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THE IMPACT OF SULFUR DIOXIDE IN THE AIR ON CLIMATE CHANGE AND ITS MONITORING

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Abstract:
The paper describes the impact of sulfur dioxide on climate change and its monitoring. As a key air pollutant, sulfur dioxide is produced by burning fossil fuels rich in sulfur, leading to aerosols and acid rain. Aerosols reflect sunlight into space, temporarily cooling the atmosphere, while acid rain negatively affects vegetation, soil, and buildings. Monitoring sulfur dioxide concentration is crucial for timely recognition and response to air pollution. Various measurement methods enable continuous air quality monitoring, including monitoring stations, mobile devices, satellites, etc. In Serbia, the SEPA network of monitoring stations is crucial for data collection and the definition and implementation of measures to reduce sulfur dioxide emissions into the air. Emission reduction can be achieved by using low-sulfur fuels, desulfurizing fuels, applying filters, and transitioning to renewable energy sources. Effective measures to reduce sulfur dioxide emissions contribute to reducing the greenhouse effect and global warming.

Keywords: *Sulfur dioxide, Air pollution, Climate change, Aerosols, Acid rain, Air quality monitoring*

Introduction

Sulfur dioxide (SO_2) created by human activities, which is emitted into the atmosphere (about 98% of the total amount of sulfur dioxide in the atmosphere), is produced as a result of burning fossil fuels that contain high amounts of sulfur and is one of the air pollutants. Sulfur dioxide is a colorless, toxic gas with an unpleasant, suffocating odor. The characteristic unpleasant odor that we sometimes detect in the air during air pollution events is primarily associated with increased concentrations of sulfur dioxide in the air. Air can be described as a mixture of gases (nitrogen – 78%, oxygen – 21%, argon – 0.93%, carbon dioxide – 0.034%, xenon, helium, neon, etc. – in minimal amounts [1]) that form the Earth's atmosphere and enable life on our planet. Excessive concentrations of sulfur dioxide in the atmosphere can significantly impact climate change.

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1. Climate change

Climate change can be described as long-term changes in the Earth's climate resulting from natural events (volcanic eruptions, solar activity, etc.) or human activities (burning fossil fuels, industrial processes producing chemicals, steel, agriculture, etc.).

According to the Intergovernmental Panel on Climate Change - IPCC climate change is: „A change in the state of the climate that can be identified by changes in the mean and/ or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use.“ [2].

United Nations Framework Convention on Climate Change - UNFCCC defines climate change as: „a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable periods. “[3].

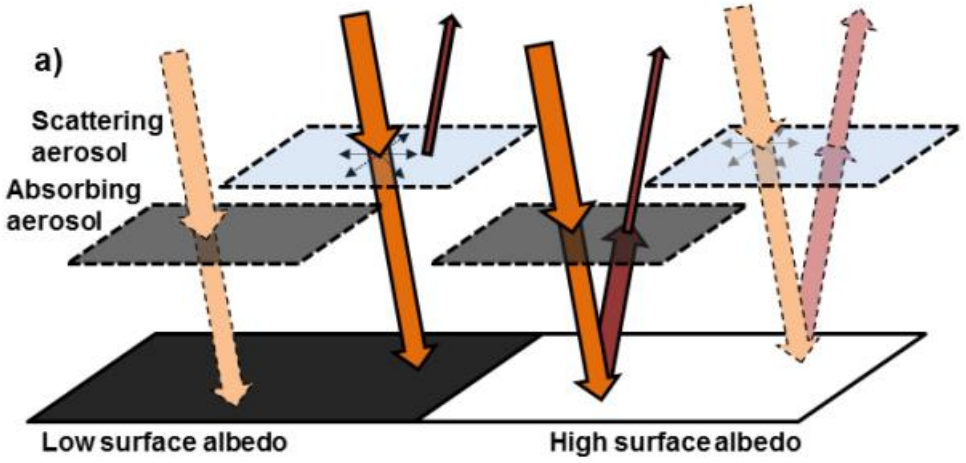
2. The impact of sulfur dioxide on climate change

2.1. Formation of aerosols and atmospheric cooling

Sulfur dioxide reacts with oxygen and water vapor upon emission into the atmosphere, forming sulfuric acid. This acid further reacts with bases to create sulfates. The sulfates condense and form tiny aerosol particles floating in the air.

The resulting aerosols reflect sunlight into space, reducing the amount of solar energy reaching the Earth's surface. This effect, known as the “albedo effect” (Picture 1), can temporarily cool the atmosphere. However, this effect is short-lived compared to the impact of greenhouse gases, such as carbon dioxide, which remain in the atmosphere for decades.

Sulfate aerosols temporarily cool the atmosphere by quickly removing them through precipitation. Their cooling effect lasts only a few weeks to a few months, while the effects of greenhouse gases can last for decades.



