Identification of Sulfur Dioxide (SO_2) Hotspots of Gujarat state using Sentinel 5P-TROPOMI

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Abstract: Sulfur dioxide (SO_2) is a widely recognized pollutant with far-reaching consequences for human health, climate, and the environment. This study aims to identify SO_2 hotspots within the state of Gujarat located in the western part of India using the Sentinel 5P TROPOspheric Monitoring Instrument (TROPOMI) satellite data. Based on the analysis of the satellite data from January 2019 to 2023, 15 hotspot regions were identified in Gujarat with significantly high concentration of SO_2. Majority of these hotspots were located in industrial areas and petroleum refineries, including Mundra port, Ahmedabad, Vadodara, Surat, and the Alang shipbreaking yard. Notably, some scattered hotspots were found near Eco-sensitive zones like Narayan Sarovar. The observed SO_2 concentrations in these hotspots vary between ~ 10 to ~ 1000 µmol/m^2, with an average concentration of ~ 300 µmol/m^2. It is also observed that SO_2 concentration is significantly elevated during winter and pre-summer months, with a marked reduction during the monsoon season. The average monthly SO_2 concentrations exhibit a distinct seasonal cycle, with the lowest levels during the monsoon and the highest during winter. Furthermore, impact of COVID induced lockdown is also perceived across the state.

Keywords: Sentinel 5P TROPOMI, Sulfur Dioxide (SO_2), Gujarat, Hotspots Identification, Urban, Pollution

1. Introduction

India is observing a rapid socio-economic and industrial development. In this development Gujarat is also playing a leading role. Though Gujarat has given priority to protect the environment along with the development in the industrial sector, the impressive industrial growth may also be accompanied by the pollution on an increasing scale. Sulfur dioxide (SO_2) is one of the major pollutant trace gases which is the main contributor in several environmental pollution problems. As per the report released by Greenpeace in 2020, India is one of the largest emitters of SO_2 in the world, contributing more than 15% of global anthropogenic emissions in 2019 (Dahiya et al., 2020). The primary reason for India's high emission output is the expansion of coal-based electricity generation over the past decade. SO_2 emissions are a significant contributor to air pollution as its direct exposure to particulate matter $PM_{2.5}$ (Fine particulate matter) and other pollutants produces sulfate particles which are harmful for human health. This exposure will also lead to acid rain (Khemani et al., 1998).

The greatest source of anthropogenic SO_2 in the atmosphere is the burning of fossil fuels in power plants and other industrial facilities. Other sources include industrial processes such as extracting metal from ore, natural sources such as volcanoes, and locomotives, ships and other vehicles and heavy equipment that burn fuel with high sulfur content.

Majority of the studies have been carried out to understand the harmful effect of SO_2 on crops (Vijayan and Bedi, 1989; Anbazhagan et al., 1989; Anbazhagan and Bhagwat 1991) in Gujarat, but recently a study using Ozone Monitoring Instrument (OMI) satellite observations were carried out indicating high emissions of SO_2 over Gujarat from industries (Kharol et al., 2020). Other studies for understanding the impact of air pollutants on human health (Sarkar and Chouhan, 2021) are available in literature but scarce studies for hotspot identification of SO_2 over Gujarat state were available (Tyagi, 2021 et al.; Naqvi et al., 2021). Apart from Gujarat, various hotspot were identified across India where majority of the locations consist of the thermal power plants in the Indo Gangetic Plain (Chutia et al., 2019; Chutia et al., 2022). The coal-fired power plants are one of the largest contributors to the pollutant such as Nitrogen Dioxide (NO_2) and SO_2 (Ghosh et al., 2016).

Various studies have been performed across the globe to understand the SO_2 variations with the help of Google Earth Engine (GEE). GEE is considered to be an open source platform which helps to analyze various database such as the land cover changes, pollutants, water resource management etc. (Huang et al., 2017; Aksoy et al., 2019). This study has been carried out with an objective to identify the hotspots of SO_2 in Gujarat state using satellite data. This study demonstrates that in the absence of any other information about SO_2 emissions from the anthropogenic or natural sources, these satellite-based estimates can fill the gap in emission inventories in a timely fashion.

