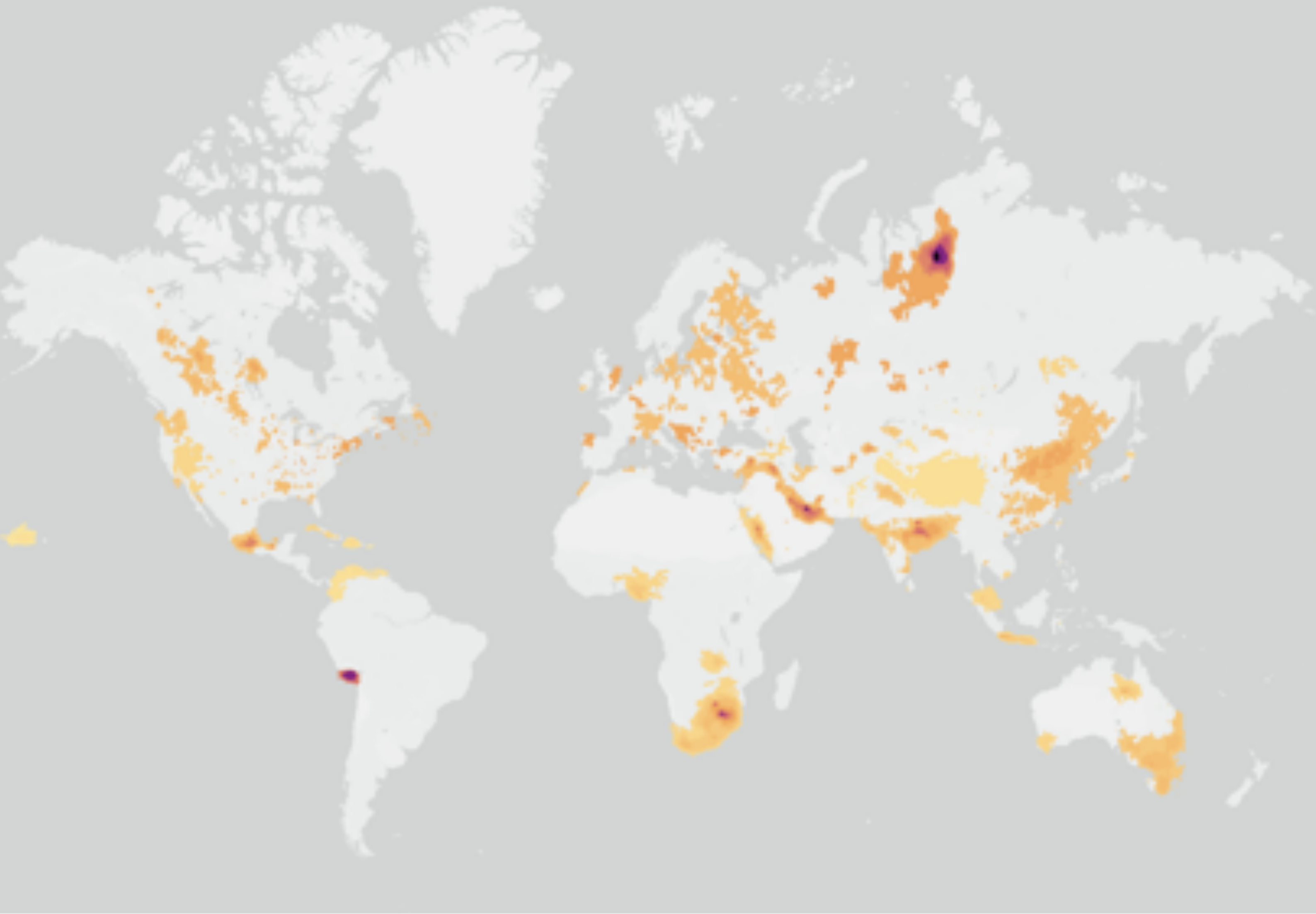
Ranking the World's Sulfur Dioxide (SO_2) Hotspots: 2019-2020

A closer look at the colourless gas that is poisoning our air and health



Centre for Research on Energy and Clean Air

GREENPEACE

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Executive summary

Sulfur dioxide (SO_2) is a colourless air pollutant that is invisible to the human eye, widespread and hazardous to human health. Breathing SO_2 increases the risk of health conditions including stroke, heart disease, asthma, lung cancer and premature death.

The single biggest source of SO_2 is from burning fossil fuels, including coal, oil and gas. Dangerous levels of SO_2 pollution are often found near coal-fired power plants, at oil refineries and in areas that are dominated by heavy industry.

Report findings

For this CREA/Greenpeace[1] report, researchers used satellite data and a global catalogue of SO_2 emissions sources from the United States National Aeronautics and Space Administration (NASA) to detect emissions hotspots. The data were analysed to identify source industries and emissions trends.

The findings indicate that anthropogenic SO_2 emissions decreased by approximately 6% worldwide in 2019. For only the second time on record, SO_2 emissions decreased in all of the top three countries with the greatest emissions: India, Russia and China. In India, emissions fell for the first time in four years because of a reduction in the use of coal.

In 2019, India emitted 21% of global anthropogenic SO_2 emissions, which was nearly twice that of the world's second largest emitter of SO_2, Russia. The primary reason for India's high emissions is the expansion of coal-based electricity generation over the past two decades.

Although China was once the world's biggest emitter of SO_2, the country's emissions have plummeted by 87% since their 2011 peak, in large part due to strengthened emissions standards and increased use of scrubbers at power plants. In 2019, China's anthropogenic SO_2 emissions fell by 5%, the slowest rate of decrease in the past decade.

South Africa also experienced a sharp decline in SO_2 emissions in 2019, bringing the country's SO_2 emissions to their lowest level on record. Further investigations are required to understand the reasons for such reductions. One of the potential factors could be the temporary reduction of coal-fired generation capacity that led to the so-called "load shedding" that year.

By contrast, SO_2 emissions rose by 14% in Turkey in 2019, one of the few countries in which emissions increased in that year. Coal-based energy production remains the major source of SO_2 emissions in Turkey.

The Norilsk smelter site in Russia was the biggest source of anthropogenic SO_2 emissions in the world in 2019. The Rabigh oil and gas hotspot in Saudi Arabia ranked second, and Zagroz in Iran ranked third.

[1] Within this report, "Greenpeace" refers to Greenpeace India, unless otherwise indicated.

In Southeast Asia, the largest SO_2 hotspot was the Suralaya coal cluster in Banten, Indonesia, followed closely by Singapore's oil and gas refineries.

Although SO_2 concentrations remain dangerously high, global SO_2 levels have continued to fall through 2020, probably because of a reduction in energy demand as a result of the COVID-19 pandemic. The largest reductions were observed in the coal and smelter sectors. In many industrial areas there was a significant drop in the amount of SO_2 detected by satellites.

Greenpeace urges governments to halt all investment in fossil fuels and shift to safer, more sustainable energy sources, such as wind and solar. At the same time, there is an urgent need to strengthen emissions standards and apply flue gas pollution control technology at power plants, smelters and other industrial SO_2 emitters.

It is encouraging that all three countries with the highest emissions reduced their emissions in 2019, but nonetheless SO_2 pollution continues to threaten the health of billions of people. The single biggest source of SO_2 is fossil fuel combustion. In most cases, new wind and solar technology is cheaper than coal, oil and gas, even before taking the cost of air pollution and climate change into account.

The solutions to air pollution are clear and widely available. Governments must prioritise renewable energy, halt investment in fossil fuels, and ensure that every person has access to safe, clean air.

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Introduction

Harmful substances are emitted when fossil fuels are burned, which has grave impacts on both the climate and public health[2,3]. Combustion processes release greenhouse gases into the air. Each year, an estimated 4.2 million people die because of exposure to ambient air pollution, and an additional 3.2 million deaths are caused by indoor and household air pollution according to an estimate by the World Health Organization (WHO) based on 2016 data[4]. Research published in 2020 that applied a refined methodology and updated risk factors for different pollutants concluded that fossil fuel combustion alone caused an estimated 4.5 million premature deaths in the 2019 and is responsible for approximately 3.3% loss to the GDP globally[5].

Sulfur dioxide (SO_2) is a toxic gas released when materials that contain sulfur, an element found in all types of coal and oil resources, are burned. The health impacts caused by the pollutant result from both direct exposure to SO_2 as well as exposure to fine particulate matter ($PM_{2.5}$)[6], which is produced when SO_2 reacts with other air pollutants. Exposure to SO_2 and $PM_{2.5}$ leads to health problems. Acute symptoms following SO_2 exposure include: a burning sensation in the nose, throat and lungs; breathing difficulties; and harm to the respiratory system. Severe, chronic health impacts include: dementia[7]; fertility problems[8]; reduced cognitive ability[9]; heart and lung disease; and premature death[10]. Researchers estimate that secondary particles (sulfates and nitrates) formed through chemical reactions from precursor gases such as SO_2 and NO_x comprise more than 10% of fine particles in China[11] and India[12], and much more during some heavy pollution episodes[13].

In addition to health impacts, every combustion process that emits SO_2 also releases substantial quantities of greenhouse gases into the atmosphere. Sources of SO_2 thus have a negative direct effect on human health as well as a negative long term impact on human wellbeing through their associated emissions of greenhouse gases, which drives global warming.

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[2] Ramanathan, V. Climate Change, Air Pollution, and Health: Common Sources, Similar Impacts, and Common Solutions. In: Al-Delaimy W., Ramanathan V., Sánchez Sorondo M. (eds) Health of People, Health of Planet and Our Responsibility. Springer, Cham. (2020). https://doi.org/10.1007/978-3-030-31125-4_5

[3] Perera, F. Pollution from Fossil-Fuel Combustion is the Leading Environmental Threat to Global Pediatric Health and Equity: Solutions Exist. *Int. J. Environ. Res. Public Health* 15(1), 16 (2017). https://doi.org/10.3390/ijerph15010016

[4] Schraufnagel, D. E. et al. Air Pollution and Noncommunicable Diseases: A Review by the Forum of International Respiratory Societies' Environmental Committee, Part 1: The Damaging Effects of Air Pollution. *Chest* 155(2), 409–416 (2019). https://doi.org/10.1016/j.chest.2018.10.042

[5] Farrow, A., Miller, K. A. & Myllyvirta, L. Toxic air: The price of fossil fuels. Seoul: Greenpeace Southeast Asia. 44 pp. February 2020.

[6] Particles with aerodynamic diameter of approximately 2.5 µm.

[7] Wu, Y.-C. et al. Association between air pollutants and dementia risk in the elderly. *Alzheimers Dement. Amst. Neth*. 1(2), 220–228 (2015). https://doi.org/10.1016/j.dadm.2014.11.015

[8] Carré, J. et al. Does air pollution play a role in infertility?: A systematic review. *Environ. Health* 16, 82 (2017). https://doi.org/10.1186/s12940-017-0291-8

[9] Shehab, M.A. & Pope, F.D. Effects of short-term exposure to particulate matter air pollution on cognitive performance. *Sci. Rep.* 9, 8237 (2019). https://doi.org/10.1038/s41598-019-44561-0

[10] Cohen, A. J. et al. Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015. *Lancet* 389(10082), 1907–1918 (2017). https://doi.org/10.1016/S0140-6736(17)30505-6

[11] Huang, R. J. et al. High secondary aerosol contribution to particulate pollution during haze events in China. *Nature*, 514(7521), 218–222 (2014). https://doi.org/10.1038/nature13774

[12] Nagar, P.K. et al. Characterization of PM2.5 in Delhi: role and impact of secondary aerosol, burning of biomass, and municipal solid waste and crustal matter. *Environ. Sci. Pollut. Res.* 24(32), 25179–25189 (2017). https://doi.org/10.1007/s11356-017-0171-3

[13] Wang, G. et al. Persistent sulfate formation from London Fog to Chinese haze. *PNAS USA* 113(48), 13630–13635 (2016). https://doi.org/10.1073/pnas.1616540113

According to NASA MEaSUREs data catalogue more than two-thirds (68%) of SO_2 emissions have anthropogenic origin. SO_2 is primarily emitted by industrial facilities that burn fossil fuels, either to generate electric power or to extract metal from ore (smelter). Other anthropogenic sources are locomotives, ships and other vehicles or heavy equipment that burn fuel with a high sulfur content.

Volcanoes are the only major natural source of SO_2, accounting for less than one-third (32%) of present-day SO_2 emissions.

By documenting and understanding the global sources of SO_2 emissions, measures can be put in place to stop SO_2 pollution, reduce the health impacts of air pollution and expose the toxic consequences of fossil fuel use. This CREA/Greenpeace report investigates the sources and geographical distribution of the industries responsible for major SO_2 emissions that have been identified by the United States National Aeronautics and Space Administration (NASA) across the globe.

Methodology

Human-maintained catalogues of pollutant emissions sources, such as the Emission Database for Global Atmospheric Research (EDGAR) inventory[14], are sometimes incomplete or out of date. The reasons for incomplete data sets include: the source may be new; the strength of the emissions may have changed since the previous revision; or the source may be unknown or unreported. This CREA/Greenpeace report analyses a global catalogue by NASA MEaSUREs which lists SO_2 emissions sources that have been derived from satellite-based observations. The regions and industry sectors responsible for major SO_2 emissions are identified in the catalogue and emissions trends are assessed through time. The use of satellite data to detect and quantify major point sources of SO_2 provides annually updated, near worldwide data coverage that is not reliant on emissions reporting on the ground.

OMI and MEaSUREs SO_2 emission catalogue

The NASA Ozone Monitoring Instrument (OMI), a satellite-based device, has been monitoring air quality from space since 2004 with high consistency. The NASA Making Earth System Data Records for Use in Research Environments (MEaSUREs) programme uses the measurements to detect and quantify major point sources of SO_2 emissions across the globe[15]. Satellite observations estimate the amount of SO_2 in the atmosphere above a point on the Earth's surface, which is used to identify pollution hotspots (**Box 1**). NASA uses a technique based on a comparison of upwind and downwind SO_2 levels to make a quantitative estimate of emissions rates for each hotspot. The emissions estimates are validated against *in situ* measurements in the United States and the European Union (EU)[16, 17]. Because the technique does not rely on an *a priori* knowledge of source locations, it also detects new sources or those that are missing from other emission inventories. NASA's worldwide observation coverage makes it possible to identify global pollution hotspots[18].

The NASA MEaSUREs SO_2 emissions source catalogue provides the geographical location and rates of emissions for hotspots for each calendar year. The catalogue is used to group the detected sources into four categories: one natural category (volcanoes) and three anthropogenic categories: power plant, oil and gas, and smelter. A complete list of all anthropogenic SO_2 emissions hotspots identified by OMI (NASA_Aura Satellite) can be found here.

[14] European Commission, Joint Research Centre (JRC)/Netherlands Environmental Assessment Agency (PBL). Emission Database for Global Atmospheric Research (EDGAR), release version 4.3.1 http://edgar.jrc.ec.europa.eu/overview.php?v=431, 2016.

[15] National Aeronautics and Space Administration. MEaSUREs SO_2 source emission catalogue. Retrieved from https://so2.gsfc.nasa.gov/measures.html on Sept 14, 2020.

[16] Fioletov, V. et al. Multi-source SO2 emission retrievals and consistency of satellite and surface measurements with reported emissions. *Atmos. Chem. Phys*. 17, 12597–12616 (2017). https://doi.org/10.5194/acp-17-12597-2017

[17] Fioletov, V. et al. Multi-Satellite Air Quality Sulfur Dioxide (SO2) Database Long-Term L4 Global V1, Greenbelt, MD, USA, Goddard Earth Science Data and Information Services Center (GES DISC) (2019). Accessed Sept 23, 2020. https://doi.org/10.5067/MEASURES/SO2/DATA403

[18] Fioletov, V. E. et al. A global catalogue of large SO2 sources and emissions derived from the Ozone Monitoring Instrument. *Atmos. Chem. Phys*. 16, 11497–11519 (2016). https://doi.org/10.5194/acp-16-11497-2016.

What are SO_2 emissions and what is SO_2 column amount?

Emission rate:

The **emission** or **emission rate** describes the quantity of a pollutant (for example, SO_2) that is released into the atmosphere by a certain source within a certain time period. The most important sources for SO_2 emissions are coal-fired power stations, smelter sites, the oil and gas industry and volcanoes. Units of emission include 'kilograms per hour', 'kilotonnes per year' and 'megatonnes per year'. The quantity or 'emission (rate)' is only meaningful for sources of SO_2 and not for locations away from the sources.

Column amount

The **boundary layer column amount,** which is abbreviated to **column amount**, is the total amount of an air pollutant that is present in the lowest layer of the Earth's atmosphere, which is called the 'planetary boundary layer'[19]. For example, this could be all the SO_2 pollution that is found in the (virtual) column of air above a 1 km square area between the Earth's surface and the top of the boundary layer. Column amount is the quantity of pollutant that satellite instruments usually measure because those instruments can penetrate the entire thickness of the atmosphere. Units for recording the quantity of air pollutants are 'kilograms per square metre' or the special unit, Dobson unit (DU). Because SO_2 sources are located at the Earth's surface, they emit into the boundary layer. In general, there is little vertical mixing from the boundary layer into the atmospheric layers above. The biggest part of the SO_2 pollution remains within the boundary layer before it sediments or converts into other chemicals.

What is the relationship between emission rate and column amount?

