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A post-pandemic analysis of air pollution over small-sized urban areas in southern Thailand following the COVID-19 lockdown

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Abstract

COVID-19 has been a pandemic with paramount effects on human health that brought about a noticeable improvement of air quality due to a reduction of anthropogenic activities. While studying this phenomenon in large cities has been a popular research topic, related research on smaller-sized urban areas has not been given the necessary attention. In the current study, we focus on the period during and after the COVID-19 pandemic over 8 small- and medium-sized urban areas in southern Thailand and present the effect of the lockdown on the air quality as quantified by the Sentinel-5P satellite and regulatory-grade surface stations over the years 2020, 2021 and 2022. Findings indicate that there is a noticeable reduction of -14%, -24% and -28% for NO_2, PM2.5 and PM10 surface concentrations, respectively, for all the 8 urban areas cumulatively for the 2-month period following the lockdown, while results for O_3 were inconclusive. An alignment between the ground and satellite observations is noticed, despite their difference in spatial scales and measuring different physical characteristics. Regression analysis between the single-pixel values over the ground station locations and the spatially-averaged pixels over the urban extent indicates an agreement between these two features, suggesting that single measurements can be representative of the air pollution status for relatively small-sized urban areas.

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Key words air pollution, sentinel-5P, COVID-19, remote sensing, Thailand.

Availability of data and materials: the Sentinel-5P NO2, CO, O3, SO2 offline products are available through the Google Earth Engine platform at https://code.earthengine.google.com. The hourly ground station air quality data are available at http://air4thai.pcd.go.th/webV3/#/History.

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Introduction

By the end of 2019 a Severe Acute Respiratory Syndrome (SARS-CoV-2) virus was discovered in Wuhan, China (Huang *et al.*, 2020). This virus, which causes the infection COVID-19, spread rapidly globally and was soon thereafter declared a pandemic. According to the World Health Organization (WHO), 774,291,287 COVID-19 cases and 7,019,704 identified deaths worldwide had been reported up to 14th January 2024 (WHO, 2024), while in Thailand there were 2,245,250 total cases and 21,780 associated deaths (Department of Disease Control, 2024). In response to the pandemic development, and to contain the transmission of the virus and its concomitant social health implications, several governments imposed regulations, such as restricting public gatherings and regulating public and private transportation. Eventually, and with the irrepressible spread of the disease, most countries imposed austere lockdown measures (*i.e.*, a restriction policy for people or a community to stay where they are to reduce the risk of exposure), which largely affected people's livelihood and had a significant economic aftermath. At the same time, the reduction of industrial and transportation activities had a unique environmental impact, and this sudden and abrupt large-scale change of pollution levels created a unique opportunity to study the impact of environmental factors on human health. As a related example, the reduction of pollutant concentration in the atmosphere has been documented in a plethora of studies during the lockdown periods all around the world, primarily with the use of earth observation data (e.g., Fardani *et al.*, 2021; Ghahremanloo *et al.*, 2021; Kanniah *et al.*, 2020; Stratoulias *et al.*, 2020). In addition, strong associations between air pollution and COVID-19 infection and mortality rates both for short-term (Zhu *et al.*, 2020) and long-term exposure (Chakraborty *et al.*, 2020; Wu *et al.*, 2020) havebeen reported. Air pollution is one of the biggest threats affecting human health with an estimated 7 million premature deaths annually (WHO 2021), and 9 out of 10 people are breathing air that is above limits deemed safe for human health (WHO, 2018a). The major air pollutants encountered in the atmosphere are sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3), carbon monoxide (CO) and particulate matter (PM) (Chen *et al.*, 2007; Ghahremanloo *et al.*, 2021; Burns *et al.,* 2020). NO_2 is a harmful gas emitted especially from the burning of fossil fuels (coal, oil and gas), transportation, power plants and industrial processes (Anenberg *et al.*, 2018; Muhammad *et al.*, 2020). NO_2 contributes to the formation of some harmful secondary air pollutants such as O_3 (Khoder 2002), tropospheric levels of which is essentially a toxic air pollutant and greenhouse gas. SO_2 is released by fossil fuel, diesel and oil burning and leads like the other gases to respiratory problems, cardiovascular diseases and eventually mortality. Finally, constituents of PM less than 2.5 micrometers in diameter (*i.e.*, $PM_{2.5}$) strongly affects the respiratory system negatively with deposits in the lungs.

At the present time, air pollution has significantly changed the atmosphere of large cities and monitoring of the phenomenon requires accurate and timely measurements. *In-situ* data provides the most accurate measurements; however, satellites hold the vantage point of continuously surveying Earth's atmosphere over space and time at the global scale. The abrupt change in emissions of air pollutants during the lockdown period in response to the COVID-19 pandemic provided a unique opportunity to study the quantification of air pollution with available surface and satellite-generated remote sensing. For instance, as part of the Environmental Impact Assessment (EIA), many countries, including Southeast Asia, participated in an analysis of air quality based on data from the Copernicus Sentinel-5 Precursor (Sentinel-5P) satellite (https://sentinels.copernicus.eu/copernicus/ sentinel-5p).

In Thailand, locally within the Bangkok metropolitan area the air quality significantly improved, although surface NO_2 and SO_2 increased in some cases due to long-range transport pollution (Wetchayont *et al.*, 2021; Oo *et al.*, 2021). Focusing on a small scale, Stratoulias et al. (2020) demonstrated that over the medium-sized city of Hat Yai, the concentrations of NO_2, $PM_{2.5}$ and PM_{10} decreased by up to 33.7%, 21.8% and 22.9%, respectively, in the first 3 weeks of the lockdown period compared to the time before the pandemic. In Vietnam, during a similar social isolation context, the national average NO_2 as quantified by Sentinel-5P decreased by 9.3% compared to the same periods in previous years. Moreover, Vuong *et al.* (2023) reported reduction of concentrations of $PM_{2.5}$ and NO_2 between March and April in the Hanoi metropolitan area by 12 and 54%, respectively, while for the same city Dang and Trinh (2022) reported a reduction of NO_2 concentration by 24% to 32% two weeks after the lockdown. Evidence of similar decreases has also been reported in Malaysia (Nadzir *et al.*, 2020; Kanniah *et al.*, 2020; Othman *et al.*, 2021; Kanniah *et al.*, 2021). Yangon, a major city in Myanmar, experienced a profound improvement in the PM-related air quality during the pandemic-related restrictive measures (Aung *et al.*, 2021), while the concentrations of PM_{10}, $PM_{2.5}$, NO_2 and SO_2 in Singapore decreased by 23%, 29%, 54% and 52%, respectively (Li *et al.*, 2020). In Indonesia, NO_2 levels decreased in Jakarta and other Indonesian cities, but the reduction was insignificant outside the capital (Fardani *et al.*, 2021). Unlike other nations in Southeast Asia, significant changes in air quality during the lockdown were not observed in Cambodia, Laos, Myanmar, Timor Leste and Brunei (CREA, 2020). Overall, however, concentrations of major atmospheric pollutants decreased considerably in most of the SoutheastAsian countries due to lockdown policies and mitigation measures imposed (Roy *et al.*, 2021), but the reduction pattern of the air pollutants has shown distinct characteristics country by country.

