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Application of a Gaussian Dispersion Model for Assessing SO_2 Concentrations from Major Coal-Fired Power Plants in the Highly Polluted Industrial Region of Türkiye

Türkiye'nin Yoğun Kirliliğe Sahip Sanayi Bölgesi'ndeki Büyük Kömür Yakıtlı Termik Santrallerden Kaynaklanan SO_2 Konsantrasyonlarının Değerlendirilmesinde Gauss Dağılım Modelinin Uygulanması

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Abstract

A significant amount of sulfur dioxide (SO_2) emissions is released from large-scale lignite-fired thermal power plants, impacting air quality in various hotspot regions of Türkiye. Among these areas, Soma stands out because it possesses two power plants, with one being the nation's oldest thermal facility lacking advanced desulfurization technology. This study employed the Gaussian dispersion model (AERMOD) to predict hourly SO_2 concentrations for 2021 in a 50 km × 50 km area using local surface parameters from a reanalysis database instead of relying on the standard surface characteristics from AERSURFACE. The results showed that hourly concentrations exceeded 2148 times during the year at 311 receptors, which the Ministry of Environment, Urbanization, and Climate Change set. Unlike hourly concentrations, the average daily, seasonal, and annual concentrations were below the limit values. Analysis of individual contributions from thermal power plants demonstrated that the highest SO_2 concentrations primarily originated from the oldest plant. The prevailing wind direction in the region revealed that pollutant emissions most impacted the study area's northern, eastern, and northeastern areas. Interestingly, the modeling results revealed that the thermal power plants did not substantially contribute to SO_2 concentrations at the air quality monitoring station due to the meteorological and topographic conditions of the region. As a policy recommendation, it is essential to focus on broader regional monitoring strategies and comprehensive emission inventories to ensure effective environmental management and to address potential sources beyond the immediate vicinity of the power plant. In addition, further examination through correlation analyses brought to light that the topographical parameters influencing the dispersion of annual average SO_2 concentrations exhibited distinct variations across regions, exerting varying degrees of the correlation coefficient.

Keywords: AERMOD, air quality, Soma, thermal power plants, Türkiye.

Öz

Büyük ölçekli linyit yakıtlı termik santrallerden önemli miktarda kükürt dioksit (SO_2) emisyonu salınmakta ve bu durum Türkiye'nin çeşitli önemli bölgelerinde hava kalitesini etkilemektedir. Bu bölgeler arasında Soma öne çıkmaktadır, çünkü burada biri desülfürizasyon teknolojisine sahip olmayan ülkenin en eski termik santrali olmak üzere iki adet kömür yakan termik santral bulunmaktadır. Bu çalışmada, 2021 yılı için 50 km × 50 km'lik bir alanda saatlik SO_2 konsantrasyonlarını tahmin etmek amacıyla Gauss dağılım modeli (AERMOD) kullanılmış olup, standart yüzey özellikleri sağlayan AERSURFACE yerine yeniden analiz veri tabanından alınan yerel yüzey parametreleri kullanılmıştır. Sonuçlar, yıl boyunca Çevre, Şehircilik ve İklim Değişikliği Bakanlığı tarafından belirlenen saatlik konsantrasyon sınır değerinin 311 alıcıda 2148 kez aşıldığını göstermiştir. Saatlik konsantrasyonların aksine, ortalama günlük, mevsimlik ve yıllık konsantrasyonlar sınır değerlerin altında kalmıştır. Termik santrallerin bireysel katkılarının analizi, en yüksek SO_2 konsantrasyonlarının esas olarak en eski santralden kaynaklandığını ortaya koymuştur. Bölgedeki hâkim rüzgâr yönü, kirletici emisyonlarının çalışma alanının kuzey, doğu ve kuzeydoğu bölgelerini en çok etkilediğini göstermiştir. Beklenenin aksine, modelleme sonuçları, bölgenin meteorolojik ve topografik koşulları nedeniyle termik santrallerin hava kalitesi izleme istasyonundaki SO_2 konsantrasyonlarına önemli ölçüde katkıda bulunmadığını ortaya koymuştur. Ayrıca, korelasyon analizleri ile yapılan daha ileri incelemeler, yıllık ortalama SO_2 konsantrasyonlarının dağılımını etkileyen topografik parametrelerin bölgeler arasında belirgin farklılıklar gösterdiğini ve farklı derecelerde korelasyon katsayısına sahip olduğunu gözler önüne sermiştir.

Anahtar Kelimeler: AERMOD, hava kalitesi, Soma, termik santraller, Türkiye.

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1. Introduction

Sulfur dioxide (SO_2), one of the most significant air pollutants in the environment, exists as a gas due to natural and industrial processes (WHO 2000). It enters the upper troposphere and lower stratosphere through volcanic activities. It reaches the Planetary Boundary Layer (PBL) via human-related emissions primarily caused by the combustion of fossil fuels (such as coal and oil), coal extraction, mineral exploitation (such as aluminum, copper, zinc, iron, and lead), as well as forest fires and agricultural activities. SO_2 readily dissolves in water and reacts with airborne particles to form sulfates and other substances, which can harm human health. The presence of SO_2 in the PBL affects individuals by influencing lung function, causing respiratory diseases, eye irritation, and cardiovascular issues, leading to higher mortality rates on days with high SO_2 levels (Khaniabadi et al. 2017, Orellano et al. 2021). Numerous studies have provided compelling evidence indicating a significant positive correlation between both short-term and long-term exposure to SO_2 and increased mortality and morbidity rates (Newell et al. 2018, Orellano et al. 2021, Adebayo-Ojo et al. 2022, Doost et al. 2023).

Furthermore, SO_2 has detrimental effects on the environment, contributing to the formation of acid rain and pollution in rivers and lands (WHO 2021). The ambient concentrations of SO_2 exhibit fluctuations throughout the day and across seasons, influenced by land-use patterns, topography, energy demands for power generation, residential heating, transportation, and meteorological conditions (Gibson et al. 2013). Consequently, policymakers, public health advocates, and the public must identify dispersion patterns of SO_2 over time and space, employing modeling techniques considering different emission sources, meteorological conditions, and pollution origins since models can offer valuable insights for effective planning and management of pollutant reduction and control (Hesami Arani et al. 2021). Dispersion modeling provides a solution by estimating the impact of pollution sources on surface air quality within a given airshed, considering accurate emission source characteristics, land use, terrain, meteorological data, and the overall atmospheric concentration within the model domain (Doost et al. 2023).

In Türkiye, lignite has been a primary energy source for electricity generation since the 1950s, as the country possesses 2.2% of the global lignite reserves (Yılmaz 2009). As of July 2021, the total installed power capacity in Türkiye reached 98263 MW, with coal-fired power plants accounting for 20% of this capacity (19917 MW). However, in developing nations like Türkiye, the utilization of low-quality fossil fuels characterized by high sulfur and ash content and low calorific value leads to high concentrations of SO_2 in the ambient air. Previous research has indicated that regions in Türkiye with significant lignite-fired power plants were associated with high levels of SO_2 (Vardar and Yumurtacı 2010, Fıratlı 2016, Akyuz and Kaynak 2019). Soma, located in the Aegean Region of Manisa, is a crucial district due to its substantial lignite reserves, which amounted to 861,450,000 tons in 2021 (Cekinir et al. 2022). Lignite extracted from the Soma region has high levels of As, Cd, Ni, Hg, Pb, Sb, Se, Th, and U (Vardar et al. 2022). It also possesses high ash and total sulfur content, as indicated by Vardar et al. (2022). The operation of thermal power plants exacerbates the air pollution in the area. Among these, the SOMA-B thermal power plant is notable, with a capacity of 1,034 MW. To address emissions violations, the Ministry of Environment, Urbanization, and Climate Change (MoEUCC) has mandated the closure of certain lignite-fired thermal power plants like Soma-B thermal power plants (Zeydan and Pekkaya 2021). Unfortunately, this plant lacks both lignite pretreatment and stack emission control technology. An assessment of air quality data from monitoring stations during 2018 and 2019 by Zeydan and Pekkaya (2021) demonstrated that the Soma station registered the highest SO_2 concentration (71.1 μg/m^3) in Türkiye, exceeding permissible limits on 220 occasions. Additionally, a modeling study by Gündoğdu (2020) utilizing air quality monitoring data from Soma between July and September 2019 identified SO_2 as the primary air pollutant in the region. The primary motivation for this study was to address the high levels of SO_2 concentrations observed in the region, which raised concerns about potential environmental and health impacts. Given the presence of an old power plant lacking modern control technologies, it was critical to assess its contribution to the high SO_2 concentrations. This study aimed to identify the plant's role in regional air quality degradation and to evaluate whether the observed SO_2 concentrations in the area could be attributed to its emissions. By providing a detailed analysis through modeling, the research also sought to inform mitigation strategies and guide policymakers in implementing more effective air pollution control measures.

The assessment of point sources' potential contributions, such as thermal power plants, is required by the Regulation for Controlling Industrial Air Pollution in Türkiye (MoEUCC 2020). This regulation stipulates using the American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD) to estimate the impacts of point sources. However, limited studies employing AERMOD in Türkiye can be found in the literature (Tuygun et al. 2017, Mentese et al., 2020, Demirarslan and Yener 2022). AERMOD has also been widely utilized for predicting the dispersion of various pollutants from different sources around the world (Kakosimos et al. 2011, Gibson et al. 2013, Siahpour et al. 2021, Doost et al. 2023, Hadlocon et al. 2015, Haq et al. 2019, Wang et al. 2022).

