NIGHTTIME LIGHT EMISSIONS EXPLAIN THE DECLINE IN NO_2 DURING A COVID-19-INDUCED TOTAL LOCKDOWN IN FRANCE

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ABSTRACT:

Referring to a total lockdown due to COVID-19 in Metropolitan France, this study investigates the geospatial correlation between nighttime light emission and the relative change of NO_2 air pollution (dNO_2 %). To address the research problem, near-surface NO_2 data and nighttime light data were implemented. Stable night lights were obtained for a long period on average (2014-2019) using Day-Night Band (DNB) data from the Visible Infrared Imaging Radiometer Suite (VIIRS). The relative change in tropospheric NO_2 was calculated using Sentinel-5P satellite data from the Tropospheric Monitoring Instrument (TROPOMI). The dNO_2 calculation was performed considering an equivalent reference period (April 2019) to the major lockdown period in France (April 2020). The correlation between the variables DNB nighttime lights and dNO_2 was tested with a statistical T-test. The findings revealed an intense phenomenon of decreasing NO_2 air pollution in France (decreases by -25% to -50%). Decreases < -50% were mainly recorded in the greater Paris metropolitan area, in Alsace, and other locations. The results showed a strong and statistically significant inverse geospatial correlation between the two variables under anti-COVID-19 control measures. The higher was the emission of nighttime lights, the higher was the degree of tropospheric NO_2 decrease in the regions of France (R^2=0.72). It is concluded that employing remote sensing techniques, DNB nighttime light is a reliable indicator to estimate the degree of air decontamination. DNB as an independent variable is recommended for future research on changes in the concentration of other pollutant gases.

Key-words: *Satellite data, NO_2, Decontamination, Visible to near-infrared, Constraint, France*

1. INTRODUCTION AND LITERATURE REVIEW

Is there a connection between emitted nighttime lights and the drop in NO_2 air pollution caused by the measures taken against COVID-19?

The outbreak of the novel SARS-CoV-2 coronavirus caused a great impact on global society. It was estimated that the pandemic may have slowed the global economy by 3% to 6% in 2020 (Jackson et al., 2021) having negative repercussions on whole societies.

From March, countries' governments imposed total or partial confinements leading to curfews (WHO, 2020a, 2020b). Moreover, transportation limitations were implemented in several countries. Consequently, the anti-COVID-19 measures have slowed the anthropogenic activities, resulting in a decrease in air pollution (Cameletti, 2020; Dutheil et al., 2020; Kumari & Toshniwal, 2020; Muhammad et al., 2020; Rugani & Caro, 2020; Zaib et al., 2021; Zambrano-Monserrate et al., 2020). In France, the first total lockdown lasted between March 17, 2020 and May 11, 2020 (Gouvernement Français, n.d.). Many impacts of human activities on the environment can be remotely monitored using satellite data. Nighttime light emissions represent an indicator of population density, urbanization, and economic development of regions (Levin & Zhang, 2017; Small & Elvidge, 2013). Furthermore, these emissions have an impact on human health and ecosystems (light pollution) (Gaston et al., 2013; Koo et al., 2016).

The use of night light data for economic growth studies is well known (Beyer et al., 2018; Ghosh et al., 2017; Ivan et al., 2020; Prakash et al., 2019). Besides, there are recent studies that addressed the phenomenon of dimming night lights during COVID-19 lockdowns (Bustamante-Calabria et al.,

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2021; Elvidge et al., 2020; Ghosh et al., 2020; S. Zheng et al., 2021). Low-light imaging satellite sensors were also implemented to detect dimming and recovery of night lights after natural disasters (Román et al., 2019; Zhao et al., 2018; Y. Zheng et al., 2019) or other social problems (e.g. wars) (Li et al., 2018), humanitarian crises (Zhang et al., 2020), or economic collapse (Elvidge et al., 2016).NO_2 data from both satellite sensors and on-site measurements were used in previous studies that addressed air pollution decrease during the pandemic (Chan et al., 2021; Ikhlasse et al., 2021; Tian et al., 2021).

This study's purpose is to examine the geospatial relationship between night light emission and the decline in NO_2 air pollution over Metropolitan France during the first total confinement (April 2020). Sentinel-5P satellite data with high spatial resolution were used to calculate the change in tropospheric NO_2 concentration. Night lights were obtained using low-light satellite imagery data collected by the National Aeronautics and Space Administration and National Oceanic and Atmospheric Administration's (NASA/NOAA) Visible Infrared Imaging Radiometer Suite (VIIRS) Day-Night Band (DNB).