Studies on the spatio-temporal development of air pollution in response to measures related to COVID-19 are common in the literature. However, evidence of the situation in smaller urban areas is a topic that has so far not been reported on. Following up from a published study where we demonstrated that the consequences of measures related to COVID-19 in regard to air pollution on a medium-sized city could be observed and quantified from satellite measurements (Stratoulias *et al.*, 2020), we proposed to investigate the applicability of this approach to smaller-sized urban areas located in southern Thailand. Specifically, in an area with relatively homogenous air-shed, meteorology and climate, we analyzed satellite observations from the Sentinel-5P satellite and hourly data from regulatory-grade air quality ground stations in an effort to: i) investigate the robustness of retrieving atmospheric concentrations of O_3, SO_2, NO_2 and CO by satellite sensors and ground measurements in small-sized cities; and ii) study the temporal evolution of the atmospheric concentrations during the COVID-19 transition and specifically the changes during and after the lockdown period. The scope of this research was to investigate air pollution parameters during the COVID-19 pandemic in the selected cities in southern Thailand and answer the questions: i) What is the effect of the COVID-19 lockdown on small-sized urban areas in terms of air pollution?; and ii) How accurate is Sentinel-5P in approximating surface air pollution parameters?

Materials and Methods

Study area

Unlike the northern and central parts of the country, which receive seasonal and trans-boundary air pollution, southern Thailand is less affected by these large-scale phenomena and has a relatively better air quality overall as presented in Figure 1. It encompasses a middle-sized city (Hat Yai) and several smaller-sized cities within a single air-shed and similar climatic characteristics; it is, therefore, a suitable study area for testing the hypothesis of our research. The southern part of Thailand consists of 14 provinces bordered by the Andaman Sea coastline on the west and the Gulf of Thailand on the east side (Figure 2). It covers an area of 70,714 km^2 and its climate is a tropical monsoon with the rainy season lasting from May to October and the dry season from February to April, which also coincides with seasonal air pollution as a consequence of collective agricultural residue burning activities. The average minimum and maximum temperatures are approximately 24°C and 40°C, respectively, and the mean annual rainfall is approximately 2,066 mm. The topography of this region is characterized as lowlands in contrast to the mountainous northern part of the region.

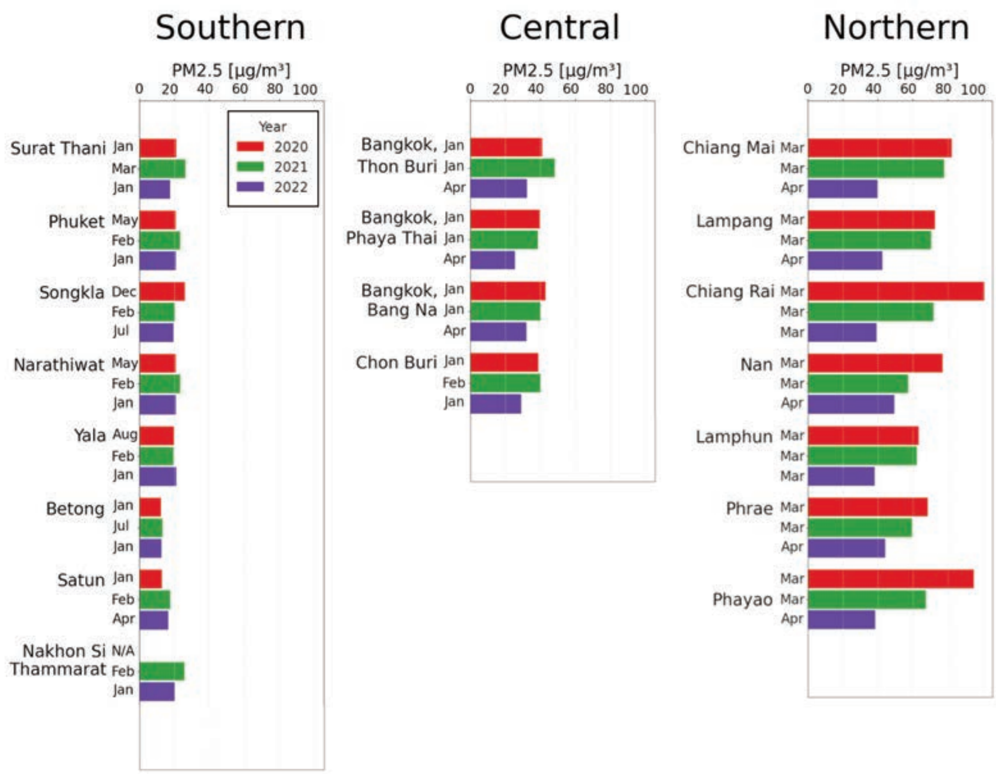

Figure 1. Maximum of the monthly $PM_{2.5}$ average surface concentration for each study year of 2020, 2021 and 2022 for 8 air quality ground stations in Southern Thailand, 4 stations in Central Thailand, and 7 stations in Northern Thailand.

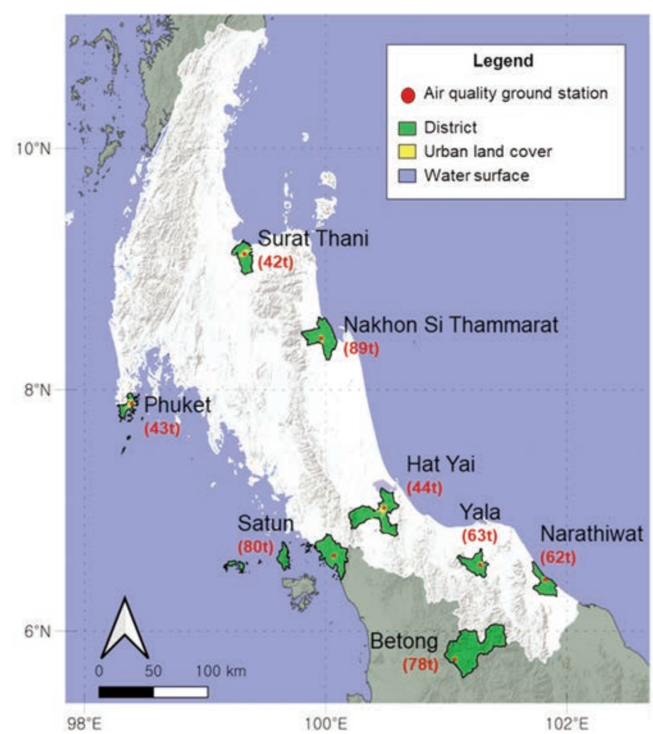

Figure 2. The study area covers the 14 southern most provinces in Thailand and the location of the 8 air quality regulatory-grade ground stations providing the study data. White: the study area; green: the administrative district boundaries of the districts; yellow the urban extent over which the cross-validation analysis was done.