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2. Study Area – Data – Methodology

This study has been carried out over the state of Gujarat in India with central coordinates of 22° 18' 33.9300" N and 72° 8' 10.4280" E. The state has about 25.2 million of registered vehicles as on March 2019, contributing around 8.5% share of the total registered vehicle in the country (Ministry of Road Transport and Highways, 2023). There has been a growth of 9.33% in electricity generation capacity of the state for year 2020 with 0.77 GW, 20.37 GW and 10.34 GW installed capacity in Hydro, Thermal and Renewable Energy sources (Ministry of Statistics and Program Implementation, 2021). Gujarat has a total of 248 industrial infrastructures (Gujarat Infrastructure Development Board, 2024) with chemical, ceramics, textiles, automobile, electronics, pharmaceuticals, food processing and renewable energy sectors covering 2.52 Lakh hectors of land (Department for Promotion of Industry and International Trade, 2022) with 20577 factories in 2017 which increased to 21032 in 2018 as per Annual survey of Industries (ASI) (Government of NCT of Delhi, 2021). The present study incorporates the use of Sentinel-5P TROPOspheric Monitoring Instrument (TROPOMI) having a revisit time of one day and data was obtained via the open-source platform of GEE. The Level 3 Near Real Time product of "COPERNICUS/S5P/NRTI/L3_SO2" consisting of SO_2 vertical column number density calculated with the help of Differential Optical Absorption Spectroscopy (DOAS) technique (Nicolas et al., 2022) was taken into account. GEE implements the harp converter to convert the Level 2 data of SO_2 into Level 3 supported by a single grid per orbit. The monthly images for the time span of 2019 to 2023 were obtained at a spatial resolution of 3.5 x 5.5 km^2 whose resolution was noted to be 3.5 x 7.0 km^2 before 6th August 2019 (Nicolas et al., 2022). As the acquired data contained the negative values of vertical column, it was masked for taking average on monthly and annual basis for generating the spatial maps (Theys et al., 2023). The time series obtained by specifying the position of the hotspot was helpful to understand the variation of SO_2 throughout the time period.

3. Results and Discussion

The monthly mean variations of the SO_2 column density obtained from the TROPOMI were taken into consideration in order to visualize the changes over the state of Gujarat during the time span of 2019 to 2023 as portrayed in Figure 1. The months such as December. January and February which fall under the winter season have high values of SO_2. The reason could be the decrease in temperature and lower boundary layer height leading to stagnant condition. This trend is found to decrease in summer (March, April and May) extending to monsoon (June - September) and again increases during post-monsoon (October and November). It is also perceived from Figure 1 that certain regions in the state have high concentration showing the emissions from these areas and are identified as hotspots which includes various urban as well as the industrial locations. These zones have SO_2 discharge magnitude with a value greater than 350 µmol/m^2.

Figure 2 describes the annual mean fluctuations in the temporal frame of 2019 to April 2023. An increasing trend is detected across the desired period except for the year 2020 which was the lockdown period caused by the COVID – 19 restrictions extending throughout the state. The similar high emission regions can be correlated with the hotspot region as in Figure 1. These hotspot regions can be determined from Figure 3. Figure 1 and Figure 2 clearly show some constant cluster of high SO_2 concentration over Gujarat at Mundra port, Morbi and urban cities such as Surat and Ahmedabad. Figure 3 shows fifteen of these locations which are identified as hotspot over the state. Among these locations which shows heavy concentration even once throughout a year is also considered. Some hotspots were observed near reserved sanctuaries. Major hotspots location marked in Figure 3 are listed in Table 1.

