Research Article

# An Interdisciplinary Approach to Predicting the Effects of Transboundary Atmospheric Transport to Northwest European Neighboring States

**Natalia Belisheva*, Alla Martynova, and Roman Mikhaylov**

Research Centre for Human Adaptation in the Arctic, Branch of the Federal Research Centre "Kola Science Centre of the Russian Academy of Science

**ORCID**
Natalia Belisheva: 0000-0002-5504-2983
Alla Martynova: 0000-0002-0701-8698
Roman Mikhaylov: 0000-0003-3744-787X

**Abstract.** The Kola North is the most industrial territory of the Arctic region, where enterprises are sources of sulfur dioxide (SO2), which disperses widely not only throughout the Kola North, but also to the territories of neighboring Northwest European countries: Norway and Finland. The purpose of this study was to reveal the main sources of atmospheric $SO_2$ pollution in the Kola North, assess the possible contribution of $SO_2$to the morbidity of respiratory diseases among children in the region, study the daily dynamics of $SO_2$ content, and examine the likelihood of transboundary transport to neighboring states. The pathways of $SO_2$ transfer throughout 2020 were revealed by using daily data about $SO_2$ surface mass, wind direction and speed selected from the Geographic Information System for the cities of Zapolyarny (69°24′55″ N, 30°48′48″ E) and Olenegorsk (68°08′35″ N, 33°15′10″ E). It was found that the prevalence of pneumonia in 0-14-year-old children was associated with Olenegorsk, where the maximum of $SO_2$ emissions was detected. The median values of $SO_2$ surface mass were 2.7 times higher for Olenegorsk than for Zapolyarny and exceeded the maximum permissible concentration. The probability of $SO_2$ transport to the territories of Norway and Finland was also estimated. This study highlights the complexity of the problem of transboundary airborne pollution transport, which requires interdisciplinary research to predict the consequences of the contamination for territories of the neighboring Northwest European countries.

**Keywords:** Kola North, sulfur dioxide, respiratory morbidity among children, transboundary atmospheric transport, neighboring states

Corresponding Author: Natalia Belisheva; email: natalybelisheva@mail.ru

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## 1. Introduction

The Kola North is the most industrial territory of the Arctic region. The peculiarity of the territorial distribution of the industries of the Kola North is in the high density of enterprises and cities in the central part of the Kola Peninsula: in the south-to-north direction with branches to the west (Kandalaksha), to the east (Olenegorsk with the

Lovozero industrial hub), and to the north-west near Murmansk (Pechengsky industrial site). All large city-forming enterprises are located in these districts and they create conditions for the wide distribution of pollutants not only throughout the Kola North, but also to territories of neighboring Northwest European countries: Norway and Finland. Sulfur Dioxide ($SO_2$)is one of the most widespread atmospheric pollutants on the Kola Peninsula. Sulfur dioxide and particles emitted from the combustion of Sulphur-containing fuels are major air pollutants in urban areas, and $SO_2$ is the principal pollutant associated with the acid deposition problem. Sulphur dioxide and particulate matter are constituents of a complex pollutant mixture, and are often analyzed together, since their effects are virtually indistinguishable [1].

Air pollution has long been linked with illnesses, particularly with respiratory symptoms and diseases [2, 3, 4, 5]. “If we don’t take urgent action on air pollution, we will never come close to achieving sustainable development.” says Dr Tedros Adhanom Ghebreyesus, Director-General of WHO. WHO recognizes that air pollution is a critical risk factor for noncommunicable diseases (NCDs), causing an estimated one-quarter (24%) of all adult deaths from heart disease, 25% from stroke, 43% from chronic obstructive pulmonary disease, and 29% from lung cancer. Air pollution does not recognize borders. Improving air quality demands sustained and coordinated government action at all levels. Countries need to work together on solutions for sustainable transport, more efficient and renewable energy production and use and waste management [6]. Some studies have found associations between outdoor air pollution by $SO_2$ and different measures of respiratory health in children [3, 7, 8, 9, 10, 11].

