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Assessment of Sulfur Dioxide Levels in Atmospheric Air Over the Period 2019–2024

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Abstract

This study investigates the spatiotemporal distribution and dynamics of atmospheric sulfur dioxide (SO_2) over the Crimean Peninsula during the period 2019–2024, employing protected natural areas as background reference sites for air quality assessment. The primary objective is to determine the variability in SO_2 concentrations in the atmosphere over Crimea. Methodologically, the study involves selecting background sites across diverse landscape levels throughout the peninsula, and applying Z-analysis to categorize ambient air pollution into four levels: conditionally low, average, elevated, and high. The analysis encompasses annual mean SO_2 levels, assessment of temporal trends, and localization of pollution hotspots. Results indicate a peak in SO_2 levels in 2020, predominantly at mid-mountain landscape level, and a minimum in 2019. Overall, a decreasing trend of 25.4 μmol/m² per year in SO_2 concentrations is observed, despite localized zones of high pollution, including areas northeast of the regional center, Simferopol. In 2022, the low-mountain landscape level of the northern macroslope exhibited the most extensive conditionally high pollution zone, covering nearly half of its territory. The novelty of this work lies in integrating protected natural areas as reference sites within the Z-analysis framework, enabling more precise identification of anthropogenic influences and the spatial distribution patterns of sulfur dioxide concentrations in the region's atmosphere.

Keywords: Sulfur Dioxide (SO_2); Atmospheric Air; Background Concentration; Protected Natural Areas; Air Pollution Levels; Z-Score Analysis; Standardized Assessment; Landscape Levels; The Crimean Peninsula.

1. Introduction

Sulfur dioxide (SO_2) is a colorless gas with a pungent, suffocating odor and a boiling point of –10 °C. It is heavier than ambient air and a highly toxic pollutant [1, 2]. The primary anthropogenic sources of SO_2 include combustion processes involving sulfur-rich fuels such as coal, fuel oil, and diesel. Additionally, it is also released into the atmosphere during the combustion of biomass, including wood, peat, and plant residues [3]. Currently, coal combustion accounts for approximately 50% of global anthropogenic sulfur dioxide (SO_2) emissions. An additional 25% of emissions originate from petroleum-based fuels. The remaining 25% emanate from industrial processes involving the heating and chemical transformation of sulfur-containing materials, during which SO_2 is emitted as a by-product [4]. Other human sources of SO_2 include the pulp and paper industry, metallurgy, and the food industry (where SO_2 is employed as a disinfectant and preservative agent) [1].

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Many studies have concentrated on quantifying the specific contribution of anthropogenic sources to atmospheric SO_2 levels. Notably, industrial and transportation sectors are primary contributors, with markedly elevated emissions reported in several regions. For example, in India, anthropogenic SO_2 emissions reach approximately 5.2 million tons per year, predominantly originating from coal-fired thermal power plants [5, 6]. Similar trends are observed in Iran [7], while in Argentina, peak SO_2 concentrations in the Cuenca basin during winter months have reached up to 2760 μmol/m² [8]. Additional significant sources include Canada [9], Japan [10], and Mexico, where power plant emissions significantly influence regional SO_2 levels [11]. Marine transportation also plays a notable role, with ships contributing to the global atmospheric SO_2 level [12].

Among natural sources, volcanic eruptions represent the dominant contributor of SO_2 to the atmosphere. Remote sensing data, particularly from Sentinel-5P TROPOMI instruments, have revealed elevated concentrations over active volcanic regions [13, 14]. For example, the Semeru volcano in Indonesia exhibited peak SO_2 levels reaching 300 μg/m³ in 2024, while the Nishinoshima volcano in Japan was shown to contribute over 90% to local $PM_{2.5}$ concentrations [13–15]. Similarly, the 2022 eruption of Mauna Loa released approximately 600 kilotons of SO_2 into the atmosphere [16]. Detection of volcanic SO_2 plumes by satellite scanners such as RST-SEVIRI achieves an accuracy of approximately 79% [17]. Following emission, SO_2 undergoes atmospheric oxidation, resulting in sulfuric acid aerosols over a timescale of several weeks, even at trace concentrations, thereby exerting significant climatic effects. Historical volcanic eruptions have generated sulfuric acid aerosols in the lower stratosphere, inducing a surface temperature decrease on the order of 0.5°C persisting for approximately three years. While such large-scale eruptions typically occur at intervals of roughly 80 years, geological records indicate periods of heightened volcanic activity with more frequent occurrences [18].

In atmospheric conditions characterized by the presence of moisture and various coexisting chemical species, sulfur dioxide (SO_2) undergoes oxidation processes leading to the formation of sulfate aerosols through condensation into fine particulate matter. Atmospheric aerosols are defined as microscopic solid or liquid particles suspended in the atmosphere [19]. These aerosols modulate the Earth's radiative balance by scattering, reflecting, and absorbing incoming solar radiation, thereby reducing the net flux of solar energy reaching the lower troposphere and the Earth's surface. According to assessments by the Intergovernmental Panel on Climate Change (IPCC) states that there is "convincing evidence of a significant negative overall radiative forcing effect on the Earth's surface" [20].

Sulfate aerosols are formed as products of volcanic eruptions, fossil fuel combustion, and wildfires, and are known to contribute to a climatic cooling effect potentially reaching up to 1°C. Nonetheless, this aerosol-induced cooling effect is insufficient to counterbalance the ongoing global warming trend, with the Earth's mean surface temperature having already increased by approximately 1.5°C relative to pre-industrial levels [21]. The combustion of coal and oil releases substantial quantities of carbon dioxide (CO_2), a principal greenhouse gas that enhances atmospheric radiative forcing by trapping outgoing longwave radiation. Simultaneously, coal and oil combustion are sources of sulfur dioxide (SO_2) emissions, which interacts with other atmospheric substances to form sulfate aerosols. These aerosols exert a cooling effect by scattering solar radiation. Beyond direct scattering effects, sulfate aerosols modulate cloud microphysical properties by serving as cloud condensation nuclei, which augment the surface area available for water vapor condensation. This mechanism promotes the formation of clouds with increased droplet concentrations and brightness, consequently enhancing cloud albedo and reflecting greater amounts of solar radiation back to space [22]. The role of sulfate aerosols and their contribution to cloud-mediated radiative forcing is widely recognized in the literature, highlighting their significance in reducing surface solar insolation [23].

Indeed, sulfur dioxide (SO_2) plays a dual role in Earth's atmospheric processes. It should be noted that sulfur dioxide (SO_2) does indeed reflect a portion of incoming solar radiation in the atmosphere, and increased concentrations leading to cooling effects that can cause temporary episodes of global cooling. This mechanism primarily explains how large volcanic eruptions can cause temporary episodes of global cooling due to SO_2 emissions into the upper atmosphere. However, the opposite effect can also occur. Massive emissions of SO_2 can exceed atmospheric capacity of the atmosphere, leading to rapid warming, with acid rain becoming particularly severe at high emission levels [24]. Additionally, excessive SO_2 levels lead to the formation of sulfuric acid upon reacting with water, forming highly corrosive liquid aerosols that contribute to acid rain. Wet sulfur dioxide is highly corrosive due to the gradual formation of sulfuric acid [25]. The presence of SO_2 in the atmosphere contributes to the formation of acid rain, which reduces crop yields, causes soil degradation [22], disrupts the acid-base balance of aquatic and terrestrial ecosystems, and can also lead to the deterioration of buildings (sulfate corrosion of concrete) [26].

Greenhouse warming and cooling associated with sulfate aerosols play a significant role in climate change driven by human activity. Without the influence of aerosols, global warming would be much more pronounced. Sulfate pollution from power plants and vehicles, as well as other anthropogenic aerosols such as organic carbon emitted from the combustion of agricultural residues and nitrates from fertilizers, can produce a cooling effect estimated to offset global warming by approximately 0.2°C to 0.9°C [20]. This cooling effect is primarily due to the scattering and reflection of solar radiation. However, sulfate aerosols and SO_2 are short-lived in the atmosphere, typically persisting from days to weeks, whereas CO_2 remains in the atmosphere for hundreds or even thousands of years. Consequently, over time, the warming effect of fossil fuel emissions will continue to intensify, while the cooling influence of sulfate aerosols diminishes. With ongoing combustion of coal and oil, short-lived sulfate aerosols will persist in the atmosphere, while CO_2 accumulates. When comparing CO_2 and SO_2, it's crucial to understand their different temporal scales: CO_2

accumulates and sustains warming over long periods, leading to persistent climate change, whereas sulfate aerosols produce transient cooling effects that fade relatively quickly. Consequently, the overall impact of CO_2 on global temperature is predominantly warming, with sulfate aerosols temporarily masking some of this warming [27].

Despite their climatic cooling properties, sulfate aerosols pose significant public health risks [28]. They can cause respiratory issues such as wheezing, shortness of breath, and chest tightness, increasing the risk of health deterioration, especially among vulnerable groups such as children, the elderly, and individuals with asthma. Furthermore, SO_2 exposure is associated with cardiovascular diseases and can cause irritation of the mucous membranes of the eyes, skin [29], nose, and throat. High ambient SO_2 levels can provoke inflammation and respiratory irritation, particularly during activity, further exacerbating health risks [30, 31].

