Spatio-temporal analysis of Tropospheric NO_2 Pollution during the COVID-19 Pandemic Lockdowns

(Master Thesis)

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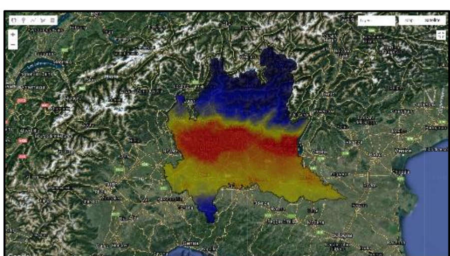

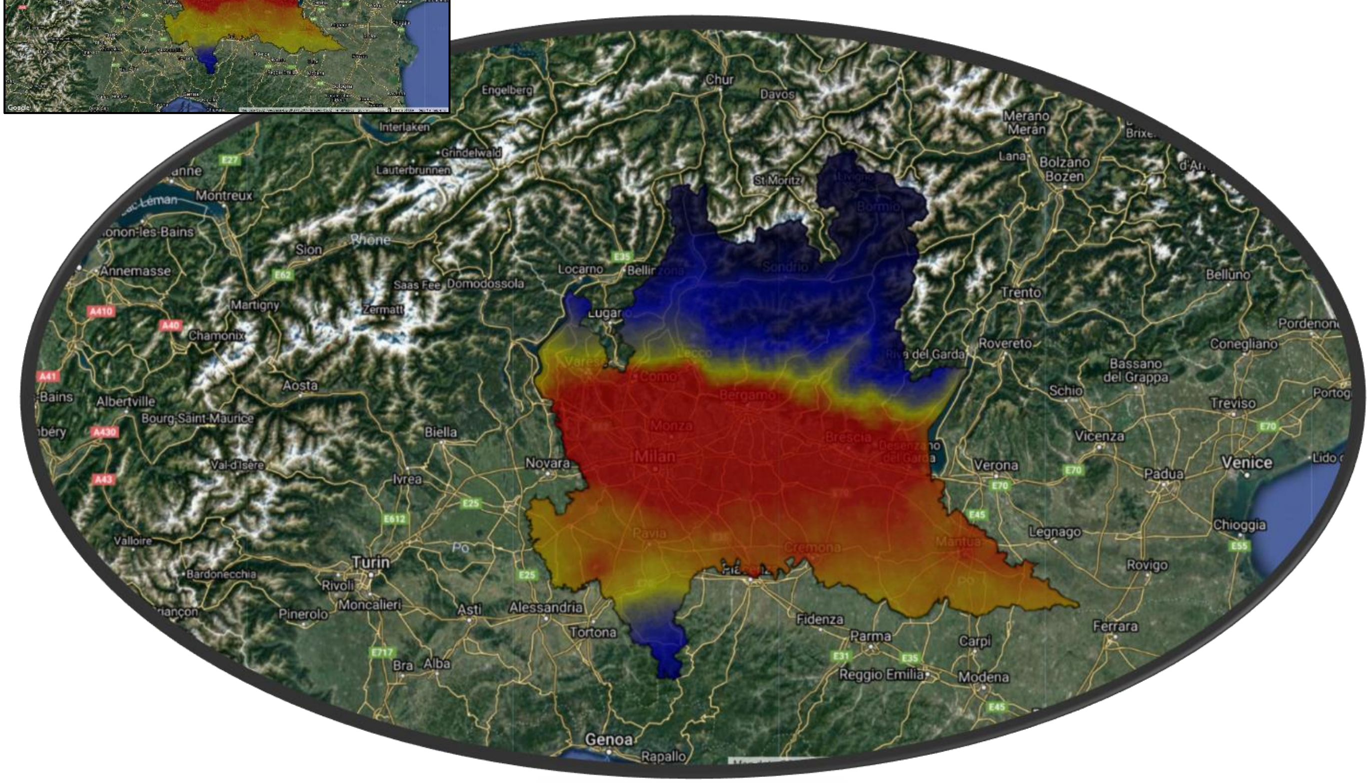

Abstract

Covid-19 pandemic forced many countries to impose nationwide lockdown to control the infection rate, and as part of lockdown measures, people mobility and economic activities got restricted. Amongst all the damage caused by lockdown measures, conversely, it improved the air quality, and a major reduction was observed in NO_2 concentration which was directly linked to anthropogenic activities. This study aims to selectively assess the reduction of NO_2 concentration around Europe and make a comparative analysis between satellite sensor data as well as ground station measurements on a Spatio-temporal scale, between two sets of similar periods from 2019 and 2020 (lockdown and post-lockdown phases). 15 regions that emerged as hotspots in 2019 Sentinel-5P Tropospheric NO_2 column number density imagery was selected to investigate in 2020 if air quality has improved due to lockdown. The study results confirmed that, in the Lockdown phase, the ITC4 region achieved 51% of NO_2 reduction followed by 39% in FR1, 37% in the ES30 region and 34% in the UKI region, whereas in the Post-Lockdown Phase under lockdown easing measures the NO_2 level began turning up again, however, when compared to the NO_2 concentration of 2019, UKI gained 33% reduction followed by 22% in NL32, 18% in the UKD and 17% in BE2, overall the air quality improved due to lockdown measures which may have linked to restricted traffic and economic practices. Despite the considerable reduction in NO_2 concentration, there is a need to look at associated pollutants and other meteorological factors which could have influenced, the study concluded that this air quality improvement is temporary and for an everlasting solution, policies towards environmental protection need to be evaluated which requires sustainable approaches and strict actions.

Keywords: Covid-19 Lockdown, Sentinel-5P, Google Earth Engine, NO_2, Air Quality

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List of Acronyms

AQI-Air Quality Index

API-Application Programming Interface

EO-Earth Observation

ESA- European Space Agency

EU- European Union

GIS- Geographic Information System

GEE-Google Earth Engine

IDE-Interactive Development Environment

IDW-Inverse Distance Weighting

LD-Lockdown Period LD

NSO-Netherland Space Office

NOAA- National Oceanic and Atmospheric Administration

NC-Normal Condition period

PM-Particulate Matters

PLD-Post lockdown period

PNC-Post-Normal Conditions period

SWIR-Short Wave Infra-Red

UV-Ultraviolet

WHO-World Health Organization

1.Introduction:

Covid-19 which was declared as a pandemic on 11th March 2020 by World Health Organization (WHO) forced many countries around the globe to impose a national lockdown to curtail the infection rate among their people [1]. As part of lockdown measures, many production and consumption activities were significantly reduced, people mobility was restricted, along with many small businesses; transport, industrial and construction sectors were badly affected [2], [3]. Among all the havoc caused by the Covid-19 pandemic lockdown on the social and economic well beings of the people, it has also brought some positive effects in improving the air quality under strict lockdown conditions and the differences were prominent in those areas which were previously known for their worst air quality level e.g., heavily industrialized cities of China [4]. Lockdown turned out to be an environmental experiment on a global scale that how quickly the air quality can be improved by minimizing the anthropogenic sources of pollution e.g., road transport, industrial combustion and powerhouses [5], [6].

According to WHO around 7 million people die on yearly basis due to prolonged exposure to pollutants in the atmosphere and air pollution is considered a silent killer which causes heart diseases, lungs and respiratory diseases and cancer [7]. Due to lockdown measures, human activity was significantly reduced which showed a reduction in air pollution associated with anthropogenic sources, especially NO2 which is linked to human activities [8], [9]. Several studies have highlighted the importance of estimating the NO_2 level in the atmosphere due to its ability to generate Particulate matters (PM2.5) and Ozone (O_3) and its correlation to road transport and combustion sources [10], [11]. The main source of NO_2 emission in Europe is road transport, consequently under strict lockdown road transport was decreased which researchers find an opportunity to evaluate the improvement in air quality based on NO_2 level in the cities [11].

Atmospheric pollutants data can be derived from ground-based stations and satellite measurements; ground stations provide NO_2 measurements at the local level but lack spatial coverage which could carry uncertainties, while satellite-based remote sensing provides NO_2

data at the global scale to evaluate the NO_2 concentrations with reliable Spatio-temporal coverage [9], [12]. In the past, OMI, MODIS, and MIR satellite sensors were used by many researchers to measure NO_2 pollution, but since October 2017 Sentinel 5P mission by the ESA Copernicus program has transformed the air quality monitoring data collection and its TROPOMI sensor data are already assessed by many studies concerning earth observation [13].

A covid-19 crisis with restricted human activity, limited transportation and economic growth could have prevented the further escalation of NO_2 pollution level in the atmosphere around us and the provision of earth observation data through the Sentinel-5P TROPOMI sensor led us to formulate the thesis project idea whether and to which degree we can observe, monitor, collect and analyse Spatio-temporal distribution of Tropospheric NO_2 data. TROPOMI sensor with Tropospheric NO_2 column number density data indicates traffic, industrial combustion and powerhouses emissions which could help to map Spatio-temporal changes in lockdown and post-lockdown period and modern tools like Google Earth Engine (GEE) makes the analysis much convenient at one platform [13], [14]. These assumptions guided us to define the main objectives and research question of this thesis project.

1.1 Problem Statement and research questions

There have been speculations as to how the lockdowns arising from the COVID-19 pandemic contributed to reducing air pollution and experiencing cleaner air. However, the main question remains unanswered whether there was less polluted air in those periods and if so, whether the difference was significant or small.

The purpose of this study is to look at Sentinel-5P TROPOMI data to monitor air pollution through the Tropospheric NO_2 level. Our objective in this study is to build a comparative analysis of Tropospheric NO_2 column number density based on the TROPOMI data between two sets of similar periods from 2019 and 2020 (lockdown (Phase1) and post-lockdown (Phase2)).

The hotspot regions based on the higher level of Tropospheric NO_2 concentration in 2019 (normal conditions) will be identified and analysed with a possibility of clean air due to lockdown and post lockdown periods. Moreover, the Covid-19 lockdown may have provided some positive environmental effects due to the limitation of traffic and economic practices. To evaluate the effect of lockdown on our atmosphere, the air pollution concerning Tropospheric NO_2 concentration will be estimated on a Spatio-temporal scale through satellite sensor data as well as ground station measurements.

Research Questions

During the study, the following Research Questions will be answered:

- What was the impact of the Covid-19 Pandemic lockdowns on the air quality using space-based and terrestrial observations when comparing these observations in pre-phase and post-phase of lockdowns?
- How useful is the Sentinel-5P TROPOMI data gathered by Google Earth Engine (GEE), for air quality monitoring compared to ground-based observations at a regional scale analysis?
- Does society need a lockdown or sustainable approaches to deal with the challenges of air pollution from anthropogenic sources in the big cities?

The thesis is structured as follows: firstly, literature focused on the research topic is described. Secondly, the data collection, processing and the overall approach adopted to achieve the project objective will be written and explained. Results and discussion will be followed by a conclusion with an emphasis if all the research questions are answered.

1.2 State of the art

Air quality changes in the Covid-19 lockdown grab the researcher's attention around the world in the early quarter of 2020, and since then lots of research studies emphasized evaluating the Air quality based on NO_2 concentrations variations with a comparative analysis of the lockdown period (2020) and normal conditions (2019) and they adopted different methodologies to report the matter. Some of the existing research on NO_2 concentration measurements during Covid-19 lockdown are listed below:

Table 1. Existing Research Studies on NO2 reduction due to Covid-19 lockdown [15]

Research studies	Study area	Data	Methodology	Findings
[11]	Milan, Paris, London	Mobility, traffic, meteorology, and air quality ground data	Descriptive and quantitative analysis	London: 71.1-80.8 % Milan: 8.6 - 42.4 % Paris: 65.7 - 79.8 % reduction in NO_2
[16]	Global (187 countries)	Sentinel 5P TROPOMI dataset, World air quality index ground measurements, covid-19 data	Machine learning, descriptive and quantitative analysis	A decline in NO_2 is associated with international travel restriction, not public transport
[6]	Barcelona and Madrid	Air quality ground observation data from 33 ground stations.	Images and descriptive analysis	Madrid and Barcelona showed a 62% and 50% reduction in NO_2 concentration, respectively.
[9]	Paris, Milan, Madrid, and Athens	Sentinel 5P dataset TROPOMI dataset, ground sensor measurements, CAMS data	Descriptive, quantitative, and empirical analysis,	Reduction of NO_2 was observed but other factors must be considered to support the findings
[12]	India	NASA Aura satellite OMI sensor, Visible Infrared Imaging Radiometer Suite data	Images and descriptive analysis	12.7-15.9% reduction in NO_2 concentration during the lockdown.
[13]	Europe	Sentinel 5P dataset TROPOMI dataset, ground-based measurements, economic and air traffic data,	Images, descriptive and quantitative and empirical analysis	Up to 85% NO_2 reduction in lockdown at a certain time
[10]	Ecuador	Sentinel 5P dataset TROPOMI dataset,	Images and descriptive analysis	22.4-35% NO_2 reduction in various cities of Ecuador
[17]	Global	World Air Quality Index (WAQI) data	Images and descriptive analysis	Overall, 42.5% NO_2 reduction over Europe and 33.3-103.5% globally.
[18]	Global (20 cities)	Sentinel 5P dataset TROPOMI dataset, Ground monitored air quality data, Mobility data.	Images, descriptive and quantitative analysis	NO_2 reduction was correlated with a decline in traffic volume, up to 60% reduction was seen in different cities.
[19]	Munich, Germany	Ground-based monitoring stations, temperature, rain, wind speed, humidity, and air-pressure data.	Descriptive, empirical, and quantitative analysis.	24-36% reduction of NO_2 concentration at traffic sites and 15-25% at other places.