This study constitutes the first modeling analysis conducted in Soma, a region hosting one of Türkiye's oldest coal-fired power plants. The primary objective was to predict ambient SO_2 concentrations emitted by these plants and assess their air quality impacts on adjacent areas. A comprehensive air quality modeling study was performed using the AERMOD dispersion model to quantify both individual and cumulative effects of all active lignite-fired power plants on receptors within Soma's complex terrain. This approach facilitated an in-depth evaluation of the contributions of heavily polluting thermal power plants to the ambient air quality in Soma, with consideration of both short-term and long-term SO_2 concentration levels.

The predicted annual, daily, and hourly SO_2 concentrations throughout the study area were also compared to regulatory standards to assess compliance with air quality limits. Furthermore, the study investigated how geographic and topographic variables influence the spatial distribution of annual average SO_2 concentrations across specific regions within the study domain. Notably, despite Soma's significant SO_2 pollution levels, a comprehensive assessment using the AERMOD has not been previously conducted, as highlighted by the literature review.

2. Material and Methods

2.1. Study Area

The study area is in the province of Manisa, Türkiye, specifically in the highly industrialized district of Soma (Figure 1). This district is known for its numerous lignite-fired power plants and is situated in western Türkiye at the coordinates of 39°11'N and 27°36'E. The district has an altitude of approximately 175 meters and covers an area of about 826 square kilometers. Soma is a rapidly developing mining town with a population of 111,218, as reported in 2021 by the Turkish Statistical Institute (TurkStat 2022). Soma is characterized by mountainous terrain, with over half of its land consisting of mountains. The southern part of the district is particularly dense and features steep hills and high mountains. There are also high mountains, a few plateaus, and other mountains to the east. The district experiences a unique climate that combines the continental climate characteristics of Central Anatolia with those of the Mediterranean climate. In 2021, atmospheric pressure has a mean value of 994.3 hPa with a standard deviation of 5.75, indicating relatively stable conditions. Relative humidity averages 69.1% with a standard deviation of 19.3, generally higher in summer and lower in winter. Wind speed is typically low, with a mean of 2.7 m/s and a standard deviation of 1.71 m/s. Temperature has a mean value of 16.7°C and a standard deviation of 9.1°C, being higher in summer and lower in winter, reflecting significant seasonal variation. Precipitation is minimal on average, with 0.077 mm and a standard deviation of 0.55 mm, but tends to be higher in winter and lower during summer, indicating distinct seasonal patterns (GDM 2022). The annual wind rose in 2021, with the dominant wind directions being 12.7% from the west, 11.5% from the south-southeast, 9.8% from the east-southeast, 9.4% from the west-southwest, and 8.5% from the north-northwest. Northern winds mainly occur in summer and autumn with the effect of low pressure, while southern winds occur in winter, and western winds are also observed in spring and autumn. Also, the wind speeds in the region mainly vary between 0.50 and 3.60 m/s. Higher wind speeds predominantly come from the north, although southerly winds are also observed occasionally.

Soma region is a significant producer of lignite in Türkiye, with its lignite plants providing 31% of the country's lignite production. Over the last 50 years, Soma has evolved from a mining town with numerous open and closed coal mines into an industrial city where lignite-fired power plants have been established for energy production (Karadag 2012). These activities in this region are crucial not only for the district's economy but also for the energy production of Türkiye. Presently, two major lignite-fired thermal power plants are operational in the region. The SOMA-B thermal power plant, which has been in operation since 1980, consists of 6 units with a total installed capacity of 990 MW and meets 12% of Türkiye's energy production. Approximately 8,000,000 tons of lignite are used annually for energy production, and no pollution abatement facilities, such as lignite pretreatment and emission control technologies, are installed at the stacks (Soma Thermal Power Plant 2015). The SOMA-B thermal power plant has two 150-meter stacks and one 250-meter stack in its facility. Each stack is connected to two units. SOMA-B operates using conventional

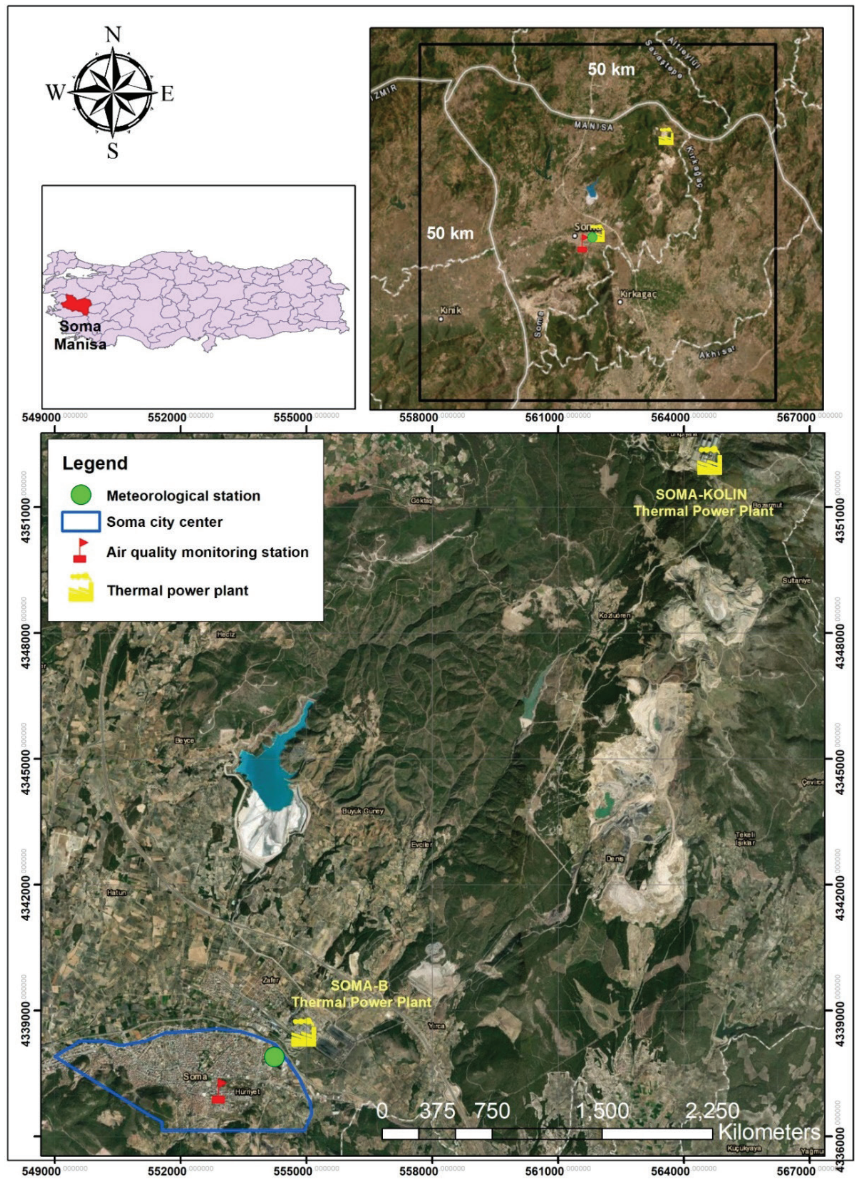

Figure 1. Study area map.

pulverized coal combustion technology. The primary fuel source is lignite coal, which is abundant in the region but has a relatively low calorific value and high moisture content. These characteristics necessitate additional pre-combustion processes and emissions control measures to ensure compliance with environmental standards. The plant is equipped with no flue gas desulfurization (FGD) systems to reduce SO_2 emissions. SOMA-A, another lignite-fired power plant, started in 1957 with a capacity of 44 MW but is currently not operational due to the insufficiencies in the environmental permit document. The third thermal power plant, SOMA-KOLIN, located in the northeastern part of Soma, has a capacity of 510 MW and was commissioned in 2019 (Figure 1). Over 30 years, 120 million tons of lignite will be used for power generation in the plant. SOMA-KOLIN employs more advanced technologies compared to SOMA-B, such as circulating fluidized bed (CFB) combustion, which offers higher efficiency and better emissions control compared to traditional methods. This technology allows for the maintaining lower levels of SO_2 emissions. (Kolin 2023). In addition, limestone is added to the boiler to remove SO_2 to meet acceptable emission limits in Türkiye and Europe (Kolin 2023). SOMA-KOLIN, on the other hand, has a single 200-meter stack.

The SOMA-B thermal power plant is located near the city center (as shown in Figure 1), while the SOMA-KOLIN thermal power plant is approximately 16 km away from the SOMA-A and SOMA-B thermal power plants. In summary, the thermal power plants in the region have a total capacity of 1500 MW, located within a radius of about 20 km from the Soma city center. Results of previous studies indicated that SO_2 pollution is the main problem in the city, mainly in winter, with the contribution of residential heating and industrial emissions and SO_2 concentrations occasionally exceed the limit values (Gundogdu 2020, Zeydan and Pekkaya 2021). According to the report published by the Manisa Provincial Directories of the Ministry of Environment, Urbanization, and Climate Change, SO_2 concentrations frequently exceeded the limit values in December (23 days), January (18 days), February (12 days), and March (11 days) of 2020 (**MPDoMEUCC** 2021).

2.2. Dispersion Modeling with AERMOD

The spatial distribution of the SO_2 concentrations was obtained using the AERMOD dispersion model, which is the steady-state Gaussian plume model in rural and urban areas on flat or complex terrain, using point, area, and volume sources (U.S.EPA 2022). To process and prepare the raw meteorological and topographical data as a proper input into the model, AERMOD has two preprocessors, AERMET and AERMAP, for meteorological and topographical data processing, respectively. AERMET considers various meteorological data, such as temperature, cloud cover, wind speed and direction, and surface characteristics, such as the Bowen ratio, albedo, and surface roughness, to derive the PBL parameters. The AERMAP module is responsible for preparing a height scale and a base elevation for each receptor. Finally, the dispersion model calculates the concentration by considering the source parameters, surface and upper meteorological data from AERMET, and terrain data from AERMAP. This model has been successfully used to predict air quality with pollutant emissions in various emission sources (Haq et al. 2019, Mousavi et al. 2021, Demirarslan and Yener 2022, Wang et al. 2022).