Ground truth data

Daily measurements of key atmospheric pollutants covering the period during and after the COVID-19 lockdown were obtained from the Thai Pollution Control Department (2022) administered by the Air Quality and Noise Management Bureau. Eight regulatory-grade ground stations located within the major urban areas as depicted in Figure 2 and Table 1 were selected. The stations record hourly measurements of concentrations of CO in parts per million (ppm), NO_2 in parts per billion (ppb), SO_2 in ppb, O_3 in ppb, PM_{10} in μg/ m^3 and $PM_{2.5}$ in μg/m^3. The reference period was between 01 January and 25 March 2020 and the reporting period between 26 March and 31 May were chosen to capture the transition from the normal condition situation to the COVID-19 lockdown. The COVID-19 pandemic in Thailand started on 13 January 2020, with the first declared case in Thailand and the lockdown was imposed on 26 March 2020. An archive from 2010 up to date exists for all surface data, except for PM_{10} measurements, which are available only from 01 Jan 2020 onwards. However, there are a few missing periods in this archive as depicted in Figure 3. Any of these and other missing data values from the rest of the stations were not taken into consideration in calculating the overall statistics. It is worth noting there is one more regulatory-grade station in southern Thailand at the province of Krabi (93t), however, this station is installed at a rural area in between the two main urban areas of this province and as such it does not satisfy the focus of urban areas that the current study has and was excluded from consideration.

Satellite data

During the COVID-19 pandemic and due to the concomitant anthropogenic activities, air quality improvement has been observed worldwide primarily based on satellite measurements, which have the advantage of covering large geographical areas continuously and consistently. A variety of satellite sensors for estimating remotely sensed air quality and their approximations of the concentrations of the air pollutants are repeatedly reported in the literature. Notably, the Moderate Resolution Imaging Spectroradiometer (MODIS) (Dinoi *et al.*, 2010; Kanabkaew *et al.*,

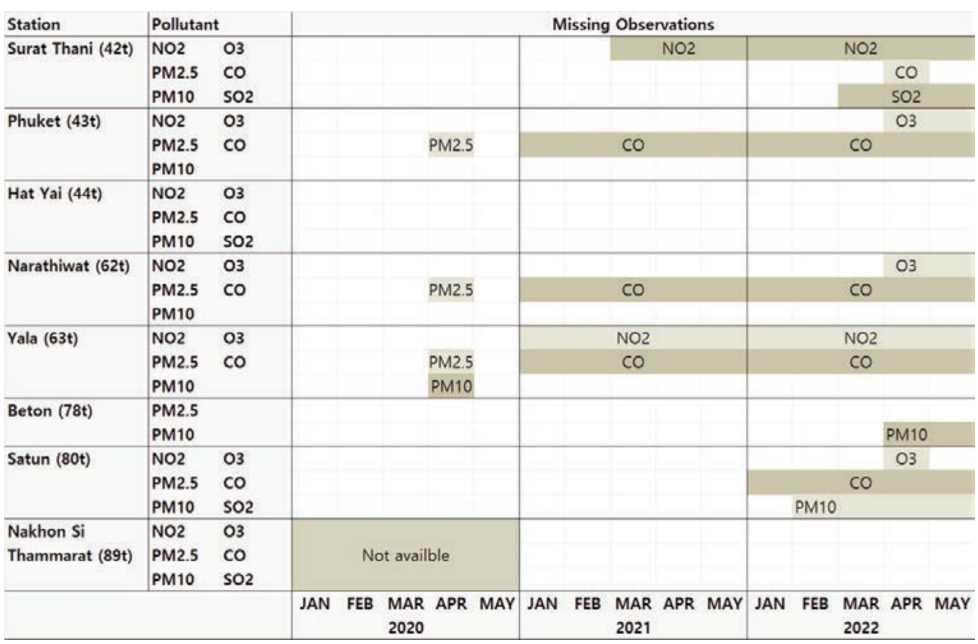

Figure 3. Availability of ground data by the air quality ground stations showing the missing periods of each pollutant observations.

Table 1. The location of the air quality surface stations.

Station	Latitude	Longitude	Altitude (m)
Makham Tia, Mueang, Surat Thani	9.126091	99.325350	7
Khlang, Mueang, Nakhon Si Thammarat	8.426950	99.961464	6
Talat Yai, Mueang, Phuket	7.884531	98.391318	5
Hat Yai, Songkhla	7.020560	100.484042	5
Phiman, Mueang, Satun	6.624709	100.066215	7
Sateng, Mueang, Yala	6.546551	101.283073	24
Betong, Yala	5.763904	101.067905	312
Bang Nak, Mueang, Narathiwat	6.426909	101.822998	4

Source: Pollution Control Department 2022.

2013) and the Sentinel-5P (Safarianzengir *et al.*, 2020; Wang *et al.*, 2020) have been extensively used. In terms of the methodological aspect, atmospheric columnar products are normally used (which approximate the total amount of the pollutant contained in a vertical column of air) or an associated index. Indicatively, Phayungwiwatthanakoon *et al.* (2014) applied the MODIS-based Aerosol Index (AI) for predicting and mapping PM_{10} concentrations between 2009 and 2010 in upper northern Thailand and reported that the AI had a good linear relationship with the reference ground-based PM_{10} data (R^2 = 0.661) with low bias at low aerosol condition. In another study looking into seasonality, Safarianzengir *et al.* (2020) analyzed CO using Sentinel-5 satellite data in Iran and found that CO concentrations were at their highest (=0.39 mol/m^2) in the cold season (April 2019). The current study used imagery from Sentinel-5P, a satellite launched on 13 October 2017 by the European Space Agency (ESA) and the European Commission. It is dedicated to monitoring the atmosphere, with the major purpose to develop global high spatiotemporal resolution atmospheric observations by measuring column densities of the atmospheric composition for monitoring urban air pollution (ESA, 2024), and namely O_3, SO_2, NO_2 and CO concentrations and the Air Quality Index (AQI). The satellite carries the Tropospheric Monitoring Instrument (TROPOMI) and the mission will be succeeded by the operational Sentinel-5 mission which is anticipated to be launched in the near future. The TROPOMI instrument is a passive sun backscatter imaging spectrometer that acquires measurements in 8 different spectral bands, namely 2 in the ultraviolet (270-320 nm), 2 in the visible (320-500 nm), 2 in the Near Infrared (NIR) (675-775 nm) and 2 in the Shortwave Infrared (SWIR) (2305-2385 nm). Sentinel-5P data are available freely from the ESA web portal (2024). The satellite provides global coverage of atmospheric composition typically once per day at 3.5 km x 7 km spatial resolution.

