. Using the Aviation Environmental Design Tool, different departure tracks from Warsaw Chopin Airport were compared in terms of their impact on air quality. First, the emissions of selected contaminants during each flight were estimated. The highest emissions were obtained for nitrogen oxides, which exceeded carbon monoxide emissions by a factor of 20 and particulate matter by a factor of 150. Subsequently, the pollutants' dispersion was simulated, resulting in contours representing the concentrations of individual toxic compounds. Among other things, a strong influence of wind direction and speed on the environmental performance of flights was observed. The largest dispersion was obtained for nitrogen oxides – small concentrations were simulated more than 50 km from the emission source.

Keywords: air pollution; airport local air quality; dispersion modeling.

INTRODUCTION

Air pollution is a major factor affecting the vitality of modern societies [1]. Air contamination is a condition when specific substances in the atmosphere exceed acceptable concentrations; it is an adverse phenomenon for both the ecological system and normal human living conditions [2, 3]. Ambient air pollution is believed to cause between 6 million and 9 million deaths a year by 2060 if strong action is not undertaken [4, 2]. In order for the measures taken to be effective it is important to know the causes of poor air quality. A factor that significantly affects local air quality is the operation of airports. Airports impact their vicinity in many different ways, e.g.: emissions of pollutants and greenhouse gases, noise emissions, collisions with birds, water pollution and waste generation [5]. In the case of contaminant emissions, a factor affecting air quality, a comprehensive analysis should take into account both substances emitted from aircraft engines as well as aircraft handling, stationary sources and vehicle traffic sources [6, 7, 8]. Aviation is growing rapidly, which is also forecast for the future [9]. This is quite understandable. In an age when time is the most precious good, it is difficult to imagine life without the fastest means of transportation, which is the airplane. Moreover, air transport is an important contributor to the economic growth of many countries [10, 11]. However, it is essential to still keep in mind the emissions growing as a result of aviation development [12, 13, 14] and the need to take measures to reduce them.

The combustion of fossil fuels in airplane engines is the primary source of pollution in aviation. The main compounds produced by aircraft engines during operation are carbon dioxide (CO_2), water vapor (H_2O), nitrogen oxides (NO_x), sulfur oxides (SO_x), unburned hydrocarbons (HC), carbon monoxide (CO), particulate matter (PM) and soot [15]. These substances have a negative impact on human health and life or adversely affect the climate. The primary product of burning fossil fuels is carbon dioxide, which is formed by the oxidation of carbon contained in the fuel. CO_2

is considered mainly as a greenhouse gas, and its excessive emissions contribute to climate change [7, 16]. However, high concentrations of this compound also have negative health effects [17].

Nitrogen oxides, mainly including nitric oxide and nitrogen dioxide [7], are toxic substances. High temperature and pressure in the engine during fuel combustion contribute to their formation. Breathing air contaminated with NO_x mainly results in respiratory diseases [18]. Nitrogen oxides also contribute to the creation of ozone in the atmosphere, which also exhibits properties harmful to health [7, 18]. Sulfur oxides are another pollutant. Their presence in the fumes results from the sulfur content of the fuel [7]. SO_x, like nitrogen oxides, have a negative effect on the respiratory tract, causing irritation, for example [18]. Furthermore, sulfur oxides react with other substances in the air or exhaust to form harmful sulfuric acid [19] or secondary particulate matter [20].

Hydrocarbons are a large class of chemicals with diverse characteristics [7], which are formed in the engine mainly by burning fuel at low temperatures. Among them are polycyclic aromatic hydrocarbons, which exhibit mutagenic and carcinogenic properties [18]. Carbon monoxide is created in the engine during incomplete combustion of fuel. Its harmful effects are related to its strong affinity for hemoglobin. Inhaling air contaminated with CO results in hypoxia of organs and tissues, which can lead, for example, to brain damage [7, 18]. A major group of toxic compounds are particulate matter. These are suspended particles that vary in both size and structure, as well as chemical composition [21]. The main division of PMs is based on the dimension of their aerodynamic diameters [20]. This is important in terms of impact on human health – the smaller the particles, the greater their ability to penetrate and accumulate in organs and tissues. Exposure to particulate matter can lead to respiratory and cardiovascular diseases, and is responsible for reduced life expectancy [21].

Pollutants in the atmosphere, once released from an emission source, undergo various processes on which their concentration at a given place and time depends. These phenomena include dispersion processes such as pollutant advection, mixing of pollutants resulting from turbulent air movements, or mass diffusion processes resulting from differences in concentration gradients [22, 23]. Of major importance in contaminant dispersion is horizontal air movement, i.e. wind (both its speed and direction are important). Next in importance is the degree of mixing, that is, the intensity of turbulence [24]. In addition, contaminants are subject to diverse chemical transformations by reacting with other pollutants or natural components of the air [23, 25]. The pollutant concentrations also depend on physical factors such the type of emission source, the release time of the toxic substance or the terrain, for example [24, 25]. Moreover, harmful compounds are subject to deposition [25], i.e., falling to the surface of land and water.