The relative humidity, cloud cover, height, wind speed and direction, temperature, pressure, and precipitation were obtained from the Soma meteorological monitoring station (18040) for 2021. Additionally, AERMOD requires atmospheric vertical profiles for pressure, temperature, and wind, obtained twice daily from an upper-air station in Izmir, the nearest station to the region. AERMET also requires input parameters for surface characteristics, such as surface roughness, Bowen ratio, and albedo. While these values are standard based on global land cover categories and seasons in the AERSURFACE module, designed to determine surface characteristic values required by AERMET, more specific information can be obtained from reanalysis databases. In this paper, instead of using the default values suggested in the model user guide, ERA-5 hourly data were used, and annual and seasonal average values were calculated. The seasonal characteristics of the site include albedo, Bowen ratio, and surface roughness values for winter, spring, summer, and autumn, respectively. The albedo values range from 0.152 to 0.169, indicating slight seasonal variation in surface reflectivity. The Bowen ratio shows notable variability, with values ranging from 0.090 in spring to 0.500 in winter, reflecting changes in the balance between sensible and latent heat fluxes. Surface roughness remains relatively consistent across seasons, with values around 0.819, indicating stable surface texture and aerodynamic properties throughout the year. The standard values in AERSURFACE are global and easy to use but do not represent the specific location. Therefore, local surface parameters from the reanalysis database can completely differ from the AERMOD global standards in absolute values and seasonal dynamics.

The study area was modeled with a resolution of 500 meters, covering an area of 50 km by 50 km, as illustrated in Figure 1. Three-point sources, specifically the two stacks from SOMA-B and one stack from SOMA-KOLIN thermal power plants, were considered for this study. Topographical data for the study area was extracted from GTOPO 30 (Global 30 Arc-Second Elevation) from the United States Geological Survey (USGS) database with a resolution of 1 km (USGS, 2018). Table 1 shows information for all data used in AERMOD.

The hourly emission calculations were performed based on hourly electricity generation data. Hourly electricity production data for two thermal power plants were obtained from the EPIAS Transparency Platform for 2021 and presented in Supplement 1. The total annual electric production for the two plants was 7,412,868 MW, with 56% of the production coming from SOMA-B and 44% from SOMA-KOLIN thermal power plants. The electricity generation data obtained was directly related to the emission factor, which was taken directly from Table 3.3 from EEA (2019) without incorporating a separate calorific value calculation. Additionally, a sulfur adjustment was applied for SOMA-B because the emission factor for SOx assumes no SO_2 abatement and is based on 1 % mass sulfur content. No adjustment was applied for KOLIN, as the sulfur content of the coal to be used is 1%. These emissions were defined on an hourly basis for the model and were integrated into AERMOD using the HOUREMIS mode. Separate emission files were generated for each hour to ensure accurate temporal representation of the emissions and their contribution to local air quality. The following equation was used for emission calculation:

$$\textbf{Emission=EF} \times \textbf{OP} \times \textbf{[S]*} \quad (1)$$

EF=Emission factor (1680g/GJ)

OP= Operational Data (Hourly Electricity Production)

[S] is sulphur content of the fuel (% w/w)

*The factor for SO_x assumes no SO_2 abatement and is based on 1 % mass Sulphur content using EF calculation

Notably, SOMA-B lacked end-of-pipe flue-gas desulfurization, while SOMA-KOLIN thermal power plant had control technology with an assumed efficiency of 90%, as noted in the report provided by Kolin Energy (Hidro-Gen Energy, 2015). Efficiency for KOLIN was also included in the emission calculation step.

Notably, SOMA-B lacked end-of-pipe flue-gas desulfurization, while SOMA-KOLIN thermal power plant had control technology with an assumed efficiency of 90%, as noted in the report provided by Kolin Energy (Hidro-Gen Energy, 2015).

3. Results and Discussion

3.1. Calculated Emissions

A total of 10,377 tons of annual SO_2 was calculated from energy production in two regional thermal power plants in this study and calculated hourly emission rates were given in Figure 2. The primary contributor to the SO_2 emissions was the SOMA-B thermal power plant, accounting for 81.1% of the total emissions. Notably, SOMA-B is the leading thermal power plant for SO_2 emissions that is not equipped with an FGD system. Supplement 1 shows the temporal distribution of SO_2 emissions in the thermal powers. The SOMA-B thermal power plant emissions were significantly higher during the summer months, November and December. On the other hand, emissions in the SOMA-KOLIN thermal power plant were variable during time and approximately five times lower than the SOMA-B thermal power plant (Figure 2).

3.2. Model Results

The annual mean concentration levels resulting from two thermal power plants varied between 0.02 $\mu g/m^3$ and 18.2 $\mu g/m^3$ across region Figure 3). Notably, none of the recep-

Table 1. Information of the data used in AERMOD

Input type	Source	Temporal Resolution	Details	Description
Meteorological Data (Upper air)	NOAA http://www.esrl.noaa.gov/raobs/	Twice a day	The station numbered 17220 was used	Processed using AERMET
Meteorological Data (Surface)	GDM	Hourly	The data from station numbered 18040 was used	Processed using AERMET defined as ONSITE data
Topographical Data	USGS https://www.usgs.gov/	Yearly	GTOPO 30 (Global 30 Arc-Second Elevation) was used	Processed using AERMAP
Surface characteristic	ERA-5 Single Level https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels?tab=overview	Hourly	Albedo, roughness length, Bowen ratio	Processed using AERMET using calculated seasonal averages over the meteorological station
Emission Data	Calculated	Hourly	Hourly SO_2 emissions were calculated with Tier 1 emission factor and sulfur content of fuel from electrical city production	Defined in HOUREMIS format for the model

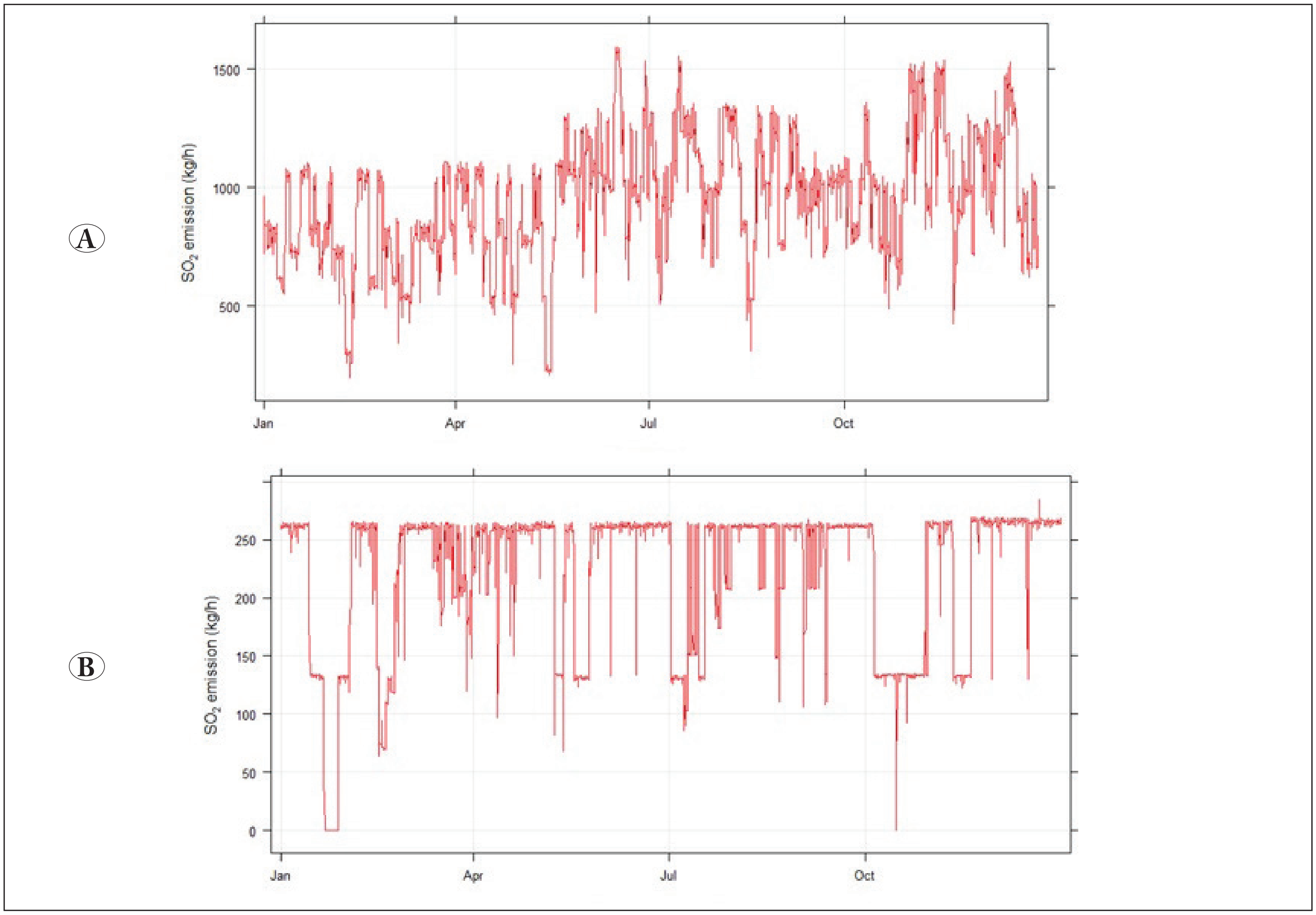

Figure 2. Hourly SO_2 emissions in SOMA-B **(A)** and SOMA-KOLIN **(B)** thermal power plants.

