



REVIEW

Recent advances in satellite mapping of global air quality: evidences during COVID-19 pandemic

Venkatesh Dutta¹ · Saroj Kumar¹ · Divya Dubey¹

Received: 16 July 2020 / Revised: 4 March 2021 / Accepted: 7 March 2021 / Published online: 29 March 2021
© Society for Environmental Sustainability 2021

Abstract

There was a significant decline in air pollution in different parts of the world due to enforcement of lockdown by many countries to check the spread of the coronavirus (COVID-19) pandemic. In particular, commercial and industrial activities had been limited globally with restricted air and surface traffic movements in response to social distancing and isolation. Both satellite remote sensing and ground-based monitoring were used to measure the change in the air quality. There was momentous decline in the averaged concentrations of nitrogen dioxide (NO₂), carbon dioxide (CO₂), sulphur dioxide (SO₂), methane (CH₄) and aerosols. Many cities across India, China and several major cities in Europe observed strong reductions in nitrogen dioxide levels dropping by around 40–50% owing to lockdowns. Similarly, concentrations of SO₂ in polluted areas in India, especially around large coal-fired power plants and industrial areas decreased by around 40% as evidenced by the comparative satellite mapping during April 2019 and April 2020. Recent advances in sensors on board various satellites played a significant role in real-time monitoring of emission regimes over various parts of the world. The satellite data is relying upon single scene profusion for real-time air quality measurements, and also using averaged dataset over certain time-period. The daily global-scale remote sensing data of NO₂, as measured through the Copernicus Sentinel-5 Precursor Tropospheric Monitoring Instrument (S5p/TROPOMI) of European Space Agency (ESA), indicated exceptional decreases in tropospheric NO₂ pollution in urban areas. Similarly, Greenhouse gases Observing Satellite (GOSAT) of Japan Aerospace Exploration Agency, with a repeat cycle of three days helped in assessing the sources and sinks of CO₂ and CH₄ on a sub-continental scale.

Keywords Air quality · Aerosols · Satellite mapping · Copernicus Sentinel-5P · COVID-19

Introduction

Land use changes, anthropogenic emissions from transport and industries and climate variability deeply affect the environmental quality globally (Stavrakou et al. 2019). In the context of the worldwide lockdown enforced due to the COVID-19 pandemic, there is an increased interest in studying changing air quality through satellite remote sensing

(Collivignarelli et al. 2020; Dantas et al. 2020; Li et al. 2020; Nakada and Urban 2020; Sharma et al. 2020). Lockdowns were imposed in several countries to impede the progress of the spread of the coronavirus pandemic within the communities. This resulted in cleaner air quality over the US, China, India and Europe. The concentration of pollutants markedly decreased over urban areas, with varying differences among primary and secondary pollutants (Bao and Zhang 2020; Huang et al. 2020; Liu et al. 2020; He et al. 2020). This was mainly achieved due to decrease in traffic and industrial activities. Satellite remote sensing is now using multi-platform system and new algorithm in the processing chain that enables better resolution of emission inventories. Significant decrease in NO₂, CO₂, SO₂, CH₄ and aerosols levels have been observed globally during the lockdown period. Real-time observations of background air quality precisely measure ‘hotspots of air pollution’ through the Copernicus Sentinel-5 Precursor Tropospheric Monitoring Instrument

✉ Venkatesh Dutta
dvenks@gmail.com

Saroj Kumar
sarojbhargava73@gmail.com

Divya Dubey
divyadubey.sai21@gmail.com

¹ Department of Environmental Science (DES), School of Earth and Environmental Sciences, Babasaheb Bhimrao Ambedkar University, Lucknow 226025, India

(S5p/TROPOMI). A 14-days average is a better depiction of the emission profile over a region, due to pollutants being affected by the short-term weather changes and cloud cover.

Various satellite images, from NASA, Copernicus Sentinel-5P satellite, from the European Union Copernicus Programme, showed many cities throughout the globe witnessing a significant drop in air pollutants ranging between 30 and 60% owing to countrywide lockdowns. Satellite remote sensing is now using new algorithm in the processing chain as well as multi-platform system that enables emission inventories over a particular region with greater accuracy and speed. The most recent ESA supported project ICOWAC (Impacts of COVID-19 lockdown measures on Air quality and Climate) also helped in assessing the effects of the imposed COVID-19 lockdown and in evaluating the air quality impact from other factors.

Most important real-time observations of air quality, particularly background NO_2 data was precisely measured by the Copernicus Sentinel-5 Precursor Tropospheric Monitoring Instrument (S5p/TROPOMI) which has been developed by the European Space Agency (ESA). Various studies have extensively used the output to assess tropospheric NO_2 levels over polluted areas, both before the lockdown and during the lockdown (Haddout and Priya 2020; Nakada and Urban 2020; Tobias et al. 2020). TROPOMI instrument provides extent of the backscattered earthshine radiation in the UV, visible, near and short-wave IR spectral ranges at the exceptional spatial resolution of $3.5 \times 7 \text{ km}^2$ (Muller et al. 2019; Veeffkind et al. 2012). The resolution further improved to $3.5 \times 5.5 \text{ km}^2$ from August 2019 onwards (Van Roozendaal et al. 2019) which helped in more precise mapping of air quality. A 14-days average is taken as a better representation of the emission profile over a region, as the concentration of the pollutants are affected by the short-term weather changes and cloud cover. Air quality forecasts by NASA use near real-time (NRT) data from NASA's 'Land, Atmosphere Near real-time Capacity for EOS' (LANCER) for monitoring a wide range of natural and anthropogenic pressure functions (NASA 2020a). The Table 1 below summarizes the satellites used by NASA for monitoring of different air quality parameters.

CH₄ emissions during COVID-19

In the atmosphere, CO_2 is more abundant and more commonly associated with increase in temperature, and considered key contributing factor that causes global warming (Florides and Christodoulides 2009; Skytt et al. 2020). On the other hand, CH_4 is approximately 30 times more powerful as a heat-trapping gas and plays a major role in climate radiative forcing. Methane has both natural and anthropogenic sources of emission. Natural sources include emission

from agricultural lands, wetlands, marshy areas and enteric fermentation in ruminant animals. Anthropogenic sources include emission from fossil fuel extraction, landfill and various other anthropogenic activities (Janssens-Maenhout et al. 2019; Heimann et al. 2020). Most of the CH_4 emissions, almost to the tune of 60%, happen in the northern hemisphere, however the extended lifetime to inter-hemispheric transport lessens the north to south (N:S) latitudinal gradient of CH_4 upto 100 ppb (Heimann et al. 2020).

The Copernicus Sentinel-5P satellite, with its instrument TROPOMI, mapped CH_4 emissions during the lockdown period. CH_4 enhancements through oil and natural gas producing regions within the US were monitored through TROPOMI (de Gouw et al. 2020). Measurements of CH_4 have been found to be in good agreement with those observed from the GOSAT instrument (Hu et al. 2018). Given its importance in the global warming, Canadian company GHGSat used mosaics of multiple satellite images (Varon et al. 2019) in association with Sentinel-5P team at SRON (Netherlands Institute for Space Research) to identify the hotspots and emission inventory of CH_4 throughout the lockdown.

The concentration of CH_4 is reported high in some regions in year 2020 as compared to year 2018, for example over a coal mine in the Shanxi province as shown in Fig. 1.

The satellite images from NASA Giovanni portal (<http://giovanni.gsfc.nasa.gov/>) showed an increase in CH_4 concentration globally as well as in Indian subcontinent and South America during March to May 2020 (lockdown period) as compared to the March–May 2019 period as shown in Fig. 2. According to Paris-based data firm Karryos, CH_4 leaks rose 32% in the first eight months of 2020 globally. The increase in the concentration of CH_4 is prominently led by drops in carbon emissions due to worldwide lockdowns. It is also due to the reduction in carbon emissions from oil and gas sectors. Karryos, that examined satellite data to estimate the extent of CH_4 emissions, elaborated that around 100 CH_4 leak episodes happened throughout the world. In some CH_4 hotspots in Russia, Algeria and Turkmenistan, the concentration of CH_4 rose upto 40% as compared to previous year for the same time period. In addition to those three countries, the US, Iran and Iraq were the three largest CH_4 emitters in the first two-thirds of 2020. In Iraq, Karryos reported largest leak, that accounts 400 tons of CH_4 per hour. The leak prolonged upto 150 miles into Saudi Arabia. However, in the US, the largest leak accounts 150 tons of CH_4 per hour, that is equal to 10 coal-fired plants working at maximum capacity resulting in increase in methane emission globally and in various subcontinents during the lockdown period (Ecowatch 2020).

Table 1 Description of various platforms used by NASA for assessing different air quality parameters; Source: Compiled from NASA (2020a)

Pollutants	Instruments and platforms used for assessing air quality	Acronyms for the platforms used	Description of the platforms	Measurement units
Carbon monoxide (CO)	Atmospheric Infrared Sounder	AIRS (Aqua)	Carbon monoxide total column (day/night) specifies the amount of carbon monoxide in the total vertical column profile of the atmosphere Measured in ppbv (parts per billion by volume) and having a sensor and imagery resolution of 45 and 2 km respectively	CO total column (day/night)
	Microwave Limb Sounder	MLS (Aura)	Mixing ratio layer of carbon monoxide at 215 h Pa (hectopascals) shows their concentration at the vertical atmospheric pressure level of 215 h Pa (hectopascals) Measured in ppbv	Carbon monoxide (215 h Pa, day/night)
	Measurement of the Pollution in the Troposphere using thermal-infrared radiation	MOPITT (Terra)	Carbon monoxide (Level 2, daily, day/night, and total column) layer indicates the total amount of carbon monoxide in the tropospheric total vertical column Expressed in mole per square centimeter (mol/cm ²) for the day and night overpasses in NRT (near real time) Measurement of MOPITT NRT uses thermal-infrared radiation of 4.5 μm to develop CO total column abundance	CO (Level 2, daily day/night, total column)

Table 1 (continued)