Emitted pollutants are dispersed in the atmosphere and transported to locations away from the source through wind and turbulence, before they sediment or convert into other chemicals. Therefore, locations that are far from emission sources may also become polluted. In general, air is more likely to be polluted in the proximity of an emission source than far away from it. On a map, emission sources are usually surrounded by an area of high column amount.

Column amount can be used as a proxy for emission, but it is important to note that the two are not the same thing. For example, a strong wind will blow pollution away from an emitting source, even if emissions are high. The area close to the source of the emissions will thus have a relatively low column amount. However, using annual emission means averages out data anomalies caused by meteorological events such as high wind. On the map of annual mean emissions, virtually all hotspots are surrounded by areas with high column amounts of SO_2.

Box 1: *Definition of SO_2 emission rate and SO_2 column amount.*

[19] The planetary boundary layer has a thickness of up to a few kilometers. The thickness varies depending on the time and global location. The planetary boundary layer is also known as the atmospheric boundary layer.

Limitations of satellite-based SO_2 observations and emission estimates

Data coverage

Satellite-based approaches for detecting and quantifying major point sources of SO_2 provide near continuous worldwide data coverage. However the satellites are limited by data resolution, noise and artifacts and so only large SO_2 sources are detected and quantified reliably; sources that emit less than ~50 kt/yr tend to have large relative uncertainties[20]. NASA estimates that sources emitting less than 30 kt/yr are not reliably detected and that the MEaSUREs catalogue accounts for about half of all known anthropogenic SO_2 emissions worldwide[21]. The detection ratio is relatively constant for most large countries and regions (50±15%) when compared to bottom-up emission inventories across different regions. Therefore, the dataset can be used to detect regional emissions trends even though the absolute values of emissions estimates do not necessarily equate to the total emissions from a country or region.

Data uncertainty

The precision of emissions estimates varies from one hotspot to another. Uncertainty in the underlying satellite data increases in the high latitudes, reducing confidence in estimates for hotspots in these regions. For hotspots with low emissions, catalogue estimates of the emission amount are not reliable because the uncertainty range may be as large as the value itself. For the country totals presented in the main part of this report, all hotspots listed in the catalogue are taken into account. When calculating country totals it is assumed that the uncertainty ranges given by NASA are meaningful even for small emission values and the errors between different hotspots are not correlated (no systematic error).

South America: the South Atlantic Anomaly

An additional source of uncertainty of particular importance is the South Atlantic Anomaly (SAA) (**Fig. 1**). The SAA affects an area covering part of South America and the southern Atlantic Ocean. Above this area the Earth's magnetic field traps high-energy charged particles and these particles substantially decrease the quality of OMI sensor measurements, thereby increasing the uncertainty in emission estimations[22]. As a consequence, the emissions data for Argentina, Brazil, Chile, Peru, Bolivia, Paraguay and Uruguay (the latter three are completely absent in the data set) cannot claim the same accuracy and completeness that prevail in other regions of the world. NASA advises to treat data from the South America and the southern Atlantic Ocean region with caution.

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[20] See full hotspot list.

[21] Fioletov, V. E. et al. A global catalogue of large SO2 sources and emissions derived from the Ozone Monitoring Instrument. *Atmos. Chem. Phys*. 16, 11497–11519 (2016). https://doi.org/10.5194/acp-16-11497-2016

[22] Zhang, Y. et al. Continuation of long-term global SO2 pollution monitoring from OMI to OMPS. *Atmos. Meas. Tech*. 10, 1495–1509 (2017). https://doi.org/10.5194/amt-10-1495-2017

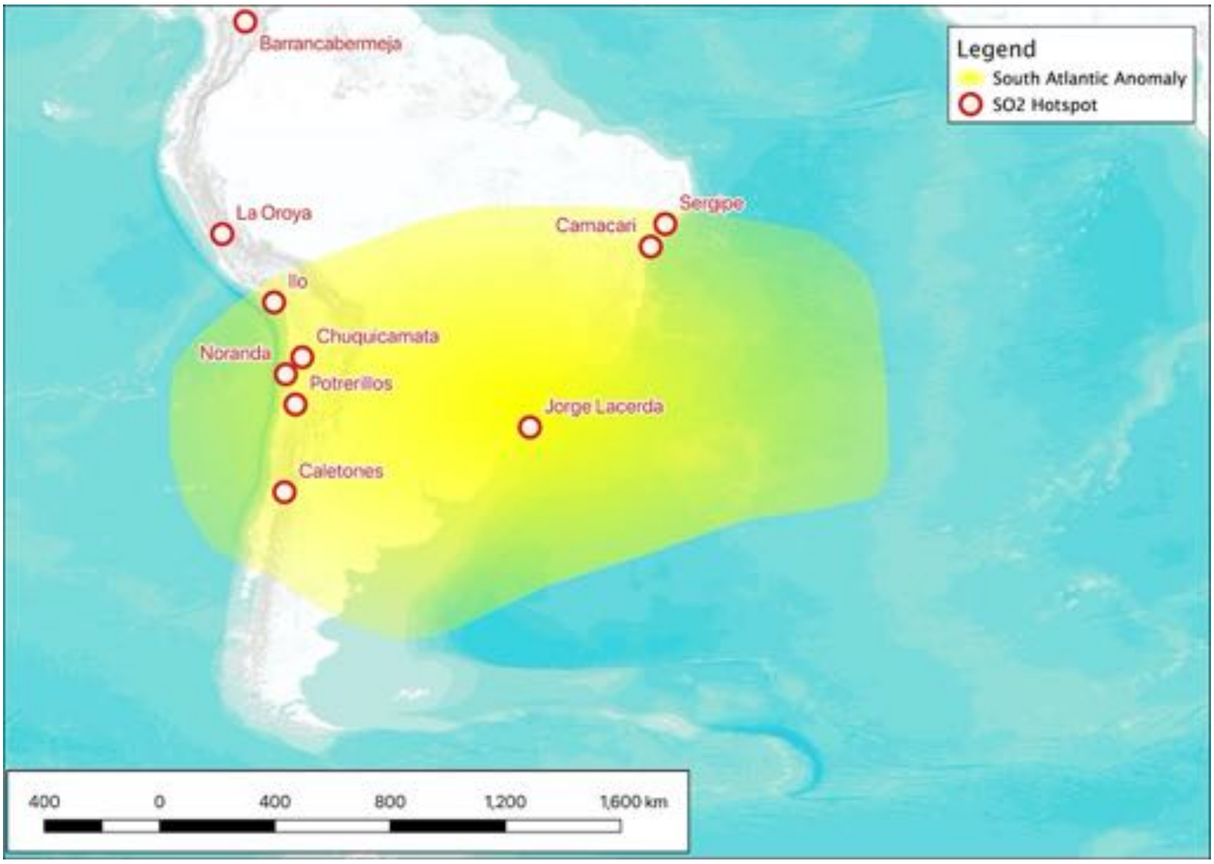

Figure 1. *Visualisation of the area affected by the South Atlantic Anomaly (yellow area) derived from figures and descriptions presented in Zhang et al (2017)*[23] *and Royal Belgian Institute for Space Aeronomy*[24]*. Affected* SO_2 *hotspots are shown in red. Data from the region covered by the anomaly must be used with caution. Sources of sulfur dioxide that exist in the South America Anomaly may not be detected. Map data copyrighted OpenStreetMap contributors and available from https://www.openstreetmap.org*

Source type reclassification and renaming

The original NASA MEaSUREs data set provides a name and source type for each hotspot. Source types are either 'power plant', 'oil and gas', 'smelter' or 'volcano'. The dominant industry of a hotspot cluster may have changed over the years since first publication in 2005, but the change may not be reflected in the source type classification in NASA's catalogue.

In this CREA/Greenpeace report, classifications and names in the catalogue have been updated when source sectors are known to have changed or when hotspot naming is not intuitive. The following modifications are made:

- **Reclassification.** The NASA source type 'power plant' is replaced with the source type 'coal' if it is a coal-fired power plant, or replaced with 'oil and gas' for gas-fired power plants/stations. A manual review of all listed anthropogenic hotspots in the original catalogue was carried out and (re)classified as 'coal', 'oil and gas' or 'smelter'.

[23] Zhang, Y. et al. Continuation of long-term global SO_2 pollution monitoring from OMI to OMPS. *Atmos. Meas. Tech*. 10, 1495–1509, (2017). https://doi.org/10.5194/amt-10-1495-2017

[24] Royal Belgian Institute for Space Aeronomy. 2011. https://sacs.aeronomie.be/info/saa.php (Accessed: 28.09.2020)

- **Secondary industries.** Hotspots can in reality be an aggregation of multiple individual nearby SO_2 sources from more than one industry. In such cases, information describing secondary industries was added to better represent the contributions of individual emitters within a larger hotspot, rather than just that of the biggest emitter. The secondary information is contained in the final data set. Rankings, however, are performed based on the principal source type.
- **Renaming.** In some cases, the hotspots in the catalogue have been renamed so that they are more readily identifiable to the reader. The names of the principal polluters are used where NASA has used a company name, and this is the only identifiable source in the region, this naming choice has been left unchanged. In cases where additional potential sources were identified, the name of the geographical region is used instead.

All modifications are documented in the full hotspot list.

Rankings

We used the modified catalogue to rank countries by SO_2 emissions at key hotspots. We also ranked the emissions clusters themselves according to their annual emissions of anthropogenic SO_2.

Interactive pollution map

An interactive map showing the raw OMI SO_2 column amounts together with the locations of the SO_2 emission sources listed in the NASA catalogue is available at energyandcleanair.github.io/202008_hotspots/ (see **Box 1** for the difference between column amount and emission rate). **Fig. 2** shows a screenshot of the map.

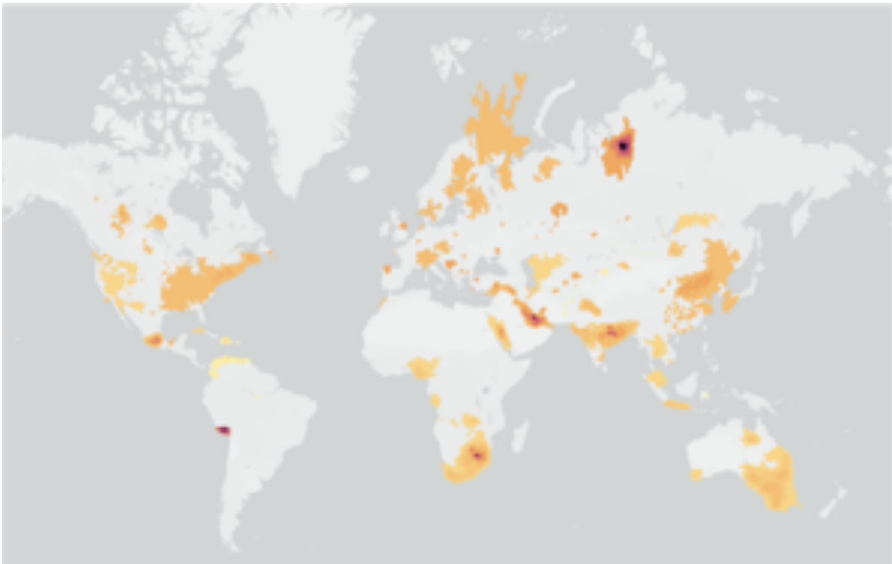

Figure 2: *Column amount of SO_2 detected by the Ozone Monitoring Instrument (OMI) sensor in 2019. The interactive map can be found at https://energyandcleanair.github.io/202008_hotspots/*

Concentrations analysis in 2020

Global emissions data for 2020 has not yet been made available by the NASA MEaSUREs project. Therefore, observed SO_2 column amounts are analysed as an indirect indicator of SO_2 emissions. The column amount data (expressed in Dobson units) were retrieved from the NASA OMI sensor in a 50 km radius around each individual hotspot.

SO_2 column amount data only provide an indirect indication of SO_2 emissions because the relationship between an observed column amount and the source emission amount is affected by weather conditions and pollutant dispersion. Nevertheless, analysis of observed SO_2 column amounts from 2020 can help to identify the most recent trends (see section: **2020 trends**).

In this CREA/Greenpeace analysis, anthropogenic SO_2 is estimated from the column amounts observed by the satellite, which includes both anthropogenic and volcanic SO_2. The raw observations are filtered using thresholds specified in the NASA MEaSUREs methodology to estimate the anthropogenic SO_2[25].

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[25] Fioletov, V. E. et al. A global catalogue of large SO2 sources and emissions derived from the Ozone Monitoring Instrument. *Atmos. Chem. Phys.* 16, 11497–11519 (2016). https://doi.org/10.5194/acp-16-11497-2016

Results and analysis

In 2019, more than two-thirds (68%) of total emissions detected by the MEaSUREs programme were caused by human activity. Anthropogenic sources of SO_2 are found in locations that have high fossil fuel consumption (coal burning, oil refining and combustion) or host smelter sites.

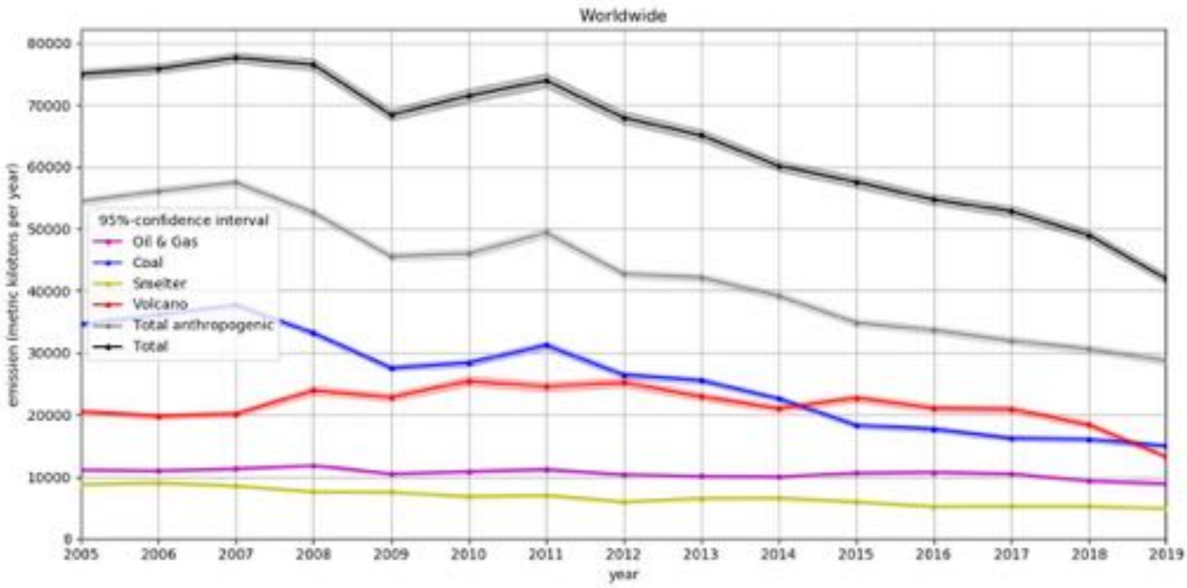

Figure 3. *Global contributions of major industry sectors and natural sources (volcanoes) to total SO_2 emissions from 2005 to 2019 (in kilotonnes per year). Data source: NASA MEaSUREs.*

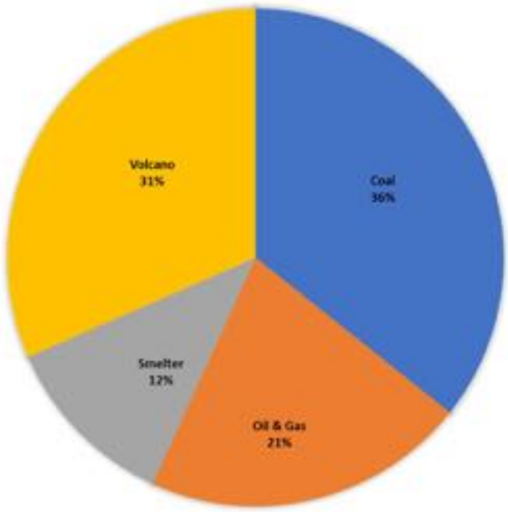

Figure 4: *Global contributions of major industry sectors and natural sources (volcanoes) to total SO_2 emissions in 2019 (in kilotonnes per year). Data source: NASA MEaSUREs.*

Locations dominated by coal combustion for power generation and industries accounted for 36%, those dominated by oil and gas refining or combustion for 21% and those dominated by smelters for 12% of the worldwide anthropogenic SO_2 emissions (**Fig. 3, Fig. 4, Table 1**).