Many of the above-mentioned studies are based on a common idea where the emphasis is on examining the effects of the Covid-19 lockdown on the air quality concerning NO_2 concentration in the atmosphere and addressing the issue with different approaches to open new avenues for further development and research.

2. Background and Theory

2.1 COVID-19 and Air Quality around Europe

2.1.1 COVID-19 and Lockdown measures

Coronavirus (Covid-19) which is known to the world since December 2019 proved to be an infectious disease that has taken 3,277,272 lives and infected 157,289,118 people so far around the world [20]. On 24th January 2020, Europe reported its first Covid-19 case in France followed by Germany and later on 22nd February 2020 Italy reported clusters of Covid-19 cased in many regions subsequently cases spread rapidly around the whole of Europe [21]. It was confirmed that Covid-19 spread due to close human interactions and through respiratory droplets, which make it inevitable to impose restrictions on human mobility to contain the further spread of Covid-19 [4].

As a preventive measure against the spread of Covid-19 countries started imposing restrictions on human mobility and declared nationwide lockdowns. Social distancing was proposed as the most effective approach in reducing the infection rate among people and to abide by this people were forced to work from home to reduce interactions with people and gatherings [22]. Countries shut down industrial activities, halted road and air travel and most of the anthropogenic activities were stopped as a lockdown measure, the industrial manufacturing and transport sector were gravely affected which impacted the world economy [23]. Lockdown measures proved to be detrimental to industrial production because of reduced demand for some products but some industries were experiencing high demand e.g. household items, the overall global economy experienced a downfall [24].

Covid-19 lockdown set off a negative impact on the social well-being of the people and the economic development while on the other hand, it has cleaned the environment where we breathe due to a reduction in many anthropogenic emissions [10], [22]. The environmental aspect of the Covid-19 spread shows a strong connection to temperature, humidity, wind and sunlight because of its ability to survive in aerosols for hours so air pollution could also be a contributing factor [25]. Many studies have established that improved air quality is linked to reduced anthropogenic activities and temporary suspension of human mobility not only helped to minimize Covid-19 infection rate but on the other hand, support to combat air pollution [26–28].

2.1.2 Air Quality and EU standards

Clean Air is inevitable for human existence and the environment, to determine the purity of the air we breathe, air quality standards are suggested to keep track of the severity of pollutants in our surroundings [29]. Air quality standards regulate the air pollutants level in the atmosphere and based on that a recommended action can be taken concerning human health [30]. Air quality in the EU is estimated based on five pollutants data e.g., NO_2, O_3, SO_2 PM_{10} and $PM_{2.5}$ on an hourly basis from almost 2000 ground monitoring stations around Europe concentration levels higher than recommended could affect human health and the environment [31]. Under EU Directive 2008/50/EU for ambient air pollution adopted by all member states, there is a legal binding to follow the recommended level of NO_2, take all the necessary measures or prepare an air quality plan in case of higher concentration level recorded for any of the above mentioned five pollutants, measurements have to recorded on zonal and agglomeration basis divided by the member states per territory [32]. Spatial and pollutant information from these monitoring stations is updated on a timely basis in the European air quality database [33].

2.1.3 NO_2

NO_2 is a trace gas that absorbs solar radiations and distorts atmospheric visibility which could have an important role in climate change if its concentration level in the atmosphere exceeds the recommended value [34]. The transportation sector and powerhouses are two main anthropogenic emission sources of NO_2 where fossil fuel is burnt [35]. NO_2 is considered harmful for human health and the environment and recommended by WHO to be monitored on a routine basis, especially in the Covid-19 crisis as of its nature to increase the risks of viral infections [36]. The recommended NO_2 concentrations by EU and WHO is 200µg/m^3 for hourly observations while the annual recommended level is 40µg/m^3 [37]. In 2019 twelve EU member states reported the NO_2 concentrations above the recommended level which were mainly from the traffic stations observations, therefore the main focus of EU policies are urban areas and traffic control and shift to electric vehicles to minimize citizens exposure to NO_2 and

CO_2 [37], [38]. Several studies predicted an improvement in air quality under restricted mobility and the air quality was mainly liked to the NO_2 sources because of its ability to disintegrate into Ozone (O_3) and Particulate Matters (PM) [4], [35], [39]. The unexpected improvement in air quality during lockdown due to reduced fossil fuel emission allow us to assess the future policies required to convert this temporary air quality gain into a long-lasting solution [6].

2.2 Atmosphere and Remote Sensing

Satellite remote sensing is proving to be a helpful tool in the provision of air quality and climate data with high temporal and spatial resolution, which provide global coverage in a single image [40], [41]. To keep track of atmospheric parameters like temperature. wind, pressure, clouds, greenhouse gases and trace gases etc. play an important role in understanding the overall atmosphere around us due to the interactive ability of all these parameters with each other and the data is available through satellite, airborne or ground-based stations [42]. Ground stations are situated far from each other even though they cover a wide range of area with more accurate results but the observations are not spatially aligned [41], [43]. To monitor air pollutants in the atmosphere, earth observations gained importance in the early 1960 and currently, satellite observations with high spatial and temporal resolution allow meteorologists to access the atmospheric data through geostationary and polar-orbiting based satellite sensors [40], [44].

Satellite data helped the concerning bodies to validate the results obtained from the ground sensors to maintain the accuracy of predicted values concerning air pollutants concentrations with the help of GIS techniques to analyse the air quality [40]. Satellite sensor estimations are more reliable under extreme events because of their ability to track smoke transportation over a global scale which is crucial under ambient air quality assessment and developing global or regional models [45]. A range of satellite sensors are used around the world for measuring air pollutants directly or indirectly in the atmosphere; OMI instrument of AURA satellite, GOME on ERS-2, SCIAMACHY on Envisat, MOPITT sensor of NASA's Terra satellite, Hyperspectral thermal emission spectrometer of NASA's Aqua satellite, GOES sensor from NOAA and among the latest is TROPOMI sensor of ESA's Sentinel-5P satellite [46].

2.2.1 NO_2 pollution level monitoring from space

NO_2 is a critical constituent of urban air pollution which originate mainly from anthropogenic sources and the transportation sector is the main perpetrator behind its emission and apart from ground level monitoring, satellite sensor monitoring is gaining importance since its ability to provide coverage on a global scale and to keep track the level of other pollutants like ozone (O_3)and particulate matter (PM) in connection with NO_2 [47]. ESA's Envisat observations through Scanning Imaging Absorption Spectrometer for Atmospheric Chartography (SCIAMACHY) sensor proved back in 2002 that how human activities are contributing to poor air quality through NO_2 measurements over Europe for a certain period, areas with insufficient ground measurements, satellite sensor measurements were an effective approach to perform analysis on a global scale [48]. During the recent Covid-19 pandemic lockdown when human activities were minimized, estimating air quality through satellite-based NO_2 measurements could elaborate further the role space monitoring could have in policymaking to highlight the potential NO_2 derived hotspots in Europe with Sentinel-5P TROPOMI sensor which is the latest addition by European Space Agency (ESA) in air pollutants monitoring.

2.2.2 Sentinel-5P

The Copernicus Sentinel-5P mission which carries the TROPOMI sensor is a collaborative mission by European Space Agency (ESA), Netherland Space Office (NSO) and scientists launched on 13th October 2017, where the major purpose is to monitor the atmospheric compositions and provide data with high Spatio-temporal resolution [49].

The Sentinel-5P mission is a single payload satellite with a TROPOMI sensor and equipped with four bands covering Ultra Violet (UV) to Short Wave Infra-Red (SWIR) as detailed in Figure-1, 824km high and can measure air pollutants like NO_2, O_3, SO_2 and aerosols level in the atmosphere[50]. Sentinel-5P has global coverage with a revisit time of 24 hours, swath width is 2600km and spatial resolution is up to $7x7km^2$ [51], [52].

TROPOMI	UV		UVIS		NIR		SWIR	
Band	1	2	3	4	5	6	7	8
Spectral coverage [nm]	270 – 320		320 – 495		675 - 775		2305 – 2385	
Full spectral coverage [nm]	267 - 332		303 - 499		660 - 784		2299 - 2390	
Spectral resolution [nm]	0.49		0.54		0.38		0.25	
Spectral sampling ratio	6.7		2.5		2.8		2.5	
Spatial sampling [km^2]	7 x 28	7 x 3.5				7 x 3.5	7 x 7	

Figure 1- Overview of Sentinel-5P Bands[53]

Sentinel-5P products are available in three levels: level-0 products are raw products for on-ground processing and tasks which are not provided to the public, level-1B are geo-referenced and corrected while level-2 products contain all air pollutants columns and their vertical profiles with cloud information, both level-1B and level-2 products can be assessed through Copernicus Open Access Hub [54].

Sentinel-5P data is available in both offline (OFFL) or near-real-time (NRTI), offline is preferred over near-real-time due to its continued availability and quality even though near-real-time data is available in 3hours after sensing [9]. Sentinel-5P Tropospheric NO_2 column number density offline data from the TROPOMI sensor is used for this study because data is freely and easily available in the designated period of Covid-19 lockdown and post-lockdown period for the year 2020 in comparison with the same timeframe for the year 2019 under normal conditions.

2.3 Spatio-temporal dynamics and variations

It has been evident that air pollution is not confined to one place and individual, it is dynamic and each individual is exposed to it at a certain level, which highlights the importance to study the air pollutant concentration variation spatially without borders and temporally with an extended time frame under the range of variables which can influence the pollutants behaviour [55], [56]. The Spatio-temporal variation of NO_2 concentration is a measure of NO_2 concentrations which is geo-referenced and recorded at a certain time, GIS-based analysis where real-time data is captured with space and time characteristics is considered Spatio-temporal analysis [57].

Road transport which is the main contributor of NO_2 pollution in the urban areas, their emission concentration in busy spells of the day can be moved further and changed under various factors, dense urban areas could restrict these pollutant concentrations within the small area while open spaces could disperse it more, consequently ground monitoring stations does not capture the Spatio-temporal variation of pollutant from a local source[56]. Spatial and temporal variation of NO_2 over Europe is investigated in this study during 2019-2020 normal conditions, Covid-19 pandemic lockdown and post lockdown periods to analyse the air quality using satellite-based earth observation data with global coverage.

2.4 Google Earth Engine (GEE)

Google Earth Engine (GEE) is a cloud computing platform which assesses, store and analyse data from several satellites e.g. Sentinel, Landsat, MODIS etc, collection contain Climate, Atmosphere, Surface Temperature, Landcover, Terrain, Cropland and other geophysical datasets which is openly and freely available [14], [58].

GEE which was launched by Google in 2010 reduced the burden on researchers to store a bulk of big data files locally and additionally, it also helped the users to save time in data pre-processing and formatting with an advantage to assess Earth Observation (EO) data through the web-based Interactive Development Environment (IDE) and internet-based Application Programming Interface (API) available in both Python and JavaScript [14], [59].

Earth Engine Code Editor, Earth Engine (EE) Explore and Earth Engine Time-lapse is are the main components of Google Earth Engine (GEE) web-based IDE which makes it easy for the users to assess, store and analyse the satellite imagery [60].

Earth Engine Explorer accommodate the user to manage and visualize the available datasets from several satellites while Earth Engine Time-lapse help to combine four-decades-old data available to visualize how the earth has changed over time[14].

GEE can process large geospatial datasets with global coverage and desired images can be sorted or filtered using spatial and temporal settings without a need to download a large number of images, additionally, a variety of processing techniques or spatial algorithms can be implemented on data through code editor [14], [61], [62].

The availability of Sentinel-5P data at the GEE platform which is specifically used to investigate the air pollutants in the atmosphere gaining the researcher's interest to use GEE for air monitoring and climatic studies where Spatio-temporal variation of pollutants can be tracked at the global scale with pre-processed and openly available data [63], [64].

This study adopted the GEE platform to access sentinel-5P data and perform analysis to track Spatio-temporal variation of NO_2 during Covid-19 pandemic lockdown using data between 2019-2020.

