RESEARCH PAPER

WINTER SPATIAL PATTERNS IN $PM_{2.5}$ CONCENTRATION AND AIR QUALITY INDEX IN THE ARCTIC TOWN

Iuliia V. Mukhartova[1,5], Alen A. Kospanov[1], Mariya E. Zubova[1], Anastasia A. Semenova[1], Uliana I. Antipina[4], Igor V. Malyutin[1], Daria Yu. Gushchina[1], Marina V. Slukovskaya[3], Varvara S. Maratkanova[1], Pavel I. Konstantinov[1,2]

[1]Lomonosov Moscow State University, Faculty of Geography, Leninskie Gory 1, Moscow, 119991, Russia
[2]Shenzhen MSU-BIT University, Longgang District, Shenzhen, 518172, PR China
[3]Kola Science Center of the Russian Academy of Sciences, Fersman str. 14, Apatity, 184209, Russia
[4]Institute of Global Climate and Ecology named after Academician Yu.A. Israel, Glebovskaya str. 20B, Moscow, 107258, Russia
[5]Lomonosov Moscow State University, Faculty of Physics, Leninskie Gory 1, Moscow, 119991, Russia
*Corresponding author: kostadini@mail.ru
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ABSTRACT. The current study presents the results of air quality research in the small mining and touristic city of Apatity (Kola Peninsula, Russian Federation, 67°34′03″N, 33°23′36″E) during the two winter expeditions in 2022 and 2024. A PurpleAir PA-II portable device was used for ground-based aerosol observations. Two measurement campaigns allowed to conduct route measurements in various synoptic conditions, including both frosty windless weather, characterized by temperature inversion (2022), and contrasting conditions of "warm" winter unusual in the Arctic and Kola Peninsula (January 2024). The obtained results demonstrate that, depending on the synoptic situation in the city, there can be both traditional accumulation of concentrations of $PM_{2.5}$ particles (up to 300 μg/m^3) dangerous for the health of inhabitants (in some areas exceeding the 20 min maximum allowable concentration of 160 μg/m^3 almost twice), and significant improvement of air quality due to precipitation and air mixing under warm winter conditions (on average, about 17 μg/m^3). The latter circumstance can noticeably improve the region's tourism potential in a warmer climate.

KEYWORDS: aerosol pollution, Arctic city, urban air quality, $PM_{2.5}$ particles, urban microclimate

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INTRODUCTION

During the last decades, air pollution has become one of the major natural and man-made hazards attracting more attention of researchers. The global community is increasingly emphasizing the causes and consequences of air pollution in terms of sustainable development and urban planning. Key challenges in such research have been the identification of factors contributing to air pollution and the development of adaptation and mitigation measures to improve the quality of life in cities.

$PM_{2.5}$ and PM_{10} are airborne mass concentrations with sizes ranging from 10 nm to 2.5 μm and up to 10 μm in diameter, respectively, either solid or as microscopic liquid droplets (Seinfeld and Pandis 2006). PM particles are divided into primary and secondary particles. Primary PM is directly emitted into the ambient air, while secondary PM can be formed by chemical reactions of substances such as sulfur dioxide, nitrogen oxides, and ammonia (various nitrates and sulfates). Primary PM can be of natural and anthropogenic origin. The source of natural PM can be, for example, soil erosion. Biological pollutants can also be considered as primary natural PM. Anthropogenic PM_{10} and $PM_{2.5}$ particles are fragments of soot, automobile tires and asphalt (due to wear and tear of road surfaces), as well as mineral salts and heavy metal oxides (Seinfeld and Pandis 2006; Arnold et al. 2016). Many papers have been devoted to the study of episodes with significant exceedances of $PM_{2.5}$ and PM_{10} standards (Chen et al. 2023; Groot Zwaaftink et al. 2022; Yasunari et al 2024; Sartz et al 2023). The main sources of anthropogenic $PM_{2.5}$ and PM_{10} are motor vehicles with internal combustion engines, combustion of solid fuels both in households and industry, as well as construction, mining, cement production, etc. Studies show that in mechanical engineering, the share of $PM_{2.5}$ and PM_{10} emissions can account for up to 13% and 40% of total suspended particles (TSP - total suspended particles) emitted, respectively; in ferrous metallurgy up to 75% and 84%, in non-ferrous metallurgy up to 43% and 88%, and in mining up to 21% and 49%, respectively (Zagorodnov et al. 2019). Construction materials production also contributes significantly to PM_{10} and $PM_{2.5}$ emissions (Prosviryakova and Shevchuk 2018). One of the problems associated with the formation of PM_{10} and $PM_{2.5}$ in industry is that particles with aerodynamic sizes smaller than 10 μm are practically not captured by the most common dust cleaning plants, in contrast to larger particles captured in amounts up to 90-95% (Strelyaeva et al. 2014; Strelyaeva et al. 2017).

Special attention to the study of urban air quality, including the concentration of $PM_{2.5}$ particles, is due to the fact that these particles are able to overcome biological barriers and penetrate into the lungs and even blood, causing significant harm to human health (Kholodov et al. 2019; Bai et al. 2007; Polichetti et al. 2009; Kowalska and Kocot 2016; Dominici et al. 2006). The concentrations of PM_{10} and $PM_{2.5}$ in ambient air affect mortality rates, respiratory and cardiovascular disease occurrence statistics, and other health indicators (Zagorodnov 2018; Di et al. 2017). Table 1 shows the maximum allowable concentrations of PM particles according to WHO recommendations[1], as well as those adopted in Russia[2], Belarus[3] and EU countries[4].

In the present work, the concentrations of $PM_{2.5}$ particles were compared under the Arctic city conditions both in clear frosty weather after prolonged intense snowfalls and in "warm" winter conditions in the presence and absence of precipitation. The effect of precipitation washout on the optical properties of smoke, and thus in the amount of aerosol, is noted in many works (Burtsev and Burtseva 1971; Pkhalagov and Uzhegov 1980). Wet aerosol deposition from the atmosphere is one of the most effective processes for its purification from pollutants (Aloyan 2002; Wallace and Hobbs 2006). The analysis of atmospheric purification by precipitation under urban conditions presents a complicated problem. Decrease in the concentration of impurities due to precipitation has been proved, but the washout effect is observed only outside of the zone of direct impact of anthropogenic aerosol sources. In (Gorbarenko and Eremina 1998), a significant dependence of aerosol optical thickness on the duration, amount, and intensity of precipitation was observed only in the warm period of the year. In (Chubarova et al. 2020) the experiments conducted in April and May 2018 and 2019 showed an exponential dependence of the decrease in aerosol content with an increase in precipitation. It was also shown that the content of suspended and dissolved aerosol fractions in precipitation samples was consistent with the high aerosol content in the atmosphere before precipitation. Experiments have demonstrated that under all precipitation regimes, the contribution of the suspended fraction to the total aerosol washout was predominant (up to 67%) compared to the dissolved one.

