Methods and Algorithms for Remote Sensing of Particulate Pollution from Space at Regional Level

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Abstract. Based on its measurements of the MODIS spectrometer installed on the TERRA and AQUA satellites, data on aerosol optical depth (AOD) with different spatial resolution are formed: 10, 3, 1 km. The relationship between AOT values measured using remote sensing and PM2.5 measured at automated observation posts (APS) was investigated. It is shown that the data with a spatial resolution of 1 km make it possible to see dusty zones inside the city. Aerosol Index was used to take into account the contribution of external factors, such as smoke from fires, to the ecological situation of the city. This information can be used as an objective assessment of the environmental situation.

Keywords: particulate matter, aerosol optical depth, MODIS, MAIAC, remote sensing, APS, pollution, remote sensing, aerosol index.

1 Introduction

Aerosols or airborne particulate matter (PM) of natural or anthropogenic origin have a significant impact on climate, environment and human health [1]. Numerous epidemiological studies have shown that there is a link between PM concentrations and various adverse health effects. [2]. Consequently, the assessment of air quality, especially in terms of PM10 and PM2.5 (PM with diameters less than 10 and 2.5 μm respectively) is an urgent problem at the moment. Ground-based observations from automated observation posts (APS) show important spatial and temporal information on PM concentrations in the atmosphere.

PM monitoring is mainly based on ground-based measurements. Although station networks exist in large cities, point measurements do not provide information on the spatial characteristics and distribution of PM across urban areas of interest. The time coverage of on-site PM measurements also varies greatly depending on the period of operation of the instrument and its functionality. These reasons have led to ongoing efforts to evaluate PM using satellite remote sensing techniques.

Aerosol optical thickness (AOT) is a parameter obtained from the satellite that is most often used as the basis for estimating PM [3]. AOT is the integrated atmospheric dispersion of radiation by aerosols in the vertical column of the atmosphere. This parameter is proportional to the number of particles in the air and depends on their mass concentration. AOT is commonly used as a basis for PM evaluation. Several methods have been used to correlate AOT with remote sensing with measured on the PM surface. These include linear relations [4], statistical and chemical transport models [5], multiple regression analysis [6] and neural networks [7].

There are several factors limiting the correlation between AOD and PM2.5, such as influence of the vertical profile of the aerosol, which is responsible for the difference between measurements in the atmospheric column (AOD) and surface (PM2.5); the complex role of relative humidity; wind speed; distribution of particle size; and composition of the particles, etc [7]. In work [8] correlation between measurements of the general AOT column and near-surface PM2.5 and these variables was investigated. These studies showed a wide range of correlations between AOT and PM2.5 mass.

In this paper, we use the 1 and 10 km resolution AOT data obtained for Krasnoyarsk to determine whether the relationship between the PM2.5 concentrations measured on earth and the AOT values becomes stronger when the spatial resolution of the AOT increases.

In this study, we used the linear method to estimate PM2.5 over the city of Krasnoyarsk, Russia, based on satellite AOD. This parameter is available from the MODIS radiometer onboard NASA Terra and Aqua satellites.

Aerosol Index (AI) was used in order to take into account the contribution to the environmental situation of the city from external sources, such as smoke from fires.

Aerosol index of the atmosphere is a qualitative indicator that indicates the presence in the air of particles that absorb radiation in the ultraviolet range. Aerosol index can take values from 0 to 5. An AI value of 5 corresponds to a very high concentration of aerosols that can reduce visibility or affect human health, and values less than 0.2 correspond to clean, clear air.

2 Materials and methods

In July 2018, there were three automated monitoring stations (AMS) of the regional ecological system in Krasnoyarsk, which measured PM2.5 concentrations. Figure 1 shows the location of the AMS from which data were used in our study.