The Committee of the Environmental and Occupational Health Assembly of the American Thoracic Society concludes that a long-range goal of air pollution research is to understand the contribution of air pollution to total respiratory, cardiovascular, and allergy morbidity and mortality. These purposes are achieved through multidisciplinary research including epidemiologic studies, controlled human studies, and animal and *in vitro* studies [10]. Compilation of information on emissions inventory, land cover and urban morphology, meteorology, and atmospheric chemistry enables air quality models to be developed and to be used as a tool for forecasting potential air pollution episodes, as well as evaluating past episodes and the efficiency of control measures. The air quality forecast can alert the public in advance about critical pollution levels, helping to prevent exposure to harmful pollutants [4].

The purpose of this study is to reveal the main sources of atmospheric $SO_2$pollution in the Kola North, to assess territorial respiratory morbidity patterns in children, to study the daily dynamics of the $SO_2$Surface Mass in the selected areas and the likelihood of trans-boundary transport to the neighboring states. This study shows the complexity of the problem of trans-boundary transport of atmospheric pollution, the solution of which requires interdisciplinary research to predict the consequences of air contamination in the neighboring states of North-West Europe.

## 2. Material and methods

The cities of Zapolyarny (69°24′55″ N, 30°48′48 ″ E) and Olenegorsk (68°08′35″ N, 33°15′10″ E) were selected as the sources of atmospheric contamination in the Kola North to be studied. Daily values of sulfur dioxide (SO2) Surface Mass (µg/m3), Wind direction (in degrees) and Wind speed (km/h) at 0, 6, 12, 18 hours (Local Time) throughout 2020 for these two cities were selected from GIS (https://earth.nullschool.net/ru/). For the GIS site, data of Air chemistry and Aerosol are taken from GEOS-5 (Goddard Earth Observing System) GMAO / NASA CAMS (Copernicus Atmosphere Monitoring System) Copernicus / European Commission + ECMWF and Weather Data are taken from GFS (Global Forecast System) EMC / NCEP / NWS / NOAA.

The Statistical Book ”Population Morbidity in the Murmansk region 2006-2010”, as well as data provided by the Murmansk Regional Medical Information and Analytical Center for 2011-2016 were used to selected the incidences of respiratory diseases among 0-14-year-old children. Average annual data for the period from 2006 to 2016 were used to evaluate incidences among children. The data were statistically processed by using the STATISTICA 10 software package; graphing was carried out using the graphic editor ORIGIN. The differences between data were considered significant at $p < 0.05$.

## 3. Results and discussion

### 3.1. The main sources of atmospheric pollution with sulfur dioxide on the Kola Peninsula

The Monchegorsk - Kolskaya Mining and Metallurgical Company (Kola MMC OJSC Combine ”Severonikel”); the Pechenga region - Kola MMC (OJSC MMC ”Pechenganikel”); the Apatity, the Kirovsk cities - OJSC ”Apatite”, the Apatity Thermal Power Plant (TPP); the Kovdor - OJSC Kovdorsky Mining and Processing Company (GOK); the Olenegorsk


**Figure** 1: The main sources of environmental pollution, including Zapolyarny and Olenegorsk, in the Murmansk Region (from [13]).

- OJSC "Olkon"; the Murmansk - OJSC "Murmanskaya TPP; the Lovozersky District - OJSC "Sevredmet" are the main sources of pollutant emissions into the atmosphere in the Kola North [12], Figure 1.

The Kola MMC is a mining and metallurgical enterprise for the extraction of sulfide copper-nickel ores and the production of non-ferrous metals. The production sites of the Kola MMC are located in three settlements of the Murmansk Region: Nikel and Zapolyarny in the north-west of the region, in close proximity to the Russian-Norwegian border, and Monchegorsk, situated at Lake Imandra.

The main sources of $SO_2$ emissions to the atmosphere are enterprises in the area of operation of the Kola MMC and in Olenegorsk area (according to selected data from https://earth.nullschool.net/), although there are many other enterprises in the Kola North that pollute the atmosphere.

Our studies show that in certain hours and days of the year $SO_2$ emissions in Zapolyarny and Olenegorsk areas exceed the daily average maximum permissible concentration (MPC), Figure 2.