Pollutant transport can occur at different spatial scales. The division of scales is based on the phenomena that occur at a given distance from the emission source [22, 26]:

- near-field phenomena, i.e., those taking place at scales up to 1 km from the emission source, e.g., down-wash effects of plume caused by building aerodynamics;
- short-range transport – less than 10 km from the source – e.g., at this scale the maximum ground-level impact of primary pollutants from an elevated source is found;
- intermediate transport or mesoscale transport, covering a scale of 10 to 100 km, e.g., the area in which the physical and chemical properties of harmful compounds begin to have significance;
- long-range (or regional or interstate transport), i.e., phenomena occurring in an area more than 100 km from the source of emissions, e.g., at this scale, phenomena such as meteorological effects and deposition and transformation are relevant;
- global effects – these are phenomena occurring in the atmospheric area of the entire planet e.g., CO_2 accumulation.

The lowest layer of the atmosphere, extending from the earth's surface to an altitude of about 10–15 km, is the troposphere. The lowest part of the troposphere up to an altitude of about 1 km is the atmospheric boundary layer (ABL) [22, 24], which is the most turbulent part of the troposphere [24]. Friction with the ground and heat are responsible for creating turbulence in ABL. They generate turbulence due to shear stress and the movement of warm and cold air, respectively [24]. The greatest amount of pollution is emitted into the ABL because most human activity takes place in it. Along with measurements, mathematical modeling techniques play a significant role in air quality assessment, and are often the main instrument used for this assessment [27].

Specialized models are used to model emissions and dispersion of pollutants – some of which are widely available and easy to use, while others require expert knowledge. For modeling and simulation of pollutant emissions and dispersion from airport operations, it is possible to use software such as atmospheric dispersion modelling system (ADMS), emission and dispersion modeling system (EDMS) and its successor aviation environment design tool (AEDT), Lagrangian simulation of aerosol-transport for airports (LASPORT) or the tool developed by the airport local air quality studies (ALAQS) project [28–31].

The purpose of the article was to compare the applied flight trajectories in terms of their impact on air pollution in the area of Warsaw Chopin Airport. Using the Aviation Environmental Design Tool, actual departure tracks were mapped and pollutant emissions were estimated for these trajectories. Then the pollutant dispersion was simulated for the selected flight.

METHODOLOGY

The airport chosen for the study was Warsaw Chopin Airport (ICAO code: EPWA). It is an international airport located about 8 km southwest of the city center operating scheduled, charter and cargo flights. It is currently the main and largest airport in Poland. EPWA ranks first in the country with regard to the number of passengers handled and passenger operations. For over a decade, the number of passengers handled has been more than doubled and the number of passenger operations about or more than tripled compared to Krakow John Paul II International Airport, ranked second [32]. Chopin Airport has two intersecting asphalt concrete runways with directions 15/33 (3690×60 m) and 11/29 (2800×50 m).

Three departures from Warsaw Chopin Airport to Bucharest Henri Coandă International Airport on January 10, 16 and 18, 2022 were analyzed (Fig. 1). The intention was to study different departure trajectories for the same destination. The flight selected was a scheduled route operated at the same time at 10:40 a.m. Using Aviation Environmental Design Tool, the tracks of each of the analyzed flights were modeled.

The whole process took place in several stages. First, departure routes were mapped a the point-type tracks. Data on flight altitude and geographic coordinates at consecutive intervals were obtained from FlightRadar24. The study included the flight stage from the start of takeoff to climb out to an altitude of 3,000 ft above field elevation (AFE). An altitude of 3,000 ft was taken as the limit, which corresponds to the maximum altitude of the landing and takeoff (LTO) cycle. The LTO cycle is used in the certification of aircraft engine emissions in accordance with Volume II of Annex 16 to the Convention on International Civil