3. Data Collection and Methodology

3.1 Regions and selected periods

Most previous studies have pre-defined the study areas and then performed the analysis to identify the effect of lockdown on air quality in those pre-selected areas, but in this study, areas with higher NO_2 concentration levels monitored by Sentinel 5P in 2019 are determined and analysis is performed at regional basis instead of city levels, which makes this study distinct from other Covid-19 lockdown related air quality studies by many researchers. All member states in European Union are divided into regions based on the NUTS classification, and it is believed that regional data is more reliable and significant when comes to comparing the regional statistics [65]. This study was conducted over Europe, which was severely affected by the Covid-19 pandemic, 15 regions that host some of the major cities of central Europe were selected for the analysis based on Sentinel-5P Tropospheric NO_2 column number density data collected daily for the period January-December 2019 as shown in the figure below:

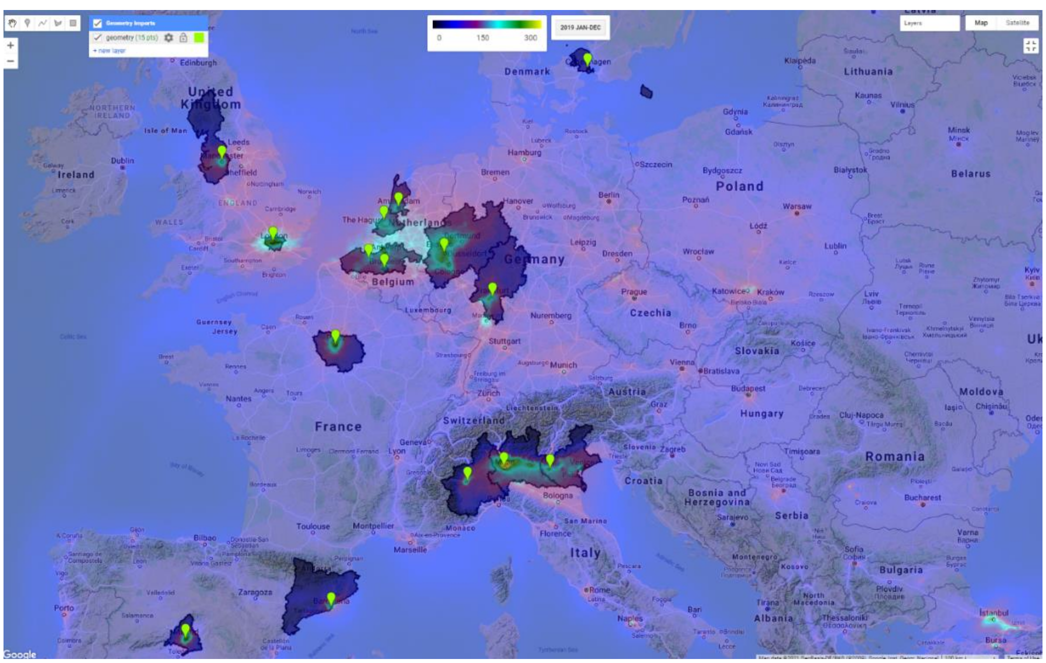


Figure 2- Regions identified by Sentinel-5P image collections with higher Tropospheric NO2 column number density and filtered date is January 2019 to December 2019.

Regions with their countries and NUTS codes as specified by NUTS classification 2016 and chosen for this study are listed below:

Table 2- Regions covering the big cities of EU member states and their NUTS classification codes *[66]*

CNTR_CODE	ECDC_NUTS	CNTR_NAME	REG_NAME	Major Cities in the region
BE	BE1	Belgium	Region De Bruxelles-Capitale Brussels Hoofdstede	Brussels
BE	BE2	Belgium	Vlaams Gewest	Antwerp, Ghent
ES	ES30	Spain	Comunidad De Madrid	Madrid
ES	ES51	Spain	Cataluna	Barcelona
FR	FR1	France	Ile de France	Paris
DK	DK01	Denmark	Hovedstaden	Copenhagen
NL	NL32	Netherlands	Noord-Holland	Amsterdam
NL	NL33	Netherlands	Zuid-Holland	The Hague, Rotterdam
IT	ITC1	Italy	Piemonte	Turin
IT	ITH3	Italy	Veneto	Verona
IT	ITC4	Italy	Lombardia	Milan
DE	DEA	Germany	Nordrhein-Westfalen	Dusseldorf, Duisburg
DE	DE7	Germany	Hessen	Frankfurt
UK	UKI	United Kingdom	London	London
UK	UKD	United Kingdom	Northwest (England)	Manchester

ECDC_NUTS codes were used throughout the study to differentiate among regions for analysis. To identify the effect of lockdown in each region, a certain lockdown period imposed in that region at the national level is considered. After a sharp surge of Covid-19 pandemic cases around Europe, each EU member state took a precautionary measure and announced a nationwide lockdown to mitigate the spread of Coronavirus and protect its citizens. These nationwide lockdown days differ in each EU member state depending on the severity of the pandemic. Instead of working on one single lockdown period for all regions, this study has considered the region's lockdown phase based on nationwide lockdown measures implemented by the EU member states separately which is illustrated in the table below:

Table 3 Lockdown periods as announced by EU member states.

Country {ECDC NUTS CODE}	**Phase-1**		**Phase-2**		Total lockdown days	Source
	Normal-Conditions (NC) (2019)	Lockdown (LD) (2020)	Post-Normal Conditions (PNC) (2019)	Post-Lockdown (PLD) (2020)		
Belgium {BE1, BE2}	18/03-11/05	18/03-11/05	12/05-05/07	12/05-05/07	55	[67], [68]
Spain {ES30, ES51}	14/03-20/06	14/03-20/06	21/06-26/09	21/06-26/09	98	[69]
France {FR1}	17/03-11/05	17/03-11/05	12/05-06/07	12/05-06/07	56	[69]
Denmark {DK01}	17/03-20/04	17/03-20/04	21/04-25/05	21/04-25/05	35	[70], [71]
Italy {ITC1, ITC4, ITH3}	08/03-04/05	08/03-04/05	05/05-01/07	05/05-01/07	58	[72], [69]
Germany {DEA, DE7}	19/03-03/05	19/03-03/05	04/05-18/06	04/05-18/06	46	[73], [74]
Netherland {NL32, NL33}	15/03-12/05	15/03-12/05	13/05-10/07	13/05-10/07	59	[75], [69]
United Kingdom {UKI, UKD}	23/03-10/05	23/03-10/05	11/05-28/06	11/05-28/06	49	[67]

To assess the gradual shift from lockdown to restricted normal condition, the post lockdown period (PLD) with the same number of lockdown days were chosen after the lockdown period (LD) ends. Analysis was divided into two phases; In the first phase, regional mean NO_2 concentrations estimated for the Normal Condition period (NC) were compared with Lockdown Period (LD) while in the second phase Post-Normal Conditions period (PNC) with Post-Lockdown period (PLD) to identify the Spatio-temporal air quality variations.

3.2 Tropospheric NO_2 Satellite data

The Tropospheric NO2 column number density data were collected from the Sentinel-5P TROPOMI sensor through the Google Earth Engine (GEE) platform. Sentinel-5P TROPOMI sensor is one of the mission by ESA among various satellite sensors that are intended to monitor air and climatic changes, TROPOMI data is accessible through Copernicus Open Access Hub in either Level-1 or Level-2 which is not compatible with Google Earth Engine (GEE) for analysis, therefore GEE converts Offline-L2 products into OFFL/L3_NO2 through the harp convert command-line tool which remove pixels with Quality Assurance (QA) value less than 75% and provide high-resolution Tropospheric NO_2 column number density imagery [76], [77]. In this study, the Spatio-temporal variation of NO_2 was assessed and analysed using Google Earth Engine (GEE) and the required data for each region was retrieved through Code Editor, which allowed us to select the tropospheric_NO_2_column_number_density band with a chosen filtered date of LD and PLD phases of the year 2020 and similar NC, PNC phases of the year 2019. Tropospheric NO_2 column number density data were collected daily and was clipped to the areas of interest (selected regions from section 3.1), more than 778 elements of mosaiced Tropospheric NO_2 column number density images were generated in the lockdown periods and post-lockdown period (2019-2020) separately for each area of interest and time-series charts were prepared for spatial visualization [16].

3.3 Ground Measurements Data

To estimate the air quality at the city-scale NO2 concentrations were retrieved from ground stations on an hourly and daily basis, European air quality data specifically for NO_2 emissions were collected from European Environment Agency Air Quality Portal [78]. The latest NO_2 air quality data was collected for the year 2019-2020 in connection with Covid-19 lockdown, available ground station data covered most of the big cities which were analysed through satellite observations at the regional scale, ground data time-series and metadata files were joined using sampling point and country code to estimate the air quality at the Spatio-temporal scale [79]. Data collected from 129 ground station in specified regions for the year 2019-2020 are listed below:

Table 4- Ground data stations for each region covering major cities.

Country	Cities monitored	Regions	Number of ground stations
Belgium	Brussels	BE1	10
Belgium	Antwerp, Ghent	BE2	8
Spain	Madrid	ES30	19
Spain	Barcelona	ES51	19
France	Paris	FR1	13
Denmark	Copenhagen	DK01	4
Italy	Turin, Milan, Verona	ITC1, ITC4, ITH3	20
Germany	Dusseldorf, Duisburg	DEA	11
Germany	Frankfurt	DE7	4
Netherland	Amsterdam, The Hague, Rotterdam	NL32, NL33	20
United Kingdom	London	UKI	9
United Kingdom	Manchester	UKD	6

In some countries such as Italy and Netherland, the data was not available for each specific city, so the regions are combined to get an insight of overall air quality in those regions.

3.4 Methodology

The entire process is divided into two types of analysis; Satellite-based analysis to cover regions and ground-station based analysis for cities and some combined regions (due to limited city-specific data as shown in Table-4). A schematic diagram of the whole methodology adopted for this study to answer some of the key research questions raised in section 1.1 is illustrated below:

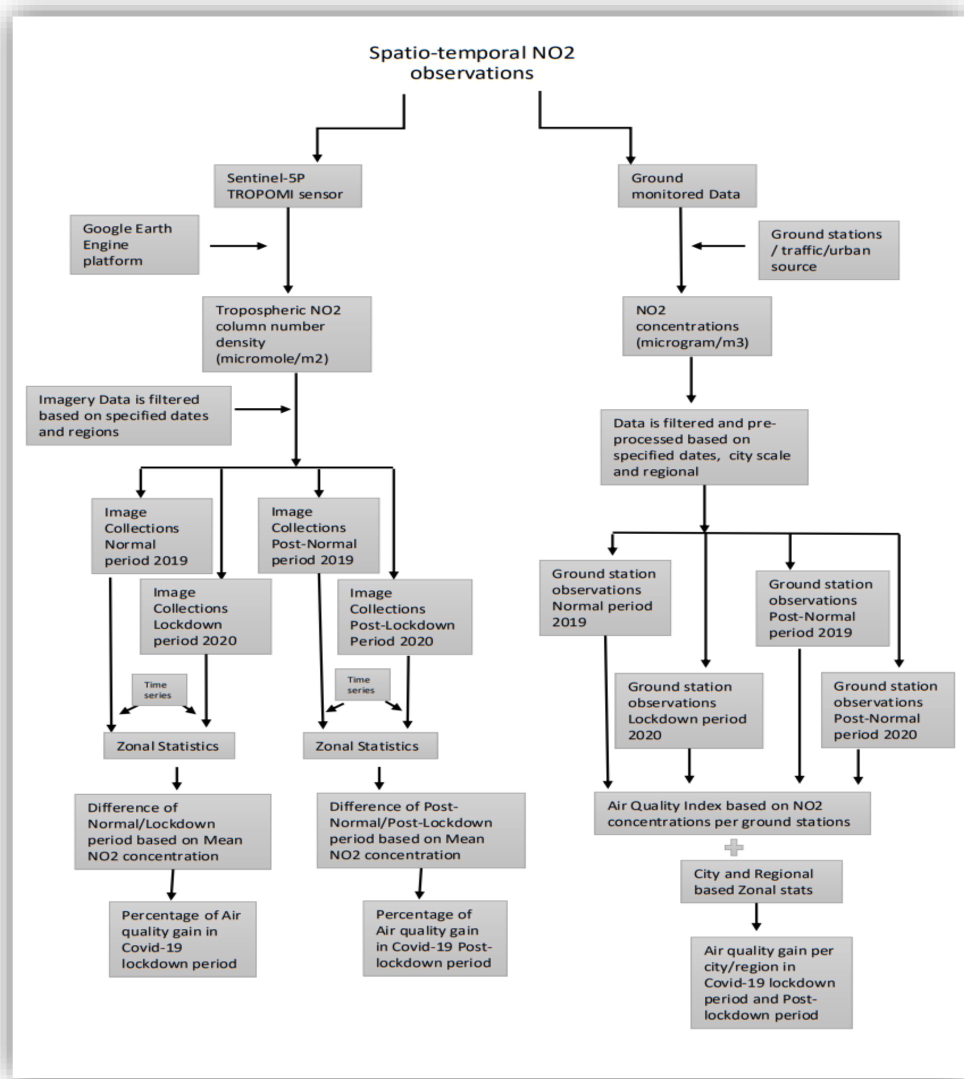


Figure 3 A schematic diagram of the methodology adopted for this study.

3.4.1 Tropospheric NO_2 pollution estimation and analysis through Google Earth Engine

To determine the Spatio-temporal air quality variation based on NO_2 concentrations due to Covid-19 pandemic lockdown, two types of approaches were employed as shown in the figure-4 above. In satellite-based analysis, Sentinel-5P TROPOMI sensor data for Tropospheric NO_2 column number density band were collected within four time periods (Table

3) for each region (Table 2) separately. Code Editor which is a web-based IDE of Google Earth Engine (GEE) was chosen for the TROPOMI data collection, visualization, and assessment.