Methodology

The overall methodology is depicted in Figure 4. The surface concentrations recorded from the 8 available ground stations were used. Data were binned in 6 reporting periods in total, 1 period during the lockdown (1st January – 25th March) and 1 period after the lockdown (26th March - 31 May) for the year 2020, and the same periods for the following two years, during which the regulation measures gradually relaxed. This 5-month time window around the official date of the lockdown (26 March 2020) was selected to evaluate if any air pollution trends might be observed and associated with this phenomenon. Values were first averaged to daily means for each of the studied parameters (O_3, SO_2, NO_2, CO, PM_{10} and $PM_{2.5}$) for each of the 8 stations. Subsequently, the mean and the Standard Deviation (SD) of all cumulative data were also calculated. Moreover, the mean of the calendar month of April for each of the years 2020, 2021 and 2022 was derived to investigate air pollution concentration differences without the influence of seasonal factors. The month of April was selected since it was the month with the lowest anthropogenic activity country-wide during the lockdown.

The data collected from the TROPOMI sensor of the Sentinel-5P satellite were harvested and processed by GEE as described by Gorelick *et al.* (2017). The level 3 offline products were used as they are reprocessed with reanalysis data, although they inherit a time lag compared to the near real-time data. The four products selected were the tropospheric NO_2 column number density, the vertically integrated CO column density, the total atmospheric column of O_3 between the surface and the top of the atmosphere and the SO_2 vertical column density at ground level, with all measurements expressed as mol/m^2. The level 3 products are pre-processed from GEE with various algorithms and readers are directed to the GEE catalog for further information regarding the individual products. Time series of 161, 149 and 147 images for the year 2020, 2021 and 2022, respectively, were retrieved and the mean values over the time windows introduced in

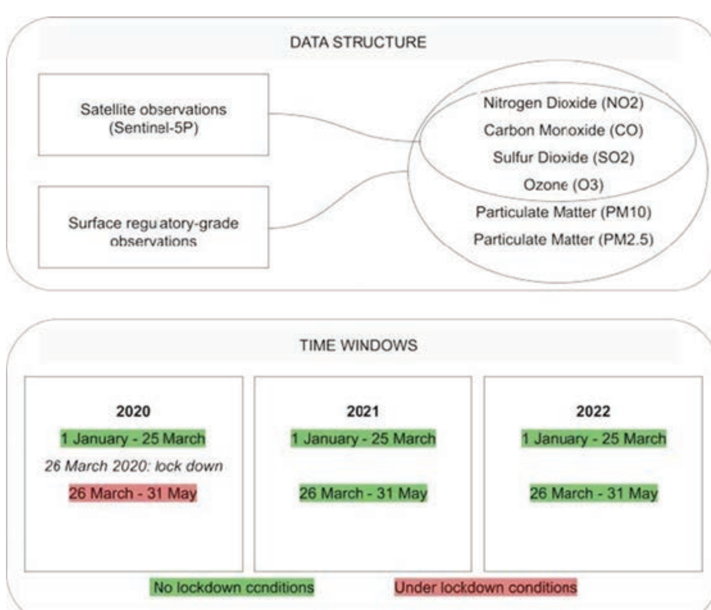

Figure 4. The data used in the current study and the 6 reporting periods selected.

the previous section were derived to compare with the ground data for the same time period. Thereafter, pixels over water or outside the study area were removed through the application of spatial masking. The mean and the SD values were used to discuss the pollutant's concentration distribution during and after the lockdown, with the relative difference of the mean values in percentage used as proxy of the pollutant concentrations. To investigate the relationship between satellite-based single point and spatially averaged values for the small-sized urban areas, the pixel values of the tropospheric NO_2 column number density satellite product overlapping with the fixed location of the ground stations were extracted and a time-series of measurements for each individual location were built. Additionally, we attempted to derive a representative value for each air pollutant over the urban area of the study areas. To accomplish this, the urban extent and the satellite pixels enclosed within this urban area were both accounted for and the spatial average value extracted. A respective time-series of the average over the urban area was then derived. The urban extent was taken from the MODIS Land Cover Type Yearly Global 500m dataset, specifically the Land Cover Type 2 layer, which represents the urban and built-up lands of at least 30% of impervious surface areas. The two time series of satellite-based measurements were judged against each other by deriving the linear regression for each period of interest and evaluating the coefficient of determination by R^2.

Results

To examine the overall situation of air pollution in southern Thailand urban areas as quantified by the ground stations, the time series of the daily-averaged concentrations for each pollutant (namely NO_2, CO, SO_2, O_3, PM2.5, PM10) as measured cumulatively by the 8 ground stations in the three reporting periods is presented in Figure 5. A considerable difference in the temporal development of NO_2 concentrations was observed for the year the lockdown was first imposed (*i.e.* 2020) and the two subsequent years; in the first year concentrations declined after the lockdown date but increased somewhat in the summer and a sharp increase of 1-1.5 ppb was observed in the beginning of April. In the case of CO, the curve for the year 2022 differed significantly compared to 2020 and 2021 by demonstrating a sharp decline at the end of March from 0.4 to 0.1 ppm. With regard to SO_2 the pattern for the years 2020 and 2021 were similar with early peaks that both declined sharply in the middle of February and then deviated from the end of March to the beginning of May. For the pollutants O_3, $PM_{2.5}$ and PM_{10} there was no strong differences around the lockdown day and thereafter, apart from peaks of PMs around 1 March in 2921, at least when considering the data from all stations cumulatively as presented in Figure 5. Table 2 presents the changes in the concentrations of the pollutants before and after the lockdown for the 3