Figure 2 shows examples of the daily average MPC of $SO_2$ emissions exceeded not only in Zapolyarny and Olenegorsk areas, but also in the atmosphere over Norway (Figure 2.1) and Finland (Figure 2.2) as a result of trans-boundary transfers. E.g., $SO_2$

concentration on December 27, 2020 at 12:00 in Norwegian territory exceeded the daily average MPC 3.8 times, and on December 26, 2020 at 15:00 in Finnish territory – 1.9 times. Figures 2.3 and 2.4 show $SO_2$ surface mass at Zapolyarny and Olenegorsk exceeding daily average MPC 3.5 and by12.6 times, respectively (MPC is 50 μg/$m^3$ as 24-h mean).

A comparison of daily $SO_2$ surface mass values for sites with geographical coordinates corresponding to Zapolyarny and Olenegorsk with Severonikel (67°54'59" N, 32°50'42" E) and Monchegorsk (67°56'22" N, 32°52'26" E), where maximum $SO_2$ air pollution could be expected, showed the maximum $SO_2$ surface mass to be associated with the Olenegorsk area.

### 3.2. The incidence of diseases associated with air pollution among children

Ambient air pollution has been associated with respiratory diseases in children , in particular, with asthma and pneumonia. Asthma is one a major childhood disease, with substantial morbidity [17,18]. The prevalence of childhood asthma increased markedly in Europe in the second half of the $20^{th}$ century. An example is the published studies of asthma in schoolchildren in Norway, which have reported an increase in prevalence from 0.4% in 1948 to 12.3% in the mid-1990s and 20% in a study performed in 2004, although the most recent study, in 2008, reported a retreat to 17.6% [19].

Pneumonia kills more children than any other infectious disease, claiming the lives of over 800,000 children under five every year, or around 2,200 every day. This includes over 153,000 newborns [20].

Sulfur dioxide can be a potential trigger for asthma exacerbation. It is known that asthmatics are sensitive to the effects of $SO_2$; however, the basis of this higher sensitivity remains incompletely understood [21]. It was also shown that exposure to $NO_2$ and $SO_2$ was associated with an increase in the incidence of pneumonia in Korea [5]. In addition, in two Central European cities with relatively high levels of air pollution (Prague, Czech Republic and Poznan, Poland), small-area based indicators of long-term outdoor winter concentrations of $SO_2$were associated with wheezing / whistling and with asthma diagnosed by a doctor [3].

To identify the possible contribution of the SO2 content in the air to respiratory diseases in children in the Murmansk Region (MR), a comparative analysis of the prevalence of asthma and pneumonia in children in areas with different SO2 surface mass values was carried out (Figure 3).

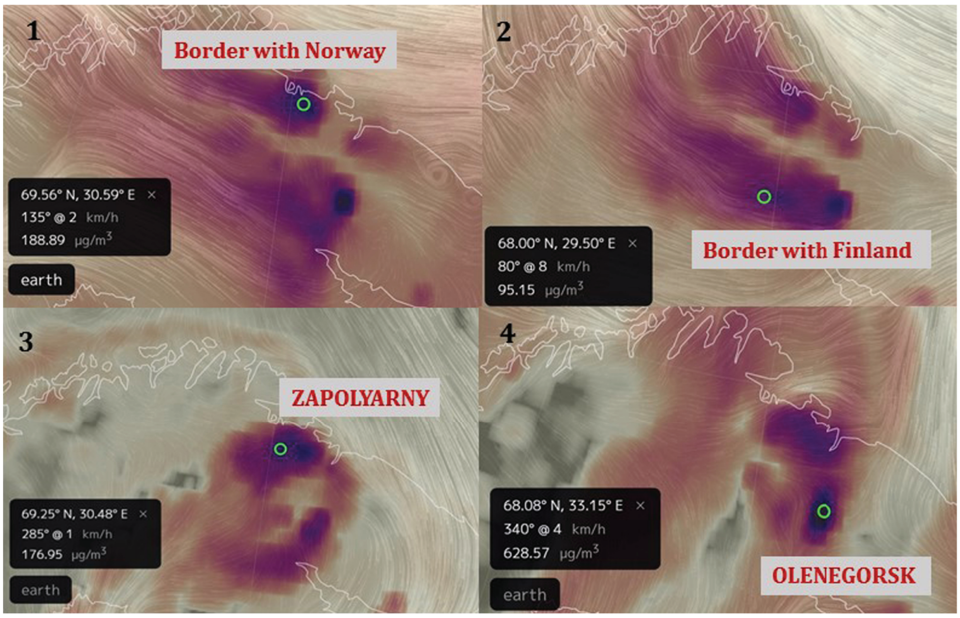
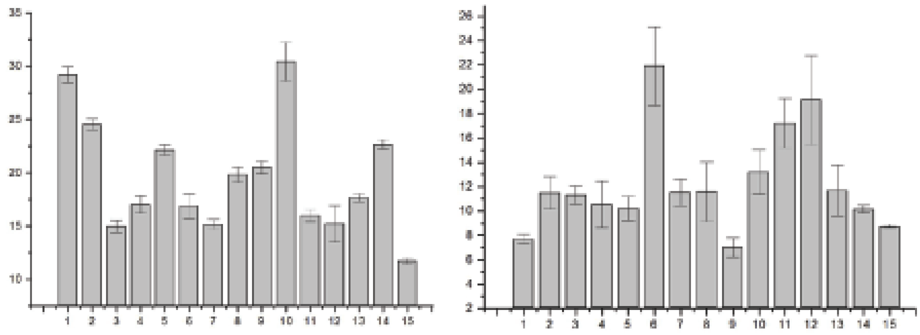