Pollutants	Instruments and platforms used for assessing air quality	Acronyms for the platforms used	Description of the platforms	Measurement units
Sulphur dioxide (SO ₂)	Atmospheric Infrared Sounder	AIRS (Aqua)	AIRS Prata SO ₂ Index Day/Night expressed in Dobson Units (DU) Derives parameter from the Level 1B Near- Real Time Infrared (IR) calibrated and geolocated radiances, (AIRBRAD_NRT) Sensor and imagery resolution are 45 and 2 km respectively Temporal resolution is once daily	Sulphur dioxide (SO ₂) (day/night Prata Algorithm)
	Microwave Limb Sounder	MLS (Aura)	Microwave limb sounder SO ₂ mixing ratio layer at 147 h Pa (hectopascals) expressed in ppbv Sensor and imagery resolution are 5 and 2 km respectively Temporal resolution is twice daily (day and night)	Sulphur dioxide (147 h Pa, day/night)
	The Ozone Monitoring Instrument	OMI (Aura)	The ozone monitoring instrument SO ₂ lower tropospheric layer specifies the column density of SO ₂ in the lower troposphere which corresponds to 2.5 km center of mass altitude (CMA) Expressed in Dobson Units	Sulphur dioxide Planetary boundary Upper, middle and lower stratosphere and troposphere
	Ozone Mapping and Profile Suit	OMPS (Suomi NPP)	Ozone mapping and profile suits NRT products complement the sulfur dioxide near real time data already available from Ozone monitoring instrument	SO ₂ Planetary boundary upper, middle and lower stratosphere and troposphere
Nitrous oxide (N ₂ O)	Microwave Limb Sounder	MLS (Aura)	The microwave limb sounder nitrous oxide mixing ratio layer at 46 h Pa (hectopascals) Measured in ppbv	Nitrous oxide (46 hPa, day/night)

Table 1 (continued)

Pollutants	Instruments and platforms used for assessing air quality	Acronyms for the platforms used	Description of the platforms	Measurement units
Aerosol index (AI)	Ozone Monitoring Instrument The Ozone Mapping and Profiler Suite	OMI (AURA) OMPS (Suomi NPP)	Sensor and imagery resolution are 25 km and 2 km respectively with daily temporal resolution The unitless range of the AI=0.00 to ≥ 5.00, where 5.0 specifies higher concentration of aerosols that can decrease the visibility and impact human health Aerosol index signal for pyrocumulonimbus (pyroCb) events, can be much larger than 5.0 that are both dense and high in the atmosphere To offer better near real-time imagery for these high aerosol index events, the pyroCb product with an upper aerosol index limit of 50.0 It has sensor and imagery resolution as 50 and 2 km respectively with daily temporal resolution	UV Aerosol and Aerosol index Aerosol Index (Pryrocumulonimbus)
Aerosol Optical Depth (AOD)	Moderate Resolution Imaging Spectroradiometer	MODIS (Terra) MODIS (Aqua)	(MODIS (Terra)) L2 Aerosol, 5-min Swath 10 km MODIS (Aqua) L2 Aerosol, 5-min Swath 10 km	Ocean and Land: Aerosol optical depth 3 km Land: Deep Blue Aerosol Angstrom Ocean: Dark target aerosol angstrom Land: deep blue aerosol optical depth Land and Ocean: Merged DT/DB aerosol optical depth
Visible Infrared Imaging Radiometer Suite Moderate Resolution Imaging Spectroradiometer	Visible Infrared Imaging Radiometer Suite Moderate Resolution Imaging Spectroradiometer	VIIRS (Suomi NPP) MODIS (Terra/Aqua) MODIS (Aqua) MODIS (Terra)	Deep Blue Aerosol L2-6Min Swath: 6 km L3 Value-added AOD MODIS (combined) MODIS (Aqua) MODIS (Terra)	Deep blue aerosol angstrom exponent Value Added AOD

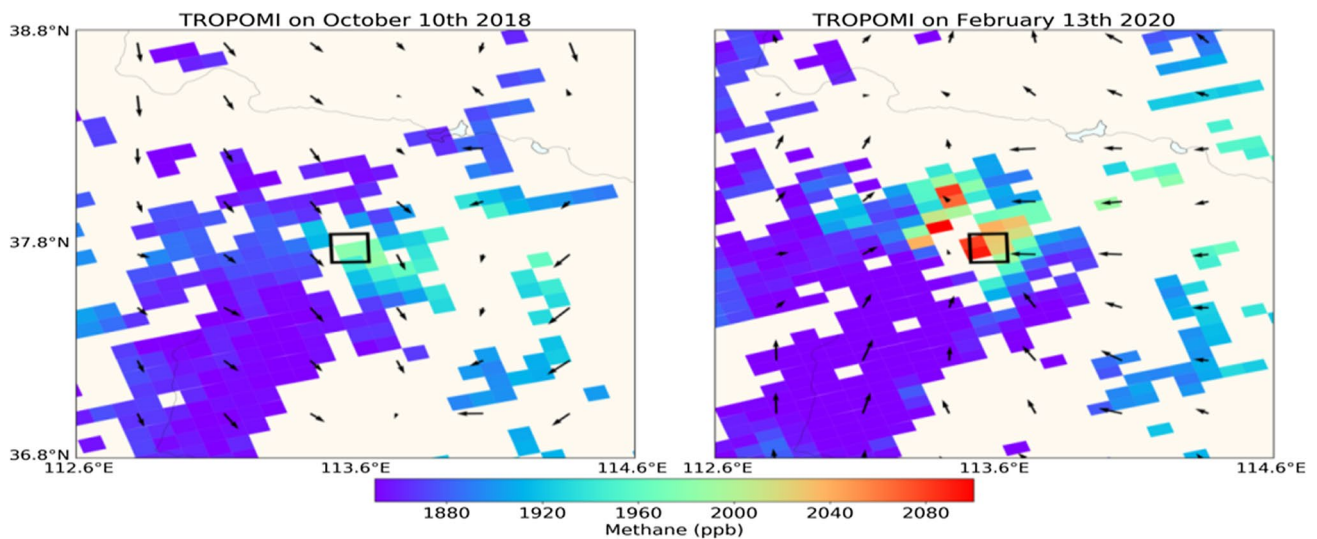


Fig. 1 TROPOMI CH₄ measurements over a coal mine in the Shanxi province, China (Source: ESA 2020)

Changes in NO₂ levels

Nitrogen dioxide is a short-lived pollutant, and its levels in the atmosphere can indicate level of economic activities, comparable to past emissions scenario and economic slowdowns. Changes in NO₂ levels are responsive to changes in meteorological conditions. There are many factors, such as sunshine hours, changes in daily wind speed and temperature, that affect the residence time and the dispersal of gas in the atmosphere. In the global NO₂ emission basket, fossil fuel combustion contributes 65% and the remaining 35% is contributed by forest fires, lightning and soils (Smith 2020). It is also true that various structural measures and emission regulations helped in improving the air quality, particularly the long-term declines in NO₂ concentrations. Oxides of nitrogen are precursors of secondary inorganic aerosols formation that has major implications for climate and human health.

A collaborative study done by atmospheric experts from the European Space Agency (ESA), Royal Netherlands Meteorological Institute (KNMI) and Royal Belgian Institute for Space Aeronomy (BIRA-IASB), determined how COVID-19 pandemic had an impact on NO₂ pollution (Bauwens et al. 2020). A sharp decrease in NO₂ levels, by about 40–55% was observed in many cities in India and China (Figs. 3 and 4). An unexpected decrease in NO₂ pollution in the range of 50–70% was observed in many cities of China due to strict lockdowns enforced in February 2020 (Fig. 5). There was a significant decrease in NO₂ pollution in Western Europe and the United States in the range of 20–38%. Cities in Europe such as Madrid, Barcelona and Milan observed a decline of NO₂ pollution in the range of 30–40% as compared to 2019 for the same period (Bauwens et al. 2020).

During the lockdown, a reduction of 30% in the NO₂ column was observed over North America and Europe in spring season. The column reduced by almost 50% in various parts of the Asia over the same period (Berman and Ebisu 2020). Furthermore, levels of particulate matter having size smaller than 2.5 microns were also reduced upto 35% over northern China (Smith 2020).

Based on 800 local ground-level monitoring stations in China, huge fall in levels of NO₂ was observed which further led to a concurrent increase in concentration of other secondary pollutants like ozone (Shi and Brasseur 2020). Ozone is a known secondary pollutant which is formed in the troposphere when favorable conditions like intense sunlight and high temperatures catalyze chemical reactions. It was found that the concentration of ozone enhanced by a factor of 2.0 ± 0.2 with mean reduction in PM_{2.5} by 30% and NO₂ levels by 40–60% in the Wuhan city during the lockdown period. Ozone is destroyed by nitrogen oxides, therefore, when nitrogen dioxide levels decreased, the ground-level ozone increased. This causes formation of nighttime NO₃ radical with increasing oxidizing ability leading to the development of secondary particulate matter (Huang et al. 2020).

In Barcelona, Spain, a momentous drop was observed for black carbon and NO₂ levels (–45 to –51%), which are primarily caused by traffic emissions (Fig. 6). The PM₁₀ levels declined by 28–31%. However, as expected with lower NO₂ levels and VOC-limited environment, O₃ levels increased by 33–57% (Tobías et al. 2020) (Fig. 7).