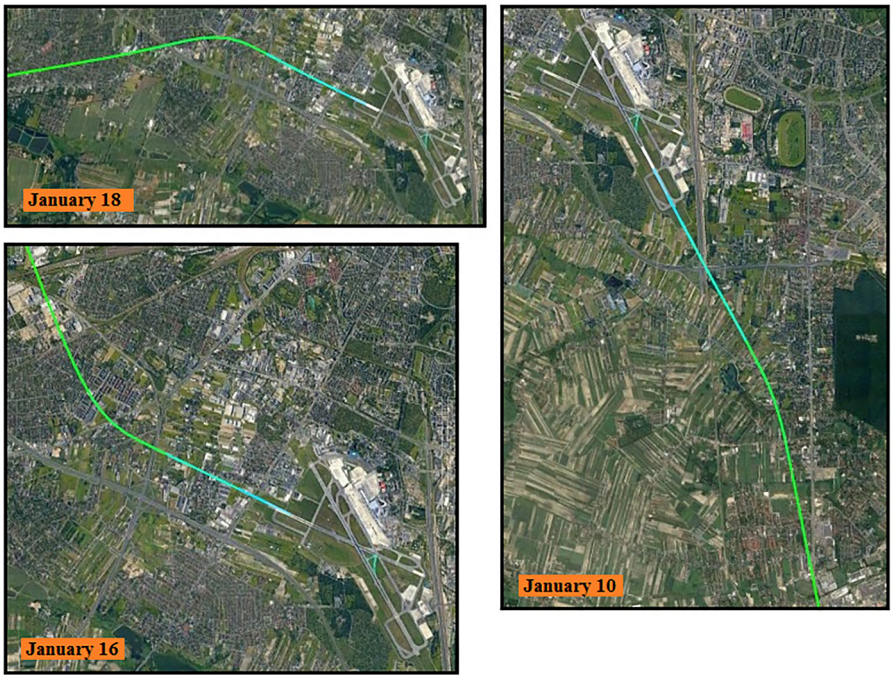

Figure 1. Departures selected for analysis

Aviation [33]. Figure 2 shows the tracks modeled in AEDT. For each of the three operations, one of the flight profiles defined in AEDT was selected (this was the STANDARD profile for departure operations and stage lenght of 2). This resulted in the fact that the altitude values entered could not be modeled one-to-one. For this reason, differences between the real and modeled altitudes occurred in some coordinates (Figure 3–5).

The aircraft chosen for the analysis was an Embraer ERJ195-LR with CF34-10E7 engines, as two of the three flights were operated by LOT Polish Airlines' ERJ-195. The aircraft is used for domestic and medium-haul flights and therefore frequently operates on this route. In the next step, the emission inventory metric result was defined. The weather conditions for the emissions simulation were set. Average airport meteorological data for 2020 was selected. ANP/BADA 3 was chosen as the aircraft performance model. The following stage was the dispersion simulation of selected pollutants. For this purpose, it was necessary to define receptors, i.e. points where pollutant concentrations are simulated. A grid was generated consisting of 1,600,000 receptors 500 meters apart vertically and horizontally. Nitrogen oxides, carbon monoxide and PM10 particulate matter were selected for dispersion analysis. For each of the three departure operations, emission concentration contour layers were estimated separately for each toxic compound. To simulate the pollutant dispersion, it was necessary to implement surface and upper air weather data. This is weather data recorded in a special format required by the atmospheric dispersion modeling syststem – AERMOD. The metorological data used was prepared for Warsaw Chopin Airport and was from the year 2020.

RESULTS

Emission results

First, the emissions were analyzed. Table 1 shows the parameters of each of the three flights: ground distance traveled, flight time, amount of fuel burned, and altitude reached above sea level.