The novelty that this study brings to the literature is to determine the geospatial connection between the intensity of nighttime anthropogenic activity and the air decontamination observed under mobility control measures. The research hypothesis was raised that the greater the night light emission in a certain territory, the greater the decline in NO_2 air pollution during the first month of total lockdown.

2. DATA USED

Night light radiance data were retrieved from Suomi National Polar-orbiting Partnership's (SNPP) Visible Infrared Imaging Radiometer Suite (VIIRS) that is compatible with the DNB sensor, providing global daily measurements of night lights in the visible and near-infrared (NIR) bands of the electromagnetic spectrum. VIIRS DNB is ultra-sensitive even in low light conditions, which allows generating high-quality by-products in terms of resolution and sensor calibration. Through these enhancements, VIIRS DNB products allow monitoring nighttime events and light emission sources associated with human activities.

VIIRS DNB data product contains the nocturnal radiance obtained in the upper part of the atmosphere. The VNP46A1 sensor contains 26 datasets, including sensor luminosity, azimuth and zenith angles, cloud mask, shortwave infrared radiance, brightness temperature, moon phase angle, moonlight fraction, and other quality indicators. With millions of times intensification of the signal, the DNB band detects electrical lighting on Earth's surface (Miller et al., 2013). The data is pre-processed to remove cloud cover, solar and lunar pollution, forest fires, and auroras (Elvidge et al., 2017). In this study, nighttime light data of monthly averaged composites of radiance were used from VIIRS's DNB. The data were accessed using Google Earth Engine (GEE) platform with lines of code.

The collection called in GEE was ee.ImageCollection ("NOAA/VIIRS/DNB/MONTHLY_V1/VCMSLCFG") (Earth Engine Data Catalog, n.d.-c). The VIIRS Cloud Mask Stray Light Corrected Nighttime DNB Composites (VCMSLCFG) were retrieved (Elvidge et al., 2021). This data is available from 2014-01-01. The used VIIRS DNB has 463.83 m spatial resolution.

Near-surface NO_2 data were obtained from the TROPOspheric Monitoring Instrument (TROPOMI) sensor onboard the Sentinel-5P satellite. TROPOMI detects atmospheric NO_2 density as concentrations via optical depth techniques in three vertical columns: total, stratospheric, and tropospheric. Tropospheric NO_2 data was accessed using GEE, by calling the ee.ImageCollection ("COPERNICUS/S5P/OFFL/L3_NO2") collection. The 'Offline' (OFFL) product was used instead of the 'Near-real time' (NRTI) product because it is considered slightly more accurate (Earth Engine Data Catalog, n.d.-a; Verhoelst et al., 2021). The band "tropospheric_NO2_column_number_density" was used, which provides NO_2 data from the tropospheric vertical column. The vertical column means the ratio between the density of the inclined NO_2 column and the factor of the total air mass. This data is available from 2018-06-28. In addition to the raster data, tropospheric NO_2 time series data were obtained from TROPOMI and Aura Ozone Monitoring Instrument (OMI/Aura) (Krotkov et al., 2019).

3. TECHNIQUES

3.1. Obtaining DNB nighttime lights and tropospheric NO_2 data, and calculating the relative NO_2 change

VIIRS DNB data was obtained using the GEE platform through javascript code (Kovács, 2021). The DNB images used represented monthly average radiances. Because this data is compiled monthly, there are areas where it is difficult to get good data coverage due to cloud cover or poleward solar illumination. Considering these technical aspects of the DNB data, an image representing annual average nightlight radiances between 2014-2019 was created over the territory of Metropolitan France. The 'cf_cvg' band was selected not assuming zero (0 indicates no observation of lights). Cloud cover was determined using VIIRS Cloud Mask (VCM). Based upon quality indicators, DNB data was subjected to a filtering process excluding the data affected by the "parasitic" light (rays, fires, ships, solar lighting, cloud cover, and temporary lights). Finally, the resulting DNB image was exported from GEE for subsequent analysis.

Tropospheric NO_2 data was also retrieved through the GEE platform by accessing Sentinel-5P's collection. Daily averaged images were created for April 2019 (lockdown-free reference period) and April 2020 (lockdown period) over Metropolitan France. The conversion of Level 2 (L2) data to Level 3 (L3) gridded data was performed using the *harpconvert* tool and *bin_spatial* operation. Then, the original NO_2 data was filtered to remove pixels with QC (quality control) values less than 75% for the NO_2 tropospheric density band (Earth Engine Data Catalog, n.d.-b). In the last step, the resulting two rasters representing NO_2 concentrations over France were exported from GEE for the subsequent analysis.

