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Global association between satellite-derived nitrogen dioxide (NO₂) and lockdown policies under the COVID-19 pandemic

Hongsheng Zhang, Yinyi Lin, Shan Wei, Becky P.Y. Loo, P.C. Lai, Yun Fat Lam, Luoma Wan, Yu Li

Department of Geography, The University of Hong Kong, Pokfulam, Hong Kong
Institute of Space and Earth Information Science, The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong
Faculty of Information Technology, Beijing University of Technology, Beijing, China

HIGHLIGHTS
• Global association among NO₂, lockdown policies & COVID-19 cases were examined.
• Global NO₂ dynamics were derived from Sentinel-5P during COVID-19 pandemic.
• Unsupervised machine learning method by Apriori algorithm was applied.
• Absence/presence of COVID-19 new cases commanded some form of lockdown policies.
• Declining NO₂ gravitated more to international travel than public transport.

ABSTRACT
The COVID-19 pandemic has severely affected various aspects of life, at different levels and in different countries on almost every continent. In response, many countries have closed their borders and imposed lockdown policies, possibly bringing benefits to people’s health with significantly less emission from air pollutants. Currently, most studies or reports are based on local observations at the city or country level. There remains a lack of systematic understanding of the impacts of different lockdown policies on the air quality from a global perspective. This study investigates the impacts of COVID-19 pandemic towards global air quality through examining global nitrogen dioxide (NO₂) dynamics from satellite observations between 1 January and 30 April 2020. We used the Apriori algorithm, an unsupervised machine learning method, to investigate the association among confirmed cases of COVID-19, NO₂ column density, and the lockdown policies in 187 countries. The findings based on weekly data revealed that countries with new cases adopted various lockdown policies to stop or prevent the virus from spreading whereas those without tended to adopt a wait-and-see attitude without enforcing lockdown policies. Interestingly, decreasing NO₂ concentration due to lockdown was associated with international travel controls but not with public transport closure. Increasing NO₂ concentration was associated with the “business as usual” strategy as evident from North America and Europe during the early days of COVID-19 outbreak (late January to early February 2020), as well as in recent days (in late April) after many countries have started to resume economic activities. This study enriches our understanding of the heterogeneous patterns of global associations among the COVID-19 spreading, lockdown policies and their environmental impacts on NO₂ dynamics.

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Keywords: COVID-19, Coronavirus, Lockdown policies, NO₂, Association rules, Apriori
1. Introduction

The COVID-19 virus started to become a public health risk in Wuhan, China at the end of 2019. It spread over the province of Hubei and then the entire country by late January 2020. On 23 January 2020, the Wuhan government imposed a city lockdown by closing the workplace, public transport and external transport with other cities, as well as enforcing strict restrictions on social gatherings and public events. Shortly after that, strict lockdown policies were implemented in most Chinese cities. The whole country became unusually quiet in February, which has always been a peak travelling season due to the Chinese New Year. The lockdowns of cities have been widely reported to bring significant positive impacts towards the environment, particularly on air quality, including sulfur dioxide (SO2), nitrogen dioxide (NO2) and fine particles (PM2.5) (Filonchyk et al., 2020; Lancet Planet Health, 2020; Lau et al., 2020; Le Quere et al., 2020; Sarfraz et al., 2020; Tobias et al., 2020; Wang and Wang, 2020; Zhao et al., 2020). As the anthropogenic NO2 is highly related to fossil fuel combustion from various transport modes, including vehicular traffic, marine shipping and commercial aircraft, the quarantine policies have resulted in a significant drop of NO2 between late January and early March 2020 by 22.8 μg/m3 in Wuhan alone and 12.9 μg/m3 for the whole of China (Agudelo-Castaneda et al., 2020; Herndon et al., 2004; Kaminska, 2019; Lancet Planet Health, 2020; Liu et al., 2020; Wang and Su, 2020). It was reported that transportation accounts for more than 50% of overall NOx (NO2 + NO) in developed countries, while more than 20% in developing countries (Crippa et al., 2018). In China, the average is about 25% (Chan et al., 2015; Li et al., 2017), and it is higher (up to 60%) in urban center and lower (down to 13%) in industrial zones. Being one of the designated criteria air pollutants, NO2 has been widely reported to cause the formation of atmospheric particulates such as ammonia nitrate (Agudelo-Castaneda et al., 2020). Consequently, NO2 can lead to cardiovascular diseases such as hypertension, coronary heart disease and stroke. A significant decrease in NO2 could reduce the number of deaths from these related diseases (Chakraborty et al., 2020; Lancet Planet Health, 2020). Recent reports have estimated that 8911 NO2-related deaths were saved in China during this period due to the reduction of ambient NO2 (Chakraborty et al., 2020; Lancet Planet Health, 2020).

The COVID-19 pandemic has disrupted almost all aspects of everyday life in different degrees worldwide. Many countries have begun to shut their borders and imposed lockdown policies such as closing schools, workplaces, and public transport. It has been reported that these lockdown policies have positive implications on the environment (Lau et al., 2020; Spinelli and Pellino, 2020). Specifically, people’s health can benefit from the better air quality via the reduction of air pollutants (Ogen, 2020; Zhu et al., 2020). These positive impacts also lead to multiple research questions. For example, what impacts has the COVID-19 pandemic brought to the world in terms of air quality, or NO2 concentration in particular? To what degree was the air quality influenced during the period of COVID-19 pandemic? What were the secondary impacts on public health from these pandemic-related changes in NO2? Obviously, these are not easy to answer questions as cause and effect relationships are not straightforward. First and foremost, changes in NO2 are often controlled by multiple factors such as NO2 emissions from various sources and meteorological conditions in different climate zones and seasons. Besides, the impacts of NO2 on public health still await further assessment. A recent study of 4443 fatalities of NO2-related diseases in Europe reported that an estimated 3487 deaths were related to high NO2 concentrations in northern Italy and central Germany (Ogen, 2020). Another study reported that reducing the exposure of NO2 could prevent a substantial portion of paediatric asthma incidents in both developing and developed countries, especially in urban areas (Achakulwisut et al., 2019).