Table 1. List of major hotspots identified in the satellite data analysis

1.	Mundra port (Thermal power plant)
2.	Morbi (Ceramic Industries)
3.	Ahmedabad (Industries, local transportation vehicles and Thermal power plant)
4.	Vadodara (Industries and Oil Refinery)
5.	Surat (Industries and Thermal Power plant)
6.	Gandhinagar (Industries & Thermal Power plant)
7.	Khambhaliya (Oil Refinery)
8.	Vapi (Industrial Area)
9.	Kim (Urban area)
10.	Narayan Sarovar (Coal Mines and Thermal Power Plant)
11.	Bhavnagar (Alang Shipyard)
12.	Ukai (Thermal Power plant)
13.	Kutchh (Port and Thermal Power plant)
14.	Babarkot (Industries)
15.	Jafrabad (Port and Industries)

The hotspots region are mostly found near the industrial locations as well as the thermal power plants. The main source of emission in these thermal power plants could be the conversion of the heat energy to the electrical by the combustion of coal. Coal constitutes substances such as pyrites and metal sulfates which are a main source of SO_2 during the combustion process (National energy Technology Laboratory; Calkins, 1994). The reason for the high SO_2 levels around the region of Narayan Sarovar could be the mining activities for limestone and lignite. Moreover, two thermal power plants are present in its vicinity (Ministry of Environment, Forest and Climate Change, 2020).

