Geoecological analysis of NO₂ content in atmospheric air in cities in the north of Moscow region based on Earth remote sensing data

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Abstract. Satellite monitoring of the NO₂ content in the ambient air of populated areas is concurrently a specific and an innovative method of environmental monitoring. It provides information on NO₂ concentrations in locations where ground-based observation systems are not available. In particular, this is typical for three cities in the north of the Moscow region being Taldom, Dmitrov and Sergiyev Posad. Analysis of satellite data on the NO₂ content in the troposphere above the indicated territories showed that the average values of Taldom were 3.4E+15 molec/cm², Dmitrov – 4.0E+15 molec/cm², Sergiyev Posad – 4.2E+15 molec/cm² for the years 2005-2020. For comparison, these indicators were lower than the level of Moscow on average by more than two times. The main source of NO₂ for the study areas is, in general, Moscow.

1. Introduction

Air is a vital component of the environment and a natural mixture of gases in the atmosphere. The study of the composition and quality of atmospheric air in the settlements of the Russian Federation is an urgent problem, since more than 70% of the population of our country is concentrated in them. Moreover, about 40% of these people live in medium-sized (up to 100 thousand people) and small cities of Russia. Such cities are the ones in the north of the Moscow region, specifically, Taldom, Dmitrov and Sergiyev Posad. The choice of these territories is due to their high tourist and recreational potential and relative proximity to the largest metropolis of Russia being Moscow. The latter as a whole can have a certain impact on the air quality in these settlements.

People’s health, flora and fauna state, the durability and strength of any structures and constructions depend on air quality. The composition of the air is formed depending on natural climatic conditions and anthropogenic factors and has a large number of chemical elements including nitrogen dioxide [5].

Nitrogen dioxide (NO₂) is a binary inorganic compound of nitrogen with oxygen. This substance plays an important role in the chemical processes taking place in the atmosphere of the planet Earth. On the one hand, it, along with other nitrogen oxides (NOₓ), determines the oxidizing potential of the atmosphere, which affects its ability to self-purify from various pollutants. On the other hand (especially being in the troposphere), this substance can itself act as a pollutant and pose a serious environmental hazard. The choice of this substance is due to the fact that this gas is extremely toxic.
According to SanPiN 1.2.3685-21 [6], NO\textsubscript{2} belongs to the second hazard class. High concentrations of this substance in the air of populated areas can provoke various diseases in living beings, including humans. The main sources of nitrogen dioxide are natural (for example: lightning, volcanic eruptions) and artificial (combustion products of thermal power plants, vehicles) sources [5].

NO\textsubscript{2} concentrations are monitored using ground-based, aircraft, balloon and satellite observations. Moreover, the last of these types of observation enables to quickly obtain information about the state of the entire atmosphere of the planet Earth [9]. In this study, preference is given to satellite monitoring, since other types of observations of the quality of atmospheric air in the cities of the north of the Moscow region are absent on an ongoing basis.

The main goal of the research is to study and analyze the content of NO\textsubscript{2} in the atmospheric air in the cities in the north of the Moscow region based on the Earth remote sensing data.

To achieve the goal, the data of modern satellite monitoring devices for atmospheric air composition have been studied.

2. Getting initial data

NO\textsubscript{2} in the Earth’s atmosphere is determined by detecting the absorption of light by this substance in certain spectral ranges (≈ 400–500 nm) using satellite equipment (spectrometers).

The main instruments currently performing daily global mapping of NO\textsubscript{2} content in the vertical column of the atmosphere are as follows: Ozone Monitoring Instrument (OMI) on the EOS-Aura satellite (NASA), TROPOspheric Monitoring Instrument (TROPOMI) on the satellite Sentinel-5P (ESA), SCanning Imaging Absorption spectroMeter for Atmospheric CHartographY (SCIAMACHY) on the satellite ENVISAT (ESA) and others [9].

Satellite measurement is usually carried out in molecules of a substance on a certain measured square of the earth practically over the entire atmospheric layer, that is, the entire determined substance is measured in a certain square of the atmosphere. Data from each instrument are freely available and published on the official websites of the National Aeronautics and Space Administration (NASA, USA), the European Space Agency (European Union) and a number of other Internet portals [8].