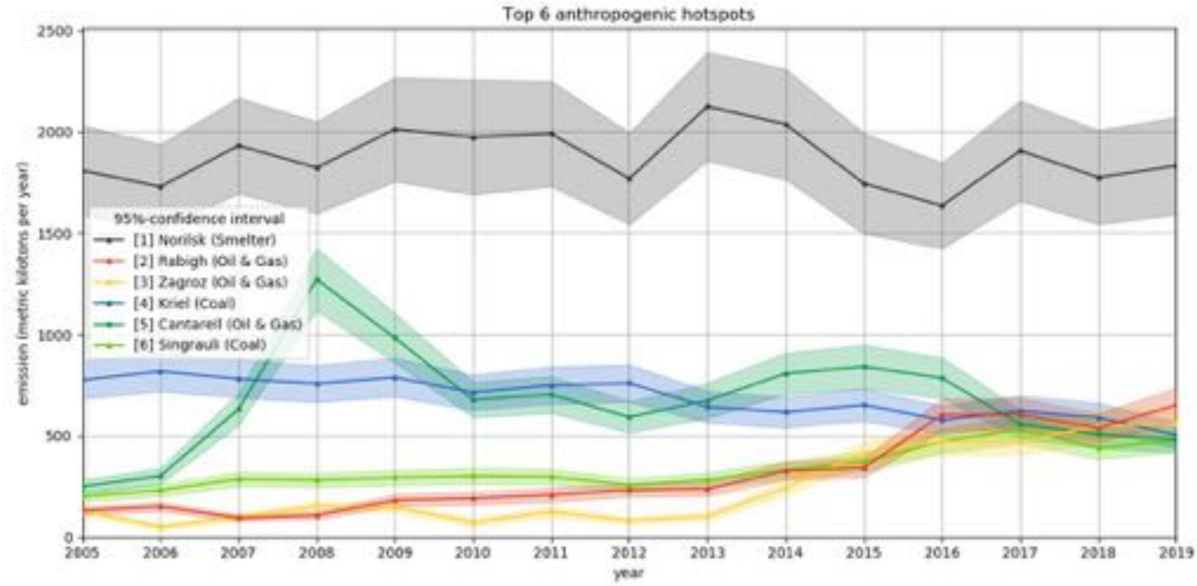

Figure 5*. The contributions of the six largest anthropogenic SO_2 emissions sources from 2005 to 2019 (in kilotonnes per year). Data source: NASA MEaSUREs.*

The Norilsk (Норильск) smelter site in Russia continues to be the largest anthropogenic SO_2 emission hotspot in the world[26], followed by the Rabigh (Saudi Arabia) and Zagroz (Iran) oil and gas hotspots and the Kriel coal burning area in the Mpumalanga province in South Africa (**Fig. 5, Table 2**). Other countries that have high coal consumption or oil and gas refining and combustion, such as Cantarell (Mexico) and Singrauli[27] (India), have high SO_2 emissions primarily because they have high fossil-fuel consumption and slow implementation of stringent emission standards.

[26] In many cases, the total emissions for a region cannot be attributed to an exact source because emissions from large sources may obscure those of other smaller contributors in the nearby vicinity. Where multiple industries are present in the cluster, we take the largest sources (coal; oil and gas or smelter) to represent all other sources.

[27] Named 'Vindhyachal' in the original NASA catalogue.

Table 1: *Global contributions of major industry sectors and natural sources (volcanoes) to total SO_2 emissions in 2018 and 2019 (in kilotonnes per year). Data source: NASA MEaSUREs.*

SO_2 Emissions in 2018 & 2019 (kt/year) from all sources.		
Source	**2018**	**2019**
Coal	16,038	14,972
Oil & Gas	9,337	8,850
Smelter	5,229	4,883
Volcano	18,384	13,227
Total	48,987	41,932

Table 2: *The top 50 anthropogenic SO_2 emission hotspots. Data source: NASA MEaSUREs (partially renamed and/or reclassified, as described above).*

Rank	Hotspot	Country / Region	Source type	Emissions 2019 (kt) (95%-confidence interval)		
				best estimate	low estimate	high estimate
1	Norilsk	Russia	Smelter	1,833	1,598	2,068
2	Rabigh	Saudi Arabia	Oil & Gas	652	569	735
3	Zagroz	Iran	Oil & Gas	558	484	632
4	Kriel	South Africa	Coal	504	443	564
5	Cantarell	Mexico	Oil & Gas	482	420	544
6	Singrauli	India	Coal	479	420	538
7	Reforma	Mexico	Oil & Gas	415	349	481
8	Ilo	Peru	Smelter	414	338	489
9	Matimba	South Africa	Coal	362	319	406
10	Al Doha	Kuwait	Oil & Gas	351	307	395
11	Kemerkoy	Turkey	Coal	328	280	376
12	Afsin Elbistan	Turkey	Coal	307	266	348
13	Shaiba	Saudi Arabia	Oil & Gas	301	260	342
14	Neyveli	India	Coal	299	260	338
15	Fereidoon	Saudi Arabia	Oil & Gas	291	243	339
16	Sarcheshmeh	Iran	Smelter	289	253	326
17	Korba	India	Coal	282	244	320
18	Das Island	United Arab	Oil & Gas	271	229	312

		Emirates				
19	Mubarek	Uzbekistan	Oil & Gas	245	212	278
20	Jeddah	Saudi Arabia	Oil & Gas	233	197	268
21	Talcher	India	Coal	221	189	253
22	Mt Isa	Australia	Smelter	208	180	237
23	Tula	Mexico	Oil & Gas	200	170	230
24	Nikola Tesla	Serbia	Coal	197	158	236
25	Almalyk	Uzbekistan	Smelter	188	162	215
26	Kurakhovskaya	Ukraine	Coal	180	142	218
27	Visakhapatnam	India	Coal	172	141	203
28	Maritsa East industrial complex	Bulgaria	Coal	170	135	205
29	Mundra	India	Coal	164	135	193
30	Khangiran	Iran	Oil & Gas	162	139	185
31	Kutch	India	Coal	161	136	186
32	Koradi	India	Coal	158	134	182
33	Zhezkazgan	Kazakhstan	Coal	155	125	185
34	Jubail	Saudi Arabia	Oil & Gas	154	128	180
35	Majuba	South Africa	Coal	149	125	173
36	Chennai	India	Coal	142	119	166
37	Vuglegirska	Ukraine	Coal	138	100	177
38	Ekibastuz	Kazakhstan	Coal	137	96	179
39	Pavlodar	Kazakhstan	Coal	136	96	175
40	Chandrapur, Maharashtra	India	Coal	135	115	156
41	Lethabo	South Africa	Coal	135	114	156
42	Baghdad	Iraq	Oil & Gas	134	113	155
43	Tuzla	Bosnia and Herzegovina	Coal	132	99	165
44	Tuxpan	Mexico	Oil & Gas	130	103	158
45	Nuevitas	Cuba	Oil & Gas	130	104	156

46	Suralaya	Indonesia	Coal	128	108	149
47	Singapore	Singapore	Oil & Gas	127	102	152
48	Wuan	China	Coal	125	100	151
49	Nicaro	Cuba	Smelter	125	100	150
50	Novocherkassk	Russia	Coal	121	77	165

Countries have different levels of SO_2 emissions (**Fig. 6; Table 2**) depending on the presence of emitting industries and the stringency and enforcement of emissions regulations. The largest sources of SO_2 pollution are discussed below; the full data set can be explored in an interactive map at: https://energyandcleanair.github.io/202008_hotspots/

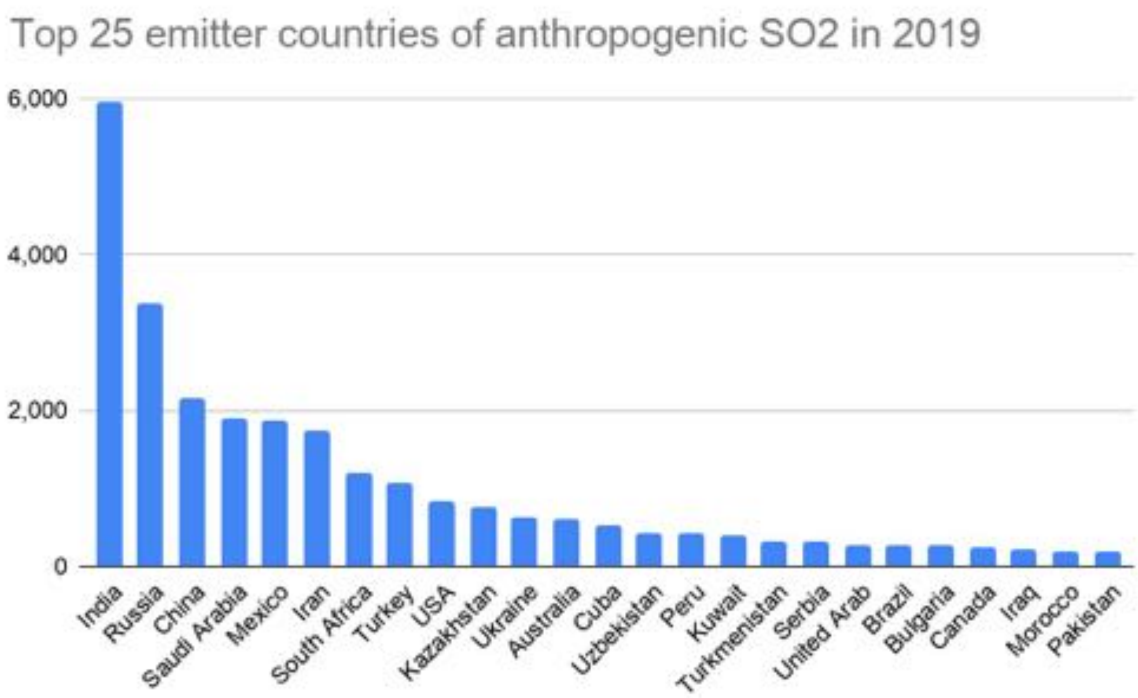

Figure 6: *The 25 countries that emitted the greatest amount of anthropogenic SO_2 in 2019 (kilotonnes per year). Data source: NASA MEaSUREs.*

Table 3: *The 25 countries that emitted the greatest amount of anthropogenic SO_2 (kt/yr) in 2018 and 2019, estimated by NASA[28]. See **Table A1** and **Table A2** for uncertainty ranges and wording scheme. Data source: NASA MEaSUREs.*

Rank	Country / Region	2018	2019	Relative change	Direction of change	Confidence in direction of change
-	worldwide	30,604	28,704	-6%	down	virtually certain
1	India	6,329	5,953	-6%	down	virtually certain
2	Russia	3,635	3,362	-8%	down	likely
3	China	2,263	2,156	-5%	down	likely
4	Saudi Arabia	1,861	1,910	3%	uncertain	
5	Mexico	1,809	1,873	4%	up	likely
6	Iran	1,977	1,746	-12%	down	virtually certain
7	South Africa	1,388	1,187	-15%	down	virtually certain
8	Turkey	938	1,072	14%	up	very likely
9	United States	864	823	-5%	uncertain	
10	Kazakhstan	776	760	-2%	uncertain	
11	Ukraine	861	628	-27%	down	virtually certain
12	Australia	627	610	-3%	uncertain	
13	Cuba	543	530	-2%	uncertain	
14	Uzbekistan	319	433	36%	up	virtually certain
15	Peru	396	414	5%	uncertain	
16	Kuwait	394	396	1%	uncertain	
17	Turkmenistan	251	325	30%	up	virtually certain
18	Serbia	349	309	-12%	down	likely
19	United Arab Emirates	419	271	-35%	down	virtually certain
20	Brazil	205	262	28%	up	likely
21	Bulgaria	263	258	-2%	uncertain	
22	Canada	187	240	28%	uncertain	
23	Iraq	370	223	-40%	down	virtually certain
24	Morocco	171	197	15%	up	likely
25	Pakistan	235	180	-23%	down	very likely

[28] The figures for Brazil and Peru must be considered with caution; see discussion about the South Atlantic Anomaly in the Methods section.

Geographical regions

The following section provides an overview of the regions that are responsible for some of the world's highest global SO_2 emissions. Reasons for the high emissions together with emissions trends and how those emissions may change in the future are suggested.

India

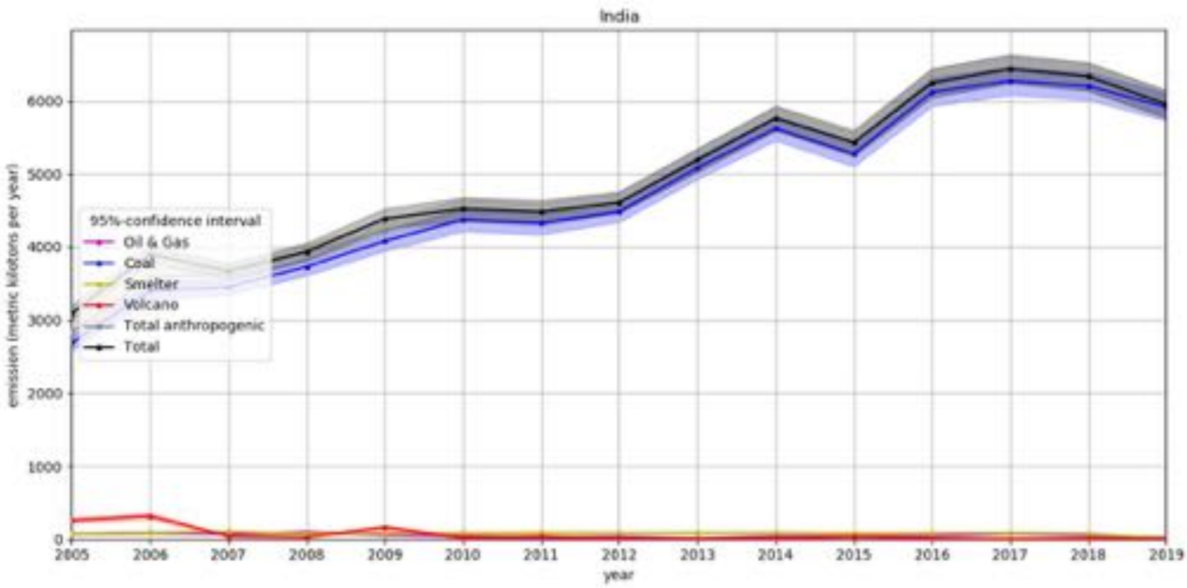

Figure 7: *Contributions of major industry sectors and natural sources (volcanoes) to total SO_2 emissions from 2005 to 2019 in India (kilotonnes per year). Data source: NASA MEaSUREs (partially reclassified, as described above).*

India is the largest emitter of SO_2 in the world, contributing more than 21% of global anthropogenic SO_2 emissions according to the NASA MEaSUREs catalogue. India's SO_2 emissions decreased by approximately 6% in 2019, the first decrease in four years. Despite the decrease, India's emissions remain very high. The primary reason for India's high emissions is the expansion of coal-based electricity generation over the past two decades (**Fig. 7**). The majority of power stations in India lack flue-gas desulfurization technology to reduce the emission of air pollutants. The biggest emission hotspots in the country are thermal power stations (or clusters of power stations): Singrauli[29], Neyveli, Sipat, Mundra, Korba, Bonda, Tamnar, Talcher, Jharsuguda, Korba, Kutch, Chennai, Ramagundam, Chandrapur and Koradi.

[29] Named 'Vindhyachal' in the original NASA data set.

In a first step to address rising air pollution levels, the Ministry of Environment, Forest and Climate Change (MoEF&CC) introduced SO_2 emission limits for coal-fired power stations for the first time in December 2015. However, the deadline of December 2017 for the installation of flue-gas desulfurization in power stations was shifted to 2022 after all units failed to install the technology within the given time frame[30]. According to reports, most power stations with phasing timelines (staggered timeline for different units) until June 2020 failed to install flue-gas desulfurization even with the extended timeline and are currently operating without compliance to standards.[31] Most other power stations are at risk of being non-compliant because they have made very little progress to comply with the phasing timeline before the December 2022 deadline[32].

This year, the Indian government has advised to close down old thermal power stations that do not meet the emission standards[33] and also allocated 4,400 crores (about US$600 million) to address the air pollution crisis.[34]. On the positive side, India has begun its green energy transition and has set itself one of the world's most ambitious renewable energy targets. The country has taken several steps to boost the renewable energy sector. The renewable energy capacity has been increasing in India's power sector, delivering more than two-thirds of India's new capacity additions during the fiscal 2019/2020 year[35].

[30] Patel, D. Toxic sulphur dioxide norms: 90% coal power plants not compliant. The Indian Express. Available at: https://indianexpress.com/article/india/toxic-sulphur-dioxide-norms-90-coal-power-plants-are-not-compliant-4878396/

[31] MoEF&CC. The Gazette of India: Extraordinary. Part II, Section 3, Sub-section (ii) S.O. 3305(S). New Delhi 2016. Available at: http://moef.gov.in/wp-content/uploads/2017/08/Thermal_plant_gazette_scan.pdf

[32] 70% power plants won't meet emission standards by 2022 deadline: CSE. The Hindu. Available at: https://www.thehindu.com/sci-tech/energy-and-environment/70-power-plants-wont-meet-emission-standards-by-2022-deadline-cse/article31642317.ece

[33] MoEF&CC. The Gazette of India: Extraordinary. Part II, Section 3, Sub-section (ii) S.O. 3305(S). New Delhi 2016. Available at: http://moef.gov.in/wp-content/uploads/2017/08/Thermal_plant_gazette_scan.pdf

[34] Sinha, A. & Ashok, S. 'Union Budget: Old, polluting coal power stations to be closed, says FM' news report published on Feb. 2, 2020. The indian Express. Available at: https://indianexpress.com/article/india/union-budget-old-polluting-coal-power-stations-to-be-closed-says-fm-6246629/ [accessed Sept. 23, 2020].

[35]Garg, V. 'IEEFA India: Investment trends in renewable energy 2019/20' news report published on June 9, 2020. Available at: https://ieefa.org/ieefa-india-investment-trends-in-renewable-energy-2019-20/ [accessed Sept. 23, 2020].