Picture 1. *The direct aerosol effect for low and high surface albedo [6]*

2.2. Acid rain

Acid rain represents one of the most significant environmental problems of today. Acid rain is caused by the emission of sulfur dioxide and nitrogen oxides into the atmosphere, where they react with water, oxygen, and other chemical elements, forming acids, which then fall back to Earth in the form of rain. Acid rain has a harmful impact on the environment, but it indirectly affects climate change as well. Some of the ways acid rain negatively impacts climate change are:

- air pollution (although acid rain itself does not directly cause global warming, air pollution caused by excessive amounts of sulfur dioxide contributes to the formation of aerosols that can reflect sunlight and have a cooling effect, but it can also lead to changes in precipitation patterns, directly affecting local climate conditions),
- vegetation damage (acid rain damages plant leaves, affecting their ability to perform photosynthesis, i.e., their ability to absorb carbon dioxide, one of the primary gases contributing to the greenhouse effect, which contributes to atmospheric warming),
- soil quality reduction (acid rain can alter the chemical composition of the soil, resulting in less fertile soil, which

negatively affects plant growth, as plants play a significant role in absorbing carbon dioxide and regulating climate conditions),

- destruction of buildings (acid rain causes the corrosion of metals and deterioration of construction materials, which results in additional construction resources for repairs and maintenance, leading to increased production of these materials and, consequently, additional carbon dioxide emissions during their production), etc.

2.3. Air pollution

High concentrations of sulfur dioxide negatively affect air quality and can cause respiratory problems and other health issues in humans and animals. Sulfur dioxide can contribute to the formation of smog, which further endangers health and contributes to air pollution. Respiratory diseases such as asthma and bronchitis are often associated with exposure to high concentrations of sulfur dioxide in the air.

3. Monitoring sulfur dioxide in the air

Effective monitoring of sulfur dioxide concentration in the atmosphere is essential for assessing its impact on the environment, human health, and climate change. Monitoring sulfur dioxide is crucial for timely recognition and response to air pollution. The collected data enable decision-makers to develop and implement appropriate measures to reduce harmful sulfur dioxide emissions into the atmosphere. Additionally, this data is vital for researching and understanding the impact of pollution on the environment.

Today, we have several devices for measuring sulfur dioxide concentration in the air, including:

- gas chromatographs – mass spectrometers,
- UV-visible spectrometers,
- electrochemical sensors,
- infrared spectrometers, and
- chemiluminescent detectors.

Monitoring air quality, i.e., the concentration of sulfur dioxide in the air, can be realized through:

- monitoring stations,
- mobile measuring devices,

- satellite monitoring,
- laboratories,
- meteorological balloons,
- lasers, etc.

Monitoring stations are fixed locations equipped with instruments for continuous air quality monitoring. In real-time, they measure the concentration of pollutants in the air, including sulfur dioxide, and provide us with long-term tracking and data for analysis.

Mobile measuring devices are portable units mounted on vehicles, drones, airplanes, etc. They collect data from various locations and altitudes, providing flexibility and coverage of wider areas. They are ideal for short-term research or targeted pollution monitoring.

Satellite monitoring involves using satellites with special instruments to detect atmospheric pollutants from high altitudes. This technique allows for global pollution monitoring and provides a broad insight into the distribution of sulfur dioxide and other pollutants.

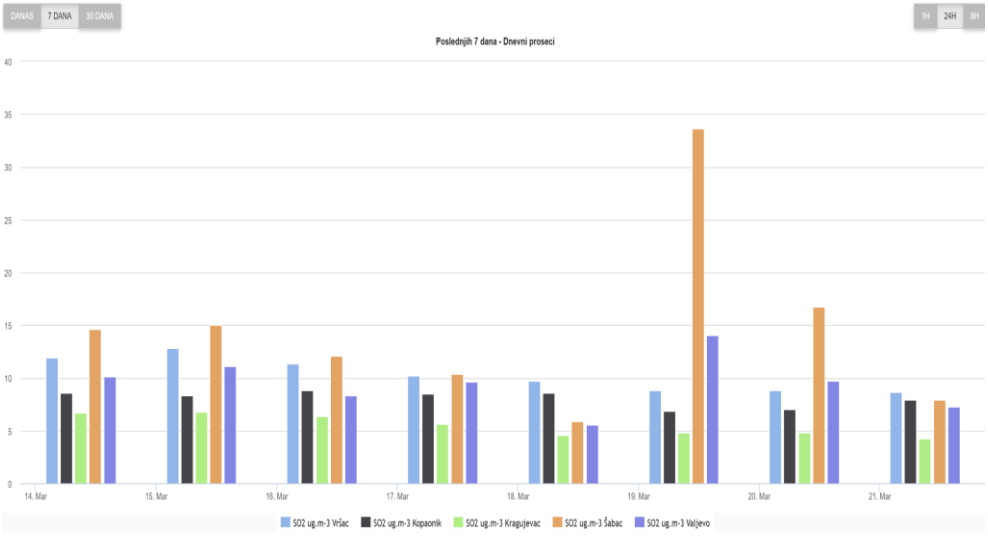
Laboratory analyses involve taking air samples from various locations and analyzing them under laboratory conditions. Sophisticated techniques, such as gas chromatography-mass spectrometry, are used to measure pollutant concentrations accurately.