The Earth Engine Code Editor allows the user to store, manage, edit and analysed the datasets through JavaScript programming language, data can be processed in a fast and effective way on one platform [80]. Code editor composed of many elements which are shown in the figure below:

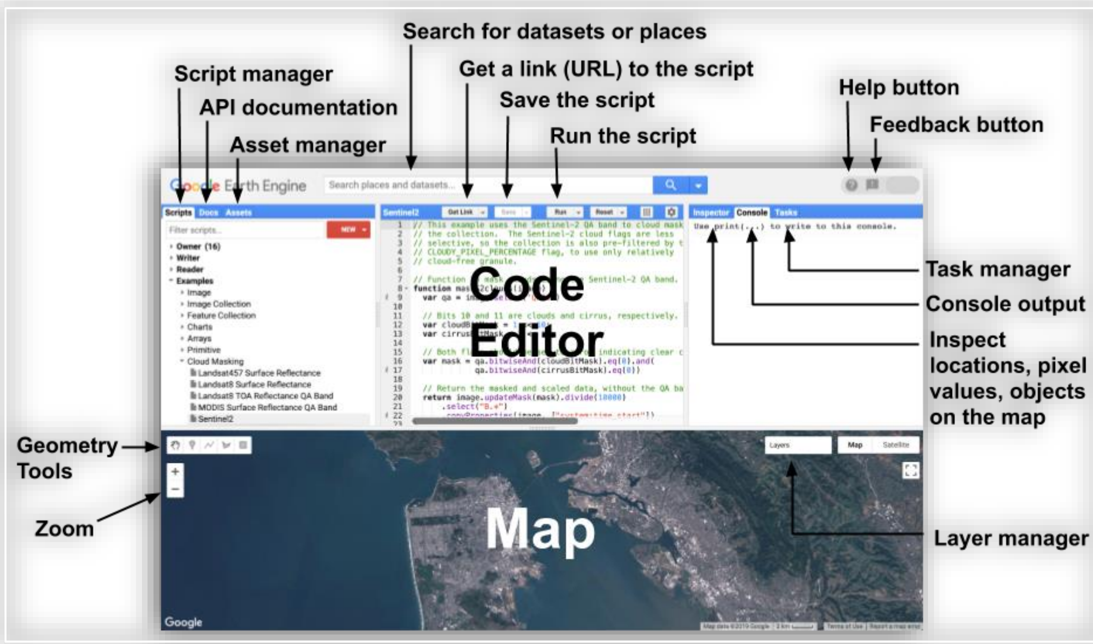


Figure 4- Earth Engine Code Editor elements illustration *[80]*

Code Editor allows the user to perform various algorithms and mathematical functions on the dataset by running a script which is then visualized in the form of Map, data in graphic forms appear in Console output which can be exported to drive or as an Asset for further analysis[80].

To proceed with the Sentinel-5P TROPOMI data collection (listed in Appendix 7.1), firstly, the area of interest (AOI) was defined based on regions (table-3), regional data shapefile was saved to the GEE Assets as a FeatureCollection and assessed using ***ee.FeatureCollection()*** tool from GEE Docs, feature selection was made using the ***collection.clip()*** function to set the geometry of analysis limited to the area of interest (AOI) layer which was added to the map for visualization.

In the second step of data collection, the date of interest (DOI) was selected using ***ee.Date()*** tool, DOI could be e.g., 1st day of lockdown in chosen AOI, Sentinel-5P offline level-3 NO_2 data with tropospheric_NO_2_column_number_density band was assessed using ***ee.ImageCollection()*** tool and collection were filtered using ***DOI.advance()*** function with the total number of lockdown days as mentioned in table-3, the number of images mosaicked through desired selection can be printed in the console which in most AOI's were around 778 elements. For better visualization of NO2 column number density and numerical analysis, the unit was converted from mole/m^2 to µmol/m^2 by multiplying the image with 10^6 using an ***image.multiply()*** function. The mosaicked image from ImageCollection can be added as a layer to the map along with visualization parameters. Visualization parameters include; opacity, min, max and colour palettes which can be set as required, to enhance the visual representation, cartographic effects and help to visualize single band image into colours[81].

All the statistical analysis functions in GEE are available in ***ee.Reduce()*** tools section under GEE Docs, ***Image.reduceRegion()*** function was performed on the ImageCollection using distinct categories of ***Reducers*** to calculate mean, median, min, max, standard deviation, and histogram, which were utilized for further analysis. Mean values of Tropospheric NO_2 column number density for each period and region (as mentioned in Table-3) were compared to evaluate the air quality gain based on NO_2 during Covid-19 lockdown and post-lockdown periods (2019-2020). Time-series for filter dates and regions were created with the help of ***ui.Chart.image.doySeriesByYear()*** tool and printed to console which were saved as CSV file individually and afterwards combined for graphical analysis among 2019 and 2020, normal and lockdown conditions. To make this Google Earth Engine data accessible through QGIS for computation of image differences and evaluate the emerging hotspots, Google Earth Engine python APIs were used in Jupyter Notebook and with the support of some codes (listed in Appendix 7.2)) and ***ee.batch.Export.image.toDrive*** tool all the required images were stored for further analysis on other platforms. Google Earth Engine allows to ***Export*** an image but a mosaic of ***ImageCollection*** must be exported using the batch tool available in Python [82].

3.4.2 NO_2 pollution estimation and analysis through Ground stations

Ground station air pollution data for NO_2 concentrations were collected through European Environment Agency (EEA) and the air pollutant data was primarily from the ground stations which were exclusively monitoring Traffic and Urban sources due to their highest contribution in increasing NO_2 level. Ground station data was retrieved for the entire year but divided into the required time frames to cover the NC, PNC, LD and PLD periods (Table-3) for each region. The time series (2019-2020), air quality index (AQI) of each ground station associated with the study regions were generated and AQI values were distributed into six levels as indicated by European Environment Agency as shown in the table below for NO_2 concentration in $\mu g/m^3$ [83]:

Table 5- Air Quality Index level by EEA for NO2 concentration [83]

Pollutant	**Index Level (based on NO_2 concentration in $\mu g/m^3$)**					
	Good	Fair	Moderate	Poor	Very Poor	Extremely Poor
Nitrogen Dioxide (NO_2)	0-40	40-90	90-120	120-230	230-340	340-1000

Reliability on the ground station data was questioned because of the insufficient data available for the selected regions, based on the available data an average NO_2 concentration was computed for each region to evaluate if computed data showing a similar trend in air quality improvement during Lockdown (Phase-1) and post-lockdown (Phase-2) periods as examined through satellite-based measurements. Ground stations data was evaluated under regional spatial scales, based on ground stations clustering (Table-4) while the temporal scale was selected from Table-3. Due to a limitation of available ground station NO_2 data for the whole region, data were interpolated using Inverse Distance Weighting (IDW) technique in QGIS, IDW is based on the weighted averaged of the sample data points while maximum and minimum values of the input sample data remain consistent during the interpolated data points[84].

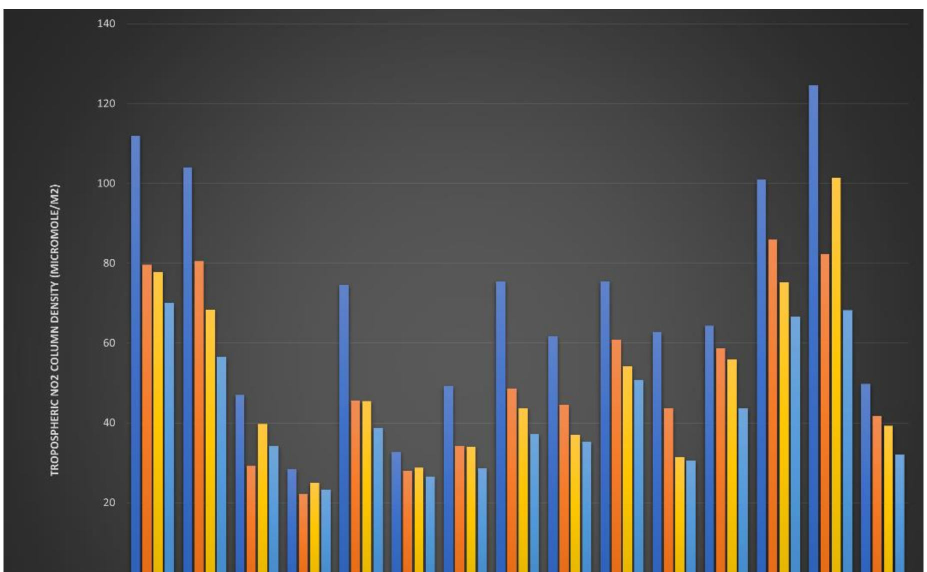
4. Results and Discussion

4.1 Results

4.1.1 Tropospheric NO_2 variations evaluated from TROPOMI sensor.

The spatial distribution of Tropospheric NO_2 column number density collected from the TROPOMI sensor is analysed for 15 regions across Europe and NO_2 concentration for each region was measured separately in two phases. In Phase one a lockdown timeframe as enforced by the states in 2020 is compared under the same period of 2019, to analyse how effective the lockdown measures were to improve the air quality when all the anthropogenic activities were significantly reduced. Phase two which is a further extension of phase-1 is evaluating how quickly NO_2 concentration is going back to the level of 2019 with lockdown easing measures.

The mean concentration of Tropospheric NO_2 in the 15 regions studied under normal conditions (NC) 2019, post-normal conditions (PNC) 2019, Lockdown (LD) 2020 and Post-lockdown (PLD) 2020 is shown in the figure-5 below:



	BE1	BE2	ES30	ES51	FR1	DK01	ITC1	ITC4	ITH3	DEA	DE7	NL32	NL33	UKI	UKD
Mean (NC)2019	111.98	103.99	47.03	28.39	74.62	32.72	49.29	75.48	61.72	75.5	62.7	64.39	100.99	124.55	49.78
Mean (LD)2020	79.65	80.47	29.2	22.15	45.55	28.01	34.16	48.57	44.44	60.8	43.68	58.78	85.89	82.34	41.67
Mean (PNC)2019	77.8	68.4	39.7	25	45.5	28.8	33.93	43.69	36.96	54.2	31.39	55.81	75.16	101.45	39.27
Mean (PLD)2020	70.1	56.52	34.14	23.2	38.78	26.6	28.68	37.22	35.25	50.8	30.59	43.76	66.56	68.26	32.12

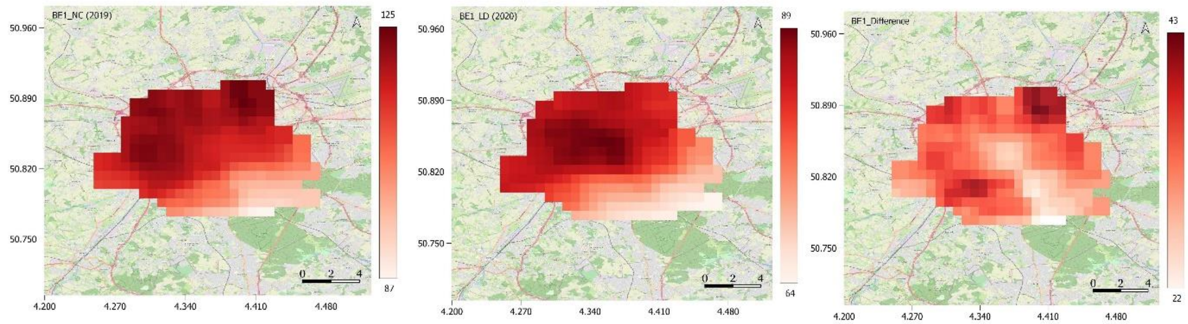
Figure-5 Mean NO_2 concentration in each region under specified conditions.