In (Plaude et al. 2012), based on 15-year measurements of atmospheric aerosol characteristics in Dolgoprudny, it was shown that a statistically significant negative correlation of aerosol particle concentration with precipitation is observed only for monthly averages and is absent for semiannual and seasonal averages. Analysis of individual precipitation events revealed their small influence on aerosol concentration in the surface layer. In the winter period, the authors observed a decrease in aerosol concentration in a narrow range of particle sizes 0.03-0.1 μm, and it amounted to no more than 30% within a few hours. In our work, however, a significant difference in $PM_{2.5}$ particle concentrations was found in the presence and absence of precipitation (snow) in urban conditions, which can be explained by a number of meteorological reasons, including inversions and wind direction.

In the cold climate cities with temperatures below freezing and persistent snow cover over a significant part of year (Järvi et al. 2017; Qian et al. 2022) the persistent surface energy deficit in wintertime creates stronger surface layer stability and temperature inversions in the lower atmosphere (Wetzel and Brümmer 2011) and a thin stable ABL (Davy 2018). Research publications about cold climate urban meteorology are scarce (Varentsov et al. 2023; Brozovsky et al. 2020; Lappalainen et al. 2022; Varentsov et al. 2022; Konstantinov et al. 2022).

An important aspect of wintertime pollution in cold cities is the prevalence of temperature inversions, which reduce the vertical dispersion. Due to extremely stable atmospheric conditions in case of low winds pollution is trapped in the shallow atmospheric layer, which significantly worsens the air quality in Arctic cities (Simpson et. al. 2024). A number of studies have investigated the main sources of pollution in Arctic cities, in particular, in Fairbanks. Fairbanks wintertime sources of PM have been studied by chemical mass balance methods (Ward et al. 2012), which indicated that wood smoke sources caused

Table 1. Maximum allowable concentrations of PM_{10} and $PM_{2.5}$

Particles	Period	MAC, μg/m³			
		WHO	Russia	Belarus	EU
PM_{10}	20 min	-	300	150	-
	1 day	50	60	50	50
	1 year	20	40	40	40
$PM_{2.5}$	20 min	-	160	65	-
	1 day	25	35	25	-
	1 year	10	25	15	20

[1]WHO air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide, 2006
[2]GN 2.1.6.3492-17 "Maximum permissible concentrations (MPC) of pollutants in the atmospheric air of urban and rural settlements" for Russian Federation
[3]Standards of maximum permissible concentrations of pollutants in atmospheric air: hygienic standard / approved by the decree of the Ministry of Health of the Republic of Belarus № 113 08.11.2016
[4]Air quality standards – European Commission, National ambient air quality standards for particulate matter, 2006

60–80% of ground-level PM from 2008–2011. The studies using positive matrix factorization (PMF) generally agreed that wood smoke was the largest single factor, but found lower percentages (40–52%) of influence in Fairbanks (Wang and Hopke 2014; Kotchenruther 2016).

The aim of this work was to study how different meteorological conditions influence the spatial distribution of pollution by $PM_{2.5}$ in Apatity during winter, as the formation of a temperature inversion and a weak mixing layer (or their absence) are bound to influence the pollutant accumulation patterns. To achieve the goal, the following tasks were performed: selection of points for measurements, direct measurements of $PM_{2.5}$ concentration in winter 2022 and 2024 on days with different meteorological conditions, and processing and analysis of measurement results.

MATERIALS AND METHODS

We conducted our research in the city of Apatity (67°34'03"N, 33°23'36"E), situated in the Murmansk region above the Arctic Circle. As noted above, for Arctic cities, air quality is a particularly critical indicator, which is associated with meteorological features of the region. Therefore, of particular interest in this work was the comparison of the spatial distribution of atmospheric pollution in different meteorological conditions: in the presence and absence of inversion, in the conditions of classical cold winter, as well as warm winter.

In addition to its geographical location, Apatity is also interesting because of its location in close proximity to the ANOF-2 and ANOF-3 apatite-nepheline enrichment plants, which are subdivisions of Apatit's Kirovsk branch. Both the ANOF factories themselves and their "tailings ponds" are sources of significant dust pollution in the cities of Kirovsk and Apatity. In this regard, it was also of interest to study the spatial distribution of pollution in Apatity under different meteorological conditions.

The studies were conducted in the winter of 2022 and 2024 as a part of the winter expedition of the Department of Meteorology and Climatology, Faculty of Geography, MSU (January 16 - 23, 2022 and January 25 - February 1, 2024). The measurements were carried out by automobile sounding for several hours. The points selected for measurements are presented in Fig. 1.

The map in Fig. 1, as well as the maps of the $PM_{2.5}$ concentration distributions presented in the Results section, were made using QGIS 3.34 software[5]. The distribution of concentration in the study area was obtained from point measurements using inverse distance weighted (IDW) interpolation method.

For both research cases, judgmental sampling was the primary sampling technique, as it allowed us to address the specifics of the $PM_{2.5}$ measurement campaigns during the two different expeditions. In 2022, the points were predominantly concentrated along the road from ANOF-2 to Apatity and in the northern part of the city (Fig. 1a) in order to detect the correlation between air quality and distance from the enterprise. Point 1 was located in the vicinity of the nepheline "tailings dump" and the ANOF-3 site (the tailings dump is located approximately 6.5 km east of point 1, ANOF-3 is located 10 km east of point 1). Point 8 is located directly at the entrance to ANOF-2, points 18 and 2 play the role of background points. Point 3, located in the village of Tik-Guba on the shore of Lake Imandra, was also considered a background point. In 2024, it was decided to distribute the points more evenly within the city (Fig. 1b), keeping point 8 near ANOF-2, point 3 on the shore of the lake (moving it closer to the weather station), as well as a number of points in the northern part of Apatity.

