Air quality development during the COVID-19 pandemic over a medium-sized urban area in Thailand

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HIGHLIGHTS

- The effect of lock-down on the air quality of a medium-sized urban area was assessed.
- NO_2 concentration decreased by 33.7% during the first 3 weeks of lock-down.
- Likewise, $PM_{2.5}$, PM_{10} and O_3 decreased by 21.8%, 22.9% and 12.5% respectively.
- Average NO_2, CO and $PM_{2.5}$ for April 2020 exhibit the lowest values in the last decade.
- Sentinel-5P observations mirror the observations of the ground station.

GRAPHICAL ABSTRACT
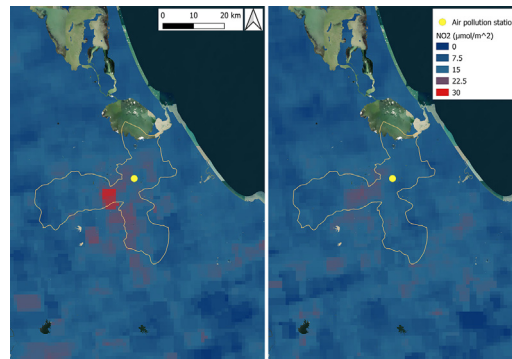
ABSTRACT

The COVID-19 pandemic has triggered an industrial and financial slowdown due to unprecedented regulations imposed with the purpose to contain the spread of the virus. Consequently, the positive effect on the environment has been witnessed. One of the most prominent evidences has been the drastic air quality improvement, as a direct consequence of lower emissions from reduced industrial activity. While several studies have demonstrated the validity of this hypothesis in mega-cities worldwide, it is still an unsubstantiated fact whether the same holds true for cities with a smaller urban extent and population. In the present study we investigate the temporal development of atmospheric constituent concentrations as retrieved concurrently from the Sentinel-5P satellite and a ground meteorological station. We focus on the period before and during the COVID-19 pandemic over the city of Hat Yai, Thailand and present the effect of the lockdown on the atmospheric quality over this average populated city (156,000 inhabitants). NO_2, $PM_{2.5}$ and PM_{10} concentrations decreased by 33.7%, 21.8% and 22.9% respectively in the first 3 weeks of the lockdown compared to the respective pre-lockdown period; O_3 also decreased by 12.5% and contrary to similar studies. Monthly averages of NO_2, CO and $PM_{2.5}$ for the month April exhibit in 2020 the lowest values in the last decade. Sentinel-5P retrieved NO_2 tropospheric concentrations, both locally over the ground station and the spatial average over the urban extent of the city, are in agreement with the reduction observed from the ground station. Numerous studies have already presented evidence of the bettering of the air quality over large metropolitan areas during the COVID-19 pandemic. In the current study we demonstrate that this holds true for Hat Yai, Thailand; we propound that the environmental benefits documented in major urban agglomerations during the lockdown may extend to medium-sized urban areas as well.

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1. Introduction

The coronavirus disease (COVID-19), caused by the newly introduced Severe Acute Respiratory Syndrome Coronavirus 2 (SARS-CoV-2), spread rapidly across the world after reportedly originating in China in the end of December 2019 (Huang et al., 2020a); soon thereafter, a pandemic was declared by the World Health Organization (WHO). SARS-CoV-2 is an RNA virus, and as such has a high mutation rate and can adapt to become more efficiently transmitted. To date no efficacious for humans vaccines or antivirals for coronavirus exist (Wang et al., 2020a) and the first vaccines for emergency use are anticipated by early 2021 (Le et al., 2020). The rapid geographic dissemination of the novel coronavirus, attributed mainly to the high percentage of undocumented infections (Li et al., 2020), make the containment of the virus challenging. Consequently, extraordinary and unprecedented public health measures have been taken with the majority of the countries imposing strict measures at local and national level to decelerate the spread of the virus in their territories. Most often, this was in the form of a city or a country lockdown and, accordingly, commercial and industrial activities as well as transportation of people and goods shrank abruptly.

This decreased anthropogenic activity had a positive impact on the natural environment (Muhammad et al., 2020; Wang and Su, 2020) and lead to the bettering of the air quality (especially in South Asia (Gautam, 2020a)) as reported worldwide in the public broadcasting (e.g. Hernandez, 2020; ESA - Applications, 2020; Papale et al., 2020) and the scientific literature alike. In a prompt response to the pandemic, several studies urged to stress the effect of the lockdown on air quality specifically over large cities. For instance, Tobías et al. (2020) found that NO_2, BC concentrations reduced by half and PM_{10} in a lower proportion over Barcelona following the city's lockdown. In a similar study concentrating on São Paulo state, Brazil, Nakada and Urban (2020) found decreased concentrations of carbon monoxide (CO), nitrogen oxide (NO) and nitrogen dioxide (NO_2) (64.8%, 77.3% and 54.3% respectively) while ozone (O_3) was increased by approximately 30%. Similarly, Kerimray et al. (2020) in a study investigating the consequent traffic-free conditions in Almaty, Kazakhstan reports reduced concentrations of particulate matter with a diameter of less than 2.5 ($PM_{2.5}$), CO and NO_2 (21%, 49% and 35% respectively) and increased O_3, benzene and toluene concentrations. Collivignarelli et al. (2020) also observe significant reductions of PM_{10}, $PM_{2.5}$, BC, benzene, CO and NO_x, increase of O_3 and no changes in sulfur dioxide (SO_2) in Milan, Italy. Nevertheless, Wang et al. (2020b) claim that the reduced anthropogenic emission during the pandemic outbreak was not sufficient to avoid severe air pollution events in 10 major cities in China.