Figure-5 illustrates that collectively mean NO_2 density was ranging between 32.72 to 124.55 µmol/m^2 in 2019 (NC) which lowered to the data range 22.15 to 85.89 µmol/m^2 in 2020 (LD) while in 2019 (PNC) the NO_2 density was between 25 to 101 µmol/m^2 and a considerable further reduction was seen in 2020 (PLD) and NO_2 column number density fall in the range 26 to 68.26 µmol/m^2. Lockdown measures by each EU member state left a positive impact on air quality when evaluated for Tropospheric NO_2 concentration for each region, in phase-1 ITC4 region achieved 51% of NO_2 reduction (75.48 µmol/m2 in 2019 and 48.57 µmol/m^2 in 2020) due to lockdown which was the highest among all the regions followed by 39% in FR1(74.62 µmol/m2 in 2019 and 45.55 µmol/m^2 in 2020), 37% in ES30 region (47.03 µmol/m2 in 2019 and 29.2 µmol/m^2 in 2020) and 34% in UKI region (124.55 µmol/m2 in 2019 and 82.34 µmol/m^2 in 2020). In Phase-2 when lockdown restrictions were easing up the NO_2 level began turning up again, however, when compared to the NO_2 concentration of 2019, UKI gained 33% reduction (101.45 µmol/m2 in 2019 and 68.26 µmol/m^2 in 2020) followed by 22% in NL32 (55.81 µmol/m2 in 2019 and 43.76 µmol/m^2 in 2020), 18% in the UKD (39.27 µmol/m2 in 2019 and 32.12 µmol/m^2 in 2020), 17% in BE2 (68.4 µmol/m2 in 2019 and 56.52 µmol/m^2 in 2020), 16% in the ITC1(33.93 µmol/m2 in 2019 and 28.68 µmol/m^2 in 2020) and 15% in FR1 region (45.5 µmol/m2 in 2019 and 38.78 µmol/m^2 in 2020). Tropospheric NO_2 level dropped due to lockdown in Phase1 and Phase2 for all regions studied are shown below:

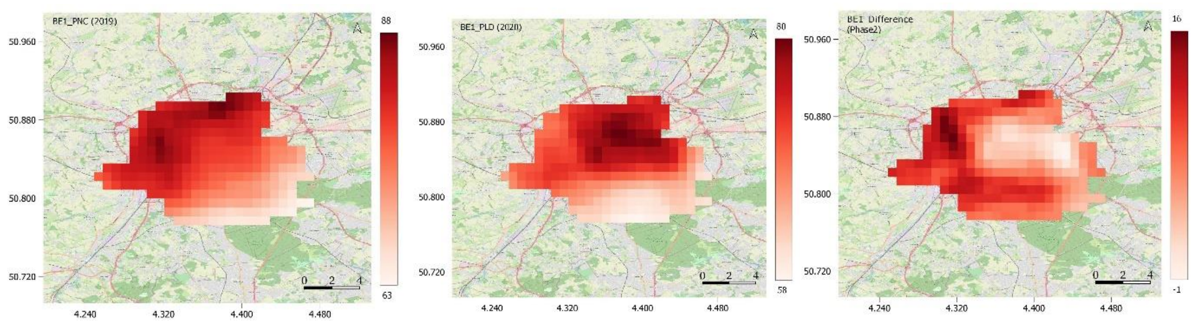
Region	BE1	BE2	ES30	ES51	FR1	DK01	ITC1	ITC4	ITH3	DEA	DE7	NL32	NL33	UKI	UKD
ΔNO2(P-1)	-29%	-23%	-37.00%	-22.00%	-39%	-14.00%	-30.00%	-51.00%	-28.00%	-19.00%	-30.00%	-9.00%	-15.00%	-34.00%	-16.00%
ΔNO2(P-2)	-10%	-17%	-14%	-7.20%	-15%	-5.60%	-16%	-15%	-5%	-6%	-2.50%	-22%	-11.00%	-33%	-18%

Figure 6- Percentage of Tropospheric NO_2 reduction during the lockdown and post-lockdown phases in each region

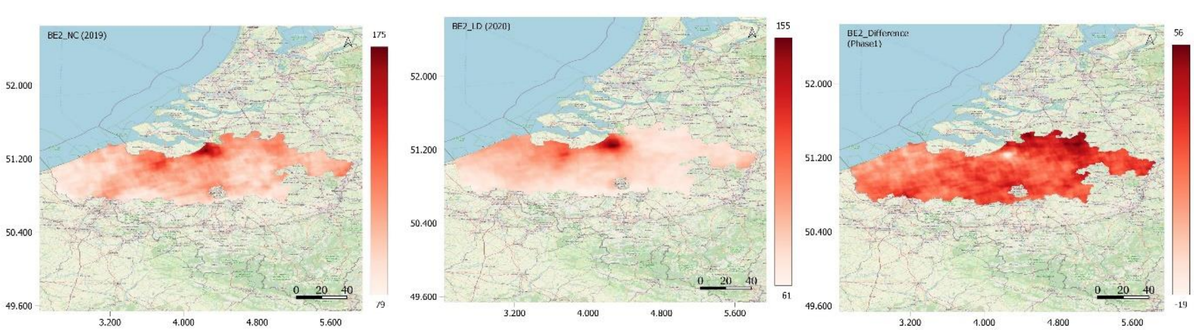
The Spatio-temporal distribution of Tropospheric NO_2 column number density as derived from the TROPOMI sensor is visualized along with the range as well as the difference of two images (from each phase and region) to evaluate the extent of NO_2 concentration is shown below:



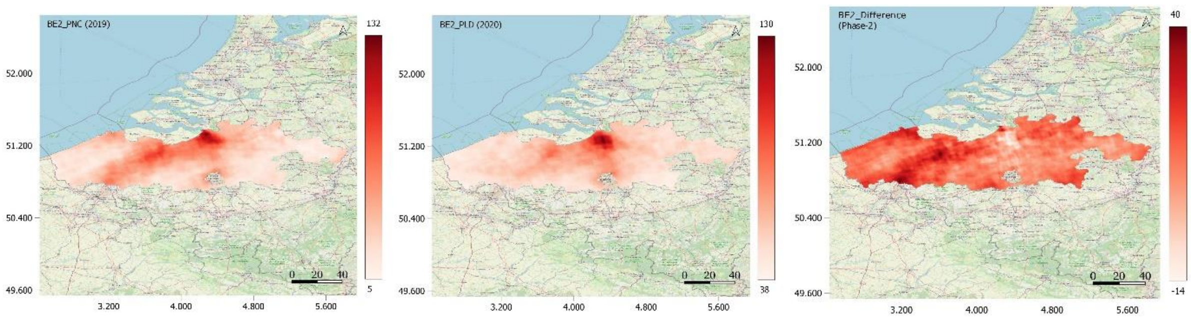
BE1-Phase1



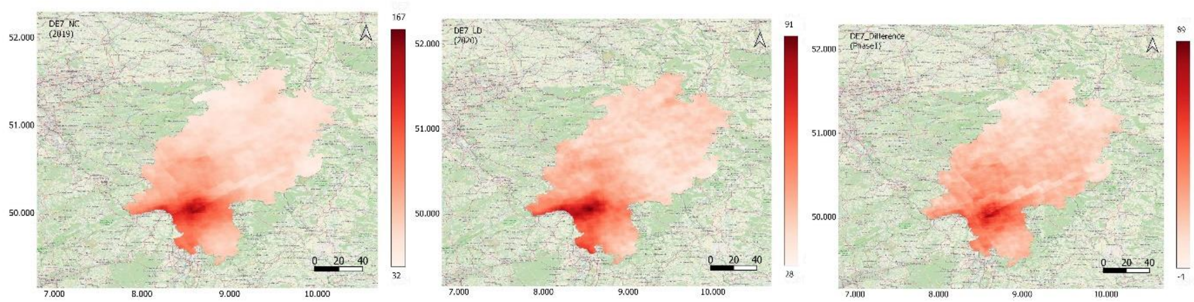
BE1-Phase2



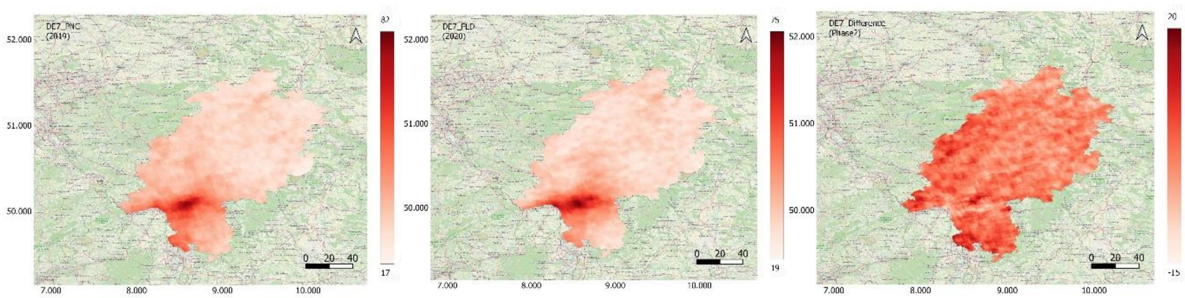
BE2-Phase1



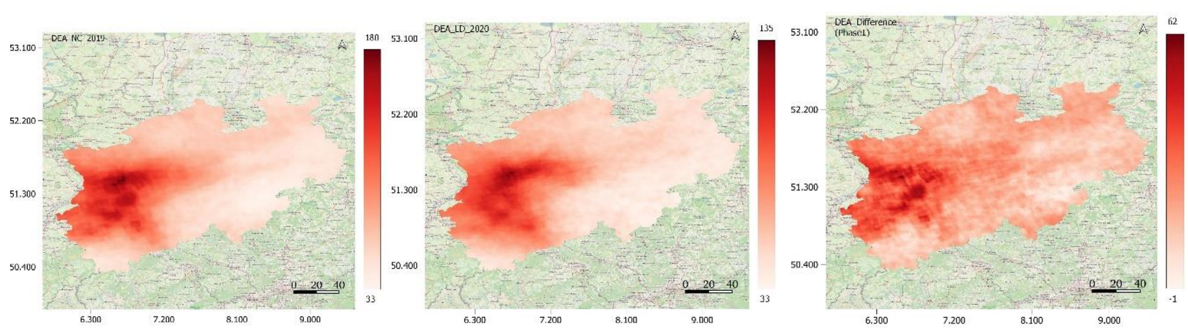
BE2-Phase2



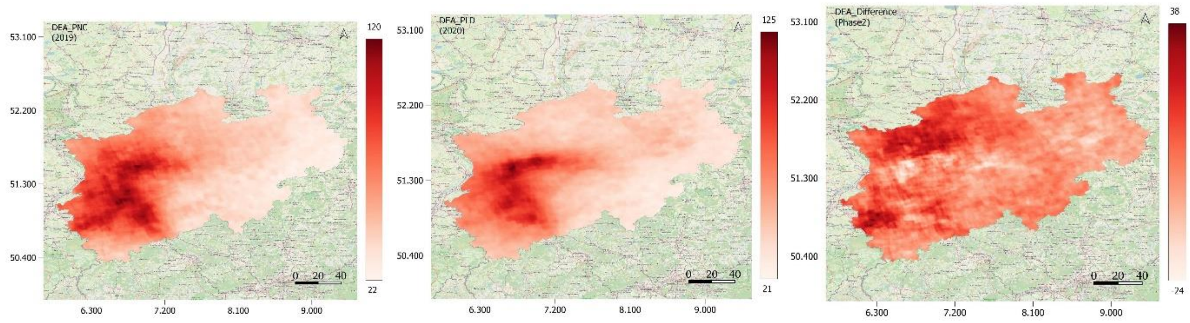
DE7- Phase1



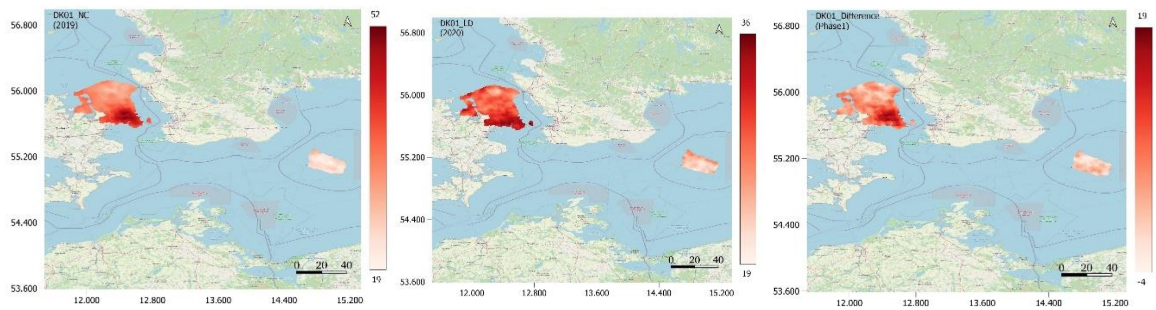
DE7- Phase2



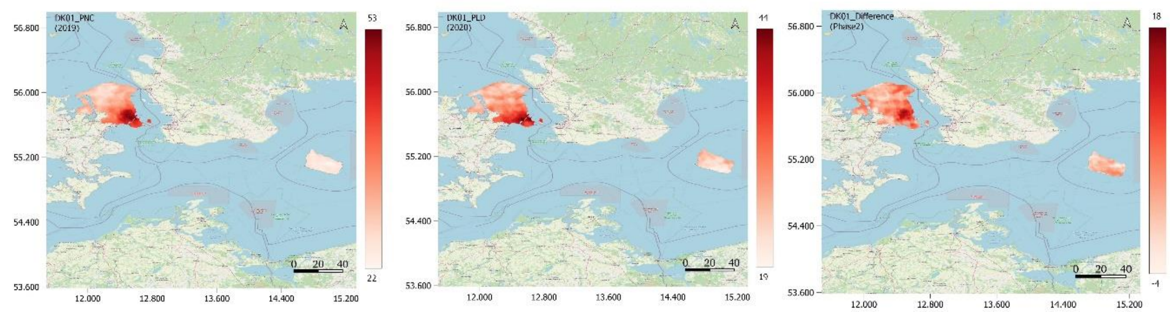
DEA-Phase1



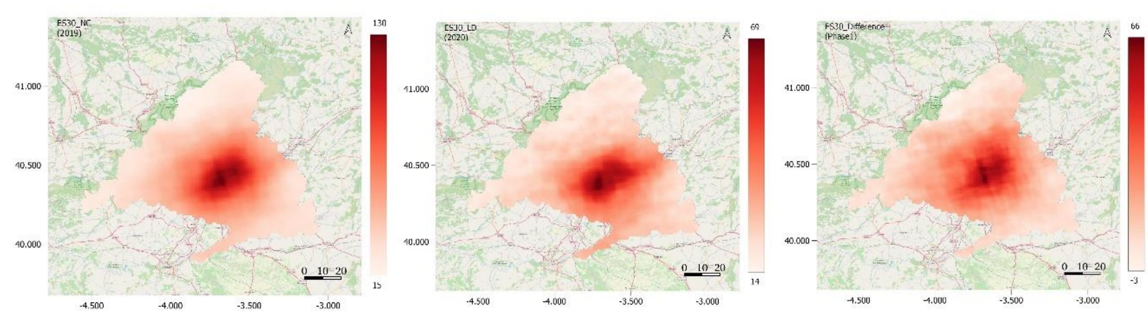
DEA- Phase2



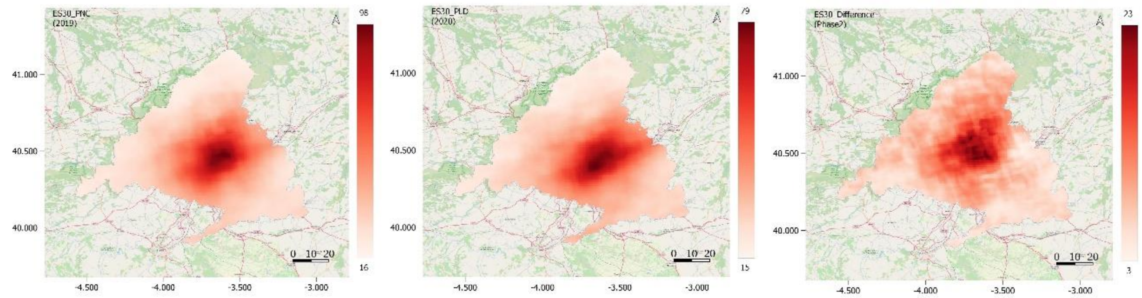
DK01-Phase1



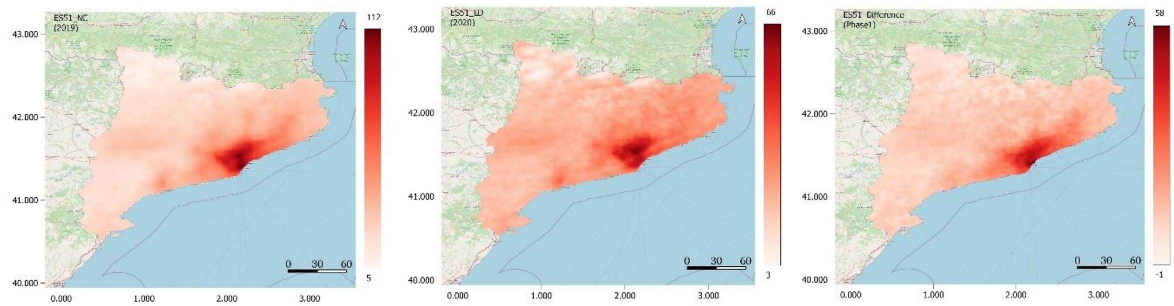
DK01-Phase2



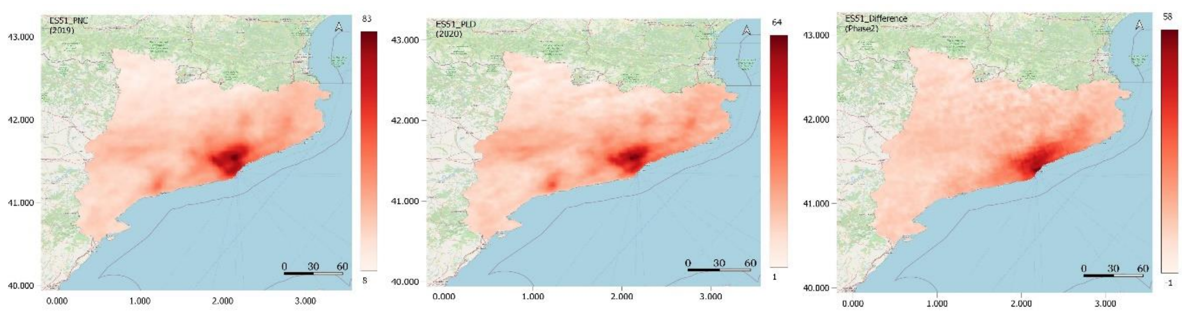
ES30-Phase1



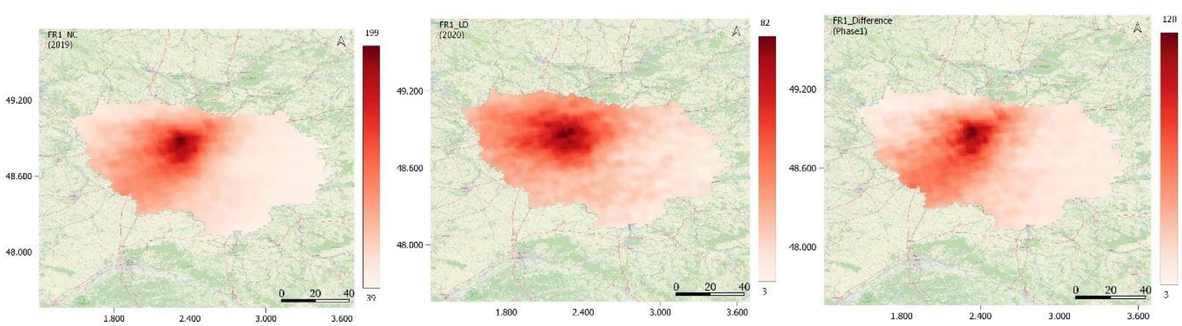
ES30-Phase2



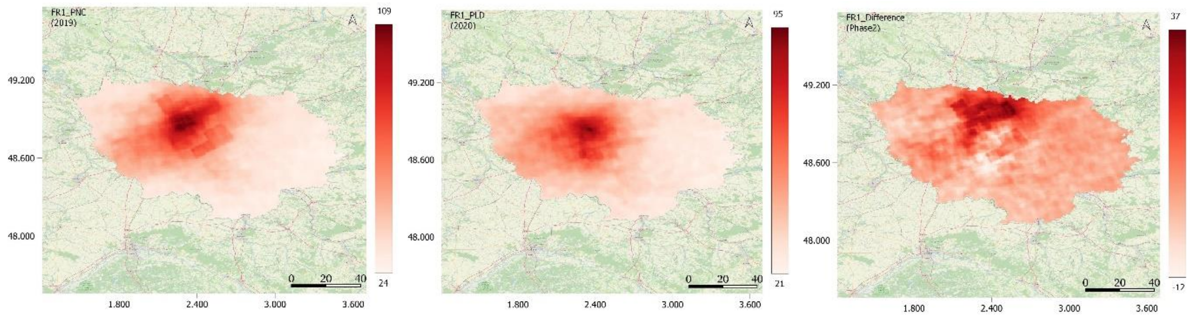
ES51- Phase1



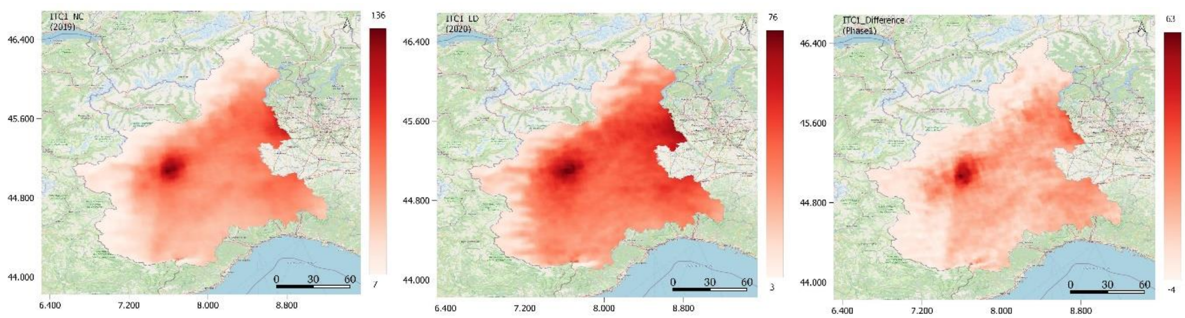
ES51-Phase2



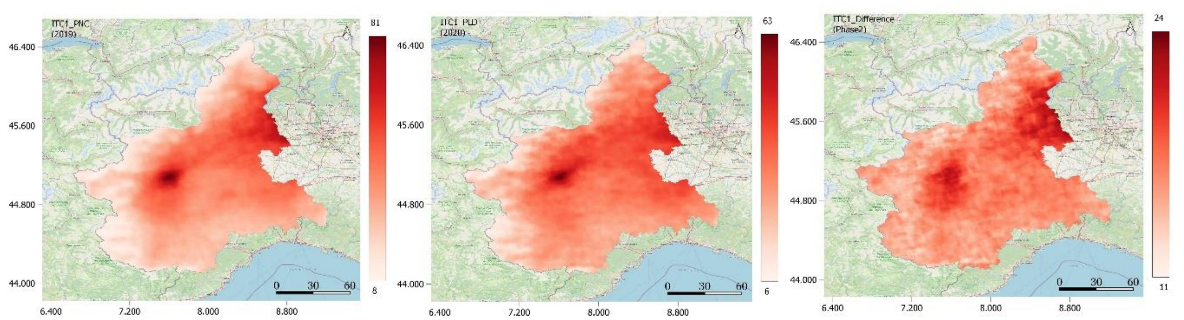
FR1- Phase1



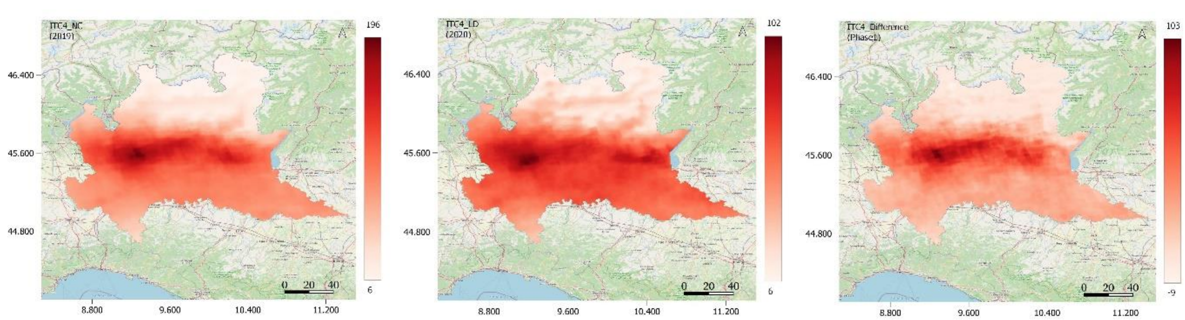
FR1- Phase2



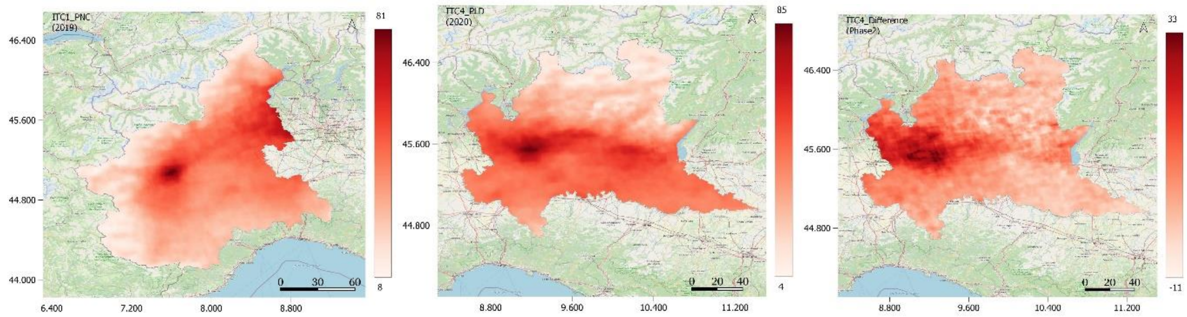
ITC1- Phase1



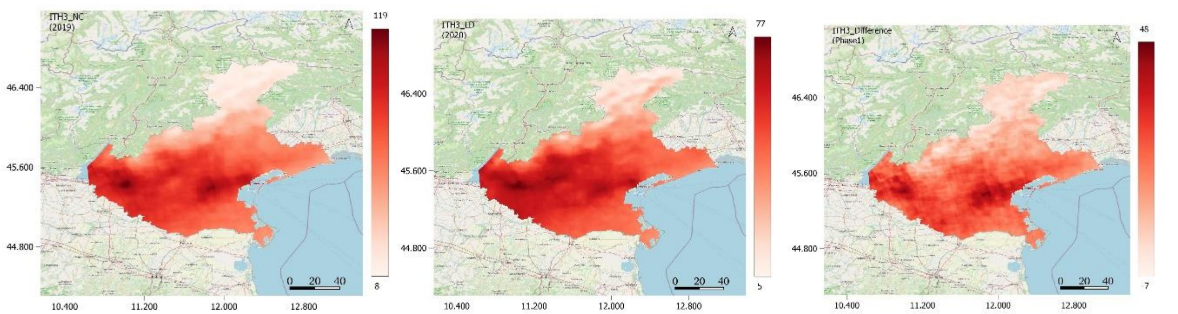
ITC1-Phase2



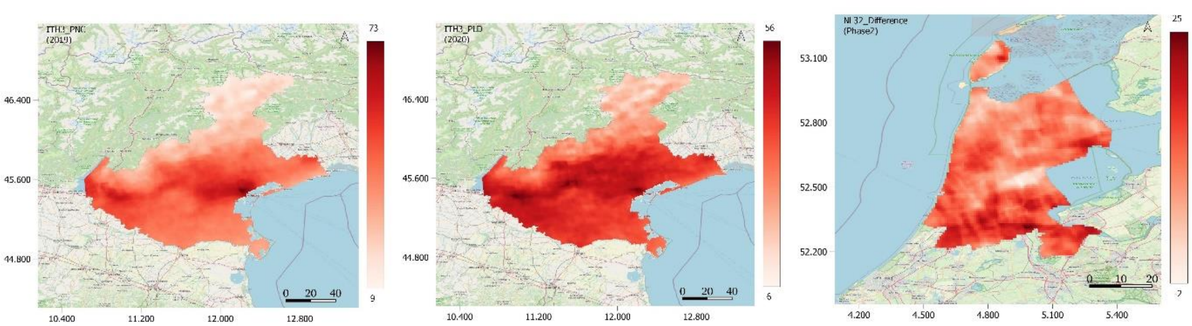
ITC4-Phase1



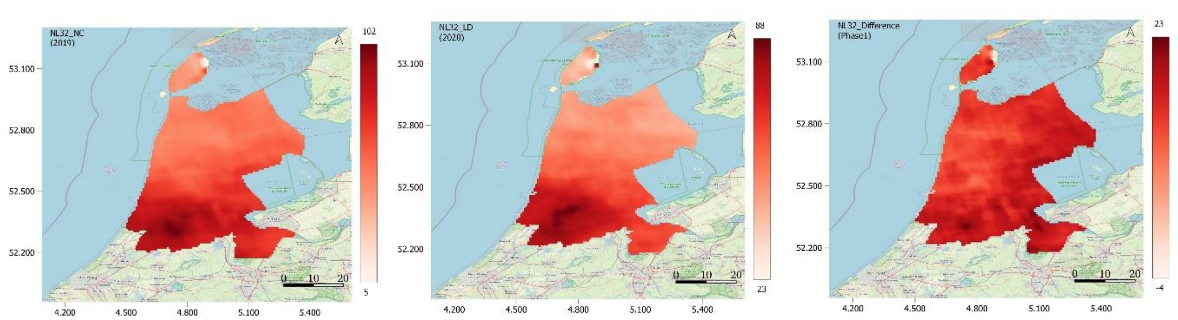
ITC4- Phase2



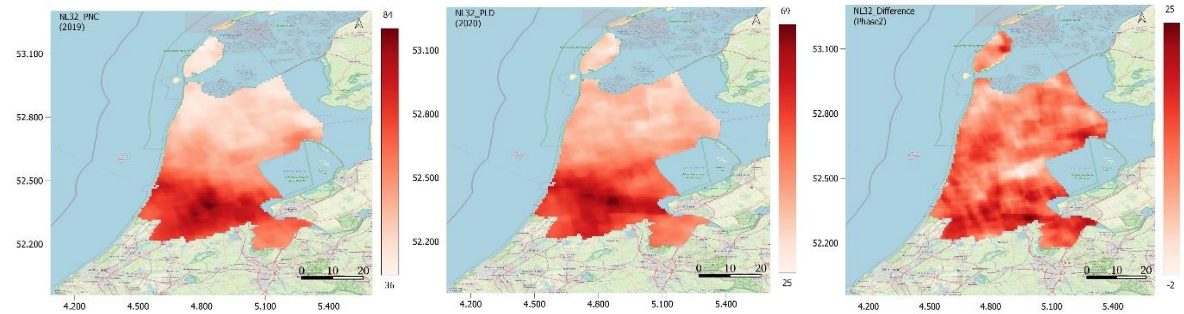
ITH3-Phase1



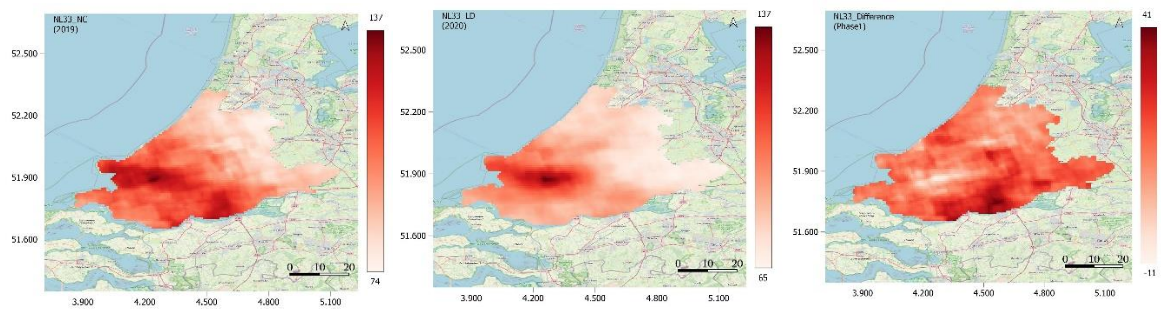
ITH3- Phase2



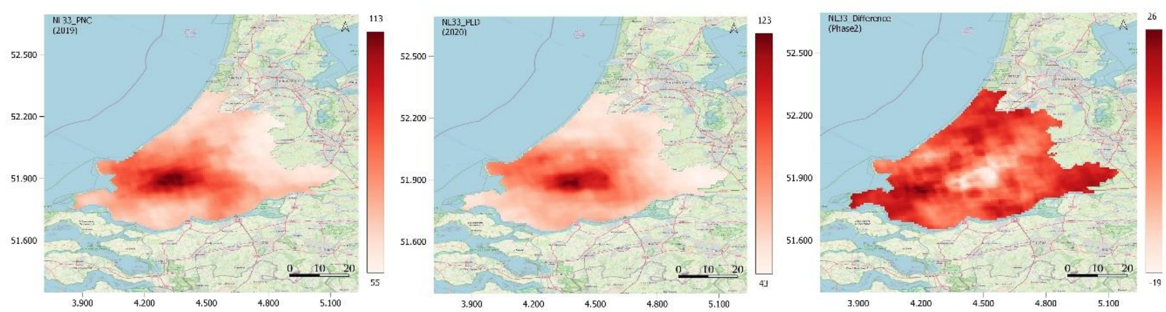
NL32-Phase1



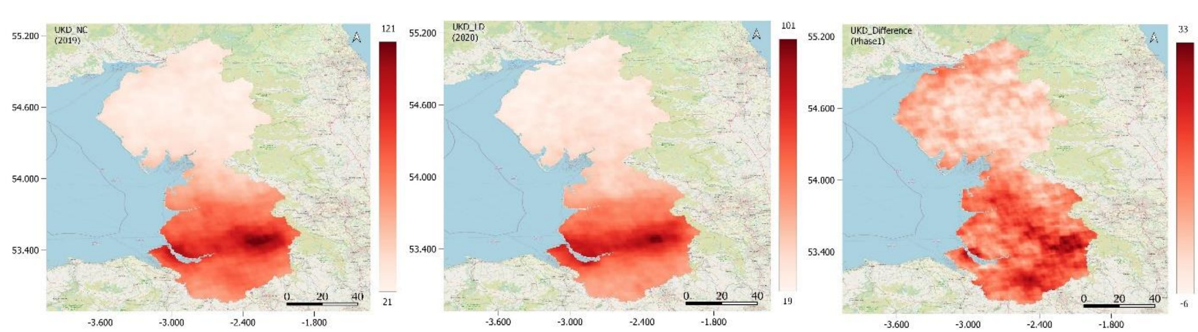
NL32-Phase2



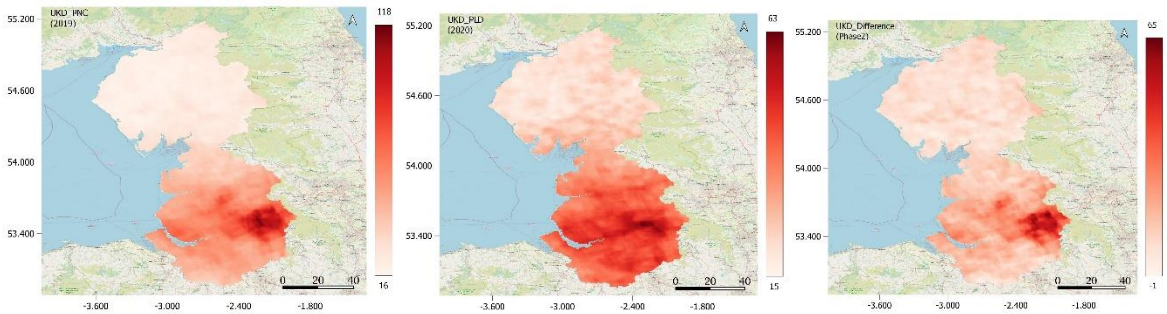
NL33-Phase1



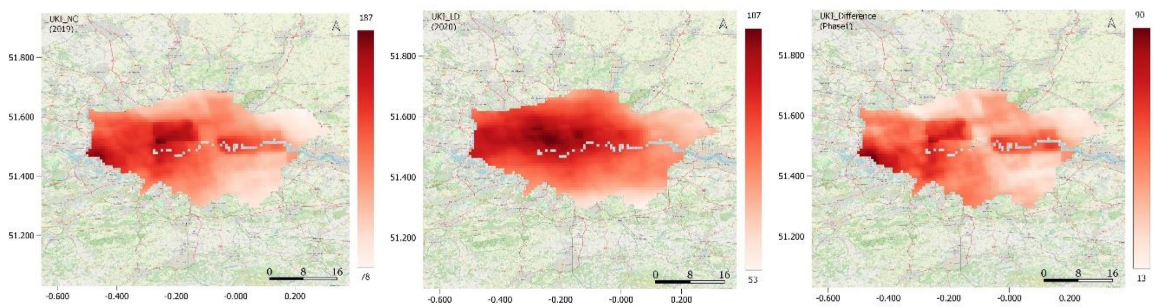
NL33-Phase2



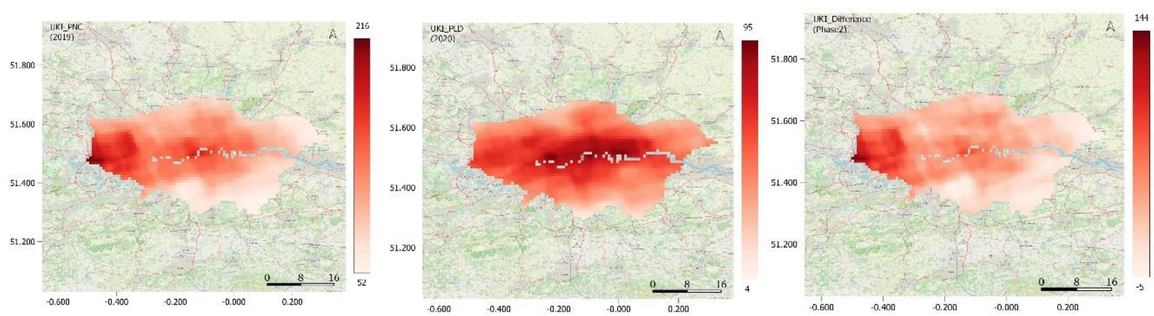
UKD-Phase1



UKD-Phase2



UKI-Phase1

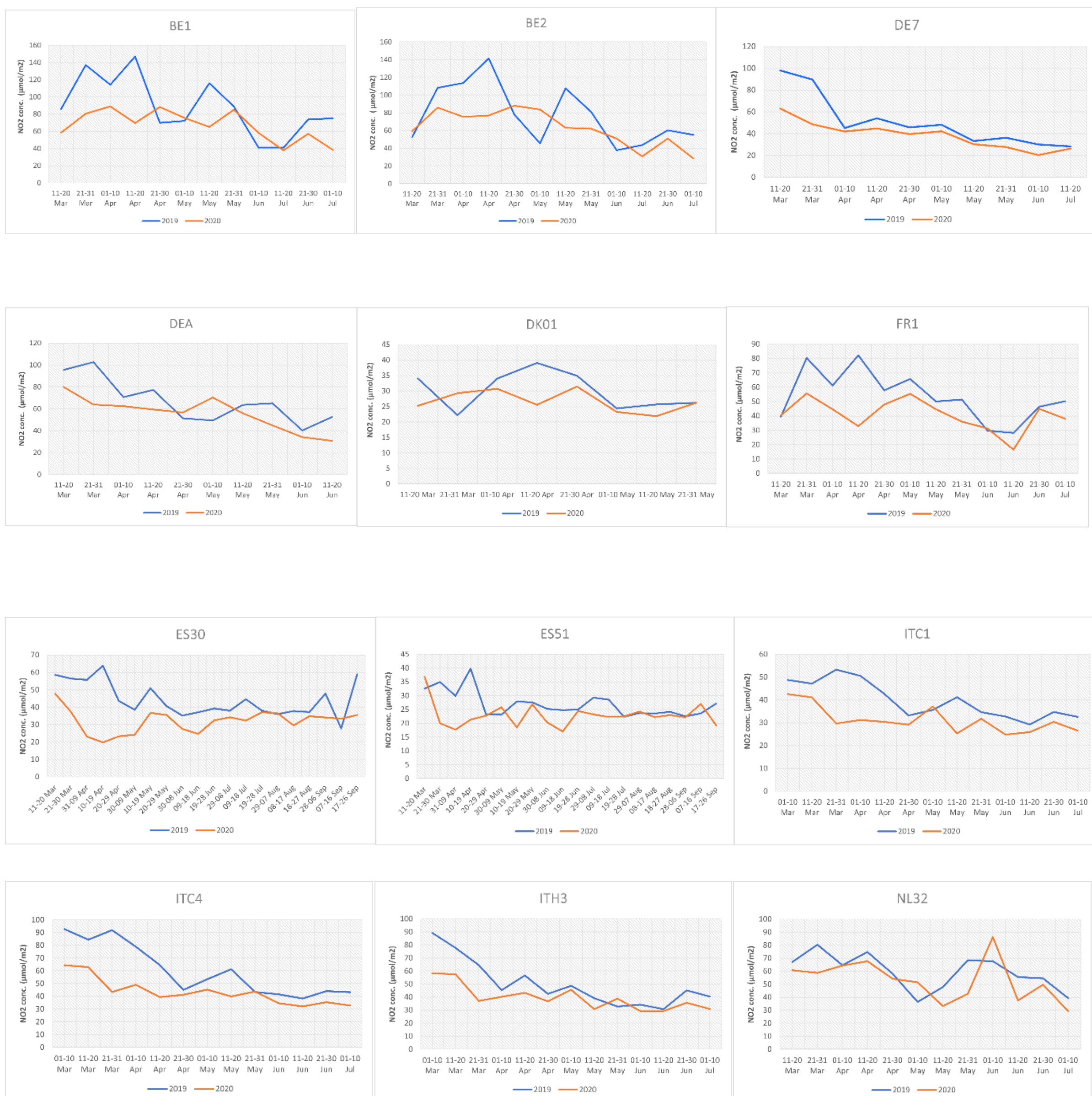


UKI-Phase2

Figure 7- Spatio-temporal Tropospheric NO_2 variation during the study phases

