Science of the Total Environment 736 (2020) 139658

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

COVID-19's impact on the atmospheric environment in the Southeast Asia region

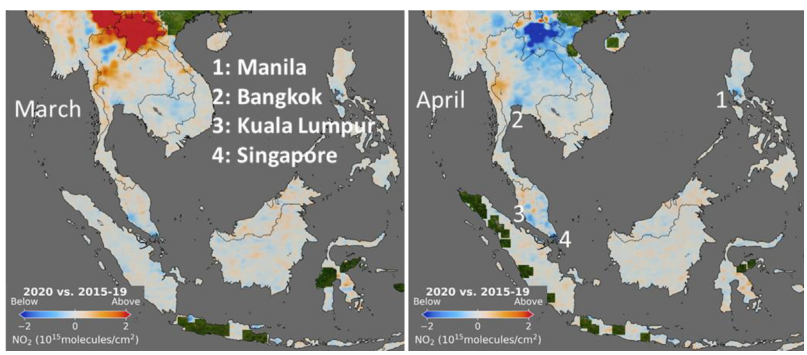
Kasturi Devi Kanniah [a,b,*], Nurul Amalin Fatihah Kamarul Zaman [a], Dimitris G. Kaskaoutis [c], Mohd Talib Latif [d]

[a] Tropical Map Research Group, Faculty of Built Environment & Surveying, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia
[b] Centre for Environmental Sustainability and Water Security (IPASA), Research Institute for Sustainable Environment, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia
[c] Institute for Environmental Research and Sustainable Development, National Observatory of Athens, 15236 Athens, Greece
[d] Department of Earth Sciences and Environment, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia

HIGHLIGHTS

- Impact of lockdown due to COVID-19 on aerosols and pollutants over Southeast Asia
- Reduction in Himawari-8 AOD at urban areas is not affected by seasonal biomass burning
- Large reductions (~27% - 34%) of tropospheric NO_2 over urban agglomerations
- Reductions in PM_{10}, $PM_{2.5}$, NO_2, SO_2, and CO are 26-31%, 23-32%, 63-64%, 9-20%, and 25-31%, respectively, in Malaysia (urban)

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 11 May 2020
Received in revised form 18 May 2020
Accepted 22 May 2020
Available online 25 May 2020

Keywords:
Aerosols
Pollutants
Himawari-8
NO_2
COVID-19
Southeast Asia

ABSTRACT

Since its first appearance in Wuhan, China at the end of 2019, the new coronavirus (COVID-19) has evolved a global pandemic within three months, with more than 4.3 million confirmed cases worldwide until mid-May 2020. As many countries around the world, Malaysia and other southeast Asian (SEA) countries have also enforced lockdown at different degrees to contain the spread of the disease, which has brought some positive effects on natural environment. Therefore, evaluating the reduction in anthropogenic emissions due to COVID-19 and the related governmental measures to restrict its expansion is crucial to assess its impacts on air pollution and economic growth. In this study, we used aerosol optical depth (AOD) observations from Himawari-8 satellite, along with tropospheric NO_2 column density from Aura-OMI over SEA, and ground-based pollution measurements at several stations across Malaysia, in order to quantify the changes in aerosol and air pollutants associated with the general shutdown of anthropogenic and industrial activities due to COVID-19. The lockdown has led to a notable decrease in AOD over SEA and in the pollution outflow over the oceanic regions, while a significant decrease (27% - 30%) in tropospheric NO_2 was observed over areas not affected by seasonal biomass burning. Especially in Malaysia, PM_{10}, $PM_{2.5}$, NO_2, SO_2, and CO concentrations have been decreased by 26–31%, 23–32%, 63–64%, 9–20%, and 25–31%, respectively, in the urban areas during the lockdown phase, compared to the same periods in 2018 and 2019. Notable reductions are also seen at industrial, suburban and rural sites across the country. Quantifying the reductions in major and health harmful air pollutants is crucial for health-related research and for air-quality and climate-change studies.

* Corresponding author at: Tropical Map Research Group, Faculty of Built Environment & Surveying, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia.
E-mail address: kasturi@utm.my (K.D. Kanniah).

https://doi.org/10.1016/j.scitotenv.2020.139658
0048-9697/

1. Introduction

Coronavirus, the novel infectious disease, was first reported in the Wuhan province, China in December 2019 (Huang et al., 2020; Chen et al., 2020). This disease (SARS-CoV-2 or COVID-19) was later spread to other countries in Asia, in Europe (mainly in Italy, Spain, France and UK), in Africa and America (mainly in the United States), and became a pandemic. COVID-19 is highly transmissible and more than 4.3 million people (confirmed cases on 16 May 2020) in 209 countries have been infected, with more than 296,000 reported deaths (16 May 2020; http://webgiscovid19.beyond-eocenter.eu/index.php), while these numbers are continuously increasing (Bai et al., 2020; Sohrabi et al., 2020; Lai et al., 2020). Some studies claim that prolonged exposure to high levels of air pollution may increase the vulnerability and mortality rates due to COVID-19 (Contini and Costabile, 2020; Liu et al., 2020), although the relative role of air pollution and aerosols to the spread of the virus and mortality rates is still under debate from the global scientific community (Conticini et al., 2020; Yao et al., 2020) and the influence of several other factors has still to be determined. However, there are some evidences, although not absolutely verified, that SARS-CoV-2 may have the potential to be transmitted via aerosols, so sanitization of surfaces, good room ventilation and clean environments are beneficial for limiting the spread of the virus (Liu et al., 2020).

Southeast Asia (SEA) was not an exception to the hit of the novel coronavirus, and several SEA countries have been hit hard by the disease since late February (WHO, 2020), but with much less deaths compared to Europe and the Unites States. A total of 66,140 confirmed cases with 2078 deaths have been reported (as of May 16) with Singapore, Indonesia, the Philippines, and Malaysia accounting for 94% of the cases and 97% of the total deaths respectively (WHO, 2020). As one of the most densely populated areas in the world, for constraining the fast spread of the disease, the SEA countries implemented a series of measures such as placing travel bans, closing international and interstate boarders, quarantine residential areas, restriction in large-scale social movement and social gatherings (including religious activities) and implementing partial/full lockdown, which included suspension of operation of public transportations, industries, shopping centres, worship places, schools and other educational institutions.

In Malaysia, COVID-19 pandemic was first reported in January 2020 (Sipalan and Holmes, 2020). However, the localized clusters began to emerge in March due to a massive religious gathering held near Kuala Lumpur in late February. Since the mid of March, active COVID-19 cases increased significantly and till 16 May 2020, the country has reported 6855 confirmed cases and 112 deaths (WHO, 2020). Consequently, the Malaysian government implemented the Movement Control Order (MCO) for two weeks starting from 18 March, which was then extended to until 9 June. With the movement control order, the Malaysian government shuts down public transport, educational institutes, busy central parks and other social interaction points in a way to curtail the spread and transmission of COVID-19.

As a result of the lockdown and the disruption in human and industrial activities in numerous countries around the world, a significant reduction in air pollution, especially in the concentration of NO_2, has been noticed in China and several European and American countries (Shrestha et al., 2020; Tobías et al., 2020; Wang and Su, 2020; Zhang et al., 2020). Recent studies by Muhammad et al. (2020), Wang and Su (2020) and Dutheil et al. (2020) have reported a NO_2 reduction ranging between 20 and 30% in China, USA, Italy, Spain and France. Data collected by the Ozone Monitoring Instrument (OMI) on board the Aura satellite (NASA) and TROPOspheric Monitoring Instrument (TROPOMI) on board the Sentinel-5P satellite (ESA) have been widely used to demonstrate the reduction of tropospheric trace gases related to pollution after the imposing of restrictive measures (e.g. lockdown) in various countries. In SEA, large cities like Bangkok, Quezon city and Kuala Lumpur have recorded reductions in Particulate Matter less than 2.5 μm ($PM_{2.5}$), emanating from vehicle exhaust and industrial activities, up to 80% during the lockdown period (Arkin, 2020). Gases and particles released from motor vehicles and industries are mostly responsible for air pollution in the large SEA cities (e.g. Kim Oanh et al., 2006; Lin et al., 2014; Pani et al., 2018, 2020), along with the seasonal forest and agricultural fires during the pre-monsoon (March–May) season (Vadrevu et al., 2015, 2019). PM can affect human health by causing respiratory problems and cardiovascular diseases, birth defects and premature death (Dominici et al., 2006; Ballester et al., 2010; Luong et al., 2019). In the urban areas of SEA, the annual-mean air pollution levels are far exceeding the limits set by WHO (20 and 10 μg m^{-3} for PM_{10} and $PM_{2.5}$, respectively) or the European Union standards of 50 and 25 μg m^{-3}, respectively, by 5–10 times and being responsible for 30–45 deaths per 100,000 capita (WHO, 2018). An increase of 10 μg m^{-3} in $PM_{2.5}$ and PM_1 is associated with 1–2% increase in risk of wheeze-associated disorders (Luong et al., 2019). Despite the various measures that have been undertaken locally to curb air pollution in SEA, the problem still remains unsolved.

Aerosol optical depth (AOD) is a measure of the attenuation of solar radiation due to light absorption and scattering by the atmospheric aerosols. Over SEA, aerosols are mainly from urban and industrial emissions (organics, sulfate, nitrate, ammonium), black carbon from fossil-fuel combustion and biofuel burning, volcanic ash, sea salts and dust transported by long distances, while during pre-monsoon extensive forest and vegetation fires occur (Chuersuwan et al., 2008; Hai and Kim Oanh, 2013; Tsai et al., 2013; Kanniah, 2014; Kanniah et al., 2016; Khan et al., 2016; Pani et al., 2018; Dahari et al., 2019). Therefore, aerosols are mixtures of various types creating hybrid particles and rendering their radiative effects highly uncertain (Pani et al., 2016). In addition, trace gases such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), ammonia (NH_3) and carbon monoxide (CO) are precursors of inorganic (sulfate, nitrate, ammonium and their mixtures, NH_4NO_3, $(NH_4)_2SO_4$, NH_4HSO_4) and organic aerosols after complex homogeneous or heterogeneous chemical reactions in the atmosphere (Pandolfi et al., 2012; Henschel et al., 2015; Kharol et al., 2018; EPA, 2020).