Consequently, as air pollution has an impact on human health such as affecting the respiratory system, some studies have stressed the important health benefits during the pandemic transition period. Chen et al. (2020) claim that the aggressive control measures to contain the outbreak led to improved air quality and consequently substantial health benefits while Venter et al. (2020) reckon that the remarkable decline of ground-level air pollution in 27 countries relate to health benefits; in fact, in the scenario that low concentrations will sustain during 2020, 0.78 million premature deaths and 1.6 million pediatric asthma cases globally could be avoided. Dutheil et al. (2020) argues that the pandemic has decreased the number of air pollution related fatalities during this period and therefore might have paradoxically decreased the total number of deaths while Isaifan (2020) takes it one step further by suggesting that the halt of anthropogenic activities, induced by the lockdown, may have saved more lives due to preventing ambient air pollution rather than preventing the infection. Bherwani et al. (2020) demonstrate in monetary terms the consequences of reduced health damages related to air pollution. Last but not least, Ogen (2020) showcases that there is a major hotspot of high NO_2 concentrations over the northern part of Italy and argues that the chronic exposure to air pollution, and the subsequent associated respiratory and inflammation

problems, is an important contributor to the high COVID-19 fatality rates observed in this region. Along the same lines, Pansini and Fornacca (2020) reckon that air quality associates inversely with SARS-CoV-2 infections in Italy and Yongjian et al. (2020) observed a significant relationship between short-term exposure to higher concentrations of $PM_{2.5}$, PM_{10}, CO, NO_2 and O_3 and COVID-19 confirmed cases.

While it is evident that air pollution has drastically changed the atmosphere of large cities and the landscape of daily ordinary activities, air quality monitoring requires accurate and timely measurements. In-situ data from ground stations provide the most accurate measurements of a condition, nevertheless, satellites hold a unique vantage point in surveying Earth's atmosphere over space and time. Since 2013 the Sentinel missions have opened up new opportunities for science (Berger and Aschbacher, 2012) and Sentinel-4 and Sentinel-5 particularly focus on atmospheric monitoring. For the time being, the Sentinel-5P satellite provides global and timely measurements of atmospheric composition (de Vries et al., 2011; Berger and Aschbacher, 2012; Veefkind et al., 2012; Theys et al., 2017) and several studies have demonstrated its usability in this context. For instance, Sharma et al. (2020) in a study looking into the air quality of 22 cities in India during the COVID-19 found that the effect of restricted human activities led to a reduction of $PM_{2.5}$ in most of the regions and Roman-Gonzalez and Vargas-Cuentas (2020) report reduction of aerosol pollution over Lima, Peru and the Amazon regions based on Sentinel-5P data. In Asia numerous studies report lower NO_2 concentrations during the pandemic based on Sentinel-5P data (e.g. Fan et al., 2020; Wang and Su, 2020; Bauwens et al., 2020).

The effect of the COVID-19 induced lockdown measures in the air quality of mega-cities has been corroborated extensively. This is anticipated as metropolitan cities host a large number of inhabitants and embody the financial and commercial nexus of a country, hence they are the center of the attention. Moreover, air pollution is typically a concern, if not a hazard, in such cities. Nevertheless, a large part of the global population, especially in SE Asia, lives in small and medium-sized urban areas (as defined by OECD (2020)) and the effect of the lockdown on the air quality for these cases has not yet been documented substantially. In the present study we investigate the effect of a two-month lockdown on the air quality over Hat Yai, a city in Thailand with a population of 156,000 people. We analyze hourly data from the local meteorological station and observations from the Sentinel-5P satellite to investigate if, due to the lockdown imposed following the COVID-19 pandemic, the air quality improved in a typical medium-sized urban area. We suggest that the positive impact on air quality extends to medium-sized urban areas Therefore, it is of importance to further investigate the evolution of the air pollution in smaller cities, as in the current study, and evaluate differences attributed to the urban extent. We propound that the environmental benefits documented in major urban agglomerations during the lockdown induced by the COVID-19 pandemic may extend to medium-sized urban areas as well.