Accordingly, the NO_2 relative change (%) between the confinement-free period (RP) and the period under lockdown restriction measures (LP) was determined as follows (1):

$$Ch_{\%} = \left(\frac{X_a}{X_b} - 1\right) * 100 \qquad (1)$$

where $Ch_{\%}$ is the relative change (%) between RP and LP, X_a is the raster image representing the NO_2 concentrations during LP, and X_b is the raster image representing the NO_2 concentrations in the equivalent calendar period RP.

3.2. Time series of average NO_2 evolution

To check the temporal evolution of NO_2 in 68 cities of France, time-series data analysis was performed using Savitzky–Golay filter. The Savitzky–Golay filtering method is based on the calculation of a local polynomial regression (of degree k) with at least k+1 equispaced points (Savitzky & Golay, 1964). The obtained result is a function similar to the input data but smoothed avoiding the presence of noise. An optimal window length of 101 with polynomial order 2 was chosen for the filter. The filter was made with Python using *scipy.signal* library: "from scipy.signal import savgol_filter". The Savitzky–Golay filter is defined as follows (Savitzky & Golay, 1964) (2):

$$Y_j = \sum_{i=\frac{1-m}{2}}^{\frac{m-1}{2}} C_i y_{j+i}, \qquad \frac{m+1}{2} \le j \le n - \frac{m-1}{2} \qquad (2)$$

where $\{x_j, y_j\}, j = 1, \dots, n$, are the set of points, x_j is the independent variable, and y_j is the observed value. The points are treated with a set of m convolution coefficients: C_i.

3.3. Establishing and testing the correlation between geospatial variables

The spatial correlation analysis between the geospatial variables DNB nighttime lights and relative NO_2 change (dNO_2) was performed by implementing zonal statistical computations for a given administrative-territorial units' level, which were the regions of Metropolitan France. For this purpose, the 'Zonal Statistics' tool of QGIS was used. For the regional units, in the case of the variable dNO_2, the average relative change value was assumed and in the case of the variable DNB night lights, the value of the most represented majority was considered. The majority statistic is a measure that returns the most represented and prevalent pixel value in a given spatial feature. Further, the correlation (R) and determination (R^2) coefficients were computed. T-test was used to verify the statistical significance of the correlation coefficient between the variables DNB and dNO_2. The T-test determines if the correlation between two variables differs significantly from zero. In a T-test for correlation, the statistically significant difference from 0 indicates that both variables are interdependent. Based on the null hypothesis (H0) of the test, it is assumed that there is no difference from 0 ($\rho = 0$), while the alternative hypothesis for that (H1) states that the correlation between the two variables is statistically different from 0 ($\rho \neq 0$). The t-test value was calculated as follows (Kanji, 2006) (3):

$$t_{r_{xy}} = \frac{r_{xy}\sqrt{n-2}}{\sqrt{1-r_{xy}^2}} \quad (3)$$

with Student T distribution and $n-2$ degrees of freedom (df). r_{xy} is the correlation coefficient between DNB and dNO_2, r_{xy}^2 is the coefficient of determination, and n is the total number of even observations. H0 is maintained if the T-test result is $t_{r_{xy}} \leq CV$ (critical value from the Student t Distribution Table, based on df). Otherwise, H0 is rejected by opting for H1 if the test's output is $t_{r_{xy}} > CV$. This analysis assumed $\alpha = 0.05$ level of statistical significance. Concerning the p-value, H0 is maintained if $p > 0.05$, and H1 is true if $p < 0.05$.

4. RESULTS

Remote sensing results on DNB nighttime lights observed over a long period (2014-2019) revealed the main areas of high anthropogenic impact in Metropolitan France (Fig***. 1***). Generally, the highest radiance values correspond to densely populated cities and their conurbations. The DNB values, beyond indicating the presence of human settlements, reflected several socio-economic aspects of the territory such as unequal population density, emptying areas, monopoly of the capital-city in the hierarchy of settlements, more developed areas with greater economic potential, and terrain orography. The visualization of stable nighttime lights (2014-2019) provided a different perspective of the territory of Metropolitan France. Unlike daytime remote sensing, this type of satellite data provides a valuable picture of the spatial distribution of multiple sources of nighttime illumination. The nighttime light data revealed social-economic patterns relating to urban environments and anthropogenic activity. Mostly, in the case of France, these relate to electrification and transportation in the national territory. The Greater Paris metropolitan area in the Île-de-France region stood out above the rest of the country. Other spots corresponding to large cities and their conurbations (Lyon, Marseille, Nice, Toulouse, Nantes, Lille, Bordeaux) were also highlighted. Apart from the capital city, zones with high DNB radiance emission were identified along the Mediterranean coast, in the Saône-Rhône valley, in Alsace, and near the Belgian border at the north.