Therefore, the use of AOD, although being a columnar quantity, may also detect changes in the concentrations of pollutant particles in the lower troposphere. Assessing the total amount of columnar aerosol is critical not only for studying its impact on human health but also on solar radiation, cloud condensation processes, and climate change over South and Southeast Asia (e.g. Dumka et al., 2015; Pani et al., 2016, 2018; Singh et al., 2020). Since the high pollution levels is a major environmental and health issue in SEA countries, it is essential to understand the degree and the spatial extent of the decrease in air pollutants and aerosols due to restriction measures during the COVID-19 period in spring 2020. Such findings can assist in formulating more stringent policies in the post COVID-19 period, in order to maintain an acceptable air quality in this region. This study aims to investigate the effect of MCO/lockdown measures on air quality in the SEA region using satellite remote sensing and ground-based measurements with special focus on Malaysia.

2. Data and methodology

Himawari 8 is a Japanese weather satellite operated by the Japan Meteorological Agency. It was launched on 7 October 2014 and it carries the Advanced Himawari Imager (AHI) sensor, which operates at 16 bands from visible to infrared (Bessho et al., 2016). The Level 3 (L3) product of Himawari-8 is an improved version of the L2 AOD product that minimized cloud contamination (Kikuchi et al., 2018). This L3 product is reported every 1 h and it has a spatial resolution of 5 km. Aerosol products (L2 V1.0, V2.1) from Himawari-8 have been compared and evaluated against AERONET and MODIS C6.1 aerosol products over Asia and the oceanic regions with satisfactory agreement (Yang et al., 2020). Furthermore, Himawari-8 observations have been widely used for aerosol studies and for estimations of solar radiation over East Asia (Shi et al., 2018; Yan et al., 2018; Hou et al., 2020). In this study, the

Himawari-8 merged L3 AOD product, covering the period 15 July 2015 to 31 December 2019, was downloaded from the Japan Aerospace Exploration Agency (JAXA) website (http://www.eorc.jaxa.jp/ptree/index.html). Himawari-8 AODs were first evaluated against AERONET AODs in order to assess their robustness to be used for studying the aerosol patterns and spatial-temporal variability over the SEA region.

AERONET (Aerosol Robotic NETwork) is a global network for ground-based aerosol monitoring using CIMEL sun photometer that provides AOD data at 7 wavelengths with a temporal resolution of 15 min under cloudless skies (Holben et al., 1998). In this study, Level 2 (cloud screened and quality assured) data were used from 2 stations in Malaysia i.e. University Science Malaysia, Penang (5.36°, 100.30°) and Kuching (1.49°, 110.35°), 1 station (Songkhla) in southern Thailand (7.18°, 100.60°) and 1 station in Singapore (1.30°, 103.78°), in order to validate the Himawari-8 AODs during the period 15 July to 31 December 2019 for the Singapore station and from 15 July 2015 to 31 December 2018 for the rest.

The Himawari-8 L3 AOD at 500 nm was directly compared with the AERONET AODs. In order to collocate the Himawari-8 AOD, the AERONET data were averaged for $\pm$30 min of the Himawari-8 overpass time (Zhang et al., 2019). A single satellite pixel (fine scale AOD) that lies over or closest to the AERONET stations was used for the validation, a method similar to that adopted by Yang et al. (2020) and Emili et al. (2011). Statistical measures such as the root mean square error (RMSE), relative bias (RB) and mean absolute error (MAE) were used to quantify the accuracy of the Himawari-8 L3 AOD against AERONET.

The tropospheric NO_2 column density is systematically measured by the Dutch-Finnish OMI sensor on board Aura satellite, which follows a sun-synchronous orbit with an equator crossing time near 13:45 local time (NASA, 2020). OMI measures the backscattered radiation from the sun using spectral bands ranging from the ultraviolet (UV) to infrared wavelengths (Levelt et al., 2018). In this study, NO_2 concentrations were obtained from the NASA website (https://so2.gsfc.nasa.gov/no2/no2_index.html). The NO_2 maps over SEA were produced using high resolution daily gridded at 0.1° x 0.1° spatial resolution, which is then averaged over a 15-day window. Therefore, we produced maps that represent 1 March, 31 March, and 17 April (the latest available data at the time of writing the original manuscript). We also used NO_2 data averaged over 2015–2019 (baseline), in order to detect the absolute differences between 2020 and the baseline data. We did not use the NO_2 data from TROPOMI because data prior to 2020 is limited.

Furthermore, ground-based measurements of PM_{10} and $PM_{2.5}$ concentrations, along with other pollution gases, such as SO_2, NO_2, CO and Ozone (O_3), were obtained from several monitoring stations across Malaysia operated by the Department of Environment (DOE) (Kanniah et al., 2016; Kamarul Zaman et al., 2017). A total of 65 Continuous Air Quality Monitoring (CAQM) stations that are strategically located at residential, industrial, busy-traffic and rural areas provide systematic measurements of air pollution. The instruments and procedures used to regularly monitor the near-surface atmospheric aerosols and pollutants in Malaysia are described in Kanniah et al. (2016).

3. Results

3.1. Himawari-8 AOD

Initially, the Himawari-8 AODs were validated against AERONET AODs from three stations in the SEA region. The validation results show a good consistency between Himawari-8 L3 and AERONET AODs with $R^2 = 0.81$, RMSE $= 0.13$, MAE $= 0.09$, a bias of 1.38% and an overall overestimation of 1% (Suppl. Fig. 1). The excellent agreement between Himawari-8 AOD and AERONET data allows for using the satellite AOD to investigate the aerosol levels and variability in the SEA region before and during the COVID-19 period.

Composite AODs are examined and compared between three periods, covering 18 March to 30 April of the years 2018, 2019 and 2020, in order to reveal possible changes over the SEA region during the COVID-19 period in spring 2020 (Fig. 1). It should be noted that for a detailed analysis and quantification of the impact of COVID-19 on the columnar AOD over SEA, climatological and meteorological factors should be taken into consideration as well as the effect of the extensive biomass burning in this season that are independent from the restriction measures and the general lockdown. A qualitative overview shows that the SEA pollution outflow (Wang et al., 2015) over the oceanic regions has been reduced during 2020, compared to the previous years, as also observed over the southern China Sea due to restriction measures and the general lockdown in China (Zhang et al., 2020; Wang and Su, 2020). Lower AODs are also seen over the northern Bay of Bengal, which is highly affected by the Ganges valley pollution outflow (Kharol et al., 2011; Srinivas and Sarin, 2014). However, higher AODs over the northern parts of the peninsular SEA (northern Thailand and Laos) are seen in 2020, despite the restriction measures in anthropogenic activities and malfunction in industries. These high AODs, which are characteristic for the pre-monsoon season, are attributed to forest and vegetation fires (Biswas et al., 2015; Pani et al., 2018; Vadrevu et al., 2019), being responsible for the haze conditions usually covering the whole Indochina (Gautam et al., 2013; Kanniah et al., 2016).

Besides the large spatio-temporal variability in AOD over SEA, a close inspection into the major cities in the region (Fig. 2) shows reduction in AOD values around Kuala Lumpur (0.23, 0.34 and 0.17 in 2018, 2019 and 2020, respectively), Brunei (0.22, 0.24, 0.18), Singapore (0.48, 0.38 and 0.23) and Manila (0.22, 0.32 and 0.25). These cities are not affected by biomass-burning plumes from the northern part of the peninsular SEA and the AOD is mainly due to anthropogenic and local emissions. Meanwhile, other parts of SEA continue to face major air pollution problems in spring 2020 despite the lockdowns. For instance, in Bangkok, Thailand the mean AOD values in 2018, 2019 and 2020 are 0.33, 0.39 and 0.46, respectively. In Vientiane, Laos the increase in AOD was very high in 2020, with an average value of 0.99 compared to those in 2019 (0.44) and 2018 (0.78), indicating significant inter-annual variability, strongly linked to biomass-burning activities, local and regional meteorology. The seasonal (pre-monsoon) haze conditions in north Thailand, north Laos and Myanmar, have been getting worse under dry conditions, common at this time of the year. Therefore, inter-annual variability in meteorological conditions strongly affects the outbreak of forest fires, onset and duration of the agricultural burning practices, while the wind regime plays a major role in the accumulation and/or expansion of the emitted plumes, often leading to extreme haze conditions with serious health issues, as occurred in June 2013 (Betha et al., 2014; Gaveau et al., 2014; Vadrevu et al., 2014).

Among the SEA countries, Malaysia enforced the movement control order (MCO) for a longer period, starting from 18 March until 6 June 2020. In addition, for a more detailed analysis over Malaysia, which is only marginally affected by the forest and vegetation fires in the northern part of SEA, the AOD values were extracted for a single pixel (Yang et al., 2020; Emili et al., 2011) that is located over or closest to the 65 monitoring stations including industrial (7), urban (10), suburban (36) and rural sites (12). The Himawari-8 L3 AODs over these sites were temporally averaged during a period of 44 days, starting from March 18 to April 30 for the years 2018, 2019 and 2020. The AOD patterns averaged for each group of sites are shown in Fig. 3. Average AOD displays a large decrease, ranging between 57% and 72% in 2020 (mean of 0.18 ± 0.08) compared to the same period in 2019 (0.64 ± 0.86) and 2018 (0.42 ± 0.37), at the industrial sites. Urban centres also show a sharp decrease (40–60%) in AOD values in 2020 (0.25 ± 0.08) compared to 2019 (0.58 ± 0.59) and 2018 (0.43 ± 0.38), while similar reductions in AOD were recorded at the suburban and rural sites. Although AODs over the rural sites may be highly influenced by farming activities, cultivation, biogenic emissions, dust, peat and vegetation fires, which explain the comparable or even higher AODs than the urban sites, a large part of the significant AOD decrease at all sites