Furthermore, NO2 is a major component of traffic-related air pollution but there are not yet detailed World Health Organization (WHO) guidelines about traffic emissions on human health (Achakulwisut et al., 2019).

The dynamics of NO2 during the COVID-19 pandemic period offer a unique opportunity to examine the relationships between various lockdown policies and NO2 changes, as well as the impacts of COVID-19 towards the environment and related public health issues. NO2 concentration is conventionally measured at ground stations. This traditional approach provides accurate and sufficient in situ data to capture time-series changes of NO2 but there is limited spatial coverage in vast and continuous areas. Fortunately, remote sensing satellites provide a new and effective way with acceptable accuracy to observe the changes of air pollutants, such as NO2 and PM2.5 (Bauwens et al., 2020; Gu et al., 2017; Kuhlmann et al., 2014; Kuhlmann et al., 2015). This study made use of the satellite observation data about NO2 column density from Sentinel-5 Precursor (Sentinel-5P), a satellite launched by the European Space Agency in 2017. The Sentinel-5P uses the ultraviolet-visible spectrum to observe daily NO2 column density at the global level with a spatial resolution of 3.5 × 7.0 km² (Zheng et al., 2019). These NO2 column density data were used to examine the potential association with the number of cumulative confirmed cases of COVID-19 and the lockdown policies engaged by different countries. This research contributes not only towards investigating the heterogeneous patterns of relationship among COVID-19 spreading, lockdowns and NO2 dynamics at the global scale.

2. Materials

2.1. Study sites

The research is a global study involving 187 countries. The basic spatial unit of the study is the country level with the exception of using provincial or state-level data for four big countries: Australia, Canada, China, and United States. Furthermore, the countries are grouped by six continents based on geographic connectivity: Asia, Europe, North America, South America, Africa, and Oceania. The study also speculates that countries within the same continent may adopt similar control policies for COVID-19 due to their geographic proximity. Fig. 1 shows that each continent is assigned to a unique colour and countries/provinces/states, hereafter referred to as countries/regions, are arranged in alphabetical order by name. The same arrangement applies to the analysis that follows.

2.2. Data

This study employs multiple datasets: (i) satellite-derived data about NO2 column density from Sentinel-5P and ground measurement data of NO2 concentration, (ii) cumulative confirmed cases of COVID-19, and (iii) lockdown policies adopted by different countries.

2.2.1. The NO2 satellite and measurement data

The NO2 tropospheric vertical column density data were retrieved from the Sentinel-5P Tropospheric Monitoring Instrument (Siddiqui et al., 2020; Veekind et al., 2012) on the Google Earth Engine platform. The offline L3 level Sentinel-5P dataset provides offline high-resolution imagery of NO2 concentration. Pixels with quality assessment band below the specified percentages were filtered out from the study: 80% for AER_AI; 75% for the tropospheric_NO2_column_number_density band of NO2; and 50% for all other datasets except for O3 and S2. The data for weekly intervals (e.g., 1–8 January) at the global coverage were mosaicked using the mean value at pixel dimension and resampled with a spatial resolution of 7 × 7 km². A total of 28 scenes of global mosaicked NO2 tropospheric vertical column density images were generated from 1 January to 30 April 2020. Furthermore, ground
measurements of NO2 concentration from the World Air Quality Index site (https://aqicn.org/data-platform/covid19/) were incorporated into the data analysis for satellite validation during the lockdown period. Data covered 380 cities over the world were collected three times a day from 22 January to 10 May 2020. Considering the geographical scope of this study, NO2 concentration data for six cities were selected: London, Los Angeles, Milan, Seoul, Tokyo, and Wuhan to assess the performance of NO2 column density data derived from Sentinel-5P.

2.2.2. The COVID-19 data

Daily cumulative confirmed cases of COVID-19 by countries between 22 January and 10 May 2020 were retrieved from the Johns Hopkins University Center for Systems Science and Engineering (https://datahub.io/core/covid-19). Some early cases before 22 January 2020 were not officially published and thus not included in this study. The COVID-19 confirmed cases data were arranged using the sequence presented in Fig. 1.

2.2.3. The lockdown policies

Data about lockdown policies came from the Oxford COVID-19 Government Response Tracker project (https://www.bsg.ox.ac.uk/research/research-projects/coronavirus-government-response-tracker; Hale et al., 2020). This dataset includes measures taken by all countries between 1 January and 10 May 2020. As mentioned before, provinces or states in Australia, Canada, China, and United States were separately considered to account for the independent measures or practices made by individual provinces or states. These measures include school closures, workplace closures, cancellation of public events, restrictions on gatherings, closing of public transports, stay at home requirements, restrictions on internal movement, and provincial or state international travel controls. There are four levels of intensity, including (1) no measures, (2) recommend closing, (3) require closing at some levels, and (4) require closing at all levels for each measure. To facilitate unsupervised machine learning methods for association mining, the four levels of intensity were combined into two: (1) no closing/restriction policies, and (2) require closing/restriction at some or all levels.