Meteorological balloons collect atmospheric data at different altitudes, including sulfur dioxide concentration.

Laser spectroscopy involves using lasers to detect and measure sulfur dioxide concentration in the air. This technique allows for precise measurements in remote locations.

In the Republic of Serbia, we have developed the Serbian National Air Monitoring Network (SEPA) for automatic air quality monitoring. This network of 84 monitoring stations has been operational since 2006 and enables continuous measurement of the concentrations of 9 air pollutants, including sulfur dioxide. The network's main purpose is to provide real-time air quality data to the public and decision-makers. The Serbian Environmental Protection Agency is responsible for managing and maintaining the network. This network is critical and crucial for monitoring air pollution and implementing measures to protect human health and the environment. Picture 2 shows a graphical representation of the measured sulfur dioxide concentration at five

monitoring stations from 14.03.2025. to 21.03.2025. [7]. Table 1 shows the numerical values of the measured sulfur dioxide concentrations for the same monitoring stations during the same period [7].



Picture 2. *Graphical representation of the measured sulfur dioxide concentration in the air at five monitoring stations from 14.03.2025. to 21.03.2025, Source: [7]*

Table 1: *Numerical values of the measured sulfur dioxide concentrations in the air at five monitoring stations during the period from 14.03.2025 to 21.03.2025*

Date	**SO_2 [ug.m-3]** Vršac	**SO_2 [ug.m-3]** Kopaonik	**SO_2 [ug.m-3]** Kragujevac	**SO_2 [ug.m-3]** Šabac	**SO_2 [ug.m-3]** Valjevo
2025-03-14	11.91	8.6	6.66	14.65	10.16
2025-03-15	12.85	8.32	6.76	15	11.08
2025-03-16	11.37	8.79	6.39	12.06	8.32
2025-03-17	10.22	8.45	5.66	10.35	9.62
2025-03-18	9.75	8.54	4.55	5.9	5.58
2025-03-19	8.78	6.87	4.78	33.64	14.02
2025-03-20	8.84	7.05	4.84	16.75	9.71
2025-03-21	8.65	7.95	4.21	7.88	7.28

Source: [7]

4. Methods of preventing sulfur dioxide emissions into the atmosphere

Some of the ways we can influence or reduce human-generated sulfur dioxide emissions into the atmosphere include:

- using low-sulfur fuels,
- desulfurizing fuels (the process of removing sulfur from fuels before combustion),
- flue gas desulfurization (contacting flue gas with a limestone suspension),
- applying filters (sulfur filters or dry filters are used to remove (absorb) sulfur dioxide from flue gases before release),
- modifying industrial processes (altering industrial processes to reduce sulfur intake or improve combustion efficiency),
- controlling emissions during combustion (implementing technologies to control temperature and adjust combustion to reduce sulfur dioxide emissions),
- using renewable energy sources (transitioning to energy sources such as solar, wind, hydro, etc.),
- improving energy efficiency (enhancing energy efficiency in industry and transportation reduces the need for fuels that produce sulfur dioxide), etc.

5. Conclusion

We can say that sulfur dioxide represents one of the key air pollutants whose presence in the atmosphere has far-reaching consequences for the environment and climate change. As a result of burning fossil fuels rich in sulfur, sulfur dioxide affects air quality and the health of living beings. Its direct consequences include the formation of aerosols and acid rain, which can cause atmospheric cooling and ecosystem damage. Acid rain negatively impacts vegetation, soil, and buildings, contributing to climate change and environmental degradation.

International organizations such as the IPCC and UNFCCC define climate change as long-term changes in the Earth's climate system, which natural processes and human activities can cause. Sulfur dioxide emissions significantly contribute to these changes, mainly by forming aerosols that temporarily cool the atmosphere. However, the long-term

greenhouse effects caused by carbon dioxide emissions have a more lasting impact on global warming.

Excessive concentrations of sulfur dioxide in the air present a serious challenge for the environment and climate change. Its continuous monitoring and the implementation of effective measures to reduce emissions are of great importance for preserving air quality and the health of living beings. Additionally, educating and raising public awareness about the importance of environmental protection can contribute to a better understanding of the problem and more active participation in addressing this global challenge.

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