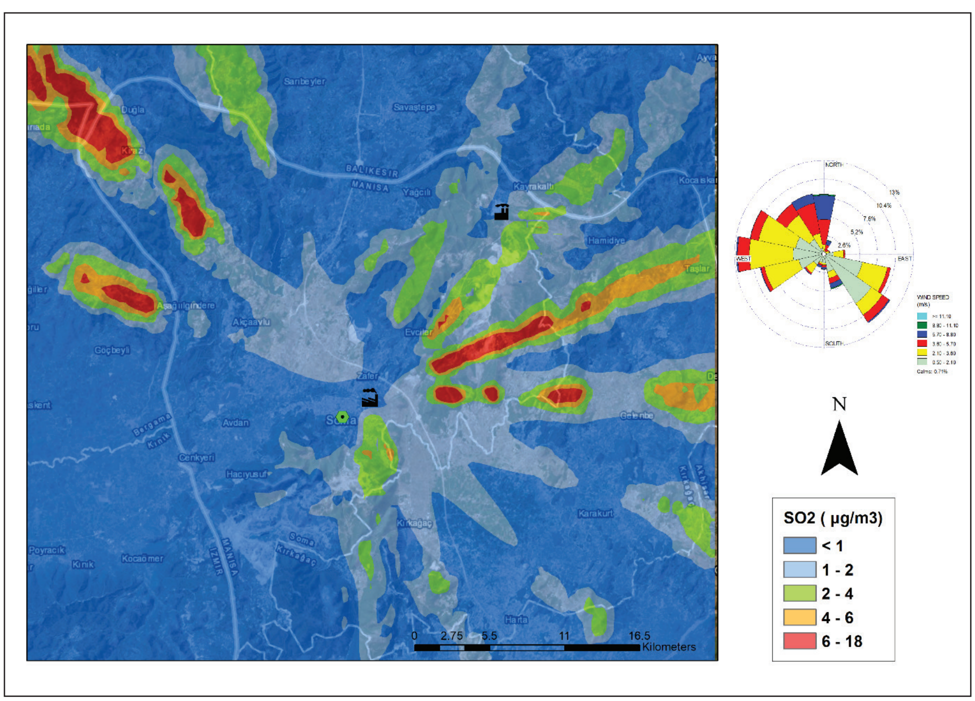

Figure 3. Spatial distribution of annual average SO_2 concentrations.

tors within the modeling domain exceeded the annual limit value of 20 μg/m^3. The highest recorded annual SO_2 concentration, 18.2 μg/m^3, was observed in the eastern vicinity of the SOMA-B thermal power plant, located approximately 5 kilometers away. The modeling outcomes indicated that maximum concentration could be entirely attributed to SOMA-B thermal power plant emissions. In contrast, the other thermal power plant in the area had minimal impact on the highest SO_2 concentration due to its utilization of an FGD system to reduce SO_2 emissions during production activities.

The annual average SO_2 concentrations were predominantly dispersed towards the eastern, northern, and northeastern areas, aligning with the wind patterns presented in the annual wind rose in Figure 3. The contributions of each thermal power plant to the annual average SO_2 concentration in Soma were estimated across the entire study domain, with results illustrated in Figure 4. The spatial analysis indicated that the SOMA-B thermal power plant exerted the most substantial impact on air quality in Soma, with contribution levels ranging from 45% to 100% (Figure 4). While the highest contributions were detected throughout most of the study region, lower contributions were mainly observed in the northwestern area, where the SOMA-KOLIN thermal power plant is located. The SOMA-KOLIN plant had a comparatively smaller impact, contributing between 5% and 95% across the region, with a considerable number of grid points experiencing lower impacts (<10%). This plant's influence was primarily confined to the northwestern section of the domain, where contributions ranged between 50% and 94%.

The maximum daily average SO_2 concentration within the study area was recorded at 99.7 μg/m^3 by the end of November. Analysis of individual power plant contributions revealed that the SOMA-B thermal power plant was the primary contributor to this peak daily concentration, which occurred approximately 9.5 kilometres northeast of the facility. Conversely, in June, the SOMA-KOLIN thermal power plant was associated with a maximum daily average concentration of 57.7 μg/m^3, observed about 3 kilometres east of the plant. Despite these peaks, daily concentration levels remained below the regulatory threshold of 125 μg/m^3, thus complying with the established air quality standards.

The estimated maximum hourly concentration from three stacks of two thermal power plants was 1496.4 μg/m^3. The hourly limit exceeded 2765 times across 465 grid points, significantly surpassing the legal maximum limit of 350 μg/m^3 (MoEUCC, 2008). Figure 5 depicts the locations and numbers of the exceedances, along with an elevation map. The number of exceedances varied from 1 to 80 in the grid points, with 28% of all grid points having only one exceedance. The largest exceedances (n=80) occurred in the eastern part of the SOMA-B thermal power plant, approximately 7 km away (coordinates 561000, 4338500, UTM 35N). The second-highest number of exceedances (n=43) was observed at 1 km from this grid. Additionally, the northeastern region was heavily impacted by hourly SO_2 concentrations due to the prevailing southwestern winds, resulting in more than 35 exceedances in five grid points in the eastern and northern areas of the SOMA-B thermal power plant. Figure 5 also illustrates the exceeding values in the study domain with pollution rose.

In a study by Siahpour et al. (2022), the AERMOD model was used to assess the environmental impact of the Shazand thermal power plant in Iran, which primarily uses mazut, a heavy and low-quality fuel known for its high sulfur content. The modeling results indicated that the maximum SO_2 concentration reached 197.85 mg/m^3 at 900 meters northwest of the plant. During an 8-hour period, the SO_2 concentration entering the city of Arak ranged from 35 to 45 mg/m^3. The average annual SO_2 concentration was approximately 1.2 to 1.6 mg/m^3, reflecting the plant's impact on the surrounding area.

In a study conducted by Vu et al. (2022) in Vietnam, the AERMOD model was employed to assess air pollution from thermal power plants. The results indicated that the 24-hour average concentration of SO_2 from power plants in 2030 is projected to contribute 10 μg/m^3 to Ho Chi Minh City's (HCMC) air quality. The annual average concentration of SO_2 from power plants contributing to HCMC's air quality in 2020 was approximately 0.17 μg/m^3. These findings suggest that the emissions from thermal power plants in the region are expected to increase significantly by 2030. In a study conducted by Mbiaké et al. (2017) in Douala, Cameroon, the observed daily SO_2 concentrations ranged from 3.8 to 23.5 μg/m^3, and the 10-minute concentrations ranged from 51.7 to 128.9 μg/m^3. Comparing these values, our study's daily peak concentration of 99.74 μg/m^3 is significantly higher than the observed daily concentrations in other regions. Similarly, the hourly peak of 1496 μg/m^3 in our study is substantially higher than the 10-minute concentrations observed elsewhere. Overall, the modeling results of this study indicate annual peak concentrations of

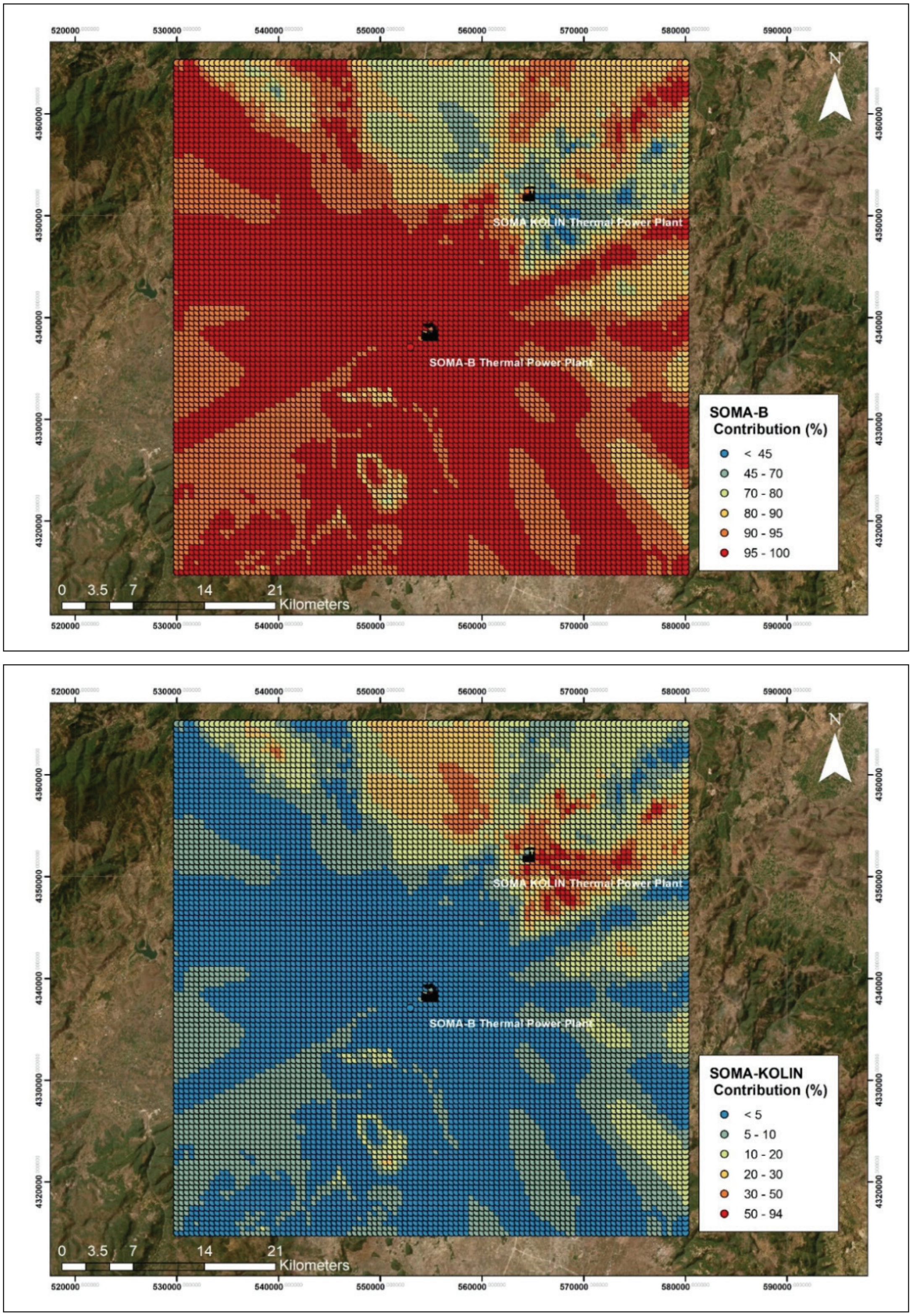

Figure 4. Contribution of each thermal power plant on annual average SO_2 concentration