Russia

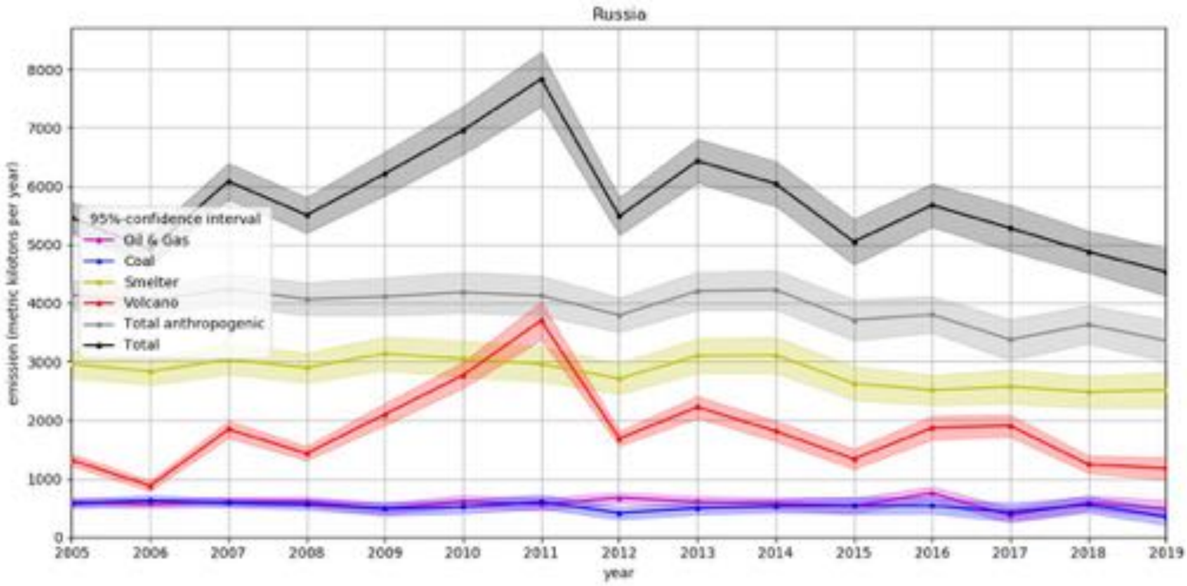

Figure 8: *Contributions of major industry sectors and natural sources (volcanoes) to total SO_2 emissions from 2005 to 2019 in Russia (kilotonnes per year). Data source: NASA MEaSUREs (partially reclassified, as described above).*

Russia emits approximately 12% of global anthropogenic SO_2 emissions and is the second largest SO_2 emitter, after India. Russia's anthropogenic SO_2 emissions have remained relatively constant over the past 15 years, with drops in one year usually being cancelled out by a rebound the following year. Data show a slight long-term downward trend in emissions of about 10% per decade. In 2019, Russia decreased its anthropogenic SO_2 emissions by about 8% compared to the previous year and reached its lowest value in the 15-year record. According to NASA estimates, coal hotspots are responsible for two thirds of this decrease, and oil and gas the remaining third, while smelter emissions slightly increased. This reduction of emissions could be partly explained by the decrease of coal-fired power generation in 2019 (-4%) as well as the oil-refinery throughput (-0.6%)[36].

Smelters are the biggest SO_2 emitting industry sector in the country, with nearly 75% of anthropogenic emissions, followed by oil and gas (15%), and coal (10%) (**Fig. 8**). The Arctic smelter site Norilsk remains by far the largest SO_2 emissions hotspot worldwide and is responsible for more than 50% of Russia's total anthropogenic SO_2 emissions. Novocherkassk, Nikel[37] and Kirovgrad are also major SO_2 hotspots in Russia, hosting smelters, gas refineries and coal combustion facilities for power and industries.

Note that significant uncertainty in NASA estimates remains. Satellite retrievals of SO_2 levels are only available four months per year at certain hotspots, including Norislk and Nikel, due to their high latitude. This uncertainty is compounded by the fact that official figures indicate total anthropogenic SO_2 emissions remained constant in 2019 (+0.3%)[38].

[36] BP, Statistical Review of World Energy 2019. Available at https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html
[37] Mis-spelled as Nickel in the NASA database.
[38]This figure includes all sources of anthropogenic SO_2, beyond the industrial clusters considered by NASA.Federal State Statistics Service. Available at https://rosstat.gov.ru/folder/11194

China

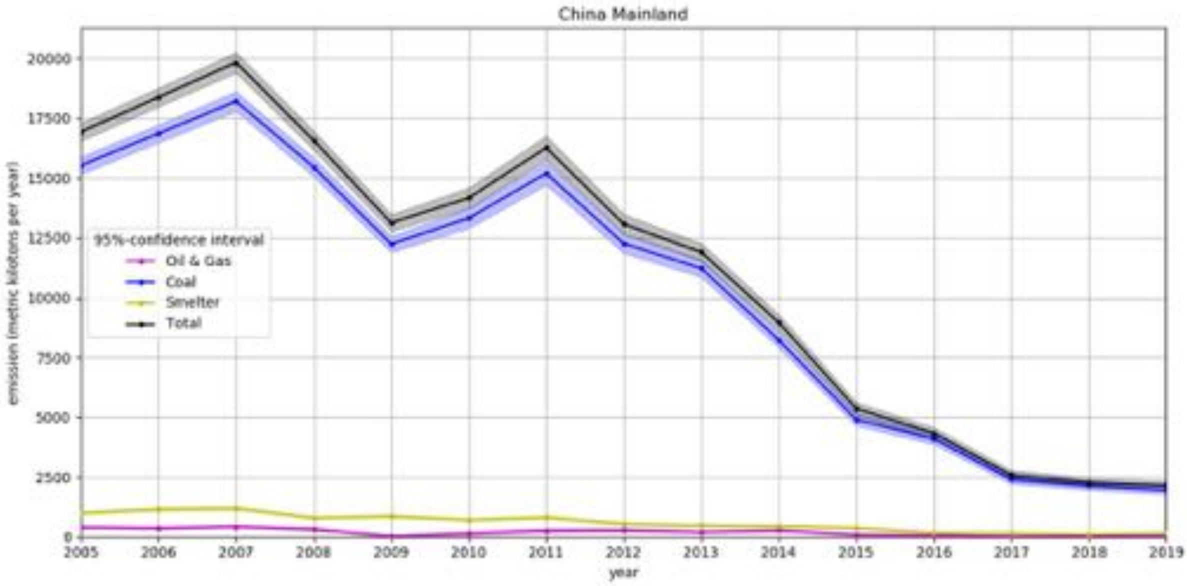

Figure 9: *Contributions of major industry sectors to total SO_2 emissions from 2005 to 2019 in China (kilotonnes per year). Data source: NASA MEaSURES (partially reclassified, as described above).*

China emitted approximately 8% of global anthropogenic SO_2 in 2019 and is the world's third largest emitter of SO_2. Until 2010, China was the world's biggest SO_2 emitter because it had the largest coal-fired power generation capacity in the world. Since it began installing flue-gas desulfurization systems across the electricity generation sector and implementing so-called Ultra-Low Emission standards – an emissions rate that is close to gas generators – China has made significant progress to reduce air pollution. By the end of 2018, 80% of China's coal power fleet had been retrofitted to meet Ultra-Low Emission standards[39], a figure that increased to 86% by the end of 2019[40]. China's SO_2 emissions have plummeted by 87% since their 2011 peak. In 2019, China's anthropogenic SO_2 emissions fell by 5%, the slowest rate of decrease in the past decade (**Fig. 9**). There is potential for a further reduction in emissions because China is expanding its Ultra-Low Emission standards from the coal power sector to steel and cement. However, air quality in China still remains far from WHO recommended levels[41], indicating the fundamental need to accelerate the country's transition away from fossil fuels.

[39] China Electricity Council, China Power Sector Development Annual Report 2019. Available at: https://cec.org.cn/detail/index.html?3-163895 [accessed Sept. 23, 2020].

[40] China Electricity Council, China Power Sector Development Annual Report 2020. Available at: https://www.cec.org.cn/detail/index.html?3-284218 [accessed Sept. 23, 2020].

[41] The Beijing News, Opinion on Air Quality data, published on June 6, 2019. Available at: http://www.bjnews.com.cn/opinion/2019/06/06/587991.html

Saudi Arabia

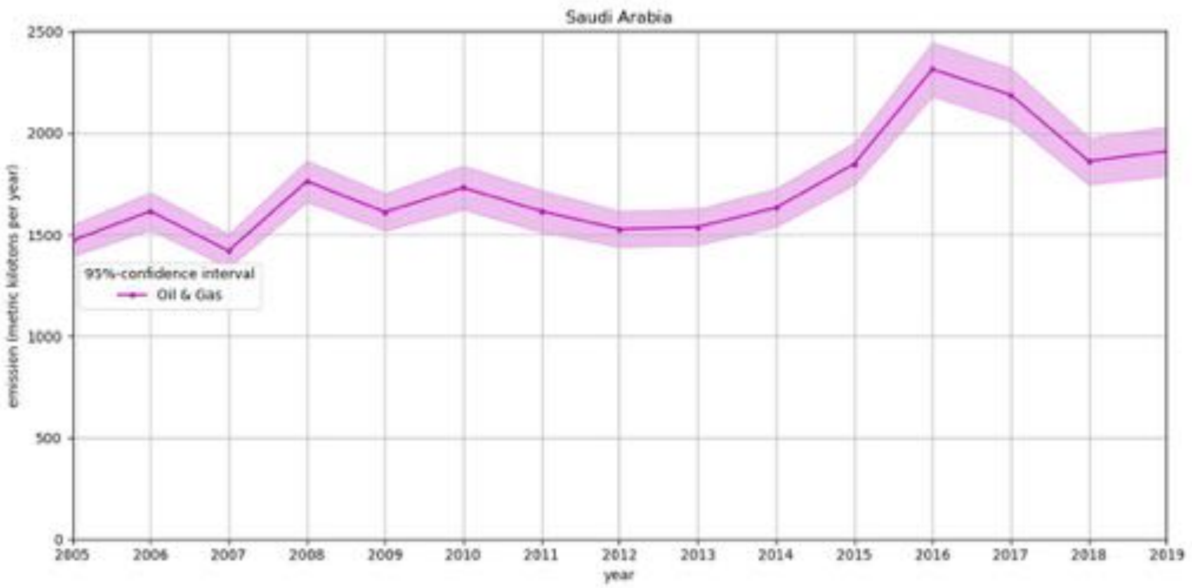

Figure 10: *Contributions of major industry sectors to total SO_2 emissions from 2005 to 2019 in Saudi Arabia (kilotonnes per year). Data source: NASA MEaSUREs.*

Saudi Arabia is the fourth largest emitter of SO_2 in the world and the largest in the Middle East and North Africa region. After strong decreases in 2017 and 2018, Saudi Arabia's SO_2 emissions remained almost constant with an indication of slight increase in 2019[42].

Emissions listed in the data set are entirely due to oil and gas combustion (**Fig. 10**). Makkah, one of the most populated provinces in the country, has large clusters of SO_2 emissions sources including in Rabigh, Shaiba and Jeddah. Oil power stations and oil refineries in these three locations emitted 62% of Saudi Arabia's total SO_2 emissions in 2019. Other major sources of SO_2 are power stations and refineries in Fereidoor Jubail, Yanbu, Al Hofuf, Riyad, Al Hofuf, Uthmaniyah and Buraydah.

[42] The observed increase is much smaller than the data precision. It is not possible to make a clear statement about the 2019 change.

Mexico

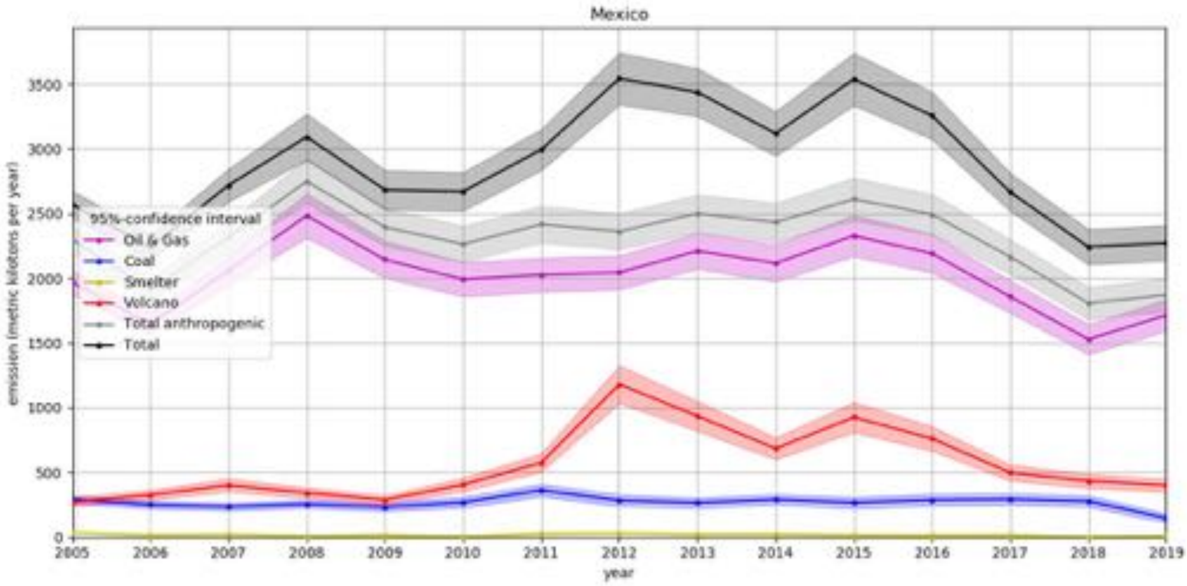

Figure 11: *Contributions of major industry sectors and natural sources (volcanoes) to total SO_2 emissions from 2005 to 2019 in Mexico (kilotonnes per year). Data source: NASA MEaSURES (partially reclassified, as described above).*

Anthropogenic SO_2 emissions in Mexico remained constant or increased slightly[43] in 2019 after having fallen for three consecutive years. Oil and gas combustion, responsible for 90% of Mexico's anthropogenic SO_2 emissions, saw a steep rise in 2019. The remaining anthropogenic emissions are from coal combustion. Mexico has not followed the global trend of decreasing SO_2 emissions, and the country is now the fifth biggest global emitter of SO_2.

Oil fields in Mexico are among the biggest hotspots in the world; the two hotspots at Cantarell and Reforma alone account for approximately 48% of the country's anthropogenic SO_2 emissions. The other major SO_2 emission hotspots in Mexico are the national refining system and fuel oil power stations, including Tula and Tuxpan (**Fig. 11**). The energy policy of the current administration aims to increase the refining capacity and the electricity generation with fuel oil and coal. Therefore, SO_2 emissions might increase in future years, which would severely affect air quality in major urban areas, including Mexico City, where air pollution regulations are weak.

Coal-fired power generation was gradually decreasing in the past decade because efforts had been made to control high pollutant emissions and because the cost of coal had increased (**Fig. 11**). But the energy sectoral programme over the next four years plans to increase coal production and coal power generation, which will mean an increase in SO_2 emissions.

[43] With the given data precision, it is 76% likely that emissions increased (see Table A2).

South Africa

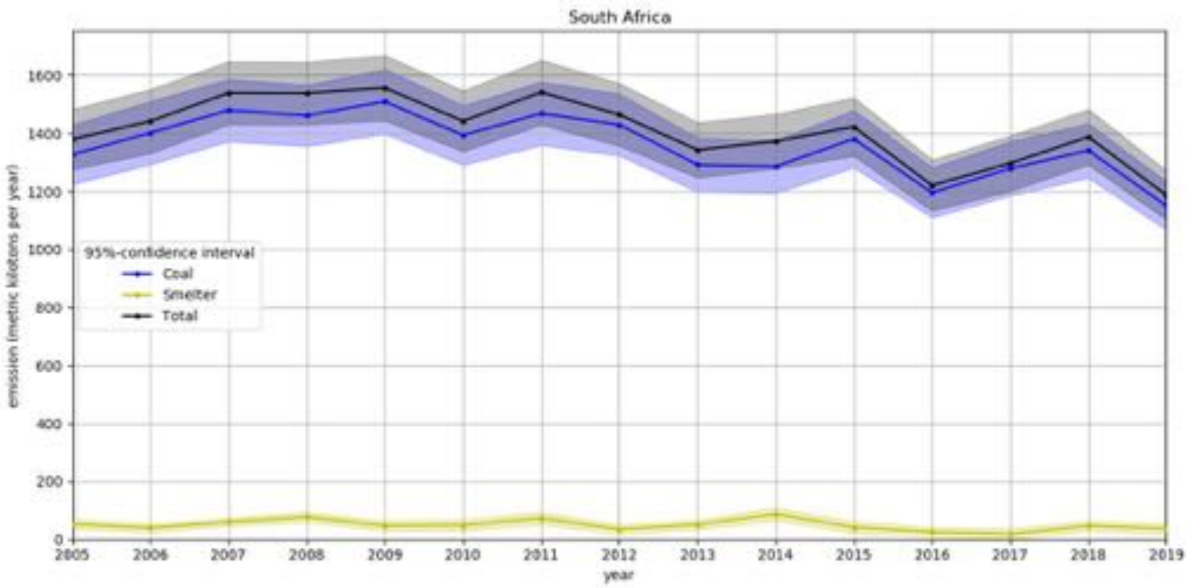

***Figure 12:** Contributions of major industry sectors to total SO_2 emissions from 2005 to 2019 in South Africa (kilotonnes per year). Data source: NASA MEaSUREs (partially reclassified, as described above).*

South Africa's SO_2 emissions are entirely anthropogenic. The country's emissions dropped by about 15% in 2019, reaching an all-time low on the 15-year record, but remain at a very high level (**Fig. 12**). Preliminary analysis indicates that the decrease in SO_2 emissions coincide with "load shedding" episodes created by the loss of power generation capacity. However, that could be one among several factors; further investigation is required to better understand the reasons for that decrease.