3. Methods

In order to investigate the association among COVID-19 spreading, lockdown policies and NO2 column density, the association rules mining technique was employed using the Apriori algorithm, which is an unsupervised machine learning method originally developed to analyze the association rules between customers and goods founded on a number of transactions. The association-mining algorithm begins by categorizing COVID-19 cases, NO2 column densities, and pandemic-related policy measures to correspond with purchased items of transactions. The technical details of categorization and the parameterization of the Apriori algorithm are described in Sections 3.1 and 3.2.

3.1. Categorization of COVID-19 cases and NO2 column density

The COVID-19 confirmed cases were categorized into two groups: (1) no new confirmed cases, and (2) with new confirmed cases. The presence of new cases, especially local new cases, is an important indicator to many local governments in making policy-related decisions. No new cases would signify one of two possible scenarios, i.e., before the COVID-19 outbreak versus nearly towards the end of an outbreak. Conversely, the presence of new cases in a province/state or a country would indicate that the virus is still spreading, and most governments would continue the quarantine policies or tighten the current policies. In this study, the presence of confirmed cases was not categorized into more subclasses to simplify the process, which is also consistent with the observation that specific policies would not change irrespective of the number of confirmed cases of COVID-19. In terms of NO2 column density, it was grouped as (1) decrease or (2) increase. This conversion (i.e., continuous decimal data to a categorial group) is intended to reflect better the change of NO2 column density associated with the lockdown policies under a short study period. Moreover, the values of NO2 column density are strongly influenced by local meteorology and the amount of emissions produced from economic activities (Lin et al., 2015). Taking the categorical approach would eliminate the data noise to the level where the relationship between NO2 and the lockdown policies can be revealed.

Fig. 1. Study area of 187 countries over six continents.
3.2. Association among the COVID-19, NO2 column density, and pandemic-related policies

The Apriori algorithm was developed to investigate the association rules in a number of transactions in which the customers and the goods they purchased were put together as a series of item sets, establishing the associations between the customers and their shopping preferences (Agrawal and Srikant, 1994). In this study, the datasets of confirmed COVID-19 cases, NO2 column density, and different policy measures adopted by each country/region were applied using the Apriori algorithm. We considered each country/region as a single transaction wherein COVID-19 cases, NO2 column densities, and pandemic-related policy measures were the corresponding purchased items of each transaction. The Apriori algorithm begins with an association rule expressed as \( X \rightarrow Y \), where \( X \) and \( Y \) are disjoint item sets denoted as \( X \cap Y = \emptyset \). Here, an item set can be any combination of the data sets about COVID-19 cases, NO2 column densities, and policy measures. Next, the frequency of each item set can be calculated from the whole data set covering all countries/regions. \( \text{Sup} (X) \) and \( \text{Sup} (Y) \) denote the frequency of the item sets \( X \) and \( Y \), respectively. The frequency of the association rule is as defined in Eq. (1).

\[
\text{Sup}(X \rightarrow Y) = \text{Sup}(X \cup Y) = P(X \cup Y)
\]

The confidence of the association rule is as defined in Eq. (2).

\[
\text{Conf}(X \rightarrow Y) = \frac{\text{Sup}(X \rightarrow Y)}{\text{Sup}(X)} = \frac{P(X \cup Y)}{P(X)}
\]

The Apriori algorithm proceeds to determine all association rules \( X \rightarrow Y \) based on Eqs. (1) and (2), subject to a minimum value of frequency \( \text{Sup}(X \rightarrow Y) \) and a minimum value of confidence for the rules \( \text{Conf}(X \rightarrow Y) \). In this study, the minimum frequency was set at 0.3 and the minimum confidence at 0.6. These two empirical thresholds were established upon consideration of uncertain variations of the NO2 column density and the lockdown policy, which will further be discussed in Sections 5.2 and 5.3. For a better investigation of impacts of each item, the item sets \( X \) and \( Y \) included only one item for each set. A more detailed description of the algorithm can be found in Agrawal and Srikant (1994). As the thresholds were set loosely, the frequency and confidence would not be sufficient to evaluate the association rules. In order to evaluate the significance of the association rules, the concept of lift was introduced to calculate the facilitation of each item set \( X \) towards the item set \( Y \) using Eq. (3).

\[
\text{Lift}(X \rightarrow Y) = \frac{\text{Sup}(X \rightarrow Y)}{\text{Sup}(X) \cdot \text{Sup}(Y)} = \frac{P(X \cup Y)}{P(X)P(Y)}
\]

4. Results

4.1. Global characteristics of COVID-19 spreading and lockdown policies

A time sequence of the COVID-19 outbreak by countries/regions in Fig. 2 illustrates the disease started to spread in Hubei Province of China, and then progressed to Zhejiang Province, followed by a gradual spread to other provinces of China. The outbreak in South Korea began in mid-February whereas Africa had very few cases of COVID-19 that were evident in Egypt and South Africa from late March. The COVID-19 situation in Africa was much better than those in Asia and other continents. The outbreak of COVID-19 in Europe started in Italy, followed by France, Germany, Spain and the United Kingdom in early February, and then spread to other European countries in early to middle of March. The North America reported escalated number of cases around middle to late March, starting from the states of New York and Washington, and then California. It then spread quickly to other U.S. states, resulting in a large number of confirmed cases in April, while the number of cases in South America and Oceania was relatively low with some cases reported in New South Wales, Queensland, and Victoria of Australia.