Reduction in tropospheric NO₂ concentration was reported over Southwest USA based on satellite images released by NASA for the period of March 25–April 25, 2015–2019 (average) as compared with average of March 25–April 25, 2020 (Fig. 8). San Francisco reported 22%, Los

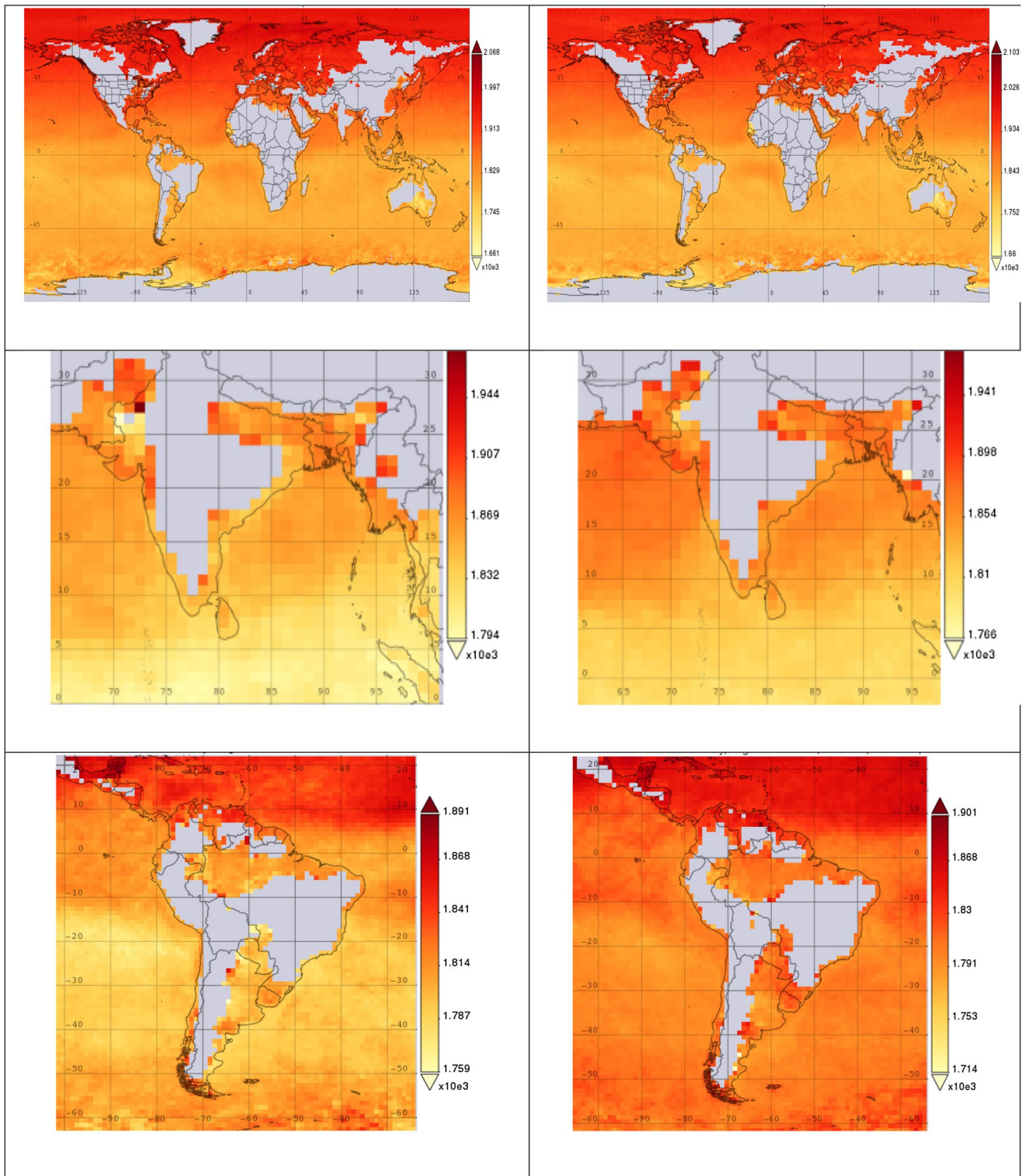


Fig. 2 Time average map of methane, mole fraction in air (Daytime/ Ascending, AIRS-only) in ppbv over different parts of the world—the left-side images are from March, 2019 to May, 2019 while the right-

side images are from March, 2020 to May, 2020 (Source: Giovanni online data system, established and maintained by the NASA GES DISC)

Fig. 3 Concentration of NO_2 before lockdown (left) and during the lockdown (right) over India as measured by Sentinel-5P (Source: ESA 2020, sentinel online)

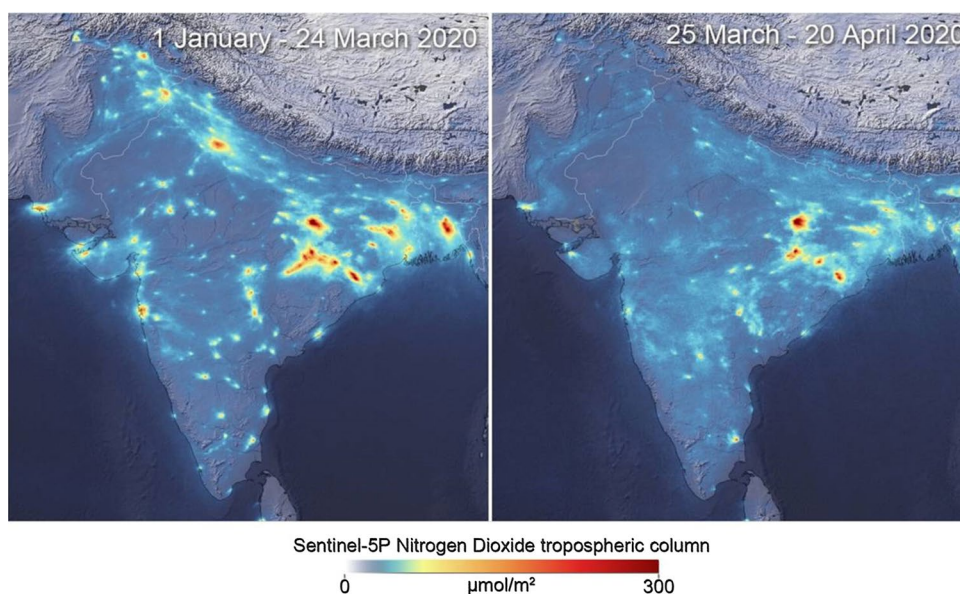
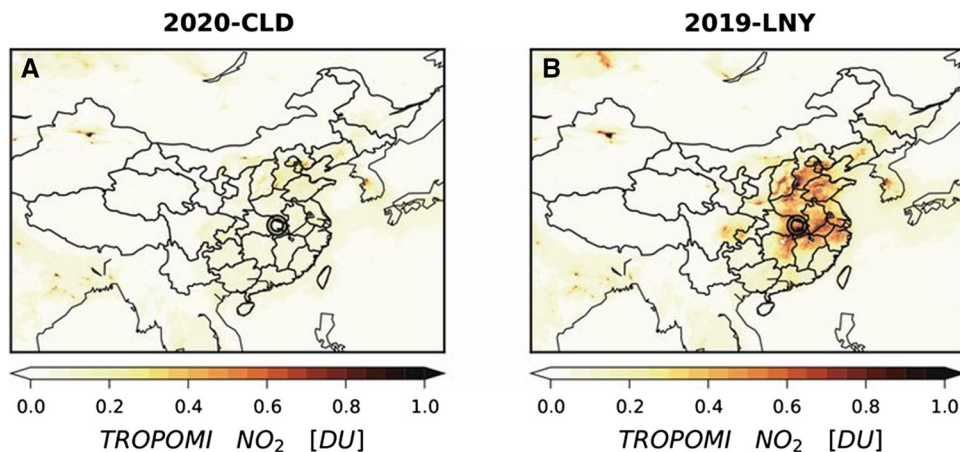


Fig. 4 NO_2 level averaged over the COVID-19 lockdown period for three weeks during Jan. 23 to Feb. 13, 2020 (left) as compared to similar timeframe in 2019, the circle in the map indicates Wuhan city, China (Source: Le et al. 2020)



Angeles 31%, San Diego 25%, Phoenix 16% and Las Vegas 10% decrease in NO_2 concentration due to lockdown. Similar decrease in tropospheric NO_2 concentration was reported in California as show in the Fig. 7 (Fig. 9).

Satellite images released by NASA showed a major decrease in tropospheric NO_2 concentration in Florida, Northeast USA, Southwest USA and Indian subcontinent during lockdown in 2020 in wake of checking COVID-19 pandemic (Fig. 10). In Indian Subcontinent, when averaged tropospheric NO_2 concentration of March 25–April 25, 2020 period was compared with 3-years average of March 25–April 25, 2017–2019 period, it showed a decrease in NO_2 concentration in Delhi by 56%, Kolkata by 23%, Mumbai by 38%, Lahore by 45%, Dhaka by 45% and Karachi by 36% (Fig. 10d).

NO_x , which is the sum total of NO (nitrogen oxide) and NO_2 , along with VOCs (volatile organic compounds) are the main precursors of photochemical production of

ground-level tropospheric ozone (O_3). The high concentration of ozone is toxic to all forms of life—including crops and human beings. The rate of ozone formation within the troposphere varied depending upon height with maximum at ground level. In the Northern Hemisphere, the production of O_3 is low in winter season at mid- and high-latitudes due to reduction in sunshine hours and temperature. The production of O_3 increases as spring and summer advances. Even though O_3 does not decrease by the same proportion as NO_x , a reduction in ground level O_3 concentrations is expected with reducing NO_x levels. However, evidence of increased tropospheric ozone levels has been reported during lockdown at several places (Korhale et al. 2020). The increase in concentration of ozone is due to the lower titration of ozone through NO because of the sharp decrease in the concentration of local NO_x by road transportation. In an unpolluted region, the reaction of VOCs with OH^- radicals dominate when the ratio of VOCs (including CO) to NO_x is