**Figure** 2: Examples of exceeding the maximum permissible concentration of sulfur dioxide at the earth's surface on the border with Norway 2020-12-27 at 12:00 (1), on the border with Finland 2020-12-26 at 15:00 (2), in Zapolyarny 2020 -05-20 at 06:00, and in Olenegorsk 2021-01-03 at 08:00, local time. The circles indicate the geographical coordinates of the sites.

Figure 3 shows the prevalence of asthma in MR (22.68±0.43) is higher (1.9-fold) than in the Russian Federation (RF) on average (11.75±0.26). In addition, the prevalence of asthma in children 0-14 years old in Murmansk, Apatity, and the Lovozersky District not only exceeds the corresponding indicators in RF (29.20±0.71; 24.55±0.50; 30.44±1.80, respectively), but is also higher than in Monchegorsk (22.17±0.52) and in MR on the whole.

The prevalence of pneumonia is also higher in MR (10.16±0.32) than Russia's average (8.76±0.16). However, the distribution of the highest incidence of pneumonia over the territory is different from that of asthma: the highest incidence of pneumonia was established for Olenegorsk (21±3.23), which is 2.5 times higher than in RF and 2.1 times higher than in MR. A high prevalence of pneumonia was also found for the Tersky, Pechenga, and Lovozersky Districts (19.2±3.6; 17.21±2.03; 13.18±1.84, respectively).

The spatial distribution of asthma prevalence most likely indicates the poly-etiology of this disease in the Murmansk Region and the indirect role of SO2 in the incidence of asthma. In particular, short- and long-term pollution with fine particulate matter (PM, particles <2.5 mm in aerodynamic diameter [PM2.5]) and exposure to higher average coarse PM levels are associated with increased asthma prevalence and morbidity [22]. Accordingly, it is exactly where dust particles are the most common (Murmansk, Apatity, Lovozersky District) [2] that we see a higher incidence of asthma.



A B

**Figure** 3: Prevalence of asthma (A) and pneumonia (B) in children 0-14 years old in certain territories of the Murmansk Region. On the abscissa: Murmansk (1), Apatity (2), Kandalaksha District (3), Kirovsk (4), Monchegorsk (5), Olenegorsk (6), ZATO Severomorsk (7), Kovdorsky District (8), Kolsky District (9), Lovozersky District (10), Pechenga District (11), Tersky District (12), Polyarnye Zori (13), Murmansk Region as a whole (14), Russian Federation (15). On the ordinate axis: average annual values of the diseases' prevalence per thousand members of the corresponding population group in the period 2006-2016 (*M*±*m*).