Results of the TROPOMI sensor's high spatial resolution data showed a significant overall decline in tropospheric NO_2 concentrations during the full-month total lockdown of April 2020 in Metropolitan France compared with the previous reference period (

Fig. 2a, b). Particularly, northern regions experienced a sharper and more general decrease than the other areas of France (i.e. Île-de-France, Hauts-de-France, Grand Est, Bourgogne-Franche-Comte, Centre-Val de Loire, Pays de la Loire, Bretagne, Normandie). Auvergne-Rhône-Alpes region also experienced a salient reduction in air pollution.

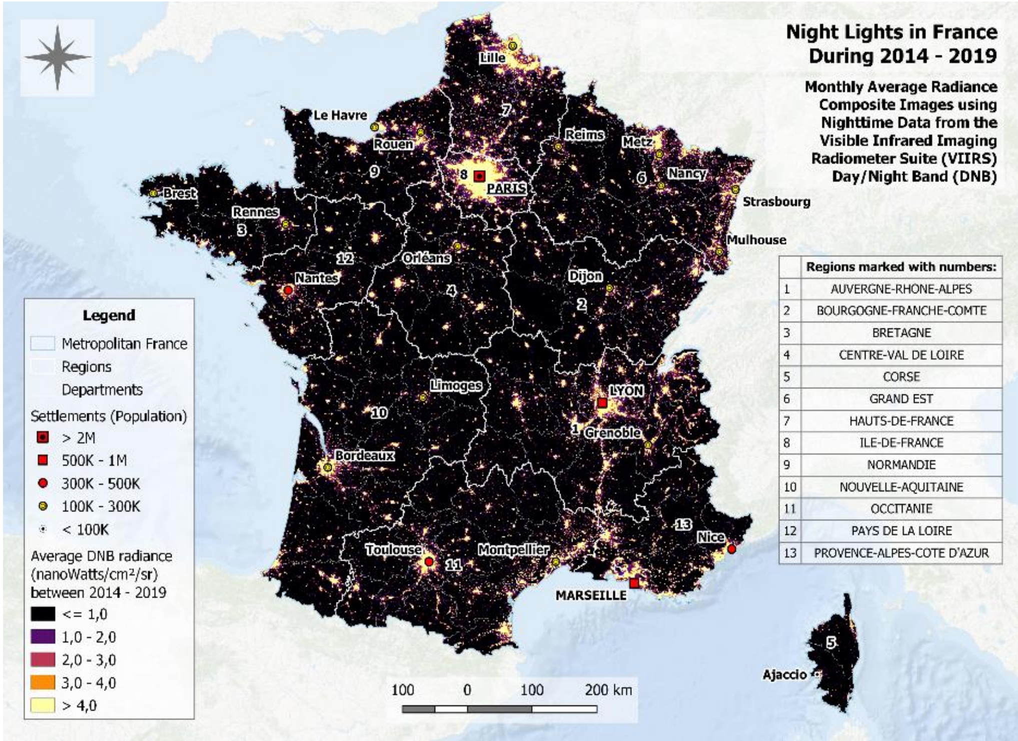

Fig. 1. Stable nighttime lights in France during 2014-2019.

The decrease in NO_2 levels was less pronounced in the southern, south-western regions, (i.e. Nouvelle-Aquitaine, Occitanie, Provence-Alpes-Côte d'Azur, Corse), but was still evident in some densely populated areas. Based on these results, it can be stated in general that the NO_2 decline phenomenon was more noticeable in all major cities of the country (

Fig. 2a, b).