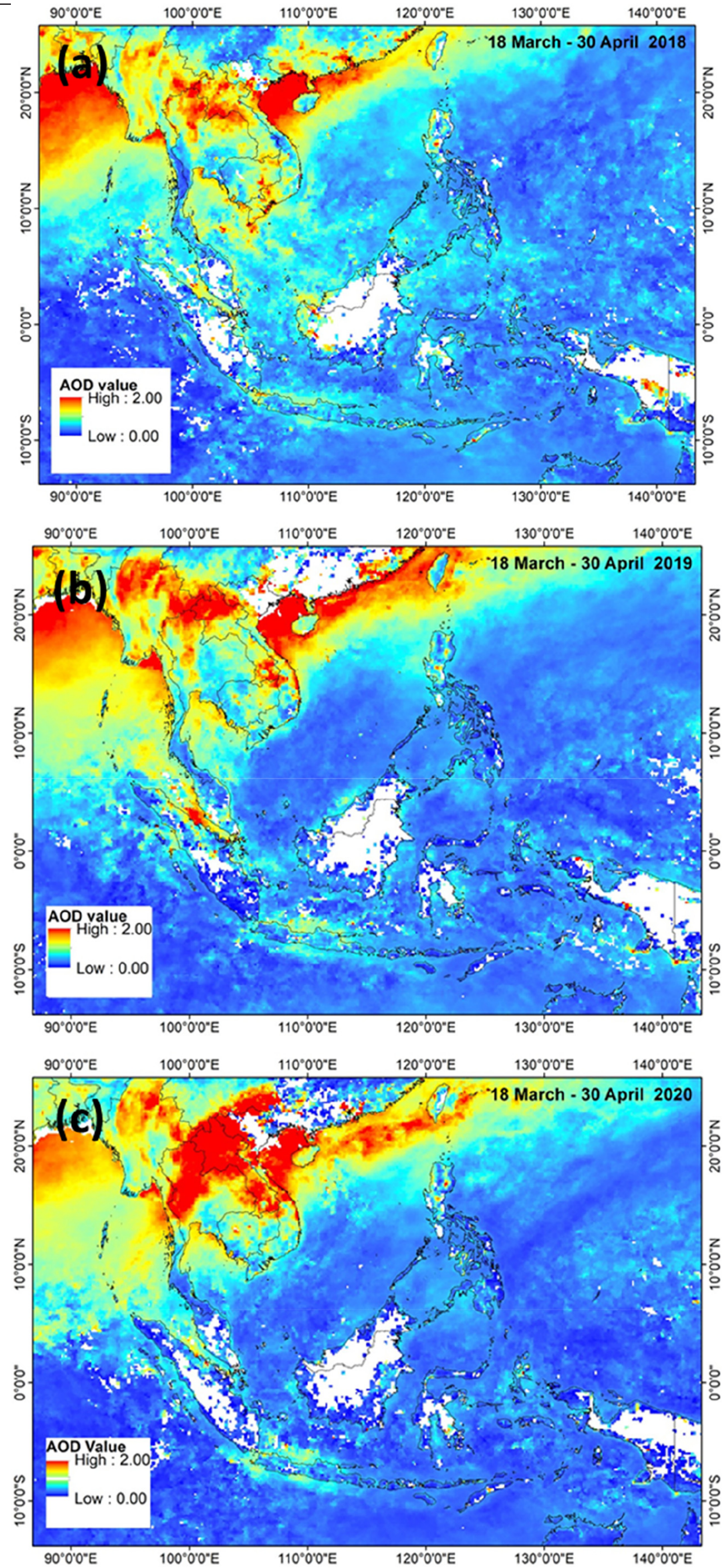


Fig. 1. AOD composite maps (March 18–April 30) for 2018 (a), 2019 (b) and 2020 (c) over the SEA region from Himawari-8 (spatial resolution of 5 km × 5 km) observations.

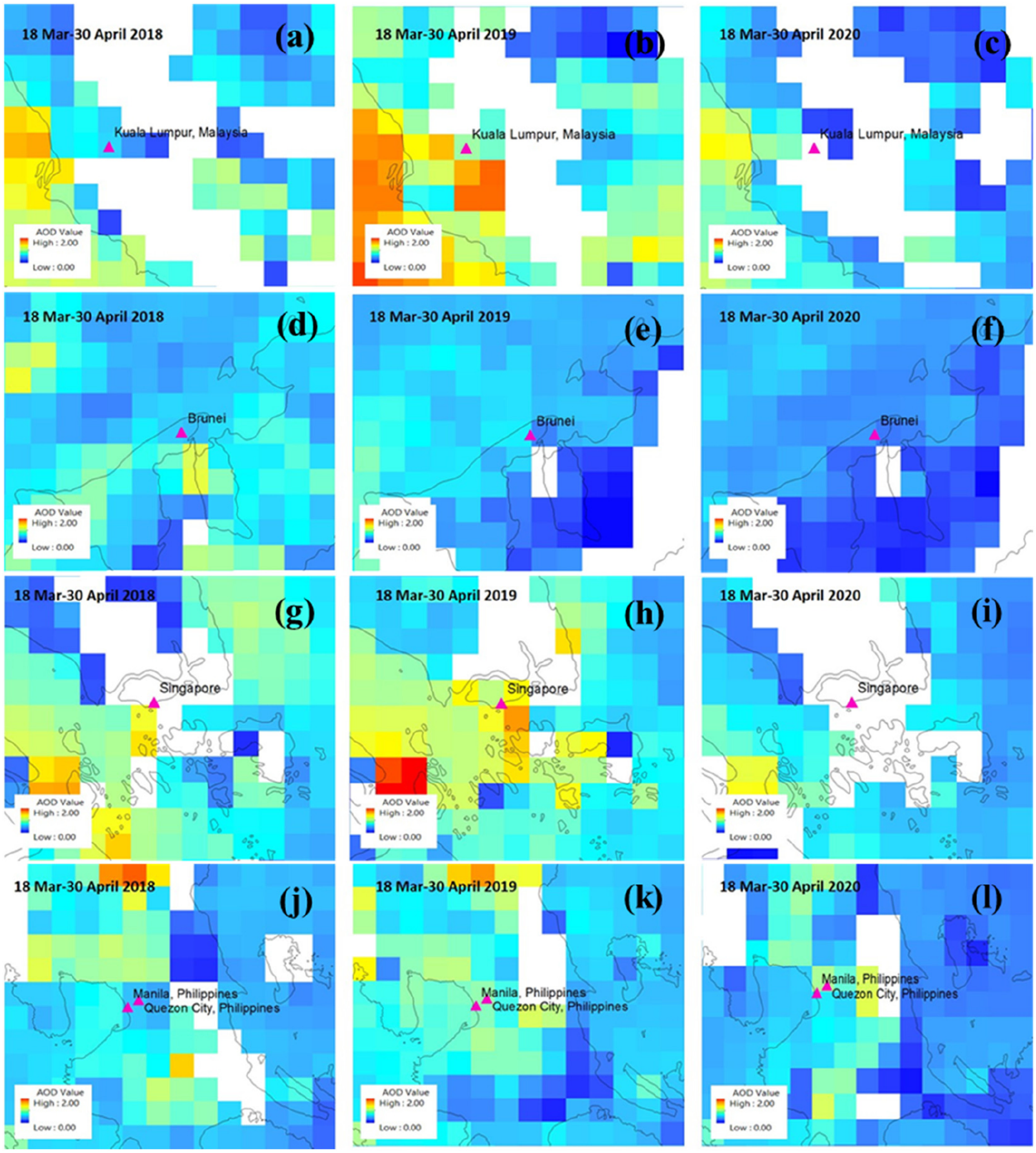


Fig. 2. Changes in the columnar AOD around Kuala Lumpur (a-c), Brunei (d-f), Singapore (g-i) and Manila (j-l) between 18 March - 30 April in the years 2018, 2019 and 2020.

is attributed to the general shutdown of the anthropogenic activities in order to restrict the expansion of COVID-19. In a previous study, it was shown that the PM_{10} concentrations alone can explain about 60% of the variation in AOD over Malaysia (Kamarul Zaman et al., 2017) and, therefore, notable reductions in the near-surface aerosols are also detected in the columnar.

3.2. Satellite observations of NO_2

Nitrogen oxides (NO_x) are primarily emitted as NO from combustion sources i.e., vehicle exhausts, industries, power plants, residential heating (e.g. Dumka et al., 2019) and is converted to NO_2 after fast oxidation processes, which is recognized as a tracer of anthropogenic combustion activities and precursor of nitrate aerosol and ozone (Zhang et al., 2020). As a major pollutant, NO_2 can cause respiratory diseases, asthma and cellular inflammation and is considered highly lethal to human health (Faustini et al., 2014; He et al., 2020) and harmful for the total environment through the formation of nitric acid (HNO_3) and acid rain (Kouvarakis et al., 2001; Zhang et al., 2020). Observations from Aura-OMI satellite sensor generally show a decrease in the concentrations of columnar NO_2 over the most parts of the SEA region in March and April 2020 compared to the mean 2015–2019 (Fig. 4). The largest reductions are detected over and around major urban centres like Manila, Bangkok, Kuala Lumpur, Singapore, while over low-dense populated and forested areas in Sumatra and Borneo, changes in NO_2 are rather marginal. On contrary, the large increase in NO_2 concentrations over the northern part of SEA in March 2020 is characteristic for the high intensity of the forest and agricultural fires.

A more detailed visualization for the Aura-OMI tropospheric NO_2 concentrations over major cities in SEA is shown in Suppl. Fig. 2. In general similarity to the AOD patterns observed over Manila, Kuala Lumpur and Singapore (Fig. 2), the NO_2 concentrations recorded a large reduction during spring 2020 compared to the previous years. This decrease approached −34%, −27% and −30% over Manila, Kuala Lumpur and Singapore, respectively, on 17 April (15-day averages) compared to NO_2 baseline data (averaged over 2015–2019) (Table 1), which is ascribed to shutting down of businesses and factories and restriction in traffic due to partial/general lockdown (Muhammad et al., 2020; Tosepu et al., 2020; Zhang et al., 2020). Note that in the strait of Singapore, the reduction in NO_2 was much lower due to continuous emissions from shipping for the international trade (Suppl. Fig. 2). Other cities that also documented reduction in NO_2 levels during the

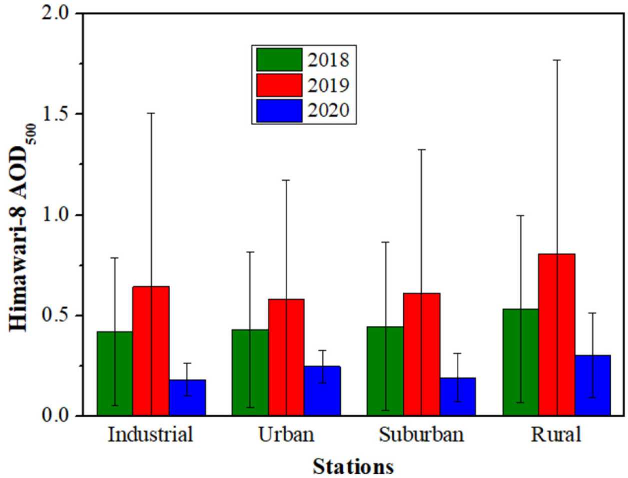


Fig. 3. Averaged AOD values from Himawari-8 L3 retrievals over industrial, urban, suburban and rural sites in Malaysia during the period 15 March – 30 April for the years 2018, 2019 and 2020. Vertical bars correspond to one standard deviation from the group-average AOD value.