A different situation is demonstrated by the data on pneumonia prevalence. The highest pneumonia prevalence rates in children are associated with the territories where the greatest sources of $SO_2$ emissions are located: in Olenegorsk and in the Pechenga District. Other reasons for the high incidence of pneumonia are possible in the Tersky District. It was shown that, with the exception of CO, all pollutants (PM10, PM 2.5, $SO_2$, $NO_2$, $O_3$) were consistently associated with pediatric pneumonia hospitalization [15] and components of PM, such as elemental carbon, organic carbon, nitrates and copper, iron, potassium, nickel, silicon, vanadium, and zinc have been linked to early-life pneumonia [23].

Thus, it can be concluded that SO2 contributes to the incidence of pneumonia and may act as a co-factor in the asthma incidence in children in the Kola North.

### 3.3. Dependence of sulfur dioxide surface mass in areas with sources of its emission on wind direction and speed

It has been shown that the incidence of respiratory diseases depends on the content of $SO_2$ in the surface atmosphere [4] and on the duration of exposure [15]. Therefore, it is necessary to assess its daily content and variations depending on the direction and speed of the wind in order to predict the local and trans-boundary effects of $SO_2$ transport. Daily monitoring of $SO_2$ surface mass at 0, 6, 12, 18 hours throughout 2020 showed significant variations in hourly, daily, and monthly values of $SO_2$ surface mass depending on the geographic coordinates of the site, on the wind direction and its speed.

Figures 4 and 5 demonstrate the daily average variations in $SO_2$ surface mass in different months of 2020 in Zapolyarny and Olenegorsk.

As seen in Figure 4, the highest daily average values of $SO_2$ surface mass in Zapolyarny were detected in January, and the lowest values were detected in February and July. Moreover, $SO_2$ surface mass can significantly exceed the maximum permissible concentration (MPC) [14] in certain hours of the day: for example, 198.6 μg/m$^3$ at 12:00 on January 12, 2020 (with daily average values of 79.81±39.85); 115.31; 161.03; 67.5 μg/m$^3$ at 0, 6, and 12 hours on January 25, 2020 (with daily average values of 93.66±28.35). This means the risk of asthmatic attacks and other complications in the respiratory and other bodily systems increases in such days.

Comparison of daily variations in $SO_2$surface mass in Zapolyarny and Olenegorsk (Figure 5) shows the daily average values of $SO_2$in Olenegorsk surface air corresponded to the MPC only on 121 days of 2020 (33% of days in the year).

The obtained results indicate the residents of the Olenegorsk area are systematically exposed to the adverse effects of $SO_2$, which leads to the risk increase of the immunity weakening and to increase in the likelihood of respiratory diseases. The highest prevalence of pneumonia (Figure 3,B) in children at the Olenegorsk illustrates this assumption. And the toxic effect of $SO_2$ can further aggravate the health problems of the population of the Kola North, especially children, under decrease in the effectiveness of immune reactions in the inhabitants of the Arctic [24].

Since the $SO_2$ content in the surface atmosphere depends on the wind direction and speed, it is necessary to know the prevailing wind directions and speeds in a given territory in order to predict the most unfavorable periods for public health.

Percentile analysis showed (Table 1) the median values (50 percentiles) of $SO_2$ content in the surface air (20.91 μg/m3) in Zapolyarny did not exceed the MPC value. At the same time, the median $SO_2$values (57.38μg/m$^3$) in Olenegorsk did exceed the MPC values. The $SO_2$ content rose significantly above the MPC (95.19 μg/m$^3$) on 25% of days of the year in Olenegorsk, while exceedance of the MPC (52.36 μg/m3) in Zapolyarny was typical only for 10% of days. It should be noted the median values of $SO_2$ content in Olenegorsk were 2.7 times higher than in Zapolyarny, as well as above the 75, 90, 97.5 percentile values (by 3-; 2.6-; 2.3-fold, respectively).