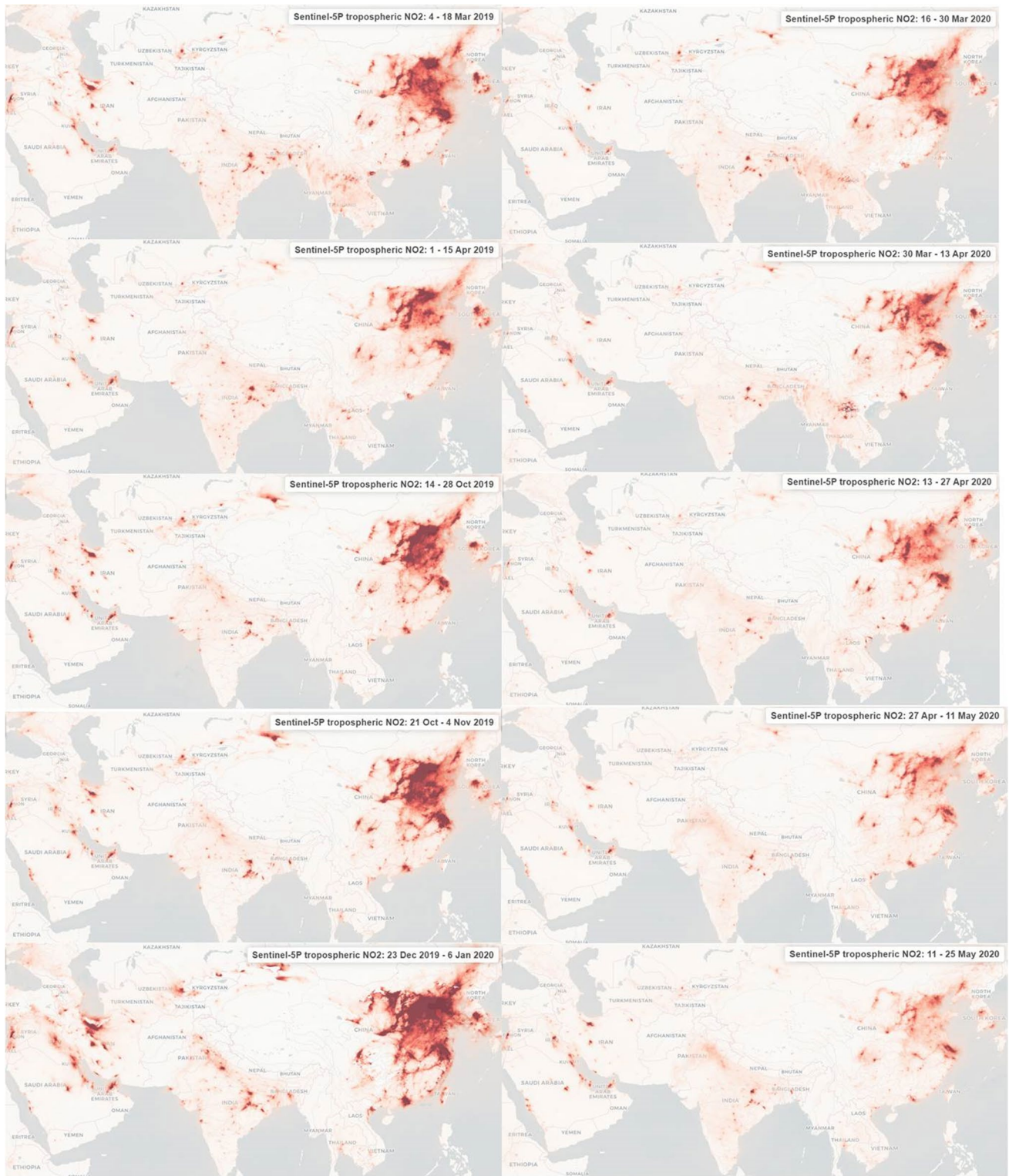


Fig. 5 Copernicus Sentinel-5P satellite data exhibiting sharp decreases in NO₂ levels over China and India during 2020 as compared to 2019 (left)

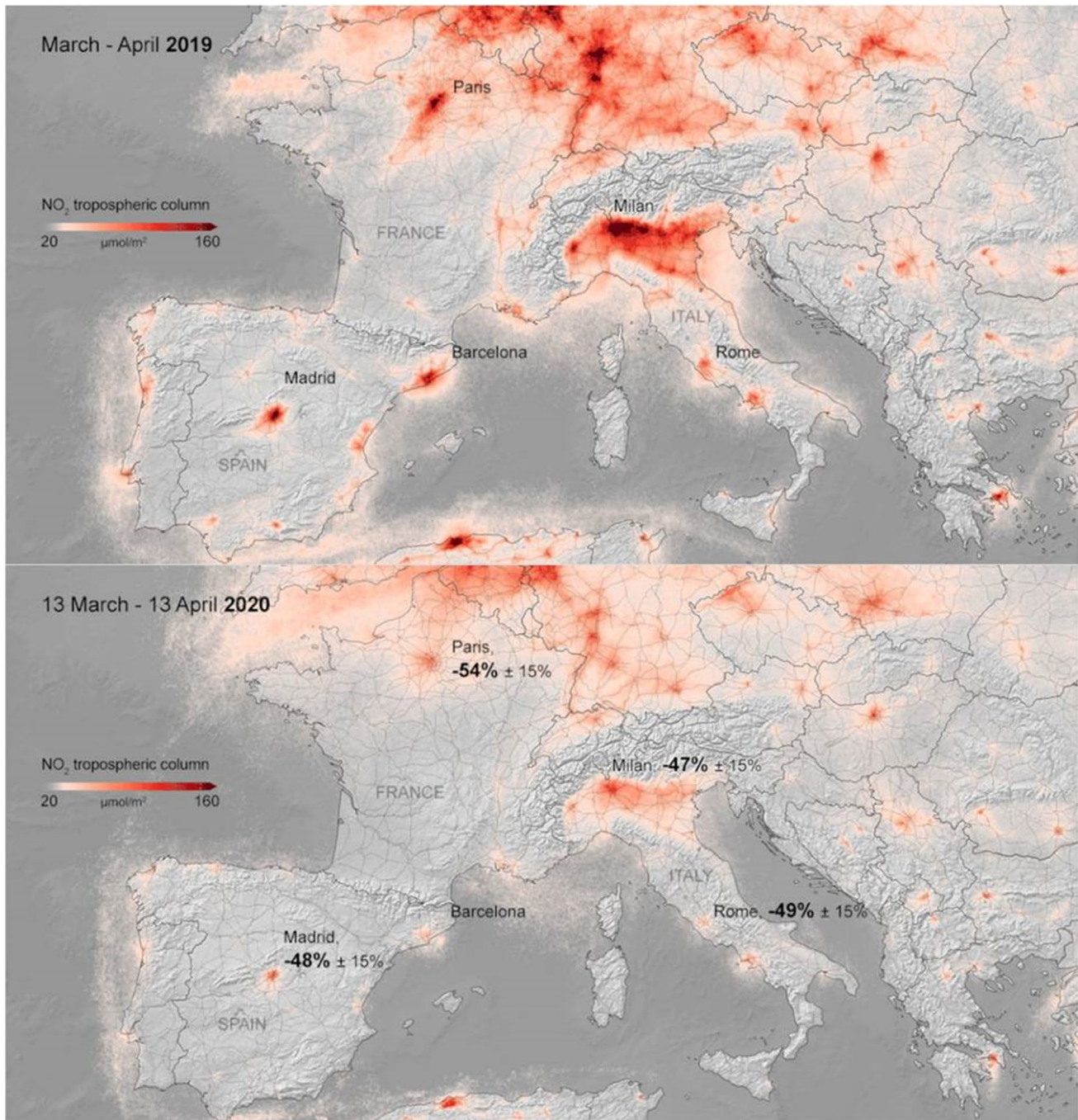
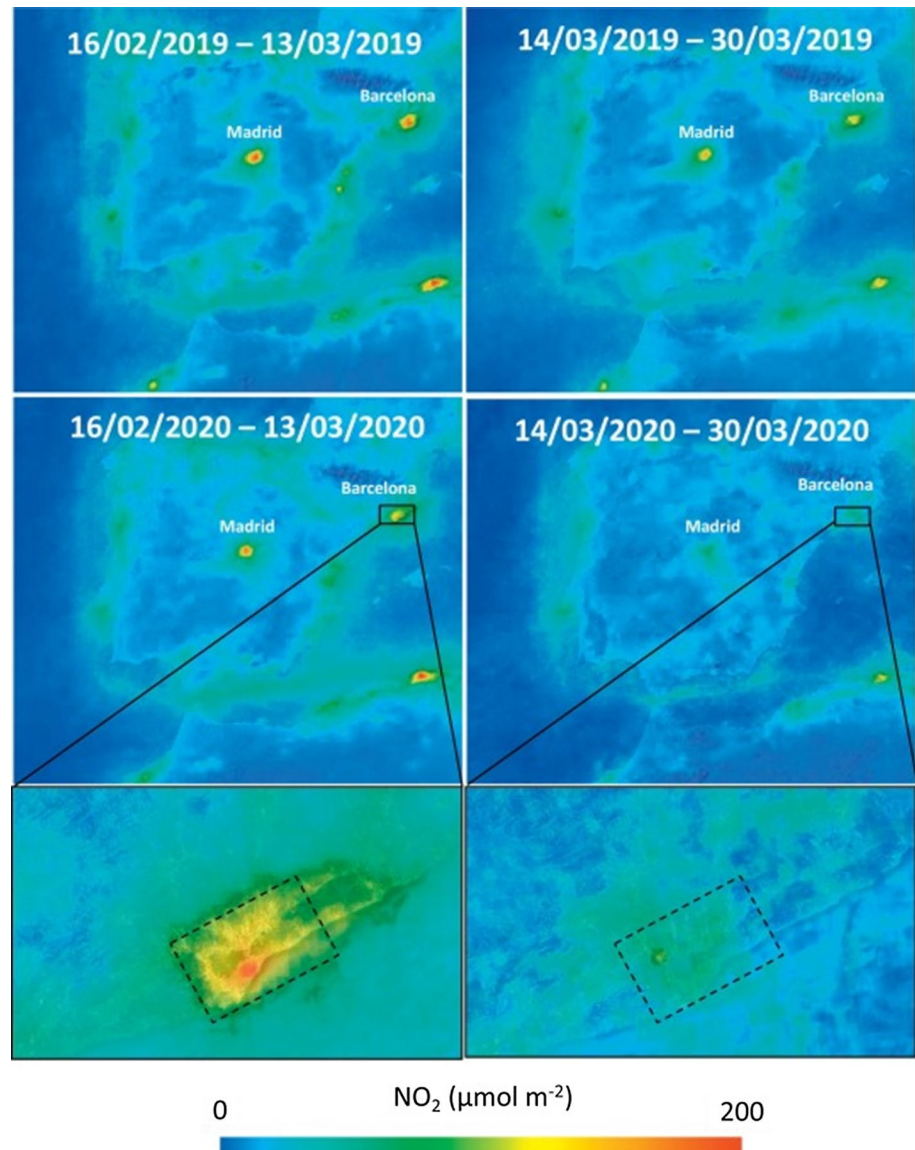


Fig. 6 Copernicus Sentinel-5P satellite data showing major drop in NO₂ levels over various cities of Europe—including Madrid, Rome and Paris (Source: ESA)

higher, consequently enhancing ozone production. Overall, the major effect of complete lockdown events on the concentrations of NO_x, PM and O₃ came from the major reduction in surface transportation. Under VOC-limited conditions and during the lockdown the main cause of the greater O₃ concentrations in cities is due to the drop in NO_x emissions to a lower ozone titration by NO. Secondly, as PM emissions

were lesser, the higher solar radiation preferred production of ozone and caused rise of ozone precursors releases (Sicard et al. 2020). This is also due to the complex variations in emissions profiles during the lockdown and indicates how mass reductions of distinct contaminants can cause a rise in others, further triggering variations in wider tropospheric composition and reactivity. During the lockdowns,

Fig. 7 Average concentration of ambient tropospheric NO₂ as quantified by TROPOMI-ESA in the Iberian Peninsula during comparable time periods in 2019 and 2020 (Source: Tobías et al. 2020)



a drop of approximately 70% of the total NO_x releases was observed, primarily due to the major drop in vehicular density on the roads. At the time of lockdown, with less NO in the ambient air to sustain the photo-stationary responses that terminate ozone molecules, the overall ozone formation went up. This shows that reducing the development of secondary contaminants such as ozone is challenging and requires strict measures to control it.