The environmental impact of sulfur dioxide (SO_2) is also significant. Accordingly, some countries have gained experience in tightening environmental standards related to this substance. Strategies include phasing out coal-fired power plants, implementing tighter emission controls across the energy and maritime sectors, and increasing reliance on renewable energy sources such as solar and wind power [4]. As noted in some scientific studies [5, 6], TROPOMI satellite data enhance the accuracy of emission estimates (with an uncertainty of 40%), by identifying point sources of pollution. When combined with meteorological data and inverse modeling techniques, these observations help reduce assessment biases and provide more reliable estimates of SO_2 emissions and their sources [6, 10]. Research in Europe demonstrates that stringent regulatory measures have successfully decreased pollutant emissions, leading to lower aerosol concentrations in the atmosphere. The resultant reduction in aerosol loading allows more solar radiation to reach Earth's surface, which can have complex climatic consequences. Specifically, increased surface insolation can intensify heat waves and elevate surface water temperatures, potentially worsening drought conditions and affecting local ecosystems and water resources [32].

In 2020, the International Maritime Organization implemented the IMO 2020 resolution, which set stricter limits on sulfur content in marine fuels to significantly reduce sulfur dioxide (SO_2) emissions from shipping. This regulatory change has resulted in a decline in aerosol concentrations over shipping lanes, potentially affecting cloud formation processes in these regions. A projected consequence of these emission reductions is a modest global temperature increase of approximately 0.05°C by 2050, equivalent to about two additional years of current emission levels. This illustrates that reducing SO_2 emissions may slightly contribute to higher surface temperatures over the long term. However, there is no direct evidence linking the decrease in SO_2 emissions from ships to the occurrence of extreme heat waves at sea or on land [33]. The role of sulfur dioxide (SO_2) in climate processes has been the subject of extensive debate, and no definitive conclusion has been reached. It is hypothesized that if all ships worldwide adopted the IMO 2020 and IMO 2023 regulations, this could contribute to a further reduction in emissions. However, shipping is only one source of SO_2, and according to some estimates, it accounts for no more than 3.5% of the global emissions of this substance into the atmosphere [34].

According to Coulibaly [35], stratospheric aerosol injection (SAI) represents a geoengineering strategy in which sulfur dioxide (SO_2) is introduced into the stratosphere to reduce atmospheric warming. SAI aims to mitigate global warming by intentionally increasing aerosols in the stratosphere to reflect more sunlight back into space, thereby cooling the Earth's surface. According to the study, SO_2 injection could have beneficial effects such as stabilizing precipitation patterns and reducing the severity and frequency of climatic extremes. This suggests that, under controlled conditions, SAI might offer a temporary or supplemental approach to slowing climate change impacts.

This study examines the spatial and temporal variability of sulfur dioxide (SO_2) concentrations in the atmosphere over the Crimean Peninsula during the period 2019–2024.

The remainder of this paper is organized as follows: Section 2 describes the study area and the methodology of standardized assessment (Z-analysis) for categorizing air pollution into four levels and calculating the corresponding sulfur dioxide (SO_2) concentration values. In addition, the sulfur dioxide (SO_2) concentration values over selected background sites are noted. Section 3 presents the air pollution level calculations by sulfur dioxide (SO_2) results and provides maps with distribution of the concentration fields in the atmospheric air and pollution zones. Section 4 discusses the peaks of atmospheric pollution on the Crimean Peninsula within various landscape levels and their dynamics in the period 2019–2024. Section 5 summarizes the study, highlighting the novelty of the research, theoretical contributions, practical significance, key limitations, and opportunities for further studies.

2. Materials and Methods

The study design is illustrated in Figure 1. This study examines the spatiotemporal variability of sulfur dioxide (SO_2) concentrations within the atmosphere over the Crimean Peninsula. Initially, the primary objective was established: to investigate the spatial and temporal characteristics of SO_2 distribution in the region. Subsequently, data acquisition involved satellite observations from Sentinel-5P, utilizing offline datasets detailing atmospheric sulfur dioxide levels. The following phase – data analysis – employed statistical techniques, notably Z-score analysis, to standardize the datasets and facilitate classification of pollution intensities. The results encompassed the creation of geographical maps illustrating SO_2 concentrations and pollution levels derived from the processed data. The obtained results were discussed and interpreted to identify significant findings relevant to the research subject.

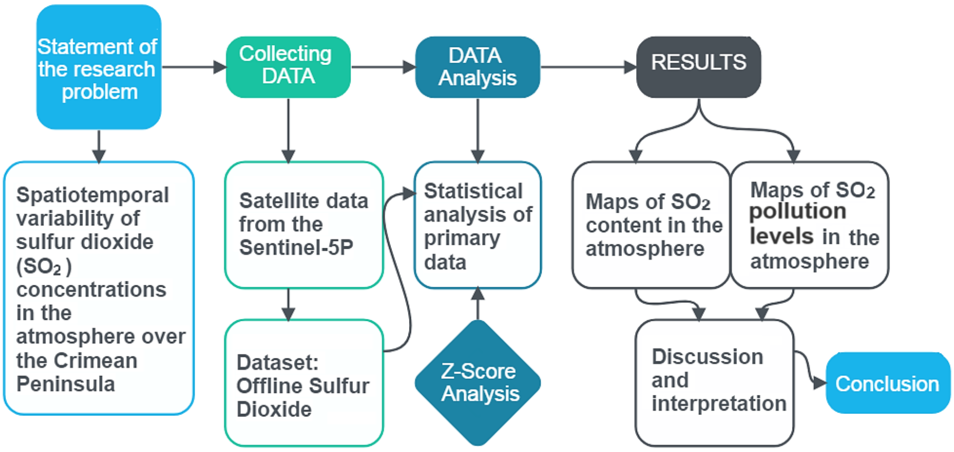


Figure 1. Flowchart of the research design

2.1. Satellite Data

Satellite data from the Sentinel-5P OFFL SO_2 dataset – produced by the TROPOMI instrument aboard the Sentinel-5 Precursor mission – were employed to estimate atmospheric sulfur dioxide (SO_2) concentrations over the Crimean Peninsula. This dataset provides information useful for air quality assessment utilizing a multispectral sensor that records reflected radiation within a wavelength range pertinent to SO_2 detection, achieving a spatial resolution of 0.01° [36]. The instrument retrieves products of the tropospheric and stratospheric sulfur dioxide (SO_2) column. Due to the presence of noise in the data, negative values are often observed in areas with no SO_2 emissions [37]. In this study, such negative values were rectified by assigning a value of zero mol/m². The satellite-derived SO_2 concentration data were accessed and processed through the Google Earth Engine cloud platform [38] to facilitate comprehensive spatiotemporal analysis. Utilizing data from references [39, 40], annual mean SO_2 concentration maps across the Crimean Peninsula from 2019 to 2024 were generated. The underlying dataset encompasses high-resolution images depicting SO_2 concentrations, covering the period from December 5, 2018, to the present. This study utilizes the average annual SO_2 concentration data for the period 2019–2024.

Specifically, the analysis employed the SO_2_column_number_density channel. Quantitative data are expressed in mol/m². The data in this channel represent the concentration of the substance in the total vertical column of the atmosphere (the ratio of the amount of SO_2 to the mass of air in this column). Satellite data visualization and map creation were conducted using ArcGIS 10.5 software.

2.2. Study Area Characteristics

The Crimean Peninsula is located in the northern hemisphere, approximately midway between the equator and the North Pole, spanning from 44°23′ to 46°15′ N latitude and 32°30′ to 36°40′ E longitude. It lies to the south of the Eastern European Plain and is bordered by the Black Sea to the west and south, and the Sea of Azov to the northeast. Both seas are part of the Atlantic Ocean drainage basin (see Figure 2).

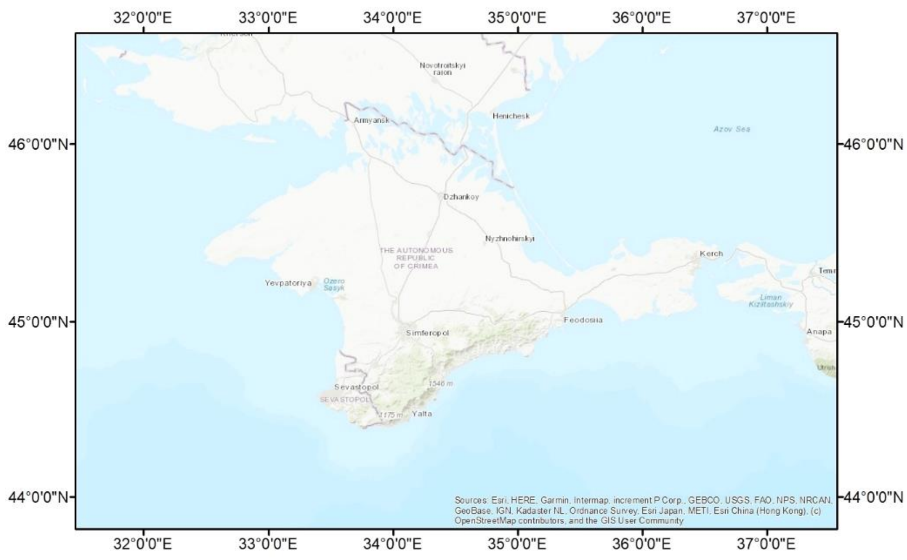


Figure 2. Territory of the Crimean Peninsula

2.3. Background Values for Sulfur Dioxide (SO_2) Concentration

The investigation of atmospheric sulfur dioxide (SO_2) pollution over the Crimean Peninsula is founded on a robust theoretical framework designed to quantify deviations from background levels. This method relies on the selection of background reference sites, statistical standardization of concentration data, and the classification of anomalies (defined as deviations from background values), which ensures comparability of results across different landscape levels and years. Background SO_2 concentrations, representing areas minimally affected by local pollution sources, serve as a baseline for assessing anthropogenic impact. To evaluate deviations from these background concentrations, specially protected natural areas were selected within distinct landscape levels, as defined by the landscape classification map of Grishankov [41]. The protected natural areas considered in this context are detailed by Drygval et al. [42]:

- Kalinovsky Nature Park (hydromorphic landscape level – HLL);
- Karadag Nature Reserve (low-mountain landscape level of the southern macroslope – LLLSM);
- Belaya Skala Nature Park (low-mountain landscape level of the northern macroslope – LLLNM);
- Tarkhankutsky Nature Park (upland landscape level – ULL);
- Crimean National Park (mid-mountain landscape level – MLL).