The global data of lockdown policies by countries/regions between 1 January and 10 May 2020 is summarized in Fig. 3. Clear differences on the time implementation of lockdown policies can be observed and the sequence of implementing lockdown policies generally follows the pattern of the rise of confirmed cases at a continental level. In China, most of the measures were concurrently imposed in late January to minimize human interactions, except for the restriction of international travels which took effect in early March. The neighbouring countries of China, including Mongolia, Korea and Vietnam, also introduced lockdown policies from...
late January to close schools, workplaces, public events, and international travels. It is also evident that most of these lockdown policies in Asia were lifted in late April when the spread of COVID-19 was seemingly under control and the situation improved. For Europe, Italy, Germany, France and San Marino started to apply the lockdown measures from mid-February, while the U.K. and other European countries followed in mid-March. In North America, lockdown policies were firstly applied in U.S. from early March and a bit later in Canada. In Africa, South America and Oceania, the policies did not take effect until the mid-March after the WHO declared COVID-19 as a global pandemic on 11 March 2020.

Generally, the policies taken in Fig. 3 were driven by the global spread of COVID-19 as illustrated in Fig. 2. However, the specific lockdown measures were also affected by culture, public awareness and other local governmental strategies. For example, significant variations in the closure of public transport have been observed among countries. In North America, most of the states in USA and provinces in Canada did not require the closure of public transport throughout the study period. For international travel controls, almost all countries on all continents applied this measure after mid-March. As lockdown policies restrict work, travel and use of some forms of transportation, it is expected that limited activities and travel will directly or indirectly affect manufacturing- and transport-related emissions that will be reflected on the global NO$_2$ dynamics. For instance, the closure of public transport can directly limit NO$_2$ emission from diesel buses. Closure of schools, workplaces, and public events will also limit the use of private cars, taxis and other motorized vehicles. Restrictions on international travels will dramatically reduce air flights and ground transportation to and from airports. All these changes in transport activities can affect NO$_2$ concentration in the atmosphere.

4.2. Comparison between satellite observations and ground measurements

The NO$_2$ column density derived from the Sentinel-5P satellite refers to the value of the vertical column at unit area through the atmosphere whereas the NO$_2$ measured on the ground is the concentration near/at the location of measurement. There are basic differences between observations from the satellite and measurements on the ground. Although some methods based on atmospheric modelling have been established to calculate the surface concentration of NO$_2$ from the satellite-based column density (Gu et al., 2017; Kuhlmann et al., 2014), the actual column density well represented the surface concentration in view of their correlation (Achakulwisut et al., 2019; Ogen, 2020). Moreover, for a large scale study of the global context, there are many complex factors (e.g., uncertainties of NO$_2$ vertical profile) to be considered before using these atmospheric models to convert the column density to surface concentration. Given that we employed the column density from satellite observation as representative of NO$_2$ concentration at the ground, there is a need to verify the reliability of this relationship in terms of correlation. We compared the column density with the ground concentrations of NO$_2$ from six selected cities with sufficient geographic spread. These cities include London (United Kingdom), Los Angeles (United States), Milan (Italy), Seoul (South Korea), Tokyo (Japan), and Wuhan (China). Fig. 4 shows the comparisons between satellite-derived NO$_2$ column densities ($\mu$mol/m$^2$) and ground measurements of NO$_2$ concentration ($\mu$g/m$^3$) for the six cities. These two datasets on different dates were plotted using double coordinates systems with primary and secondary y-axes. As the levels of column density and surface concentration were significantly different in different cities, the scales of primary and secondary y-axes were also adjusted accordingly to facilitate comparison.

Correlation and significance levels between these two datasets were also included in Fig. 4 demonstrating the generally good and significant correlations in those stations. Specifically, satellite observations appeared very consistent with the ground measurements in Wuhan, Milan and Los Angeles, with correlation coefficients exceeding 0.8 and p-values less than 0.001. For Seoul, Tokyo and London, it displayed medium consistency with correlation coefficients between 0.5 and 0.8 and p-values less than 0.001. This spatial variation is probably a result of spatial heterogeneity of NO$_2$ concentration on the ground, coupled with strong meteorological factors in these selected cities located in different climate zones. The
physical characteristics and geographic position of these cities have direct implications on the atmosphere to cause measurement differences between satellite and ground-based observations. Nevertheless, these two datasets are comparable in the global setting to investigate the dynamics of NO$_2$ during this specified period of COVID-19.

4.3. Spatial and temporal variations of NO$_2$

The NO$_2$ column density data were processed at weekly intervals within each month. Fig. 5 shows the spatial and temporal variations of NO$_2$ column density for a total of 16 weekly intervals from January to April 2020. It is evident that the column density in China was high in early January, especially in central and eastern China. The high density of NO$_2$ continued in China until mid-January, i.e., 15–21 January 2020 (Fig. 5a), and rapidly dropped in late January (Fig. 5b). Two possible reasons contributed to this phenomena. First, it could be due to the lock-down of some cities in China after 23 January 2020. Second, it might be due to the typical effects of peak travel before the Chinese New Year on 25–28 January 2020. The situation of low column density that continued after the Chinese New Year until mid-February (Fig. 5c–d) was likely to be caused by lockdowns of most cities throughout China. From late February onwards (Fig. 5e–k), the column density began to rise and eventually reached the levels in early January. Notably, the column density increased in central, eastern and southern China in April (Fig. 5l–m), which was a direct result from relaxed pandemic control and the re-opening of workplace and public transport from late March. Fig. 5 shows that the NO$_2$ column density in Europe was low in January (Fig. 5a–b) but started to rise in early February (Fig. 5c). The NO$_2$ levels remained relatively stable in Europe for the whole of February until early March (Fig. 5c–g). Although the column density may be decreasing in some European cities, such as Milan (Italy) in Fig. 4, most European countries other than Italy did not have COVID-19 outbreak in February. With the COVID-19 spread in Europe from mid-March, more European countries began to introduce policies of lockdown. The column density over Europe showed a general decline in mid-March (Fig. 5g–h), while it started to increase again in April (Fig. 5j–k). The column density in North America was generally stable with some fluctuations. Significant changes occurred mainly in the eastern United States, where the column density was low in January (Fig. 5a–b), but rose in February until early March (Fig. 5c–g). However, the NO$_2$ started to drop significantly from the middle to late March (Fig. 5h–j), due to the COVID-19 outbreak in New York. For other continents including Africa, South America and Oceania, the column density did not exhibit clear changes throughout the study period.