The study favors OMI readings due to the large data coverage and acceptable resolution. An example of data retrieved from the OMI tool is shown in Figure 1.

The OMI spectrometer is on board the American research satellite Aura, which was launched in 2004 as part of the NASA Earth Observation System program. It measures solar radiation reflected by the atmosphere and the Earth’s surface in the range from 270 to 500 nm. The width of the surveyed strip of the surface is about 2,600 km, and the orbital period of the satellite is 98.5 minutes. This enables to measure NO\textsubscript{2} on a planetary scale and cover almost the entire Earth’s surface in one day. The pixel size when shooting on a global scale in the nadir direction is 13×24 km along and across the survey strip, respectively. The spectrometer measurement data are used to determine the vertical profiles of O\textsubscript{3}, as well as the concentrations of other chemicals being NO\textsubscript{2}, SO\textsubscript{2}, HCHO, BrO, and OClO, surface illumination and a number of cloud characteristics [9].

The algorithm assessing NO\textsubscript{2} includes several stages [1]. At the first stage, the total content of the measured gas component on an inclined path is determined using the DOAS (Differential Optical Absorption Spectroscopy) technique, which consists in minimizing the differences between the observed spectra and a linear combination of known molecular absorption spectra (NO\textsubscript{2}, O\textsubscript{3}, H\textsubscript{2}O), regarding the effects of aerosols, molecular and Raman scattering, surface albedo, and the Ring effect in the spectral range of 405–465 nm [1]. The slope content of NO\textsubscript{2} in the troposphere is defined as the difference between the slope concentrations of NO\textsubscript{2} in the entire atmospheric column and in the stratosphere. Further, based on the solution of the solar radiation transfer equation for various measurement conditions, the average optical path of the light beam in the atmosphere, characterized by the air mass coefficient AMF (Air Mass Factor), followed by the extraction of the tropospheric and stratospheric components, is calculated. The vertical gas content is calculated by dividing the slope by the AMF [7].
Figure 1. OMI instrument data on the NO$_2$ content in the troposphere over the territory of the Moscow region as of August 10, 2020. Survey spatial resolution: 0.25°x0.25°. Measurement unit: molecules/cm$^2$ [8]

The accuracy of determining the concentration of nitrogen dioxide depends on a combination of the following factors: measurement errors of the spectrometer, telemetry errors, accuracy of the solar radiation transfer model used, accuracy of the initial spectroscopic and a priori information, as well as algorithmic features [2].

Comparisons of tropospheric NO$_2$ data from the OMI spectrometer with ground-based monitoring data carried out by different scientists show that, on the whole, the data differ from each other – the correlation coefficient values for months are 0.6–0.7 [3]. It is noted that the greatest correspondence of the data is observed in the spring-summer period, the least – in winter. The total error of measurements carried out by OMI, according to the source [3], can reach 30-60%. Gruzdev A.N. [4] recommends using the OMI data with caution. It is also noted that even with such a relatively low accuracy, the data of the indicated spectrometer enables to obtain rather valuable information.

3. Initial data analysis
For geoecological analysis of the NO$_2$ content in the troposphere over the cities of the north of the Moscow region, daily data from the NASA electronic archive being Goddard Earth Sciences Data and Information Services Center [8] for the period from January 1, 2005 to December 31, 2020 were used.

The data were obtained for the points: Taldom city (coordinates: N 56.731041, E 37.528919), Dmitrov (coordinates: 56.345087, 37.519091), Sergiyev Posad (56.310465, 38.131228) and Moscow (Lianozovo region) (55.902027, 37.573494). The city of Moscow is used in the study exclusively for comparative analysis.

In just 5,844 days from 2005 to 2020, the OMI spectrometer managed to obtain data for 2,484 days for Taldom, 2,522 days for Dmitrov and 2,471 for Sergiyev Posad. On average, the specified time period is covered by data by 42.6%. During the rest of the time, data were not obtained due to the high percentage of cloudiness over cities or other reasons. Table 1 shows the number of days for each year
for which data were available. Analysis of the table shows that data covers on average about 150 days of the year for each specific city, of which about 118 days with simultaneous data coverage for all cities.