The designated background areas under consideration cover an area of more than 2,000 hectares, thus ensuring the representativeness of the dataset and minimizing the potential influence of local pollution sources. The closest settlement to the boundary of the protected natural areas is Gurzuf, located approximately 1 km from the border of the Crimean National Park. The boundaries of the selected protected natural areas, corresponding to various landscape levels, are illustrated in Figure 3, providing a clear spatial delineation for the analysis

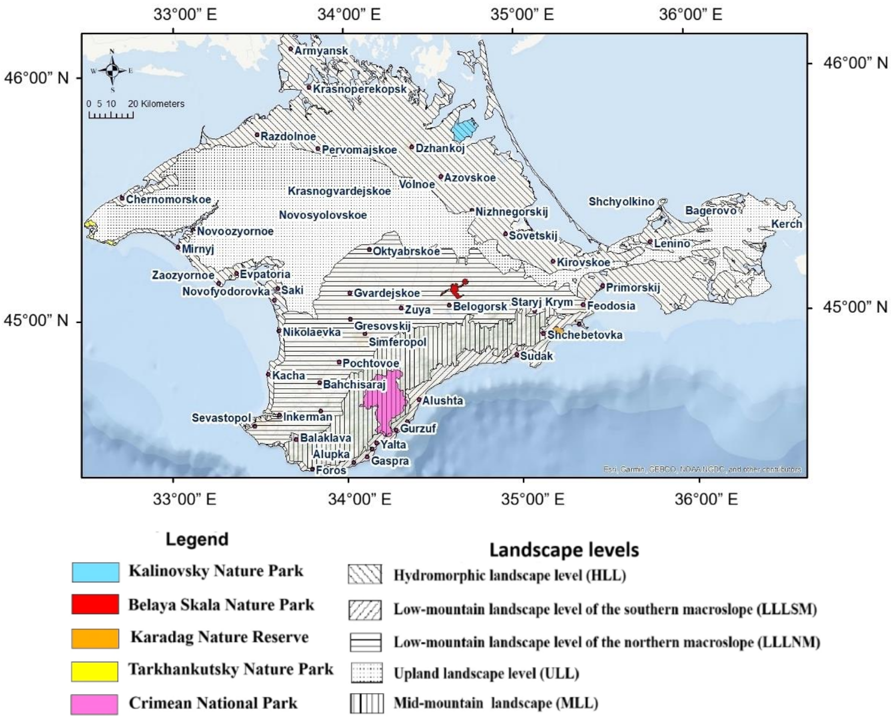


Figure 3. Protected natural areas (background areas) within the landscape levels of the Crimean Peninsula [41]

The selection of such background areas is due to the fact that protected natural areas (PNAs) are considered zones with minimal anthropogenic impact, allowing isolation of natural background pollution levels. This approach excludes mixing of signals from local sources (e.g., industrial facilities or transport) and focuses on regional trends associated with regional emissions.

To characterize deviations of average annual sulfur dioxide (SO_2) concentrations from established background levels, a statistical analysis was conducted on the annual average SO_2 concentrations across the atmosphere over the Crimean Peninsula. This analysis included the computation of standardized anomalies, defined as deviations expressed in terms of standard deviations from the background mean. In the present study, thresholds exceeding +2 and +3 standard deviations above the background level were employed to assess and classify pollution intensity. Identification of these standardized anomalies was based on statistical evaluation of the longitudinal data series spanning from 2019 to 2024.

A standardized score (Z-score) is a measure of the dispersion of a data series within a sample of values, indicating how many standard deviations this dispersion deviates from the mean value (i.e., the mean background concentration in this study). This dimensionless metric facilitates comparison across variables with differing units or scales. Prior to detailed statistical evaluation, it is essential to verify whether the data conform to an expected distribution, typically a Gaussian (normal) distribution. Under such conditions of a normal Gaussian distribution, Z-values exceeding +3 or falling below -3 are expected to occur in approximately 0.13% of cases, constituting strong anomalies – either significantly elevated or diminished levels – relative to the overall data set. Additionally, about 2.14% of data points are anticipated to lie within the ranges $2 < Z < 3$ and $-3 < Z < -2$, respectively, classifying them as pre-anomalous. The calculated Z-score provides a standardized means for comparing anomalies across different spatial points arranged on a regular coordinate grid, thus allowing assessment of deviations under varying natural conditions. In this study, the focus is exclusively on positive anomalies ($z > 2$ and $z > 3$), since only elevated SO_2 concentrations – indicative of pollution – are relevant for the analysis.

The Z-score standardizes concentration data, enabling the detection of outliers and trends independently of their absolute values. A normal (Gaussian) distribution of the data is assumed, which is preliminarily verified (e.g., using normality tests such as the Shapiro-Wilk test or graphical methods for determining data distribution). This ensures objectivity in the assessment, minimizing the influence of random variations in values. The obtained standardized values are distributed across the following intervals relative to background concentration levels [42]:

- Conditionally low pollution level ($z < 1$);
- Conditionally average pollution level ($1 < z < 2$);
- Conditionally elevated pollution level ($2 < z < 3$);
- Conditionally high pollution level ($z > 3$).

The term «conditionally» is employed in this study to acknowledge that background concentrations – used as reference values for calculating and classifying standardized Z-scores – are specific to each year and landscape level within the boundaries of the protected natural areas. These background values serve as benchmarks for assessing atmospheric air pollution based on their qualitative characteristics. However, it is important to recognize that air pollution levels are inherently variable; background concentrations fluctuate annually and across different landscape levels. These values are only valid under the specific conditions or relative to concentrations within the selected protected natural areas boundaries and the year under consideration. This variability justifies the use of the term «conditionally» throughout the analysis.

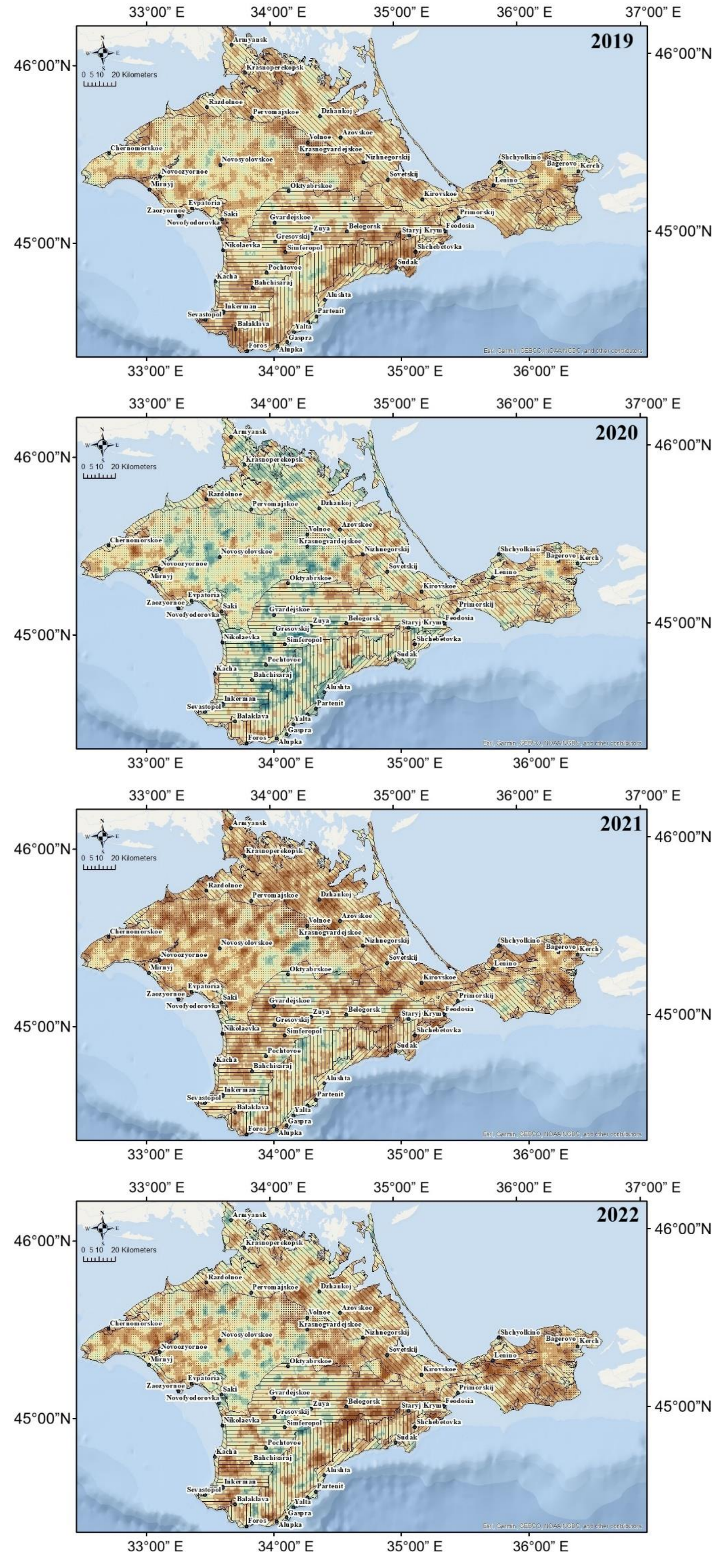
The average annual concentrations of sulfur dioxide (SO_2) above the selected background areas on the Crimean Peninsula are presented in Table 1.