Global CO₂ emission reduction during the lockdown

Several countries throughout the world experienced significant drop in CO₂ concentration of more than 40% than the previous year due to lockdown restrictions during 2020. As

a result, the air quality improved greatly and the risk of several respiratory diseases, for example bronchitis, asthma and other lung diseases also decreased markedly (Watts 2020). In China, which is accountable for the world's highest carbon emissions, a drop of around 250 Mt of carbon sources was observed, which is more than half of the annual output for the whole UK. Correspondingly, in Europe, the reduction of carbon sources of around 390 Mt as a result of lockdown was reported. In USA, CO₂ emissions reduced to ~40% due to reduction in commuter vehicles, which is one of the major sources of CO₂ emissions. A decrease of ~44% car sells and fossil fuel consumption in London also resulted in decreased emissions (Paital 2020). A different study by Sharma et al. (2020) in 22 cities of various regions of India for the period of 16 March–14 April 2020 described substantial decrease in AQI, which were up to 29% (East), 32% (West), 15%

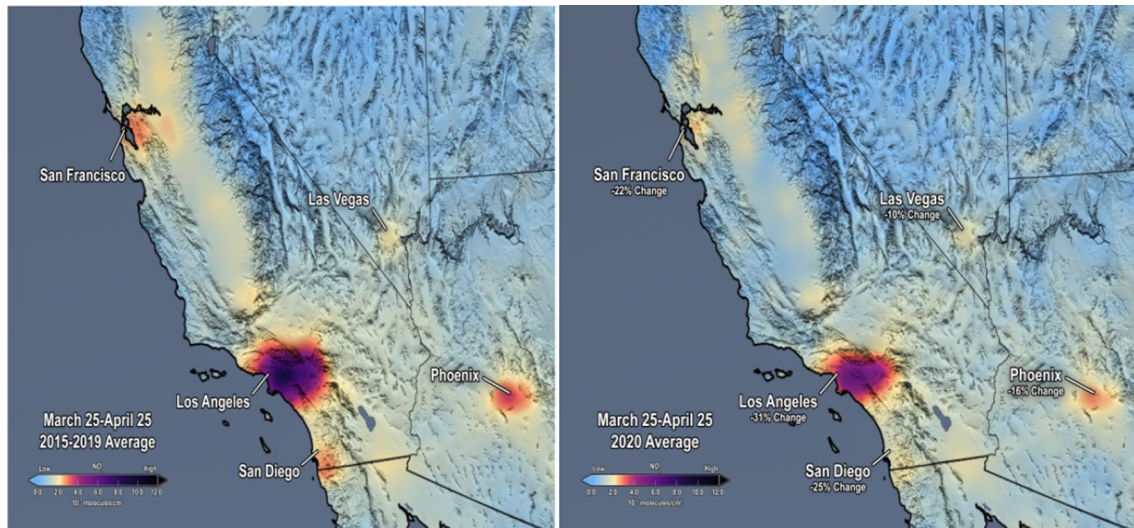


Fig. 8 Tropospheric NO₂ column over Southwest USA during March 25–April 25, 2015–2019 (averaged) compared with March 25–April 25, 2020 (averaged) (Source: NASA 2020b)

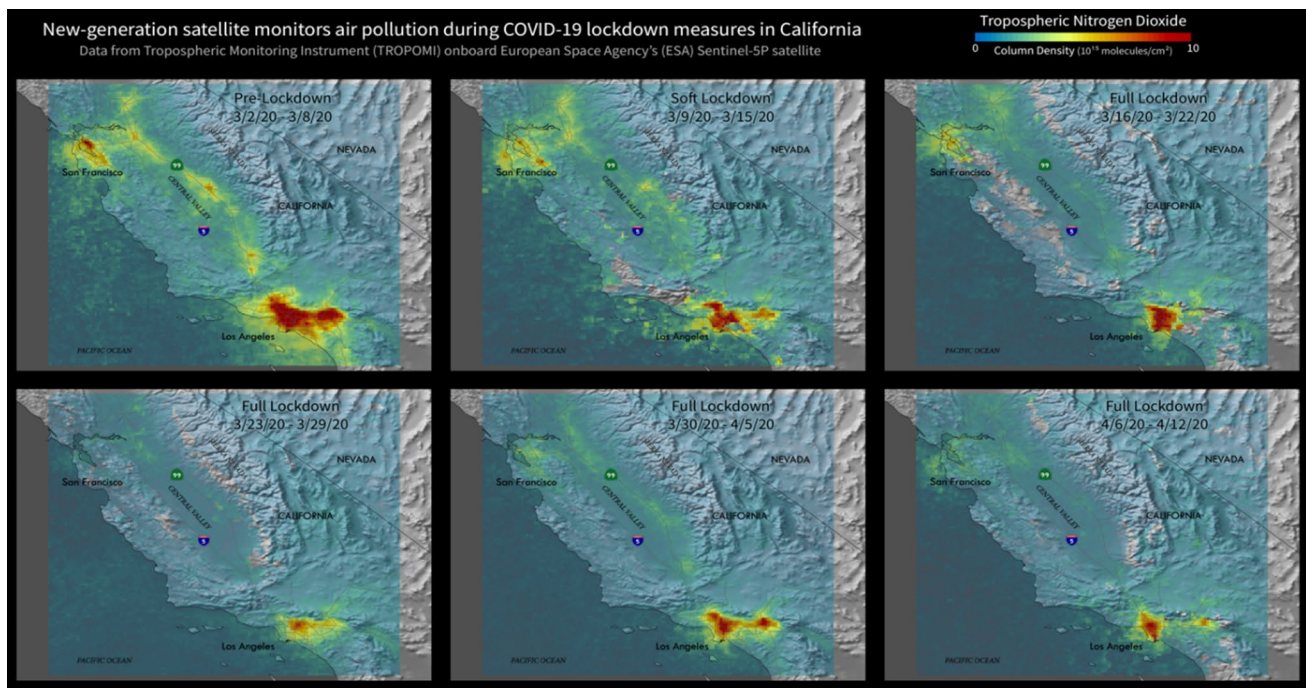


Fig. 9 Decrease in tropospheric NO₂ concentration during COVID 19 lockdown in California (Source: NASA 2020b)

(Central), 44% (North) and 33% (South) as compared to several preceding years for the same monitoring period. Duteilh et al. (2020) obtained data from the TROPOMI which reported 6% reduction in CO₂ concentration worldwide with 25% drop in China alone. They also clarified that mortalities might have also reduced due to decline in air pollution. Paital (2020) evaluated the influence of air pollutants such as

CO₂, NO₂, PM and weather variables globally on the infection and rate of thinning out of corona virus. Air pollution was associated to an elevated risk of corona virus infection and consequently, early and complete lockdown (particularly in China and India) led to noteworthy drop in the concentration of CO₂ as explained in above studies. However, such deviations in CO₂ concentrations were temporary and are

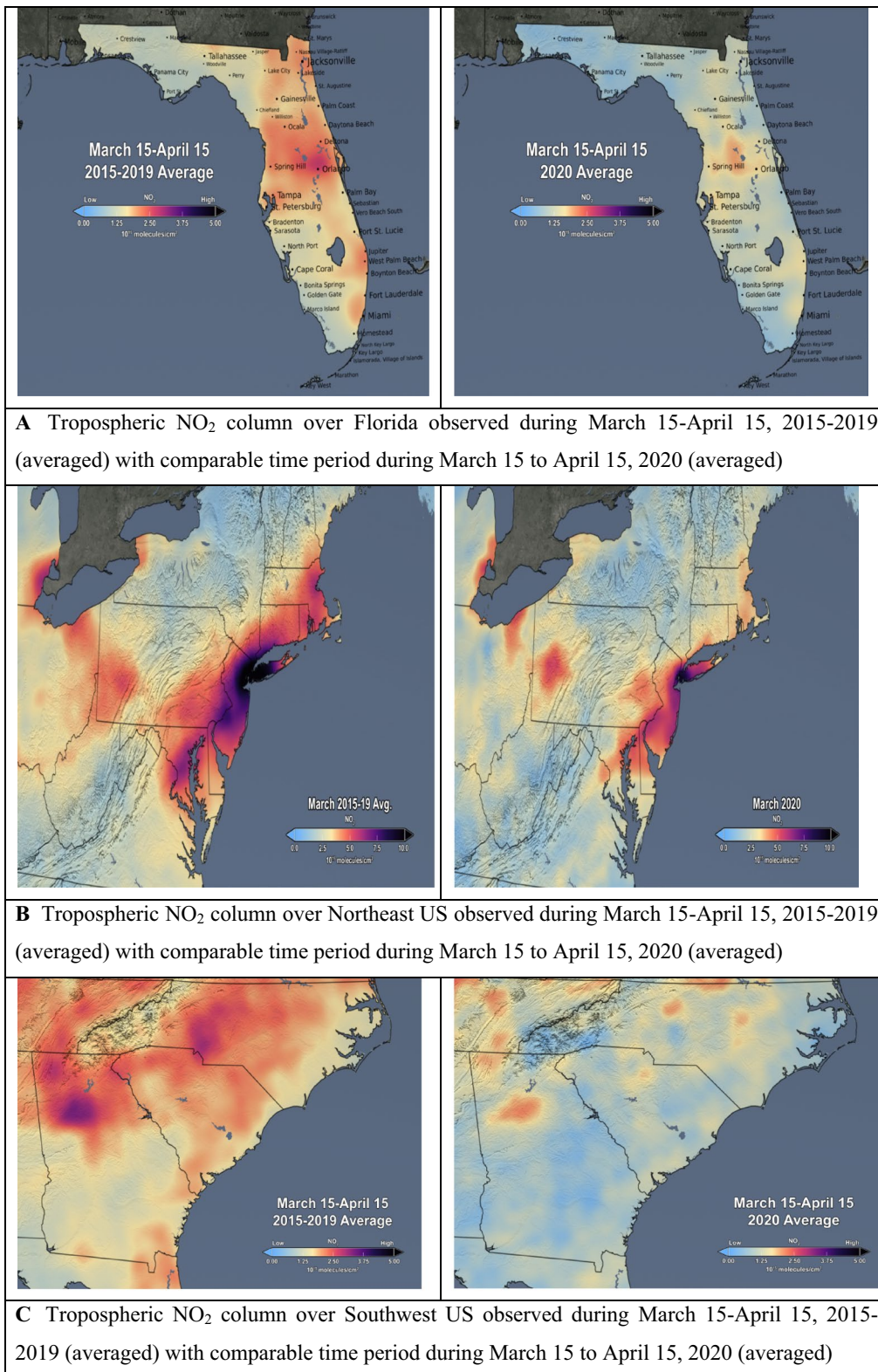


Fig. 10 a–d Satellite images showing decrease in tropospheric NO₂ concentration in Florida, Northeast USA, Southwest USA and Indian sub-continent during lockdown in 2020 (Source: NASA 2020c)