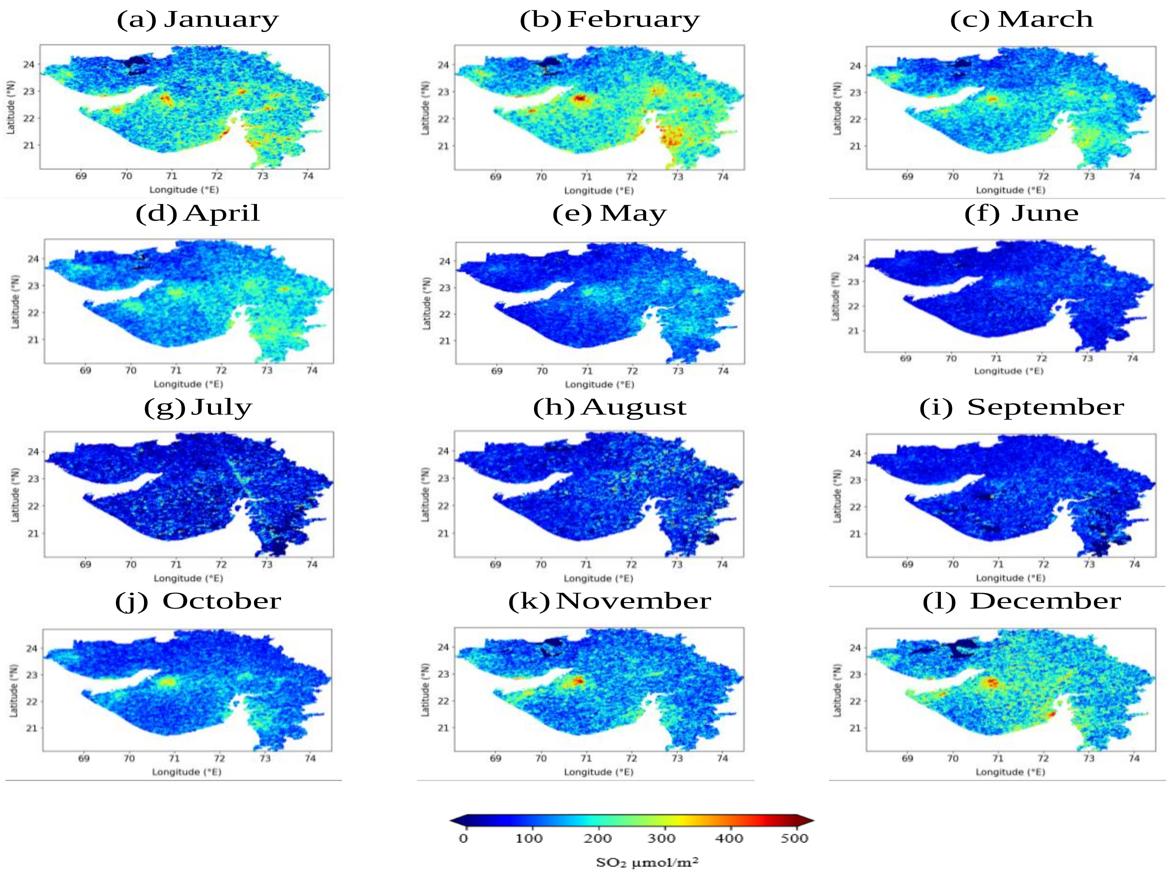

Figure 1. Monthly mean variation of SO_2 over Gujarat for year 2019-2023

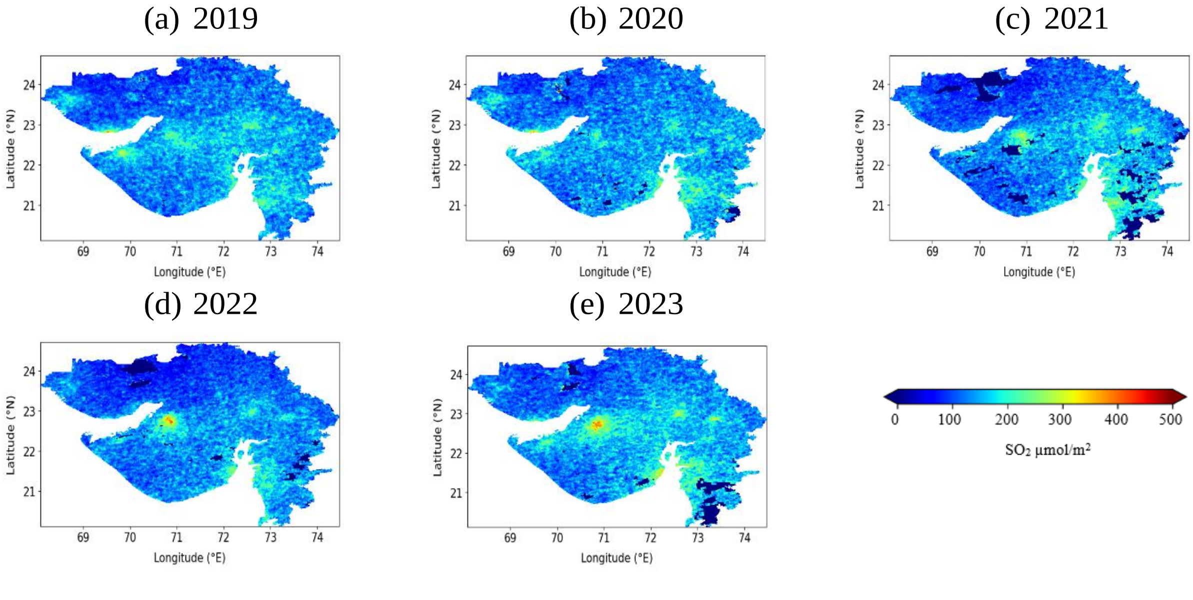

Figure 2. Yearly mean variation of SO_2 over Gujarat for year 2019-2023

While across the coast line, there is movement of ship tankers as well as location of various ports which suggest high fuel combustion and emission from tankers and other vessels (Indian Coastal Green Shipping Programme, 2023). It has also been observed that the cities like Ahmedabad fall under the category of hotspot since it consists of various industries which makes use of diesel generators and brick furnaces (Urban Emissions.info, 2019). The state capital of Gujarat, Gandhinagar, has notable SO_2 sources from industrial activities and transportation. The diamond, textiles and various IT firms are present in the Surat city which require the power from coal fired stations in turn can increase the SO_2. It is considered to be one of the top polluted regions according to the 2019 Greenpeace Report (Down to Earth, 2019). The city of Vapi, comprises a cluster of around 250 industries (Energy and Resources Institute, 2022) which mainly manufactures dyes and pigments. Further, the geography plays an important role in the dispersion of pollutants, as Vapi is located in a close proximity to the Arabian Sea, where the movement and concentration of the pollutants are affected by the land-sea breeze (Nigam et al., 2021).

