

Satellite monitoring of atmospheric sulphur dioxide pollution in polar latitudes

V B Kashkin¹, D V Zuev¹, M A Kurako¹, A A Romanov¹, T V Rubleva¹ and K V Simonov²

¹ Siberian Federal University, 79 Svobodny pr., 660041, Krasnoyarsk, Russia

² Institute of Computational Modeling SB RAS, 50/44 Akademgorodok, 660036, Krasnoyarsk, Russia

E-mail: mkurako@sfu-kras.ru

Abstract. The study is devoted to the mapping of areas of environmental risk. Risk assessment is based on a satellite monitoring data and an evaluation of the impact of air pollution on the vegetation cover of urban areas. Ecological risk zones mapping is shown on the example of Norilsk industrial zone impact on vegetation cover. There is a brief description of the existing system of satellite monitoring data of sulphur dioxide emission for the Norilsk industrial zone. Our approach for risk assessment mapping uses elastic grid method for generating elastic net and visualizing spatial satellite data from OMI and OMPS databases. The results of calculations based on the methodology of mapping zones of environmental risk are presented.

1. Introduction

The work of Norilsk industrial zone factories leads to technogenic pollution of atmospheric air, reservoirs, and destruction of the fertile layer of the earth and vegetation cover. The share of sulphur dioxide emission by Norilsk industrial zone (NIZ) factories is 25% of Russian industrial emission [1]. High concentration of sulphur dioxide in the atmosphere causes serious damage to the leaves, which leads to chronic plant damage. Emission of sulphur dioxide (SO₂) causes changes in soil composition and damage to forests around the factories of the northern territories of the Krasnoyarsk region.

Sulphur dioxide is a pollutant that has a significant impact on the environment and climate at the global, regional, and local levels. It is oxidized to sulphate aerosols that reduce visibility, influence on the cloud formation, and cause acid rains. Remote satellite monitoring enables new possibilities in studying the gas composition of the atmosphere, monitoring the state of the environment, forecasting technogenic and natural emergencies, as well as simplify the study of climate change.

Evaluation of the ecological situation allows to obtain objective information on the state of the environment and population health; establish scientifically-based boundaries of the territory or its individual sections; organize a system of monitoring by priority indicators of environmental change and population health; rationale emergency and rescue activities for the rehabilitation of public health and environment.

It should be noted that it is important not to be limited only to the total value of environment pollution, when considering the degree of ecological disadvantage of urban territory. It is necessary to consider the indicators of the public health because of the total technogenic load on a person. Any industrial cluster is characterized by almost complete change of environmental parameters: soil



pollution, atmosphere, reservoirs, climate, etc. The urgency of these problems is very high and will increase in future.

There are sanitary and hygienic standards that are used for assessing an impact on plant ecosystem, but these standards are not adapted to that purpose in view of biodiversity [1-2]. The ecological risk, as a probability of occurrence of environment adverse situations because of economic activity of people, allows more reasonably estimate a degree of influence of negative factors on components of environment. Therefore, the problem of estimating an environment risk of impact on urban territory vegetation cover is very important. However, environmental risk assessment in the Arctic zone is not sufficient. In this regard, the aim of the work is to outline the methodological issues of assessing and mapping environmental risks on plant ecosystem using remote sensing data.

2. Data description and evaluation

Monitoring of sulphur dioxide (SO_2) emission is performed by OMI and OMPS spectrophotometers. The Ozone Monitoring Instrument (OMI) data [3-14] is a key source for sulphur dioxide emission levels. The OMI measures SO_2 emission concentration in Dobson units (DU) for four altitudes above the sea level: 0.9 km, 2.5 km, 7.5 km and 17 km. 1 DU equals 0.01 mm of sulphur dioxide deposited layer thickness at 0 °C and atmospheric pressure equals 1013 GPA. Also, OMI provides graphical database of SO_2 emission for the NIZ territory. Database incorporates data from 2004 to 2018 and includes data about SO_2 emission mass, distribution area, maximum values of SO_2 concentration and time of measurement.

OMPS is a new instrument for SO_2 emission monitoring [15, 16]. The OMPS spectrometer, like its predecessor, carries out the control of SO_2 emission on a global scope. The OMPS graphical database has the same format as the OMI graphical database. It contains detailed information about SO_2 emission and incorporates data from April 2013 to 2018.