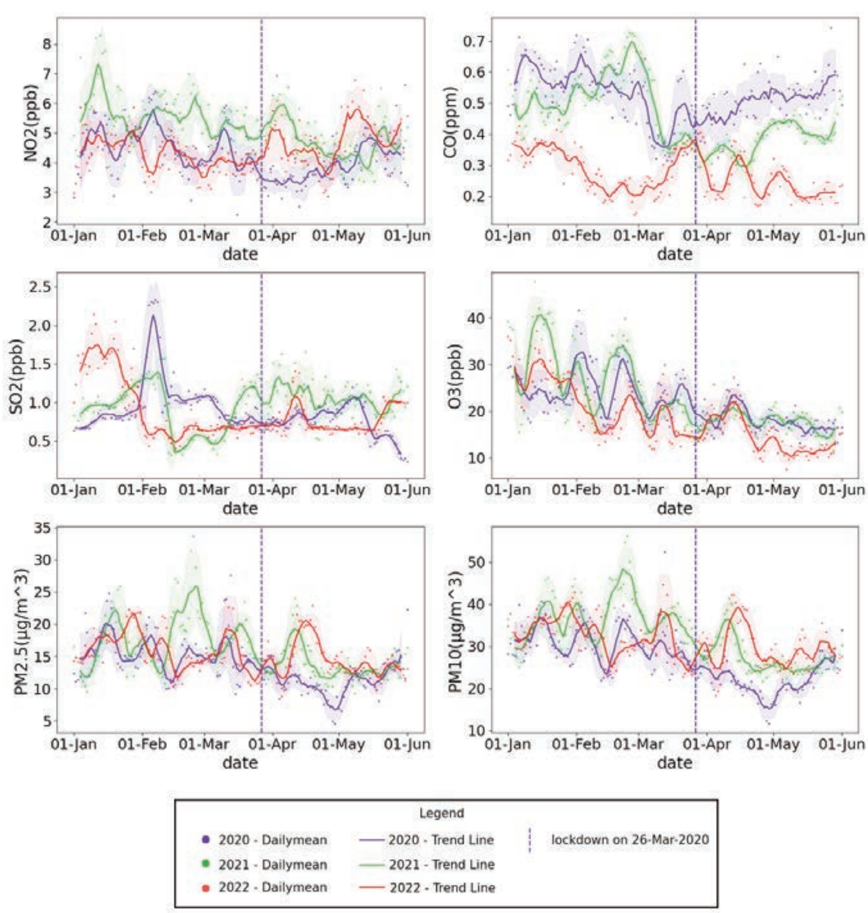

Figure 5. The daily-averaged concentration of the 6 pollutants from the 8 air quality ground stations aggregated. The vertical blue line shows the lockdown date (*i.e.* 26th March 2020); the curves show the 7-day average trend line; and the shaded areas the standard deviations.

time periods of interest. It is apparent that for the year 2020, all 6 pollutants show a reduction in the mean concentrations after the lockdown was imposed. For the years 2021 and 2022, reductions were also observed in all pollutants except for SO_2 for year 2021. For the year 2022 an increase of 11% was observed in the mean surface concentration of NO_2 between the reporting periods before and after the lockdown. April is the primary month of interest when investigating the lockdown influence as it was the first month following the restrictive measures and any change might exhibit strongly during this period. Figure 6 presents the average for the month of April from the 8 ground stations cumulatively for the 3 years of concern and for each pollutant separately. Overall, concentrations for the pollutants $PM_{2.5}$, PM_{10} and SO_2 were lower for the year 2020, however, for the rest of the pollutants this was not the case. While the aforementioned results are derived based on the ground stations point measurements, satellite images represent the situation of the phenomenon over a larger geographical extent, which in our case is the southern part of Thailand. An anal-

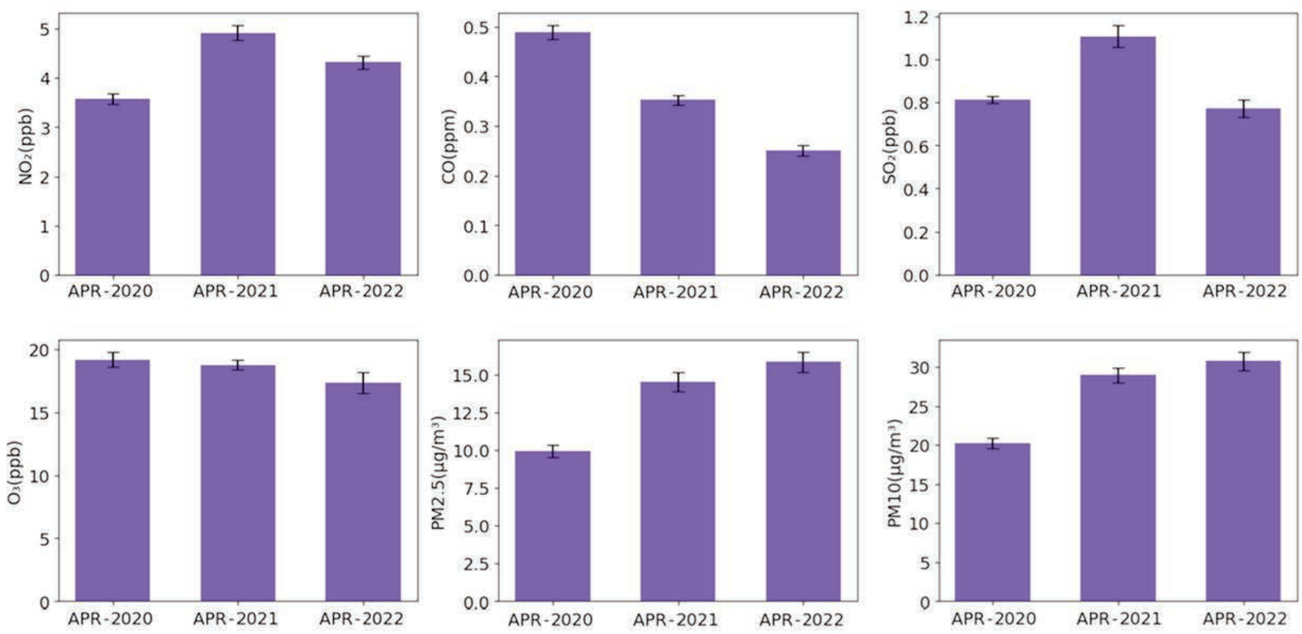

Figure 6. The monthly average concentrations of each pollutant for the month of April for the for the month of April each study year. Blue bars depicts the cumulative data for all 8 air quality ground stations and the whisker sthe standard errors. The data are cumulative from all 8 ground stations.