To better understand the numerical attributes of spatial and temporal dynamics of NO$_2$ column density, the weekly differences of NO$_2$ data between each consecutive interval were calculated. Fig. 6 shows the graphical plots by continents where each dot/column represents a country/region. The patterns are in general agreement with observations made of Fig. 5, which convey general fluctuations throughout the study period for Asia, Europe and North America, and overall stability in Africa, South America and Oceania, reporting small variations mainly within 6 μmol/m$^2$ throughout the period. Fig. 6 also reflects the outbreak of COVID-19 and lockdown policies taken in different periods in Asia (late January), Europe (late February to early March) and North America (middle to late March).

Most countries in Asia witnessed an average decrease of around 18 μmol/m$^2$ in NO$_2$ from 22 to 31 January 2020, principally a result of the serious COVID-19 outbreak in many parts of China and the subsequent widespread lockdowns of Chinese cities and border closures with other Asian countries. The variations of column density were generally low for most countries in Europe during the entire study period. The two declining periods were from late January to early February and from late February to early March. The former period was likely to be under the influence of local meteorological conditions and the latter corresponded with the lockdowns of cities due to serious local COVID-19 outbreaks. North America experienced a drop in column density over two-time intervals in early February and late March. As with Europe, the decline of NO$_2$ in early February was linked with local meteorological factors and that in late March was affected by lockdown policies from local COVID-19 outbreaks.

4.4. Association among COVID-19, NO$_2$ and lockdown policies

The one-to-one item association by means of Apriori algorithm investigates the role of each item and its connections with each other. The confidence threshold was set at 60% and the parameter Lift at >1. Fig. 7 shows a graph with one item each in X and Y to reflect the rules. A total of 20 nodes/variables (marked by numbers) denote the overall situation. Each node represents a condition or policy, including 1 = with new cases of COVID-19 situations (nodes 1 and 2) and NO$_2$ column density, 17 = restrictions on international movement, and 26 = no international travel controls (see Fig. 7). Each link between two nodes denotes an identifiable rule with an arrow-head indicating the direction of association. Four nodes about the COVID-19 situations (nodes 1 and 2) and NO$_2$ changes (nodes 6 and 7) were highlighted with symbols of a larger size. The edges and nodes in the directed graph were drawn in two different colours. Blue denotes situations involving no new COVID-19 cases, increasing NO$_2$ column density, and
policy measures were not applied. Red indicates situations with new COVID-19 cases, decreasing NO$_2$ column density, and implementation of policy measures. Association findings from Fig. 7 can be summarized into two categories: (a) COVID-19 and lockdown policies; and (b) NO$_2$ and lockdown policies during COVID-19.

4.4.1. COVID-19 and lockdown policies
Firstly, countries with no new cases (node 1) tended not to impose any lockdown policies (nodes 19–25). This finding seems reasonable when local infection was not apparent in a country since there was not a need to close schools, workplace or public transport (nodes

Fig. 5. Spatial and temporal dynamics of NO$_2$ column density over the world, January–May 2020.
19–20, 23), cancel public events (node 21), set restrictions on gatherings, homestay, and internal movement (nodes 22 and 24–25). Secondly, countries with more new cases (node 2) were likely to introduce some forms of lockdown policies, including closure of schools and workplace (nodes 11–12), cancellation of public events (node 13), setting restrictions on gatherings, homestay, internal movement, and

Fig. 6. Weekly differences of NO$_2$ column density by continents during the COVID-19 pandemic. (Note that different vertical scales along the y-axis were used for each continent).

Fig. 7. The association among the COVID-19 confirmed cases, NO$_2$ column density and lockdown policies.
international travel controls (nodes 14 and 16–18). This set of association rules is consistent with our earlier observations (see Fig. 3) in which many countries started to enforce lockdown policies soon after more confirmed cases were reported in these countries.

4.4.2. NO2 and lockdown policies

Thirdly, decreasing NO2 column density (node 6) was associated with international travel controls (node 18) but not with the closure of public transport (node 23). This finding indicates that the column density is more affected by air travel whereby a reduction in international travel contributed to decreasing NO2 emission. The association rules can be explained by observing characteristics of lockdown policies shown in Fig. 3, which indicates widespread enforcement of international travels but limited closure of public transport during the period of COVID-19 outbreaks. The fact that the column density is less affected by public transport should be interpreted from a global perspective involving 187 countries. Indeed, the association between NO2 and public transport differ among countries. For countries/regions with busy air movement (node 25), From the dynamics of the NO2 column density home requirements (node 24), as well as no restriction on internal movements (node 20), public transport (node 23), and stay-at-home (node 15) were missing from Fig. 7 indicating an insignificant contribution of public transport closure during the COVID-19 pandemic from a global perspective.