2. Material and methods

2.1. Study area

The city of Hat Yai is located at southern Thailand in Songkhla Province at the geographic coordinates 7°01′00″N latitude and 100°28′00″E longitude (Fig. 1). It is the largest metropolitan area in southern Thailand and the third largest of the country, nevertheless, it holds a population of approximately only 156,000 inhabitants in the city and 800,000 in the greater area. Thus, it is a relatively medium-sized city, but at the same time an active commercial and transportation nexus for the greater area. The city is surrounded by vegetation, primarily plantations and secondarily paddy rice and forests (Appianing et al., 2016; Nuthammachot and Stratoulias, 2019a). The climatic conditions prevailing in southeast Asia are hot and humid weather, typical for the tropics. At a regional scale, specifically Southern
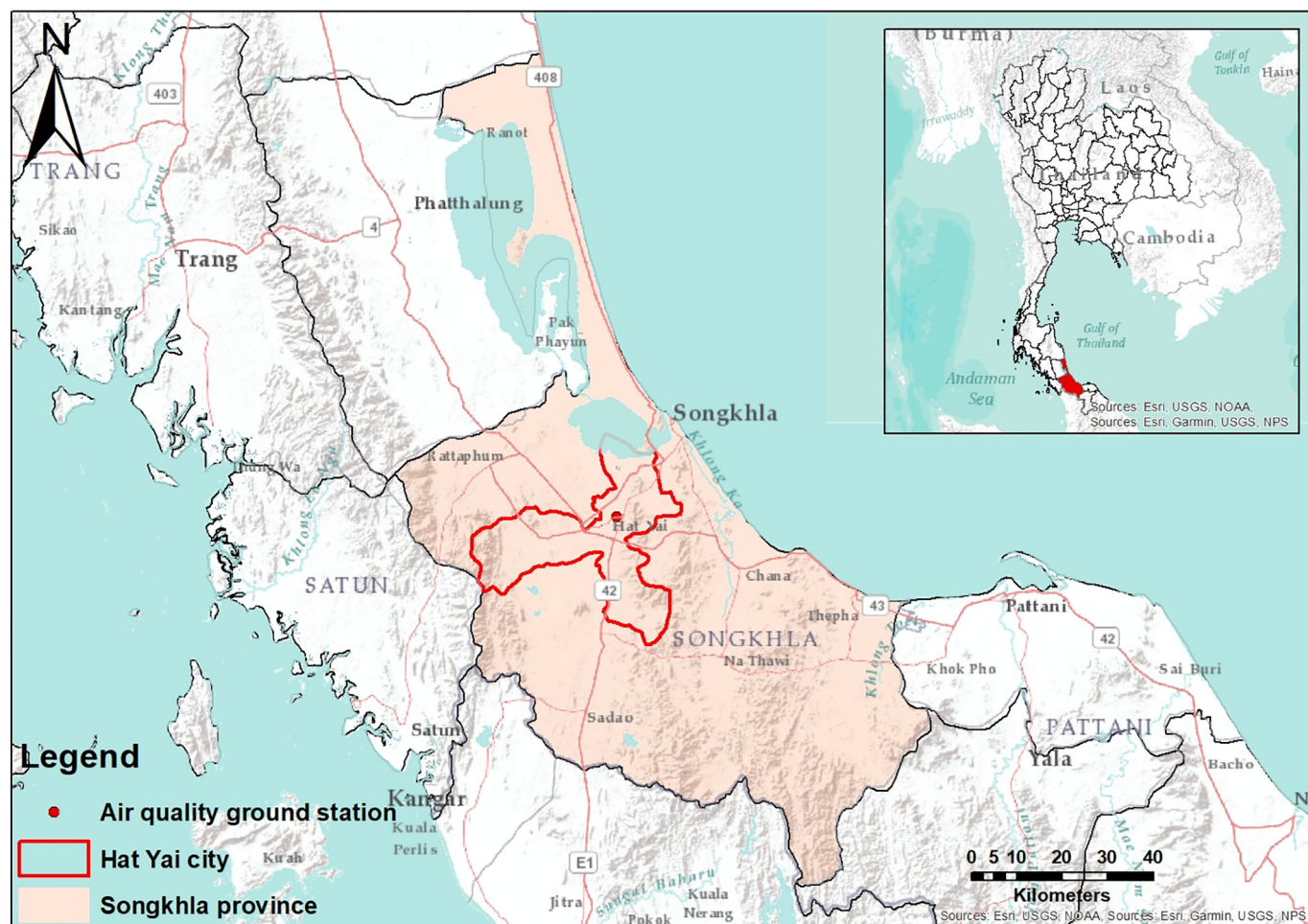
Fig. 1. Study area depicting the location of the meteorological station, the city of Hat Yai and the Songkhla province (main map) and the Songkhla province within the administrative areas in Thailand (inset).

Thailand observes a distinct for the greater area climatic pattern with the dry season lasting from January to April while the period between May to December is characterized by high precipitation and wet conditions (Nuthammachot and Stratoulias, 2019b). Official lockdown measures (closure of commercial enterprises and nation-wide curfew) took effect in Hat Yai on 26 March 2020 (Royal Thai Government Gazette 2020); meanwhile, the measures have been relaxed incrementally since then. Nationwide night curfew was also imposed during the night from 3rd April 2020 until 16th May 2020 (10:00 pm–04:00 am) and 16th May 2020 until nowadays (11:00 pm–04:00 am). Despite the fact that Thailand was the first country reporting a SARS-CoV-2 case outside China (Wang et al., 2020a; Sriwijitalai and Wiwanitkit, 2020), the country has seen a remarkable containment of the virus spread, perhaps attributed to the strict lockdown regulations imposed (at national and provincial level) and the rapid response for screening measures (incoming travelers from Wuhan were screened at major Thai international airports since 3rd January 2020 (Okada et al., 2020)). Moreover, tropical regions maintain to date a relatively lower number of COVID-19 cases compared to Europe and America (Lal et al., 2020), which may be related to the climatic weather conditions (several studies indicate an inverse correlation between temperature and confirmed COVID-19 cases (e.g. Araujo and Naimi, 2020; Prata et al., 2020; Wang et al., 2020c; Tobías and Molina, 2020). Between 20th March 2020 and 22nd April 2020, 17 cases of the novel coronavirus infections have been officially documented in Hat Yai (Department of Disease Control (กรมควบคุมโรค), 2020).

2.2. Ground data

The ground station is situated at the geographic coordinates 7°01′14.0″N latitude and 100°29′02.5″E longitude (Fig. 1) and records hourly measurements of the atmospheric constituents CO (parts per million (ppm)), NO_2 (parts per billion (ppb)), SO_2 (ppb), O_3 (ppb), PM_{10} (μg/m^3) and $PM_{2.5}$ (μg/m^3) at 3 m height above the ground. An archive from 2010 up to date exists, with a few missing periods. PM_{10} measurements have been available since 01 Jan 2020 onwards, and there are no in-situ records for the past years. Likewise, data for all parameters between February 2019 and June 2019 do not exist. The data were obtained from the Air Quality and Noise Management Bureau, Pollution Control Department, Thailand (2020).