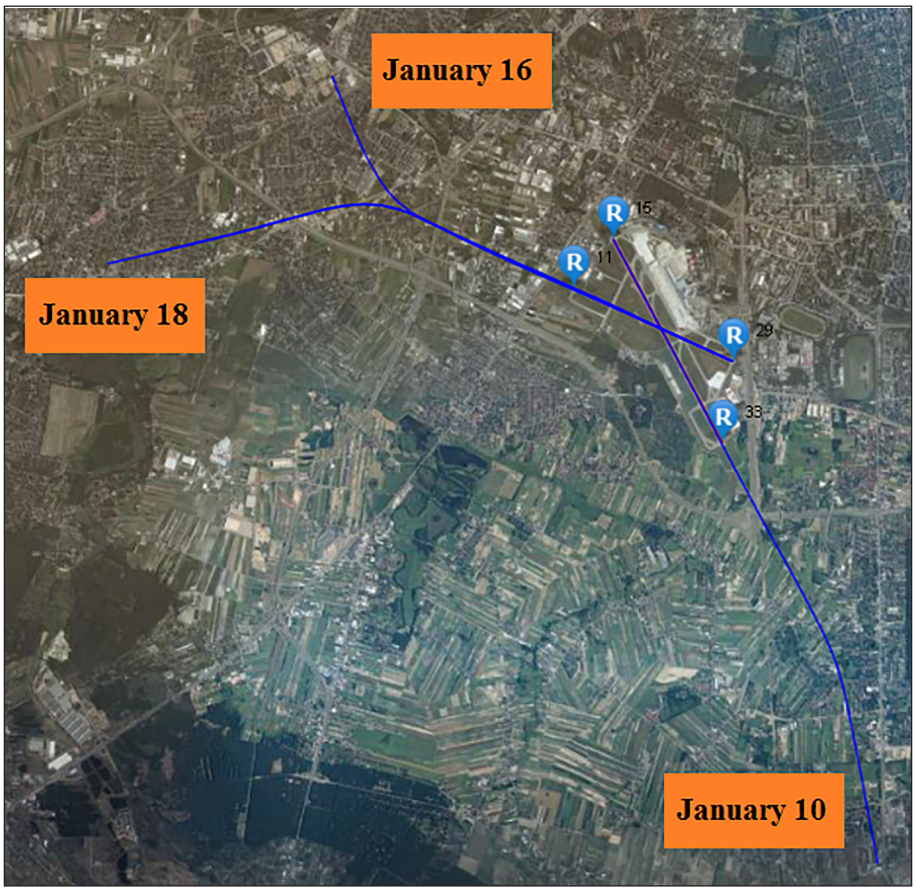

Figure 2. Modeled flight tracks

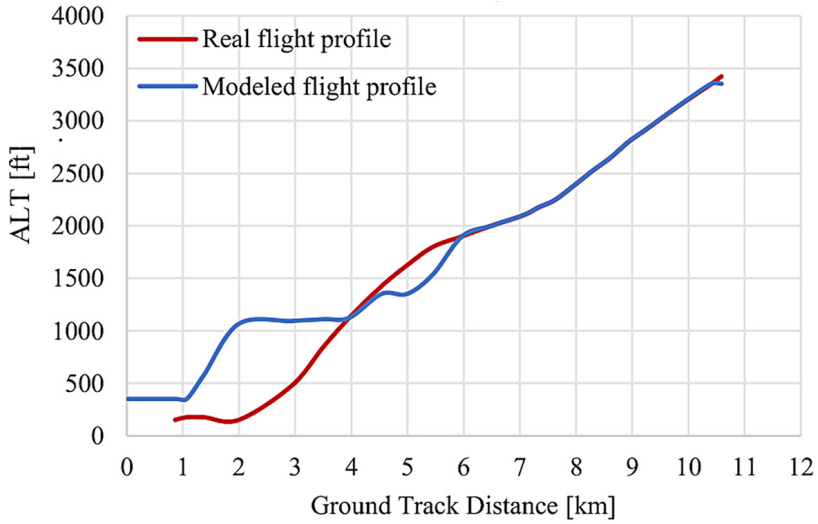

Figure 3. The flight profile for the January 10 track

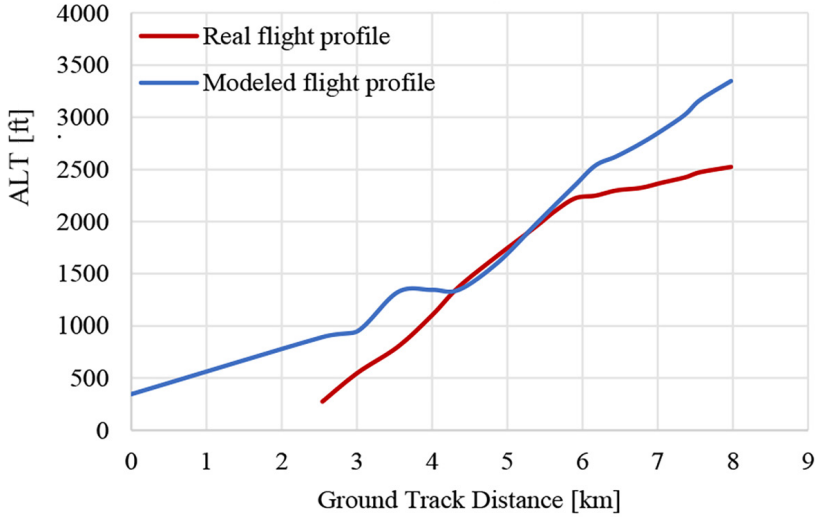

Figure 4. The flight profile for the January 16 track

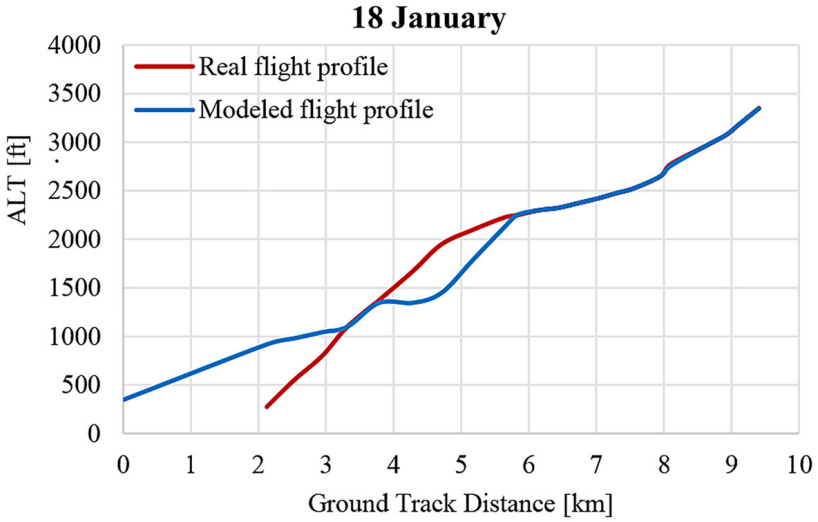

Figure 5. The flight profile for the January 18 track

Table 1. Parameters of the flights

Date	Distance [km]	Duration	Fuel burn [kg]	Max. altitde MSL [ft]
10 January	10.95	2 min 20 sek	185.28	3352.31
16 January	8.28	1 min 51 sek	165.14	3346.3
18 January	9.93	2 min 07 sek	176.66	3346.3

Figures 6, 7, 8 present the emissions of nitrogen oxides, carbon monoxide and PM10 particulate matter. In each case, the lowest emissions were obtained on January 16 and the highest on January 10. For each of the three departures, NO_x emissions exceeded CO emissions by about 20 times and PM10 emissions by about 150 times.