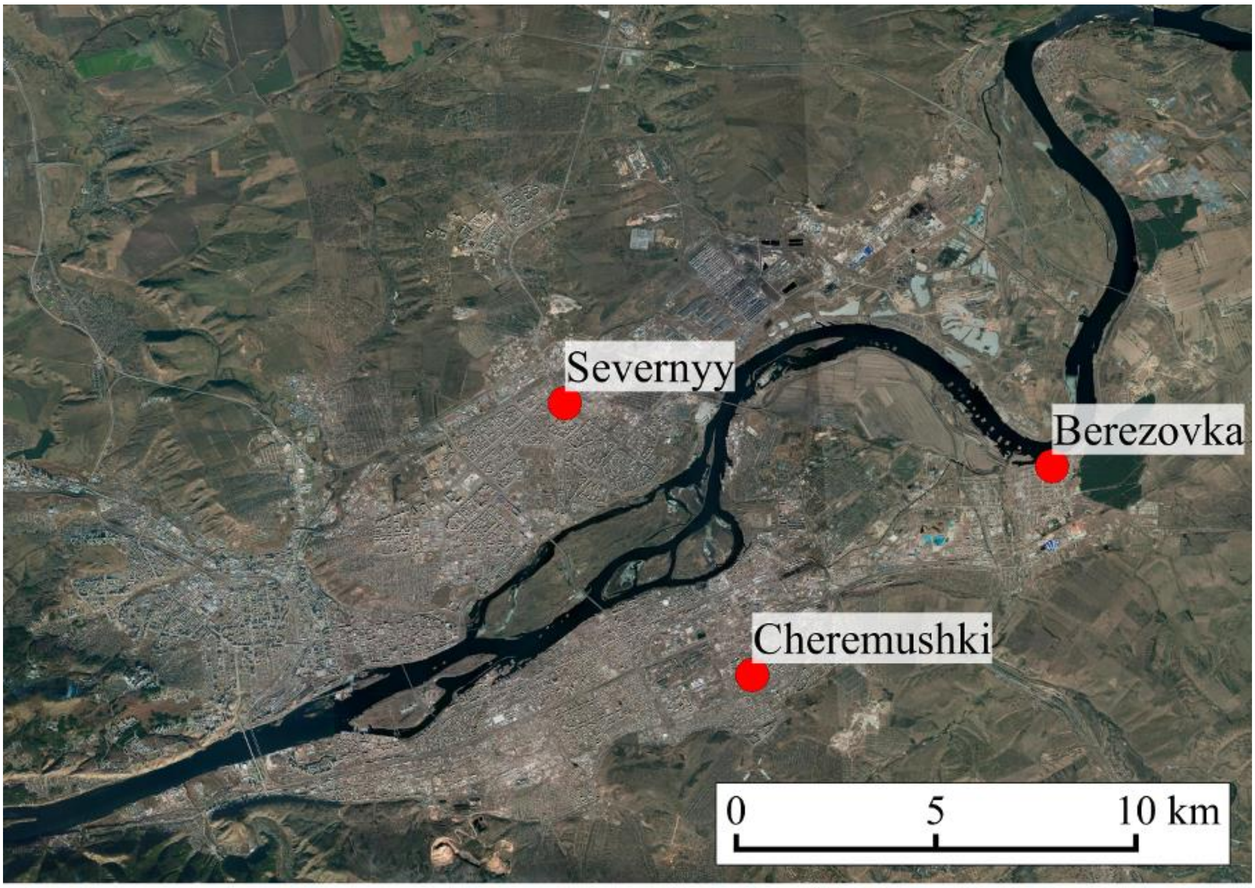

Figure 1. Location of monitoring stations in Krasnoyarsk, which were used in our work.

To measure PM2.5, the AMS equipment uses radioisotope principle of operation, which is generally accepted all over the world. It is based on the absorption of β-radiation by dust particles deposited on the filter belt. The isotope C14 is used as a source of β-radiation. Dust is deposited on the filter belt as a result of pumping the air sample by the pump. Measurement of the radiation absorption value is carried out using the built-in Geiger-Muller detector counter. We used average daily concentrations to estimate the amount of air pollution.

We also used the MAIAC algorithm [9], which was developed for processing MODIS data. MAIAC extracts aerosol parameters above ground with a resolution of 1 km. The MCD19A2 (MAIAC) MODIS product contains spectrophotometer data from Terra and Aqua satellites. This product was published on May, 2018, and contains AOT data from February, 2000 [10]. Aerosol parameters include optical depth at wavelengths from 0.47 to 0.67 μm and aerosol type, including background, smoke and dust models [11].

In our study, we used AOT data at a wavelength of 0.47 μm.

In [12] the correlation between ground measurements of PM2.5 and satellite measurements of AOT at different wavelengths was carried out. In this study, it was shown that the correlation between PM2.5 is greater for a wavelength of 0.47 μm.

Improved accuracy of MAIAC results from use of the method of the apparent surface characteristics in contrast to the empirical approach to parameterize the surface, which is used in the MOD04/MYD04 algorithms. Moreover, MAIAC incorporates a cloud mask algorithm, based on spatiotemporal analysis, which complements traditional methods for the detection of clouds at the pixel level [13]. MAIAC provides a uniform grid resolution of 1 km in the selected projection regardless of the scanning angle.