2.3. Satellite data

The Sentinel-5 Precursor (Sentinel-5P) satellite mission was developed by the European Space Agency (ESA) with the aim to fill in the data gap between the decommissioned Ozone Monitoring Instrument (OMI) and the SCanning Imaging Absorption spectroMeter for Atmospheric CartograpHY (SCIAMACHY) onboard satellites Aura and ENVISAT respectively and the anticipated launch of the Sentinel-5 mission. The satellite was launched on 13 October 2017 with an estimated lifespan of 7 years. The main objectives of this mission is to provide space observations for operational monitoring of air quality, ozone

and surface UV radiation and the climate by providing timely measurements of atmospheric composition (Veefkind et al., 2012).

The TROPOspheric Monitoring Instrument (TROPOMI) onboard Sentinel-5P satellite is a high spatial resolution instrument offering global daily coverage from UltraViolet (UV) to ShortWave InfraRed (SWIR) at designated spectral regions which allow for the retrieval of key atmospheric constituents, namely (NO_2), (O_3), formaldehyde (CH_2O), (SO_2), methane (CH_4), carbon monoxide (CO), aerosol and clouds (ESA, 2020). Sentinel-5P inherits a high signal-to-noise ratio and consequently can operate in dark conditions (Voors et al., 2017). Sentinel-5 is part of the EU's Copernicus programme and therefore data are provided based on a free and open data policy via the Copernicus Open Access Hub.

2.4. Methodology

The 6 parameters measured at the ground station in the last 6 months (1st December 2019–31st May 2020) were studied to investigate whether there is any trend in pollutants' concentration at ground level due to the pandemic. The hourly values were averaged to daily values. Moreover, the average of the whole month of April for each year between 2010 and 2020 was derived to examine differences in concentration independent of seasonal factors. April was chosen as it is the month that the city was completely under lockdown and represents the lowest industrial and commercial activity; at the time of writing, Thailand is theoretically still under lockdown, however, cities have gradually been brought back to the usual pace of rhythm. Other months were also examined, however, as the paper concentrates on the effect of the pandemic on pollutants and not the generic temporal exhibition of pollution, the results are not presented herein. In order to get a representative image of the changes induced during the lockdown period, statistics for the period of 3 weeks just before (4 Mar–24 Mar 2020) and after (25 Mar–14 Apr 2020) the lockdown were calculated. The mean and the standard deviations are used to discuss the pollutant's

concentrations values before and after the transition date and the relative difference of the mean values in percentage is used as a proxy of the pollutants concentrations.

Earth Observation data were collected from the Sentinel-5P TROPOMI sensor and were processed in Google Earth Engine (Gorelick et al., 2017). The level 3 offline products of the NO_2 tropospheric vertical column was considered. Offline data are delivered with a time lag in comparison to near real-time data, however, they are reprocessed with analysis data. A time series of 2532 images acquired between 4th December 2019 and 31st May 2020 were processed. A water mask was applied to the dataset and the mean value over for the periods before and after the lockdown were calculated. Subsequently, we investigated the effect of the spatial resolution for this relatively small city; the complete time series of the pixel value over the ground station coordinates and the averaged value over the urban extent of the city were calculated. The urban extent was estimated based on the MODIS Land Cover Type Yearly Global 500 m dataset of the year 2018, which is derived via supervised classification of MODIS Terra and Aqua reflectance data; the Land Cover Type 2 was considered, corresponding to urban and built-up lands of at least 30% impervious surface area including building materials, asphalt and vehicles. The Pearson's product-moment correlation coefficient (r), the coefficient of determination (R^2) and the associated p-value were used to assess the correlation between the two variables. The linear regression was estimated and plotted to assess the association between the parameters and potential outliers.

3. Results

Time series of daily means of pollutants' concentrations for the ground station over the last 6 months can be seen in Fig. 2. During the first three weeks of lockdown there is a steady decrease in NO_2 concentrations, reaching a local minima of 1.52 ppb on April 15th; thereafter, the concentrations increase sharply until middle of May (max
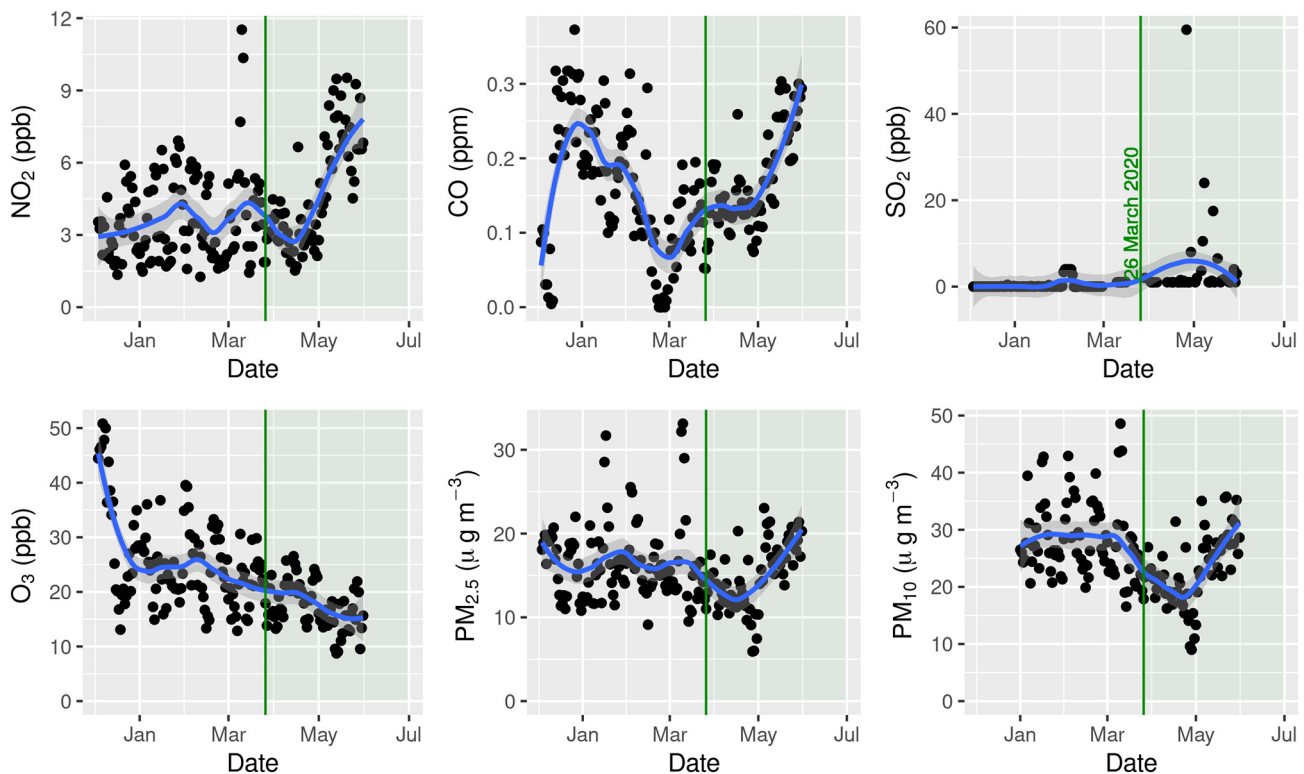