Table 2. Surface concentrations from all 8 stations cumulatively for the two reporting periods for each of the three years.

Pollutant	2020 Jan-Mar (SD)	2020 Mar-May (SD)	2020 Rel. mean difference (%)	2021 Jan-Mar (SD)	2021 Mar-May (SD)	2021 Rel. mean difference (%)	2022 Jan-Mar (SD)	2022 Mar-May (SD)	2022 Rel. mean difference (%)
NO_2	4.489 (0.881)	3.876 (0.718)	-14	5.515 (0.969)	4.7 (0.853)	-15	4.277 (0.669)	4.763 (0.861)	11
CO	0.534 (0.104)	0.508 (0.074)	-5	0.508 (0.104)	0.383 (0.059)	-25	0.295 (0.073)	0.239 (0.058)	-19
SO_2	0.978 (0.385)	0.746 (0.218)	-24	0.901 (0.343)	1.064 (0.237)	18	0.941 (0.459)	0.774 (0.195)	-18
O_3	24.517 -5.442	17.9 (2.93)	-27	26.665 -8.352	17.783 -2.391	-33	21.527 -6.699	14.541 -4.216	-32
$PM_{2.5}$	15.783 -3.493	11.966 -2.615	-24	18.465 -4.876	13.061 -2.902	-29	15.882 -3.424	14.784 -3.055	-7
PM_{10}	30.391 -4.988	22.021 -4.165	-28	36.419 -6.239	27.086 -4.264	-26	32.513 -5.627	29.467 -5.153	-9

The relative difference was calculated between the values reported before (1 Jan - 25 Mar) and after (26 Mar - 31 May) the lockdown.

ysis at regional scale based on the Sentinel-5P data is presented in Figure 7, which depicts the spatial distribution for NO_2, SO_2, CO and O_3 (for the case of $PM_{2.5}$ and PM_{10}, current satellite technology does not provide directly quantitative results). The value presented is the total average from the satellite data collected over the reporting periods for the years 2020-2022. For SO_2, the situation is relatively stable for 2020, while for the next two subsequent years a reduction is observed. CO showcases the same spatial pattern for years 2020 and 2021 when there is noticeable reduction, while for year 2022 a slight increase is observed in the northern part of the study area. With regard to O_3, an increase was observed that gradually grew stronger from the first to the last year. With respect to NO_2 an overall reduction was observed over a large part of southern Thailand during the transitioning of the lockdown for the year 2020, while for 2021 an increase was observed for the period in question that for 2022 was relatively unchanged. This particular effect is better demonstrated in the anomaly figure introduced in Figure 8, illustrating the degree by which the mean tropospheric

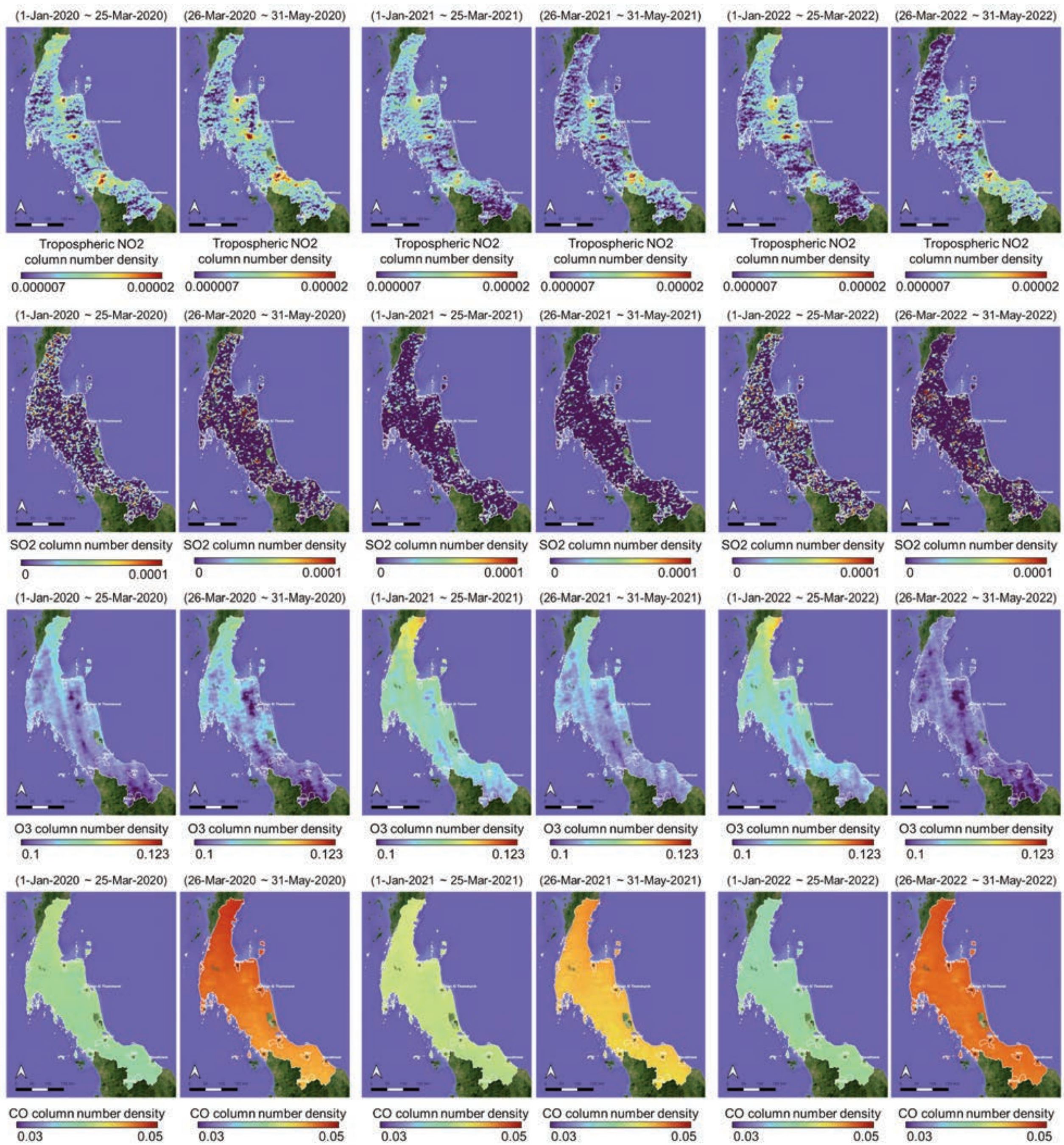

Figure 7. The spatial distribution of the vertical column density of each pollutant averaged for each reporting period over south of Thailand as recorded by the Sentinel-5P satellite. The vertical column density is a satellite-based measurement of the total amount of the pollutant found in the atmosphere integrated along the vertical path from the satellite to the ground.