Table 1
Reduction in Aura-OMI NO_2 levels in 2020 as compared to 5-years average values. Data averaged over a window of 15-days on 1 March, 31 March and 17 April.

Cities	Changes in NO_2 as compared to baseline (2015–2019) levels (%)		
	March 1, 2020	March 31, 2020	April 17, 2020
Kuala Lumpur	-6	−33	−27
Singapore	−16	−27	−30
Bangkok	−1	−21	−22
Hanoi	+25	Not enough data	Not enough data
Ho Chi Minh city	+3	−9	+1
Jakarta	−13	−10	−34
Manila	+5	−31	−34
Phnom Penh	+10	−4	−6
Vientiane	−5	−0	−9
Yangon	+1	−4	+3

same time period are Bangkok (−22%), Jakarta (−34%) and Phnom Penh (−6%) (Table 1). In Ho Chi Minh city, Vietnam, and Yangon, Myanmar NO_2 concentrations increased by about 1% and 3%, respectively compared to their long term (2015–2019) average values, justifying the larger impact from non-fossil combustion sources like biomass burning and forest wildfires (Pani et al., 2018; Bukowiecki et al., 2019; Nguyen et al., 2019). This is also supported by the large inter-annual and intra-seasonal variability in NO_2 levels around Vientiane, Laos due to severe biomass burning on certain periods, like 15–31 March 2020 (Suppl. Fig. 2), which prevents the extraction of robust results regarding the impact of lockdown on atmospheric pollution. Tropospheric NO_2 levels are highly associated with biomass-burning activity over the SEA region (Itahashi et al., 2018; Ul-Haq et al., 2016, 2018) and can be influenced by several other factors, including meteorology (such as insolation, precipitation, advection) and other pollution emissions. However, at local level, above and around the urban areas, NO_2 levels seem to be significantly lower in 2020 (Suppl. Fig. 2; Table 1).

3.3. Ground-based measurements of aerosol and air pollutants in Malaysia

This section investigates the changes in PM_{10} and $PM_{2.5}$ concentrations and in air pollutant (NO_2, SO_2, CO, O_3) levels at 65 air-pollution monitoring stations located all over Malaysia and include industrial (7), urban (10), suburban (36) and rural (12) sites. This analysis would help in evaluating the contribution of each source (e.g., industry, power plants, transportation, residential cooking and heating, agricultural activities) to the general reduction in aerosol and pollutant levels over the whole Malaysia during the COVID-19 period. The comparison was performed between the periods 18 March–30 April of the years 2018, 2019 and 2020 (Fig. 5). In general, the comparison shows a notable decrease in PM_{10}, $PM_{2.5}$ and NO_2 concentrations at the industrial and urban sites during the MCO period. The PM_{10} levels are much lower than the limit of 50 μg m^{-3} and in 2020 they are close to the 20 μg m^{-3} recommended by the WHO, indicating good air quality conditions across the country, with $PM_{2.5}$ levels below 25 μg m^{-3}. More specifically, the PM_{10} concentrations reduced by 28–39% (statistically significant at 95% confidence level) at the industrial sites and by 26–31% in the urban areas (statistically significant at 95% confidence level) in 2020 compared to 2019 and 2018, respectively (Fig. 5a). The respective reductions for $PM_{2.5}$ were found to be 19–42% at industrial and 23–32% at the urban sites (Fig. 5b). Even larger decreases occurred in NO_2 levels, which have been reduced by 33–46% in the industrial areas and by 63–64% in the urban centres relative to 2018 and 2019 (Fig. 5c). The respective decreases at the suburban and rural sites, not directly or less affected by anthropogenic emissions, were found to be slightly lower, since PM_{10} revealed a decrease of 22–27% at suburban and 10–24% at rural sites, $PM_{2.5}$ a decrease of 15–28% (suburban) and 4–27% (rural areas), while reductions in the range of 55–56% was found for NO_2 in the suburban areas and much lower (26–34%) at the rural background sites. During daytime, NO_2 reacts with OH radicals for the formation of HNO_3, while at night-time, reactions with NO_3 radicals are an important source of HNO_3, which is the precursor for nitrate aerosol (NO_3^-) formation (Sheinfeld and Pandis, 2016). Therefore, the large reduction in NO_2 levels during the COVID-19 period may limit

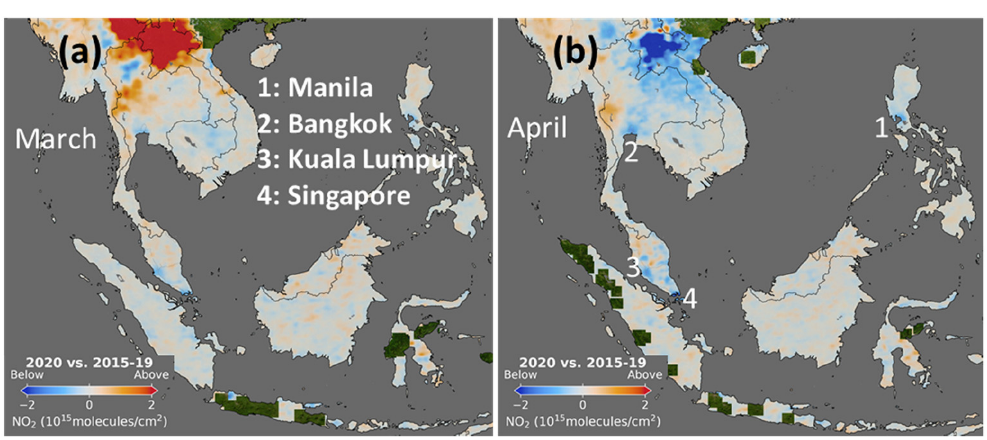


Fig. 4. Absolute differences of Aura-OMI tropospheric NO_2 concentrations in March **(a)** and April **(b)** 2020 from the 2015–2019 period mean over Southeast Asia.

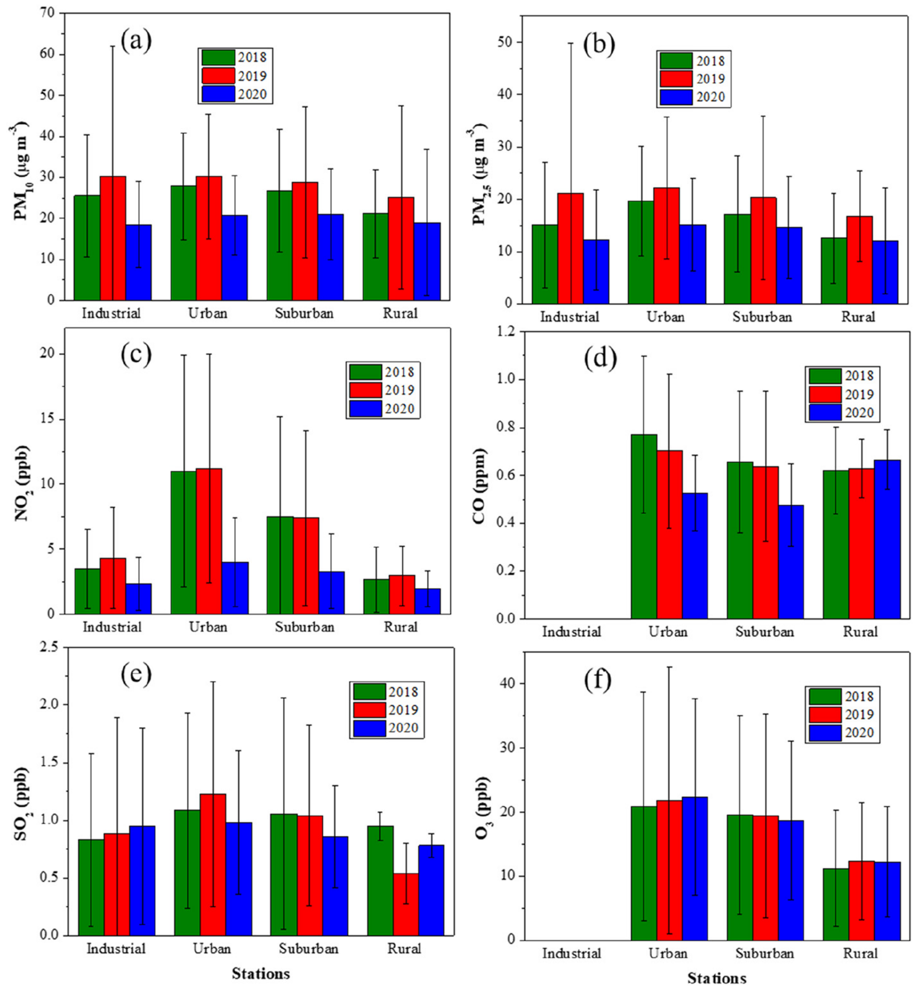


Fig. 5. Mean concentrations of aerosols (PM_{10} and $PM_{2.5}$) and pollutant gases at different stations in Malaysia during 18 March – 22 April for the years 2018, 2019 and 2020.

the built-up of HNO_3 and NO_3^- aerosols (Bardouki et al., 2003; Cuccia et al., 2013; Titos et al., 2014).

