Sulfur dioxide emission assessment using OMI data

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Abstract. The study is devoted to the estimation of sulfur dioxide emissions into the atmosphere based on satellite monitoring data in the area of the Norilsk industrial zone from 2010 to 2018. According to the measurements of the Ozone Monitoring Instrument - AURA satellite the NASA database is used. The maximum sulfur dioxide emissions amounted to 95 kt/month in November 2016, and the minimum - 0.185 kt/month in August 2011. The largest share of emissions is in January-May and November (90%). Comparison of the data obtained by the satellite method with the ground method revealed a difference of 30 to 65%, and with the method using aircraft carrier by 14 percent.

1. Introduction

In the northern territories of the Krasnoyarsk Region, the environmental situation is formed as a result of the production activities of metallurgical enterprises of PJSC MMC Norilsk Nickel. The work of the enterprises of the Norilsk production zone (NPZ) leads to technogenic pollution of atmospheric air, water bodies, as well as the destruction of the fertile layer of the earth and vegetation. The share of sulfur dioxide emissions at NPZ enterprises is 25% of Russian industrial emissions [1].

SO₂ emissions are spread over large distances from the source of pollution (up to a thousand kilometers). SO₂ is the main substance involved in the formation of toxic sediments and smog. The interaction of SO₂ with water results in acid precipitation, which has a negative effect on both the biosphere and soil with water bodies. The rate of decomposition of organic substances is significantly reduced, which affects the fertility of the soil, and, consequently, leads to inhibition of the growth of vegetation.

The development of monitoring tools allows us to expand measurements to daily global coverage of the entire atmosphere of the Earth. The data obtained as a result of satellite measurements of SO₂ emissions are accumulated in the Ozone Monitoring Instrument (OMI) database [2]. Assessment of the environmental situation provides objective information on the state of the environment and public health; establish scientifically based boundaries of the territory and its individual sections; organize a monitoring system for priority indicators of environmental change.

OMI measures the concentration of SO₂ emissions in Dobson units at four altitudes: 0.9 km, 2.5 km, 7.5 km and 17 km. 1 e. D. is equal to 0.01 mm of the thickness of the layer of precipitated sulfur dioxide at 0 and atmospheric pressure of 1013 hPa, which amounts to 1 molecule of sulfur dioxide.

Table 1 presents a fragment of the OMI database for sulfur dioxide emissions into the atmosphere. A typical background value of the concentration of sulfur dioxide is less than 1 E.
Table 1. OMI database of atmospheric emissions of sulfur dioxide in October 2010.

| Time since the beginning of the year UTC, s | 10468 | 10470 | 10472 | 10474 |
|-------------------------------------------|-------|-------|-------|-------|
| Latitude, h     | 68.98 | 69.01 | 69.05 | 69.08 |
| Longitude, deg  | 88.93 | 88.61 | 88.28 | 87.96 |
| SO$_2$ at an altitude of 0.9 km, e.D.   | 4.281 | 5.12  | 2.674 | 1.801 |
| SO$_2$ at an altitude of 2.5 km, e.D.   | 0.813 | 7.724 | 6.496 | 6.355 |
| SO$_2$ at an altitude of 7.5 km, e.D.   | 0.18  | 1.804 | 1.377 | 1.253 |
| SO$_2$ at an altitude of 17 km, e.D.    | 0.073 | 0.767 | 0.57  | 0.516 |

The OMI spectrophotometer is designed to detect solar radiation reflected and scattered by the atmosphere and Earth's surface in the range from 264 to 504 nm. The width of the shooting strip of the surface is 2600 km at a viewing angle of the camera of 114$^\circ$.

The OMI instrument measures the backscattered flux of ultraviolet radiation. Two spectral channels are used to estimate sulfur dioxide content. Strong absorption is observed in the first channel, and weak in the second. In addition to sulfur dioxide, ozone is an absorber in the UV range. The algorithm for estimating the sulfur dioxide content in the atmosphere is based on the use of vertical model profiles of sulfur dioxide and ozone. The average square of the difference between the measured and model parameters is minimized by varying the model [3].

In addition to the satellite method, there is a ground-based environmental monitoring method and a monitoring method using aircraft carrier. The satellite method has both advantages and disadvantages. The advantages include the possibility of daily coverage of a large territory, however, it gives information only once a day and about one pollutant, depending on weather conditions. The ground-based method allows to obtain data on emissions of various pollutants several times a day, but at discrete points and the surface layer [1]. Monitoring using aviation media is the most informative, but the use of this method is episodic in nature [1,5-8].