Comparison of the prevailing wind directions in Zapolyarny and Olenegorsk shows the south-easterly wind direction with a predominance of the southern component (200°, or in the windrose network: SSE) is characteristic for these cities during six months (50 percentiles) in the year. Winds of the north-westerly (320° and 350° or NW and NNW directions) and north-easterly (5-15° and 40-60° or NNE and ENE) directions are typical

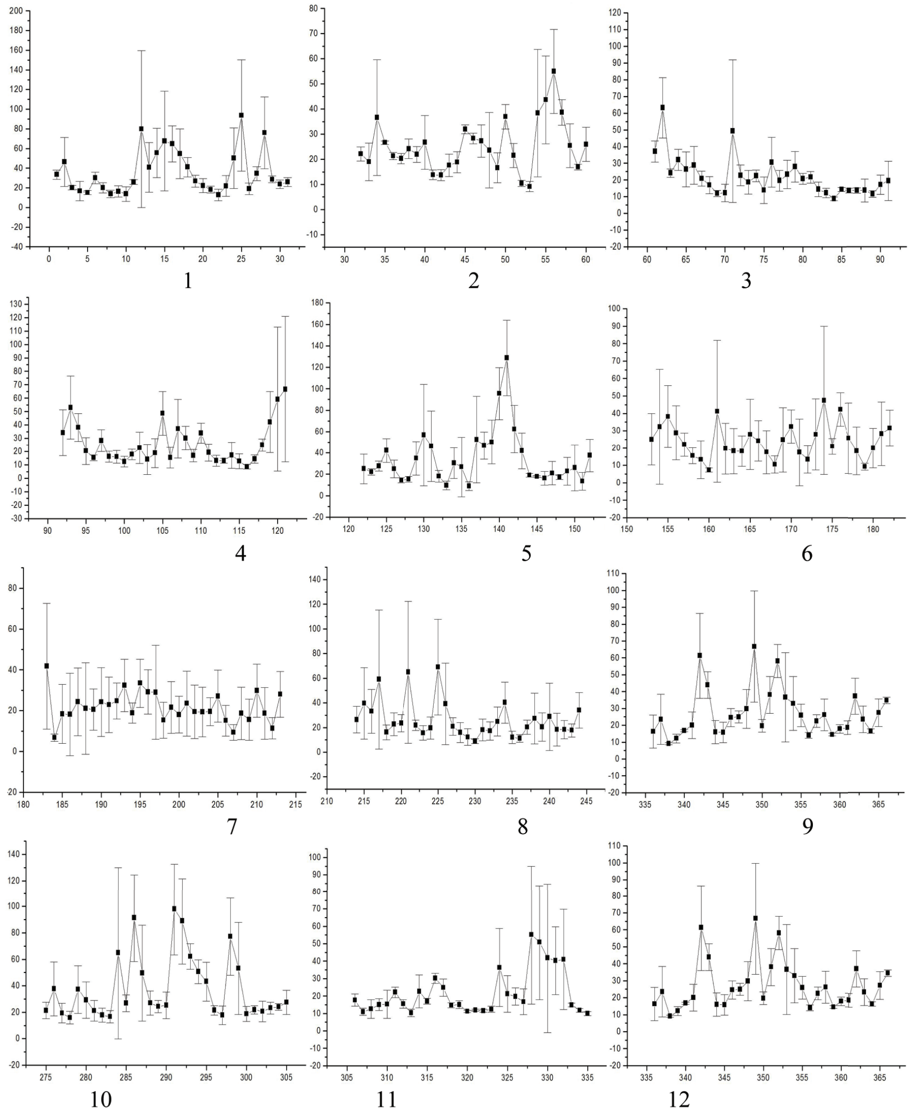


**Figure** 4: Dynamics of daily average values of sulfur dioxide ($SO_2$) surface mass in Zapolyarny area (69°24′55″ N, 30°48′48″ E) in different months of 2020: January (1), February (2) March (3) April (4) May (5) June (6) July (7) August (8) September (9) October (10) November (11) December (12). The abscissa shows the days of the year. Y-axis - $SO_2$Surface Mass ($M \pm \sigma$), μg/m$^3$.

in 10% cases (90 percentiles) in Zapolyarny and in Olenegovsk. The probability of $SO_2$ transport to Norway increases (corresponds to 25 percentiles) when the wind blows from the SSE direction (150°, 165°). The probability of $SO_2$ transfer to Finland increases (10 percentiles) when the wind blows from the NE and ENE directions.