In addition, the limitation in combustion activities resulted in a decrease in CO levels, a direct pollutant from incomplete combustion sources (vehicular traffic and biomass burning). The reduction in CO is higher (25–32%) at the urban and suburban (25–27%) sites, whereas the rural background sites do not display any significant variability between the three years (6–7%), implying rather different sources of CO, most likely agricultural burning or even a rather stable background (Fig. 5d). Sulfur dioxide (SO_2) is directly emitted from anthropogenic emissions related to fossil-fuel burning and it's the predominant anthropogenic sulfur-containing air pollutant. The average lifetime of SO_2 is of the order of one day within the planetary boundary layer and up to about 15 days in the free troposphere, so it presents mostly regional characteristics (Ealo et al., 2018). As a major emission pollutant from stationary sources (industries and power plants), SO_2 displays reduction at the urban (9–20%) and suburban (17–19%) sites in 2020 compared to 2019 and 2018, but not at industrial ones, since major power plants and industries were continuously operating for reasons of common good and welfare (Fig. 5e). At the rural areas, SO_2 concentrations are more variable between the years and may be highly influenced by local/regional meteorology and downwind impact from nearby urban areas or industrial units (Collivignarelli et al., 2020). In contrast, O_3 did not record significant changes in the examined periods between the years, since it's a secondary pollutant formatted by NO titration in the presence of UV light or via volatile organic compounds (VOCs) (Reche et al., 2018) and its levels are kept mostly unchanged in Malaysia over a certain period of the year. However, a small increase (3–7%) was observed at the urban sites during 2020 (Fig. 5f) due to reduction in NO levels, similarly to other urban environments (Dantas et al., 2020; Kerimray et al., 2020; Li et al., 2020; Nakada and Urban, 2020; Tobías et al., 2020).

Finally, the lockdown effect on the daily PM_{10}, $PM_{2.5}$ and NO_2 concentrations, averaged at the urban and industrial sites in Malaysia, during the period 1 March–22 April for the years 2018, 2019 and 2020 is shown in Fig. 6. The MCO day (18 March 2020) is also determined, which defines a period of decreasing PM and NO_2 levels at both urban and industrial sites in 2020. At the industrial sites, the mean ratio of PM_{10} for periods after and before the MCO was found to be 0.80 in 2020, compared to 0.98 in 2019 and 1.15 in 2018. At the urban sites, the respective PM_{10} ratios were 0.79 in 2020, 0.87 in 2019 and 1.052018. $PM_{2.5}$ levels in 2018 and 2019 were notably higher than those in 2020, while the MCO further reduced the $PM_{2.5}$ concentrations, with the mean ratios for after/before the MCO to be 0.9 at the industrial sites and 0.85 at the urban ones. As PM_{10} and $PM_{2.5}$ may have various sources, apart from the anthropogenic ones, the MCO had a larger effect on the NO_2 levels. Therefore, in 2020, NO_2 has been reduced by 34% (54%) after the MCO compared to the period before at industrial (urban) sites, whilst the NO_2 ratios in 2019 were found to be 1.04 and 1.06, and those in 2018 were 1.17 and 1.00 for the industrial and urban sites, respectively. This analysis further highlights the significant decrease in NO_2 emissions at the industrial and urban areas in Malaysia, as a result of the restriction measures for preventing the dispersion of COVID-19.

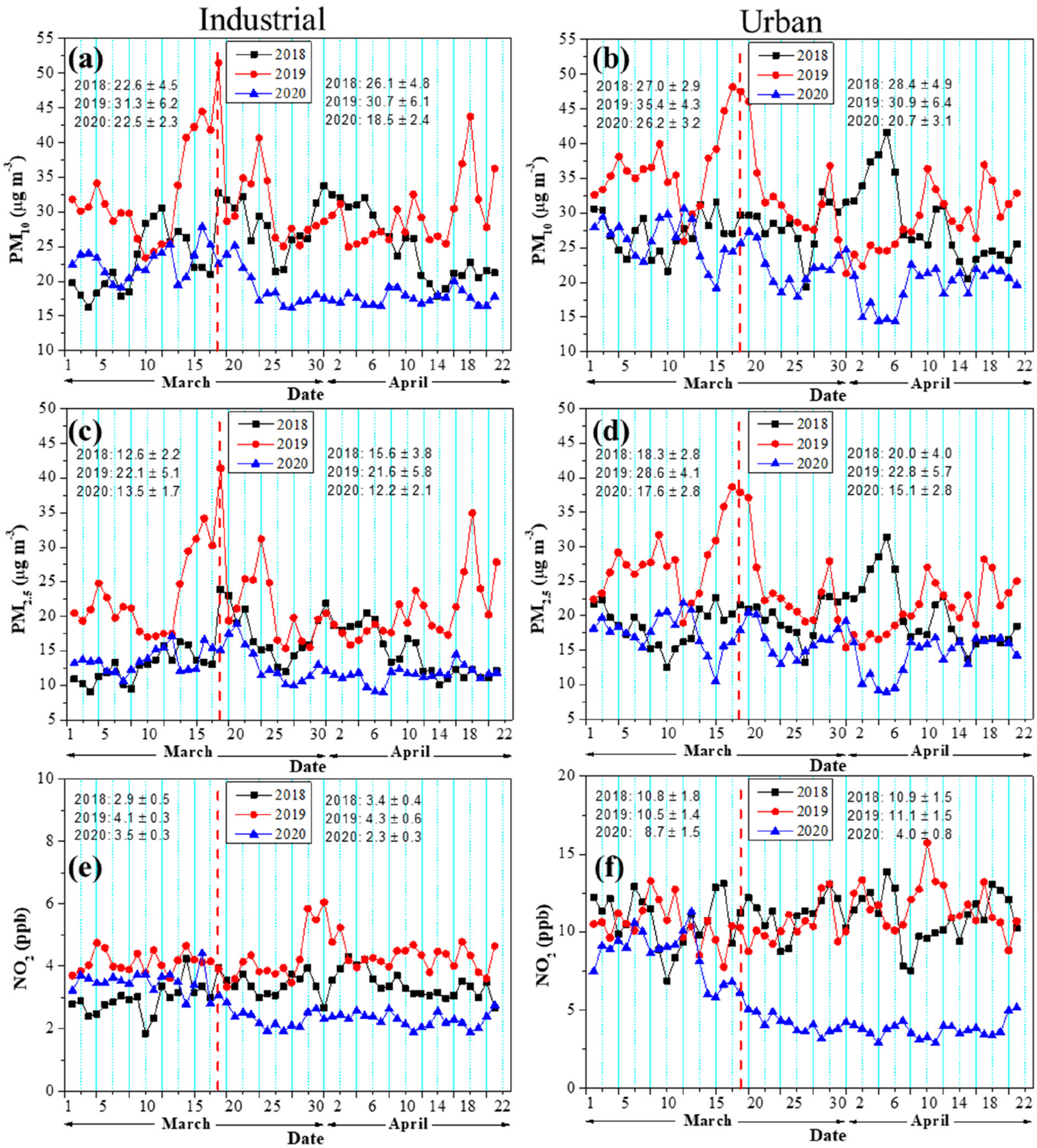


Fig. 6. Daily variability of the PM_{10} (a, b) $PM_{2.5}$ (c, d) and NO_2 (e-f) concentrations at industrial and urban sites in Malaysia for the period 1 March – 22 April of the years 2018, 2019 and 2020. The dashed line defines the beginning of the movement control order (MCO) on March 18, 2020 due to COVID-19 pandemic. The average and standard deviation values before and after MCO in each year are provided in the graphs.

4. Discussion

During the last 1–2 months, several studies have been published dealing with the impact of the lockdown on air quality at several cities in developed and developing countries around the world. Nearly all these studies revealed large declining trends in PM concentrations and in a series of air pollutants, with these trends being strongly related to the specific characteristics of each site, the relative influence from traffic and industrial sources, the impact of natural emissions (forest fires, desert dust) and the proximity to major power plants that are under continuous operation. This section discusses results from recent studies dealing with the decreasing trends in aerosols and air pollutants due to COVID-19 lockdown at several places around the world.

According to the Ministry of Ecology and Environment of China (2020), the concentrations of six major air pollutants during the COVID-19 period (January–March 2020), have been drastically reduced compared to previous year(s), recording a mean reduction of −20% for PM_{10}, −15% for $PM_{2.5}$, −25% for NO_2, −6% for CO, and −21% for SO_2, while O_3 remained rather steady from year-to-year (Wang and Su, 2020). Especially in Wuhan, where the general lockdown first established on 23 January 2020, the NO_2 levels have reduced by about 50% compared to the previous year (Wang and Su, 2020). Another study (Zhang et al., 2020), reported an average reduction of 52% in NO_x emissions in east China during the period after the lockdown compared to the levels before. Average decreases of 24.7%, 13.7%, 6.8%, 5.9%, and 4.6%, for NO_2, PM_{10}, SO_2, $PM_{2.5}$ and CO, respectively were reported in 44 cities in northern China (Bao and Zhang, 2020), while significant reductions in air pollutants due to lockdown were also observed at the Yangtze River Delta, also captured by the WRF-CAMx model (Li et al., 2020). However, nowadays, the NO_x levels have been gradually regained in some Chinese provinces after the termination of the quarantine period and return-to-work day (Zhang et al., 2020). Continuous monitoring of the pollution levels and future studies will reveal the degree of the pollution re-appearance over major urban areas in Malaysia as well, after the re-opening on the economy.

In India, PM_{10}, $PM_{2.5}$, NO_2 and CO concentrations analyzed during 16 March–14 April from 2017 to 2020 in 22 cities over the country revealed reductions by 43%, 31%, 18% and 10%, respectively during the lockdown period compared to previous years. On contrary, SO_2 exhibited marginal changes, whereas an increase of 17% was seen for O_3 (Sharma et al., 2020). Other studies in Delhi, revealed maximum reductions for PM_{10} and $PM_{2.5}$ concentrations (50%) compared to the pre-lockdown period (Mahato et al., 2020), while compared to 2019, PM_{10} and $PM_{2.5}$ decreased by about 60% and 35–39%, respectively (Chauhan and Singh, 2020; Mahato et al., 2020). In addition, NO_2 decreased by 52.7% and CO by 30.4% during the lockdown period (Mahato et al., 2020). Large reductions in CO (37.0% - 64.8%) and NO_2 (24.1% - 54.3%) levels were also observed in megacities in south America, like Rio de Janeiro (Dantas et al., 2020) and Sao Paolo (Nakada and Urban, 2020), during the lockdown phase compared to the period before or previous years. In Almaty, Kazakhstan, CO and NO_2 levels reduced by 49% and 35%, respectively during the lockdown compared to the 2018–2019 averages of the same period, while $PM_{2.5}$ reduced by 21% (Kerimray et al., 2020).