Analysis of SO_2 emission is performed by MATLAB script using data from graphical database for Norilsk industrial zone. Script generates daily and monthly average concentration values and allows to build SO_2 emission concentration map for the studied day. Based on the obtained evaluation data set, the possibilities of using OMI–OMPS data for the NIZ territory was studied [11-13, 17].

Firstly, the correlation of data was evaluated according to the method described in [15, 16]. There are two types of correlation. Spatial correlation is the correlation between OMI and OMPS average annual SO_2 concentration values within the NIZ. Temporal correlation is the correlation between the OMI and OMPS daily masses of SO_2 for the studied area. Correlation calculation encompasses period from 2013 to 2017.

The spatial correlation of OMI-OMPS annual averages is high and equal to 0.8. The relative difference equals 8.2%. It can be explained by the difference in observation time, since the SO_2 column can move relatively quickly in space. The maximum value (0.91) of spatial correlation of average annual values was observed in 2017. Average annual concentrations of SO_2 are 3.56 DU and 2.64 DU for OMI and OMPS, respectively. Average relative difference OMPS-OMI equals 26%. The minimum value (0.79) was observed in 2014, while the relative difference is comparable to other years and equals 11.7%. Temporal correlation of OMI-OMPS data is based on daily SO_2 emission masses in 2013–2017. The calculation involves only days, when both values were registered. The lowest value of correlation coefficient is 0.62. The average daily SO_2 emission mass equals 3.56 kt for OMI and 2.65 kt for OMPS data, respectively. The highest value of correlation corresponds to May, July and November.

In general, SO_2 emission mass from OMI is slightly higher than that of OMPS. A comparison of OMI and OMPS data shows that there is a well enough correlation for the NIZ region. OMPS-based metrics are slightly smaller than OMI metrics, probably due to lower spatial resolution for the studied region. However, despite these differences the OMPS spectrometer is capable to perform monitoring with given accuracy.

3. Monitoring data mapping by elastic grids method

In this section, we demonstrate our approach for mapping and visualizing OMI and OMPS data. These data are currently being used to provide daily information about regional air pollution and average annual information about point sources of pollution. Consider, following [18], the data visualization algorithm based on elastic grids method.

Let us define a grid with $p \cdot q$ nodes and enumerate nodes y_{ij} with indexes $i = \overline{1, p}, j = \overline{1, q}$. The grid should satisfy to the following properties:

- Closeness to the data points. Grid should be in some sense like the plane of the first two principal components.
- Elasticity. This property provides a uniformity and smoothness of the grid.

Let us divide data set X into $p \cdot q$ subsets $K_{ij}, i = \overline{1, p}, j = \overline{1, q}$, where each subset contains only points, which are closer to the y_{ij} node than any other node and denote this condition as follows

$$K_{ij} = \left\{ x \in X \mid \|y_{ij} - x\|^2 \leq \|y_{kl} - x\|^2, \forall k, l \right\}. \quad (1)$$

Measure of closeness between nodes and data points is defined as Root Mean Square (RMS) distance. Each node (except the boundary nodes) is connected to four neighbors. The greater the average edge length, the stronger grid is stretched. The degree of curvature is determined by a point estimate of the second difference derivative. As a result, we obtain the following functional:

$$D = \frac{D_1}{|X|} + \lambda \frac{D_2}{pq} + \mu \frac{D_3}{pq}, \quad (2)$$

where λ, μ are the elastic coefficients, responsible for stretching and bending, respectively, D_1 is the measure of closeness, D_2 is the measure of grid stretching, D_3 is the measure of grid curvature. Terms D_1, D_2, D_3 are defined as follows:

$$D_1 = \sum_{i,j} \sum_{x \in K_{ij}} \|x - y_{ij}\|^2, \quad (3)$$

$$D_2 = \sum_{i=1}^p \sum_{j=1}^{q-1} \|y_{ij} - y_{i,j+1}\|^2 + \sum_{i=1}^{p-1} \sum_{j=1}^q \|y_{ij} - y_{i+1,j}\|^2, \quad (4)$$

$$D_3 = \sum_{i=1}^p \sum_{j=2}^{q-1} \|2y_{ij} - y_{i,j-1} - y_{i,j+1}\|^2 + \sum_{i=2}^{p-1} \sum_{j=1}^q \|2y_{ij} - y_{i-1,j} - y_{i+1,j}\|^2. \quad (5)$$

Emission concentration maps based on the elastic grids method and emission and concentration values for NIZ in 2015–2017 were constructed. Figure 1 depicts SO₂ concentration mapping for 2015–2017 and spatial distribution of emission, where colors indicate the SO₂ concentration. Note that almost the entire territory of the NIZ near Norilsk has an increased value of SO₂ concentration.