The urban regions in the state have the presence of various industries such as pharmaceuticals, petrochemicals as well as agricultural units (Official Gujarat State Portal). Various textile production units and rice processing plants are part of Ahmedabad and Surat urban regions (Consulate General of India in Osaka-Kobe, 2019). The residual waste that is generated by these industries consists of SO_2 gas (Pradan and Sahu, 2004). Apart from this the fruit and vegetable processing units as well as certain bakeries are present in the Ahmedabad metropolitan which can be a source of SO_2 (Consulate General of India in Osaka-Kobe, 2019; U.S. Environmental Protection Agency, 1995). Vadodara comprises of petrochemical complexes and dairy plants (Government of India) whose manufacturing processes can also lead to the emission of pollutant gases out of which SO_2 is one of its constituents (Verheijen, 1996). One of the reason for the effusion of SO_2 from the urban build up zones like Ahmedabad, Vapi, and Vadodara (Ministry of MSME, 2011; Ministry of Chemicals & fertilizers, 2023) could be the presence of pharmaceuticals factories (Hu, 2019).

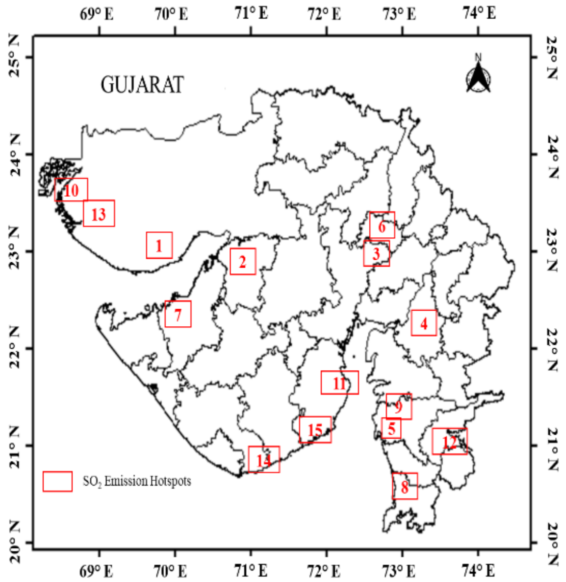

Figure 3. Map of Gujarat with marked locations of SO_2 hotspot identified using TROPOMI