Based on the relative changes detected in NO_2 concentrations (dNO_2 %) over the entire Metropolitan France, results showed that there were extensive areas experiencing decreases ranging from -25% to -50% (**Fig. 3**). It was determined that the greatest drop in air pollution occurred predominantly in the northern parts (in Île-de-France, Grand Est, and Centre-Val de Loire regions) where NO_2 was decreased by <= -50% in several areas, especially around the city of Paris and in the Alsace region. However, the central and southern areas of the country also experienced reductions ranging from -25% to -50% and even below -50%. This was especially perceptible around large cities (Marseille, Nice, Lyon, Limoges, Toulouse, Montpellier) and localities in mountainous valleys (the Pyrenees, Alps, Massif Central, Corsica).

Consequently, during total confinement, NO_2 pollution levels decreased significantly in northern France across a west-east line, as well as in the Saône, Rhône, and Isère valley regions across a north-south axis (**Fig. 3**). Besides, significant decreases occurred locally in the south-southwest zones too. Overall, on average, Île-de-France has experienced the most decline (-39.03%), followed by Grand Est (-33.69%) and Centre-Val de Loire (-31.71%) regions. By regional average, the smallest decrease in NO_2 was recorded in the case of Corsica Island (Corse), where a slight increase was detected compared with the reference period (4.07%). This was followed by Nouvelle-Aquitaine (-11.04%) and Provence-Alpes-Côte d'Azur (-12.02%) regions.

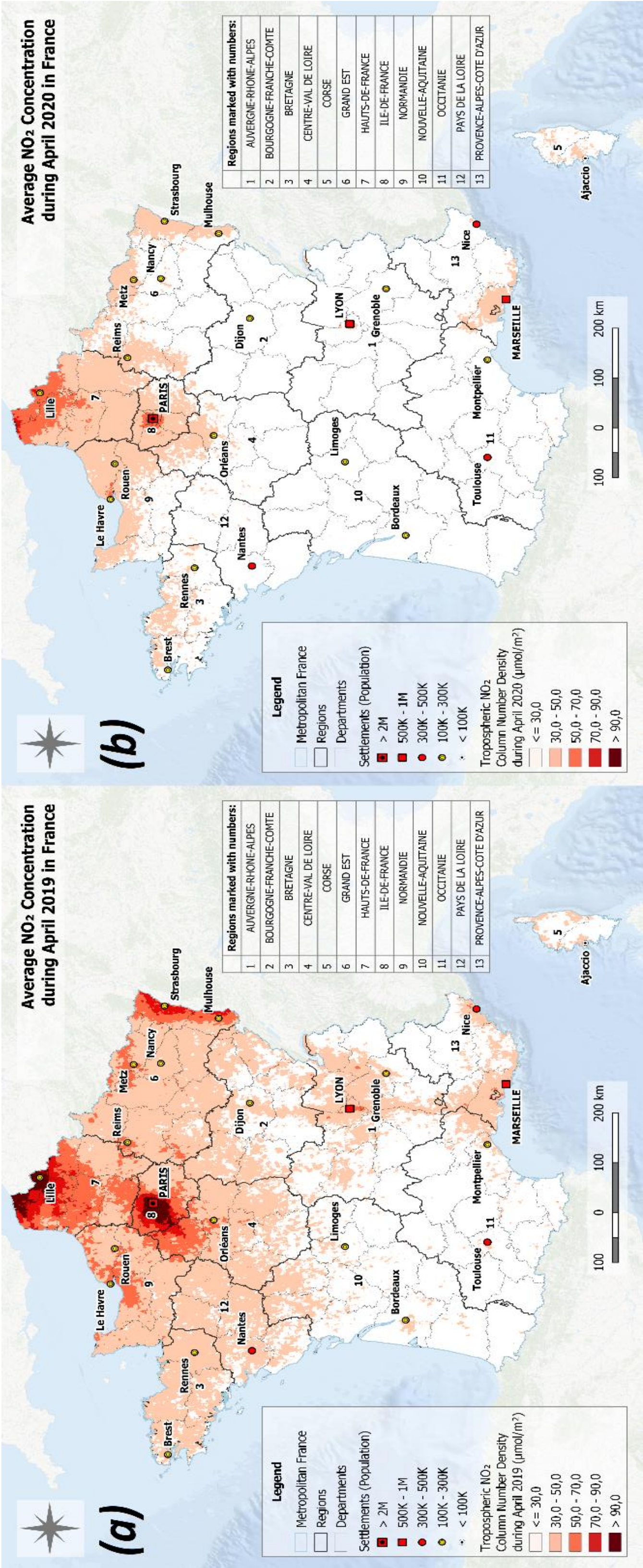

Fig. 2. Average NO_2 concentration during **(a)** April 2019 and **(b)** April 2020 in Metropolitan France