Mpumalanga in South Africa is the largest SO_2 emission hotspot in Africa. The cluster of mega power stations in Nkangala, including Duvha, Kendal and Kriel coal-fired power stations, is the biggest source of anthropogenic SO_2 within Mpumalanga. There are 12 coal-fired power stations in the province, located just 100-200 km from South Africa's largest populated area, Gauteng City region, posing a significant health threat to local residents. This year, the South African government relaxed SO_2 emission regulations for coal power stations, doubling the permitted emission rate. The change took effect on 1 April 2020 despite severe SO_2 pollution across the region[44]. Weakening SO_2 emission standards is a direct concession to the country's power utility companies {Eskom and Sasol (synfuel company)} who called it "costly" to comply with the regulations around SO_2[45].

[44] Vlavianos, C. 'SA government gazettes approval for air pollution increases.' Greenpeace Africa press release on March 30, 2020. Available at: https://www.greenpeace.org/africa/en/press/9221/sa-government-gazettes-approval-for-air-pollution-increases/ [accessed Sept. 23, 2020].

[45] Ms Creecy, B. D. Ministry of Forestry, Fisheries and the Environment. Republic of South Africa. Letter to Ms Kate Handley. July 20, 2020. Available at: https://drive.google.com/file/d/1nekGK0_CFh10EwjldodUVCk-64oN-Q-y/view

Turkey

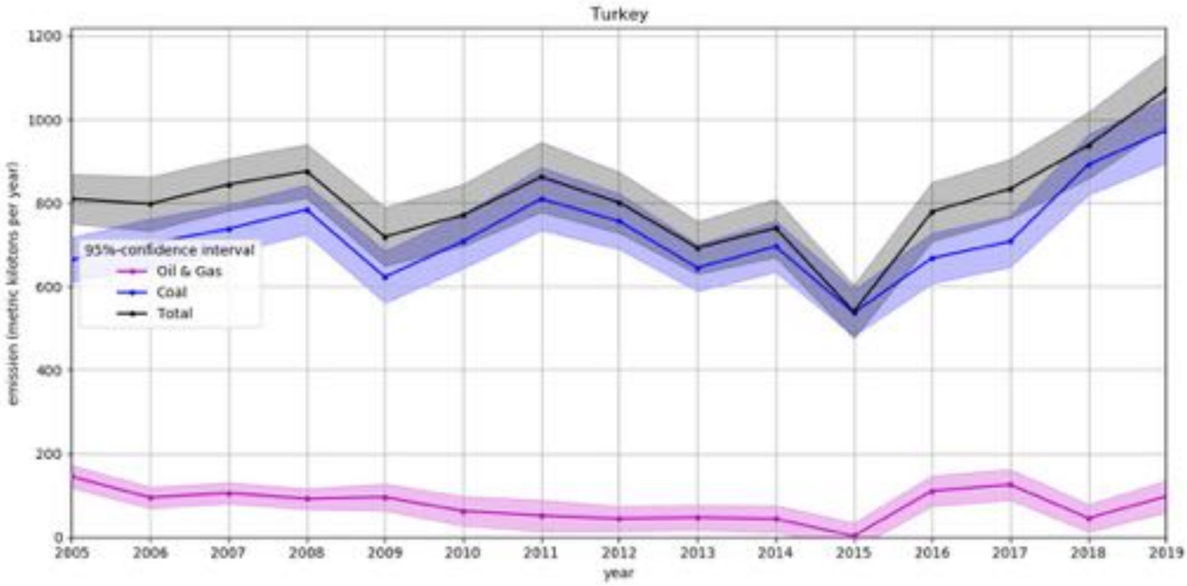

Figure 13: *Contributions of major industry sectors to total SO_2 emissions from 2005 to 2019 in Turkey (kilotonnes per year). Data source: NASA MEaSURES (partially reclassified, as described above).*

In 2018, Turkey took its place among the top ten SO_2 emitter countries, emitting more than 1,000 kt of anthropogenic SO_2 into the atmosphere. Turkey is one of the few countries that saw a substantial increase (14%) in emissions in 2019, marking the country's fourth consecutive year of rising SO_2 emissions. Turkey's SO_2 emissions in 2019 were twice as high as those in 2015. Turkey is now the eighth largest emitter of SO_2, up from tenth place in 2018. Coal-based energy production remains the major source of SO_2 emissions in Turkey (**Fig. 13**)[46].

The major SO_2 hotspot cluster in Muğla is an aggregation of the Kemerköy, Yeniköy, and Yatağan coal-fired power stations and is the biggest emissions hotspot in Turkey. It is also the 11th largest anthropogenic emission source in the world, followed by the region around Kangal coal-fired power station and Afşin Elbistan coal-fired power stations.

The prediction for Turkey is that the upwards trend in SO_2 emissions will continue because government ambitions are to increase national coal power capacity with new lignite coal mines. Turkey is the nation with the second highest capacity in pre-construction development with 31.7 GW after China[47]. Despite public opposition and an economic crisis, the Turkish government continues to support service extensions to ageing coal power stations through capacity mechanisms payments. Combined, these factors might push Turkey higher in the SO_2 ranking in coming years.

[46] Chamber of Environmental Engineers (2020). Air Pollution Report in 2019, Ankara, (in Turkish). Available at: http://www.cmo.org.tr/resimler/ekler/7666bf4c3e1e4bb_ek.pdf [accessed Sept. 23, 2020].

[47] Shearer, C. et al. Boom and Bust 2020: Tracking the Global Coal Plant Pipeline. Global Energy Monitor, Greenpeace International, CREA and Sierra Club (2020). Available at: https://endcoal.org/wp-content/uploads/2020/03/BoomAndBust_2020_English.pdf [accessed Sept. 23, 2020].

Europe

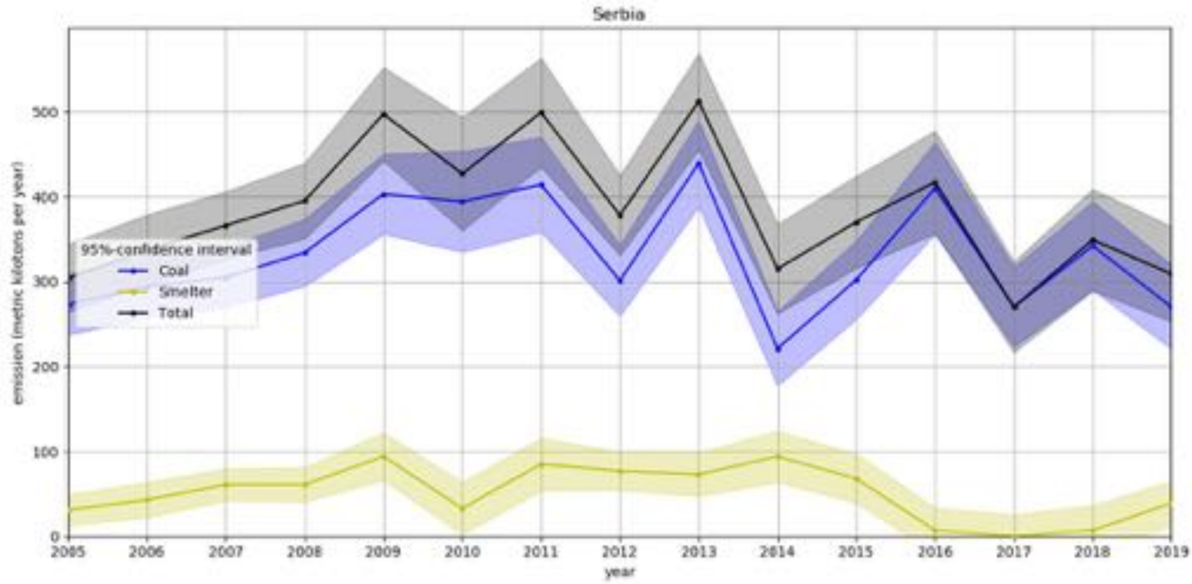

Figure 14: *Contributions of major industry sectors to total SO_2 emissions from 2005 to 2019 in Serbia (kilotonnes per year). Data source: NASA MEaSUREs (partially reclassified, as described above).*

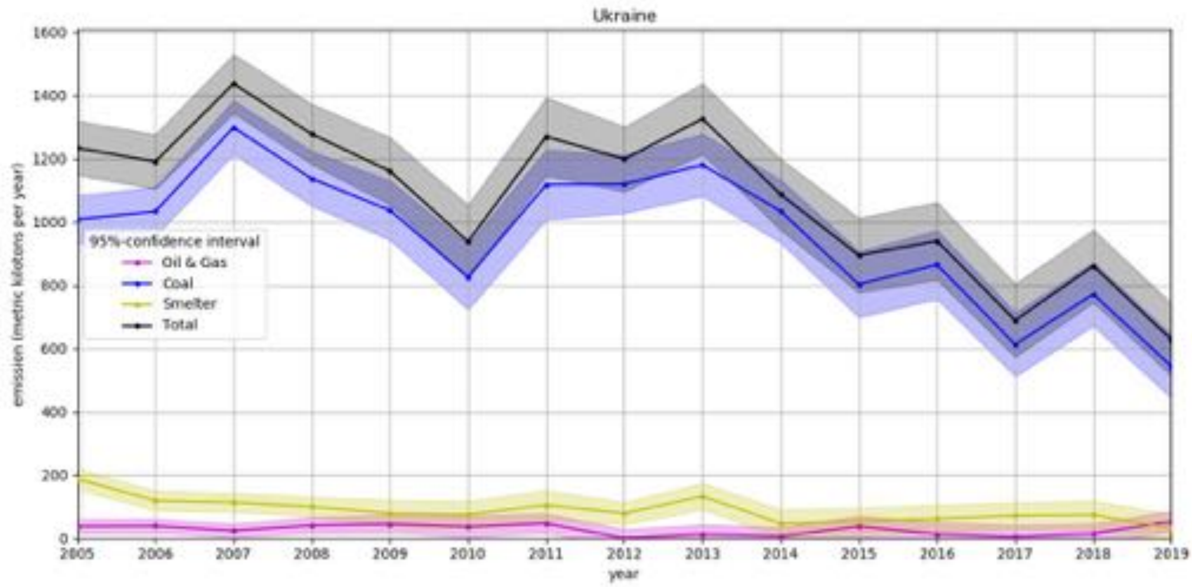

Figure 15: *Contributions of major industry sectors to total SO_2 emissions from 2005 to 2019 in Ukraine (kilotonnes per year). Data source: NASA MEaSUREs (partially reclassified, as described above).*

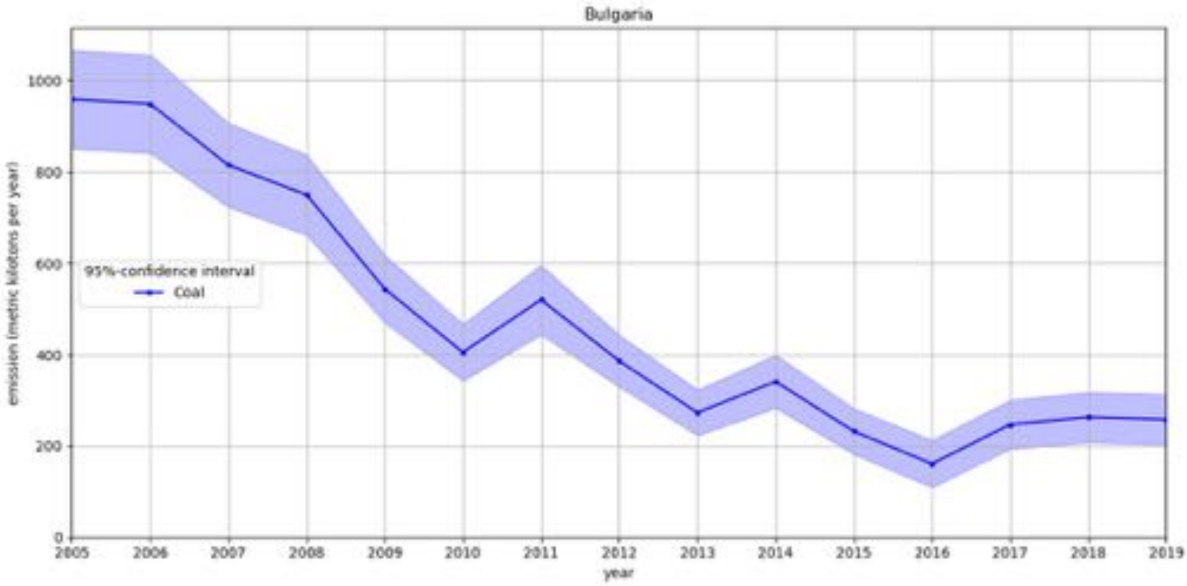

Figure 16: *Contributions of major industry sectors to total SO_2 emissions from 2005 to 2019 in Bulgaria (kilotonnes per year). Data source: NASA MEaSURES (reclassified, as described above).*

Ukraine, Serbia and Bulgaria are the biggest SO_2 emitters in Europe and rank among the world's top 25 SO_2 emitters. Bulgaria is the only European Union country in the global top 25 SO_2 polluters. Coal combustion is the primary source of SO_2 emissions in all three countries. Emissions from coal decreased in Serbia (**Fig. 14**) and Ukraine (**Fig. 15**) in 2019, but remained constant in Bulgaria (**Fig. 16**). In Serbia, the decrease was partially offset by an increase in emissions from smelters.

In 2017 the European Union adopted strict SO_2 emission limits for coal-fired power stations, but the Bulgarian administration opposes the new rules and continues to permit power stations to emit more than is allowed under European Union law. The country also seeks exemptions from the rules instead of taking steps to phase-out coal. One of the biggest coal-fired power stations on the Balkan Peninsula – the state-owned Maritsa East 2 – has been permitted to emit more than four times the specified European Union limit for SO_2 set by the Industrial Emissions Directive[48,49].

[48] Greenpeace Bulgaria. For the Earth - access to justice appeals the derogation of TPP Maritsa East 2 and insists that the company prove that it has a plan for a cleaner future

Greenpeace Bulgaria press release on Jan. 24, 2019. Available at: https://www.greenpeace.org/bulgaria/press/1377 (in Bulgarian) [accessed Sept. 14, 2020]

[49] Doyle, D. & Stoilova, R. The Balkans' biggest power station – why thinking beyond Maritsa East 2 matters.' Energypost.eu news report on Sept. 3, 2019. Available at: https://energypost.eu/the-balkans-biggest-power-station-why-thinking-beyond-maritsa-east-2-matters/ (in English) [accessed Sept. 14, 2020].

Australia

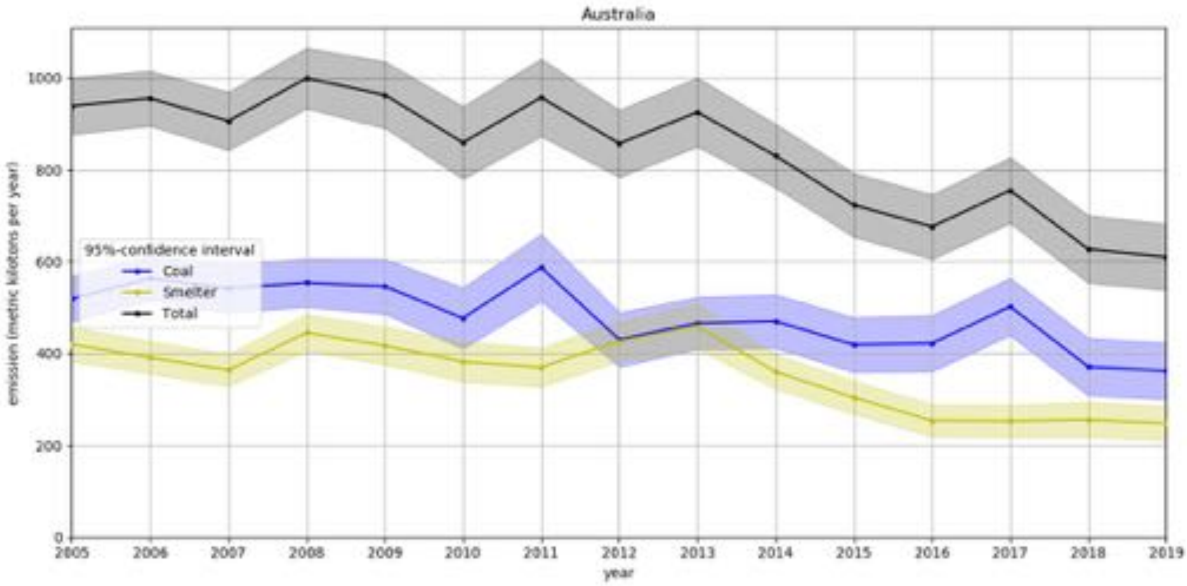

Figure 17: *Contributions of major industry sectors to total SO_2 emissions from 2005 to 2019 in Australia (kilotonnes per year). Data source: NASA MEaSUREs (partially reclassified, as described above).*

Australia's SO_2 emissions are entirely anthropogenic. In 2019, Australia was the 12th biggest emitter of SO_2 in the world – the same as in 2018 – because no significant emissions reductions were made. The largest SO_2 emission hotspots in Australia are Mount Isa in Queensland (a complex of mining operations with lead and copper smelters) followed by Lake Macquarie and Hunter Valley in New South Wales and Latrobe Valley in Victoria. In all four locations, coal-fired power stations contribute to high SO_2 emissions (**Fig. 17**). Despite the existence of major global SO_2 emission hotspots, there are currently no coal-fired power stations equipped with flue-gas desulfurization technology to control SO_2 emissions and SO_2 pollution limits are weak or non-existent. Australia's system of SO_2 pollution regulation lags behind China, the United States and the European Union.