Ground-based aerosol observations were carried out using a PurpleAir PA-II portable device (PurpleAir LLC, Draper, UT, USA) incorporating a pair of PMS5003 laser optical particle counter sensors (Plantower Ltd., Beijing, China). The principle of particle concentration measurement in the PurpleAir PA-II device is based on optical light scattering technique. The use of light scattering technique makes the sensors cheaper to manufacture, reduces their power consumption and response time (Tanzer et al. 2019). When a particle passes through the sensor, it scatters light. The intensity of the scattered light is measured by a phototransistor and correlated with the dimension of the particle. This method is sensitive to air temperature and humidity, so the PurpleAir PA-II also contains temperature, relative humidity and barometric pressure sensors (BME 280, Bosch Sensortec GmbH, Reutlingen, Germany). In our study all measurements were provided in recommended temperature range -40°F to 185°F (-40°C to 85°C).

All sensors in PurpleAir PA-II are connected to a microcontroller with a wireless communication module. The device allows data to be recorded and transmitted via Wi-Fi to a cloud platform, from where it can be downloaded at 2-minute intervals. The PMS5003 sensor provides digital outputs for 12 data fields. The first three ones correspond

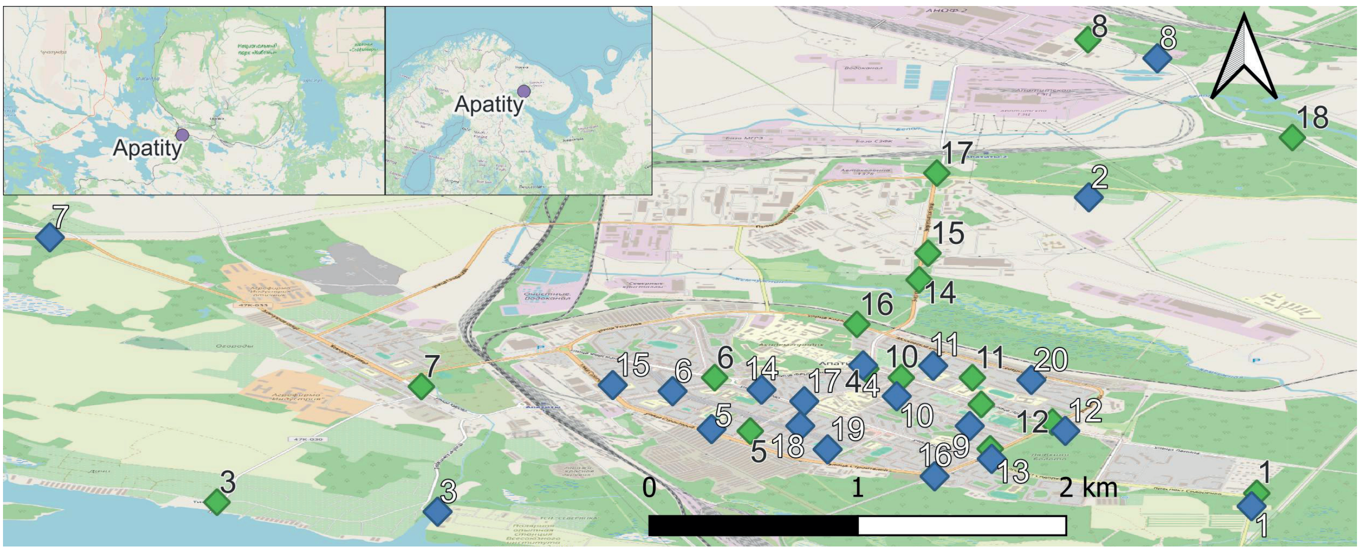

Fig. 1. The location of measurement points in and around Apatity for 2022 (green points) and for 2024 (blue points)

[5]QGIS.org, 2024. QGIS Geographic Information System. QGIS Association. http://www.qgis.org

to the mass concentrations of PM_1, $PM_{2.5}$ and PM_{10} fractions without applying any correction. The next three ones correspond to the corrected mass concentrations obtained after applying the proprietary algorithm developed by Plantower Ltd. The next six data fields contain the cumulative particle size distribution in six size ranges (>0.3 μm, >0.5 μm, >1 μm, >2.5 μm, >5 μm and >10 μm). In addition to these parameters, the PA-II instrument also reports temperature, relative humidity, and barometric pressure from each of the two PM5003 sensors (Stavroulas et al. 2020).

The study of accuracy of low-cost PurpleAir monitors for measuring ambient fine particulate matter ($PM_{2.5}$) and the exploration of methods for improving their precision were made in (Tryner et al. 2020). Initially, the researchers tested the linear response of PurpleAir monitors to a known $PM_{2.5}$ standard and derived a laboratory-based correction factor. Then they deployed the monitors alongside portable filter samplers at 15 outdoor sites to assess the effectiveness of ambient relative humidity (RH) data in improving measurement accuracy. Authors found out that 72-h $PM_{2.5}$ (μg m^{-3}) measured by portable and conventional filter samplers agreed.

The PurpleAir PA-II device was used to measure $PM_{2.5}$ concentration at each of the measurement points for 1-2 min. The data was updated every 10 seconds. For further work and analysis, averaging of measurement results was performed. Although we measured essentially instantaneous concentrations, the corresponding values of the sub-index AQI were calculated based on concentrations of $PM_{2.5}$ in μg/m^3 to illustrate the assessment of air quality. In the following, pollution distribution maps show data in AQI units. The relation of AQI index values and $PM_{2.5}$ concentrations in μg/m^3, as well as the classification of AQI levels and the corresponding recommendations for 24-hour human exposure to the corresponding pollution level are given in Table 2[6]. Recommendations on the relation between AQI levels and the degree of danger to human health have been developed for an average 24-hour exposure. In our study, measurements at each point were carried out for several minutes. Hence, to assess the level of pollution, we used concentrations in μg/m^3 and compared them with the 20-minute MAC according to accepted Russian standards.

The period of the 2022 expedition was characterized by strong snowfalls, which made it impossible to carry out measurements for several days. The measurements were carried out after the snowfall was over, on 22.01.2022, when typical anticyclonic conditions were established, characterized by almost complete absence of wind, significant temperature inversion, and air temperature of about -20°C. The concentration of $PM_{2.5}$ particles was measured in the morning and afternoon hours.