Table 1.Average annual concentrations of sulfur dioxide (SO_2) in the atmosphere above the protected natural areas of the Crimean Peninsula (background concentration values) for the years 2019–2024

Year	Kalinovsky Nature Park	Karadag Nature Reserve	Belaya Skala Nature Park	Tarkhankutsky Nature Park	Crimean National Park
	µmol/m²				
2019	181.1	126.4	169.7	178.1	176.2
2020	233.1	190.7	192.3	171.4	248.3
2021	116.7	150.0	138.3	141.0	161.4
2022	190.3	136.7	102.3	179.4	192.2
2023	143.6	89.4	91.1	134.7	149.3
2024	184.3	145.4	145.4	150.9	167.1

3. Results

The spatial and temporal distribution of average annual sulfur dioxide (SO_2) concentrations within the landscape levels of the Crimean Peninsula is shown in Figure 4.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Novosyolovskoe
Novoozyornoe
Mirnyj
Sovetskij
Oktyabrskoe
Kirovskoe
Shchyolkino
Bagerovo
Kerch
Lenino
Evpatoria
Zaozyornoe
Saki
Novofyodorovka
Gvardejskoe
Zuya
Belogorsk
Staryj Krym
Primorskij
Feodosia
Gresovskij
Simferopol
Nikolaevka
Shchebetovka
Sudak
Pochtovoe
Kacha
Bahchisaraj
Alushta
Inkerman
Sevastopol
Partenit
Balaklava
Yalta
Gaspra
Foros
Alupka

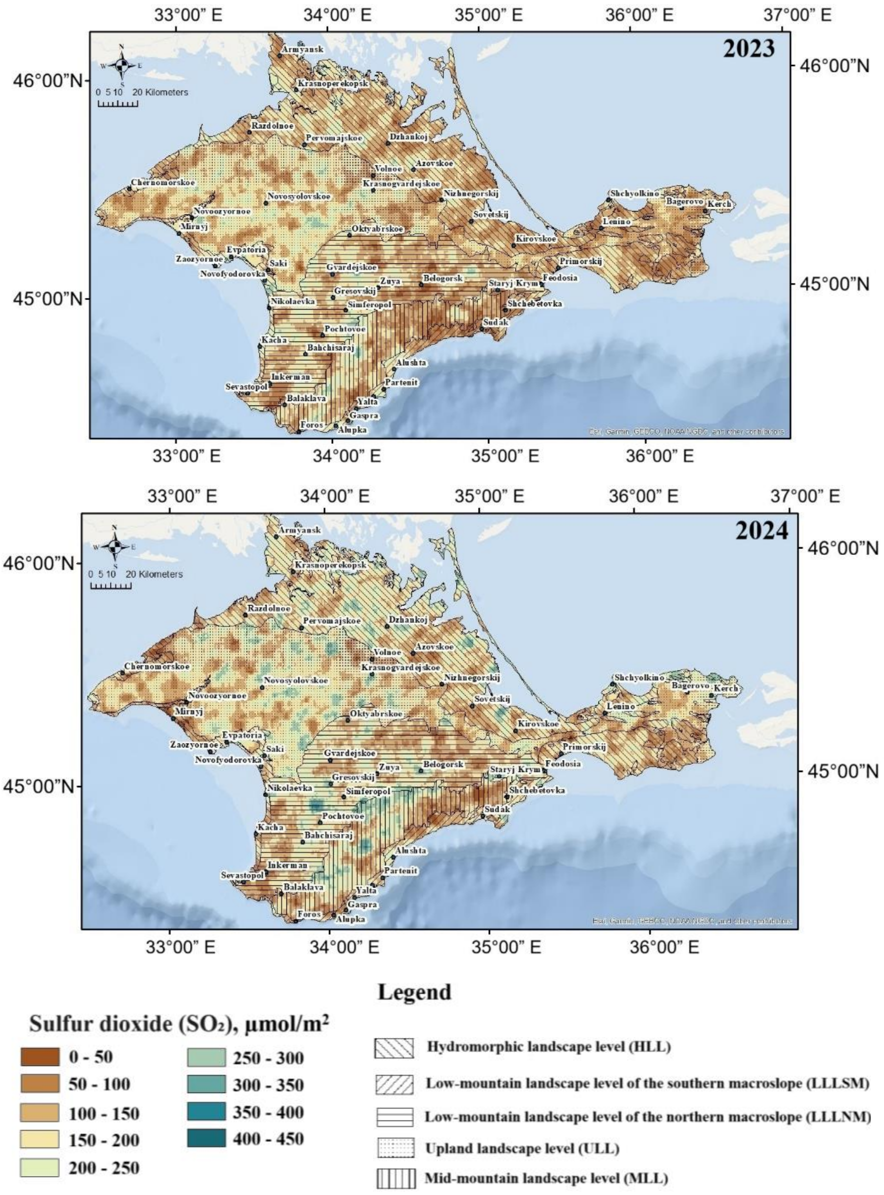


Figure 4. Distribution of average annual sulfur dioxide (SO_2) concentrations in the atmosphere over the Crimean Peninsula for the period 2019–2024

Table 2 provides statistical data describing atmospheric sulfur dioxide (SO_2) concentrations over the Crimean Peninsula. The parameters include the minimum and maximum observed concentrations (extreme values), and the arithmetic mean of concentrations. Additionally, the table reports the standard deviation of concentration values within the territorial units, defined according to landscape levels based on G.E. Grishankov's landscape map [41], for the period from 2019 to 2024.

The average concentration values in the air of the Crimean Peninsula range from 142.0 μmol/m² (in 2021) to 201.0 μmol/m² (in 2020) with a peak in 2020 followed by a decline in 2021–2023, but an increase in 2024 (163.5 μmol/m²). The range of values is broad (302.7–400.0 μmol/m²), with maxima reaching up to 420.1 μmol/m², indicating significant variability across the entire territory of Crimea. The standard deviation, as a measure of data dispersion (40.7–55.9 μmol/m²), reflects the uneven distribution, with minimum values often equaling 0 since 2021. These uneven dynamics of air concentration values and variability within the entire region underscores the necessity to consider smaller key area (landscape levels in the present study) considering their specific geomorphological and climatic environmental conditions.

To assess the distribution of sulfur dioxide (SO_2) concentrations in the atmosphere over the Crimean Peninsula, concentration limits were calculated that are statistically equivalent to Z-values. For each landscape level, based on the prevailing concentration values in protected natural areas, specific limits for SO_2 in atmospheric air will be established (illustrated in Table 3).

Table 2. Average annual concentrations of sulfur dioxide (SO_2) in the atmosphere over the Crimean Peninsula for the period 2019–2024 within landscape levels