Southeast Asia

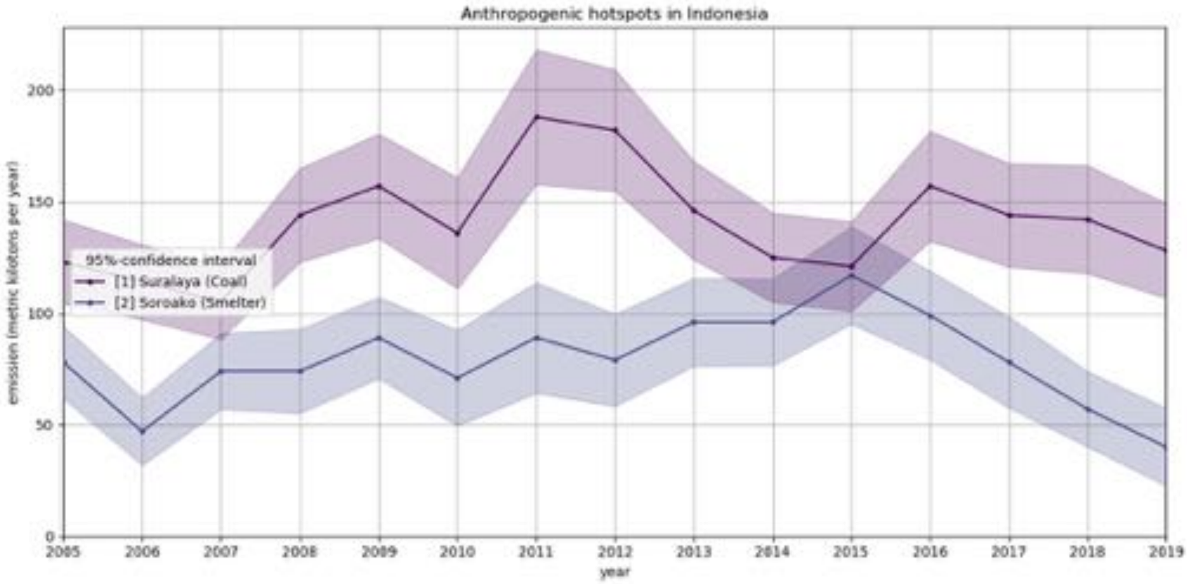

__Figure 18:__ SO_2 emissions of the largest hotspots in Indonesia from 2005 to 2019 (kilotonnes per year). Data source: NASA MEaSUREs (partially renamed and/or reclassified, as described above).

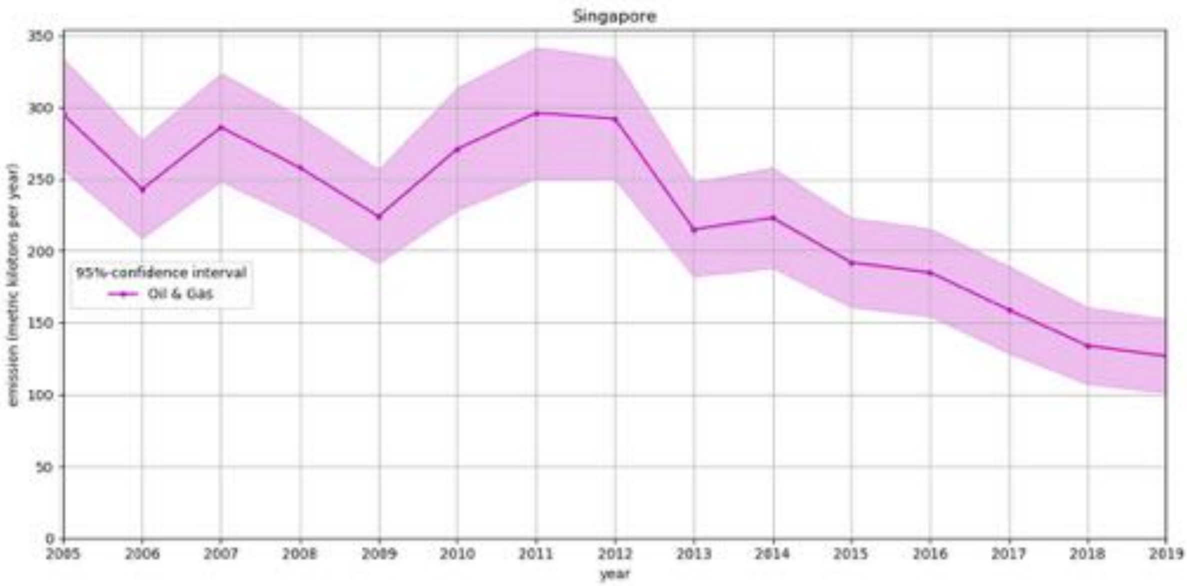

__Figure 19:__ SO_2 emissions of the largest hotspots in Singapore from 2005 to 2019 (kilotonnes per year). Data source: NASA MEaSUREs.

In 2019, Indonesia (**Fig. 18**) and Singapore (**Fig. 19**) accounted for approximately 90% of anthropogenic SO_2 in Southeast Asia, with coal emissions from Thailand accounting for the remaining share. Although the majority of Indonesia's SO_2 is from volcanic activity and 2019 emissions decreased overall, the Banten Suralaya power complex accounts for three-fourths of the country's anthropogenic SO_2. Suralaya is the largest hotspot in the region but Singapore's oil and gas refineries, which are responsible for all of its emissions, are a close second. The remaining one-quarter of Indonesia's emissions are from nickel smelters in Soroako, from which there has been a consistent decrease in emissions since 2015.

New emissions standards for stationary sources from the Indonesian Ministry of Environment and Forestry (MoEF) were enacted in 2019. However, it remains to be seen whether stricter regulations for SO_2 have resulted in the installation of necessary control technologies. Units 1 and 2 of the Banten Suralaya complex have been operating for nearly 35 years,[50] and should be scheduled to enter retirement,[51] yet they continue to operate and emit high levels of SO_2 in the area. Despite a government review of the Suralaya plants' operations, the state electricity company (PLN) is calling for a ten-year delay in the enforcement of the new emission standard regulation on existing coal power plants.[52]

Major polluting sectors

The following section provides an overview of the sectors responsible for SO_2 emissions.

Coal combustion

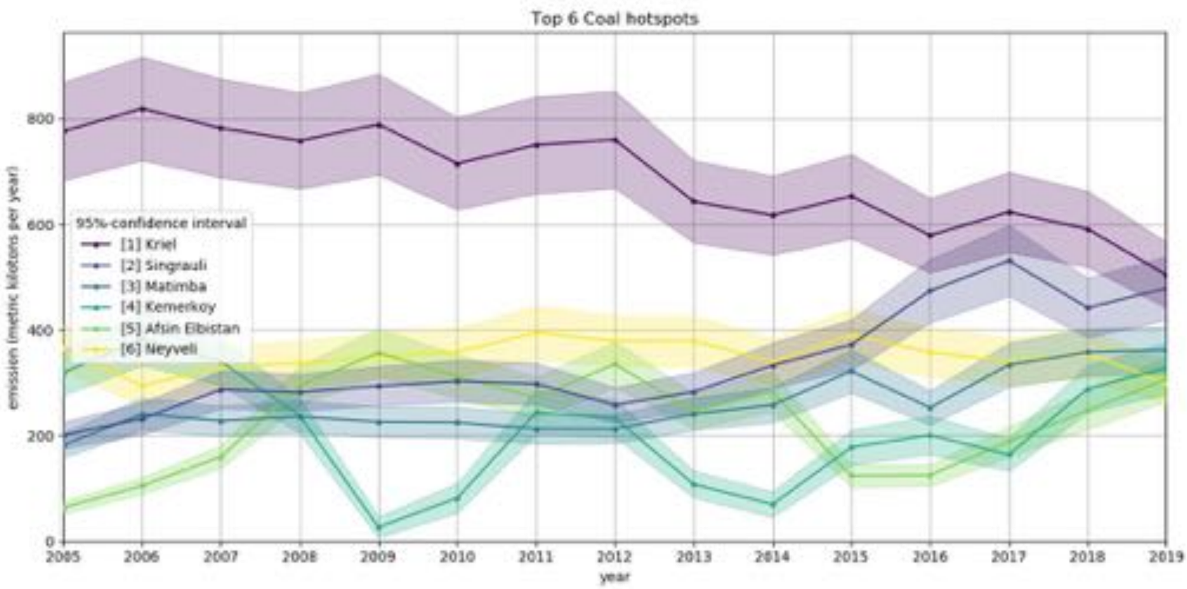

Figure 20: *SO_2 emissions of the largest six coal hotspots globally from 2005 to 2019 (kilotonnes per year). Data source: NASA MEaSUREs (partially renamed and/or reclassified, as described above).*

Hotspots that use coal combustion for power generation and industry account for more than 52% of total global anthropogenic SO_2 emissions. The 50 coal hotspots with the highest SO_2 emissions as identified in the NASA Measures data are listed in **Table 4**; emissions trends for the six hotspots with the greatest emissions are named in **Fig. 20.**

[50] Operationalized years available at: www.gem.wiki/Banten_Suralaya_power_station

[51] Government Shuts Down Old PLTU Replaced with Renewable Energy Generators. News report. January 30, 2020. www.merdeka.com/uang/pemerintah-tutup-pltu-tua-digantikan-dengan-pembangkit-energi-terbarukan.html

[52] Feeling burdened, PLN asks for relaxation in the enforcement of power plant emission standards. News report. September 26, 2020. Available at: www.dunia-energi.com/merasa-terbebani-pln-minta-relaksasi-pemberlakuan-baku-mutu-emisi-pembangkit-listrik/

Coal-fired power stations are the major source of SO_2 emissions in India, China, South Africa, Turkey, the United States, Kazakhstan, Ukraine, Australia, Russia, Serbia and Bulgaria.

Over the past decade, many states and regions, including China, India, South Africa and Indonesia, have imposed or enhanced emission standards for SO_2 and deployed flue gas desulfurization technology. However, regulations and enforcement differ between countries and in most places emissions standards are still far too weak to improve air quality. The discrepancy in emissions regulations and SO_2 pollution control efficiency results in a large difference of SO_2 emissions per one unit of output from these fossil fuel burning facilities.. A detailed list of national power station emission standards is provided in **Appendix B**, which depicts the wide range of emission limits ranging from 10 mg/Nm^3 to more than 4000 mg/Nm^3 across different geographies.

Table 4: *Top 50 global SO_2 hotspots that use coal combustion as the major energy source. Data source: NASA MEaSUREs (partially renamed and/or reclassified, as described above).*

Rank	Hotspot	Country / Region	Source type	Emissions 2019 (kt) (95%-confidence interval)		
				best estimate	low estimate	high estimate
1	Kriel	South Africa	Coal	504	443	564
2	Singrauli	India	Coal	479	420	538
3	Matimba	South Africa	Coal	362	319	406
4	Kemerkoy	Turkey	Coal	328	280	376
5	Afsin Elbistan	Turkey	Coal	307	266	348
6	Neyveli	India	Coal	299	260	338
7	Korba	India	Coal	282	244	320
8	Talcher	India	Coal	221	189	253
9	Nikola Tesla	Serbia	Coal	197	158	236
10	Kurakhovskaya	Ukraine	Coal	180	142	218
11	Visakhapatnam	India	Coal	172	141	203
12	Maritsa East industrial complex	Bulgaria	Coal	170	135	205
13	Mundra	India	Coal	164	135	193
14	Kutch	India	Coal	161	136	186
15	Koradi	India	Coal	158	134	182
16	Zhezkazgan	Kazakhstan	Coal	155	125	185
17	Majuba	South Africa	Coal	149	125	173
18	Chennai	India	Coal	142	119	166
19	Vuglegirska	Ukraine	Coal	138	100	177
20	Ekibastuz	Kazakhstan	Coal	137	96	179
21	Pavlodar	Kazakhstan	Coal	136	96	175
22	Chandrapur,	India	Coal	135	115	156

	Maharashtra					
23	Lethabo	South Africa	Coal	135	114	156
24	Tuzla	Bosnia and Herzegovina	Coal	132	99	165
25	Suralaya	Indonesia	Coal	128	108	149
26	Wuan	China	Coal	125	100	151
27	Novocherkassk	Russia	Coal	121	77	165
28	Tangshan	China	Coal	120	90	151
29	Sundance	Canada	Coal	118	77	159
30	Jorf Lasfar	Morocco	Coal	107	80	134
31	Ramagundam	India	Coal	102	85	119
32	Lake Macquarie	Australia	Coal	101	77	124
33	Zouping, Binzhou	China	Coal	98	72	124
34	Shizuishan-Wuhai	China	Coal	97	80	113
35	Raigarh	India	Coal	92	70	113
36	Seyitomer	Turkey	Coal	87	65	110
37	Bobov Dol	Bulgaria	Coal	84	60	108
38	Kothagudem	India	Coal	83	66	101
39	Soto de Ribera	Spain	Coal	82	51	114
40	Turceni	Romania	Coal	76	51	102
41	Petacalco	Mexico	Coal	75	47	103
42	Hazira	India	Coal	75	55	94
43	Carbon	Mexico	Coal	73	53	93
44	Kostolac	Serbia	Coal	73	44	102
45	Hunter Valley	Australia	Coal	72	54	90
46	Miami Fort	USA	Coal	71	40	102
47	Latrobe Valley	Australia	Coal	69	34	105
48	Novatsi	Macedonia (FYROM)	Coal	69	48	91
49	Zaporizhya	Ukraine	Coal	69	36	102
50	Surat	India	Coal	68	50	85

Oil and gas refining/power generation

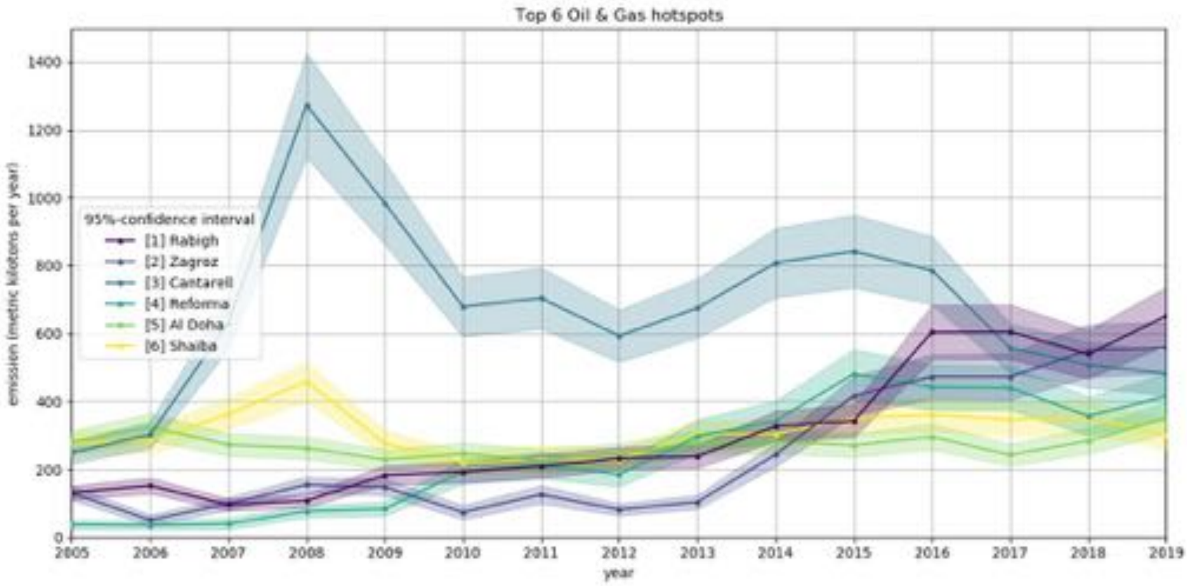

Figure 21: *SO_2 emissions of the world's six largest oil and gas hotspots from 2005 to 2019 (kilotonnes per year). Data source: NASA MEaSUREs (partially renamed and/or reclassified, as described above).*

Oil refining and gas industries/power generation are a major source of SO_2 emissions into the atmosphere in Mexico, Saudi Arabia, Iran, Russia and the United Arab Emirates. Cantarell, Reforma/Cactus and Tula in Mexico are the country's greatest SO_2 emissions hotspots, primarily from oil refining and gas processing. Significant emission hotspots from oil refining/combustion are in the Middle East, including Rabigh in Saudi Arabia, which is the largest oil and gas-based SO_2 emissions hotspot in the world (**Fig. 21, Table 5**).