In addition to MAIAC data, we used daily aerosol data from MODIS Level 2, Collection 6.1 from Aqua and Terra satellites, which were obtained with a spatial resolution of 10×10 km^2 (in nadir). MYD04/MOD04 aerosol products were obtained on the basis of spectral radiation measured by MODIS using seven spectral channels in the wavelength range from 470 to 2130 nm [14]. Additional wavelengths in other parts of the spectrum are used to identify and mask clouds, snow, and suspended river sediments [15].

In our study we used measurements of PM2.5 from AMS ground-based posts and satellite measurements of AOT for July 2018. We studied the relationship between measurements of AOT and PM2.5 on the scale of Krasnoyarsk. The frequency of AMS measurements is 1 measurement in 20 minutes. We used average PM2.5 values per day. For the correlation at city level between the data of AOT and PM2.5 was available 10 days, only 30 pairs. The days were chosen taking into account the absence of clouds.

The study used AI calculated from satellite data of the OMPS device (Ozone Mapping Profiler Suite), installed on the American meteorological satellite Suomi NPP. The spatial resolution of one pixel is 50×50 km^2 (in nadir). The Aerosol Index is calculated using backscattered UV radiation in the range 300-380 nm [15]. According to AI, the contribution to the ecological situation of the city of Krasnoyarsk from fires occurring in the period from 14 to 24 July 2019 was visually assessed. The direction of smoke plumes from fires and the value of AI over Krasnoyarsk, during the period of strong smoke of the city, was considered.

3 Results and discussion

Figure 2 shows the city pollution data calculated using algorithms with high resolution of MAIAC 1 km (a, c) and low resolution of 10 km (b, d). High spatial resolution data show the spatial variability of AOT at both low (a, b) and moderate (c, d) pollution levels that lower spatial resolution data cannot provide.