2. Analysis of sulfur dioxide emissions into the atmosphere

During the research, the analysis of sulfur dioxide emissions into the atmosphere by the enterprises of PJSC MMC Norilsk Nickel was performed. Table 2 provides information on the mass of sulfur dioxide emissions from 2010 to 2018 according to OMI data from January to November. When weather conditions did not allow estimating the mass of sulfur dioxide, values were accepted that are equal to the arithmetic mean mass of SO$_2$ emissions. Figure 1 shows a histogram of the mass emissions of SO$_2$ for 2011-2018 according to the table 2.

Table 2. The data on the mass of sulfur dioxide emissions from 2004 to 2012.

| Month/year | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
|------------|------|------|------|------|------|------|------|------|------|
| January    | -    | 54.992 | 20.897 | 80.822 | 64.956 | 35.862 | 48.985 | 81.088 | 45.459 |
| February   | -    | 37.222 | 19.851 | 61.943 | 44.816 | 17.530 | 46.774 | 84.508 | 70.578 |
| March      | -    | 7.125 | 5.954 | 16.555 | 9.728 | 3.930 | 14.199 | 3.848 | 17.935 |
| April      | -    | 37.102 | 38.317 | 8.603 | 22.823 | 14.207 | 45.411 | 9.6 | 15.829 |
| May        | -    | 34.028 | 29.096 | 45.22 | 21.257 | 50.929 | 34.247 | 8.402 | 31.35 |
| June       | -    | 4.983 | 4.343 | 6.791 | 2.706 | 6.680 | 13.792 | 2.685 | 2.180 |
| July       | -    | 2.889 | 0.265 | 1.763 | 2.107 | 1.084 | 1.938 | 0.545 | 2.561 |
| August     | -    | 0.187 | 0.951 | 0.836 | 63.015 | 0.383 | 0.458 | 0.233 | 1.099 |
| September  | -    | 1.449 | 0.573 | 1.851 | 1.271 | 0.425 | 4.293 | 1.317 | 1.475 |
| October    | 1.396 | 3.556 | 7.292 | 6.22 | 7.349 | 2.585 | 5.136 | 1.894 | 21.542 |
November 95.356 25.582 75.303 89.253 80.695 27.293 51.087 41.967 45.949
Overall volume 96.752 209.115 202.842 319.857 320.723 160.908 266.320 236.087 265.957

The minimum emissions in 2011 were recorded from June to October, when the mass of emissions did not exceed 5 kt/month. The maximum emissions were observed from January to May and in November; the average monthly value of the mass of emissions of sulfur dioxide during this time was approximately 33 kt. The peak of emissions was in January and amounts to 55 kt/month. The total emissions for 2011 were recorded at 209 kt/year. The minimum emissions in 2012 are in July, equal to 0.265 kt/month, and the maximum in November is 75 kt/month. The total emissions for 2012 is \( \sim 203 \) kt/year.

![Figure 1. Mass emission of SO\(_2\) according to OMI for 2011-2018.](image)

In 2013, the mass of sulfur dioxide emissions increased sharply by 117 kt/year, reaching 319.857 kt/year. Minimum values of sulfur dioxide emissions into the atmosphere from June to October, in August - 0.836 kt/month. The maximum values were recorded from January to May, the peak in November was 89 kt/month. The largest volume of emissions was recorded in 2014 - 320.723 kt/year. The maximum values of emissions were also recorded in January-May, with a peak in November - 80.615 kt/month, but in 2014 there was a high level of emissions and in August - 60.015 kt/month. The low level of emissions in July is 1.271 kt/month.

The smallest volume of emissions was observed in 2015 - 160.908 kt/year. The highest level of emissions was recorded in May - 50.929 kt/month. Minimum emissions of sulfur dioxide in the atmosphere in June-October (no more than 7 kt / month). Table 3 presents the volumes of nickel and copper production (kt) from 2010 to 2017. In 2016, due to an increase in copper and nickel production to 484 kt, there is a sharp jump in sulfur dioxide emissions to 266.32 kt/year. The minimum value of emissions was recorded in August - 0.458 kt/month, and the maximum value in November - 51.087 kt/month.