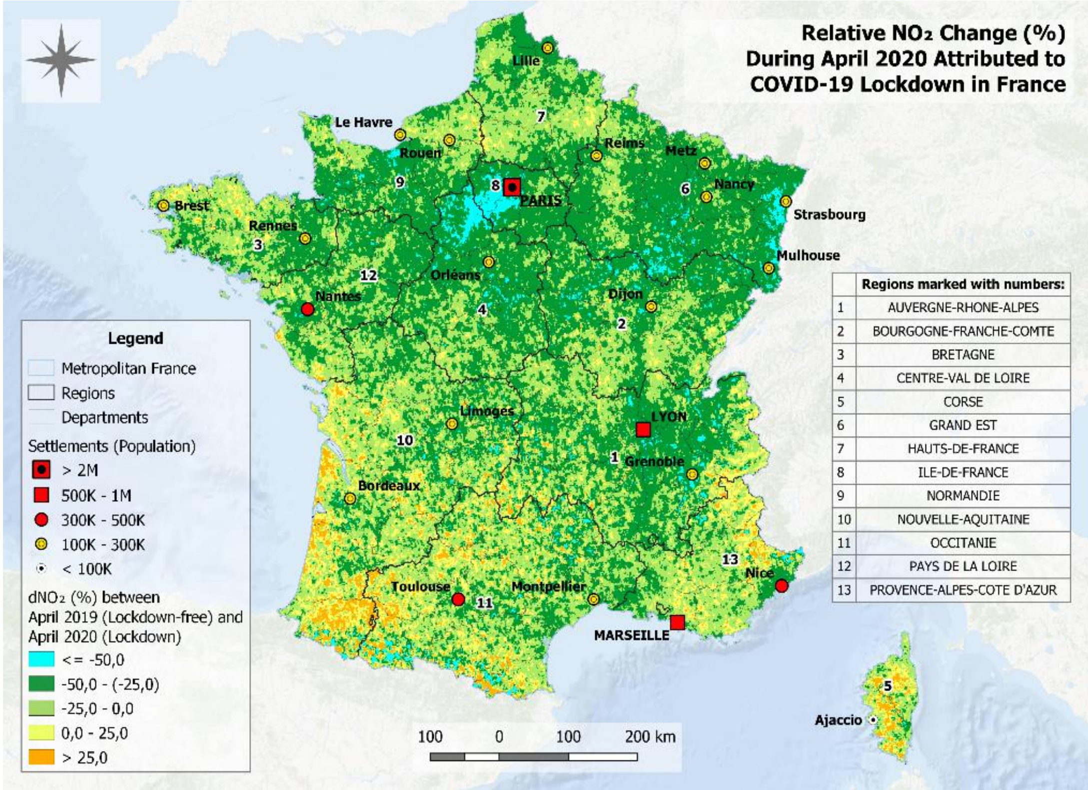

Fig. 3. Relative NO_2 change (dNO_2 %) during April 2020 attributed to COVID-19-induced total confinement in Metropolitan France.

The regression and correlation analysis with the T-test demonstrated that there was a statistically significant inverse relationship between the intensity of DNB night lights and decreases in NO_2 concentrations during total confinement in Metropolitan France (**Fig. 4**).

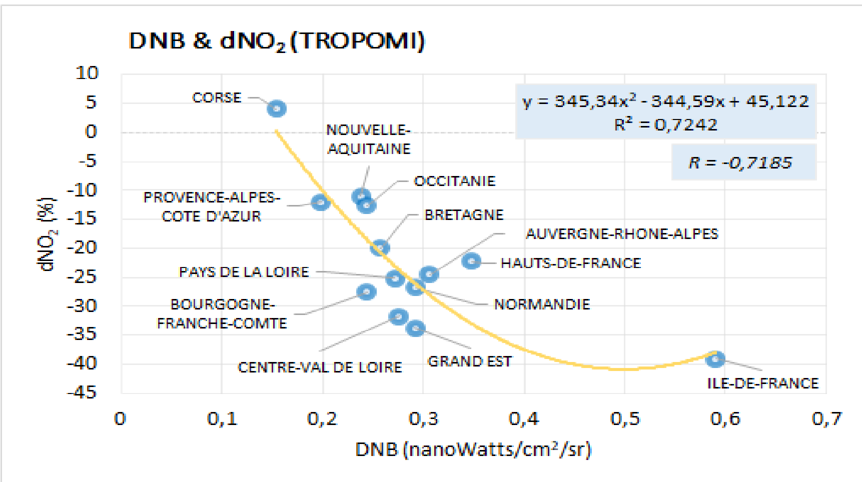

Fig. 4. Scatter diagram of the relationship between DNB and the relative change in NO_2 concentrations in the troposphere during April 2020 (COVID-19 lockdown) in French regions.