Subsequently, emissions were examined for climbing out to an altitude of 1,000 ft above field elevation (Table 2). The smallest amount of toxic compounds was emitted for the January 18 departure. The lowest amount of fuel burned and the least distance traveled were also observed for the flight from that day. For each operation, there is also a correlation that NO_x emissions exceeded approximately 20 times and 150 times those of CO and PM10, respectively.

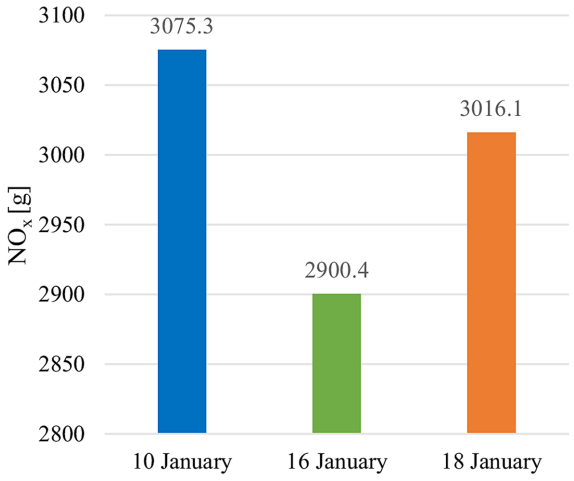

Figure 6. NO_x emissions

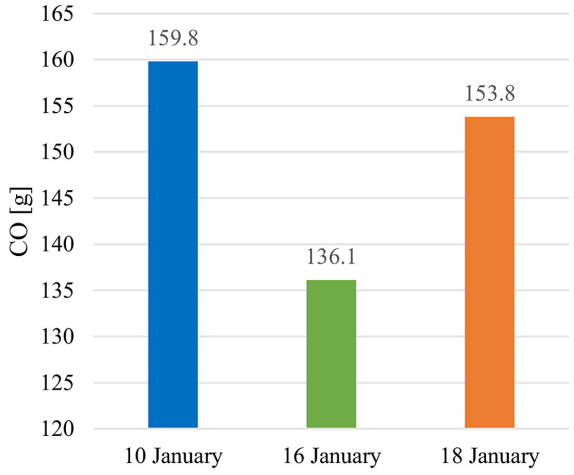

Figure 7. CO emissions

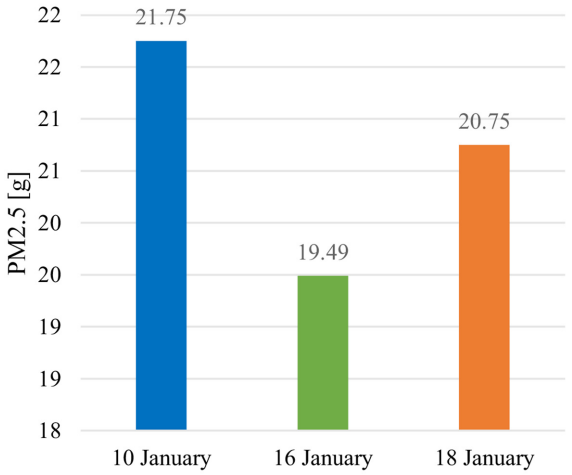

Figure 8. PM10 emission

Dispersion results

Figures 9–11 show the results of simulations of pollutant dispersion. It can be seen that on a given day, all pollutants disperse in the same direction. In each case, the highest concentration was achieved for nitrogen oxides: 4.169 µg/m³ on January 10, 2.444 µg/m³ on January 16 and 4.099 µg/m³ on January 18. Carbon monoxide ranked second each day, with concentrations of 0.166 µg/m³, 0.097 µg/m³ and 0.158 µg/m³, respectively. For PM10 particulate matter, maximum concentrations reached 0.027 µg/m³, 0.016 µg/m³ and 0.027 µg/m³ on January 10, 16 and 18, respectively.

On January 10, the area covering NO_x concentrations above 3.78 µg/m³ includes industrial buildings. The zone above 1.68 µg/m³ mostly covers the airport area, but also residential buildings. The 0.84 µg/m³ contour extends for about 3.5 km from the center of the airport, while the 0.42 µg/m³ contour reaches about 6.5 km. Interestingly, the zone in which even the minimum

Table 2. Simulation results – climb to approximately 1000 ft AFE

Date	Climb below 1000 ft AFE					
	Fuel burn [g]	Distance [km]	Duration	NO_x [g]	CO [g]	PM10 [g]
10 January	101409.27	3.99	1 min 8 s	1789.03	86.5	12.44
16 January	97094.61	3.79	1 min 6 s	1687.93	80.4	11.91
18 January	91974.32	3.34	1 min	1636.03	74.9	11.28