Table 5: *Top 50 SO_2 hotspots with oil and gas combustion as the major source. Data source: NASA MEaSUREs (partially renamed and/or reclassified, as described above).*

Rank	Hotspot	Country / Region	Source type	Emissions 2019 (kt) (95%-confidence interval)		
				best estimate	low estimate	high estimate
1	Rabigh	Saudi Arabia	Oil & Gas	652	569	735
2	Zagroz	Iran	Oil & Gas	558	484	632
3	Cantarell	Mexico	Oil & Gas	482	420	544
4	Reforma/Cactus	Mexico	Oil & Gas	415	349	481
5	Al Doha	Kuwait	Oil & Gas	351	307	395
6	Shaiba	Saudi Arabia	Oil & Gas	301	260	342
7	Fereidoon	Saudi Arabia	Oil & Gas	291	243	339
8	Das Island	United Arab Emirates	Oil & Gas	271	229	312
9	Mubarek	Uzbekistan	Oil & Gas	245	212	278
10	Jeddah	Saudi Arabia	Oil & Gas	233	197	268
11	Tula	Mexico	Oil & Gas	200	170	230
12	Khangiran	Iran	Oil & Gas	162	139	185

13	Jubail	Saudi Arabia	Oil & Gas	154	128	180
14	Baghdad	Iraq	Oil & Gas	134	113	155
15	Tuxpan	Mexico	Oil & Gas	130	103	158
16	Nuevitas	Cuba	Oil & Gas	130	104	156
17	Singapore	Singapore	Oil & Gas	127	102	152
18	Minatitlan	Mexico	Oil & Gas	116	87	145
19	Guiteras	Cuba	Oil & Gas	115	95	135
20	Ufa	Russia	Oil & Gas	98	47	149
21	Yanbu	Saudi Arabia	Oil & Gas	98	78	119
22	Astrakhan	Russia	Oil & Gas	97	67	127
23	Orenburg	Russia	Oil & Gas	94	56	131
24	Abadan	Iran	Oil & Gas	91	70	112
25	Manzanillo	Mexico	Oil & Gas	86	65	106
26	Aliaga Kardemir	Turkey	Oil & Gas	84	50	119
27	Dehloran	Iran	Oil & Gas	77	62	92
28	Paraguana	Venezuela	Oil & Gas	76	51	101
29	Zhanazhol	Kazakhstan	Oil & Gas	76	47	104
30	Salina Cruz	Mexico	Oil & Gas	72	51	92
31	Mesaieed	Qatar	Oil & Gas	70	54	86
32	Angarsk	Russia	Oil & Gas	70	41	99
33	Swedieh	Syria	Oil & Gas	70	55	84
34	Riyad	Saudi Arabia	Oil & Gas	67	56	79
35	Neka	Iran	Oil & Gas	65	41	88
36	Bandar Abbas	Iran	Oil & Gas	64	46	83
37	Laffan	Qatar	Oil & Gas	61	39	84
38	Cairo	Egypt	Oil & Gas	59	43	74
39	Tampico	Mexico	Oil & Gas	58	36	81
40	Arak	Iran	Oil & Gas	58	47	70
41	Mariel	Cuba	Oil & Gas	54	36	73
42	Al Hofuf	Saudi Arabia	Oil & Gas	53	42	64
43	Ryazan	Russia	Oil & Gas	53	11	94
44	Kiev	Ukraine	Oil & Gas	53	19	86
45	Novokuybshevsk	Russia	Oil & Gas	51	4	97
46	Xan	Guatemala	Oil & Gas	49	30	68
47	Narva	Estonia	Oil & Gas	49	0	103
48	Az Zour South	Kuwait	Oil & Gas	45	27	63
49	Choloma	Honduras	Oil & Gas	44	27	62
50	Bayji	Iraq	Oil & Gas	43	26	61

Smelters

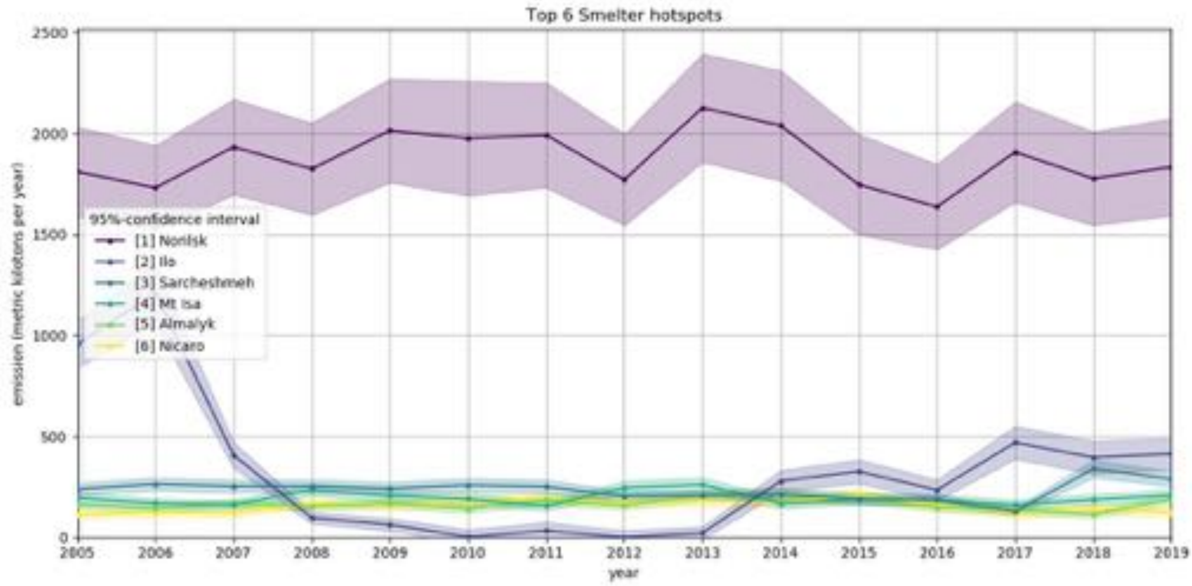

Figure 22: *SO_2 emissions of the largest six smelter hotspots globally from 2005 to 2019 (kilotonnes per year). Data source: NASA MEaSUREs (partially renamed and/or reclassified, as described above).*

The operation of metal smelters and associated infrastructure, especially those without proper pollution control devices, emits large amounts of SO_2 into the atmosphere. Smelters are the principal contributor to SO_2 in many of the biggest detected hotspots. Emission rates for the top 15 smelter hotspots are shown in **Table 6** and the top six are shown in **Fig. 22**. The Norilsk smelter site in Russia remains by far the biggest SO_2 emission hotspot worldwide. The second largest smelter hotspot, according to the NASA MEaSUREs data, is Ilo in Peru, followed by Sarcheshmeh in Iran, Mt Isa in Australia, Almalyk in Uzbekistan and Nicaro in Cuba.

Table 6: *Top 15 SO_2 hotspots with smelter industry as the major source. Data source: NASA MEaSUREs (partially renamed and/or reclassified, as described above).*

Rank	Hotspot	Country / Region	Source type	Emissions 2019 (kt) (95%-confidence interval)		
				best estimate	low estimate	high estimate
1	Norilsk	Russia	Smelter	1,833	1,598	2,068
2	Ilo	Peru	Smelter	414	338	489
3	Sarcheshmeh	Iran	Smelter	289	253	326
4	Mt Isa	Australia	Smelter	208	180	237
5	Almalyk	Uzbekistan	Smelter	188	162	215
6	Nicaro	Cuba	Smelter	125	100	150
7	Nikel	Russia	Smelter	106	36	177
8	Kirovograd	Russia	Smelter	102	42	162
9	Camacari	Brazil	Smelter	87	52	122

10	Noranda	Chile	Smelter	83	45	122
11	Mednogorsk	Russia	Smelter	83	47	120
12	Krasnouralsk	Russia	Smelter	82	26	138
13	Manchester	Jamaica	Smelter	81	61	101
14	Che Guevara	Cuba	Smelter	72	49	96
15	Karabash	Russia	Smelter	68	20	116

2020 trends (OMI data)

In 2020, the COVID-19 pandemic dramatically altered daily life in many regions of the world. As a result of lockdowns, there was a substantial, but probably temporary, reduction in global demand for energy and electricity in the first half of 2020. The reduction in energy demand resulted in improved air quality in many locations where demand for energy from fossil fuels was reduced. In Europe for instance, power generation from coal fell by 37% and measures to prevent the spread of severe acute respiratory syndrome coronavirus 2 have led to an approximately 40% reduction in average level of nitrogen dioxide (NO_2) pollution[53].

NASA estimations of SO_2 emissions are not yet available for 2020. In this section, we rely on SO_2 column amounts around emission hotspots as an indirect proxy for emissions themselves (see **Box 1** within the Methodology section for the difference between SO_2 emissions and SO_2 column amounts).

Analysis of 2020 SO_2 column amounts shows a decrease relative to 2019 (see **Fig. 23** and **Fig. 24** below). However, the high interannual variability and the unaccounted-for weather effects prevent us from attributing the observed decreases to the COVID-19 pandemic with certainty.

Regions

In **Fig. 23**, we look at average SO_2 column amounts around anthropogenic hotspots within important SO_2 emitting countries or regions. A 365-day running average is used to limit the effects of seasonality.

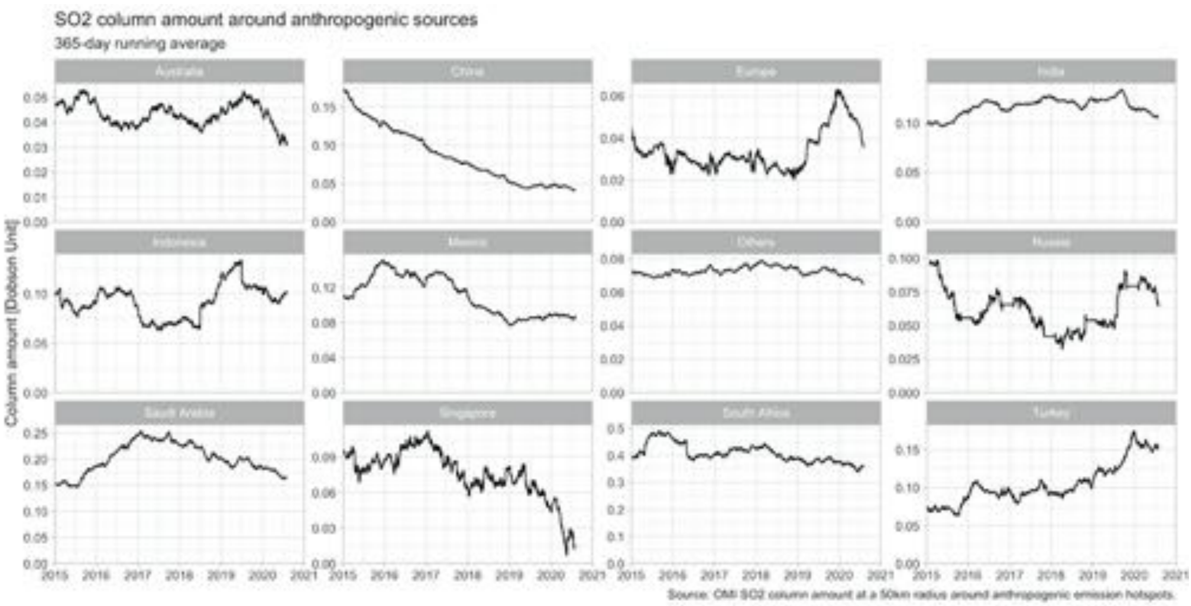

Figure 23: *The 2015–2020 SO_2 column amounts within 50km of anthropogenic sources in countries that have large emissions. 365-day running average. 'Others' refers to all other countries combined. Data source: OMI.*

[53] Myllyvirta, L. & Thieriot, H. 11,000 air pollution-related deaths avoided in Europe as coal, oil consumption plummet. CREA (2020). Available at: https://energyandcleanair.org/wp/wp-content/uploads/2020/04/CREA-Europe-COVID-impacts.pdf [accessed Sept. 23, 2020].

Many regions and countries show a marked decrease in SO_2 emissions in 2020, with only Indonesia observing an increase following a previously notable downward trend (**Fig. 23**). Abrupt decreases are observed for Australia, Singapore, Turkey, Europe and Russia, with less pronounced reductions in India and Saudi Arabia. On January 1, 2020, five of Turkey's 16 coal power plants suspended operations, potentially contributing to the abrupt and coincident reduction in SO_2 observed here[54]. Oil refining in Singapore (its main emission sector) has reportedly seen its production rate drop to around 60% of capacity[55]. In India, the coal consumption for power generation decreased by 10.4% in January-August 2020 compared to 2019, according to official statistics[56].

Observed SO_2 column amounts across the preceding five years show long term trends and inter-annual variability in many of the selected regions. The SO_2 column amount reductions identified between 2019 and 2020 are the result of several factors, and not only the COVID-19 crisis.

Sectors

Analysis of the atmospheric column amount of SO_2 around hotspots attributed to different source sectors reveals global trends in emissions from coal, oil and gas, and smelter hotspots. The 365-day running average SO_2 column amount over the past five years around coal and oil and gas hotspots have shown a steady decline. In turn, the decline in SO_2 column amounts during 2020 seems to be the sharpest within the coal and smelter sectors (**Fig. 24**), suggesting a stronger impact of the COVID-19 pandemic on these two sectors.

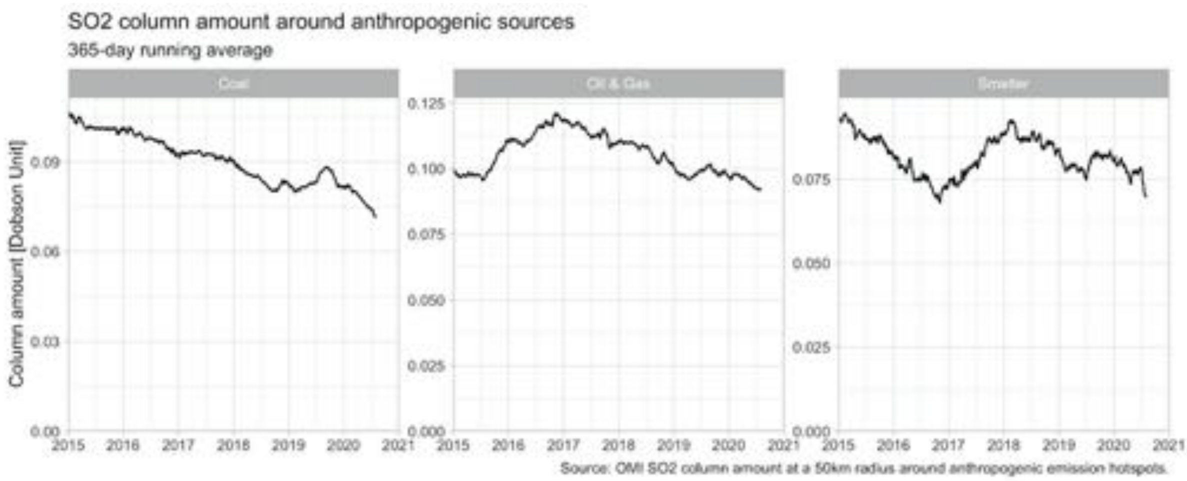

Figure 24: *The 2015-2020 SO_2 column amount around anthropogenic sources in various sectors. 365-day running average. Data source: OMI.*

Reduction rates in SO_2 emissions for the coal and smelter sectors are the largest observed in the past ten years, when considering the April to August period (**Fig. 25, Table 7**). In the three sectors, reduction rates exceed 20% year-on-year (**Tables 8, 9, 10**).

[54] Gündüzyeli, E. & Kutluay, D. 'Turkey's dilemma: Risky coal or clean development.' Europe Beyond Coal news report on Feb. 7, 2020. Available at: https://beyond-coal.eu/2020/02/07/turkeys-dilemma-risky-coal-or-clean-development/ [accessed Sept. 23, 2020].

[55] Bloomberg. 'Singapore Coastline Packed With Ships Full of Oil No One Wants' published on 27 April 2020. Available at https://www.bloomberg.com/news/articles/2020-04-27/oil-glut-swells-off-asian-trading-hub-on-global-storage-scramble [accessed Sept. 29, 2020]

[56] Central Electricity Authority (CEA), Ministry of Power, Government of India, Monthly coal statement, http://cea.nic.in/monthlycoal.html [Assessed on 25th September 2020]

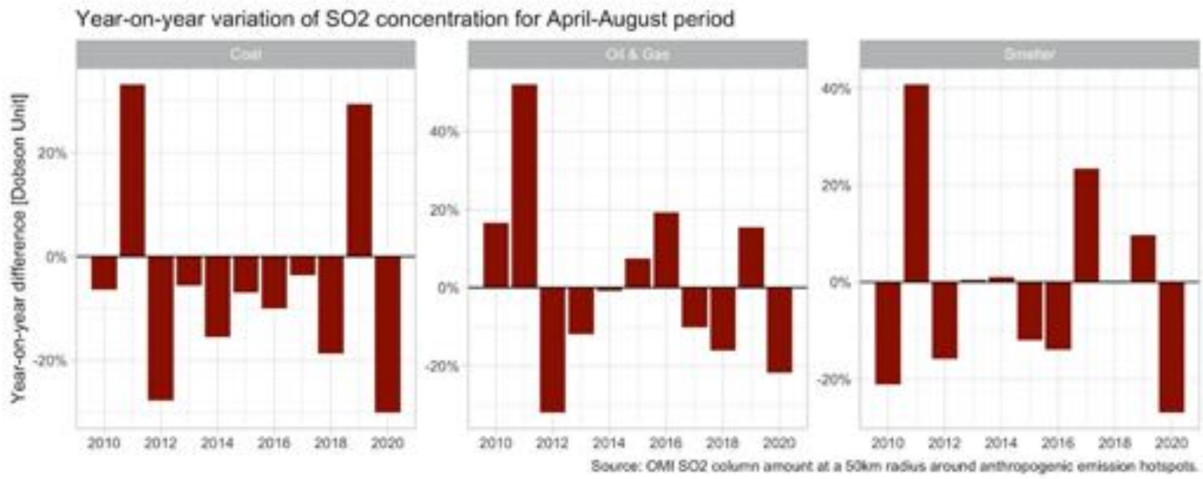

Figure 25. *Year-on-year change of SO_2 column amount averaged from April to August, per sector. Data source: OMI.*

Observations consistently portray a decrease in SO_2 column amount during 2020 across sectors and regions. Although SO_2 column amount (i.e. concentration) can be used as a simple proxy for emission data, the relationship between SO_2 column amount and SO_2 emissions is complicated by factors including weather conditions. Further analyses of emissions statistics are therefore required before making any definitive claims about SO_2 emission trends in 2020.