NO_2 column cumulative for the years 2021-2022 deviated from the respective mean of the year 2020 for the two months before and the two months after the lockdown. The results show that for the 2-month period before the lockdown, the anomaly was minimal and the NO_2 concentrations remained relatively stable between the year 2020 and the average of the years 2021-2020. However, for the period of 2 months following the imposition of lockdown regulation, several isolated localized clusters of increased NO_2 activity in the years 2021-2022 compared to 2020 were observed. These locations were notably found in the suburbs of the cities of Surat Thani, Nakhon Si Thammarat and Hat Yai.

Finally, the relationship between the NO_2 point data (*i.e.* pixel coinciding with the ground station location) and the spatially averaged over the urban area from the Sentinel-5P data is presented in *Supplementary Materials, Figure 1*. High correlation values were observed for all cases, with R^2 ranging between 0.64 and 0.97 except for the case of Betong for the years 2020 and 2022 in which case the R^2 ranged between 0.51 and 0.57. This relationship is representative of the homogeneity of the spatial distribution of the NO_2 over the urban area, and indicates the degree to which single point data can be used as a proxy for the air pollution situation of an urban area, and specifically the small-sized urban areas that we are examining in this study.

Discussion

Past studies have revealed that people residing in urban settings are more likely to face health risks caused by air pollution (WHO, 2018b). Air pollution and urbanization are both increasing all around the world and especially in developing countries, which are typically low- and middle-income countries. Evidence indicates that over 90% of premature deaths due to air pollution occur in these countries (WHO, 2023) and it is established that they are the ones which suffer and are impacted the most from air pollution. Thailand is one of the middle-income countries with such problems and consistently records high air pollution levels. The latter, in conjunction with the fact that over 50% of the Thai population lives in urban areas (National Statistical Office, 2023), calls for the study of the distribution of urban air pollution holistically and at regional levels.

During the COVID-19 pandemic, reduced anthropogenic activities created a unique global setting with several studies in the scientific and gray literature reporting bettering of environmental indicators, especially from the human perspective. This situation has provided the opportunity to evaluate the degree at which state-of-the-art technology is able to detect and quantify the change of several phenomena, one of which is air pollution. Many studies have reported a reduction of air pollution in Southeast Asia (e.g., Kanniah *et al.*, 2020; Roy *et al.*, 2021) primarily over densely populated areas. While in a previous study, Stratoulias *et al.* (2020) demonstrated that this is true also for a medium-sized city, there is still insufficient research on the effect in sparsely populated areas and small-sized cities. In the current study we investigated the degree of agreement of the previous findings when expanding the study area to the whole South of Thailand, which encompasses populated settings of small-sized urban areas.

Our main finding indicates that, for the 2-month period following the lockdownover small-sized urban areas, it is evident that there is a noticeable reduction of NO_2 compared to the pre-lockdown respective period. This appears in the data from the ground stations as there was cumulatively, and for all 8 stations, a reduction of the mean NO_2 by 14% for the year that the restrictions were imposed, namely 2020 (Table 2). On the other hand, for the year 2022 an increase of 11% was observed between the reporting period before and after the lockdown (Table 2). The latter might be a direct consequence of the return of the economic and anthropogenic activity to pre-COVID levels. Qualitatively, this is also apparent in Figure 7, which depicts the results retrieved from Sentinel-5P covering the whole region of southern Thailand as well as Figure 8, which introduces the anomaly figure for the year 2020 against the average for 2021-2022 for the two intra-annual periods. This aligns with general findings from other related studies which indicate that NO_2 is the pollutant demonstrating the

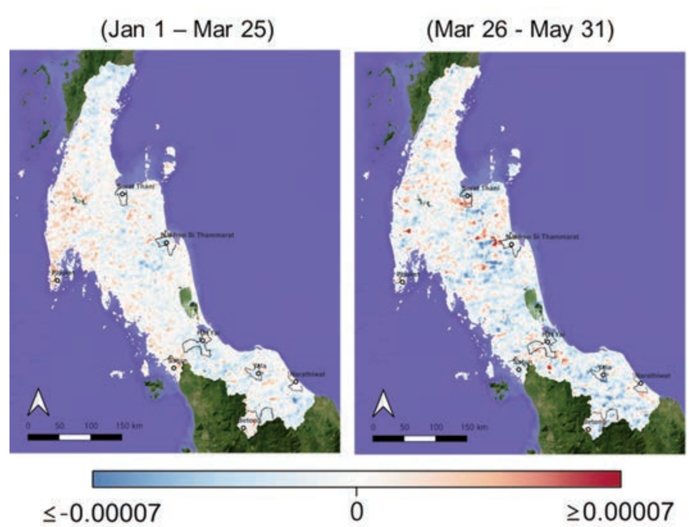

Figure 8. Anomaly of the mean tropospheric NO_2 column density of the average for the years 2021-2022 compared to the corresponding value for the year 2020. Lockdown measures were imposed in March 2020; left: situation for the two 2-month periods before the lockdown; right: situation for for the two 2-month periods after the lockdown.

largest and most apparent reduction in urban agglomerations of Southeast Asia after the lockdown regulations (Kanniah *et al.*, 2020). This is justified on the basis that NO_2 is emitted by vehicles, industrial facilities, and power plants, the reduced activities of which led to less NO_2 release into the atmosphere. Nevertheless, it is important to note that the seasonal variations and long-range pollution transport have not been taken into account in the current explanation, and this may be especially important for the reporting periods selected in the current study, because the months of March and April (which is when the lockdown regulations were imposed) were a transitional period from the dry to the rainy season and atmospheric and weather patterns are dynamic. This seasonal effect might be demonstrated in 2021 and 2022 seen in Figure 5, years during which industrial activity gradually returned to normal and the NO_2 temporal distribution followed the same pattern.

Our study indicates that CO is also decreasing for the year 2020 both from the ground measurements (by 5%) and the satellite data, however, SO_2 seems to have a reduction of 24% which is not evident in the satellite data as in the former case there is a considerable amount of missing data specifically for SO_2. This pollutant has been reported not to exhibit large differences in the COVID-19 lockdown scenario as demonstrated by Caraka *et al.* (2020) and Srivastava *et al.* (2020). With regard to O_3, a reduction by 27% is evident in the ground measurements, something that appears to be increasing in the satellite data (Figure 6). The disagreement between ground and satellite data may be attributed to the fact that ground stations measure point data at the surface, while the satellite product used the total atmospheric column of O_3 which measures the columnar concentration in the troposphere and stratosphere.