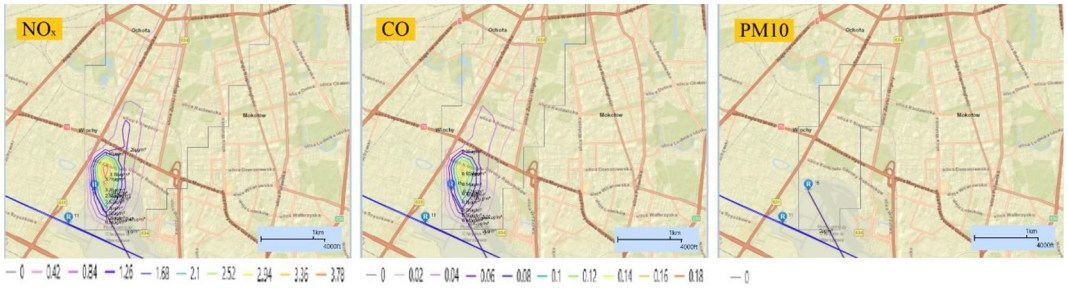

Figure 9. The results of pollutant dispersion simulation on January 10 (results given in μg/m³)

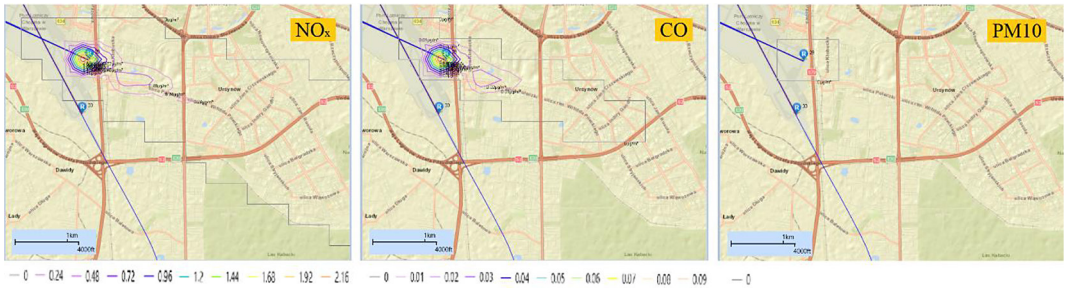

Figure 10. The results of pollutant dispersion simulation on January 16 (results given in μg/m³)

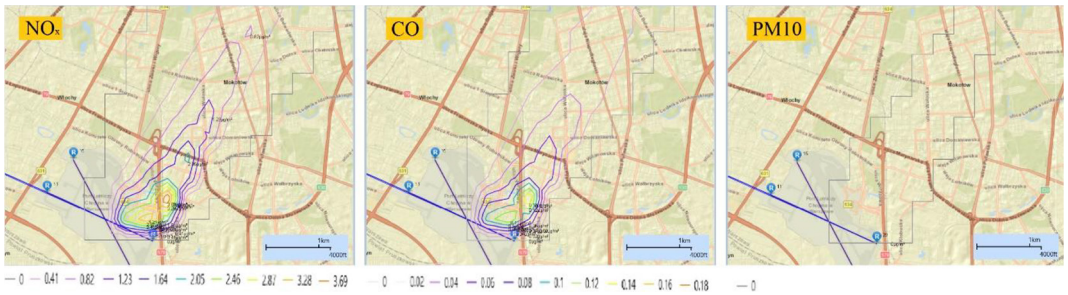

Figure 11. The results of pollutant dispersion simulation on January 18 (results given in μg/m³)

values of nitrogen oxide concentrations were simulated extends more than 170 km northwest of the airport. The impact boundaries of carbon monoxide largely coincide with the spread of nitrogen oxides. The area with the highest CO concentrations, above 0.16 μg/m³, is inside the area with the highest NO_x concentrations. A contour of 0.04 μg/m³ extends to a distance of about 3.5 kilometers from the center of the airport, a contour of 0.02 μg/m³ extends to a distance of about 5 kilometers, and a contour of 0 μg/m³, marking the area at the border of which the pollutant concentration decreases to zero, extends to about 17 kilometers from the airport toward the city center. The PM10 influence zone faces the same direction as the NO_x and CO areas. Due to the very low concentrations, AEDT only simulated the 0 μg/m³ contour, which reaches about 4.5 from the airport.

On January 16, the contour of the highest concentrations of nitrogen oxides, above 2.16 μg/

m^3, is small and located within the airport. It is situated near the threshold of runway 29. Concentrations above 0.72 μg/m^3 also occurred mainly within the airport. The concentration contour of 0.48 μg/m^3 extends about 3 km from the center of the airport and about 1.5 km from the runway 29 threshold to the southwest and is located over a residential area. In contrast, concentrations of nitrogen oxides above 0.24 μg/m^3 were recorded up to about 2.5 km from the threshold of runway 29 (about 4 km from the center of the airport). In the case of this departure, as for the January 10 departure, the area demarcating the 0 μg/m^3 boundary spans a considerable distance of more than 120 km from the airport. The tendency to create "new emission sources" can also be noted. This manifests itself in the fact that although NO_x concentrations decline with increasing distance from the emission source, areas of higher concentrations suddenly appear. The same applies to CO dispersion (Figure 12). The area of highest carbon monoxide concentrations overlaps with the area of highest nitrogen oxide concentrations, except that the individual contours present lower concentration values. The zone with concentrations above 0.02 μg/m^3 extends to about 2.5 km from the center of the airport, above 0.01 μg/m^3 - to about 3 km, while the area above 0 μg/m^3 extends to about 5 km from the airport and includes residential areas. Regarding PM10, there were also low concentrations of this compound on this day as on January 10. The area where even minimal concentrations were detected spread roughly within a radius of about 1.7 km from the threshold of runway 29.