18.2 μg/m^3, daily peaks of 99.74 μg/m^3, and hourly peaks of 1496 μg/m^3. The results are notably higher than those reported in the literature. These discrepancies may be attributed to several factors, including differences in fuel types, emission control technologies, plant capacities, and operational efficiencies. Additionally, variations in meteorological conditions, topography, and receptor locations can influence dispersion patterns and concentration levels. These findings highlight the importance of conducting localized air quality modelling to accurately assess the environmental impact of thermal power plants, considering the unique characteristics and operational parameters of each facility

Finally, in the study conducted by Yassin and Al-Awadhi in Kuwait in 2011, the thermal power plants under investigation had capacities like those of the Soma power plants. The study indicated that hourly SO_2 concentrations frequently exceeded the Kuwait Environmental Protection Agency (KW-EPA) threshold of 444 mg/m^3 in most residential

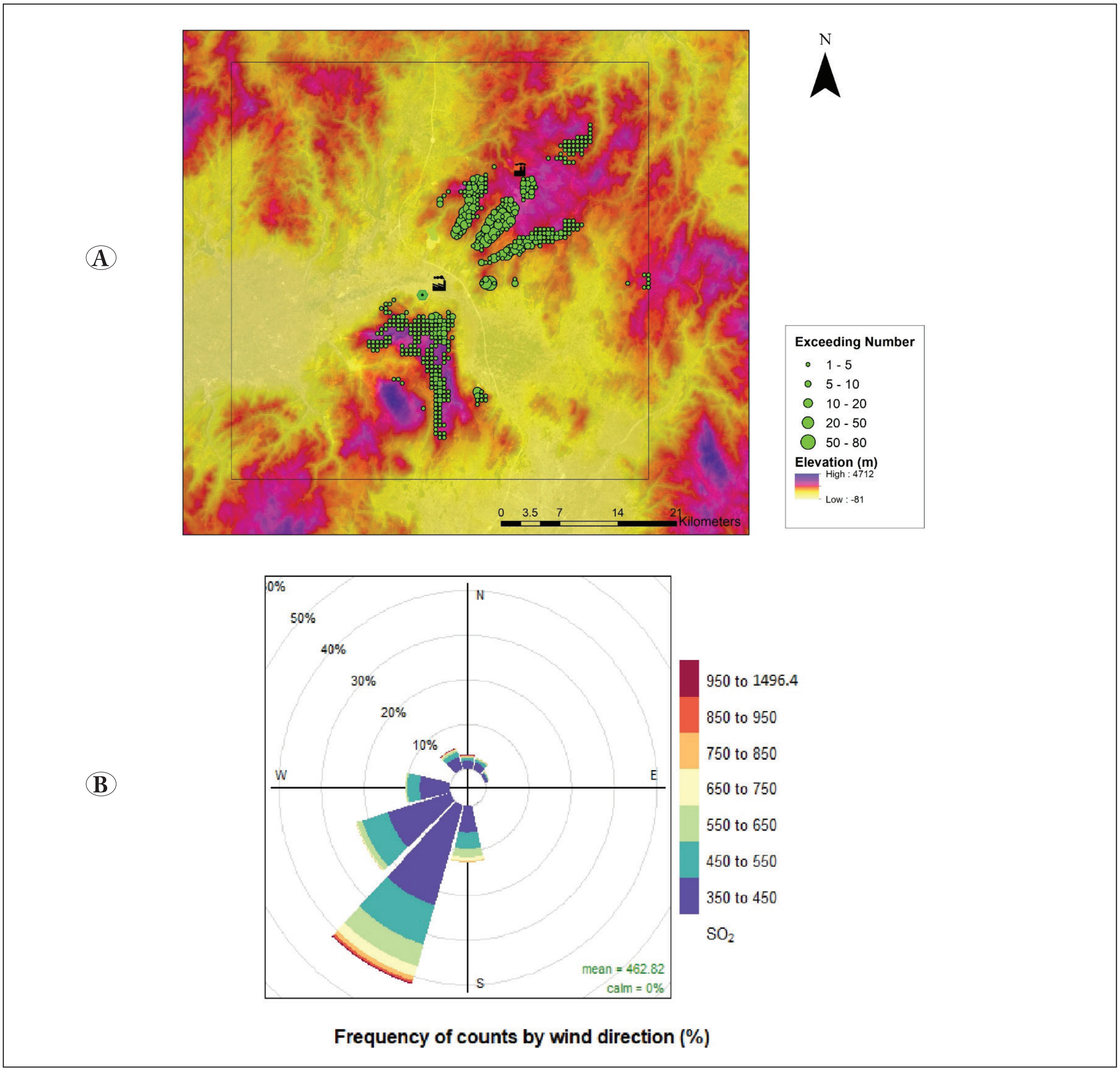

Figure 5. Total hourly SO_2 exceeding values in one year in the grid points **(A)** and pollution rose for hourly exceeding values **(B)**

areas. The highest simulated hourly SO_2 concentration recorded was 1246 mg/m^3, located approximately 4.6 km away from the power stations. Most hourly violations were also concentrated during the peak months of energy consumption. During the year 2008, the study recorded only one violation of the annual simulated SO_2 concentration. Comparing these findings with our study, the hourly concentrations are like ours; we do not exceed the limit values annually, but here, one point has been exceeded.

The maximum seasonal average estimated SO_2 concentrations were 12.0 **µg**/m^3, 25.4 **µg**/m^3, 18.4 **µg**/m^3, and 9.0 **µg**/m^3 in spring, summer, autumn, and winter, respectively. The SO_2 pollution primarily impacted the lower regions of the study area, which were influenced by prevailing seasonal wind directions and variations in terrain elevations (as illustrated in Figure 6a-d). The northern, eastern, and northeastern parts of the study region were found to be most affected by SO_2 pollution from thermal power plants throughout the year. The results suggest that they are likely to experience significant levels of SO_2 pollution, potentially exceeding regulatory limits, which could be attributed to various anthropogenic sources, including residential heating during winter months. On the other hand, the southwestern part of the study region was less impacted by SO_2 pollution in all seasons, possibly due to a lower frequency of northeastern winds.

Hourly SO_2 concentrations were collected from the Soma air quality monitoring station in the National Air Quality Monitoring Network operated by the MoEUCC (https://www.havai-zleme.gov.tr/). Within the scope of the study,