Fig. 2. Daily average concentrations of NO_2, CO, SO_2, O_3, $PM_{2.5}$ and PM_{10} as measured by a ground station over Hat Yai, Thailand between 1st December 2019 and 1st June 2020. Lockdown measures were imposed on 26th March 2020 (date indicated with a green line) and have been incrementally relaxed in May and June. Blue curve indicates the average and the shadowed area the standard deviation.

Table 1
Mean and standard deviation of pollutants concentrations (at their respective units of measurement) as recorded at the ground station for the periods of 3 weeks before and after the lockdown (26 March 2020), and their relative difference.

Pollutant	4 Mar–24 Mar 2020	25 Mar–14 Apr 2020	Relative difference of the mean (%)
CO	0.117 ± 0.042	0.129 ± 0.036	9.9
NO_2	4.576 ± 2.621	3.034 ± 0.834	-33.7
O_3	21.870 ± 5.035	19.129 ± 4.050	-12.5
$PM_{2.5}$	16.808 ± 6.801	13.148 ± 1.929	-21.8
PM_{10}	26.864 ± 8.733	20.700 ± 2.678	-22.9

9.52 ppb on May 20th). A similar trend is observed for CO, $PM_{2.5}$ and PM_{10}, with a time lag of a few days; the latter three constituents reach local minima concurrently in the end of April (5.91 for $PM_{2.5}$ on 27th April; 0.074 ppm for CO and 9 PM_{10} on 28th April). Thereafter, concentrations steadily increased fourfold for all these three constituents until the end of May. O_3 exhibits a steady decline from 21 ppb on the day the lockdown was imposed to 14 ppb on May 31st while SO_2 concentrations remain at low levels except a few bursts.

Changes in the mean concentration values during the periods preceding 3 weeks before and 3 weeks after the imposed lockdown day are presented in Table 1. All pollutants except CO present major decline; NO_2 is the pollutant with the highest change from 4.576 ± 2.621 to 3.034 ± 0.834 which translates to a decrease of 33.7%. $PM_{2.5}$ and PM_{10} are also decreased by 21.8% and 22.9% respectively. It is worth noting the comparatively lower standard deviation for these three pollutants for the 3-week period following the lockdown.

The average of April's values from 2010 to 2020 (Fig. 3) indicate reduced levels of NO_2, CO and $PM_{2.5}$, average for O_3 and no available comparative data for SO_2 and PM_{10} for the year 2020 in comparison to the rest of the past years. This is a flag that the month during lockdown Hat Yai experienced reduced overall pollution comparatively to the preceding decade.

The differences on NO_2 concentration right before and after the lockdown data are also evident in the data from the Sentinel-5P satellite (Fig. 4). A time series analysis of the available dataset 1 week before and after the lockdown indicates that the mean values of background tropospheric NO_2 are considerably higher over the urban area of Hat Yai. Specifically, there is clustered area of higher concentrations southwest of the ground station and within the urban territory. A few other areas around Hat Yai experience lower comparative concentrations, but to a lesser degree.

Regarding the relationship between point data over the ground station and spatially averaged over the urban area data from Sentinel-5P (Fig. 5), there is strong positive correlation ($r = 0.852$, $R^2 = 0.726$) and a very low p-value ($p = 2.2e-16^{***}$) indicating a strong evidence of significance and linear trend with a relatively small standard deviation. Only a few outliers can be observed.