During the winter expedition of 2024, the synoptic situation was atypical for the Kola Peninsula and the time of the year. Constant active cyclonic activity accompanied by the passage of atmospheric fronts with sharp temperature variations at different altitudes, as well as gusty winds that provoked intensive vertical air mixing in the lower layers

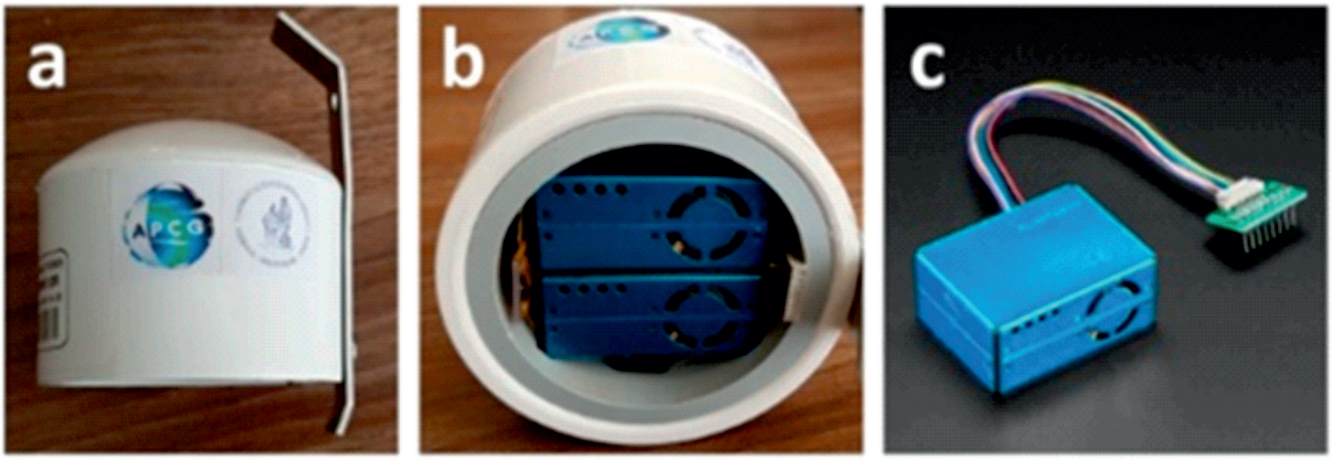

Fig. 2. The configuration of a Purple Air PA-II portable device (a); PMS5003 sensor from above (b); PMS5003 sensor with a microcontroller (c)

Table 2. The relation of AQI air quality index and $PM_{2.5}$ concentration in μg/m^3

AQI Levels (US)	$PM_{2.5}$, μg/m^3	Recommendations (at 24 hours exposure)
0-50 (good)	0-9.0	Good air quality, no or low health risk.
51-100 (satisfactory)	9.1-35.4	Sensitive groups of people are better off avoiding outdoor activity as they may experience respiratory symptoms.
101-150 (bad for sensitive groups of people)	35.5-55.4	People in the middle and particularly sensitive groups are at some risk of eye, skin and throat irritation, as well as respiratory problems.
151-200 (bad)	55.5-125.4	There is an increased likelihood of exacerbation of heart and lung disease in the general population.
201-300 (very bad)	125.5-225.4	Impact on the general population. Sensitive groups should limit outdoor activity.
301+ (dangerous)	225.5+	The general public is at risk of experiencing severe eye, skin and throat irritation, as well as having adverse health effects that can trigger cardiovascular and respiratory diseases. Outdoor activity should be avoided.

[6]Mintz D. (2016).Technical Assistance Document for the Reporting of Daily Air Quality – the Air Quality Index (AQI) U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards (ERA-454/B-16-002), https://www.airnow.gov/sites/default/files/2018-05/aqi-technical-assistance-document-may2016.pdf

of the atmosphere, created difficult conditions for the fulfillment of the planned studies. However, this atypical situation also provided a unique opportunity to investigate the air quality of the city of Apatity during an unusually warm winter. Wind weakening by the beginning of the night on January 26 allowed the first air quality measurements to be made. During the measurements, precipitation in the form of heavy snow was observed; temperature ranged from -3 to -2.4°C. The second series of measurements was conducted in the afternoon of 26.01.2024, at a temperature of -5°C, with a westerly wind of about 1 m/s and showers of slight snow. The final series of air quality measurements was carried out in the morning and afternoon hours of 31.01.2024 under conditions of elevated inversion, a north wind of 0-1 m/s, and a temperature of -3°C.

RESULTS

Tables 4, 6, 8, and 10 show the results of $PM_{2.5}$ concentration measurements during the day on 22.01.2022, the night of 25.01.2024 to 26.01.2024, the day of 26.01.2024, and 31.01.2024, respectively. The graphs in Figs. 3-6 show the spatial distribution of the AQI index for $PM_{2.5}$ particles in Apatity on the indicated dates.

Measurements on 22.01.2022 were carried out in the morning and afternoon hours between 11:00 and 15:00. The meteorological conditions for the measurement period are presented in Table 3 (according to the Apatitovaya weather station, Russia, WMO_ID=22213).

The cloud cover is represented by low-level clouds (St neb. or St fr.) and middle-level clouds (As at 12:00 and Ac or Ac with As or Ns near 15:00).

Here in Table 3 and further, the following notations are used: *T* is the air temperature; P_0 is the atmospheric pressure at the station level; *P* is the atmospheric pressure reduced to the mean sea level; P_a is the baric tendency (change in atmospheric pressure over the last 3 hours); *DD* is the wind direction (at an altitude of 10-12 m above the surface); *Ff* is the wind speed; *U* is relative humidity of the air; *N* is total cloud cover (in %); Nh is the total number of low-level clouds and clouds of vertical development (in %).

The measurement period corresponded to a weak wind of east-southeast direction and no more than 1 m/s speed, or calm. There was no precipitation. Fog, or icy fog, was observed, and the diameter of the frost deposit was 25 mm. There was a strong inversion of about 10°C from the surface to the level of 920 hPa (approximately 660 m).

The results of measurements on 22.01.2022 showed that good air quality with a concentration of $PM_{2.5}$ less than 10 μg/m^3 (AQI<50) was observed only at background points 2 and 14, located outside the city. The northeastern part of Apatity has better air quality than the southwestern part. At points 1, 3 (Tik-Guba village), 8 (near ANOF-2), 9, 13 and 18 (located on the side of a highway outside the city limits), air quality is satisfactory, on average, at about 20 μg/m^3, that is 8 times lower than 20 min MAC of 160 μg/m^3. The corresponding AQI index for $PM_{2.5}$ in these points is less than 100. At points 5 and 7 (southwestern part of the city), a hazardous level of $PM_{2.5}$ was recorded (300.94 μg/m^3 and 269.91 μg/m^3, respectively, that is approximately 1.9 and 1.7 times higher than 20 min MAC).