Finally, increasing NO2 column density (node 7) was associated with the “business as usual” status where there was no closure policies for the workplace (node 20), public transport (node 23), and stay-at-home requirements (node 24), as well as no restriction on internal movements (node 25). From the dynamics of the NO2 column density shown in Fig. 6, the column density was on the rising trend mainly in Europe and North America before late February, and in African, South American, and some Oceania countries throughout the study period. Combined with COVID-19 situations portrayed in Fig. 2, increasing the column density coincided with periods when COVID-19 was not spreading. As a result, many governments did not impose closure of certain essential facilities (such as workplace and public transport; nodes 20 and 23) or movement restrictions (nodes 24–25). Fig. 7 also shows that the presence of lockdown policies such as the closure of schools, public events, gatherings and international travels (nodes 11, 13–14, 18) did not have a direct association with further reduction in column density because many countries have already adopted such measures at an earlier stage (Fig. 3).

5. Discussion

5.1. The categorization of datasets to fit the association mining method

This research quantifies the association among the COVID-19 confirmed cases, NO2 column density and the lockdown policies, which has caught great attention worldwide. However, most previous studies have quantified the relationship between COVID-19 spreading and NO2 data, while the lockdown policies were limited in a qualitative manner (Filonchyk et al., 2020; Lau et al., 2020; Tobias et al., 2020). The major contribution of this study is the quantification of lockdowns with regard to various aspects of policies, including school closures, workplace closures, cancellation of public events, restrictions on gatherings, closing of public transport, stay at home requirements, restrictions on internal movement, and provincial or state international travel controls. Therefore, the different roles or impacts of different policies related to the environment, e.g. air pollution, can be better understood. With the association rules mining technology, this study quantifies and compares the impacts of different lockdown policies to the dynamics of NO2 during the COVID-19 period.

To achieve this goal, a technical difficulty was related to the use of both numerical (i.e., COVID-19 confirmed cases and NO2 density) and categorical (i.e., lockdown policies) data sets. Given that the Apriori algorithm requires all items to be categorized, the numerical data were pre-processed as follows: (1) COVID-19 numbers were grouped by two levels - no new cases versus with new cases; (2) NO2 column densities were transformed into two classes - decreasing versus increasing; and (3) lockdown policies were sorted into two groups - imposing versus waiving specific lockdown policies. The number of levels for the data variables (COVID-19, NO2 column density, and lockdown policies) was determined empirically through trial runs, which eventually ended up with the two-level design yielding some significant rules as presented in this paper.

5.2. Seasonal variations of NO2 column density

Our findings reveal that the association between COVID-19 confirmed cases and NO2 column density is not a linear relationship. When COVID-19 began to spread in a country, the local government might introduce lockdown and movement restraining orders which would cause the column density. With COVID-19 cases continued to rise in a country, the government might not take further actions as the necessary policies had already been implemented. As a result, more COVID-19 new cases would not necessarily lead to a further decrease in NO2 emission. Moreover, NO2 concentration fluctuates with seasonal changes affected by local meteorological conditions, such as wind speed and directions (Lin et al., 2015). It is theoretically possible to employ global chemistry models to simulate changes in NO2 column density across different regions of the world. The impacts of different factors can be separated via the modelling process after incorporating lockdown policies and COVID-19 data into the models. There is, however, the difficulty of incorporating lockdown policies in the conventional numerical model framework. More research on the quantification of non-numerical data sets and incorporating them into global chemistry models is needed.

5.3. Public awareness and actions responding to lockdown policies in different countries

Public awareness is an important yet a difficult factor to evaluate or quantify since it is highly related to local culture and also varies within a country. The eight policy measures in this study included school closures, workplace closures, cancellation of public events, restrictions on gatherings, closing of public transport, stay-at-home requirements, restrictions on internal movement, and international travel controls. Some of these measures can be attributed to organizations and effectively enforced, such as school closures, workplace closures, public transport closures and international travel controls. Effectiveness of the remaining measures (including stay at home, restrictions on internal movements, and cancellation of public events) would rely on public adherence. It was widely reported by the media that many people continued to have gatherings and public events during the COVID-19 pandemic despite restraining orders. This study did not consider mask-wearing as a policy because of the lack of reliable data. Even though facemasks appear to be effective when supplemented with hand hygiene and social distancing, its use was not always mandated as a policy but an advisory or a recommendation. Public mask-wearing remains a controversial issue for policymakers especially when its effectiveness is being challenged and opinions remain divisive.

5.4. Lessons on lifestyle changes during COVID-19

Transit-oriented development and active transport (including cycling, walking and other micro-mobility means) have been encouraged as sustainable transport alternatives over the last few decades (De Vos et al., 2014). High infectivity of the COVID-19 virus has discouraged...
people from using public transport and led to the increased use of private vehicles. This study shows that NO2 column density changes were not associated with public transport closure. The emphasis on social distancing in COVID-19 may foster the return of an automobile-oriented society to bring back air pollution, such as NO2 and PM2.5, which is detrimental to the health of the urban population (Loo and Tsoi, 2018). It is thus important to revitalize a safe and healthy environment for public transport and other active transport modes. At the same time, lockdown policies such as the closing of schools and workplace, international travel ban, as well as the cancellation of public events, have triggered online teaching and learning, e-commerce, e-business and various e-networking activities. This shift to e-platforms requires a serious re-thinking of people's lifestyle changes and the ways of conducting and planning different activities.