4. Discussion

The COVID-19 pandemic has brought up an unusual reduced human activity, which Rutz et al. (2020) coined as 'anthropause', and simultaneously a unique opportunity to study the environmental response to this change. On the middle-sized city of Hat Yai, Thailand air pollution quality changes following the city lockdown are evident concurrently from ground and space observations. Most notably, a drop in NO_2 concentration of 33.7% between the period of 3 weeks before and after the lockdown is observed (Table 1). Apparently, just after lockdown measurements imposed on 26th March 2020, the NO_2 concentrations drop sharply and shortly after (Fig. 2). Likewise, similar results have been reported at global scale (Lal et al., 2020), as well as regionally in Asia; Kanniah et al. (2020) report reductions (~27%–34%) of NO_2 concentrations during the pandemic over most urban agglomerations in SE Asia, Suhaimi et al. (2020) report a reduction of 43%–63% in NO_2 in major Malaysian cities and 49%–68% in Klang Valley (the main urban conglomeration encompassing Kuala
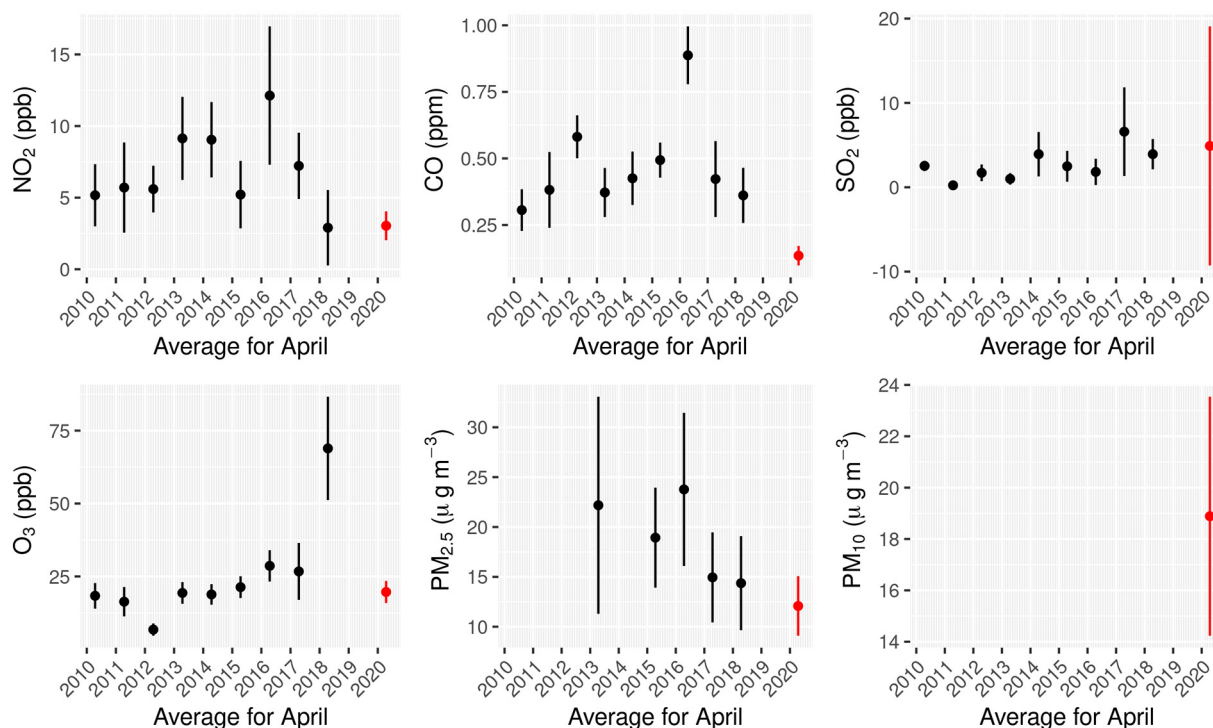
**Fig. 3.** April average concentrations of NO_2, CO, SO_2, O_3, $PM_{2.5}$ and PM_{10} for the years 2010–2020 as measured by a ground station over Hat Yai, Thailand. April is the month of 2020 when the city was completely under lockdown.
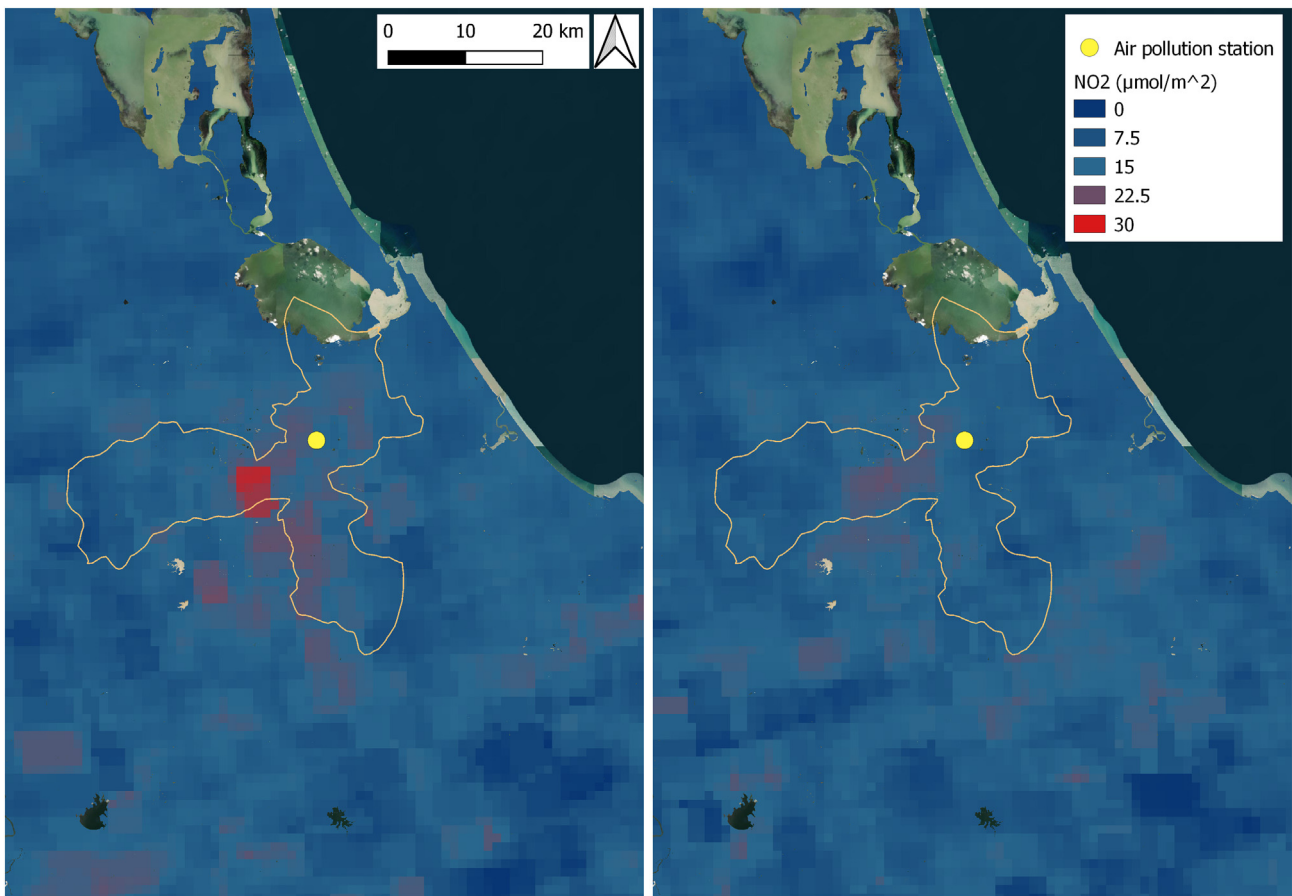
Fig. 4. Average background tropospheric NO_2 over Hat Yai 1 week before (left) and 1 week after (right) the lockdown date as recorded by the Sentinel-5P TROPOMI.