When analyzing the results from years 2021 and 2022 (Figure 5 for all pollutants and Figure 7 for all pollutants except $PM_{2.5}$ and PM_{10}), there is a strong agreement in the trends of O_3, PM2.5 and PM10, although it is worth noting that the O_3 trend is similar for all 3 years (Figure 5) and the average for month of April remains the same (Figure 6). This might be indicative of the strong effect of the seasonality for this pollutant. However, it is worth noting that specifically from 29 March until 14 April (the time for O_3 culmination in all three years), the O_3 was lower in 2020 compared to the two subsequent years. O_3 has reportedly increased after the lockdown in several studies (Dantas *et al.*, 2020; Sharma *et al.*, 2020; Tobías *et al.*, 2020; Dejchanchaiwong *et al.*, 2021) and is attributed to the reduction of nitrogen oxides level, which in turn causes an increase of tropospheric O_3. Nevertheless, in a previous related study (Stratoulias *et al.*, 2020) concentrated on only one city (Hat Yai that is also included in the current study) in which it was suggested that this reduction in 2020 was a climatic contribution rather than related to the lockdown as the magnitude observed in not strong; however, the current study presents contrasting data for the years 2020 and the two subsequent years, so the differentiation in O_3 levels during this period of the year requires further detailed research investigation. When comparing the graphs for $PM_{2.5}$ and PM_{10} covering the three study years, it is apparent that for the first five weeks after lockdown, the average for April (Figure 6) was considerably lower and the trend for the year 2020 (Figure 5) reversed and declining, which is an indication that this was the direct effect of the lockdown measures for the year 2020. For NO_2 and CO, the years 2021 and 2022 follow the same trend after the middle of March, while the similarity is weaker for SO_2. Overall, when comparing the data from the three years and reporting periods, we suggest that the lockdown imposed in 2020 had an immediate effect on the cumulative surface concentrations of NO_2, $PM_{2.5}$ and PM_{10} over the major urban areas in southern Thailand. The cause behind this reduction may be attributed to the government interventions (national emergency decree), which consequently led to reduced industrial activities, less vehicular use and incoming tourism as indicated by other similar studies for Thailand (Kodaka *et al.*, 2021). With regard to the association between the satellite-based point and urban-averaged data as analyzed from Sentinel-5P data (*Supplementary Materials, Figure 1*), we wish to draw attention to our findings for the city of Hat Yai in light of the preceding study (Stratoulias *et al.*, 2020).Both studies integrate data from the pre- and a post-lockdown periods, although the study conducted in 2020 uses a longer time frame (from 1 December 2019 until 1 June 2020) compared to the current study (from 1 January 2020 to 31 May 2020). The current results are similar to those of the preceding study, whose recorded R^2 was 0.73for the whole study periodin the year 2020, while our current study yielded $R^2 = 0.75$ for the pre-lockdown period and $R^2 = 0.68$ for the post-lockdown periodin 2020. For the year 2021 the R^2 values are in a similar range between 0.71 and 0.75, while for the year 2022 the R^2 values drop to 0.66 and 0.64 respectively. This suggests that there is no clear association between the lockdown and the measurements and between the two studies on the global extension of the NO_2 quantification from the satellite and the homogeneity of the phenomenon of air pollution. When considering the results from all the stations (*Supplementary Materials, Figure 1*), there no clear pattern over the pre- and the post-lockdown time periods. Moreover, the overall R^2 ranges and those for each station individually maintained values above 0.51. This indicates that the point data (*i.e.* single pixel value) associates well with the urban-averaged data. Nevertheless, this association is time-dependent and translates to different environmental and atmospheric conditions for the reporting periods. Another interesting observation arising from *Supplementary Materials, Figure 1* is that the regression slope was lower for the post-lockdown reporting period compared to the pre-lockdown for all stations except two (namely Yala and Satun). This observation was especially pronounced in the most populated cities, namely Hat Yai and Phuket. The regression slope may be the quantitative indicator of choice for tracking and observing changes in conditions directly from satellite data when important environmental changes occur.

Conclusions

The COVID-19 pandemic created a unique state of sudden atmospheric improvement, which is a suitable scenario for experimenting with the capabilities of state of the art technologies. Satellite remote sensing is making large leaps in improving the capabilities of monitoring air pollution from space. In this context, the current paper focuses on studying the usability of the Sentinel-5P satellite and regulatory-grade surface observations in quantifying the concentration of air pollutants over southern Thailand. It is envisaged that this study would help in identifying the association between the measurements and air quality improvement due to reduction of air pollutants proliferation.

Our main finding suggests that a noticeable reduction of NO_2, PM2.5 and PM10 surface concentrations for the 2-month period following the lockdown compared to the pre-lockdown respective period is observed cumulative for southern Thailand for 2020. NO_2 has been reported as the pollutant demonstrating the greatest reduction during the pandemic in several cities in SE Asia (Roy *et al.*, 2021) and we have quantified this reduction of the mean NO_2 cumulative for all 8 main but rather small-sized cities in southern Thailand for 2020 to be 14%. O_3 does not provide solid conclusions in our study, perhaps due to the fact that the total O_3 column was analyzed, and the results are inconclusive suggesting further research is required for this pollutant. PM2.5 and PM10 present a short-lived reduction immediately after the lockdown in the year 2020, something which is opposite to the years 2021 and 2022, which reinforces our finding that the driver behind this reduction is the lockdown. Most importantly, the current study has taken into consideration a large geographical area and surface stations from 8 different provinces, and the results agree with a preceding study focusingon a single medium-size city which is included in the current study as well. This fact, in conjunction with the fact that the results indicate a close association between the ground and satellite data observations that correspond to the lockdown imposed in most of the cities, proves the robustness of using satellite observations for quantifying air pollution, which may be especially useful to areas where ground measurements are limited (Ngo *et al.*, 2021). Overall, we suggest that, based on satellite-based estimations of pollutant concentrations, an abrupt transition in air quality improvement following the lockdown imposed for the year 2020 is observed for small-sized urban areas, which is different in pattern from the 2 subsequent years judged from surface and satellite observations. Satellite remote sensing manifests to be a robust tool for operational use in the context of monitoring, regulation enforcement and air pollution abatement in terms of policy making.

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Online supplementary materials

Figure 1. Correlation between Sentinel-5P NO□ pixel value over the ground station and average of pixel values enclosed by the extent of each small-sized urban area for NO□ for each reporting period. Each graph corresponds to a single surface station with the red solid line representing the regression line.