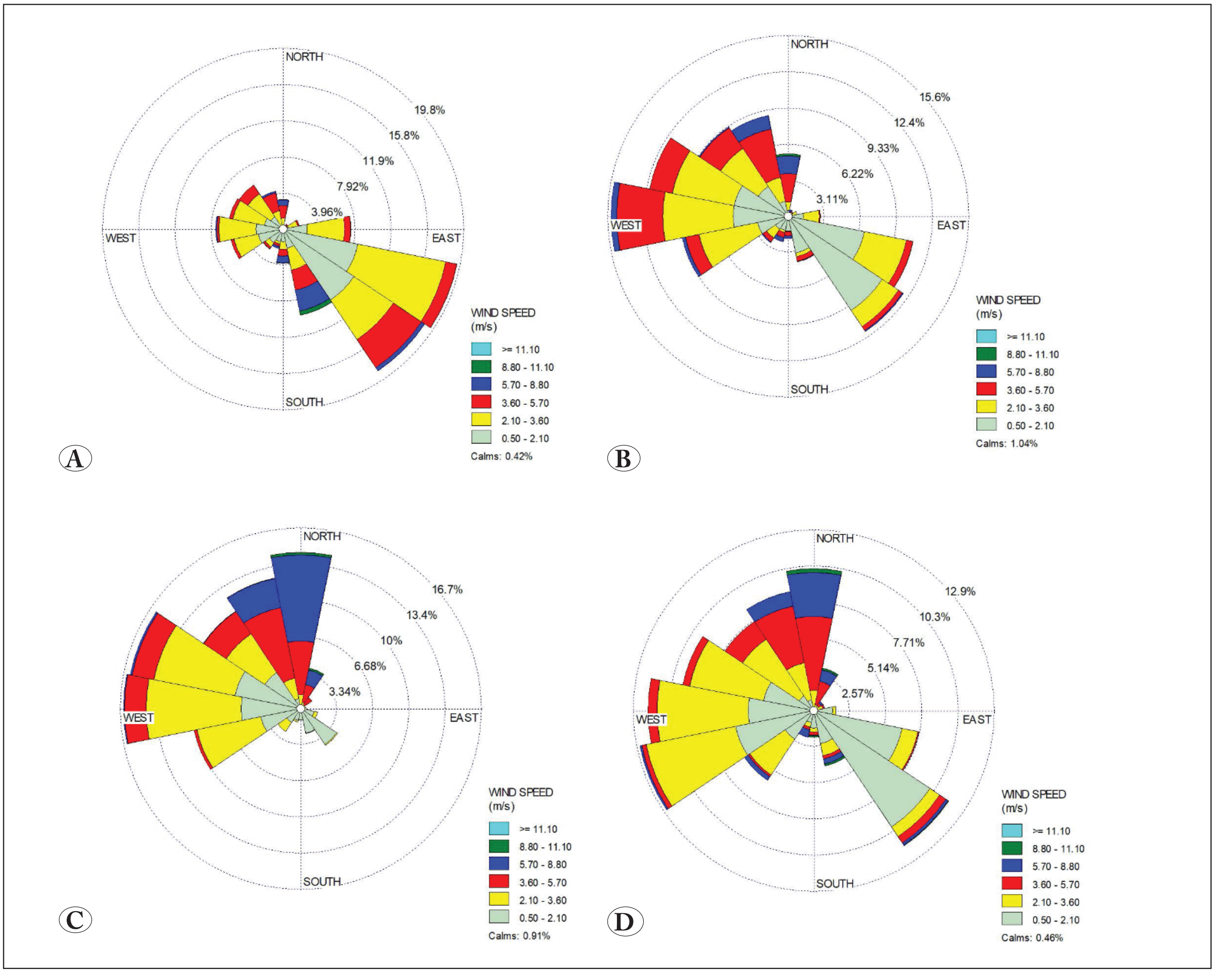

Figure 6. Wind roses for winter **(A)**, spring **(B)**, summer **(C)**, and autumn **(D)**

concentration values with 0 or negative values in the measurement data were removed. Table 2 presents an overview of the seasonal and annual variations in SO_2 levels at the monitoring station throughout the year. The annual average concentration of SO_2 was very high, reaching 71.9 **µg**/m^3, exceeding the annual limit value of 20 **µg**/m^3. Moreover, 195 hourly SO_2 concentrations were measured above the defined exceedance level of 350 **µg**/m^3 in 2021. Minimum and maximum hourly concentrations recorded were 0.71 **µg**/m^3 and 976.4 **µg**/m^3, respectively, with a high standard deviation (104.5 **µg**/m^3) in the station. Seasonal variations in SO_2 concentrations indicated a significant increase in winter months (Table 2). According to the data in Table 2, the mean SO_2 concentration during the winter season was 176 **µg**/m^3, while the mean concentration during the summer season was lowest at 17.2 µg/m^3. The mean concentration during spring and autumn was higher than in summer, with values of 53.8 **µg**/m^3 and 62.6 µg/m^3, respectively. Throughout the study period, the seasonal mean concentrations of SO_2 consistently exceeded the hourly Turkish Air Quality Limit of 350 µg/m^3 in every season, primarily during the winter season, which occurred 136 times with a noticeable increase in SO_2 concentrations. On the other hand, the exceedance number in summer (n=2) was negligible. In summer, SO_2 concentrations decreased and remained below the hourly limit value. However, there is still a possibility of exceedances in spring (n=14) and autumn (n=43), respectively.

Interestingly, the modeling results revealed that the thermal power plants did not substantially contribute to SO_2 concentrations at the station due to the meteorological and topographic conditions of the region. Within the region, a single air quality monitoring station is in the center of the Soma district, serving as the urban station. The annual average concentration was estimated to be 0.44 **µg**/m^3, while the maximum daily and hourly SO_2 concentrations were calculated to be 6.93 **µg**/m^3 in September and 106.6 **µg**/m^3 in December, respectively. Notably, most of the contribution to SO_2 concentrations originated from the SOMA-B thermal power plant, as the SOMA-KOLIN thermal power plant is situated considerably from the measurement station. Due to its proximity to the station, the center of the Soma district exhibited a contribution level like that of the monitoring station.

Table 2. Descriptive statistics for seasonal measured SO_2 concentrations at Soma air quality station.

season	Min	Mean±Std	Max	N of exceeding
winter	4.2	176.0±139.9	976.4	136
spring	0.8	53.8±77.6	455.2	14
summer	0.7	17.2±36.1	499.3	2
autumn	1.4	62.6±85.1	605.8	43
overall	0.71	71.9±104.5	976.4	195

Upon conducting detailed analyses, it was observed that specific periods, particularly in April and October and during the afternoon hours, exhibited values closely aligned with the station data. This alignment was particularly prominent in three distinct time intervals when the wind direction originated from the northwest, specifically the direction of the Soma-B Thermal Power Plant. Notably, both the station measurements and model-derived values demonstrated nearly identical concentrations during these instances (Supplement 2).

The comparison of station and model results during the times of direct wind flow from the location of the Soma-B Thermal Plant is depicted in Figure 7. The results obtained outsite the winter months displayed a significant consistency among themselves. However, it should be acknowledged that the station's positioning within the region poses challenges in accurately determining the full extent of the power plant's impact, owing to various factors. These factors include the Soma-B Thermal Power Plant's considerable stack height (250 m), the local topography, and the absence of prevailing winds blowing directly from the power plant's location.

To assess the contribution of power plants to regional air quality, it may be necessary to establish new measurement stations in the vicinity. It is worth noting that the area where the station is situated experiences heightened exposure to pollution derived from heating sources during the heating season, as well as intensified traffic emissions resulting from the continual transportation of coal to the power plant located in the southwest of the city, adjacent to coal deposits.

3.4. Effects of Topographic and Geographical Variables

The topographic and geographic features can influence the degree of air pollution and the residence time of polluted air in a region. While topographical features are not direct causes of air pollution, they affect the extent and duration of air pollution in the environment. In this study, the x and y coordinates of the grid points, as well as the distance to the pollution source (DISTSRC), were considered geographical features. Elevation (ELEV), SLOPE, and ASPECT were

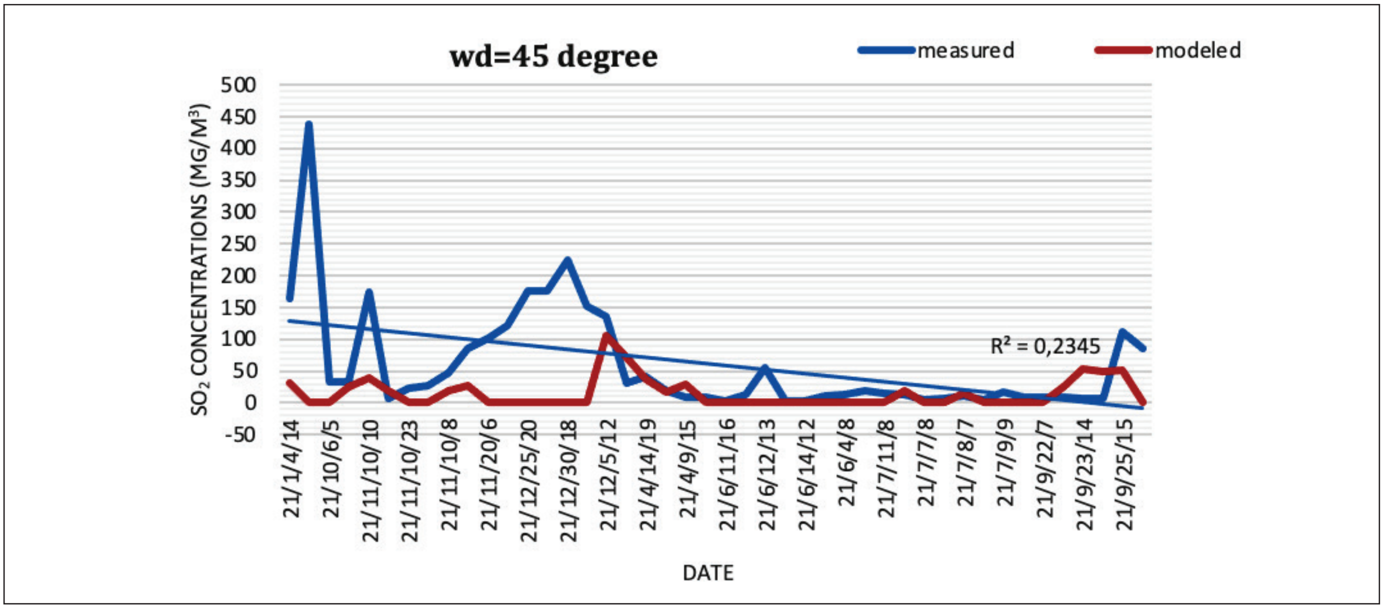

Figure 7. The relationship between the measured and modeled data during the times when the wind blows from the direction of the SOMA-B thermal power plant.

regarded as topographical factors to identify the factors influencing the annual average SO_2 concentrations in the region.

Aspect refers to the direction of sun exposure or the view of mountains in a region. It indicates the position of a place relative to the sun, which in turn affects the timing of sunlight exposure. Elevation and slope factors are related to pollution as they influence the dispersion of the pollution. The X and Y coordinates of the grid points and DISTSRC are other important variables affecting the distribution of SO_2 concentration in a region. Increasing DISTSRC, which is essential due to higher stack heights of thermal power plants, leads to higher SO_2 concentrations at greater distances from the source. The spatial distribution of these features in the study area can be observed in Supplement 3.