Table 7: *Year-on-year change in country totals of SO_2 column amount around emission hotspots averaged from April to August. Data source: OMI.*

COUNTRY/REGION	SO_2 column amount
	April 2020 - Aug 2020 vs previous year
Australia	-14%
China	-38%
Europe[57]	-100% (see footnote 57)
India	-23%
Indonesia	13%
Mexico	-12%
Russia	-73%
Saudi Arabia	-24%
South Africa	0%
Turkey	-23%

[57] NASA OMI retrieval algorithm admits negative value for planet boundary layer column amounts, which, albeit not physically realistic, can be interpreted as an extremely sharp decrease. In this analysis the decrease is capped at -100%.

Table 8: *Change in country totals of* coal*-based SO_2 emissions during April to August 2020 compared to the same period in 2019. Data source: OMI.*

COUNTRY/REGION	**SO_2 column amount**
	April to August 2020 in comparison to April to August 2019
Australia	0%
China	-38%
Europe	-100% (see footnote 57)
India	-23%
Indonesia	26%
Mexico	-16%
Russia	-100% (see footnote 57)
Saudi Arabia[58]	-
South Africa	3%
Turkey	-4%

Table 9: *Change in country totals of oil and gas-based SO_2 emissions during April 2020-August 2020 compared to the same period a year prior to that. Data source: OMI.*

COUNTRY/REGION	**SO_2 column amount**
	April 2020 - Aug 2020 vs previous year
Australia	-
China	-100% (see footnote 57)
Europe	-100% (see footnote 57)
India	-25%
Indonesia	-
Mexico	-9%
Russia	-89%
Saudi Arabia	-24%
South Africa	-
Turkey	-100%

[58] The figure for change in SO_2 emissions is not available here because of absence of a coal-dominated SO_2 hotspot in Saudi Arabia. Similar cases are shown for other countries and sectors, represented by "-" in tables.

Table 10: *Change in country totals of* smelter*-related SO_2 emissions during April to August 2020 compared to the same period in 2019. Data source: OMI.*

COUNTRY/REGION	SO_2 column amount
	April 2020 - Aug 2020 vs previous year
Australia	-34%
China	0%
Europe	141%
India	-26%
Indonesia	-8%
Mexico	-100% (see footnote 57)
Russia	-53%
Saudi Arabia	-
South Africa	-38%
Turkey	-

The way forward

Fossil fuel combustion leads to the release of SO_2 and other hazardous pollutants into the air, water and land ecosystems. Pollution degrades ecosystems and has adverse impacts on human health, including premature death. This CREA/Greenpeace report has identified the world's largest SO_2 emission hotspots, all of which are related to extensive fossil fuel combustion. Fossil fuel combustion is the main culprit behind air pollution and the climate emergency, and the two urgent crises share many of the same solutions.

The countries that emit the greatest quantities of SO_2 must stop investing in fossil fuels and shift to safer, more sustainable sources of energy such as solar and wind energy, and increase restrictions on emissions. Requiring coal power stations to install flue-gas desulfurization could capture more than 99% of the SO_2 in a wet flue-gas desulfurization process[59,60] and would reduce impacts to human health.

As governments prepare to recover from the COVID-19 pandemic, it becomes even more important to direct funds spent on energy sources towards renewable energy. In 2020, fossil fuels have become an outdated energy source, with many coal-fired power stations around the world severely underused, standing idle or even nearing closure.[61,62] Any new fossil fuel investments risk becoming stranded assets, as the world moves on to more economical and climate-friendly technologies.

[59] Poullikkas, A. Review of Design, Operating, and Financial Considerations in Flue Gas Desulfurization Systems. *Energy Technol. Policy* 2(1), 92-103 (2015). https://doi.org/10.1080/23317000.2015.1064794

[60] Carpenter, A. M. Low water FGD technologies. IEA Clean Coal Centre (2019). Available at: https://usea.org/sites/default/files/112012_Low%20water%20FGD%20technologies_ccc210.pdf [accessed Sept. 23, 2020].

[61] Tripathi, S. 'Coal power plant capacity falls in India, Paris Agreement goal still far'. Business Standard news report on March 27, 2020. Available at: https://www.business-standard.com/article/companies/coal-power-plant-capacity-falls-in-india-paris-agreement-goal-still-far-120032700712_1.html [accessed Sept. 29, 2020]

[62] Piven, B. 'EU power sector emissions drop as coal collapses across Europe'. Al Jazeera news report on Feb. 5, 2020. Available at: https://www.aljazeera.com/economy/2020/02/05/eu-power-sector-emissions-drop-as-coal-collapses-across-europe/ [accessed Sept. 29, 2020]

Appendix A. Data uncertainty ranges

Table A1: *Top 25 countries of anthropogenic SO_2 emissions in 2019.*[63]

Rank	Country / Region	2019 anthropogenic SO_2 emissions (kt) (95%-confidence interval)		
		best estimate	low estimate	high estimate
-	worldwide	28,704	28,050	29,358
1	India	5,953	5,768	6,138
2	Russia	3,362	3,335	3,717
3	China	2,156	2,044	2,344
4	Saudi Arabia	1,910	1,874	2,027
5	Mexico	1,873	1,849	1,998
6	Iran	1,746	1,708	1,858
7	South Africa	1,187	1,167	1,270
8	Turkey	1,072	1,072	1,157
9	USA	823	814	1,025
10	Kazakhstan	760	657	863
11	Ukraine	628	580	740
12	Australia	610	589	681
13	Cuba	530	509	584
14	Uzbekistan	433	422	476
15	Peru	414	289	490
16	Kuwait	396	396	444
17	Turkmenistan	325	282	364
18	Serbia	309	300	364
19	United Arab Emirates	271	271	315
20	Brazil	262	262	350
21	Bulgaria	258	258	312
22	Canada	240	229	353
23	Iraq	223	186	259
24	Morocco	197	197	240
25	Pakistan	180	104	217

[63] Brazil and Peru must be considered with caution, see discussion about the South Atlantic Anomaly in the Methods section.

Table A2: *Top 25 countries of anthropogenic SO_2 emissions.[64] Relative change from 2018 to 2019 with uncertainty range. Confidence in the direction of change is translated from numbers to words by this scheme: >99% - virtually certain, >95% - very likely, >75% - likely, else - uncertain.*

Total anthropogenic SO_2 emissions									
Rank	**Country / Region**	**Emissions (kt) (best estimate)**		**Relative change (95%-confidence interval)**			**Direction of change**	**Confidence in direction of change**	
		2018	**2019**	best estimate	low estimate	high estimate		in numbers	in words
-	worldwide	30,604	28,704	-6%	-9%	-3%	down	100%	virtually certain
1	India	6,329	5,953	-6%	-10%	-2%	down	100%	virtually certain
2	Russia	3,635	3,362	-8%	-20%	5%	down	88%	likely
3	China	2,263	2,156	-5%	-16%	7%	down	79%	likely
4	Saudi Arabia	1,861	1,910	3%	-6%	11%	uncertain	72%	
5	Mexico	1,809	1,873	4%	-6%	13%	up	76%	likely
6	Iran	1,977	1,746	-12%	-20%	-4%	down	100%	virtually certain
7	South Africa	1,388	1,187	-15%	-23%	-6%	down	100%	virtually certain
8	Turkey	938	1,072	14%	1%	27%	up	98%	very likely
9	USA	864	823	-5%	-37%	27%	uncertain	61%	
10	Kazakhstan	776	760	-2%	-21%	17%	uncertain	59%	
11	Ukraine	861	628	-27%	-43%	-11%	down	100%	virtually certain
12	Australia	627	610	-3%	-19%	13%	uncertain	63%	
13	Cuba	543	530	-2%	-17%	12%	uncertain	63%	
14	Uzbekistan	319	433	36%	16%	56%	up	100%	virtually certain
15	Peru	396	414	5%	-24%	33%	uncertain	62%	
16	Kuwait	394	396	1%	-16%	17%	uncertain	52%	
17	Turkmenist an	251	325	30%	7%	52%	up	99%	virtually certain
18	Serbia	349	309	-12%	-33%	10%	down	85%	likely
19	United Arab Emirates	419	271	-35%	-49%	-21%	down	100%	virtually certain
20	Brazil	205	262	28%	-44%	100%	up	78%	likely
21	Bulgaria	263	258	-2%	-31%	27%	uncertain	55%	
22	Canada	187	240	28%	-61%	117%	uncertain	73%	

[64] Brazil and Peru must be considered with caution, see discussion about the South Atlantic Anomaly in the Methods section.

23	Iraq	370	223	-40%	-51%	-28%	down	100%	virtually certain
24	Morocco	171	197	15%	-24%	54%	up	78%	likely
25	Pakistan	235	180	-23%	-43%	-3%	down	99%	very likely

Appendix B. Power Station Emission Standards

***Table B1**. National emission standards for SO_2 for large coal-fired power stations (mg/Nm^3)[65]*

Country/ Region	Old Stations/Units		New Stations/Units	
China[66,67]	Rest of the country	200	"Ultra Low Emission" standards to be adopted by 2020 (already applies to new units)	35
	Key regions	50		
India[68]	Units commissioned until 2003	600	Units commissioned after 2017	100
	Units commissioned 2004-2016	200		
USA[69]	Power stations commissioned after 1997-2011	160	New power stations after 2011	60
	Power stations commissioned between 1978-1996	640		
EU[70]	PC Pulverized combustion boilers[71] Capacity ≥ 300 MW	10-130	PC Pulverized combustion boilers Capacity ≥ 300 MW	10-75
	Fluidised bed boiler Capacity ≥ 300 MW	20-180	Fluidised bed boiler Capacity ≥ 300 MW	10-75
Mexico[72]	Mexico City metropolitan area, commissioned before 2011	1441	Mexico City metropolitan area, new units	79
	Critical zones, old units	2882	Critical zones, new units	183-262
	Rest of the country, old units	5765	Rest of the country, new units	576- 1834
South Korea[73]	Commissioned until 2014	142	Commissioned after 2015	71
South Africa[74]	Built before 2010, decommission before 2030[75]	4760	All power stations after 2025	680

[65] Converted from other units as required. Most countries normalise flue gas oxygen content to 6% or 7%, and temperature to 0°C or 25°C; this makes a difference of less than 10% and has not been harmonised. South Africa uses reference oxygen content of 10% which has been converted to 6%.

[66] Standardization Administration of China. Emission standard of air pollutants for thermal power plants. GB 13223-2011. Available at : http://english.mee.gov.cn/Resources/standards/Air_Environment/Emission_standard1/201201/W020110923324406748154.pdf

[67] Ministry of Ecology and Environment of China. The work plan for "Ultra Low Emission" standards of coal power plants. Available at: https://www.mee.gov.cn/gkml/hbb/bwj/201512/W020151215366215476108.pdf

[68]MoEF&CC. The Gazette of India: Extraordinary. Part II, Section 3, Sub-section (ii) S.O. 3305(S). New Delhi 2016. Available at: http://moef.gov.in/wp-content/uploads/2017/08/Thermal_plant_gazette_scan.pdf

[69] Electronic Code of Federal Regulations. Available at: http://www.ecfr.gov/cgi-bin/text-idx?tpl=/ecfrbrowse/Title40/40cfr60_main_02.tpl [accessed Sep. 24, 2020]

[70] The European Commission. *Official Journal of the European Union* L212/1, 31 July 2017. Available at: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32017D1442&from=EN [accessed Sep. 24, 2020] to enter into force on 17.08.2021.

[71] Coal is ground into fine particles and then injected with heated combustion air through a number of burners into the lower part of the furnace. Particles burn in suspension and release heat which is transferred into the steam cycle.

[72] Las Normas Oficiales Mexicanas. Contaminación atmosférica-Niveles máximos permisibles de emisión de los equipos de combustión de calentamiento indirecto y su medición. Nom 085, Semarnat, 2011. Available at: http://www.dof.gob.mx/normasOficiales/4632/semarnat/semarnat.htm [accessed Sep. 24, 2020]

[73] Ministry of Environment of The Republic of Korea. Air pollutant emission standards (related to Article 15). Enforcement Regulations of the Air Conservation Act. Decree No. 866. May 27, 2020. Available at: http://www.law.go.kr/lsBylInfoPLinkR.do?bylCls=BE&lsNm=%EB%8C%80%EA%B8%B0%ED%99%98%EA%B2%BD%EB%B3%B4%EC%A0%84%EB%B2%95+%EC%8B%9C%ED%96%89%EA%B7%9C%EC%B9%99&bylNo=0008&bylBrNo=00 /(in Korean) [accessed Sept. 24, 2020]

[74] Listed Activities and Associated Minimum Emission Standards Identified in terms of Section 21 of the National Environmental Management: Air Quality Act, 2004 (Act 39 of 2004). Available at: https://www.environment.gov.za/sites/default/files/gazetted_notices/nemaqa_listofactivities_g33064gon248_0.pdf

[75] Existing plants will have to comply to emission limit of 1000 mg/Nm^3 (at 10% O_2, 273 K and 1 atmosphere) by 2030 (approximately 1367 mg/Nm^3 at 6% O_2)

Thailand[76]	Capacity < 300 MW Commissioned 1996-2010	1830	Capacity < 50 MW Commissioned after 2010	1030
	Capacity 300- 500 MW Commissioned 1996-2010	1287	Capacity > 50 MW Commissioned after 2010	515
	Capacity > 500 MW Commissioned 1996-2010	912		
Indonesia[77]	Built before enactment of MoEF Regulation No. 15/2019	550	Built after enactment of MoEF Regulation No. 15/2019	200
Philippines[78]	Built before 2000	1500	Built after 2000	700
Vietnam[79]	Units operating prior to October 17, 2005	1500	Units operating since October 17, 2005	500
Russia[80]	Units installed before 2001 Capacity ≥ 300 MW (Binding)	2000-3000	Units installed after 2001 Capacity ≥ 250 MW (Binding)	700
	Facilities licensed before 2002 and launched before 2003 Capacity > 300 MW (Recommended)	400	Facilities licensed before 2013 and launched before 2014 Capacity ≥ 300 MW (Recommended)	200
Australia[81]	Large differences from one jurisdiction to another. Many of the power stations in Australia still lack any kind of emission limits for SO_2.	820-2692 or unlimited	Large differences from one jurisdiction to another. Many of the power stations in Australia still lack any kind of emission limits for SO_2.	820-2692 or unlimited
Turkey[82]	Power stations in operation before 2019 100 MW ≤ Fuel Calorific Power ≤ 500 MW	2000 in 2004 400 in 2019	New power stations that came into operation in 2019 For units ≥ 300 MW	200
	Power stations in operation before 2019 Fuel Calorific Power ≥ 500	1000 in 2004 400 in 2019		

[76] Pollution Control Department. Air Pollution Standards for Stationary Sources. Available at: http://www.pcd.go.th/info_serv/reg_std_airsnd03.html / (in Thai) [accessed Sept. 24, 2020]

[77] Ministry of Environment and Forestry of The Republic of Indonesia. Regulation Number P.15. 1-4-2019. Available at: https://app.box.com/s/zc4547qjic4jxzv8yvk2780ga02oq2zi /(in Indonesian) [accessed Sept. 24, 2020]

[78] IMPLEMENTING RULES AND REGULATIONS FOR RA 8749. DENR Administrative Order No. 2000 - 81. November 7, 2000. Available at: http://pab.emb.gov.ph/wp-content/uploads/2017/07/RA-8749-IRR-DAO-2000-81.pdf

[79] https://www.env.go.jp/air/tech/ine/asia/vietnam/files/law/QCVN%2022-2009.pdf

[80] STATE STANDARD OF THE RUSSIAN FEDERATION. GOST R 50831-95. January 1, 1997. Available at: http://docs.cntd.ru/document/1200026436 /(in Russian) [accessed Sept 24, 2020]

[81] Lipski, B., Rivers, N. & Whelan, J. Toxic and terminal: How the regulation of coal-fired power stations fails Australian communities. Environmental Justice Australia, 7 August 2017. Available at: https://www.envirojustice.org.au/sites/default/files/files/EJA_CoalHealth_final.pdf

[82] Aytaç, O. Pollutants in the Flue Gas of Coal-Fired Thermal Power Plants, Permitted Emission Limit Values, Current Status of Flue Gas Treatment Plants in Power Plants in Turkey. Chamber of Mechanical Engineers, MMO Energy Working Group, 2018. Available at: https://www.mmo.org.tr/sites/default/files/9_3.pdf /(in Turkish) [accessed Sept 24, 2020].