| Metal / year | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 |
|-------------|------|------|------|------|------|------|------|------|
| Nickel, kt   | 304  | 309  | 324  | 339  | 338  | 351  | 361  | 353  |
| Copper       | 124  | 124  | 124  | 122  | 119  | 122  | 123  | 127  |
| Total kt     | 428  | 433  | 448  | 461  | 457  | 473  | 484  | 480  |
In 2017, due to a slowdown in nickel and copper production by 4 kt/year, there is a decrease in sulfur dioxide emissions by 30.234 kt/year and amounts to 236.086 kt/year [2]. From March to October, the level of sulfur dioxide emissions into the atmosphere does not exceed 10 kt/month. The minimum emissions were recorded in August - 0.233 kt/month. The maximum emissions are observed in January, February and November and amounts to 207.56 kt/month. In 2018, the total mass of sulfur dioxide is 265.957 kt/year. Low emissions are observed from June to September - do not exceed 2.2 kt/month. The maximum emissions are observed from January to May, October, November with a peak in February - 70.578 kt/month. Figure 2 presents a histogram of the production of nickel and copper according to the data from table 3.

One can see the connection between the level of sulfur dioxide emissions and production volumes. About 350-710 kt sulfur dioxide are emitted into the atmosphere per 1 ton of nickel and copper produced by the plant. The largest contribution to the concentration of sulfur dioxide in 2011-2018 was recorded from January to May and in November. Figure 3 shows the total recorded monthly sulfur dioxide emissions for 2011-2018.
The contribution to the annual concentration of sulfur dioxide for 2011-2018 is in the range from 4% in March to 22% in January and November. A noticeable decrease in the concentration of sulfur dioxide is observed from June to October. This is due to weather conditions, the maximum emissions of sulfur dioxide are achieved in clear weather without wind, and during strong winds, emissions are small, but the tail from the emission stretches for hundreds of kilometers, capturing vast spatial land and part of the Arctic Ocean [4]. Since sulfur dioxide is bound by frozen water crystals and is located in the surface layer of the atmosphere for a long time, sulfur dioxide is carried over even greater distances during periods of heavy snowfall during strong winds [4].

In the warmer months (June-August), there is a sharp decrease in sulfur dioxide emissions in the air, and then an increase starting in October, reaching a maximum in January-February. This is due to the fact that the maximum number of days with snowstorms falls in January and February, which leads to high emissions of sulfur dioxide. The duration of snowstorms is 2-4 days, and sometimes more, as a result, a huge amount of sulfur dioxide and its products of chemical reactions are transferred along with precipitation, because of this the scale of the spread of pollution becomes catastrophic.

The Center for Radiation and Environmental Monitoring of the Control and Analytical Department conducts ground-based monitoring of atmospheric air. The Center operates a mobile environmental laboratory, equipped with instruments for determining the content of sulfur dioxide in the atmosphere. The obtained sulfur dioxide emissions data for the day are summarized: observations are carried out discretely at regular intervals every 6 hours starting from 1 hour at three posts.

To compare OMI data with the data of other environmental control methods, the fixed figure corresponding to the mass of sulfur dioxide was multiplied by 4 because OMI takes measurements once a day. Table 4 presents the results of ground and space monitoring from 2010 to 2018.

| Table 4. Comparative analysis of ground and space monitoring. |
|---------------------------------------------------------------|
| **Sulfur dioxide emission mass:**                              |
| according to terrestrial measuring instruments, kt             |
| 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 |
| 1898.39 | - | - | - | 1858.87 | 1850.96 | 1848.89 | - | - |
| according to OMI satellite data, kt                           |
| 836.46 | 811.37 | 1279.89 | 1282.89 | 643.63 | 1065.28 | 944.35 | 1063.83 |

The obtained OMI data were compared with the results of studies conducted by the Institute of Atmospheric Optics of SB RAS in 2008 and 2010 using An-30 Optika-E laboratory airplane and the ground-based environmental monitoring complex in the Norilsk industrial region. In terms of emissions, all three methods give a similar picture in terms of quality. However, according to daily satellite monitoring data, the maximum falls on the winter months, and the minimum on the summer months, at the same time, according to single measurements of the IAO of SB RAS, on the contrary, on the winter minimum and on the summer maximum. Comparison of terrestrial and satellite varies by 30-65%. Most likely, the differences are due to the fact that the ability to measure with the OMI instrument directly depends on the presence of cloudiness, in addition, the measurement is carried out once a day, the accuracy of the ground method also depends on weather conditions.

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