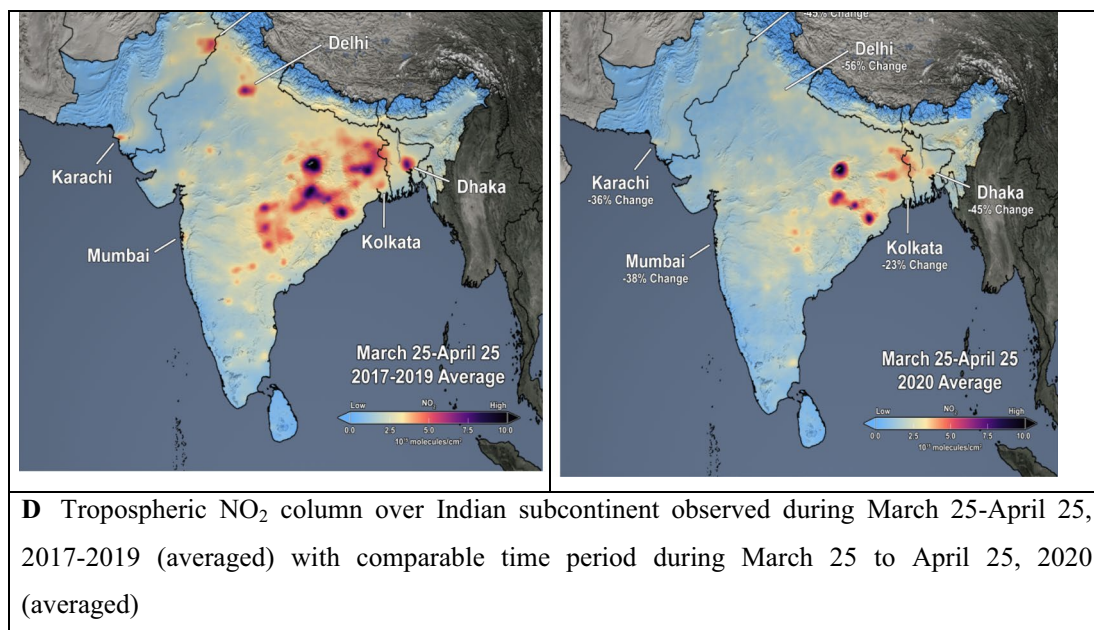


Fig. 10 (continued)

rising back after lockdown has been lifted (Watts 2020). Satellite images from NASA exhibited 25% reduction in carbon emissions in China approximating to 6% of the global emissions in Feb 2020 majorly due to quarantine imposed reduction in transportation activities (Isaifan 2020).

Changes in SO₂ levels

There is a rapid increase in the emissions of SO₂ in India during the past one decade due to increase in traffic network, coal-based power plants and biomass burning. The higher levels of emissions intensify the problem of haze over the several parts of the nation, especially during winter season when the air is relatively stable. However, their concentration dropped drastically due to the extensive restriction on social, commercial and industrial activities since the lockdown imposed on 25 March 2020. The rapid decline was primary due to restricted traffic movements and industrial activities worldwide. It is observed that concentrations of SO₂ in polluted regions of India have dropped upto 40% during the second phase of the lockdown between April 2019 and April 2020. Using remote sensing data from the Copernicus Sentinel-5P satellite, from the European Union Copernicus Programme, a large reduction in concentrations of SO₂ throughout the country is observed during the lockdown (Fig. 11).

The darker shades of purple and red color represent the higher concentrations of SO₂ in the atmosphere. The black dots in the picture indicate the sites of large coal-fired

thermal power plants where SO₂ emissions are relatively high. The darker emission zones are represented by three states namely Odisha, Jharkhand, and Chhattisgarh which have large number of coal-fired thermal power plants. NASA satellite images of Indian subcontinent for the years 2017–2019 compared with March 25–April 25, 2020 in three highlighted Area 1, Area 2 and Area 3 show decrease in SO₂ emissions—concentration of SO₂ in Area 2 decreased by 25%, and by 12% in Area 3 of power generation whereas Area 1 showed increase in SO₂ concentration by 83% as shown in the Fig. 12.

Measurement of reduction in aerosols through MODIS

Aerosols over Indian region were lowest in the past two decades during the lockdown period (NASA 2020a). NASA's Terra and Aqua satellites (Sentinel-5P and AURA) use Moderate Resolution Imaging Spectroradiometer (MODIS) to measure both size distribution and optical depth (AOD) of ambient aerosol globally every hour. A marked reduction in the level of AOD was observed within few weeks of reduced anthropogenic activities. The images of Indian sub-continent taken during March 31–April 5 for 2016–2020 from NASA Earth Observatory exhibited depleting AOD extents over Indian region. In addition, the AOD average in 2020 (lockdown period) is much lower than the average during 2016–2019 (Fig. 13). It is clear from the images that light yellow pixels, tan pixels and dark brown pixels and illustrate

Fig. 11 Averaged SO_2 concentrations in April 2019, compared to April 2020 and location of power plants in India, 1 Dobson Unit (DU)=0.4462 mmol m^{-2} . (Source: Sentinel-5P satellite European Union Copernicus Programme)

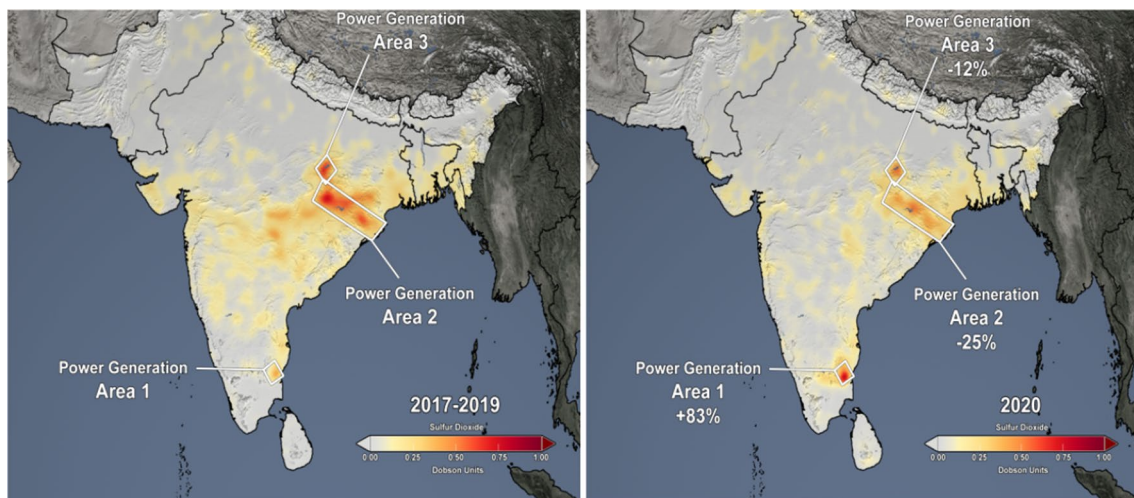
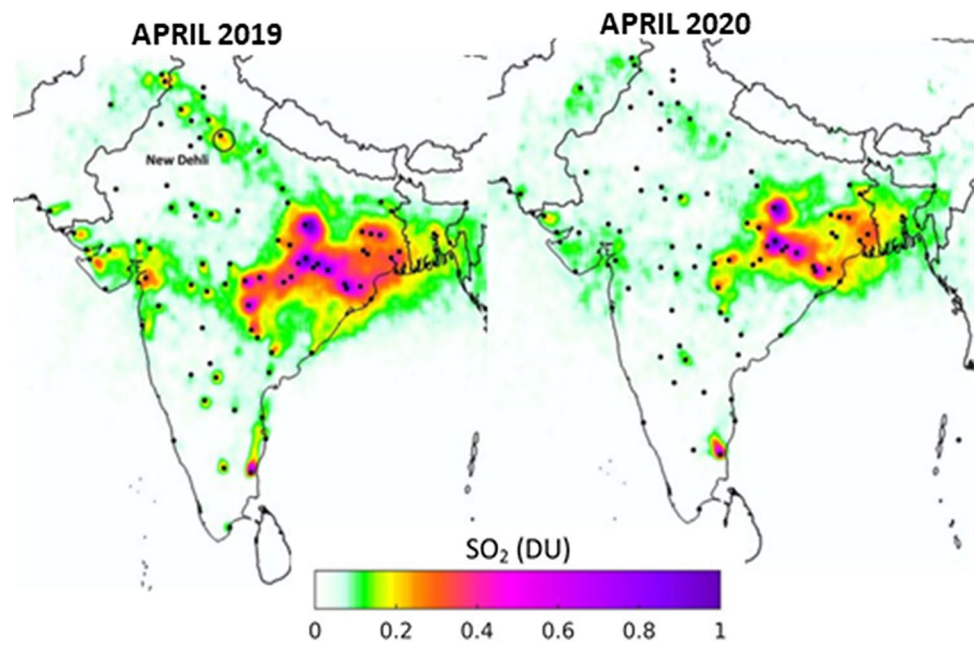


Fig. 12 Tropospheric SO_2 column for the averaged years during 2017–2019 (left) as compared with time period during 25 March–25 April, 2020 in the Indian subcontinent (Source: NASA 2020c)

the small to negligible, lower to moderate and high aerosol concentrations respectively (Gautam 2020). Reliability and accuracy level of various satellites used for monitoring air pollutants in the atmosphere is provided in the Table 2.