The measurements on the night of 25.01.2024 to 26.01.2024 were carried out between approximately 23:30 and 03:00. The northwesterly wind was of about 5 m/s with gusts up to 8 m/s. The first half of the measurement period was accompanied by showers of slight snow, which turned into light or moderate drifting snow closer to 03:00. The main meteorological parameters are presented in Table 5, and the results of measurements are presented in Table 6 and in Fig. 4.

The low-level clouds and clouds of vertical development were presented by Cb, Cu, St, and Frnb at 00:00 and by Sc at 3:00. The middle-level clouds were presented by Ac or Ac with As or Ns.

Very low $PM_{2.5}$ concentrations were obtained during this route. The single instantaneous outliers of values during the measurements led to average concentration values less than measurement error levels. Formally, the estimated measurement error was added to the data in Table 6 with a sign plus/minus for uniformity, but, of course, there can be no negative concentrations.

On the night from 25.01.2024 to 26.01.2024, the measurements detected very good air quality. This may be related to meteorological conditions: the day before

Table 3. Meteorological parameters for the period of 12:00-15:00, 22.01.2022

Time	T, °C	P_0, mmHg	P, mmHg	P_a, mmHg	DD	Ff, m/s	U, %	N, %	Nh, %
12:00	-18.2	751.3	764.9	0.1	-	-	94	100	60
15:00	-18.6	751.4	765.1	0.1	East – South-East	1	93	100	40

Table 4. Results of $PM_{2.5}$ concentration measurements during the period 11:00 – 15:00, 22.01.2022

№ of point	AQI value	$PM_{2.5}$, μg/m^3	№ of point	AQI value	$PM_{2.5}$, μg/m^3
1	69.47 ±7.77	19.01 ±1.40	10	136.03 ±12.76	49.73 ±2.30
2	36.69 ±8.31	6.61 ±1.50	11	132.17 ±8.29	48.16 ±1.49
3	73.03 ±10.39	20.92 ±1.87	12	103.06 ±12.65	36.33 ±2.28
4	164.81 ±2.81	75.19 ±0.51	13	75.33 ±11.95	22.16 ±2.15
5	374.86 ±63.86	300.94 ±16.00	14	38.06 ±10.92	6.85 ±1.97
6	150.19 ±11.95	54.35 ±2.15	15	90.03 ±9.06	30.05 ±1.63
7	335.19 ±20.08	260.91 ±3.61	16	165.00 ±8.47	75.47 ±1.52
8	69.36 ±6.25	18.96 ±1.12	17	126.06 ±8.62	45.68 ±1.55
9	73.00 ±8.73	20.91 ±1.57	18	72.06 ±6.40	20.40 ±1.15

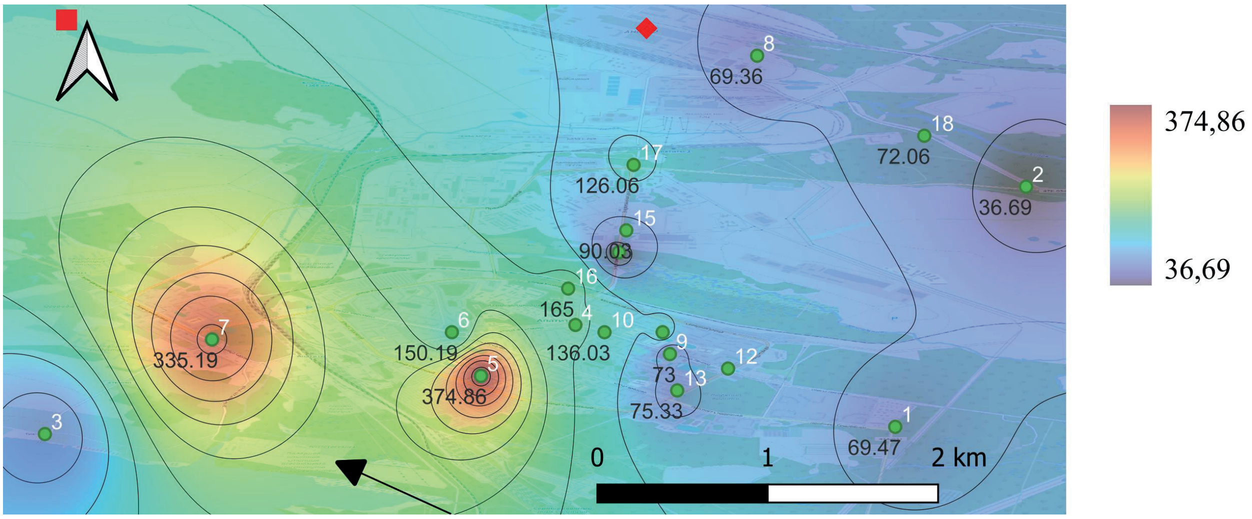

Fig. 3. Spatial distribution of AQI values in Apatity according to measurement data, 11:00-15:00, 22.01.2022. The points denote measurement sites, the numbers of key points are denoted in white color, the red diamond indicates the position of ANOF-2, the red square indicates the part of the ANOF-2 "tailings dump", the black arrow shows the mean wind direction

Table 5. Meteorological parameters for the period of 00:00-03:00, 26.01.2022

Time	T, °C	P_0, mmHg	P, mmHg	P_a, mmHg	DD	Ff, m/s	U, %	N, %	Nh, %
00:00	-2.4	746.6	759.3	1.1	North-West	5	79	90	60
03:00	-3.0	747.2	760.0	0.6	North-West	5	81	70-80	50

Table 6. Results of measurements during the period 23:30-03:00, the night from 25.01.2024 to 26.01.2024