Lumpur) specifically, while Wang and Su (2020) and Bauwens et al. (2020) based on Sentinel-5P data report a sharp decline in NO_2 concentrations over China and South Korea respectively. NO_2 is a byproduct emitted by power plants, industrial facilities and vehicles and an industrial and commercial slowdown will consequently result to reduced production of NO_2 in large cities; in the current study we observe a reduction of NO_2 concentration in a medium-sized city as well.
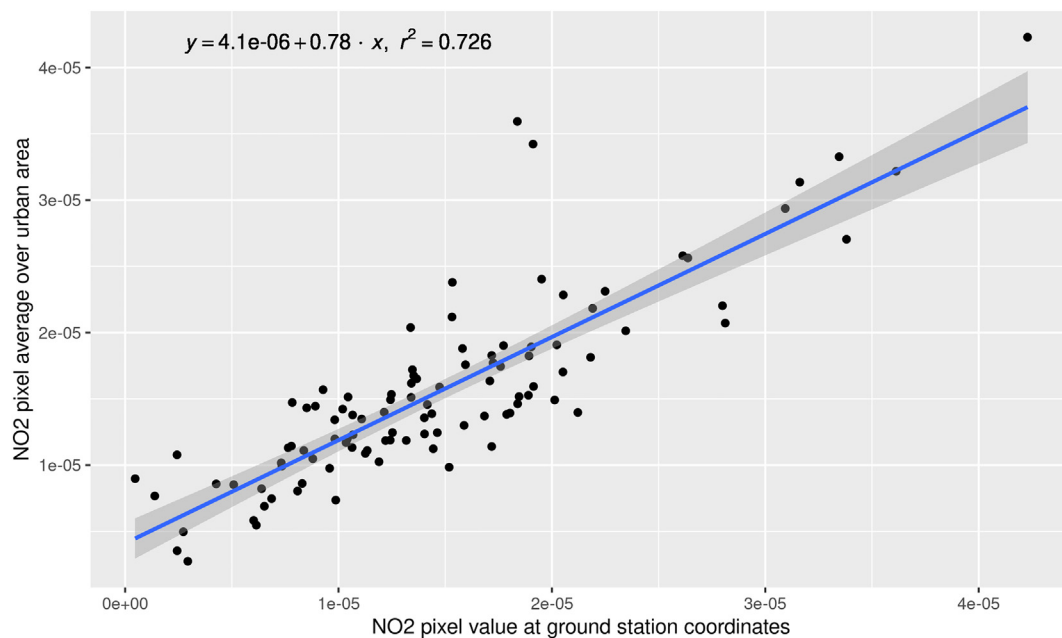
Fig. 5. Correlation between Sentinel-5P NO_2 pixel value over the ground station and average of pixel values enclosed by the urban extent of the city of Hat Yai. Data between 1st December 2019 and 1st June 2020 were considered.

Nevertheless, NO$_2$ concentration can vary daily because of weather changes. Moreover, tropospheric NO$_2$ concentration depends on the season as well as the latitude and altitude and has a short lifespan (Beirle et al. (2003) estimated a 6 h lifetime in summer and 18–24 h in winter over Germany). However, by averaging the hourly values and integrating a large number of days in the observations, the short-term contributions of weather and daily fluctuations cancel out. Nevertheless, caution should be taken in interpreting these results because we have not taken into consideration meteorological variability as the current study aims to evaluate the changes in air quality induced by the lockdown, and not attribute the causes.

SO$_2$ concentrations and the associated fluctuation are generally at normal background level during the study period of beginning of December 2019 until end of May 2020. This observation of non-significant difference of SO$_2$ is also reported in different regions of Indonesia (in SE Asia) by Caraka et al. (2020). There are a few exceptions of short periods where they burst, notably on the 26th April which coincide with very high average rainfall over SE Thailand (data from the Thai Meteorological Department (Climatological Center (2020)). Nevertheless, there is no apparent trend.