6. Conclusions

The COVID-19 pandemic has brought profound influences on various aspects of the environment and peoples' livelihood in many parts of the world. Many countries have imposed lockdown policies to close schools, workplace, public transport, and their international borders. It has been reported that these lockdown policies have brought some positive impacts towards the environment at the city or country level (Filonchyk et al., 2020; Lau et al., 2020; Sarfraz et al., 2020; Siddiqui et al., 2020). This study evaluated these impacts of COVID-19 pandemic towards the global NO2 dynamics based on data from 187 countries/regions. In particular, different lockdown policies were quantified with a process of categorization to be incorporated in the association rules mining method using the Apriori algorithm, so that different lockdown policies were investigated regarding their impacts on the NO2 dynamics. Results suggested that countries without new cases would not implement lockdown policies whereas those with new cases would enforce some lockdown policies, including the closing of schools, workplace, and cancellation of public events. A decline in the NO2 column density was associated with international travel restrictions but not public transport whereas an increase in the column density was associated with the absence of lockdown policies. Nevertheless, some limitations still need to be further addressed, mainly related to the categorization of datasets and the incorporation of seasonal variations of NO2 which are highlighted in detail in the Discussion section. These are sources of possible errors. Additionally, some implications from the research findings are identified to enhance the public awareness and actions responding to different lockdown policies, as well as to adjust our lifestyle during the COVID-19, and potentially after the COVID-19 pandemic.

CRediT authorship contribution statement

Hongzheng Zhang: Conceptualization, Methodology, Investigation, Software, Writing – original draft. Yinyin Lin: Investigation, Software, Visualization. Shan Wei: Investigation, Software, Visualization. Becky P.Y. Loo: Conceptualization, Writing – original draft, Supervision. P.C. Lai: Conceptualization, Writing – original draft. Yun Fat Lam: Conceptualization, Investigation, Writing – original draft. Luoma Wan: Writing – review & editing. Yu Li: Conceptualization, Writing – review & editing.

Declaration of competing interest

The authors declare no conflict of interest.

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References

Achakulsukwit, P., Brauer, M., Hystad, P., Penenberg, S.C., 2019. Global, national, and urban burdens of paediatric asthma incidence attributable to ambient NO2 pollution: estimates from global datasets. Lancet Planet Health 3.

Agrawal, R., & Srikant, R. (1994). Fast algorithms for mining association rules. In 20th Int. Conf. Very Large Data Bases, VLDB (pp. 487-499).

Aguiar-Méndez, D., De Paoli, F., Margarit, D.H., Mendoza, E., Parody, A., Maturana, A.Y., Teixeira, E.C., 2020. Assessment of the NO2 distribution and relationship with traffic load in the Caribbean coastal city. Sci. Total Environ. 720.

Bauwens, M., Compernolle, S., Stavrakou, T., Müller, J.F., van Gent, J., Eikes, H., Levet, P.F., van der A, R., Veefkind, J., Yu, H., & Zehner, C. (2020). Impact of corona-virus outbreak on NO2 pollution assessed using TROPOMI and OMI observations. Geophys. Res. Lett. 47.

Chakraborty, P., Jayachandran, S., Paladkar, P., Siddiqui, L., Chakraborty, S., Ram, S. Bhasin, S. V, Sivavastava, M., 2020. Exposure to nitrogen dioxide (NO2) from vehicular emission could increase the COVID-19 pandemic fatality in India: a perspective. Bull. Environ. Contam. Toxicol. 105, 198–204.

Chan, K.L., Hart, A., Lam, Y.F., Xie, P.H., Liu, W.Q., Cheung, H.M., Lam, J., Pohler, D., Li, A., Xu, J., Zhou, H.J., Ning, Z., Wenig, M.O., 2015. Observations of tropospheric NO2 using ground based MAX-DOAS and OMI measurements during the Shanghai World Expo 2010. Atmos. Environ. 91, 119–45.

Crippa, M., Guizziardi, D., Muntean, M., Schal, E., Dentener, F., van Aardenne, J.A., Monni, S., Doering, U., Olivier, J.G.J., Paglieri, V., Janssens-Maenhout, G., 2018. Gridded emissi- on of air pollutants for the period 1979-2012 within EDGAR v4.3.2. Earth System Science Data 10, 88–1007.

De Vos, J., Van Acker, V., Wilcox, F., 2014. The influence of attitudes on transit-oriented development: an exploratory analysis. Transp. Policy 35, 326–329.

Filionchyk, O., Harynovych, V., Yasa, G., Shapiro, K., 2020. Impact assessment of COVID-19 on variations of SO2, NO2, CO and AOD over East China. Aerosol Air. Qual. Res. 20, 1530–1540.

Gao, W., Yu, J., Liu, C., Li, S.S., Tan, J.H., Fan, M., Xiong, ZX., Wang, Z.F., Shang, H.Z., & Su, L., (2017). Ground-level NO2 concentrations over China inferred from the satellite-derived NO2 and CMAQ model simulations. Remote Sens., 9.

Hale, T., Webster, S., Petherick, A., Phillips, T., Kira, B., Oxford COVID-19 Government Response Tracker. https://www.ox.ac.uk/research/research-projects/coronavirus-government-response-tracker#data. (Accessed 15 May 2020).

Herndon, S.C., Shorter, J.H., Zahniser, M.S., Nelson, D.D., Jayne, J.T., Brown, R.C., Miake-Lye, N.C., Wozniak, S., Lanni, T., Demerjian, K., Kolb, C.E., 2004. NO and NO2 emission ratios measured from in-use commercial aircraft during taxi and takeoff. Environ. Sci. Technol. 38, 6078–6084.

Kaminska, J.A., 2019. A random forest partition model for predicting NO2 concentrations from traffic flow and meteorological conditions. Sci. Total Environ. 651, 475–483.