The large atmospheric impact of COVID-19 in Barcelona, Spain was detected with a reduction of −45.4% in the BC concentrations and of −47.0% and −51.4% of the NO_2 levels at urban-background and traffic sites, respectively (Tobías et al., 2020). Lower reductions in the PM_{10} concentrations were recorded, in the range of 27.8% and 31.0% at urban-background and traffic sites, respectively, since PM_{10} is related to several other sources like regional recirculation, dust resuspension or long-range transport, secondary aerosol formation, constructions, biogenic and marine emissions. This is in agreement with the lower (%) reductions in PM_{10} and $PM_{2.5}$ concentrations in Malaysia compared to those of NO_2. The daily O_3 levels in Barcelona increased by 29% to 58% at the urban-background and traffic sites (Tobías et al., 2020), while at the urban sites in Malaysia, the average increase was much lower (7.3%). The increase in O_3 is mostly attributed to the large decrease in NO_x levels within a VOCs limited urban environment, and to reduction in primary NO emissions that lower down the O_3 consumption via titration (Kerimray et al., 2020; Tobías et al., 2020). However, changes in O_3 may be also related to changes in insolation that facilitates its production. In Milan, Italy, which has been severely affected by SARS-CoV2 (Conticini et al., 2020), lockdown determined a period with a significant reduction in PM_{10}, $PM_{2.5}$, NO_x, CO, black carbon and benzene levels, while SO_2 remained rather unchanged and O_3 increased due to lower NO concentrations (Collivignarelli et al., 2020).

A new unpublished research at the time writing this article (Shrestha et al., 2020), analyzed the changes in concentrations of six air pollutants (PM_{10}, $PM_{2.5}$, NO_2, SO_2, CO and O_3) in 40 cities all over the world in February–March 2019 and 2020. In the majority of the cities, the 2020 levels were lower than those in 2019, while after lockdown, significant reductions in NO_2, CO, $PM_{2.5}$ and PM_{10} levels were found in 19, 9, 8 and 7 cities, respectively. Summarizing, the worldwide lockdown due to COVID-19 pandemic drastically reduced the anthropogenic emissions and air pollution, which, however, is diachronically responsible for acute health issues like chronic obstructive pulmonary disease, which increased significantly the mortality risk due to COVID-19.

5. Conclusions

In this study, the impact of the lockdown due to COVID-19 on the spatio-temporal variation of main atmospheric pollutants over SEA, and particularly in Malaysia, was investigated. A combination of aerosol (AOD, PM_{10} and $PM_{2.5}$) and gases (NO_2, SO_2, CO and O_3) data obtained from the Himawari-8 satellite, Aura-OMI and ground stations in Malaysia was used. A reduction in AOD values obtained from Himawari-8 was observed over the southern SEA region, in Singapore, Brunei, Malaysia and the Philippines. In Malaysia, the AOD values over industrial and urban sites displayed a large decrease (~40% and ~70%) in March–April 2020 compared to the same period in 2019 and 2018. In contrast, in the northern part of the peninsular SEA, AODs remained at very high levels (maximum values of around 2.0) even during the lockdown period, due to extensive forest fires and agricultural burning in this area. This was also supported by the highest NO_2 concentrations (between 4 and 5×10^{-15} mol cm^{-2}). In addition, NO_2 levels exhibited large reductions (~27%–34%) during the COVID-19 period at most of the cities in SEA, except for Ho Chi Minh and Yangon. This reduction in NO_2 levels was strongly linked with the countries' efforts to restrict the movement of people within and across countries and control the industrial/business activities. Countries like Brunei, Malaysia, and Singapore enacted aggressive measures, including border closures, prohibiting mass gatherings, restricting religious activities and partial lockdowns enforced by the military. Other countries like Cambodia, Indonesia, Laos, Myanmar, Thailand and the Philippines only enacted limited measures or belated steps. Especially in Malaysia, these strict measures and the MCO established on 18 March resulted in a significant decrease in PM_{10} (by 28–39% in the industrial and by 26–31% in the urban areas) and $PM_{2.5}$ (20–42% at industrial and 23–32% at urban sites) compared to previous years. A larger decrease occurred in NO_2 levels, which reduced by 33–46% in the industrial sites and by 64% in the urban centres. Lower reductions were observed for SO_2 and CO, while O_3 did not record significant changes over the years. The results of this study are indicative of the degree that the restriction measures and the regional lockdown due to COVID-19 affected the air pollution over a region with high levels of aerosols and pollutants from non-traffic and non-industrial activities. Therefore, aiming to evaluate the COVID-19 impact on air quality over the SEA region is a real challenge, especially during the pre-monsoon (March–April) period with extensive forest, vegetation and peat fires. Moreover, the role of meteorology has neither been evaluated nor quantified in this study and more detailed analysis is needed in the future. The beneficial for air quality restriction measures due to COVID-19 seem to be a unique opportunity for pollution-control policies and mitigating strategies against climate change over the SEA countries, although this is a very difficult and challenging task.

CRediT authorship contribution statement

Kasturi Devi Kanniah: Conceptualization, Methodology, Formal analysis, Data curation, Writing - original draft. **Nurul Amalin Fatihah Kamarul Zaman:** Investigation, Formal analysis, Writing - original draft. **Dimitris G. Kaskaoutis:** Methodology, Formal analysis, Data curation, Writing - original draft, Writing - review & editing. **Mohd Talib Latif:** Investigation, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors extend their thanks to the Ministry of Education, Malaysia via the Fundamental Research Grant (R.J130000.7852.5F216) and WNI WXBUNKA Foundation, Japan via research grant R. J130000.7352.4B406 and for providing research funding. We would like to thank the Japan Aerospace Exploration Agency (JAXA) and NASA for making Himawari-8 and OMI data available to users. The authors would also like to thank the Department of Environment, Malaysia for providing the near-surface pollutant data and AERONET team for maintaining and making the data publicly available. D.G. Kaskaoutis acknowledges the support by the PANACEA project (PANhellenic infrastructure for Atmospheric Composition and climatE change; MIS 5021516).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.139658.

References

Arkin, F., 2020. Asian COVID-19 lockdowns clear the air of pollutants. Sci. Dev. Net. https://www.scidev.net/asia-pacific/environment/news/asian-covid-19-lockdowns-clear-the-air-of-pollutants.html, Accessed date: 5 August 2020

Bai, Y., Yao, L., Wei, T., Tian, F., Jin, D.-Y., Chen, L., et al., 2020. Presumed asymptomatic carrier transmission of COVID-19. Jama 323, 1406–1407.

Ballester, F., Estarlich, M., Iniguez, C., Llop, S., Ramon, R., Esplugues, A., Lacasana, M., Rebagliato, M., 2010. Air Pollution Exposure During Pregnancy and Reduced Birth Size: A Prospective Birth Cohort Study in Valencia. Environmental Health, Spain.

Bao, R., Zhang, A., 2020. Does lockdown reduce air pollution? Evidence from 44 cities in northern China. Sci. Total Environ. 731, 139052. https://doi.org/10.1016/j.scitotenv.2020.139052.

Bardouki, H., Liakakou, H., Economou, C., Sciare, J., Smolík, J., Ždímal, V., Eleftheriadis, K., Lazaridis, M., Mihalopoulos, N., 2003. Chemical composition of size resolved atmospheric aerosols in the eastern Mediterranean during summer and winter. Atmos. Environ. 37, 195–208.

Bessho, K., Date, K., Hayashi, M., Ikeda, A., Imai, T., Inoue, H., Kumagai, Y., Miyakawa, T., Murata, H., Ohno, T., Okuyama, A., 2016. An introduction to Himawari-8/9—Japan's new-generation geostationary meteorological satellites. Journal of the Meteorological Society of Japan. Ser. II 94 (2), 151–183.

Betha, R., Behera, S.N., Balasubramanian, R., 2014. Southeast Asian smoke haze: fractionation of particulate-bound elements and associated health risk. Environ. Sci. Technol. 48 (8), 4327–4335.

Biswas, S., Vadrevu, K.P., Lwin, Z.M., Lasko, K., Justice, C.O., 2015. Factors controlling vegetation fires in protected and non-protected areas of Myanmar. PLoSOne 10, e0124346.

Bukowiecki, N., Steinbacher, M., Henne, S., Nguyen, N.A., Nguyen, X.A., Hoang, A.L., Nguyen, D.L., Duong, H.L., Engling, G., Wehrle, G., Gysel-Beer, M., Baltensperger, U., 2019. Effect of large-scale biomass burning on aerosol optical properties at the GAW Regional Station Pha Din, Vietnam. Aerosol Air Qual. Res. 19, 1172–1187.

Chauhan, A., Singh, R.P., 2020. Decline in PM2.5 concentrations over major cities around the world associated with COVID-19. Environ. Res. 187, 109634. https://doi.org/10.1016/j.envres.2020.109634.

Chen, H., Guo, J., Wang, C., Luo, F., Yu, X., Zhang, W., Li, J., Zhao, D., Xu, D., Gong, Q., Liao, J., Yang, H., Hou, W., Zhang, Y., 2020. Clinical characteristics and intrauterine vertical transmission potential of COVID-19 infection in nine pregnant women: a retrospective review of medical records. Lancet https://doi.org/10.1016/S0140-6736(20)30360-3.

Chuersuwan, N., Nimrat, S., Lekphet, S., Kerdkumrai, T., 2008. Levels and major sources of PM2.5 and PM10 in Bangkok metropolitan region. Environ. Int. 34 (5), 671–677.

Collivignarelli, M.C., Abbà, A., Bertanza, G., Pedrazzani, R., Ricciardi, P., Miino, M.C., 2020. Lockdown for CoViD-2019 in Milan: what are the effects on air quality? Sci. Total Environ. 732, 139280. https://doi.org/10.1016/j.scitotenv.2020.139280.

Conticini, E., Frediani, B., Caro, D., 2020. Can atmospheric pollution be considered a cofactor in extremely high level of SARS-CoV-2 lethality in northern Italy? Environ. Pollut. 261, 114465. https://doi.org/10.1016/j.envpol.2020.114465.

Contini, D., Costabile, F., 2020. Does air pollution influence COVID-19 outbreaks? Atmosphere 11 (4), 377. https://doi.org/10.3390/atmos11040377.