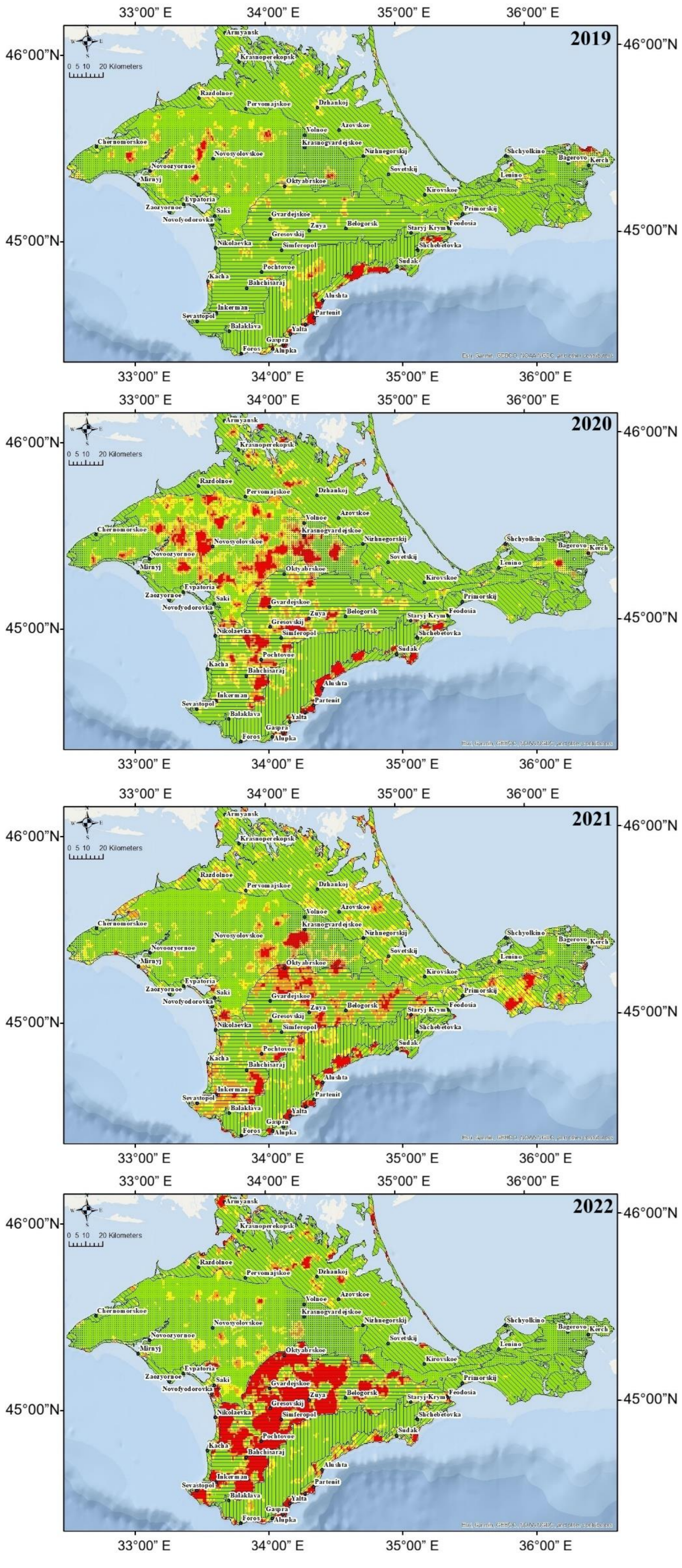
Year	Min. concentration value, µmol/m²	Max. concentration value, µmol/m²	Range of values, µmol/m²	Average value, µmol/m²	Standard deviation, µmol/m²
Crimean Peninsula					
2019	5.0	307.7	302.7	152.5	40.7
2020	20.1	420.1	400.0	201.0	54.4
2021	0	361.9	361.9	142.0	48.5
2022	0	399.0	399.0	160.2	55.9
2023	0	355.5	355.5	142.2	45.1
2024	0	388.5	388.5	163.5	52.5
Hydromorphic landscape level (HLL)					
2019	25.4	307.7	282.3	150.9	37.3
2020	29.7	377.3	347.6	192.8	50.0
2021	0	346.1	346.1	134.5	44.5
2022	0	339.5	339.5	156.5	50.7
2023	9.3	354.2	344.9	137.4	42.6
2024	0	343.5	343.5	162.2	50.7
Low-mountain landscape level of the southern macroslope (LLLSM)					
2019	17.5	252.0	234.5	147.6	39.9
2020	67.8	409.2	341.4	227.0	54.5
2021	3.7	310.9	307.2	154.7	52.3
2022	8.6	399.0	390.4	176.8	54.9
2023	4.7	269.9	265.2	118.0	49.7
2024	2.8	296.0	293.2	139.2	51.3
Low-mountain landscape level of the northern macroslope (LLLNM)					
2019	12.5	301.4	288.9	151.1	41.4
2020	58.3	419.6	361.3	211.4	57.8
2021	0	306.7	306.7	149.6	50.4
2022	0	367.5	367.5	166.3	60.5
2023	3.2	355.5	352.3	142.5	46.9
2024	14.1	388.5	374.4	160.6	52.4
Upland landscape level (ULL)					
2019	30.3	307.7	277.4	156.6	39.5
2020	20.1	371.2	351.1	197.9	52.6
2021	0	361.9	361.9	137.6	47.1
2022	0	367.7	367.7	158.4	55.2
2023	31.0	286.9	255.9	151.3	41.9
2024	0	347.8	347.8	167.9	48.7
Mid-mountain landscape level (MLL)					
2019	5.0	303.0	298.0	149.0	51.4
2020	49.0	420.1	371.1	209.4	60.5
2021	3.7	352.1	348.4	163.6	52.0
2022	0	367.5	367.5	161.0	62.5
2023	0	333.6	333.6	134.1	51.7
2024	0	358.6	358.6	166.4	66.7

Table 3. Concentration limits of sulfur dioxide (SO_2) in protected natural areas of the Crimean Peninsula

Year	Z=1	Z=2	Z=3
Kalinovsky Nature Park (hydromorphic landscape level (HLL)), μmol/m²			
2019	210.4	239.7	269.0
2020	261.6	290.2	318.7
2021	154.7	192.7	230.7
2022	213.5	236.6	259.8
2023	169.5	195.4	221.3
2024	236.0	287.7	339.3
Karadag Nature Reserve (low-mountain landscape level of the southern macroslope (LLLSM)), μmol/m²			
2019	137.8	149.1	160.5
2020	206.5	222.3	238.1
2021	161.1	172.3	183.4
2022	162.8	188.9	215.0
2023	116.3	143.2	170.1
2024	169.8	194.3	218.7
Belaya Skala Nature Park (low-mountain landscape level of the northern macroslope (LLLNM)), μmol/m²			
2019	210.4	251.1	291.7
2020	227.3	262.3	297.2
2021	166.0	193.7	221.4
2022	123.3	144.2	165.2
2023	121.9	152.6	183.4
2024	192.1	238.8	285.5
Tarkhankutsky Nature Park (upland landscape level (ULL)), μmol/m²			
2019	202.6	227.1	251.6
2020	204.9	238.4	271.9
2021	178.0	214.9	251.9
2022	231.6	283.8	335.9
2023	172.5	210.3	248.1
2024	188.7	226.4	264.2
Crimean National Park (mid-mountain landscape level (MLL)), μmol/m²			
2019	213.4	250.7	287.9
2020	305.4	362.4	419.5
2021	209.4	257.4	305.5
2022	249.3	306.4	363.5
2023	208.2	267.2	326.1
2024	236.9	306.8	376.6

Based on the calculated standardized concentration values across different background areas, certain features stand out, which will subsequently be used in the analysis to construct maps of the spatial distribution of deviations from background sulfur dioxide (SO_2) concentrations in the atmospheric air over the Crimean Peninsula. The Kalinovsky Natural Park (hydromorphic landscape level) exhibits a peak in 2020 (318.7 μmol/m²), followed by a decline in 2021–2023 (down to 221.3 μmol/m²), and an increase in 2024 (339.3 μmol/m²). The variability in background concentration values is high. The Karadag Nature Reserve (low-mountain landscape level of the southern macroslope) shows a peak in 2020 (238.1 μmol/m²) and minimum values in 2019 (160.5 μmol/m²). This territory has relatively low concentrations compared to other background areas. The Belaya Skala Natural Park (low-mountain landscape level of the northern macroslope) also peaks in 2020 (297.2 μmol/m²). The Tarkhankutsky Natural Park (upland landscape level) has a peak in 2022 (335.9 μmol/m²). The territory is characterized by relatively stable SO_2 concentration limits in the air during other years. The Crimean National Park (mid-mountain level) displays the highest peak in concentration limits among all background areas in 2020 (419.5 μmol/m²).

Based on these calculated Z-score thresholds and background concentration levels, maps of atmospheric SO_2 concentration were constructed, with concentrations classified by pollution levels from 2019 to 2024 (illustrated in Figure 5).


2019
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Pervomajskoe
Dzhankoj
Azovskoe
Volnoe
Krasnogvardejskoe
Chernomorskoe
Novosyolovskoe
Nizhnegorskij
Novoozyornoe
Sovetskij
Mirnyj
Oktyabrskoe
Shchyolkino
Bagerovo
Kerch
Lenino
Kirovskoe
Evpatoria
Zaozyornoe
Saki
Novofyodorovka
Gvardejskoe
Zuya
Belogorsk
Primorskij
Feodosia
Starыj Krym
Gresovskij
Simferopol
Nikolaevka
Shchebetovka
Pochtovoe
Sudak
Kacha
Bahchisaraj
Alushta
Inkerman
Partenit
Sevastopol
Balaklava
Yalta
Gaspra
Foros
Alupka