№ of point	AQI value	$PM_{2.5}$, µg/m³	№ of point	AQI value	$PM_{2.5}$, µg/m³
1	2.86 ±3.02	0.51 ±0.54	11	1.71 ±2.14	0.31 ±0.38
2	2.29 ±3.15	0.41 ±0.57	12	0.57 ±1.51	0.10 ±0.27
3	1.71 ±2.14	0.31 ±0.38	13	0.57 ±1.51	0.10 ±0.27
4	3.57 ±7.83	0.64 ±1.41	14	1.71 ±2.14	0.31 ±0.38
5	0.57 ±1.51	0.10 ±0.27	15	2.29 ±3.15	0.41 ±0.57
6	1.14 ±1.95	0.21 ±0.35	16	0.57 ±1.51	0.10 ±0.27
7	0.00 ±0.00	0.00 ±0.00	17	0.00 ±0.00	0.00 ±0.00
8	0.00 ±0.00	0.00 ±0.00	18	2.86 ±1.95	0.51 ±0.35
9	0.57 ±1.51	0.10 ±0.27	19	0.00 ±0.00	0.00 ±0.00
10	2.86 ±3.02	0.51 ±0.54	20	1.71 ±2.14	0.31 ±0.38

measurements had a moderate westerly to northwesterly wind (5-6 m/s). There was no pronounced diurnal temperature variation, and during the measurements, precipitation in the form of snow was observed. Thus, the conditions were favorable for good mixing. During the nighttime measurements, there were practically no pollution sources. Precipitation also contributed to air purification.

In the afternoon of 26.01.2024 measurements were carried out approximately from 14:00 to 17:30 in conditions of weak (about 1 m/s) westerly wind and showers of slight snow. A very slight elevated inversion of about 2°C was observed at an altitude of 800 hPa. The corresponding meteorological parameters are presented in Table 7, and the results of measurements are presented in Table 8 and in Fig. 5.

The low-level clouds and clouds of vertical development were presented by Cb with St, Frnb (or without them). The middle-level clouds were presented by Ac or Ac with As or Ns in the first half of the day. Near 18:00, there were no mid-level clouds.

The measurement results in the afternoon of 26.01.2024 again demonstrated the difference between the air quality in different parts of Apatity. At point 7, the $PM_{2.5}$ concentration was actually 0, and at point 3 (Tik-Guba), the mean concentration was less than the measurement error level. The southwestern part of the city is more polluted than its northeastern part. The concentration of $PM_{2.5}$ did not reach health hazardous levels. At points 15 and 16 in the southwest and south of the city, the maximum values of $PM_{2.5}$ were obtained, which are 2.8 and 3.8 times lower than the instant (20min) MAC, respectively.

The last series of measurements was carried out on the afternoon of 31.01.2024 in the period from 12:00 to 15:00 in light wind conditions (calm around 12:00, turning into a light north wind up to 1m/s closer to 15:00) and an elevated

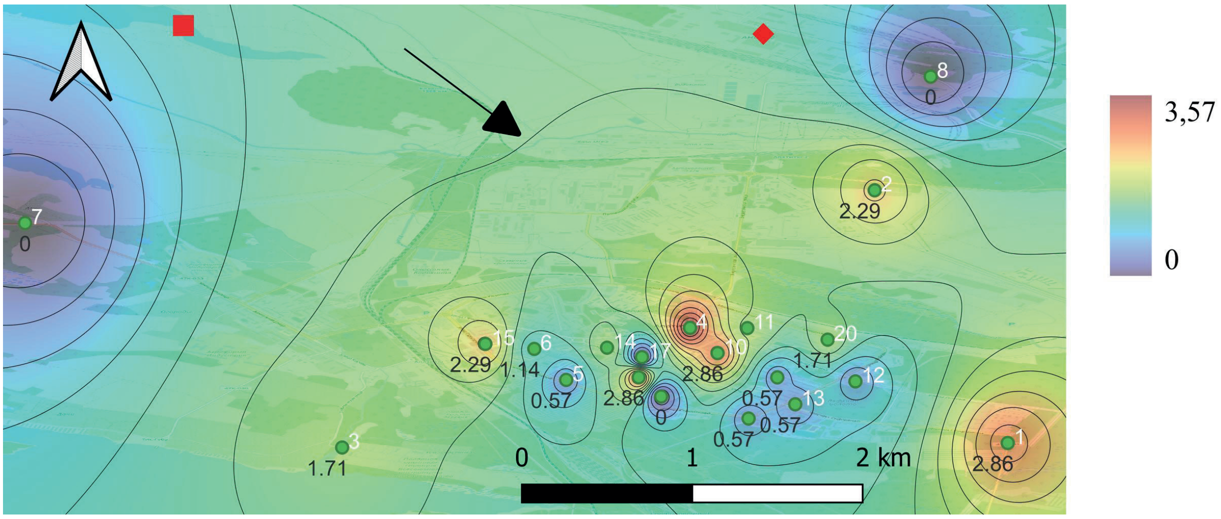

Fig. 4. Spatial distribution of AQI values in Apatity according to measurement data, 23:30-03:00, the night from 25.01.2024 to 26.01.2024. The points denote measurement sites, the numbers of key points are denoted in white color, the red diamond indicates the position of ANOF-2, the red square indicates the part of the ANOF-2 "tailings dump", the black arrow shows the mean wind direction

Table 7. Meteorological parameters for the period of 12:00-18:00, 26.01.2022

Time	T, °C	P_0, mmHg	P, mmHg	P_a, mmHg	DD	Ff, m/s	U,%	N, %	Nh, %
12:00	-5.0	748.1	760.9	-0.3	West	1	93	90	40
15:00	-4.7	747.5	760.3	-0.6	West	1	93	100	70-80
18:00	-5.2	746.9	759.7	-0.6	-	-	95	100	100

Table 8. Results of measurements in the daytime during the period 14:00-17:30 on 26.01.2024

№ of point	AQI value	$PM_{2.5}$, μg/m^3	№ of point	AQI value	$PM_{2.5}$, μg/m^3
1	54.43 ±8.41	10.94 ±1.51	11	22.86 ±3.61	4.11 ±0.65
2	16.71 ±1.90	3.01 ± 0.34	12	16.21 ±6.14	2.92 ±1.11
3	1.71 ±2.58	0.31 ±0.47	13	52.86 ±10.29	10.10 ±1.85
4	22.50 ±6.24	4.05 ±1.12	14	17.57 ±4.93	3.16 ±0.89
5	71.93 ±12.50	20.33 ±2.25	15	152.14 ±3.37	57.13 ±0.61
6	32.36 ±6.06	5.82 ±1.09	16	115.86 ±7.39	41.53 ±1.33
7	0.00 ±0.00	0.00 ±0.00	17	9.00 ±3.04	1.62 ±0.55
8	33.86 ±7.41	6.09 ±1.33	18	20.07 ±5.90	3.61 ±1.06
9	27.79 ±3.64	5.00 ±0.66	19	84.50 ±8.83	27.08 ±1.59
10	22.93 ±3.87	4.13 ±0.70	20	27.43 ±6.70	4.94 ±1.21

inversion of about 6°C from the level of 875 hPa to 800hPa. Precipitation was not observed during the measurement period. The meteorological parameters are presented in Table 9, and the results of measurements are presented in Table 10 and in Fig. 6.