Matrix correlation analysis was carried out to identify the links between daily $SO_2$ surface mass, wind direction and speed. The analysis revealed significant ($p < 0.05$) correlation coefficients between $SO_2$ values and wind direction (r = - 0.29), between $SO_2$ and wind speed (r = - 0.58), between wind direction and speed (r = 0.22) for Zapolyarny. For Olenegorsk, significant ($p < 0.05$) correlation coefficients were also revealed between $SO_2$ values and wind speed (r = - 0.59), between wind direction

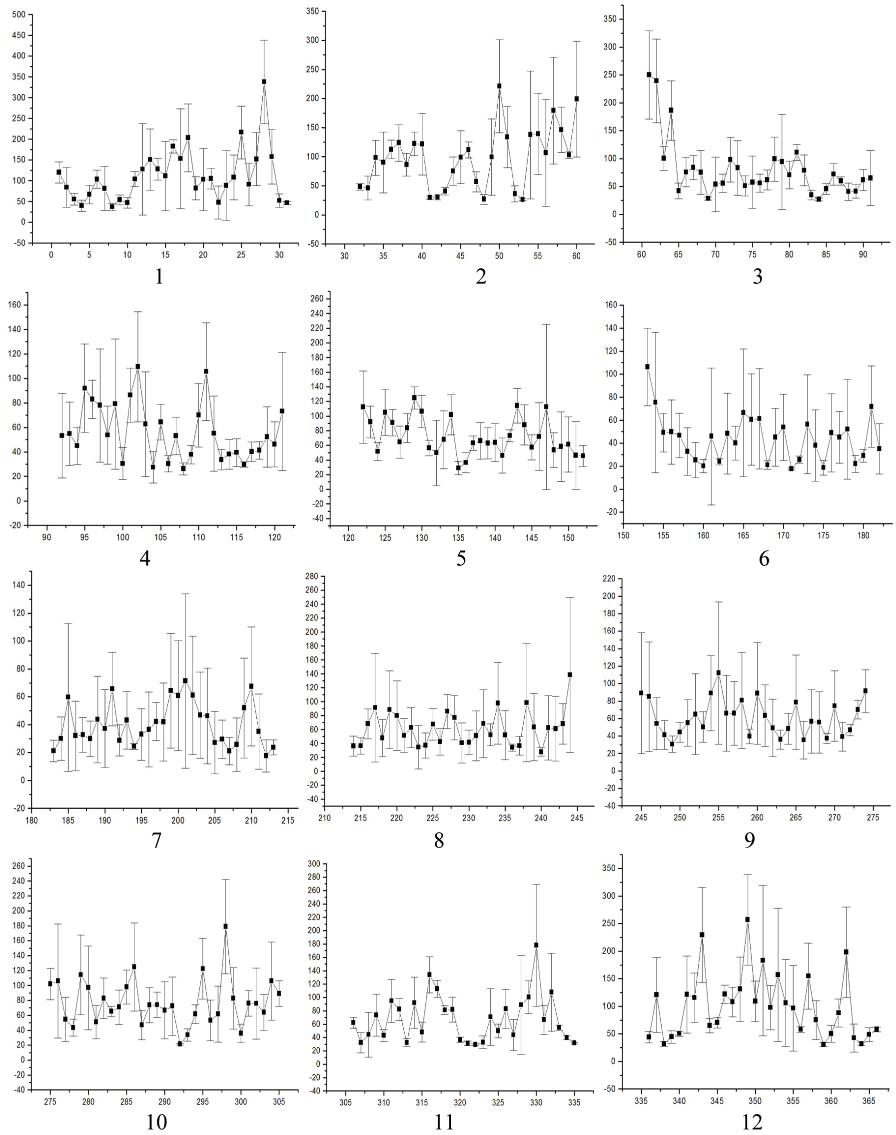


**Figure** 5: Dynamics of daily average values of sulfur dioxide ($SO_2$) surface mass in Olenegorsk area (68°08′35″ N, 33°15′10″ E) in different months of 2020: January (1), February (2 ) March (3) April (4) May (5) June (6) July (7) August (8) September (9) October (10) November (11) December (12). The abscissa shows the days of the year. Y-axis - $SO_2$surface mass ($M \pm \sigma$), μg/m$^3$.

and speed (r = 0.23), but not between $SO_2$ and wind direction (r = 0.10; p> 0.05). These correlations between $SO_2$ air pollution and wind parameters reveal certain trends, which can form the basis for long-term prediction of unfavorable days of the year for the cities of Zapolyarny and Olenegorsk, as well as for trans-boundary $SO_2$ transport to Norway and Finland.