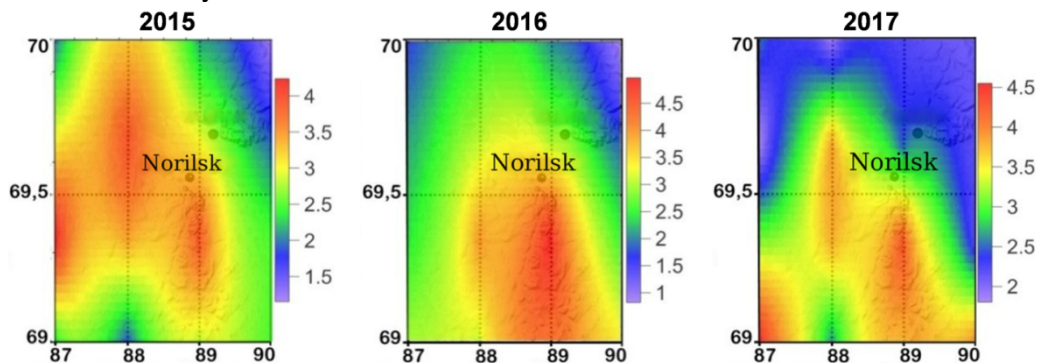


Figure 1. SO₂ emission concentration mapping for the NIZ in 2015–2017.

4. Environmental risk assessment

Environmental risk is a quantitative or qualitative assessment of environment hazard of adverse impact on environment [2, 19–20]. Environmental risk is considered as probability of adverse situation occurrence, ecosystem destruction or animal population death because of economic activity of people. There are two the most studied risk assessment areas: assessment of the possibility of death or public health damage and determination of the average risk of damage caused by atmosphere pollution.

The constant presence of SO₂ in the environment increases a degree of environmental risk. There are three levels of environmental risk: acceptable, high, and unacceptable [2, 20]. An important issue is the determination of the concentrations of pollutants corresponding to different levels of risk.

The level of atmospheric pollution in the fractions of Maximum Permissible Concentration (MPC) corresponding to the zone of unacceptable risk is determined by data and methodological materials [2, 19]. Air pollution degree is calculated considering the excess of the average annual value of MPC, pollutant hazard class, permissible repeatability of concentrations of a given level, and the mass of substances.

The annual average MPC_a is associated with an average daily value of MPC_d as follows

$$MPC_a = a \cdot MPC_d, \quad (6)$$

where a is the coefficient in the range 0.1 to 1.0 depending on the pollutant hazard class.

Unacceptable risk zone is defined as the territory, where the value of average annual air pollution index P corresponds to the environmental emergency and is equal 8, the value of a for SO₂ is 1:

$$8MPC_a = 8 \cdot (1 \cdot MPC_d) = 8MPC_d. \quad (7)$$

MPC_d for SO₂ equals 0.05 mg / m³. Therefore, the boundary of unacceptable level of risk equals 1.28 DU [20]. If the atmosphere is contaminated with substances with different hazard classes, complex variant of air pollution index is calculated:

$$P = \sqrt{\sum_j K_j^2}, \quad (8)$$

where K_j is the MPC for j th pollutant converted to the concentration of third hazard class pollutant.

Consider the proposed approach for building risk maps. Existing methodological developments to risk assessment are outlined in [2]. The risk assessment is carried out by combining data for all significant natural hazards (air quality, water quality, vegetation cover quality) typical for the studied region. Construction of risk maps is based on geodatabase with topographic and thematic layers, as well as template of cartographic material (with color-coded information).