The correlation coefficient between DNB night lights and dNO_2 was $R = -0.72$. The coefficient of determination between the two variables using a quadratic function curve was $R^2 = 0.72$. Based on the T-test for correlation, it was found that: $T(11) = -2.922 > CV = 2.201$, $\alpha = 0.05$; $p = 0.014$. According to these findings tested with statistical methods, as the intensity of night lights was higher, the greater was the decrease in NO_2 pollution in France due to anti-COVID-19 measures. Tropospheric NO_2 time series data in 68 cities evidenced that two peaks of high NO_2 concentration occurred each year, one in autumn and the other during winter-spring. Lower NO_2 levels tended to occur during summer. The Savitzky-Golay filter indicated that during the total lockdown in 2020, the second peak was much smaller than in 2018, 2019, or 2021. Past observations indicated that after the first peak follows a second one. However, time-series data showed that during total lockdown the second peak was diminished (**Fig. 5**). This result indicated that during April 2020 the previous "normal" behavior of the NO_2 was modified due to the anti-COVID-19 measures.

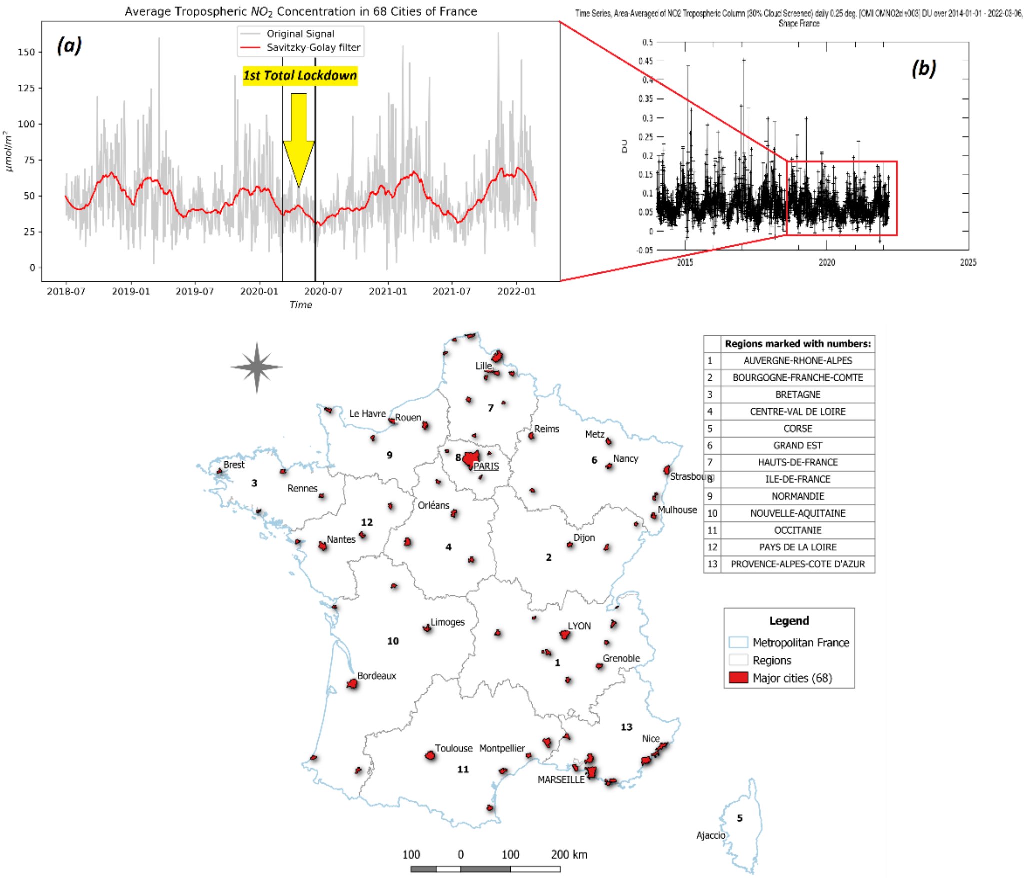

Fig. 5. Time series evolution of the tropospheric NO_2 concentration in 68 cities of Metropolitan France measured by **(a)** the TROPOMI and **(b)** OMI.