Kuhlmann, G., Hartl, A., Cheung, H.M., Lam, Y.F., Wenig, M.O., 2014. A novel gridding algorith- m to create regional trace gas maps from satellite observations. Atmospheric Measurement Techniques 7, 451–467.

Kuhlmann, G., Lam, Y.F., Cheung, H.M., Hartl, A., Fung, J.C.H., Chan, P.W., Wenig, M.O., 2015. Development of a custom OMI NO2 data product for evaluating biases in a regional chemistry transport model. Atmos. Chem. Phys. 15, 5627–5644.

Lancet Planet Health, 2020. The positive impact of lockdown in Wuhan on containing the COVID-19 outbreak in China. Journal of Travel Medicine 27.

Lee, H., Keshoawgour, V., Kochach, P., Mikolajczyk, A., Schubert, J., Bania, J., Keshoawgour, T., 2020. The positive impact of lockdown in Wuhan on containing the COVID-19 outbreak in China. Journal of Travel Medicine 27.

Le Quere, C., Jackson, R.B., Jones, M.W., Smith, A.J.P., Abernethy, S., Andrew, R.M., De-Gol, A.J., Willis, D.R., Yasa, G., Canadel, O.S., Friedlingstein, P.R., Eyring, E.L., & Peters, E., 2020. Temporary reduction in daily global CO2 emissions during the COVID-19 forced confinement. Nat. Clim. Chang. 10, 647–+.•

Li, M., Zhang, Q., Kurukawa, J., Woo, J.H., He, K.B., Li, Z.F., Ohara, T., Song, Y., Streets, D.G., Carmichael, G.R., Cheng, Y.F., Hong, C.P., Hsu, H., Jiang, X.J., Kang, S.C., Liu, F., Su, H., Zheng, B., 2017. MIX: a mosaic Asian anthropogenic emission inventory under the inter- national collaboration framework of the MICS-Asia and HTAP. Atmos. Chem. Phys. 17, 935–963.

Lin, J.T., Liu, M.Y., Xin, J.Y., Boersma, K.F., Sprod, R., Martin, R., Zhang, Q., 2015. Influence of aerosols and surface reflectance on satellite NO2 retrieval: seasonal and spatial characteris- tics and implications for NOx emission constraints. Atmos. Chem. Phys. 15, 11217–11241.

Liu, H., Page, A., Strode, S.A., Yoshida, Y., Choi, S., Zheng, R., Lansal, L.N., Li, C., Korotkov, N.A., Eikes, H., van der A, R., Veefkind, P., Levet, P.F., Hauser, O.P., & Joiner, J., 2020. Abrupt decline in tropospheric nitrogen dioxide over China after the outbreak of COVID-19. Sci. Adv., 6.

Loo, B.P.Y., Tsoi, K.H., 2018. The sustainable transport pathway: A holistic strategy of five transformations. Journal of Transport and Land Use 11, 961–980.

Ogen, Y., 2020. Assessing nitrogen dioxide (NO2) levels as a contributing factor to clo- navirus (COVID-19) fatality. Sci. Total Environ. 726.

Sarfraz, M., Shehzad, K., Farid, A., 2020. Gauging the air quality of New York: a non-linear Nexus between COVID-19 and nitrogen dioxide emission. Air Qual. Atmos. Health 13, 1135–1145.

Siddiqui, A., Siddiqui, A., Halder, S., Chauhan, P., Kumar, P., 2020. COVID-19 pandemic and City-level nitrogen dioxide (NO2) reduction for urban centres of India. Journal of the Indian So- ciety of Remote Sensing, 1–8. http://doi.org/10.1007/s12224-020-01130-7 Advance online publication.

Spinelli, A., Pellino, G., 2020. COVID-19 pandemic: perspectives on an unfolding crisis. Br. J. Surg. 107, 785–787.
Tobias, A., Carnerero, C., Reche, C., Massague, J., Via, M., Minguillon, 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.

Veefkind, J.P., Aben, I., McMullan, K., Forster, H., de Vries, J., Otter, G., Claas, J., Eskes, H.J., de Haan, J.F., Kleipool, Q., van Weele, M., Hasekamp, O., Hoogeveen, R., Landgraf, J., Snel, R., Tol, P., Ingmann, P., Voors, R., Kruizinga, B., Vink, R., Visser, H., Levelt, P.F., 2012. TROPOMI on the ESA Sentinel-5 Precursor: A GMES mission for global observations of the atmospheric composition for climate, air quality and ozone layer applications. Remote Sens. Environ. 120, 70–83.

Wang, Q., Su, M., 2020. A preliminary assessment of the impact of COVID-19 on environment – a case study of China. Sci. Total Environ. 728.

Wang, Q., Wang, S., 2020. Preventing carbon emission retaliatory rebound post-COVID-19 requires expanding free trade and improving energy efficiency. Sci. Total Environ. 746.

Zhao, Y.B., Zhang, K., Xu, X.T., Shen, H.Z., Zhu, X., Zhang, Y.X., Hu, Y.T., Shen, C.F., 2020. Substantial changes in nitrogen dioxide and ozone after excluding meteorological impacts during the COVID-19 outbreak in Mainland China. Environ. Sci. Technol. Lett. 7, 402–408.

Zheng, Z.H., Yang, Z.W., Wu, Z.F., Marinello, F., 2019. Spatial variation of NO2 and its impact factors in China: an application of sentinel-5P products. Remote Sens. 11.

Zhu, Y.J., Xie, J.G., Huang, F.M., Cao, L.Q., 2020. Association between short-term exposure to air pollution and COVID-19 infection: evidence from China. Sci. Total Environ. 727.