Most plants are more sensitive to harmful factors than people. Taxonomic groups of plants according to the degree of sensitivity to phytotoxic gases are arranged in the following order [19]: mosses, lichens and mushrooms, softwood trees, hardwood trees, and grass vegetation. It should be noted [2, 19] that environmental standards of air quality on the level of chemical pollution are recommendatory in nature and are not currently defined for all pollutants. The sensitivity of groups of plants was determined by analysis of the environmental standards [2, 19].

Environmental risks mapping is based on the following sensitivity coefficients: 1 for grass vegetation, 0.75 for small-leaved forest, and 0.5 for softwood forest. The higher the sensitivity, the lower concentrations of pollutants cause damage to the relevant vegetation types. Levels of environmental risk are selected in accordance with the sensitivity coefficient for each group of plants (Table 1).

Table 1. Levels of air pollution (DU).

Environment risk level	Softwood forest	Small-leaved forest	Grass vegetation
Unacceptable	>0.625	>0.94	>1.25
High	0.625...0.50	0.94...0.75	1.25...1
Acceptable	<0.50	<0.75	<1

Figure 2 shows an example of mapping environmental risk zones for the Northern territories of the Krasnoyarsk region (April, 2017).

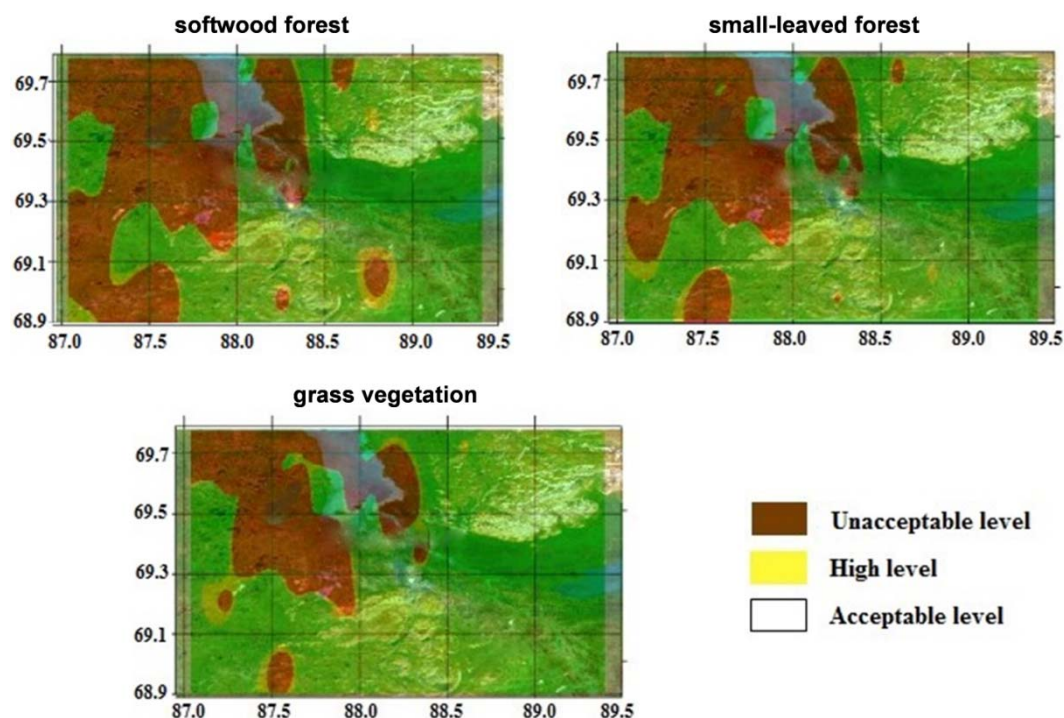


Figure 2. Environmental risk zones mapping for the Northern territories of the Krasnoyarsk territory.

There is a significant air pollution caused by SO_2 emission for the studied area, leading to an increased risk of negative impact to the human body and plants. These maps can serve as a signal for the factories of the Northern territories of the Krasnoyarsk region to reduction of production capacity. Thus, the satellite monitoring makes it possible to carry out environmental monitoring of the atmosphere, while being one of the most cost-effective methods of observation. OMI and OMPS instruments provide information on SO_2 emission at different altitudes and an opportunity to determine the future direction of emission. The satellite monitoring is an independent and objective source of information, which allows to draw conclusions about changes in the composition of the atmosphere for the Northern territories of the Krasnoyarsk region.

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