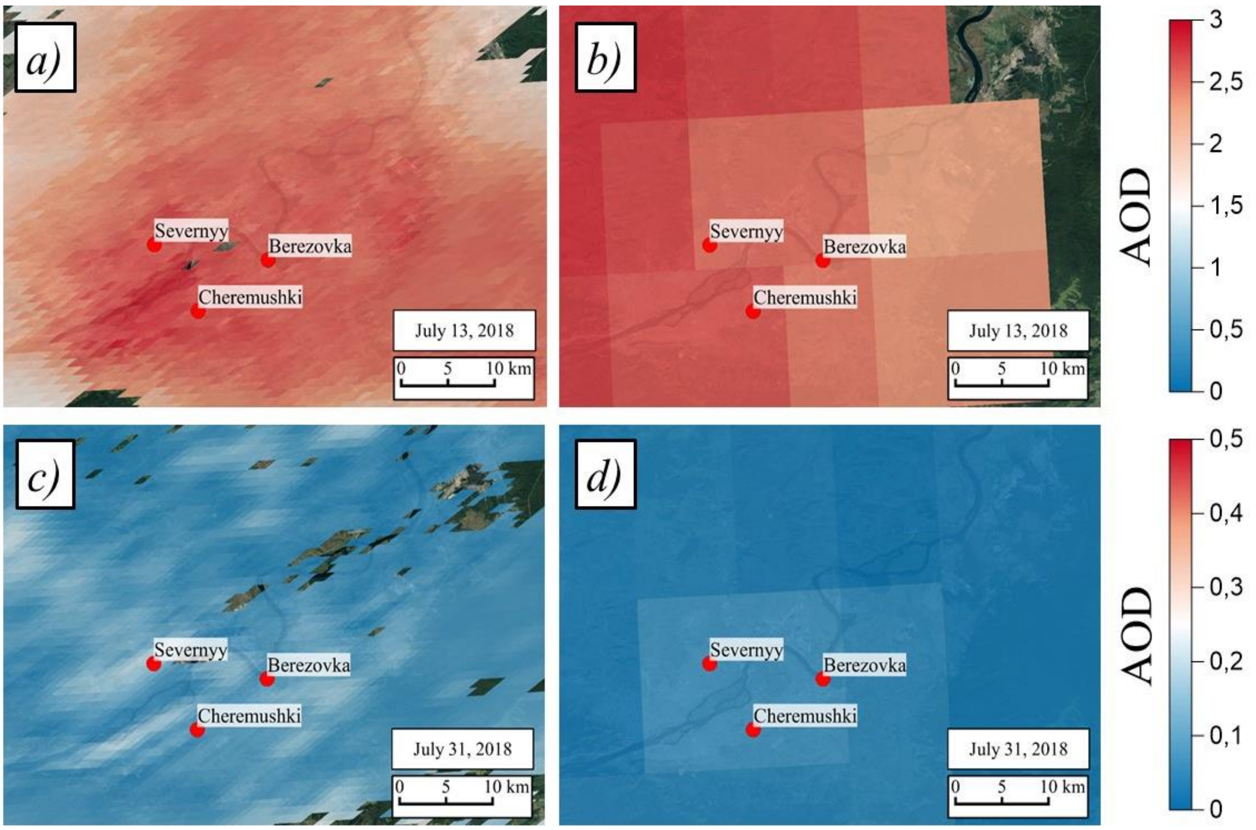

Figure 2. Aerosol optical thickness (AOT) over Krasnoyarsk calculated by algorithms with 1 km (a, c) and 10 km (b, d) spatial resolution for low (a, b) and moderate (c, d) city pollution level.

Figure 3 shows the relationship between the results of determining the AOT on one of the days of July 2018 according to the MAIAC algorithm with a spatial resolution of 1 km and an average daily value of PM2.5 measured at 3 APS in Krasnoyarsk. The coefficient of determination in this case is 0.53 (R2=0.53). It should be noted that for different satellite images over the study period, the coefficient of determination ranged from 0.5 to 0.8, indicating a good connection with ground measurements of PM2,5. The correlation values for the 10 km resolution algorithm were comparable.

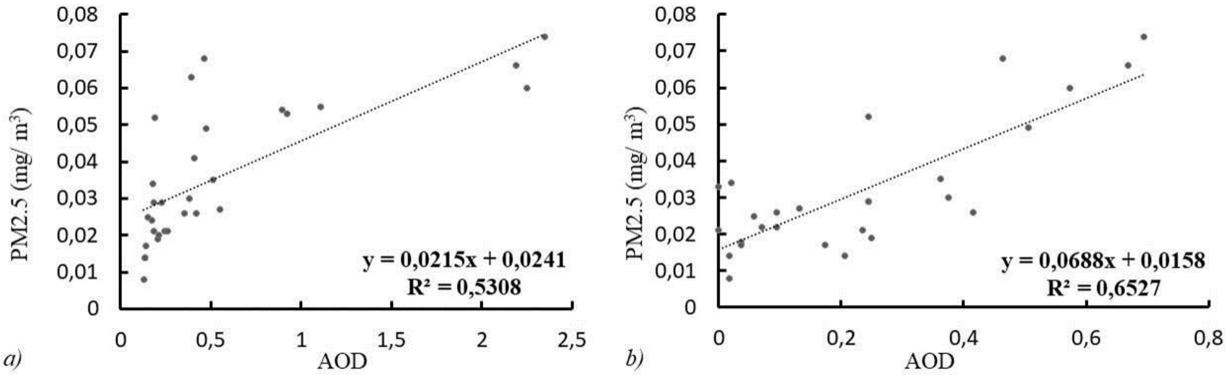

Figure 3. Correlation of ground-based measurements of PM2.5 with satellite AOT data calculated by algorithms of 1 km (a) and 10 km (b) spatial resolution.

Different approaches to air quality assessment allow to see pollution at different scales. In particular, using the MAIAC product it is possible to track pollution on an intra-urban scale. However, for a larger area, the use of this algorithm is hampered by the lack of data for the cloud-covered area. Aerosol index well detects smoke from fires. Aerosol index of the atmosphere – a qualitative indicator that indicates the presence in the air of particles that absorb radiation in the ultraviolet range.

In Krasnoyarsk in the period from 14 July to early August established a dense haze of forest fires. Using the AOD parameter gives large data gaps, making it difficult to track pollution dynamics. The use of AI, on the contrary, makes it possible to trace the dynamics of the spread of smoke plumes from fires over the city.

Figure 4 shows the spread of smoke plume from fires for the period from 14 to 24 July 2019.