5. DISCUSSION

The results of this study indicate that there was a strong geospatial correlation between the past emission of nighttime lights and the relative change in near-surface NO_2 concentration. Using TROPOMI data, the analysis revealed that during total confinement there was a strong NO_2 air pollution reduction phenomenon over most of the territory of Metropolitan France. Taking a reference period prior to COVID-19 confinement, it was found that NO_2 levels dropped by -25% to -50% over large areas of the country, and an even greater drop of -50% was recorded in the vicinity of Paris (Île-de-France), in areas of the Grand Est (Alsace) and the localities of the Pyrenees and Alps valleys. Generally, a reduction of -25% - (-50%) was detected in all major cities (**Fig. 3**). The study also found a statistically significant connection between DNB night lights (independent variable) and the degree of NO_2 decrease in the context of anti-COVID-19 measures (dependent variable).

In accordance with the research's hypothesis, the study showed that the higher the intensity of nighttime light emissions in a given territory, the greater the NO_2 decontamination of the air (**Fig. 4**). This clearly indicates the relationship between the impact of anthropogenic activities estimated by remote sensing observations and their effect on the change of atmospheric pollution (Levin & Zhang, 2017; Small & Elvidge, 2013). This suggests that nighttime lights are also an indicator of atmospheric pollution and the potential degree of decontamination, in addition to their consequences on ecosystems and the health of living beings (Gaston et al., 2013; Koo et al., 2016). The stable correlation between DNB night lights and dNO_2 showed that air pollution is also a social-environmental problem that can be studied with satellite sensor's nighttime lights imaging data (Zhao et al., 2018; Y. Zheng et al., 2019, Zhang et al., 2020, Li et al., 2018).

As an alternative to previous research, in terms of mobility control measures, this study provides new insight into the relationship between nighttime light emission before the COVID-19 crisis and air pollution reduction during COVID-19 also detected with remote sensing techniques (Chan et al., 2021; Ikhlasse et al., 2021; Tian et al., 2021). Observations on the magnitude of the NO_2 decrease due to COVID-19 control measures were in agreement with recent research on this phenomenon in different countries (Cameletti, 2020; Dutheil et al., 2020; Kumari & Toshniwal, 2020; Muhammad et al., 2020; Rugani & Caro, 2020; Zaib et al., 2021; Zambrano-Monserrate et al., 2020). Recent investigations addressed the phenomenon of nighttime light's dimming during confinements (Bustamante-Calabria et al., 2021; Christopher D. Elvidge et al., 2020; Ghosh et al., 2020; S. Zheng et al., 2021), however, these studies focused on specific urban areas where particularly there was an effect on nighttime illumination, therefore dimming was not a general and widespread phenomenon in many areas.

The methodological choices of the study were constrained by the current low temporal resolution of Sentinel-5P data accessible since mid-2018. The equivalent reference period for the confinement was therefore exclusively April 2019. Despite this condition of the data, the relative change in NO_2 concentrations could be determined between a period under confinement measures and another equivalent confinement-free period. To strengthen this limitation of the TROPOMI Sentinel-5P data, a time series analysis of the tropospheric NO_2 was performed based on satellite data (**Fig. 5**). In addition, it is beyond the scope of this study to address the relationship between the emission of nighttime lights and the change in the concentration of other types of pollutant gases due to containment actions. In this direction, future research is needed to analyze air quality (AQ) as a whole.

6. CONCLUSIONS

Since the effect of total and partial confinements have so far demonstrated the importance of human involvement in the change of air pollution, it becomes important to understand the contribution of anthropogenic processes to these dynamics. Analyzing a period of COVID-19 confinement, this study investigated the connection between the emission of nighttime lights and the relative change of near-surface NO_2 concentration. The investigation focused on Metropolitan France. The results of the analysis revealed a broad phenomenon of decreasing NO_2 concentrations in the country. In addition, the geospatial correlation analysis showed that the higher the observed DNB nighttime light emission, the higher the NO_2 reduction during the April 2020 confinement in the administrative-territorial units of France. This demonstrates that utilizing remote sensing techniques, DNB nighttime lights can explain the change in NO_2 air pollution over large territories.

In the context of other lockdowns or similar regulatory measures, future research on the remotely sensed nighttime lights and air pollution change should be aimed at improving our understanding of the behavior of other gases or particulate matter (PM).

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