**Table 1.** Number of days per year for which data from the OMI instrument on the NO$_2$ content in the troposphere over the cities in the north of the Moscow region and over the city of Moscow are available [8]

| City / year | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 |
|-------------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|------|
| Taldom      | 194  | 174  | 191  | 175  | 144  | 164  | 157  | 160  | 151  | 178  | 134  | 119  | 117  | 167  | 134  | 125  |
| Dmitrov     | 190  | 173  | 196  | 177  | 144  | 166  | 155  | 166  | 155  | 182  | 141  | 123  | 117  | 171  | 135  | 131  |
| S.-Posad    | 184  | 170  | 191  | 182  | 141  | 166  | 145  | 158  | 147  | 173  | 141  | 119  | 116  | 175  | 131  | 132  |
| Moscow      | 192  | 182  | 187  | 167  | 134  | 156  | 133  | 157  | 139  | 165  | 137  | 116  | 112  | 173  | 127  | 131  |
| (Lianozovo district) | 152  | 139  | 151  | 140  | 109  | 127  | 110  | 123  | 112  | 134  | 105  | 83   | 87   | 137  | 98   | 89   |

The largest number of days for which data are available are in late spring, almost all summer and early autumn. In winter, there is little or no data available.

Table 2 gives a ranking of the days on which certain values of NO$_2$ concentrations were observed in the troposphere over the cities in the north of the Moscow region and in Moscow. Analysis of the table shows that in more than 70% of cases in cities the values 1E+16 or less NO$_2$ molecules per square centimeter (hereinafter molec/cm$^2$) of territories were denoted. In 29% of cases, the values varied from 1E+16 to 5E+16 molec/cm$^2$. On some days, values of more than 5E+16 were observed.

As for Taldom, the dates with the highest levels of NO$_2$ in the atmospheric air were in November 21, 2014 with a value of 4.31E+16 molec/cm$^2$, December 31, 2010 – 4.35E+16 and February 26, 20015 – 5.38E+16. For Dmitrov, these dates were March 30, 2007 – 4.45E+16, February 26, 2015 – 6.05E+16 and February 3, 2017 – 7.86E+16. In Sergiyev Posad, the days with the highest rates were March 30, 2007 – 5.43E+16, April 8, 2010 – 5.99E+16 and February 3, 2017 – 7.86E+16 molec/cm$^2$.

A graphical presentation of OMI data on days of maximum NO$_2$ concentrations in cities in the north of the Moscow region are shown in Figure 2.

Analysis of the data presented in Figure 2 allows for the conclusion that the main source of NO$_2$ on the days of its maximum content in the atmospheric air over the cities in the north of the Moscow region was the entire city of Moscow (except for February 3, 2017 when it was not possible to visually identify the source due to clouds). On three pictures of the OMI device (March 30, 2007, April 8, 2010, February 26, 2015), the plume of the investigated substance coming from the capital was clearly distinguished. The maximum NO$_2$ concentrations were observed mainly with southerly, southwesterly and southeasterly winds.

Analysis of data for other days with lower NO$_2$ values showed that there were no large sources of this substance in the cities under study for the entire study period. An increase in the concentration of the substance was confirmed during southerly, westerly and easterly winds, as well as under no wind conditions. The main source of NO$_2$ in the cities of the north of the Moscow region, on other days, was also Moscow.

Based on all available data, the authors calculated the average annual values of NO$_2$ in the troposphere in the cities under study (Figure 3).
**Table 2.** Ranking of days with certain values of NO₂ concentrations in the troposphere over cities in the north of the Moscow region and in Moscow [8]

| City                     | Taldom | Dmitrov | Sergiyev Posad | Moscow (Lianozovo) |
|--------------------------|--------|---------|----------------|--------------------|
| Total number of days with available content | 2,484  | 2,522   | 2,471          | 2,408              |
| data NO₂:                |        |         |                |                    |
| 5E+15 and less           | 2,026  | 1,945   | 1,824          | 845                |
| from 5E+15 to 1E+16      | 332    | 378     | 431            | 825                |
| from 1E+16 to 1.5E+16    | 66     | 108     | 127            | 375                |
| from 1.5E+16 to 2E+16    | 30     | 44      | 43             | 176                |
| from 2E+16 to 2.5E+16    | 11     | 18      | 22             | 89                 |
| from 2.5E+16 to 3E+16    | 9      | 12      | 11             | 41                 |
| from 3E+16 to 3.5E+16    | 4      | 6       | 9              | 25                 |
| from 3.5E+16 to 4E+16    | 3      | 7       | 0              | 8                  |
| from 4E+16 to 4.5E+16    | 2      | 2       | 1              | 7                  |
| more than 5E+16          | 1      | 2       | 3              | 8                  |