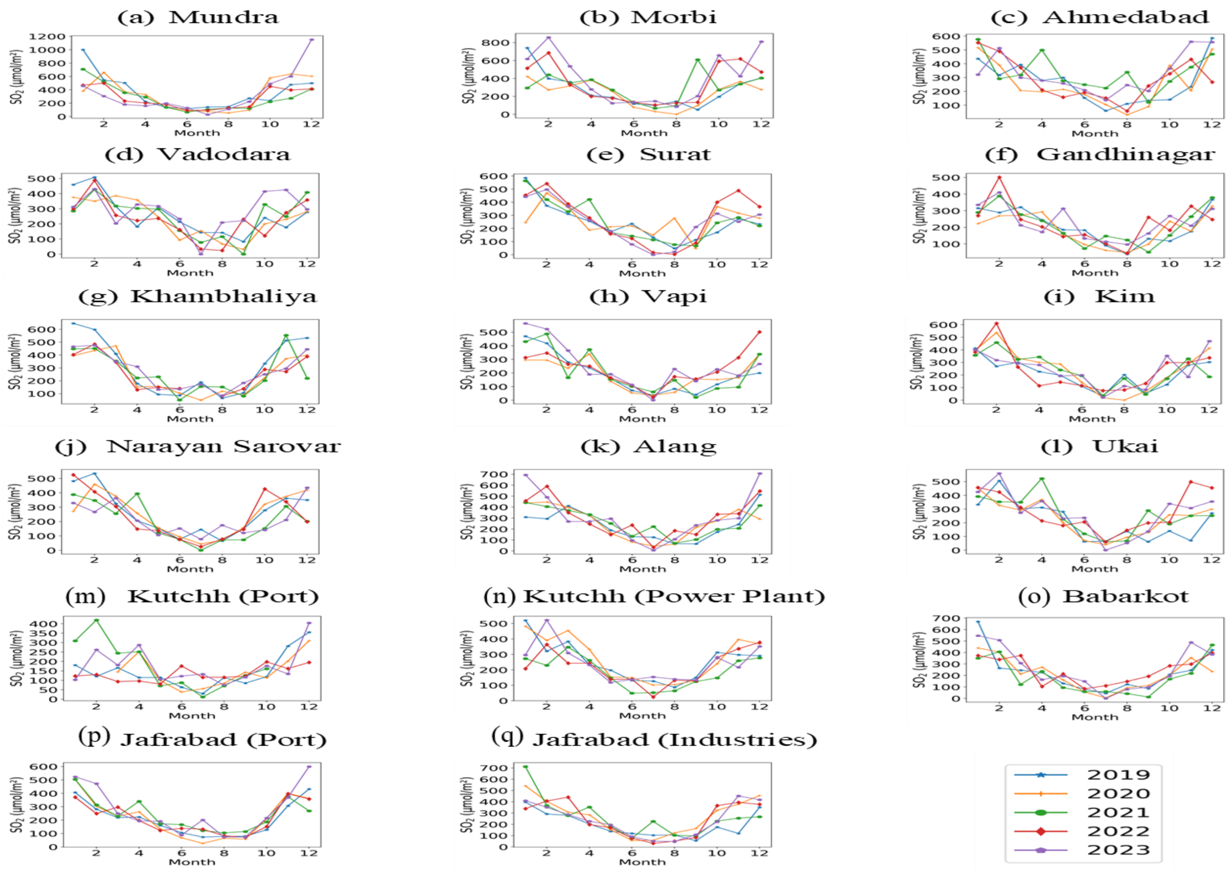

Figure 4. Monthly variation of SO_2 on fifteen hotspots of Gujarat listed in Table 1 portraying the years 2019 - 2023

Apart from the industries, sulfur is present in some amounts in Compressed Natural Gas, diesel as well as gasoline (The Economic Times, 2020). The sulfur pollution is found to increase due to the increase in the number of automobiles (Alagumalia et al., 2022) in the city areas. In order to understand the seasonal pattern of SO_2 over the hotspots, average concentration of the described regions Figure 3 were considered monthly variations throughout the time scale which is shown in Figure 4. The hotspot areas show similar pattern of SO_2 across the defined time period. Seasonality has been recognized in the monthly time series. The graph shows higher concentration in winter followed by summer and pre-monsoon and decreases to lowest in monsoon, following an increase with post-monsoon which can also be noted from Figure 1. Although, it can be seen that the trend followed by the pollutant over the hotspots is same, the difference is observed in terms of the concentration magnitude, the highest of which is observed near Morbi which is an industrial area consisting of various ceramic industries and Mundra possibly due to the location of thermal power plant and a ship port.

4. Conclusions

Gujarat is one of the leading contributors in industrial development in India. In this study, spatio-temporal variations of SO_2 were analysed for Gujarat state in India for the period of 60 months i.e. January 2019 – December 2023 using TROPOMI satellite data through GEE platform. The SO_2 vertical column data available at higher resolution were gridded and locations with concentrations higher than 350 μmol/m^2 were considered for classification as hotspots. From analysis of the images, we identified 15 hotspot regions in the state of Gujarat. Most of these hotspot locations falls in industrial region such as Mundra port and petroleum refineries, while some scattered near wildlife sanctuary area of Narayan Sarovar, it was observed that the concentration of SO_2 is significantly high in the months of winter and pre-summer compared to the other months of the year. The observed SO_2 concentrations in these hotspots reaches upto ~ 1000 µmol/m^2, with an average concentration of ~ 300µmol/m^2. Minor drop in SO_2 concentration is also observed during COVID lockdown. This however proved to be a stable variation when compared for the study time period.

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