Our results demonstrate that Olenegorsk city territory is more critical in terms of $SO_2$ emissions than Zapolyarny despite the higher wind speed in the Olenegorsk area (wind speed, in accordance with all percentile values, is twice higher in Olenegorsk than in Zapolyarny).

Table 1: Percentiles for daily parameters: $SO_2$ (sulfur dioxide surface mass, μg/m$^3$), wind° (wind direction in degrees), wind (wind speed at the indicated altitude, km/h), recorded at 0, 6, 12, 18 hours during 2020 at geographic coordinates corresponding to the location of Zapolyarny (1) and of Olenegorsk (2).

| Parameters | | | | percentiles | | | |
|---|---|---|---|---|---|---|---|
| | **2.5** | **10** | **25** | **50** | **75** | **90** | **97.5** |
| SO2_1 | 6.92 | 9.55 | 13.69 | 20.91 | 31.38 | 52.36 | 95.30 |
| SO2_2 | 16.07 | 24.05 | 33.28 | 57.38 | 95.19 | 137.36 | 225.40 |
| Wind°_1 | 15.00 | 60.00 | 150.00 | 200.00 | 260.00 | 320.00 | 350.00 |
| Wind°_2 | 5.00 | 40.00 | 165.00 | 200.00 | 245.00 | 320.00 | 350.00 |
| Wind _1 | 0.80 | 1.60 | 2.60 | 4.10 | 6.20 | 8.30 | 10.30 |
| Wind _2 | 2.00 | 4.00 | 6.00 | 10.00 | 15.00 | 21.00 | 28.00 |

## 4. Conclusions

In this research we found the main sources of atmospheric SO2pollution in the Kola North, which include the cities of Zapolyarny (69°24′55″ N, 30°48′48″ E) and Olenegorsk (68°08′35″ N, 33°15′10″ E), the latter being more critical in terms of SO2 emissions. We show that in certain days SO2 emissions exceed the daily average maximum permissible concentration (MPC) of SO2 surface mass not only in these two cities but also in Norwegian and Finnish as a result of trans-boundary transport from the Kola North.

Analysis for possible correlation between atmospheric pollution with $SO_2$ and respiratory disease morbidity in the Kola North revealed a clear association of pneumonia in children with the main sources of $SO_2$emissions. The highest prevalence of pneumonia was registered in Olenegorsk, where it was 2.5 times higher than the Russian average and 2.1 times higher than in the Murmansk Rregion as a whole. The distribution of asthma prevalence over the territory points to a probable poly-etiology of this disease in the Murmansk Region and the indirect role of $SO_2$in the incidence of asthma. Dust particles may contribute to the asthma prevalence in children in the Kola North. Where dust particles are the most common (Murmansk, Apatity, Lovozersky District), we see a higher incidence of asthma in children.

Daily monitoring of the $SO_2$surface mass at 0, 6, 12, 18 hours throughout 2020 year showed significant variations in hourly, daily, and monthly values of $SO_2$ content in the surface air depending on the geographic coordinates of the site, wind direction and its speed. We estimated the probability of $SO_2$ transport to Norway and Finland by using the percentile analysis. The probability of $SO_2$ transport to Norway proved to increase when the wind blew from the SSE direction. When the wind blows from the NE and ENE directions, the probability of $SO_2$ transfer to Finland increases.

This study highlights the complexity of the problem of trans-boundary air-borne pollution transport, the solution of which requires interdisciplinary research to predict the consequences of air contamination in the territories of the neighboring Northwest European states. Such research should include epidemiologic studies, controlled human studies, animal and in vitro studies, studies of the land cover and urban morphology, meteorology and atmospheric chemistry. Multidisciplinary research would enable air quality models to be developed and used as a tool for forecasting potential air pollution episodes, as well as evaluating past episodes and the efficiency of control measures.

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## Conflict of Interest

No conflict of interest

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