*Unit of measurement: molecules/cm²

**Figure 2.** OMI instrument data on the NO₂ content in the troposphere over the territory of the Moscow region as of March 30, 2007, April 8, 2010, February 26, 2015, February 3, 2017. Spatial resolution of the survey: 0.25°x0.25°. Measurement unit: molecules/cm² [8]
Figure 3. Calculated mean annual values of NO$_2$ content in the troposphere over cities in the north of the Moscow region and above Moscow based on OMI data [8]

Having analyzed the data obtained, the following conclusions were made:

1. In general, in the cities of the north of the Moscow region, changes in the average annual concentrations of NO$_2$ within $1E+15$ molec/cm$^2$ are recorded annually. The biggest change occurred in 2020 being an increase in all cities by an average of $1.48E+15$ molec/cm$^2$.

2. The average content of NO$_2$ in the troposphere over the cities of the north of the Moscow region for the period from 2005 to 2020 was as follows: in Taldom – $3.40E+15$ molec/cm$^2$, Dmitrov – $4.07E+15$ molec/cm$^2$, Sergiyev Posad – $4.25E+15$ molec/cm$^2$. For comparison, in the northern part of Moscow, it was equal to $8.78E+15$ molec/cm$^2$.

3. The highest content of nitrogen dioxide was recorded in Taldom in 2020 ($4.45E+15$ molec/cm$^2$), Dmitrov and Sergiyev Posad – in 2007 ($5.27E+15$ and $6.14E+15$ molec/cm$^2$). The lowest NO$_2$ content was recorded in Taldom and Dmitrov in 2011 ($2.4E+15$ and $3.02E+15$ molec/cm$^2$), Sergiyev Posad – in 2013 ($3.02E+15$ molec/cm$^2$).

4. Compared to 2005, in 2020 in Taldom, the amount of NO$_2$ increased by $4.75E+14$, in Dmitrov it increased by $2.08E+14$, in Sergiyev Posad – decreased by $1.74E+14$ molec/cm$^2$. Compared to 2005 in Moscow, the amount of NO$_2$ in 2020 decreased by $4.49E+15$ molec/cm$^2$.

4. Conclusion

The use of remote sensing tools to measure the content of NO$_2$ in the Earth’s atmosphere is a rather innovative solution in the environmental monitoring system. These technologies enable to determine NO$_2$ concentrations almost anywhere in the world and even in those places where there are no ground-based observation systems. However, at present, these tools have a number of disadvantages. Specifically, their use is highly dependent on weather phenomena and the data obtained from them can have a significant error. Moreover, satellite observations cannot fully replace the monitoring carried out on Earth. Nevertheless, these data enable to obtain quite valuable information about the general ecological situation in different territories.

The conducted geocological analysis of the nitrogen dioxide content in the atmospheric air in Taldom, Dmitrov and Sergiyev Posad showed that, in general, the average annual content of NO$_2$ in these cities is more than two times lower than in Moscow. In Taldom and Dmitrov for the period from 2005 to 2020, there was an increase in the average annual concentration of NO$_2$ from $3.98E+15$ to $4.45E+15$ molec/cm$^2$ in Taldom and from $4.82E+15$ to $5.03E+15$ molec/cm$^2$ in Dmitrov. In Sergiyev
Posad, a decrease in its content was recorded from $4.94 \times 10^{15}$ to $4.76 \times 10^{15}$ molec/cm$^2$. In total, Moscow has the greatest influence on the change in NO$_2$ concentrations in the troposphere over the cities under study. The observed annual decrease in the concentration of the investigated substance in Moscow suggests a possible decrease in its concentration already in the cities of the north of the Moscow region in the future. To confirm this fact, it is necessary to continue monitoring NO$_2$ concentrations using ground-based equipment. Observations are also necessary for the prompt detection of a sharp increase in NO$_2$ concentrations as a result of industrial accidents.

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