Cuccia, E., Massabò, D., Ariola, V., Bove, M.C., Fermo, P., Piazzalunga, A., Prati, P., 2013. Size-resolved comprehensive characterization of airborne particulate matter. Atmos. Environ. 67, 14–26.

Dahari, N., Muda, K., Latif, M.T., Hussein, N., 2019. Studies of atmospheric PM2.5 and its inorganic water soluble ions and trace elements around Southeast Asia: a review. Asia-Pacific J. Atmos. Sci. https://doi.org/10.1007/s13143-019-00132-x.

Dantas, G., Siciliano, B., França, B.B., da Silva, C.M., 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. https://doi.org/10.1016/j.scitotenv.2020.139085.

Dominici, F., Peng, R.D., Bell, M.L., Pham, L., McDermontt, A., Zeger, S.L., Samet, J.M., 2006. Fine particulate air pollution and hospital admission for cardiovascular and respiratory diseases. J. Am. Med. Assoc. 295 (10), 1127–1134.

Dumka, U.C., Kaskaoutis, D.G., Srivastava, M.K., Devara, P.C.S., 2015. Scattering and absorption properties of near-surface aerosol over Gangetic–Himalayan region: the role of boundary layer dynamics and long-range transport. Atmos. Chem. Phys. 15, 1555–1572.

Dumka, U.C., Tiwari, S., Kaskaoutis, D.G., Soni, V.K., Safai, P.D., Attri, S.D., 2019. Aerosol and pollutant characteristics in Delhi during a winter research campaign. Environ. Sci. Pollut. Res. 26, 3771–3794.

Dutheil, F., et al., 2020. COVID-19 as a factor influencing air pollution? Environ. Pollut. 263, 114466. https://doi.org/10.1016/j.envpol.2020.114466.

Ealo, M., Alastuey, A., Pérez, N., Ripoll, A., Querol, X., Pandolfi, M., 2018. Impact of aerosol particle sources on optical properties in urban, regional and remote areas in the north-western Mediterranean. Atmos. Chem. Phys. 18, 1149–1169.

Emili, E., Lyapustin, A., Wang, Y., Popp, C., Korkin, S., Zebisch, M., Petitta, M., 2011. High spatial resolution aerosol retrieval with MAIAC: application to mountain regions. J. Geophys. Res.-Atmos. 116 (D23).

EPA, 2020. https://www.epa.gov/pm-pollution/particulate-matter-pm-basics.

Faustini, A., Rapp, R., Forastiere, F., 2014. Nitrogen dioxide and mortality: review and meta-analysis of long-term studies. Eur. Respir. J. https://doi.org/10.1183/09031936.00114713.

Gautam, R., Hsu, N.C., Eck, T.F., Holben, B.N., Janjai, S., Jantarach, T., Tsay, S.C., Lau, W.K., 2013. Characterization of aerosols over the Indochina peninsula from satellite-surface observations during biomass burning pre-monsoon season. Atmos. Environ. 78, 51–59.

Gaveau, D.L.A., Salim, M.A., Hergoualc'h, K., Locatelli, B., Sloan, S., Wooster, M., Marlier, M.E., Molidena, E., Yaen, H., DeFries, R., Verchot, L., Murdiyarso, D., Nasi, R., Holmgren, P., Sheil, D., 2014. Major atmospheric emissions from peat fires in Southeast Asia during non-drought years: evidence from the 2013 Sumatran fires. Sci. Rep. 6112. https://doi.org/10.1038/srep06112.

Hai, C.D., Kim Oanh, N.T., 2013. Effects of local, regional meteorology and emission sources on mass and compositions of particulate matter in Hanoi. Atmos. Environ. 78 (Supplement C), 105–112.

He, M.Z., Kinney, P.L., Li, T., Chen, C., Sun, Q., Ban, J., Wang, J., Liu, S., Goldsmith, J., Kioumourtzoglou, M.A., 2020. Short- and intermediate-term exposure to NO2 and mortality: a multi-county analysis in China. Environ. Pollut. 261, 114165. https://doi.org/10.1016/j.envpol.2020.114165.

Henschel, S., Le Tertre, A., Atkinson, R.W., Querol, X., Pandolfi, M., Zeka, A., Haluza, D., Analitis, A., Katsouyanni, K., Bouland, C., Pascal, M., Medina, S., Goodman, P.G., 2015. Trends of nitrogen oxides in ambient air in nine European cities between 1999 and 2010. Atmos. Environ. 117, 234–241.

Holben, B.N., Eck, T.F., Slutsker, I., Tanré, D., Buis, J.P., Setzer, A., Vermote, E., Reagan, J.A., Kaufman, Y.A., 1998. AERONET-a federated instrument network and data achieve for aerosol characterization. Remote Sens. Environ. 66, 1–16.

Hou, N., Zhang, X., Zhang, W., Wei, Y., Jia, K., Yao, Y., Jiang, B., Cheng, J., 2020. Estimation of surface downward shortwave radiation over China from Himawari-8 AHI data based on random Forest. Remote Sens. 12 (1), 181. https://doi.org/10.3390/rs12010181.

Huang, C., Wang, Y., Li, X., Ren, L., Zhao, J., Hu, Y., Zhang, L., Fan, G., Xu, J., Gu, X., Cheng, Z., Yu, T., Xia, J., Wei, Y., Wu, W., Xie, X., Yin, W., Li, H., Liu, M., Xiao, Y., Gao, H., Guo, L., Xie, J., Wang, G., Jiang, R., Gao, Z., Jin, Q., Wang, J., Cao, B., 2020. Clinical features of patients infected with 2019 novel coronavirus in Wuhan, China. Lancet 395, 497–506. https://doi.org/10.1016/S0140-6736 (20) 30183-5.

Itahashi, S., Uno, I., Irie, H., Kurokawa, J.-I., Ohara, T., 2018. Impacts of biomass burning emissions on tropospheric NO2 vertical column density over continental Southeast Asia. Book: Land-Atmospheric Research Applications in South and Southeast Asia. https://doi.org/10.1007/978-3-319-67474-2_4.

Kamarul Zaman, N.A.F., Kanniah, K.D., Kaskaoutis, D.G., 2017. Estimating particulate matter using satellite based aerosol optical depth and meteorological variables in Malaysia. Atmos. Res. 193, 142–162.

Kanniah, K.D, Lim, H.Q., Kaskaoutis, D.G., Cracknell, A.P, 2014. Investigating aerosol properties in Peninsular Malaysia via the synergy of satellite remote sensing and ground-based measurements. Atmospheric Research 138 (1), 223–239.

Kanniah, K.D., Kaskaoutis, D.G., Lim, H.S., Latif, M.T., Kamarul Zaman, N.A.F., Liew, J., 2016. Overview of atmospheric aerosol studies in Malaysia: known and unknown. Atmos. Res. 182, 302–318.

Kerimray, A., Baimatova, N., Ibragimova, O.P., Bukenov, B., Kenessov, B., Plotitsyn, P., Karaca, F., 2020. Assessing air quality changes in large cities during COVID-19 lockdowns: the impacts of traffic-free urban conditions in Almaty, Kazakhstan. Sci. Total Environ. 730, 139179. https://doi.org/10.1016/j.scitotenv.2020.139179.

Khan, M.F., Latif, M.T., Saw, W.H., Amil, N., Nadzir, M.S.M., Sahani, M., Chung, J.X., 2016. Fine particulate matter in the tropical environment: monsoonal effects, source apportionment, and health risk assessment. Atmos. Chem. Phys. 16 (2), 597–617.

Kharol, S.K., Badarinath, K.V.S., Kaskaoutis, D.G., Sharma, A.R., Gharai, B., 2011. Influence of continental advection on aerosol characteristics over Bay of Bengal (BoB) in winter: results from W-ICARB cruise experiment. Ann. Geophys. 29, 1423–1438.

Kharol, S.K., Shephard, M.W., McLinden, C.A., Zhang, L., Sioris, C.E., O'Brien, J.M., Vet, R., Cady-Pereira, K.E., Hare, E., Siemons, J., Krotkov, N.A., 2018. Dry deposition of reactive nitrogen from satellite observations of ammonia and nitrogen dioxide over North America. Geophys. Res. Lett. 45, 1157–1166. https://doi.org/10.1002/2017GL075832.

Kikuchi, M., Murakami, H., Suzuki, K., Nagao, T.M., Higurashi, A., 2018. Improved hourly estimates of aerosol optical thickness using spatiotemporal variability derived from Himawari-8 geostationary satellite. IEEE Trans. Geosci. Remote Sens. 56 (6), 3442–3455.

Kim Oanh, N.T., Upadhyay, N., Zhuang, Y.H., Hao, Z.P., Murthy, D.V.S., Lestari, P., Villarin, J.T., Chengchua, K., Co, H.X., Dung, N.T., Lindgren, E.S., 2006. Particulate air pollution in six Asian cities: spatial and temporal distributions, and associated sources. Atmos. Environ. 40, 3367–3380.

Kouvarakis, G., Mihalopoulos, N., Tselepides, A., Stavrakaki, S., 2001. On the importance of atmospheric inputs of inorganic nitrogen species on the productivity of the eastern Mediterranean Sea. Glob. Biogeochem. Cycles 15, 805–817.

Lai, C.-C., Shih, T.-P., Ko, W.-C., Tang, H.-J., Hsueh, P.-R., 2020. Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) and coronavirus disease-2019 (COVID-19): the epidemic and the challenges. Int. J. Antimicrob. Agents 55, 105924.

Levelt, P.F., Joiner, J., Tamminen, J., et al., 2018. The ozone monitoring instrument: overview of 14 years in space. Atmos. Chem. Phys. 18, 5699–5745.

Li, L., Li, Q., Huang, L., Wang, Q., Zhu, A., Xu, J., Liu, Z., Li, H., Shi, L., Li, R., Azari, M., Wang, Y., Zhang, X., Liu, Z., Zhu, Y., Zhang, K., Xue, S., Ooi, M.C.G., Zhang, D., Chan, A., 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. https://doi.org/10.1016/j.scitotenv.2020.139282.

Lin, N.H., Sayer, A.M., Wang, S.H., Loftus, A.M., Hsiao, T.C., Sheu, G.R., Hsu, N.C., Tsay, S.C., Chantara, S., 2014. Interactions between biomass-burning aerosols and clouds overSoutheast Asia: current status, challenges, and perspectives. Environ. Pollut. 195, 292–307.