The low-level clouds were presented by Sc, and the middle-level clouds were presented by Ac or Ac with As or Ns. Near 12:00 high-level clouds (Ci fib, sometimes Ci unc.) were also observed.

The measurements on 31.01.2024 showed no clear division into southwest and northeast parts of the city based on the air quality. No health hazardous $PM_{2.5}$ concentration values were observed. AQI values exceeded 70 at points 4, 15, and 18 within the urban area, as well as at point 3 at Tik-Guba on the lakeshore.

DISCUSSION

The study demonstrated the pronounced difference in air quality under varying winter conditions. In the "classic" cold winter of the Kola Peninsula with strong temperature inversions, $PM_{2.5}$ concentrations, which are unfavorable (and sometimes dangerous for human health) may be found in the city. In the afternoon of 22.01.2022, concentrations in its southwestern part were recorded to exceed the 20-min MAC of $PM_{2.5}$ by approximately 1.9 times. The maxima generally were located near the automobile road (Sovetskaya street) with an extensive territory occupied by garages and by low-rise residential buildings to the south. High concentrations of $PM_{2.5}$ were largely related to fuel combustion in the aforementioned buildings for heating purposes. The measurements were

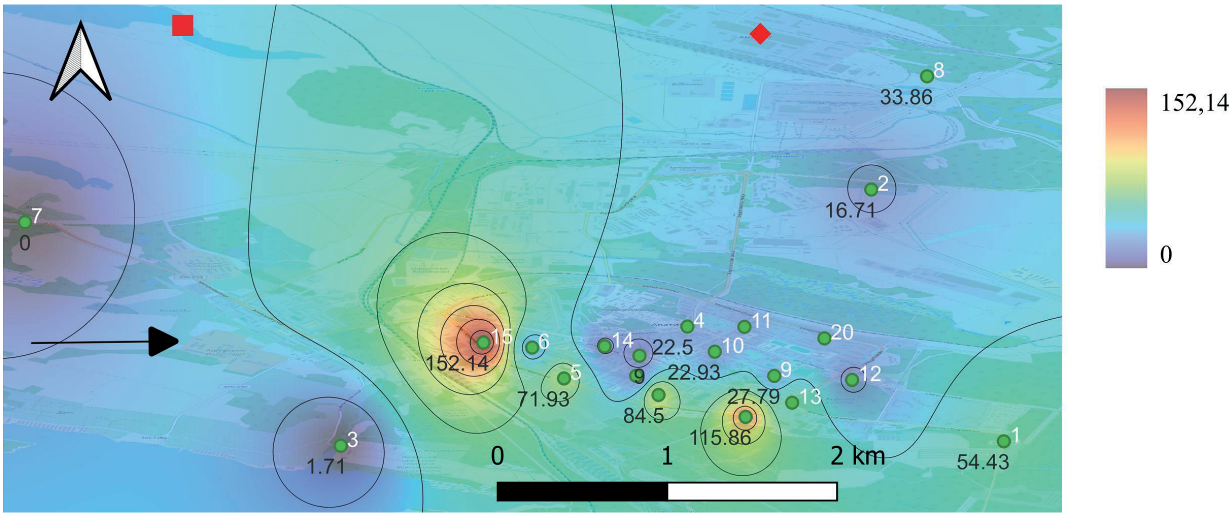

Fig. 5. Spatial distribution of AQI values in Apatity according to measurement data, 14:00-17:30, 26.01.2024. The points denote measurement sites, the numbers of key points are denoted in white color, the red diamond indicates the position of ANOF-2, the red square indicates the part of the ANOF-2 "tailings dump", the black arrow shows the mean wind direction

Table 9. Meteorological parameters for the period of 12:00-15:00, 31.01.2022

Time	T, °C	P_0, mmHg	P, mmHg	P_a, mmHg	DD	Ff, м/с	U, %	N, %	Nh, %
12:00	-3.5	735.7	748.2	-0.7	-	-	69	90	60
15:00	-2.3	735.0	747.4	-0.7	North	1	81	100	70-80

Table 10. Measurement results during the period 12:00-15:00, 31.01.2024

№ of point	AQI value	$PM_{2.5}$, μg/m³	№ of point	AQI value	$PM_{2.5}$, μg/m³
1	7.58 ±2.34	1.37 ±0.42	11	46.46 ±7.69	8.36 ±1.38
2	50.17 ±3.95	8.65 ±0.71	12	8.17 ±2.66	1.47 ±0.48
3	82.50 ±40.05	26.01 ±7.21	13	16.67 ±3.05	3.00 ±0.55
4	85.46 ±54.62	27.59 ±11.04	14	26.25 ±7.26	4.73 ±1.31
5	21.00 ±9.79	3.78 ±1.76	15	80.50 ±17.16	24.93 ±3.09
6	19.46 ±5.84	3.50 ±1.05	16	14.54 ±3.55	2.62 ±0.64
7	5.33 ±1.93	0.96 ±0.35	17	19.29 ±6.84	3.47 ±1.23
8	15.42 ±4.52	2.78 ±0.81	18	71.50 ±6.67	20.10 ±1.20
9	27.54 ±9.78	4.96 ±1.76	19	54.63 ±1.64	11.05 ±0.29
10	23.42 ±3.39	4.22 ±0.61	20	48.46 ±5.87	8.72 ±1.06

carried out in calm conditions or very weak wind of the East–South-East direction. There was also a calm in the previous hours (from 06:00 to 12:00) or a wind of the east or southeast direction up to 1 m/s (at night). Therefore, since ANOF-2 and its tailings dump are located to the north and northwest of the city, respectively, the observed high concentrations of $PM_{2.5}$ in the southern and southwestern parts of the city cannot be associated with advection from the enterprise. Thus, when winter inversions are observed, stove heating can contribute to the accumulation of hazardous concentrations of $PM_{2.5}$.