Learning from the pandemic: stronger policy regime needed to control emissions

Despite global pledges to reduce the emissions, the air quality is witnessing significant peaks in stark contradiction to the worldwide efforts in reducing GHGs. The

lockdown period also indicated failure to meet many binding targets of emission reductions by large emitters such as China and the US. The short-term emissions reductions indicated the need for several policy level challenges along with multiple forms of international cooperation and deeper engagements (Fig. 14). The pandemic and deteriorating air quality standards both have potentially distressing global implications which need quicker response framework at scale for any future crises (Klenert et al. 2020). There is also a need for rapid remediating interventions from both public and private sectors (Goulder 2020). The slower response in phasing

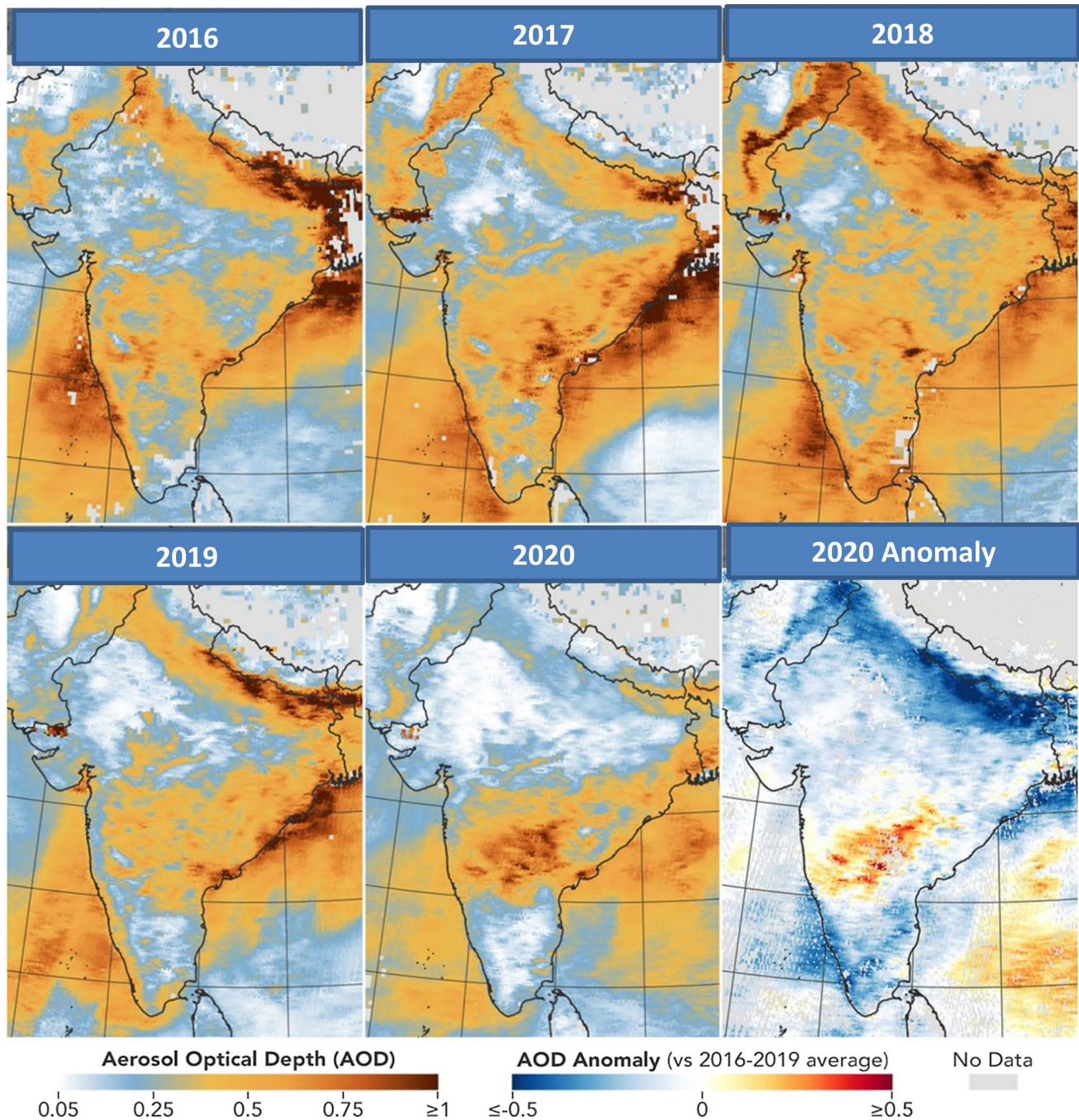


Fig. 13 Aerosol optical thickness (Terra/Modis) over Indian sub-continent during March 31–April 5 in 2016, 2017, 2018, 2019 and 2020 (NASA 2020b)

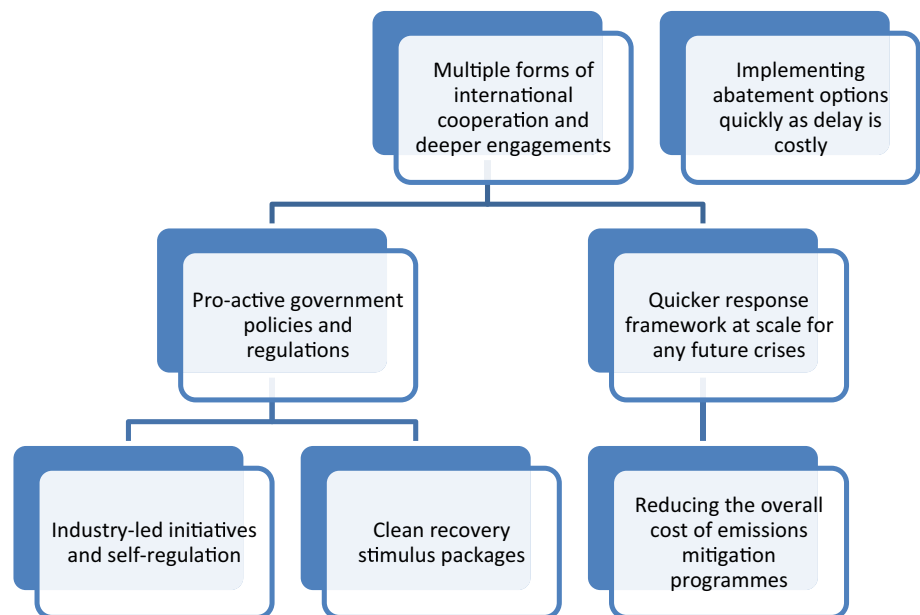
out polluting industries and technologies locks local and regional economies into carbon-intensive futures that further reduce flexibility in developing future mitigation strategies.

The lockdown imposed only a limited window to reduce the emissions not because of the structural measures, but due to a sudden and abrupt closure of the pollution sources. The global methane emissions maintained a steeply increasing

trend, indicating the dominance of oil and gas industry and lower impacts of policies and regulations. The response of the industry has also been slow in cleaner technology investment.

Table 2 Reliability and accuracy level of various satellites used for monitoring air pollutants in the atmosphere (Wang et al. 2020)

Satellites	Monitoring Parameters	Methods	Reliability	Accuracy (%)
MODIS, Himawari-8, GF-1/4/5, HJ-1	AOD	Dense dark vegetation and multi-angle polarization	Consistent for total column concentration	80–85
MODIS, GF-1/4/5/6, HJ-1	PM _{2.5} , PM ₁₀	Regression models, network models	Consistent when ground observation sites are adequate	70–80
OMI, AIRS, Sentinel-4/5P, GF-5, GOME	SO ₂	DOAS (differential optical absorption spectroscopy), BRD	Difficult	60–70
OMI, GOME, Sentinel-4/5P, GF-5	NO ₂	DOAS	Consistent for total column concentration	80
OMI, GOME, Sentinel-4/5P, GF-5, AIRS	O ₃	DOAS	Consistent and dependable for total column	95
GF-5 GMI, GOSAT, AIRS	CH ₄	OE (optimal estimation)	Consistent	98.5
GF-5 GMI, GOSAT, OCO2	CO ₂	OE (optimal estimation)	Consistent	99

Fig. 14 Policy strategies needed to control emissions

Conclusion and future directions

The various satellite observations unequivocally show that Northern China, Western Europe, Indian-subcontinent and the US witnessed a substantial decline in air pollution during the lockdown period, as compared to the same time last year. It is evident that the sharp decreases in air pollution are mainly credited to the lockdown measures taken to contain the spread of the Covid-19 pandemic. The period of lockdown witnessed sharp reductions in surface and air traffic movements and industrial activities. As several countries around the globe enforced lockdowns, a broad spectrum of indicators showed massive decline in electricity demand, transport use and industrial activities with shift in working hours and reduction in mobility and

working patterns. However, such sudden reductions were not due to structural changes or quality enforcements, but due to restraining of the population's mobility and shutting down of a large number of commercial and industrial units. The levels are again going up as the lockdown phase eased off. In most parts of the Europe, a similar decline in emissions, though limited to 20% was observed during the economic slowdown caused by the global recession (Castellanos and Boersma 2012). The available data shows that it is difficult to attribute the decline in emissions solely to the pandemic, given that there are numerous reasons of falling demand of fossil-fuel during March 2020, relative to the same month in preceding years. The lockdown period provided a unique opportunity to study the ambient environment and assess the effects of the cutback of various emission sources and to evaluate

introduction of stricter air quality standards and regulatory policies. This requires for a global effort to frame more stringent regulatory standards and climate policies so that drastic improvements in air quality could be achieved. For accurate and early warning of poor air quality, satellite monitoring over a large area can play a significant role in emission surveillance, from the point of stricter regulation and structured control management. There is also a need of refining the modeling techniques for better prediction of air quality (Dentener et al. 2020). For strengthened scientific strategies to control emissions, further analysis is urgently needed over longer time periods to substantiate the changing emission profile as observed in column changes observed from various satellites. This information is crucial because emission scenarios give people and policy makers various options to lessen the risk of exposure of poor air by taking appropriate measures. Various satellite images are available for the users which are easy to visualize and are used for mitigating the effects of bad air quality.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s42398-021-00166-w>.