The O$_3$ concentration is declining, in contrast to similar studies which have reported an increase of O$_3$ concentration (e.g. Collivignarelli et al., 2020; Tobías et al., 2020; Sharma et al., 2020; Dantas et al., 2020). The latter studies claim that the O$_3$ increase is attributed to the decreased NO$_x$ emissions, which increase O$_3$ radical formation and consequently the generation of secondary pollution (Huang et al., 2020b); in other words, it is the reduction of anthropogenic pollution that causes the increase of O$_3$ tropospheric concentration. However, the magnitude of NO$_x$ decrease in the present study is not large to justify substantial O$_3$ reduction; in fact, we speculate that the decrease in O$_3$ in this case is a climatic contribution rather than secondary pollution generated in the urban environment. The month of April is a transition month for Southern Thailand from the dry and hot season to the wet and cooler season, as explained earlier. Therefore, and as ozone formation is favored by high temperatures and solar irradiation, seasonal changes are causing the reduction of O$_3$, a pattern which follows an annual cycle (results not shown here). The impact of meteorological conditions cannot be neglected and in some cases counterbalance, if not suppressing as in the present study, the urban pollution emissions.

CO, PM$_{2.5}$ and PM$_{10}$ follow a similar pattern just after the lockdown with a steady decrease which reaches a minimum at the end of April, and thereafter increases. The decrease during the month of April is indicative of the overall bettering of the ground-level air quality, while the increase following thereafter can be perhaps attributing to the beginning of incremental relaxations of the lockdown measures in May. The former decreases are evident not only in the pollutant's concentrations before and during the lockdown, but also when comparing the historic levels (i.e. 2010–2019) with the 2020 levels during the month of April. This is best demonstrated in Fig. 3, where the average of the month is plotted against the years from 2010 to 2020. Except SO$_2$ and PM$_{10}$ (for which comparative data are not available), O$_3$ is at an average value and all other pollutants exhibit the lowest values of the decade.

Satellite and ground measurements generally follow the same pattern, as it has also been documented in similar studies (e.g. Constantin et al., 2013; Venter et al., 2020). Ialongo et al. (2019) found a correlation of $r = 0.68$ between the two data types and reckoned that TROPOMI total columns underestimate ground-based observations; they attributed this effect to the relatively large size of the Sentinel-5P pixel resolution (i.e. 3.5×7 km). Likewise, in the current study it is evident in Fig. 4 that overall the NO$_2$ concentration after the lockdown is reduced compared to the condition just the week preceding. More importantly, there is a considerably large part of an urban area SW of the ground station with elevated NO$_2$ averaged values.

Regarding the relationship between point values and spatially averaged over the urban area from Sentinel-5P (Fig. 5), there is strong correlation ($R^2 = 0.726$) which indicates that the temporal evolution of pollutants over the ground station follows the same pattern with the one of the average of the whole city. In other words, the pollution over the city of Hat Yai is spatially homogeneous in temporal terms, which might be attributed to the relatively small size of the city in comparison to mega-cities suffering from intense pollution. This is perhaps the main difference of pollution concentration and dispersal between large and small/medium cities; in the latter case the homogeneity of the city and the non-existence of large industrial zones allows for drawing overall conclusions for the whole city instead of demarcating the spatial extent into sub-regions based on the land use.

Another notable aspect of this global pandemic peculiar response is the speed of air quality improvement; Gautam (2020b) presented evidence of significant changes in air quality in the Indian region just a week after reduced human activities took place, while Mahato et al. (2020) concentrated on air quality of the mega-city of Delhi found that PM$_{10}$ and PM$_{2.5}$ concentrations reduced by half while NO$_2$ and CO also demonstrated considerable decline; in the same study they report that already on the 2nd day of lockdown the air quality improved by about 40%, indicating a rapid environmental response to stability. Likewise, in the current study it is apparent (Fig. 2) that changes occur instantaneously following the lockdown and this is evident both in the ground station measurements as well as the Sentinel-5P observations.

5. Conclusions

In the current study we test the hypothesis of reduced ground-level and tropospheric air pollution over a medium-sized urban area (i.e. 156,000 inhabitants) as a result of the slowdown of economic activity and transportation following the lockdown measures imposed due to the COVID-19 pandemic. Data from the local meteorological station and the Sentinel-5P satellite were used. In agreement with similar recent studies in SE Asia, we observed decreased concentrations of NO$_2$, PM$_{2.5}$ and PM$_{10}$ by 33.7%, 21.8% and 22.9% respectively during the first 3 weeks of lockdown based on data collected from a ground station. O$_3$ also decreased by 12.5%, in contrast to other studies, which is perhaps attributed to the small size of the city. Annual average values of the atmospheric constituents present an overall reduction of pollution for April of year 2020 compared to the preceding years from 2010 until 2018. Sentinel-5P satellite observations indicate a higher concentration of NO$_2$ within the urban extent for the week following the city close-down in comparison to the week before. Moreover, satellite pixel values over the ground station and the spatially averaged value over the urban extent correlate strongly ($r = 0.852$) which is an indication of the homogeneity of the pollution over the city. Last but not least, the Sentinel-5P temporal pattern follows the same trend for point data over the ground station and the average over the urban area, indicating an overall agreement between the ground and satellite data.

The COVID-19 pandemic offers a unique opportunity to study sudden anthropogenic environmental disruptions. The vast majority of published studies focus on air pollution over metropolitan areas since these areas frequently exhibit pollution levels dangerous for the human health. Still, in certain parts of the world such as SE Asia, the urbanization has not yet peaked (Nguyen and Nguyen, 2018) and a large number of urban residents dwell in medium-sized or small cities; for instance, the Hat Yai greater area with 800,000 inhabitants is the 3rd largest city in Thailand, a country with a total population of approximately 70 million people (United Nations 2019). Therefore, it is of importance to further investigate the evolution of the air pollution in smaller cities, as in the current study, and evaluate differences attributed to the size of urban areas.

CRediT authorship contribution statement

Dimitris Stratoulias: Conceptualization, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Narissara Nuthammachot:** Data curation, Investigation, Writing - original draft.

Declaration of competing interest

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