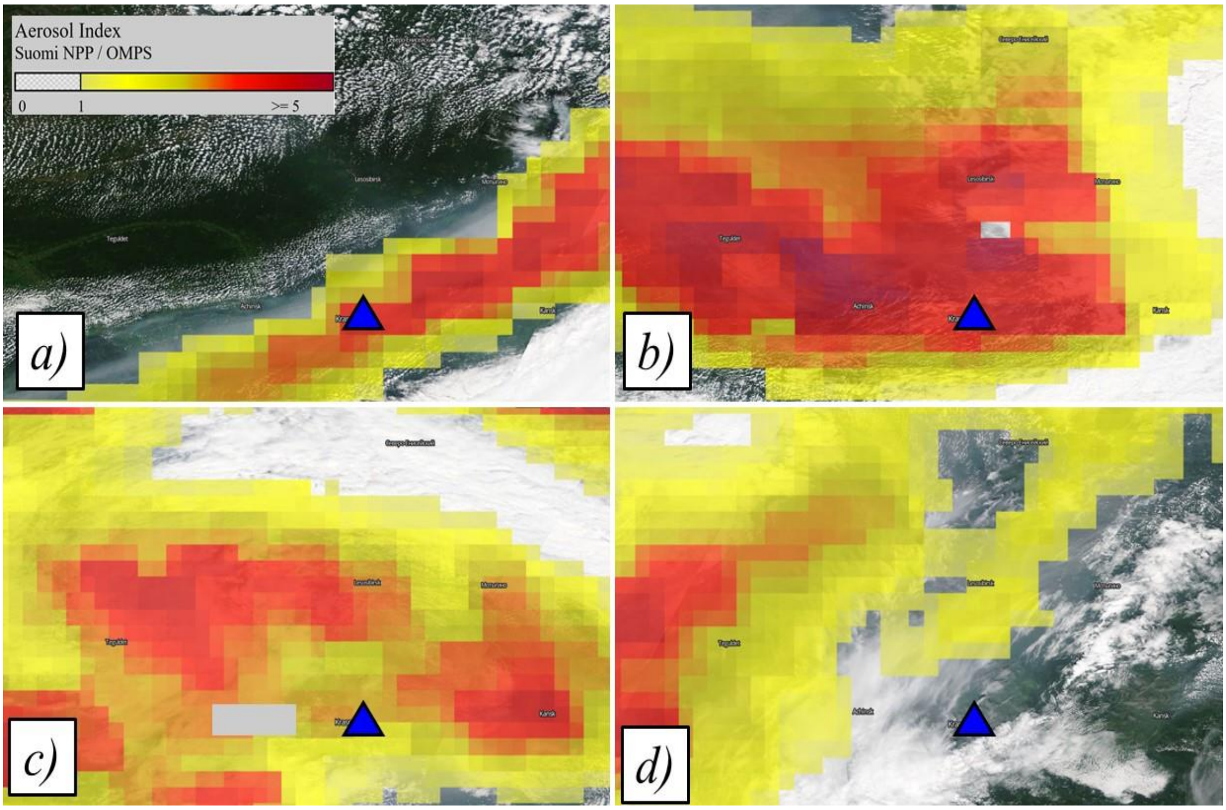

Figure 4. Dynamics of Aerosol Index values in the vicinity of Krasnoyarsk..

Figure 4 shows the AI values based on data from the OMPS device installed on the Suomi NPP satellite. The blue triangle indicates the city of Krasnoyarsk. Figure 4a shows the smoke plume from the fire on July 14, 2019. The AI values above the city are 3.5, which corresponds to high pollution. Figure 4b shows the AI values for July 20, 2019, above the city the value is 4.2. On this day, the city was in the area of the cyclone, which tightened the smoke from the fires that were in the area of the anticyclone. A similar situation is depicted in Figure 4c, from July 21, 2019, where the value of AI over the city was 2.8. After July 24, 2019 (Figure 4d) the zone of action of the cyclone is displaced from the territory of the city of Krasnoyarsk and the values of AI are reduced to 0.15, which corresponds to low levels of pollution.

According to Figure 4, the dynamics of smoke plumes distribution in Siberia and over Krasnoyarsk is visible. It is possible to identify in what period of time the city was in the zone of the smoke plume using AI data, as well as to estimate the strength of the smoke.

3 Conclusions

In this paper, we used a new MAIAC algorithm to estimate AOT from MODIS data with a spatial resolution of 1 km, comparing it with a classical algorithm with a coarser spatial resolution of 10 km. Our analysis shows that the correlation between PM2.5 and AOT with a spatial resolution of 1 and 10 km is approximately similar. However, using a higher spatial resolution, it is possible to identify areas of dust pollution in the city on the block level of details. This will make it possible to determine more qualitatively environmentally unfavorable areas of the city. Using the ground-based AMS data, in addition to satellite data with high spatial resolution (MAIAC), it is possible to create an information basis for a modern system of environmental monitoring on a regional scale and contribute to the improvement of the environmental situation in the city.

At a time when monitoring of AOD data is not possible, the environmental situation can be monitored using AI, but it has a rather low spatial resolution, which makes it inapplicable to the identification of dust pollution zones on an intra-urban scale. However, the use of this index helps to identify external factors affecting the environmental situation in the city, regardless of the time of year and the presence of clouds.

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