Acknowledgements Analyses and visualization used in this paper were produced with Giovanni online data system developed and maintained by the NASA GES DISC. Thanks are also due to ESA's Copernicus Sentinel data.

Declarations

Conflict of interest The authors declare no conflict of interest.

References

- Bao R, Zhang A (2020) Does lockdown reduce air pollution? Evidence from 44 cities in northern China. *Sci Total Environ* 731:139052
- Bauwens M, Compennolle S, Stavrou T, Müller JF, Van Gent J, Eskes H, Levelt PF, van der AR, Veefkind JP, Vlietinck J, Yu H (2020) Impact of coronavirus outbreak on NO₂ pollution assessed using TROPOMI and OMI observations. *Geophys Res Lett.* <https://doi.org/10.1029/2020GL087978>
- Berman JD, Ebisu K (2020) Changes in US air pollution during the COVID-19 pandemic. *Sci Total Environ* 739:139864
- Castellanos P, Boersma KF (2012) Reductions in nitrogen oxides over Europe driven by environmental policy and economic recession. *Sci Rep* 2:265
- Collivignarelli MC, Abbà A, Bertanza G, Pedrazzani R, Ricciardi P, Miino MC (2020) Lockdown for CoViD-2019 in Milan: What are the effects on air quality? *Sci Total Environ* 732:139280
- Dantas G, Siciliano B, França BB, da Silva CM, Arbilla G (2020) The impact of COVID-19 partial lockdown on the air quality of the city of Rio de Janeiro, Brazil. *Sci Total Environ* 729:139085
- de Gouw JA, Veefkind JP, Roosenbrand E, Dix B, Lin JC, Landgraf J, Levelt PF (2020) Daily satellite observations of methane from oil and gas production regions in the United States. *Sci Rep* 10(1):1–10
- Dentener F, Emberson L, Galmarini S, Cappelli G, Irimescu A, Mihailescu D, Van Dingenen R, van den Berg M (2020) Lower air pollution during COVID-19 lock-down: improving models and methods estimating ozone impacts on crops. *Philos Trans Roy Soc A* 378(2183):20200188
- Dutheil F, Baker JS, Navel V (2020) COVID-19 as a factor influencing air pollution? *Environ Pollut (Barking, Essex: 1987)* 263:114466
- Ecowatch (2020) Large Methane Leaks Soar 32% Despite Lockdowns and Green Pledges. Article published on Oct. 15, 2020, available at <https://www.ecowatch.com/global-methane-emissions-rise-2020-2648215695.html>
- ESA (2020) https://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-5P/Detecting_methane_emissions_during_COVID-19
- Flórides GA, Christodoulides P (2009) Global warming and carbon dioxide through sciences. *Environ Int* 35(2):390–401
- Gautam S (2020) The influence of COVID-19 on air quality in India: a boon or inutility. *Bull Environ Contam Toxicol* 1
- Goulder LH (2020) Timing is everything: how economists can better address the urgency of stronger climate policy. *Rev Environ Econ Policy* 14:143–156
- Haddout S, Priya KL (2020) Unveiling the causes of reduction in troposphere NO₂ in two cities of Morocco during COVID-19 lockdown. *Environ Forensics* 21(3–4):237–240
- He G, Pan Y, Tanaka T (2020) The short-term impacts of COVID-19 lockdown on urban air pollution in China. *Nat Sustain* 7:1–7
- Heimann I, Griffiths PT, Warwick NJ, Abraham NL, Archibald AT, Pyle JA (2020) Methane Emissions in a Chemistry-Climate Model: feedbacks and climate response. *J Adv Model Earth Syst* e2019MS002019
- Hu H, Landgraf J, Detmers R, Borsdorff T, Aan de Brugh J, Aben I, Butz A, Hasekamp O (2018) Toward global mapping of methane with TROPOMI: first results and intersatellite comparison to GOSAT. *Geophys Res Lett* 45(8):3682–3689
- Huang X, Ding A, Gao J, Zheng B, Zhou D, Qi X, Tang R, Wang J, Ren C, Nie W, Chi X (2020) Enhanced secondary pollution offset reduction of primary emissions during COVID-19 lockdown in China. *Natl Sci Rev*
- Isaifan RJ (2020) The dramatic impact of Coronavirus outbreak on air quality: Has it saved as much as it has killed so far? *Global J Environ Sci Manage* 6(3):275–288
- Janssens-Maenhout G, Crippa M, Guizzardi D, Muntean M, Schaaf E, Dentener F et al (2019) EDGAR v4.3.2 Global Atlas of the three major greenhouse gas emissions for the period 1970–2012. *Earth SystSci Data* 11(3):959–1002
- Klenert D, Funke F, Mattauch L, O'Callaghan B (2020) Five lessons from COVID-19 for advancing climate change mitigation. *Environ Resour Econ* 76:751–778
- Korhale N, Anand V, Beig G (2020) Disparity in ozone trends under COVID-19 lockdown in a closely located coastal and hilly metropolitan of India. *Air Qual Atmos Health* 31:1–0
- Le T, Wang Y, Liu L, Yang J, Yung YL, Li G, Seinfeld JH (2020) Unexpected air pollution with marked emission reductions during the COVID-19 outbreak in China. *Science* 369(6504):702–706
- Li L, Li Q, Huang L, Wang Q, Zhu A, Xu J, Liu Z, Li H, Shi L, Li R, Azari M (2020) Air quality changes during the COVID-19 lockdown over the Yangtze River Delta Region: an insight into the impact of human activity pattern changes on air pollution variation. *Sci Total Environ* 732:139282
- Liu F, Page A, Strode SA, Yoshida Y, Choi S, Zheng B, Lamsal LN, Li C, Krotkov NA, Eskes H, Veefkind P (2020) Abrupt decline in tropospheric nitrogen dioxide over China after the outbreak of COVID-19. *SciAdv* 6(28):eabc2992
- Muller JF, Bauwens M, Stavrou T, Boersma F, van Geffen J (2019) Rest days detected by OMI and TROPOMI: on the weekly cycle of NO₂ columns over world's largest cities. *AGUFM* 2019:A32C-06

- Nakada LYK, Urban RC (2020) COVID-19 pandemic: impacts on the air quality during the partial lockdown in São Paulo state, Brazil. *Sci Total Environ* 730:139087
- NASA (2020a) <https://earthdata.nasa.gov/earth-observation-data/near-real-time/hazards-and-disasters/air-quality>. Accessed on 9 July 2020
- NASA (2020b) NASA, 2020. <https://earthobservatory.nasa.gov/images>. Accessed on 5 July 2020
- NASA (2020c) NASA, 2020. <http://svs.gsfc.nasa.gov/images>. Accessed on 8 July 2020
- Paital B (2020) Nurture to nature via COVID-19, a self-regenerating environmental strategy of environment in global context. *Sci Total Environ* 729:139088
- Sharma S, Zhang M, Gao J, Zhang H, Kota SH (2020) Effect of restricted emissions during COVID-19 on air quality in India. *Sci Total Environ* 728:138878
- Shi X, Brasseur GP (2020) The response in air quality to the reduction of Chinese economic activities during the COVID-19 outbreak. *Geophys Res Lett*. <https://doi.org/10.1029/2020GL088070>
- Sicard P, De Marco A, Agathokleous E, Feng Z, Xu X, Paoletti E, Rodriguez JJ, Calatayud V (2020) Amplified ozone pollution in cities during the COVID-19 lockdown. *Sci Total Environ* 20:139542
- Smith J (2020) Coronavirus Lockdowns and the Impact on Global Nitrogen Dioxide. Available at <https://www.naturalhealthresearch.org/coronavirus-lockdowns-and-the-impact-on-global-nitrogen-dioxide/> accessed on July 7, 2020
- Skytt T, Nielsen SN, Jonsson BG (2020) Global warming potential and absolute global temperature change potential from carbon dioxide and methane fluxes as indicators of regional sustainability—a case study of Jämtland, Sweden. *EcolInd* 110:105831
- Stavrakou T, Muller JF, Bauwens M, De Smedt I, Van Roozendaal M, Vigouroux C, Palm M (2019) How well can we constrain non-methane volatile organic compounds emissions over South America using OMI and TROPOMI formaldehyde data? *AGUFM* 2019:A22A – A31
- The Week (2020) Ozone pollution increased during lockdown: study published on June 25, 2020
- Tobías A, Carnerero C, Reche C, Massagué J, Via M, Minguillón MC, Alastuey A, Querol X (2020) Changes in air quality during the lockdown in Barcelona (Spain) one month into the SARS-CoV-2 epidemic. *Sci Total Environ* 726:138540
- Van Roozendaal M, Lerot C, De Smedt I, Theys N, Bauwens M, Cheng Z, Friedrich MM, Hedelt P, Hendrick F, Loyola DG, Muller JF (2019) Improved mapping of formaldehyde and glyoxal emission sources using S5P/TROPOMI. *AGUFM* 2019:A43J-2953
- Varon DJ, Jacob D, Scarpelli T, McKeever J, Jervis D, Maasackers JD, Pandey S, Houweling S, Aben I (2019) Quantifying methane emissions from individual point sources with the GHGSat-D satellite instrument. *AGUFM* 2019:A53F – A63
- Veefkind JP, Aben I, McMullan K, Förster H, De Vries J, Otter G, Claas J, Eskes HJ, De Haan JF, Kleipool Q, Van Weele M (2012) TROPOMI on the ESA Sentinel-5 Precursor: a GMES mission for global observations of the atmospheric composition for climate, air quality and ozone layer applications. *Remote Sens Environ* 120:70–83
- Wang Z, Ma P, Zhang L, Chen H, Zhao S, Zhou W, Wang Y (2020) Systematics of atmospheric environment monitoring in China via satellite remote sensing. *Air Qual Atmos Health* 1–13
- Watts J (2020) Climate crisis: in coronavirus lockdown, nature bounces back—but for how long. *The Guardian*

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.