On January 18, the zone of highest nitrogen oxide concentrations, above 3.69 μg/m^3, appeared about 2.5 kilometers from the center of the airport. The prevailing region of high concentrations, above 2.05 μg/m^3, covers the airport area and sparsely inhabited areas. The contour of 1.64 μg/m^3 reaches about 2.5 km from the center of the airport and the contour of 0.82 μg/m^3 reaches about 6 km. NO_x concentrations above 0.41 μg/m^3 have been recorded as far as 10 km from the airport toward the Warsaw city center. As in the case of the previous two flights, the contour marking the 0 μg/m^3 concentration limit extends over a considerable distance of more than 180 km. The zone of maximum CO concentration occupies a similar area as the zone of maximum NOx concentration, however, the values are much smaller (from 0.14 to about 0.158 μg/m^3). The contour of 0.06 μg/m^3 spans less than 3 km from the airport's center. About 8 km from the airport it is possible to detect concentrations higher than 0.02 μg/m^3. The 0 μg/m^3 zone extends quite far, about 30 km, and stretches through the city center. For particulate matter, the situation of the past two days is repeated. So the concentrations are small, which is why AEDT generated only the 0 μg/m^3 contour. However, on this day, the range of occurrence of even these small concentrations is larger and is about 6.5 km from the airport.

DISCUSSION

Analyzing the data on flight parameters, it can be seen that the most fuel was burned during the departure on January 10. This is undoubtedly due to the greatest distance traveled and the longest duration of the flight. The shorter horizontal route and duration for flights from the other days resulted in correspondingly less fuel burned. Interestingly, on January 16 and 18 the same maximum altitude was reached at different distances.

The flights analyzed include two phases of the LTO cycle: a short takeoff and a much longer climb out. Nitrogen oxides had the highest

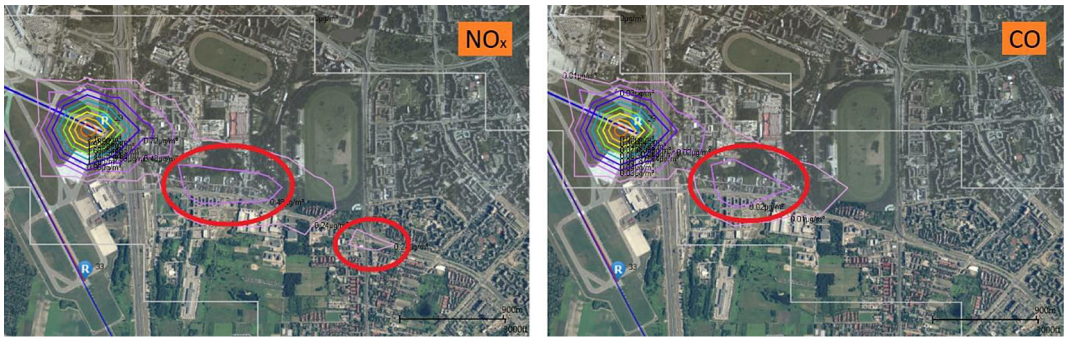

Figure 12. The formation of "new emission sources"

emissions. This is explained by the fact that most of these toxic substances are produced precisely during the climb out phase [34, 35]. It is directly a result of the engines' high thrust, which, according to the reference LTO cycle, corresponds to 85% of rated thrust. The engine is then subject to high temperature and pressure, thus ideal conditions for NOx formation, as opposed to CO, which is created during low-temperature combustion. Furthermore, the climb out phase is second only to the taxi phase in terms of its contribution to the total emissions of the LTO cycle [35]. PM10 emissions are low compared to nitrogen oxides and carbon monoxide emissions. It is presumed that it would be much higher if the taxiing phase were included [20]. However, it should be borne in mind that in the case of particulate matter, it is not only its mass that matters, but also its size [3]. Particulate matter with the smallest diameters represents a small fraction of the mass of all particles, but their number can be significant.

When we look at the emissions data at a climb out up to 1,000 ft AFE, we can see that the best departure is that of January 18. The smallest amount of fuel burned and the lowest emissions of the analyzed harmful compounds were obtained. Therefore, it can be concluded that despite the advantage of the January 16 flight in the overall calculation, the January 18 flight appears to be more environmentally friendly, as less emissions occurred at a lower altitude.