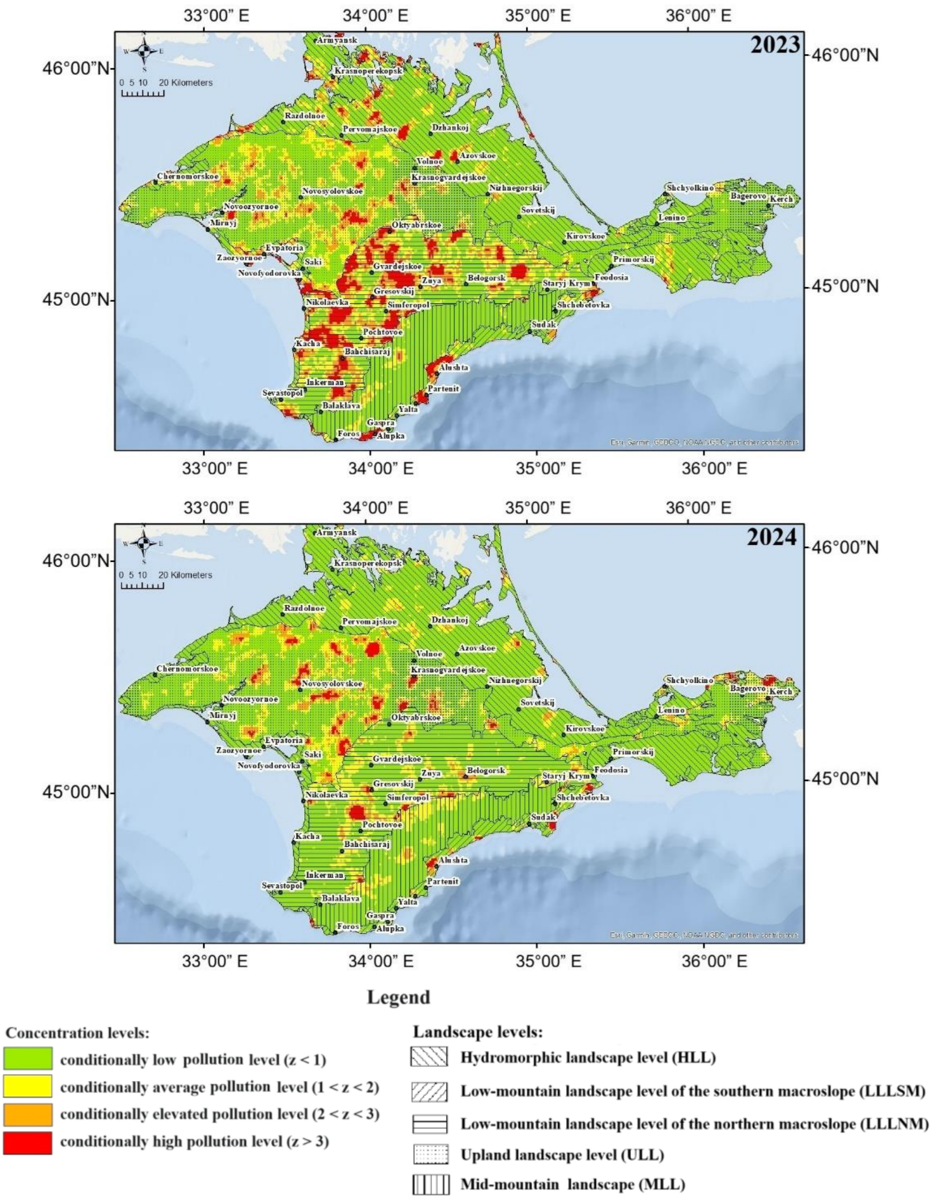

Figure 5. Spatial distribution of deviations of sulfur dioxide (SO_2) concentrations from background values in the atmosphere over the Crimean Peninsula in 2019–2024

4. Discussion

The highest average annual concentrations of sulfur dioxide (SO_2) were recorded in 2020 at the mid-mountain landscape level reaching 420.1 μmol/m². The lowest values of sulfur dioxide (SO_2) concentrations are 0 μmol/m², indicating noise over particularly clean areas and occurring in all years except 2019 and 2020. In some places, the absence of sulfur dioxide (SO_2) concentrations is characteristic across all landscape levels, except for the low-mountain landscape level of the southern macroslope, where the minimum concentrations occur in 2024 and amount to 2.8 μmol/m².

The main areas of elevated concentrations are located northeast of Simferopol, between the settlements of Gresovsky, Pochtovoye, Bakhchisaray, and Kuibyshevo. In the southern part of the peninsula in 2020, high concentrations were observed within the cities of Alushta and Gurzuf, the territory east of the city of Stary Krym, and in the northern part of the peninsula near the city of Krasnoperekopsk (from 350.0 μmol/m² and above).

In general, the hotspots of elevated concentrations are comparable to industrially active areas where fossil fuel combustion is carried out, among other activities. One of the most evident examples is the Simferopol Thermal Power Plant (TPP), which is located near the regional center – Simferopol city – and can generate continuous emissions, particularly during the winter heating season. Similar effects are produced by power plants in Kerch, Sevastopol, and Saki. Additionally, sources of air pollution associated with vehicle emissions along highways (e.g., the Yalta–Sevastopol route) are distinctly highlighted. A relatively high level of atmospheric air pollution by SO_2, linked to coal combustion in stove heating, is noted, with this type of pollution expected to increase specifically in winter during the heating season, as indicated by Kashirina et al. [43] on the Crimean region.

The lowest concentrations of sulfur dioxide (SO_2) were recorded in 2021 and 2023. The minimum concentrations in 2021 were primarily distributed across the flat Crimea and the northern slopes of the Crimean Mountains, whereas in 2023, the areas with minimum concentrations shifted and became more prevalent within mountainous Crimea (including above the inner ridge of the Crimean Mountains) and the Kerch Peninsula (50.0 μmol/m² and below).

In general, the distribution of sulfur dioxide (SO_2) concentration fields in the atmospheric air of the Crimean Peninsula from 2019 to 2024 is mosaic in nature, with local hotspots of elevated concentrations associated with various natural and anthropogenic processes. In the atmosphere, sulfur dioxide (SO_2) can occur at low concentrations as a result of biological decomposition of organic matter and forest fires [21]. Regarding anthropogenic sources, the combustion of fossil fuels – such as in coal-fired power plants, oil refineries, industrial furnaces, and metal smelting processes – as well as chemical production related to sulfuric acid manufacturing, should be noted [25].

Overall, during the six-year period under review (2019–2024), the highest concentrations (> 350.0 μmol/m²) are widespread and localized in the areas of settlements such as Novoselovskoye, Krasnogvardeyskoye, Armyansk, the territory east of Krasnoperekopsk, Simferopol, Nikolaevka, Kuibyshevo, Yalta, Alushta, Stary Krym, Pochtovoye, the territory east of Bakhchisaray, and Belogorsk. It should be noted that the areas with elevated average annual concentrations may vary across different years: for example, in 2021, the settlement of Armiansk exhibited minimum sulfur dioxide concentrations (up to 50.0 μmol/m² and below), whereas in 2022, this area was among those in Crimea where elevated levels of this substance were observed in the atmospheric air (up to 350.0 μmol/m²). Elevated concentrations of air pollutants over urbanized or industrial areas can persist for extended periods under adverse meteorological conditions. One of which is temperature inversion within the atmospheric boundary layer. Yachmioneva et al. [44] established that in 61% of cases, pollutant concentrations in the ambient air increase during inversion events.

Considering the entire territory of the Crimean Peninsula, it is noted that the lowest concentrations occurred in 2019 (ranging from 50.0 to 307.7 μmol/m²), while the highest were observed in 2020 (ranging from 20.1 to 420.1 μmol/m²). However, during 2021–2024, there are areas with zero SO_2 concentrations (small zones near the settlements of Gvardeyskoye, Dzhankoy, and Stary Krym in 2021; south of Belogorsk and Lenino in 2022; east of Bakhchisaray in 2023; north of Sudak and the settlement of Mirny in 2024), which indicates the presence of noise or potential measurement artifacts in the data. In general, a downward trend in SO_2 concentrations across all landscape levels is observed over the six-year period, despite the overall wave-like dynamics of this pollutant in the atmosphere over the Crimean Peninsula (decreasing in odd years: 2019, 2021, 2023, and increasing in even years: 2020, 2022, 2024). Moreover, the maximum average annual concentrations of SO_2 in the air at all landscape levels were recorded in 2020 (illustrated in Figure 6).

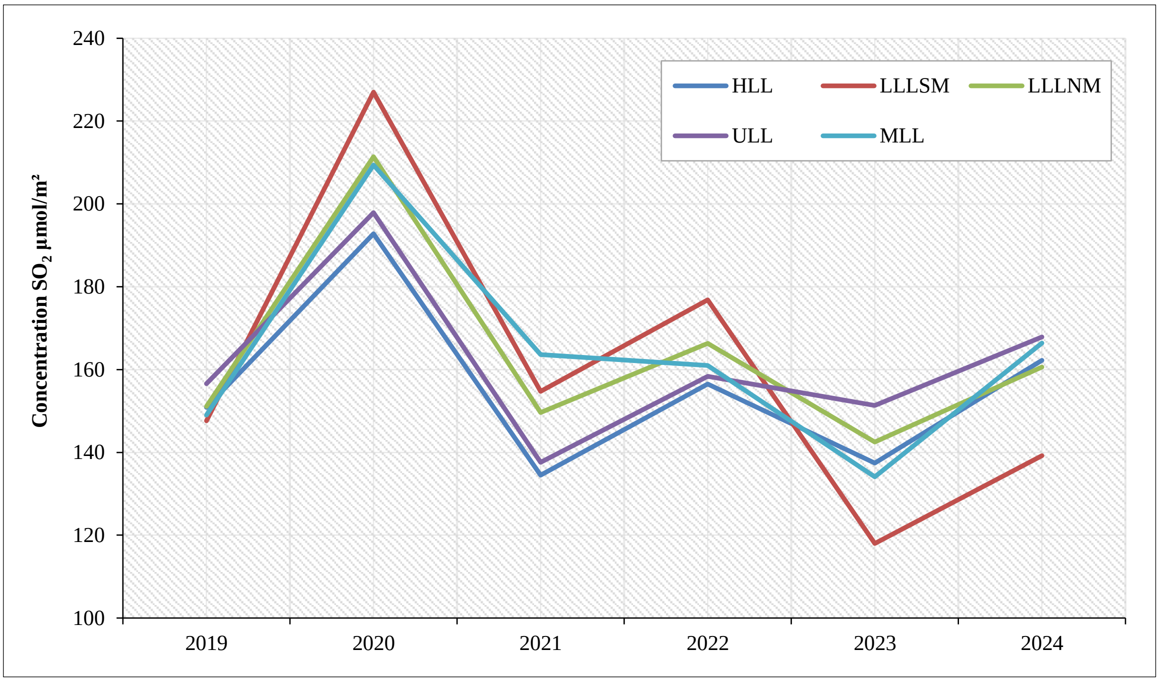

Figure 6. Dynamics of average annual sulfur dioxide (SO_2) concentrations across landscape levels of the Crimean Peninsula in 2019–2024 (Note: HLL – hydromorphic landscape level; LLLSM – low-mountain landscape level of the southern macroslope; LLLNM – low-mountain landscape level of the northern macroslope; ULL – upland landscape level; MLL – mid-mountain landscape level).