Routine air quality measurements in the afternoon of 26.01.2024 from 14:00-17:30 also showed the negative difference in the air quality between the southwestern part of the city and its northeastern part. A western wind of less than 1 m/s was observed during this period, which ceased in the evening, and windless weather was established. Air temperatures ranged from -5 to -6°C. The $PM_{2.5}$ concentration values significantly increased compared to the night measurements conducted from 25.01.2024 to 26.01.2024, specifically from 23:30 to 3:00. $PM_{2.5}$ concentrations did not reach health-hazardous levels, but the maximum concentration values at the points 15 and 16 reached 0.4 and 0.3 of instant (20 min) MAC, respectively. Point 13 (the Pushkin City Park) was characterized by high values of $PM_{2.5}$ particle concentration in two cases out of three route measurements. This finding may be explained by the accumulation of pollution from nearby sources due to weaker ventilation under the plant canopy.

High values of $PM_{2.5}$ concentration at the southern and southwestern borders of the city correlate with wind direction and the assumption about the presence of pollution sources (automobile road, garages, stove heating) at the southern and southwestern outskirts of Apatity and in the nearest suburb. At the same time, in these meteorological conditions, urban development

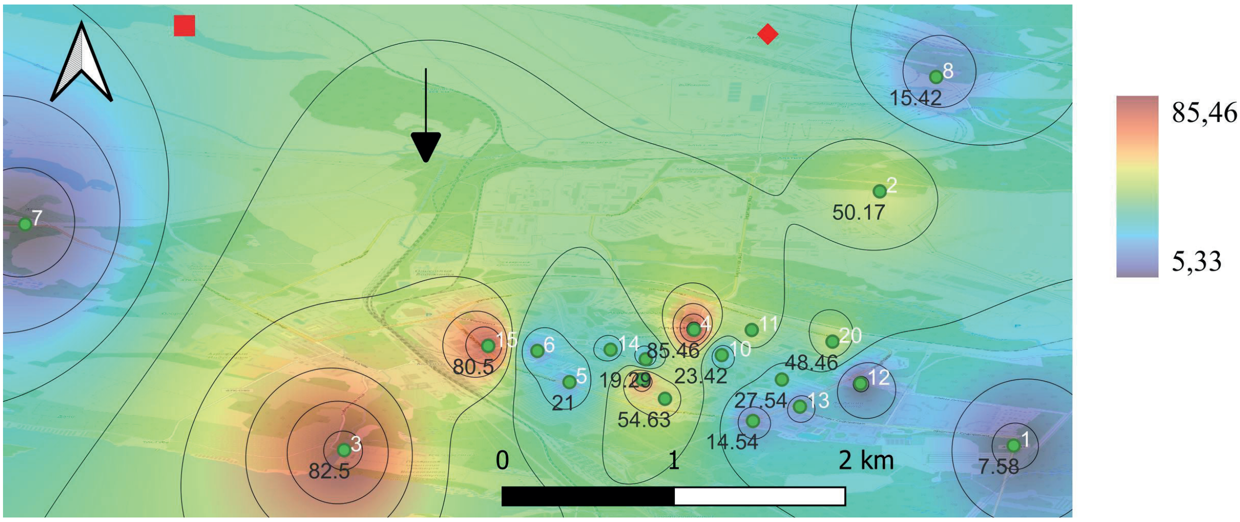

Fig. 6. Spatial distribution of AQI values in Apatity according to measurement data, 12:00-15:00, 31.01.2024. The points denote measurement sites, the numbers of key points are denoted in white color, the red diamond indicates the position of ANOF-2, the red square indicates the part of the ANOF-2 "tailings dump", the black arrow shows the mean wind direction

turns out to be a good barrier for pollution spreading, as there is an accumulation of $PM_{2.5}$ particles on the southern and southwestern border of the city, and it is enveloped by polluted air.

Final measurements of the air quality in Apatity were made in the afternoon of 31.01.2024 when weather conditions stabilized. The measurement period was characterized by light wind weather (the day before, 30.01.2024 there was a wind of western, northwestern direction with the speed of 2-4 m/s) and air temperatures between -2 and -3°C. An elevated temperature inversion of about 6°C was observed from the level of 875 hPa to 800 hPa. Maximum concentration values of $PM_{2.5}$ were observed at points 3, 4, 15 (>24.9 μg/m^3) and 18 (>20 μg/m^3). On the night of 31.01.2024, the wind was western or southwestern up to 3 m/s, which changed direction to eastern by 6:00. By 9:00, a calm was established, which lasted until 12:00. Closer to 15:00, a weak (up to 1m/s) northern wind was observed; therefore, closer to 15:00, an increase in the concentration of $PM_{2.5}$ in the northern part of the city may be explained by advection from ANOF-2. However, the high concentrations of $PM_{2.5}$ on the southern borders of the city and especially at point 3, located in the Tick-Guba village, are most likely related to the influence of stove heating because an accumulation of pollution happens in the conditions of windless weather and weak mixing.

At the time of measurements at point 15, snow plowing equipment was operating nearby. Therefore, a series of measurements was carried out directly at point 15 and at a distance of about 100 m from it in the visibility zone of snowplowing equipment. The mean $PM_{2.5}$ concentration values were almost identical (about 25 μg/m^3). However, the values in the nearest point 6 (two front yards separated from point 15 by residential buildings) were significantly lower (about 3.5 μg/m^3). It suggests that, under the conditions of weak mixing, urban development (mainly 5-storey buildings) in Apatity contributes to the accumulation of pollution near medium-height residential houses in the presence of sources. However, the same apartment buildings prevent a significant spatial spread of pollution.

CONCLUSIONS

During the winter expeditions of 2022 and 2024, we observed wide range variability of synoptic situations and study the microclimate of Apatity under conditions of a "classic" cold winter, with the temperature inversions that prevent air mixing present, as well as "warm" conditions for Russian Arctic. The conducted measurements allow us to better understand the effect of climatic changes on the region and its microclimatic features. Measurement results have demonstrated that, under the conditions of temperature inversion in the city, dangerous levels of $PM_{2.5}$ particle pollutant concentrations (up to 300 μg/m^3, that is approximately 1.9 times higher than 20 min MAC = 160 μg/m^3) are observed. A number of observations indicate that such pollution is largely caused by motor vehicles and fuel combustion for heating purposes in low-rise residential areas. In addition, the study has established that warm winters, characterized by higher wind speeds due to cyclonic activity and heavy precipitation, significantly improve air quality in the city of Apatity.

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