The direction of pollutant dispersion is undeniably related to the direction of the wind [36] [37]. According to weather data from the Warsaw Meteo Station [38], at 10 a.m. on January 10, a south wind was blowing, followed by a southwest wind for several hours. On January 16, on the other hand, from 10 a.m. until about 3 p.m., the wind blew from a northwesterly direction. On January 18, at 10 and 11 a.m., a southerly wind was registered, after which, for the next several hours, the wind direction was close to westerly.

On January 10, the departure was from runway 15, which also explains the occurrence of the highest pollutant concentrations just near the threshold of this runway. The maximum values, for both NO_x and CO, are shifted to the northeast of the runway threshold, which is consistent with the wind direction. Even though the aircraft was flying south, the blowing wind determined the direction of the pollutants' dispersion in the opposite way. Although the emitted contaminants come only from a single departure, the extent of their impact is considerable, especially in the case of nitrogen oxides. Moreover, they disperse toward the city center, a densely populated area. It can be assumed that in the case of larger emissions, pollutant concentrations would be correspondingly higher.

The dispersion results for the January 16 flight from runway 29 are quite different. The highest concentrations occurred near the threshold of this runway. Although the flight was directed toward the center of Warsaw, the pollutants dispersed in the opposite direction, downwind. The NO_x contour range of 0.48 μg/m^3 is about 2 times smaller than the 0.42 μg/m^3 contour range of January 10. The reason for this is probably due to lower emissions on January 16. Similarly, the CO contour ranges are smaller.

In the case of the January 18 departure, which took place from runway 29, the maximum contaminant concentration was detected north of the runway threshold. This is due to the southerly wind direction around 11 a.m. Even though a westerly wind prevailed in the following hours, the pollutants did not spread to the east, but to the northeast. This could result from temporary changes in wind direction. In addition, despite the fact that both pollutant emissions and maximum concentrations for that day's flight were smaller than for the January 10 flight, for example, the NO_x contour range of 0.41 μg/m^3 turned out to be one and a half times larger than the NO_x contour range of 0.42 μg/m^3 obtained for the January 10 departure. Perhaps this is explained by the lower wind speed on January 18, which increased from a value of 1.5 m/s to less than 4 m/s from 10 am to 2 pm. On January 10, during the same hours, the wind speed changed from 2 to about 5 m/s. With lower wind speeds, higher pollutant concentrations are shown [39, 40]. Moreover, there was a small amount of precipitation on January 10, which could also have had an impact on the occurrence of lower pollutant concentrations that day due to the removal effect [40, 41].

A very large NO_x impact range of more than 100 km was obtained for each of the three departures. Certainly, such a considerable range of NO_x is the result of the highest emissions of all the compounds studied. Furthermore, the height of the emission release may also be important. As mentioned earlier, most nitrogen oxides are emitted during the climb out phase of the aircraft. In this phase, the aircraft is in the air above buildings and other obstacles. In contrast to the pollutant dispersion just off the

ground, the emitted harmful substances encounter fewer terrain barriers. This results in less turbulent airflow [42]. However, it should be kept in mind that the AERMOD system implemented in AEDT is designed to model contaminant dispersion over short-range distances of up to 50 km [43]. For this reason, results obtained at distances above 50 km from the emission source may not be reliable. The achieved results would have to be verified using a model designed to model the dispersion of harmful compounds at larger scales.

CONCLUSIONS

Currently, there are more than 40,000 different types of airports in the world [44]. Some of them are located near large cities, i.e. densely populated areas. Passengers appreciate the proximity of the airport to the city center because of the ability to commute quickly. Unfortunately, it is also associated with exposure to pollution emitted from airport activity. The major source of airport-related emissions is aircraft operations [45]. Any analysis investigating the impact of the specific phases of the landing and takeoff cycle on local air quality is therefore reasonable.

The study conducted here used computer simulations to evaluate the impact of different flight tracks on air pollution around Warsaw Chopin Airport. The emission analysis showed that the least pollution was generated during the departure characterized by the shortest duration and the smallest ground distance traveled. However, with climb out to 1,000 ft AFE, it was not the same flight as with climb out to 3,000 ft AFE. In each case, the highest emissions were obtained for nitrogen oxides due to the main contribution of the climb out phase in the flight stage considered.

Concentrations of individual pollutants appeared to depend primarily on the amount of emissions and wind direction and speed, as well as the height of the emission release. The lowest concentrations occurred for the January 16 departure, which was characterized by the smallest total emissions. Moreover, on that day, the pollutants dispersed to the southeast, to a less inhabited area, despite the fact that the flight was directed toward the city center. Therefore, it can be assumed that this departure turned out to be the best of the three included in the study. For the other two flights, their trajectories were in the opposite direction from the center of Warsaw, however, the pollutants were aimed precisely at the city. Surprisingly, the departure that emitted a larger amount of harmful compounds turned out to be more favorable. Thus, it can be concluded that the key role in the environmental impact of the analyzed flights was not their tracks, but the factors responsible for the amount of emissions and pollutant dispersion.

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