Liu, Y., Ning, Z., Chen, Y., Guo, M., Liu, Y., Gali, N.K., Sun, L., Duan, Y., Cai, J., Westerdahl, D., Liu, X., Xu, K., Ho, K.-f., Kan, H., Fu, Q., Lan, K., 2020. Aerodynamic analysis of SARS-CoV-2 in two Wuhan hospitals. Nature https://doi.org/10.1038/s41586-020-2271-3.

Luong, Ly.M.T., Sly, P.D., Thai, P.K., Phung, D., 2019. Impact of ambient air pollution and wheeze associated disorders in children in Southeast Asia: a systematic review and meta-analysis. Rev. Environ. Health 34 (2), 125–139.

Mahato, S., Pal, S., Ghosh, K.G., 2020. Effect of lockdown amid COVID-19 pandemic on air quality of the megacity Delhi, India. Sci. Total Environ. 730, 139086. https://doi.org/10.1016/j.scitotenv.2020.139086.

Ministry of Ecology and Environment of China, 2020. Report on the state of surface water and ambient air quality nationwide in March and January–March. http://www.mee.gov.cn/xxgk2018/xxgk/xxgk15/202004/t20200414_774254.html.

Muhammad, S., Long, X., Salman, M., 2020. COVID-19 pandemic and environmental pollution: a blessing in disguise? Sci. Total Environ., 138820 https://doi.org/10.1016/j.scitotenv.2020.138820.

Nakada, L.Y.K., Urban, R.C., 2020. COVID-19 pandemic: impacts on the air quality during the partial lockdown in São Paulo state, Brazil. Sci. Total Environ. 730, 139087. https://doi.org/10.1016/j.scitotenv.2020.139087.

NASA, 2020. https://so2.gsfc.nasa.gov/no2/no2_index.html.

Nguyen, T.T.N., Le, H.A., Mac, T.M.T., Nhung, N.T.T., Van, H.P., Bui, H.Q., 2019. Current status of PM2.5 pollution and its mitigation in Vietnam. Glob. Environ. Res. 22, 73–83.

Pandolfi, M., Amato, F., Reche, C., Alastuey, A., Otjes, R.P., Blom, M.J., Querol, X., 2012. Summer ammonia measurements in a densely populated Mediterranean city. Atmos. Chem. Phys. 12, 7557–7575.

Pani, S.K., Wang, S.H., Lin, N.H., Lee, C.T., Tsay, S.C., Holben, B.N., Janjai, S., Hsiao, T.C., Chuang, M.T., Chantara, S., 2016. Radiative effect of springtime biomass-burning aerosols over northern Indochina during 7-SEAS/BASELInE 2013 campaign. Aerosol Air Qual. Res. 16 (11), 2802–2817.

Pani, S.K., Lin, N.H., Chantara, S., Wang, S.H., Khamkaew, C., Prapamontol, T., Janjai, S., 2018. Radiative response of biomass-burning aerosols over an urban atmosphere in northern peninsular Southeast Asia. Sci. Total Environ. 633, 892–911.

Pani, S.K., Wang, S.-H., Lin, N.-H., Chantara, S., Lee, C.-T., Thepnuan, D., 2020. Black carbon over an urban atmosphere in northern peninsular Southeast Asia: characteristics, source apportionment, and associated health risks. Environ. Pollut. https://doi.org/10.1016/j.envpol.2019.113871.

Reche, C., Moreno, T., Amato, F., Pandolfi, M., Pérez, J., de la Paz, D., Díaz, E., Gómez-Moreno, F.J., Pujadas, M., Artíñano, B., Reina, F., Orio, A., Pallarés, M., Escudero, M., Tapia, O., Crespo, E., Vargas, R., Alastuey, A., Querol, X., 2018. Spatio-temporal patterns of high summer ozone events in the Madrid Basin, Central Spain. Atmos. Environ. 185, 207–220.

Sharma, S., Zhang, M., Anshika, Gao, J., Zhang, H., Kota, S.H., 2020. Effect of restricted emissions during COVID-19 on air quality in India. Sci. Total Environ. 728, 138878, doi: https://doi.org/10.1016/j.scitotenv.2020.138878.

Shi, S., Cheng, T., Gu, X., Letu, H., Guo, H., Chen, H., Wang, Y., Wu, Y., 2018. Synergistic retrieval of multi-temporal aerosol optical depth over north China plain using geostationary satellite data of Himawari-8. J. Geophys. Res. https://doi.org/10.1029/2017JD027963.

Shrestha, A.M., Shrestha, U.B., Sharma, R., Bhattarai, S., Tran, H.N.T., Rupakheti, M., 2020. Lockdown caused by COVID-19 pandemic reduces air pollution in cities worldwide. Environ. Pollut. (submitted paper).

Singh, P., Sarawade, P., Adhikary, B., 2020. Carbonaceous aerosol from open burning and its impact on regional weather in South Asia. Aerosol Air Qual. Res. 20, 419–431.

Sipalan, J., Holmes, S., 25 January 2020. Malaysia Confirms First Cases of Coronavirus Infection. Reuters Archived from the original on 18 February 2020. Retrieved 18 February 2020.

Sohrabi, C., Alsafi, Z., O'Neill, N., Khan, M., Kerwan, A., Al-Jabir, A., et al., 2020. World health organization declares global emergency: a review of the 2019 novel coronavirus (COVID-19). Int. J. Surg. 76, 71–76.

Srinivas, B., Sarin, M.M., 2014. Brown carbon in atmospheric outflow from the Indo-Gangetic Plain: mass absorption efficiency and temporal variability. Atmos. Environ. 89, 835–843.

Titos, G., Lyamani, H., Pandolfi, M., Alastuey, A., Alados-Arboledas, L., 2014. Identification of fine (PM1) and coarse (PM10-1) sources of particulate matter in an urban environment. Atmos. Environ. 89, 593–602.

Tobías, A., Carnerero, C., Reche, C., Massagué, J., Via, M., Minguillón, M.C., 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. https://doi.org/10.1016/j.scitotenv.2020.138540.

Tosepu, R., Gunawan, J., Effendy, S.D., Ahmad, A.I., Lestari, H., Bahar, H., Asfian, P., 2020. Correlation between weather and Covid-19 pandemic in Jakarta, Indonesia. Sci. Total Environ. 725, 138436. https://doi.org/10.1016/j.scitotenv.2020.138436.

Tsai, Y.I., Sopajaree, K., Chotruksa, A., Wu, H.-C., Kuo, S.-C., 2013. Source indicators of biomass burning associated with inorganic salts and carboxylates in dry season ambient aerosol in Chiang Mai Basin, Thailand. Atmos. Environ. 78, 93–104.

Ul-Haq, Z., Tariq, S., Ali, M., 2016. Spatiotemporal patterns of correlation between atmospheric nitrogen dioxide and aerosols over South Asia. Meteorog. Atmos. Phys. https://doi.org/10.1007/s00703-016-0485-6.

Ul-Haq, Z., Rana, A.D., Tariq, S., Mahmood, K., Ali, M., Bashir, I., 2018. Modeling of tropospheric NO2 column over different climatic zones and land use/land cover types in South Asia. J. Atmos. Solar-Terr. Phys. 168, 80–99.

Vadrevu, K.P., Lasko, K., Giglio, L., Justice, C., 2014. Analysis of Southeast Asian pollution episode during June 2013 using satellite remote sensing datasets. Environ. Pollut. 195, 245–256.

Vadrevu, K.P., Lasko, K., Giglio, L., Justice, C., 2015. Vegetation fires, absorbing aerosols and smoke plumecharacteristics in diverse biomass burning regions of Asia. Environ. Res. Lett. 10, 105003.

Vadrevu, K.P., Lasko, K., Giglio, L., Schroeder, W., Biswas, S., Justice, C., 2019. Trends in vegetation fires in South and Southeast Asian countries. Sci. Rep. 9, 7422. https://doi.org/10.1038/s41598-019-43940-x.

Wang, Q., Su, M., 2020. A preliminary assessment of the impact of COVID-19 on environment–a case study of China. Sci. Total Environ. 728, 138915. https://doi.org/10.1016/j.scitotenv.2020.138915.

Wang, S.H., Welton, E.J., Holben, B.N., Tsay, S.-C., Lin, N.-H., Giles, D., Stewart, S.A., Janjai, S., Nguyen, X.A., Hsiao, T.-C., Chen, W.-N., Lin, T.H., Buntoung, C.S., Wiriya, W., 2015. Vertical distribution and columnar optical properties of springtime biomass- burning aerosols over northern Indochina during 2014 7-SEAS campaign. Aerosol Air Qual. Res. 15, 2037–2050.

WHO, 2018. https://www.who.int/westernpacific/news/details/02-05-2018-one-third-of-global-air-pollution-deaths-in-asia-pacific.

WHO, 2020. https://www.who.int/docs/default-source/coronaviruse/situation-reports/20200516-covid-19-sitrep-117.pdf?sfvrsn=8f562cc_2.

Yan, X., Li, Z., Luo, N., Shi, W., Zhao, W., Yang, X., Jin, J., 2018. A minimum albedo aerosol retrieval method for the new-generation geostationary meteorological satellite Himawari-8. Atmos. Res. 207, 14–27.

Yang, X., Zhao, C., Luo, N., Zhao, W., Shi, W., Yan, X., 2020. Evaluation and comparison of Himawari-8 L2 V1.0, V2.1 and MODIS C6.1 aerosol products over Asia and the oceania regions. Atmos. Environ. 220, 117068. https://doi.org/10.1016/j.atmosenv.2019.117068.

Yao, M., Zhang, L., Ma, J., Zhou, L., 2020. On airborne transmission and control of SARS-Cov-2. Sci. Total Environ. 731, 139178. https://doi.org/10.1016/j.scitotenv.2020.139178.

Zhang, R., Zhang, Y., Lin, H., Feng, X., Fu, T.-M., Wang, Y., 2020. NOx emission reduction and recovery during COVID-19 in east China. Atmosphere 11 (4), 433. https://doi.org/10.3390/atmos11040433.

Zhang, W., Xu, H., Zhang, L., 2019. Assessment of Himawari-8 AHI aerosol optical depth over land. Remote Sens. 11 (9), 1108.