For most of the Crimean Peninsula, sulfur dioxide (SO_2) concentrations in the atmosphere are classified as conditionally low pollution levels throughout the entire period under review from 2019 to 2024. Areas with conditionally high pollution levels are less common. Conditionally average and elevated pollution levels are observed only in very small areas of the Crimean Peninsula.

In 2019, the territory was least affected by conditionally high levels of sulfur dioxide (SO_2) pollution in the atmospheric air. The main area affected by conditionally high pollution levels that year was the southern coast of Crimea (within the low-mountain landscape level of the southern macroslope). Although concentrations were higher in other landscape levels, the conditionally high level was notable here due to the low background concentration values of the pollutant – specifically, in the Karadag Nature Reserve, where the conditionally high pollution level in 2019 began at 160.5 μmol/m², compared to the Belaya Skala Nature Park, where the same level in 2019 started at 291.7 μmol/m². The smallest area of conditionally high pollution levels within the low-mountain landscape of the southern macroslope was recorded in 2024 – only within Alushta and the eastern part of Cape Meganom.

Within the upland landscape level, the greatest number of areas with high pollution levels was observed in 2020. These areas are scattered throughout the entire territory under consideration, with concentrations exceeding 271.9 μmol/m². The low-mountain landscape level of the northern macroslope in 2022 was characterized by the expansion of the largest zone with a conditionally high level of sulfur dioxide (SO_2) pollution, covering nearly half of the entire territory. This was due to low pollutant concentrations above the background territory and conditionally high concentrations within the rest of the landscape level. In 2022, the average annual concentration within the Belaya Skala Nature Park was 102.3 μmol/m², while maximum concentrations within the landscape level reached 367.5 μmol/m², with conditionally high concentrations starting at 165.2 μmol/m² that year.

Within the mid-mountain landscape level, local areas with conditionally high sulfur dioxide (SO_2) pollution are rare (isolated), occurring only in small zones in 2019, 2021, and 2023. In 2019 and 2021, conditionally high pollution levels were observed in the territory north and northeast of the background area (Crimean National Park), whereas in 2023, conditionally high levels were detected within the northern part of the background territory itself. This indicates fairly uniform conditions for the dispersion of the pollutant both within the background area and across the entire mid-mountain landscape level.

A similar pattern of distribution and temporal dynamics of conditionally high sulfur dioxide (SO_2) pollution is observed within the hydromorphic landscape level. Here, pockets of conditionally elevated levels appear locally in 2020, 2021, 2022, and 2023, and are nearly point-like in 2024 (primarily in the northern part of the Kerch Peninsula). When analyzing the dynamics of the spread of such zones with conditionally high sulfur dioxide (SO_2) pollution across the territory, their locations vary from year to year.

The concentration values themselves, corresponding to conditionally high levels of sulfur dioxide (SO_2) pollution, also varied from year to year (illustrated in Figure 7).

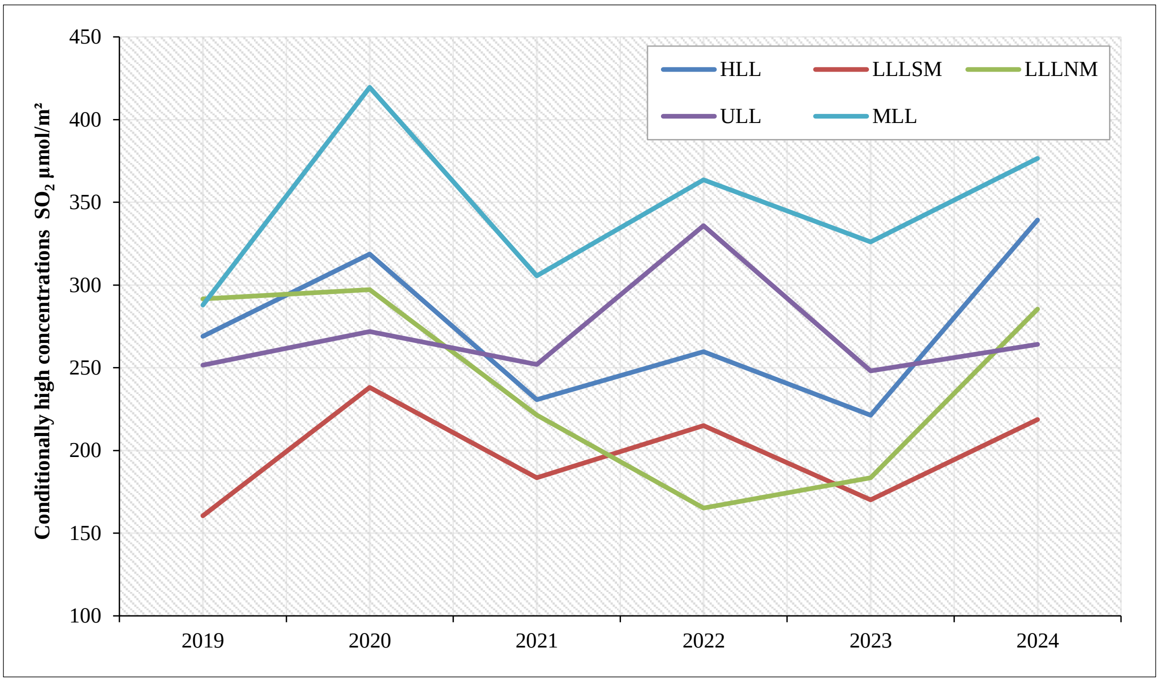

Figure 7. Dynamics of concentrations corresponding to a conditionally high level of sulfur dioxide (SO_2) pollution at landscape levels of the Crimean Peninsula during the period in 2019–2024 (Note: HLL – hydromorphic landscape level; LLLSM – low-mountain landscape level of the southern macroslope; LLLNM – low-mountain landscape level of the northern macroslope; ULL – upland landscape level; MLL – mid-mountain landscape level).

For each landscape level, the maximum concentrations above which the pollution level was defined as conditionally high varied within the following ranges: hydromorphic landscape level (from 221.3 μmol/m² in 2023 to 318.7 μmol/m² in 2020); low-altitude landscape level of the southern macroslope (from 160.5 μmol/m² in 2019 to 238.1 μmol/m² in 2020); low-lying landscape level of the northern macroslope (from 165.2 μmol/m² in 2022 to 297.2 μmol/m² in 2020); plateau landscape level (from 335.9 μmol/m² in 2022 to 248.1 μmol/m² in 2023); mid-mountain landscape level (from 287.9 μmol/m² in 2019 to 419.5 μmol/m² in 2020).

Despite the downward trend in the average annual concentration of SO_2 over the Crimean Peninsula (averaging 25.4 μmol/m² per year) during the period from 2019 to 2024, the areas characterized by conditionally high levels of pollution are expanding, primarily due to a decrease in background SO_2 concentrations over protected natural areas. The observed trend towards decreasing sulfur dioxide (SO_2) concentrations in the region may be attributed to the gradual implementation of the State Program for Environmental Protection and Rational Use of Natural Resources of the Republic of Crimea. This program focuses on measures to reduce atmospheric pollution from stationary sources [45, 46]. Additionally, it is noteworthy that over the past decade, Crimea has faced sanctions and economic restrictions, leading to a decline in production within key industrial sectors. These factors may have contributed to a reduction in SO_2 emission volumes in the region.

If we examine sulfur dioxide (SO_2) concentrations in other regions of the world, we find that the Crimean Peninsula and its constituent parts do not exhibit the highest or lowest values globally. Table 4 presents SO_2 concentrations across various regions worldwide.

Table 4. Sulfur dioxide (SO_2) concentration values across various regions of the world (compiled by the authors from sources [39, 40, 47–52])

Region/territory	Source	Min., μmol/m²	Max., μmol/m²	Mean, μmol/m²
Western Bulganak River Basin (2019-2022)	[39]	-	-	182.5
Alma River Basin (2019-2022)	[39]	-	-	192.5
Kacha River Basin (2019-2022)	[39]	-	-	185.0
Belbek River Basin (2019-2022)	[39]	-	-	172.5
The Chernaya River Basin (2019-2022)	[39]	-	-	152.5
Sunzha River Basin (2018-2023)	[47]	-	-	152.5
Sulak River Basin (2018-2023)	[47]	-	-	114.4
Ulluchai River Basin (2018-2023)	[47]	-	-	134.5
Karachay River Basin (2018-2023)	[47]	-	-	137.3
Atachay River Basin (2018-2023)	[47]	-	-	180.6
Heraz River Basin (2018-2023)	[47]	-	-	127.8
Gorgan River Basin (2018-2023)	[47]	-	-	149.7
Fatala River Basin (2019-2022)	[40]	0	510.0	164.0
Lahore, Pakistan (2018-2020)	[48]	-	-	544.0
Arak, Iran (2020)	[49]	-	-	480.0
Gujarat state (India)	[50]	-	-	470.0
Saudi Arabia (2019-2023)	[51]	-47.6 (0?)	881.6	43.0-149.0
Poland (2018-2022)	[52]	-	11.98	0.07

In Medan, Indonesia [53], reported SO_2 concentrations range from 341 μmol/m² in 2022 to as high as 925 μmol/m². However, the average values presented in the same study appear unusual: they are negative for 2020, close to zero (approximately 10 μmol/m²) for 2022 and 2023, and reach a maximum of 210 μmol/m² in 2021. This anomaly is likely due to the authors not excluding negative values—interpreted as noise or measurement errors—from their calculations of the averages, which can distort the reported mean concentrations.