To analyze the factors influencing the distribution of SO_2 over the study region, four critical areas were selected based on the annual average SO_2 distribution and the grid points exceeding hourly values, as shown in Supplement 4. Supplement 5 presents descriptive statistics for the extracted values related to the selected regions. The average elevation ranged from 377.8 m for Area-1 to a maximum of 485.8 m for Area-2. The average distance to the pollution source (DISTSRC) varied from a minimum of 9812.8 m for Area-2 to 21089.4 m for Area-1. The minimum and maximum slopes, derived from elevation, ranged from 3.8% (Area-4) to 7.7% (Area-3), respectively. The mean aspect was 177.1o for Area-1 and 202.1o for Area-4.

Pearson correlation analyses were conducted to assess the influence of geographic and topographic factors on the annual average SO_2 concentrations emitted from thermal power plants in the region (Table 3). The correlation analyses revealed that annual average SO_2 concentrations exhibited varying degrees of correlation (correlation coefficients, r) with geographical and topographical variables. The correlation between SO_2 concentrations and aspect was weak (r=-0.13-0.02) across all regions. The most influential factors affecting SO_2 dispersion varied depending on the region. For instance, in Area-1, elevation (r = 0.40) was the most significant factor since pollution tends to be more prominent in the trough regions, characterized by topographical features extending perpendicular to the dominant wind direction. In Area-3, the X coordinate and DISTSRC showed strong positive and negative correlations (r=0.58 and r=-0.49). In Area-4, the Y coordinate and slope displayed higher positive correlations (r=0.46, r=0.30), while the Y coordinate showed a higher negative correlation (r=-0.47) in Area-2. The impact of the Y coordinate could be evaluated due to its strong correlation with DISTSRC (Table 3). The significance of DISTSRC in SO_2 dispersion arises from the fact that stack height is one of the multiple factors contributing to the long-range transport of air pollution. Reports and experts in the field indicate that taller stacks generally disperse

Table 3. Pearson correlation coefficients for topographic variables with annual average SO_2 concentration in four selected regions.

Area	X	Y	ELEV	DISTSRC	SLOPE	ASPECT
Area-1	-0.11	0.19	0.40	0.18	0.23	-0.07
Area-2	0.06	-0.47	0.18	-0.25	0.13	0.02
Area-3	0.58	0.26	-0.02	-0.49	0.06	-0.13
Area-4	-0.04	0.46	-0.03	-0.28	0.30	-0.03

pollutants over greater distances than shorter stacks. However, this is contingent upon various other variables, such as total emissions, temperature and velocity of emissions, and meteorological conditions (U.S. GAO, 2011).

In the studied region, the Y coordinates of grid points hold more importance than the X coordinates since pollution sources demonstrate spatial distribution primarily in the Y direction. ELEV is predominant in Area-1, where the highest annual average SO_2 concentrations are observed, influenced by the prevailing wind direction during winter, as depicted in Figure 6d. While DISTSRC exhibited a negative correlation in all regions except Area-1, ASPECT, and SLOPE, it did not significantly impact SO_2 dispersion in the region (Table 3).

4. Conclusion

To better understand regional SO_2 emissions, comprehensive hourly calculations of SO_2 emissions from two major power plants were conducted in the Soma region and estimated air quality levels using the AERMOD modeling system in detail. Seasonal differences and the contribution of each power plant to annual average concentrations were analyzed, and hourly, daily, and annual exceeding values were evaluated across the region. The contribution of geographical and topographical variables to annual average SO_2 concentrations using Pearson correlation coefficients was calculated to detail the modeling analyses. The study determined the total SO_2 emissions originating from thermal power plants in the study area to be 10,378 tons/year, with the SOMA-B thermal power plant being the region's largest contributor to SO_2 emissions. This power plant, which began operation in 1980, is one of the oldest lignite-fired power plants in Türkiye. Our results indicate that effective improvement of regional air quality can be achieved by implementing SO_2 emission control techniques at the SOMA-B thermal power plant.

The impact of wind direction on SO_2 concentrations was visible throughout the region. The general direction of dispersion was towards the region's north, northeast, and northwest. However, hourly SO_2 concentrations exceeded the limit value (350 **µg**/m^3) in 311 grid points (2148 times). This preliminary study provides insights into the contribution of primary SO_2 pollutant sources to air quality levels in the Soma region. It demonstrates that the AERMOD modeling system can effectively predict air quality at local scales with complex terrain and limited monitoring stations. These results are particularly significant for policymakers as they provide insights into regions that may require additional monitoring infrastructure or targeted mitigation strategies. For instance, the identification of affected areas outside the immediate vicinity of the plant suggests the need to reassess the placement of monitoring stations to better capture the plant's emissions. Our findings could help inform the policy makers of site selection for new monitoring stations and evaluation of SO_2 levels originating from thermal power plants in the region.

Furthermore, this study underscores the necessity of incorporating modeling approaches like AERMOD in policy frameworks to complement monitoring data, especially for evaluating the contribution of specific sources to regional air quality. The findings can guide strategies such as emission reduction plans, the establishment of new monitoring stations, or the revision of existing air quality management policies to better address local and regional pollution challenges

Our study highlights the importance of considering hourly variations in SO_2 concentrations and the potential influence of geographical variables in future air quality assessments for the Soma region. Modeling results showed that variables such as the grid points' ELEV, X, and Y coordinates and DISTSRC mainly affect the SO_2 dispersion based on selected regions. Future studies could determine additional emission sources such as residential heating, transportation, and industry better to understand the dynamics of air pollution in the region. Additionally, exploring the impacts of long-term trends could provide valuable insights into the effectiveness of existing emission control strategies and inform future policy decisions. To strengthen the recommendations, we propose installing new monitoring stations focusing on areas with high SO_2 concentrations identified by the model. Model updates should include refining emission factors, incorporating additional pollutants (e.g., PM and NOx), and enhancing meteorological resolution. Additionally, real-time emission data from continuous monitoring systems could be integrated to further improve model accuracy. Lastly, comprehensive studies, including epidemiological research and community engagement, are suggested to evaluate the plant's long-term environmental and health impacts.

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Author contribution: Author Gizem TUNA TUYGUN: Planned, designed the study, gathered and analyzed data and wrote the article.

Ethics committee approval: There is no need for ethical approval.