The study by Kafia et al. [54] reports that the average sulfur dioxide SO_2 concentrations from 2018 to 2023 in the Razavi and South Khorasan provinces of Iran exhibit spatial heterogeneity, ranging between 0.0001 and 0.0007 mol/m². Similarly, in the area surrounding the Oben gas flow station in Edo State, Southern Nigeria, maximum average SO_2 concentrations were recorded as 3.99×10^{-5} mol/m² in 2019 and 4.26×10^{-5} mol/m² in 2020 [55].

The study by Turakhia et al. [56] indicates that in the state of Gujarat, located in western India, SO_2 concentrations during winter can reach 500 µmol/m², with certain industrial areas experiencing levels as high as 1000 µmol/m². The average SO_2 concentration in the region is approximately 300 µmol/m². This is primarily due to Gujarat being one of the leading states contributing to India's industrial development. At the same time, it is noteworthy that the lowest SO_2 concentrations in this region are observed during the summer months. Chaturvedi & Tak [57] conducted a comprehensive assessment of air quality dynamics over the city of Ajmer (India) and found that SO_2 values ranged from 9180 µmol/m² in July 2021 to 58040 µmol/m² in December 2023.

It is important to note that some studies, such as Turakhia et al. [56], primarily present analyses based on average monthly SO_2 concentration values. This focus can complicate direct comparisons with datasets that include daily or higher-resolution measurements. For instance, the satellite data in Turakhia et al. [56] indicate that the highest monthly SO_2 concentrations in Poland were 10.21 nmol/m² in Gorzow Wielkopolski and 9.95 nmol/m² in Legnica. In Ukraine, similar satellite observations reported maximum values of 7.10 nmol/m² in the Kyiv region and 6.15 nmol/m² in the Poltava region.

Another challenge in conducting research is the variation in units of measurement used across different studies. For example, employs ppm [58], uses mol/cm² [59], reports mol/mm² [60] (which is likely incorrect), and utilizes mg/m² [61], among others. In Corradino et al. [60], it is noted that both values are provided in GEE in mol/m² but can be manually converted into Dobson Units (DU) using the conversion factor 1 DU = 44.615×10^{-4} mol/m² [60]. Some studies provide cartographic materials and their descriptions; however, the units of measurement for SO_2 concentration [62] are not specified.

The Sentinel-5P satellite (Sentinel-5 Precursor), equipped with the Tropospheric Monitoring Instrument (TROPOMI), provides valuable data on the global distribution of sulfur dioxide SO_2, particularly from volcanic and anthropogenic sources. However, it has several methodological, technical, and physical limitations that affect data accuracy, resolution, and interpretation of the data. One such limitation is the spatial resolution (~1 km²), which precludes local-scale studies of SO_2 emissions and confines analysis to regional and global scales. Additionally, artifacts associated with negative data values over areas with low or near-zero SO_2 concentrations, as previously documented, can compromise data quality. Due to the current resolution, significant emissions (such as those from volcanic eruptions or large industrial facilities) are detectable, whereas smaller sources may remain unnoticed against the background noise. Another limitation is the temporal frequency of observations; individual emission events may be recorded, necessitating cautious interpretation. Despite these constraints, the SO_2 data provided by Sentinel-5P remains an invaluable resource for monitoring atmospheric pollution and assessing global air quality.

5. Conclusion

The lowest concentrations of sulfur dioxide (SO_2) were recorded in 2019, ranging from 5.0 to 307.7 µmol/m², while the highest concentrations were observed in 2020, ranging from 20.1 to 420.1 µmol/m². The period during which the Crimean territory was least affected by conditionally high levels of SO_2 pollution in the atmosphere was 2019. The primary area of elevated pollution levels that year was the southern coast of Crimea. The highest concentrations of sulfur dioxide (SO_2) throughout the entire review period (2019–2024) were recorded at different landscape levels: in 2019 – upland landscape level (307.7 µmol/m²); in 2020 – mid-mountain landscape level (420.1 µmol/m²); in 2021 – upland landscape level (361.9 µmol/m²); in 2022 – low-mountain landscape level of the southern macroslope (399.0 µmol/m²); in 2023 – low-mountain landscape level of the northern macroslope (355.5 µmol/m²); and in 2024 – low-mountain landscape level of the northern macroslope (388.5 µmol/m²).

During the period from 2021 to 2024, areas with zero SO_2 concentrations were observed on the Crimean Peninsula, including small zones near the settlements of Gvardeyskoye, Dzhankoy, and Stary Krym in 2021; south of Belogorsk and Lenino in 2022; east of Bakhchisaray in 2023; and north of Sudak and the settlement of Mirny in 2024. These occurrences likely indicate the presence of noise in the data.

There has been a consistent downward trend in SO_2 concentrations across all landscape levels over the past six years, with an average decrease of 25.4 µmol/m² per year. Within the low-mountain landscape level of the northern macro-slope, 2022 exhibited the largest zone of conditionally high sulfur dioxide (SO_2) pollution across all years analyzed, covering nearly half of the territory. This was associated with elevated SO_2 concentrations above background levels. Specifically, the average annual concentration within the Belaya Skala Nature Park was 102.3 µmol/m², while the maximum concentration within the landscape level reached 367.5 µmol/m². Notably, the conditionally high concentrations in that year began at 165.2 µmol/m².

Multiple factors influence the distribution of conditionally high sulfur dioxide (SO_2) pollution levels across the Crimean Peninsula during the study period, including natural sources such as forest fires and biological decomposition of organic matter, as well as anthropogenic sources like fossil fuel combustion, oil refinery operations, metal smelting, and chemical production related to sulfuric acid manufacturing.

5.1. Scientific Novelty

A regional assessment of the SO_2 content in the atmosphere of the Crimean Peninsula was carried out. Based on satellite data obtained using the TROPOMI instrument of the Sentinel-5 Precursor mission, the territory of the peninsula was zoned according to the level of pollution with this substance, the dynamics of pollution changes from 2019 to 2024 were revealed.

5.2. Theoretical Contributions

During the observational period, the lowest concentrations of sulfur dioxide (SO_2) were documented in 2019, whereas the highest levels were recorded in 2020. The year 2019 was characterized by minimal impact from elevated pollution levels, with primary contributions attributed to emissions along the southern coast of Crimea. Throughout the study timeframe, peak SO_2 concentrations were observed at varying landscape levels (LL): in 2019 at upland LL, in 2020 at mid-mountain LL, again at upland LL in 2021, and at low-mountain LL of the southern macroslope in 2022, with the low-mountain LL of the northern macroslope the highest levels during 2023–2024. A statistically significant decreasing trend in SO_2 concentrations was observed over the six-year period, with an average annual reduction of 25.4 μmol/m².

5.3. Practical Implications

Overall, it can be concluded that the highest concentrations of sulfur dioxide (SO_2) throughout the entire review period (2019–2024) were recorded at different landscape levels: in 2019 – upland landscape level (307.7 μmol/m²); in 2020 – mid-mountain landscape level (420.1 μmol/m²); in 2021 – upland landscape level (361.9 μmol/m²); in 2022 – low-mountain landscape level of the southern macroslope (399.0 μmol/m²); in 2023 – low-mountain landscape level of the northern macroslope (355.5 μmol/m²); and in 2024 – low-mountain landscape level of the northern macroslope (388.5 μmol/m²).

Within the low-mountain landscape level of the northern macro-slope, 2022 exhibited the largest zone of conditionally high sulfur dioxide (SO_2) pollution across all years analyzed, covering nearly half of the territory. This was associated with elevated SO_2 concentrations above background levels. Specifically, the average annual concentration within the Belaya Skala Nature Park was 102.3 μmol/m², while the maximum concentration within the landscape level reached 367.5 μmol/m². Notably, the conditionally high concentrations in that year began at 165.2 μmol/m². In 2022, the largest SO_2 zone with a high level of pollution was observed, covering almost half of the territory.

5.4. Research Limitations

There are certain limitations in the utilization of satellite data on atmospheric SO_2 concentrations, including temporal coverage, as the dataset is available only from December 5, 2018. Additionally, some regions exhibit zero SO_2 concentrations, which likely indicates the presence of noise in the data.

5.5. Future Research Directions

In general, future research should focus on evaluating the distribution patterns and pollution levels of the Crimean Peninsula's atmosphere with respect to a broader spectrum of pollutants, including climatically active gases. An additional avenue of investigation involves conducting a comprehensive regional assessment of atmospheric composition, pollution sources, and their environmental impacts

6. Declarations

6.1. Author Contributions

Conceptualization, A.D.; methodology, A.D., P.D., and V.T.; software, A.D.; validation, A.D. and P.D.; formal analysis, A.D., P.D., and V.T.; investigation, P.D. and A.D.; resources, V.T., A.D., and P.D; data curation, P.D. and A.D.; writing—original draft preparation, A.D. and P.D; writing—review and editing, P.D., A.D., and V.T.; visualization, A.D. and P.D.; supervision, A.D. and P.D.; project administration, P.D.; funding acquisition, A.D., P.D. and V.T. All authors have read and agreed to the published version of the manuscript.

6.2. Data Availability Statement

The data presented in this study are available in this article.

6.3. Funding

This work was conducted within the framework of the state assignment of the T.I. Vyazemsky Karadag Scientific Station –Nature Reserve of RAS –Branch of A.O. Kovalevsky Institute of Biology of the Southern Seas of RAS, on the topic “Spatial and temporal variability of the carbon cycle in the landscapes of southeastern Crimea: comprehensive analysis and modeling” (State Registration Number 125061006869-4).

6.4. Conflicts of Interest

The authors declare no conflict of interest.

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