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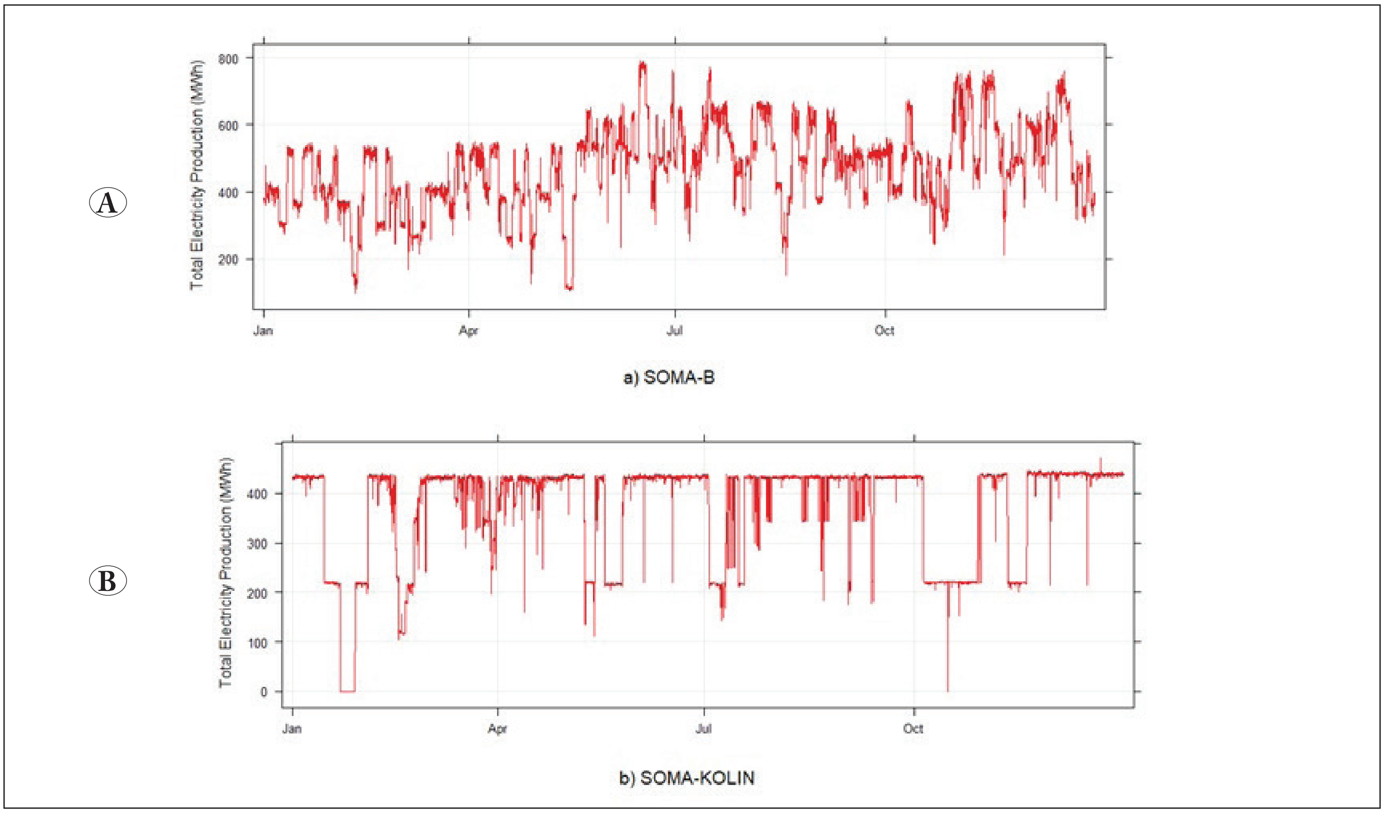
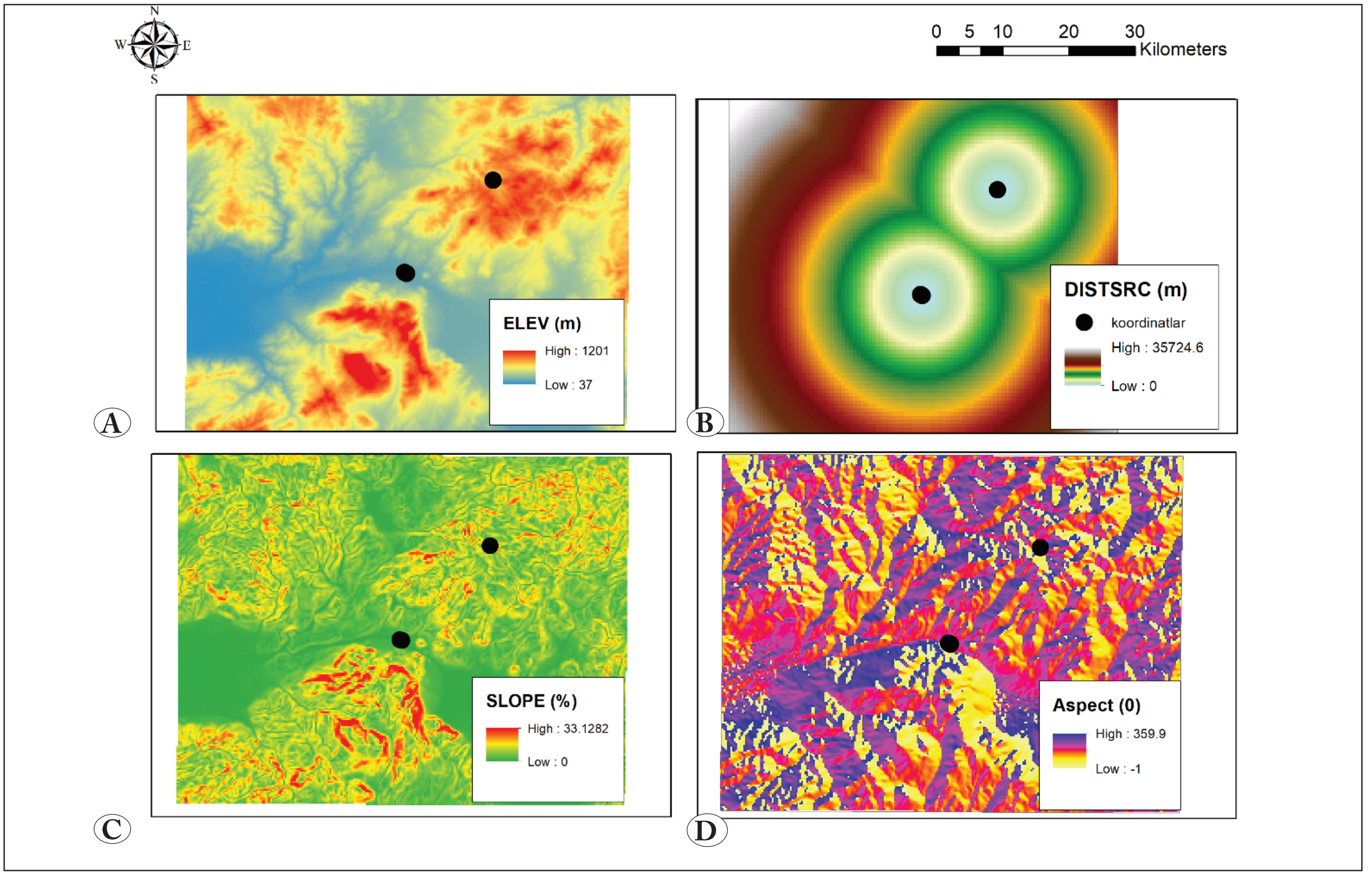


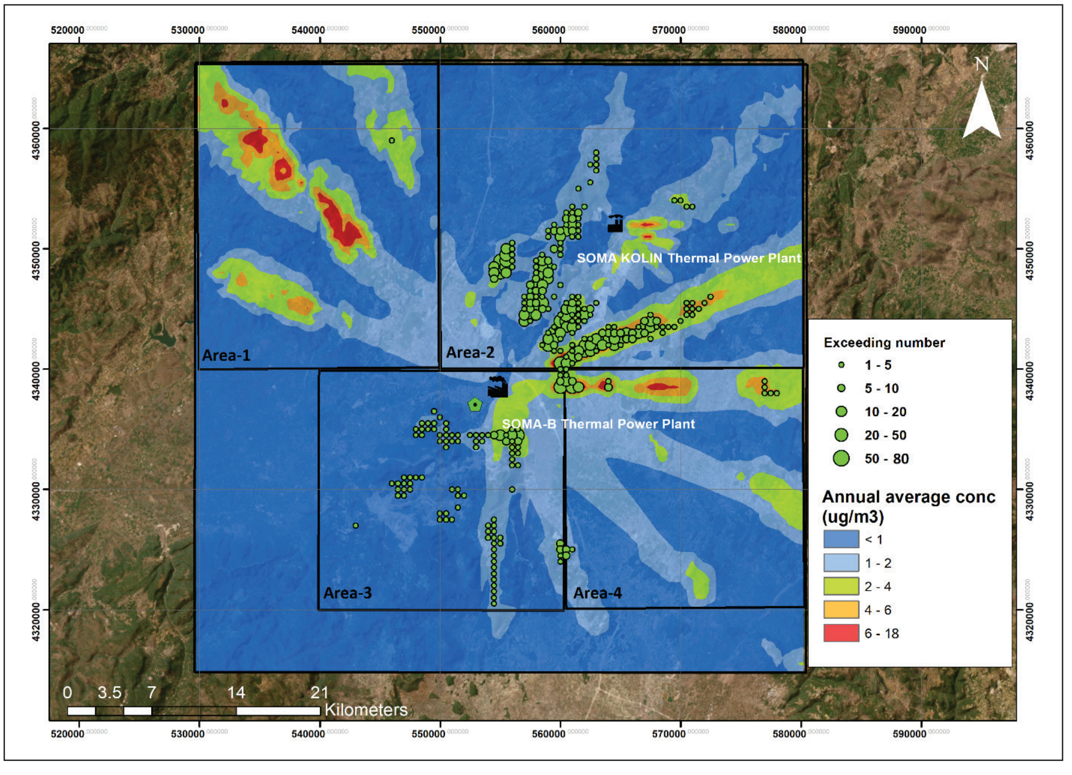
Supplement 1. Hourly electricity production in SOMA-B **(A)** and SOMA-KOLIN **(B)** thermal power plants

Supplement 2. Nearly identical concentrations of both the station measurements and model-derived values when the wind direction originated from the direction of the Soma-B Thermal Power Plant

Year	Month	Day	Hour	measured	modeled	wd	ws	CBLH
21	10	16	15	6.79	6.76	112.5	0.9	329
21	10	13	15	1.58	1.50	225	1.6	412
21	6	1	15	2.22	2.10	270	1.7	481
21	10	13	14	1.70	1.34	225	2	540
21	4	10	17	4.84	4.36	22.5	1.3	433
21	4	10	18	5.55	4.96	202.5	0.6	151
21	10	13	13	1.68	0.96	270	2.3	635
21	10	13	12	1.37	0.64	270	2.6	730
21	10	14	17	1.91	1.00	135	1.3	291
21	10	14	15	2.24	1.27	360	1.5	377
21	4	28	18	19.67	16.80	45	3.4	986
21	4	7	18	8.96	4.39	180	0.7	205
21	4	14	19	41.63	37.02	45	0.6	152



Supplement 3. The spatial of topographic variables elevation **(A)**, distance to the source **(B)**, slope **(C)**, aspect **(D)**.



Supplement 4. Illustration of selected areas based on annual average SO_2 concentration and hourly exceeding values in the study region.

Supplement 5. Summary statistics of geographical variables for each selected region

Area	Variables	Min	Max	Mean	Std
Area-1	**X (m)**	530000	550000	540000	5917.495
	Y (m)	4340000	4365000	4352500	7361.561
	ELEV (m)	54.2	869.8	377.8	166.1
	DISTSRC (m)	5220.2	36431.4	21089.4	6418.3
	SLOPE (%)	0.0	22.8	6.4	3.5
	ASPECT (°)	-1.0	359.9	177.1	91.2
Area-2	**X (m)**	550500	580000	565250	8660.466
	Y (m)	4340000	4365000	4352500	7361.004
	ELEV (m)	134.2	926.0	485.8	174.3
	DISTSRC (m)	0.0	19849.4	9812.8	4102.5
	SLOPE (%)	0.0	23.2	6.3	3.8
	ASPECT (°)	0.0	359.9	196.5	98.5
Area-3	**X (m)**	540000	560000	550001.7	5916.513
	Y (m)	4320000	4340000	4330004	5918.602
	ELEV (m)	60.3	1179.3	431.2	263.0
	DISTSRC (m)	0.0	23817.0	11784.3	5319.9
	SLOPE (%)	0.0	30.7	7.7	5.9
	ASPECT (°)	-1.0	359.6	191.9	108.1
Area-4	**X (m)**	560500	580000	570250	5773.503
	Y (m)	4320500	4340000	4330250	5773.503
	ELEV (m)	37.3	1179.3	388.3	205.3
	DISTSRC (m)	5500.0	30805.8	17928.3	5538.4
	SLOPE (%)	0.0	23.6	3.8	3.2
	ASPECT (°)	-1.0	359.6	202.1	94.0