Spatio-temporal Tropospheric NO_2 variation in Figure-7 above disclosed the areas which experienced the highest NO_2 level in 2019 but lockdown brings down the ranges and the differences can be seen in terms of improved air quality. UKI, DE7, BE2 and FR1 were some of the regions where the highest NO_2 level was observed in 2019, and a considerable reduction in NO_2 levels in 2020, the difference of images from 2019 and 2020 reveal some of the hotspots which remained consistent throughout the analysis and air quality based on NO_2 can be observed fluctuating around those hotspots.

To evaluate if the highest amount of Tropospheric NO_2 level at a certain time of the year within the selected time frame for this study is not influenced by some specific incident, a time-series with 10 days averaging for each region in the specified time frame of 2019 and 2020 was generated which is shown below:



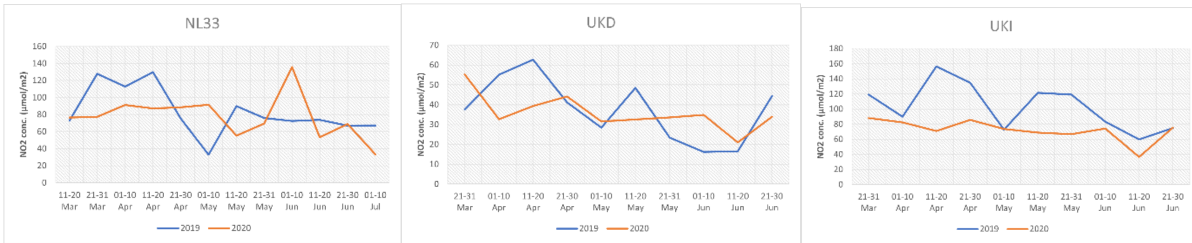


Figure 8- Tropospheric NO_2 concentration Time-series with 10-days averaging.

The above-mentioned 10-days averaging time-series for all regions demonstrate the downward trend in NO_2 level in 2020 due to lockdown when compared with 2019 apart from some peaks which can be seen in NL32 and NL33 regions could be associated with some incident lasted around 10 days.

4.1.2 NO_2 concentration variation observed through ground data.

NO_2 concentration data from 129 ground stations (Table-4) were collected on an hourly basis for the specified time frame chosen for this study (Table-3). The ground stations were selected because they were situated in the centre of the big cities contained in the selected regions as specified in Table-4 and covering the urban traffic sources which significantly contribute to elevating the NO_2 level in the big cities. A time series was generated for each ground station NO_2 measurements ($\mu g/m^3$) within the selected timeframe which is shown in the figure below:

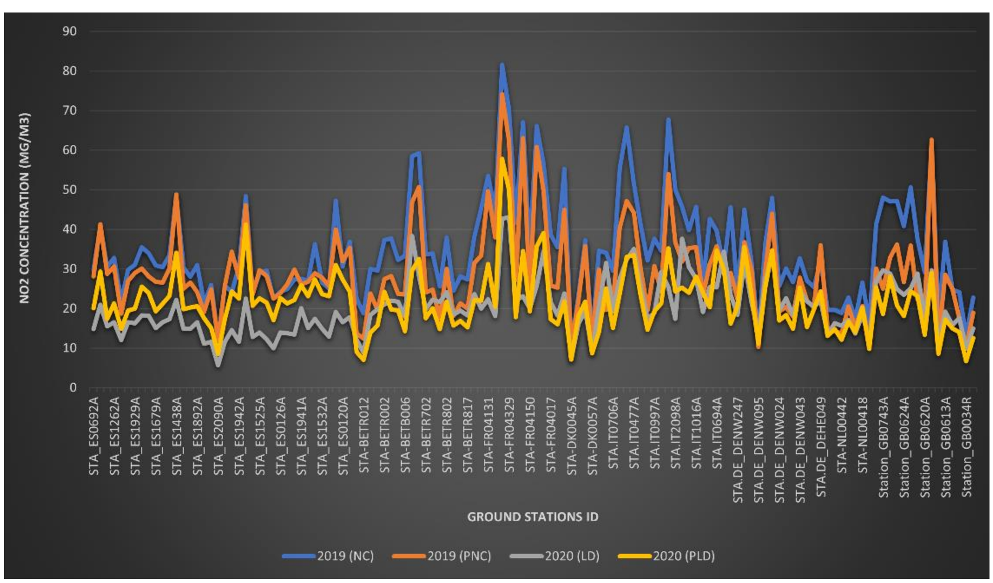


Figure-9 NO_2 ground station observations (µg/m3) within selected study timeframe for each region

NO_2 concentrations for different ground stations associated with chosen regions demonstrate a similar pattern of higher level in 2019 and considerable reduction in 2020 as revealed by satellite based NO_2 concentration measurements. The highest level NO_2 concentration observed was 83 µg/m3 which is more than double the annual NO_2 concentration recommended by EEA and WHO.

To evaluate the NO_2 pollution reduction due to lockdown, an average of all ground stations located in selected regions was measured which got us the following results on a regional basis:

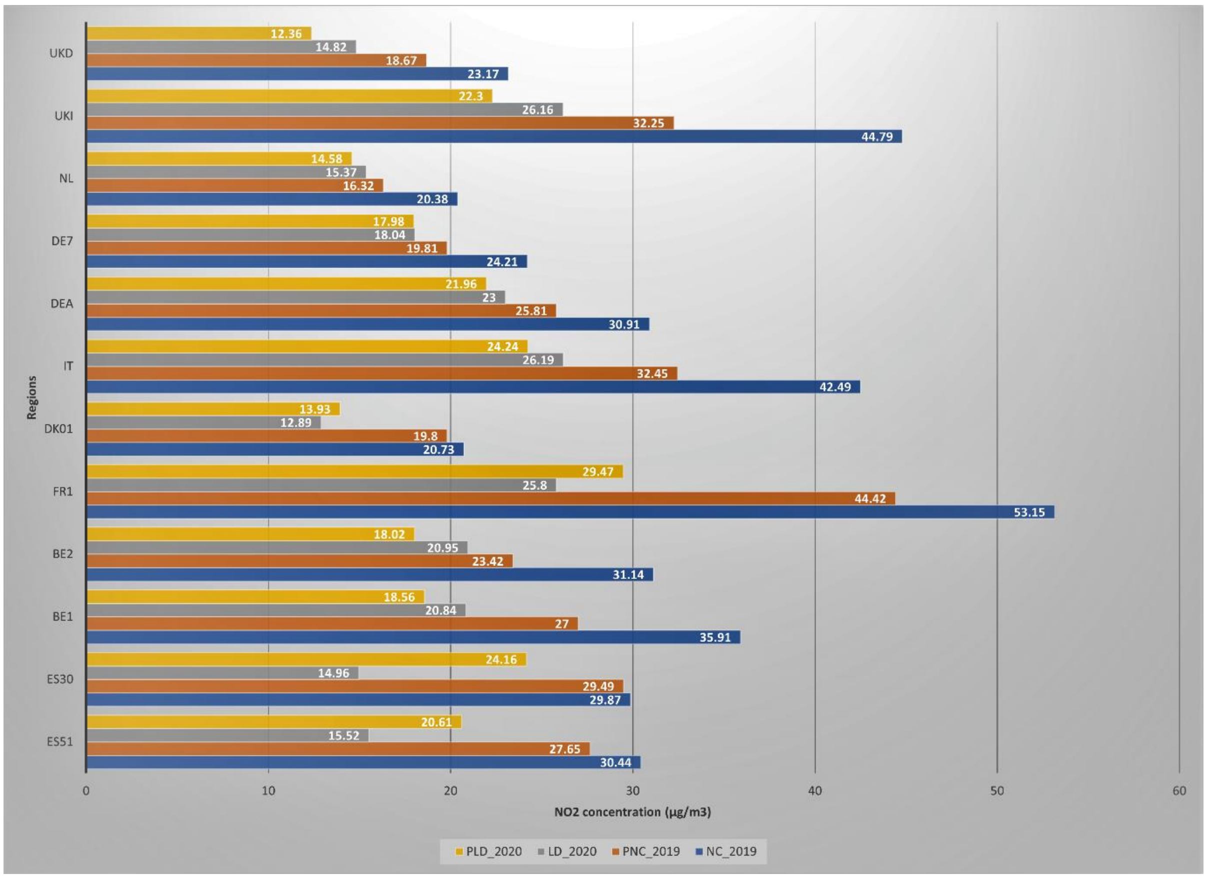


Figure-10 NO_2 ground data evaluation on a regional basis

London (UKI), Milan (IT4) and Paris (FR1) with the highest amount of NO_2 pollution recorded by ground stations in 2019 and was considered above the WHO recommended NO_2 level (40µg/m3), showed a significant reduction due to lockdown as shown above in figure-10. The percentage of NO_2 reduction per region are listed below when estimated for phase1 and Phase2:

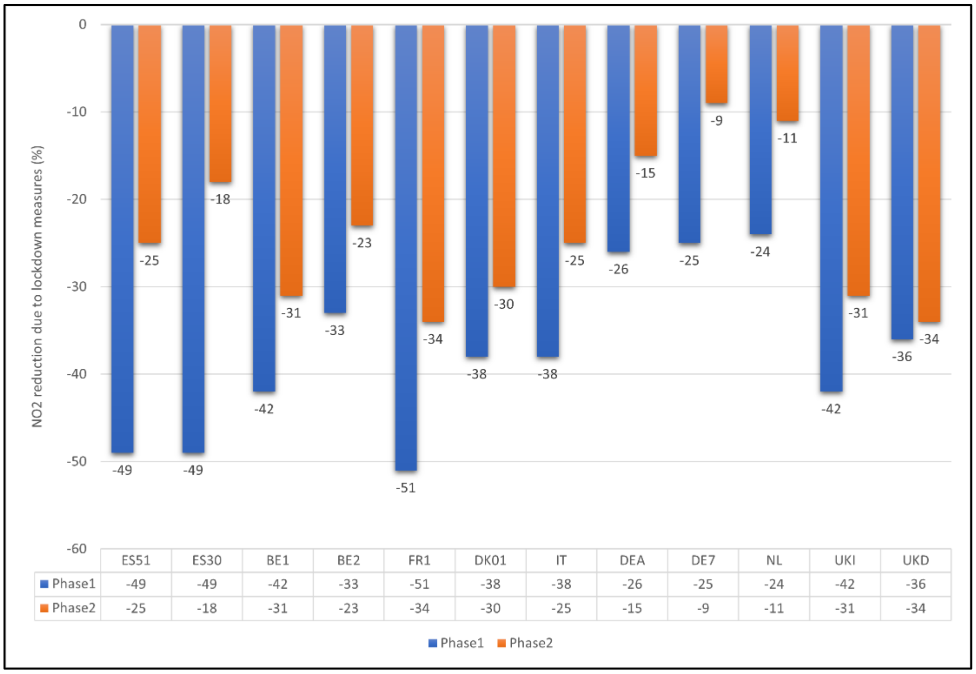


Figure-11 NO_2 pollution reduction (%) due to lockdown measures for Phase1 and Phase2 on a regional basis

For spatial distribution of NO_2 concentration, ground data was IDW interpolated due to limited data availability especially when the regional analysis was considered, so a study extent approach was utilized, and the results are visualized below for each timeframe of 2019 and 2020 as well as the difference of interpolated results:

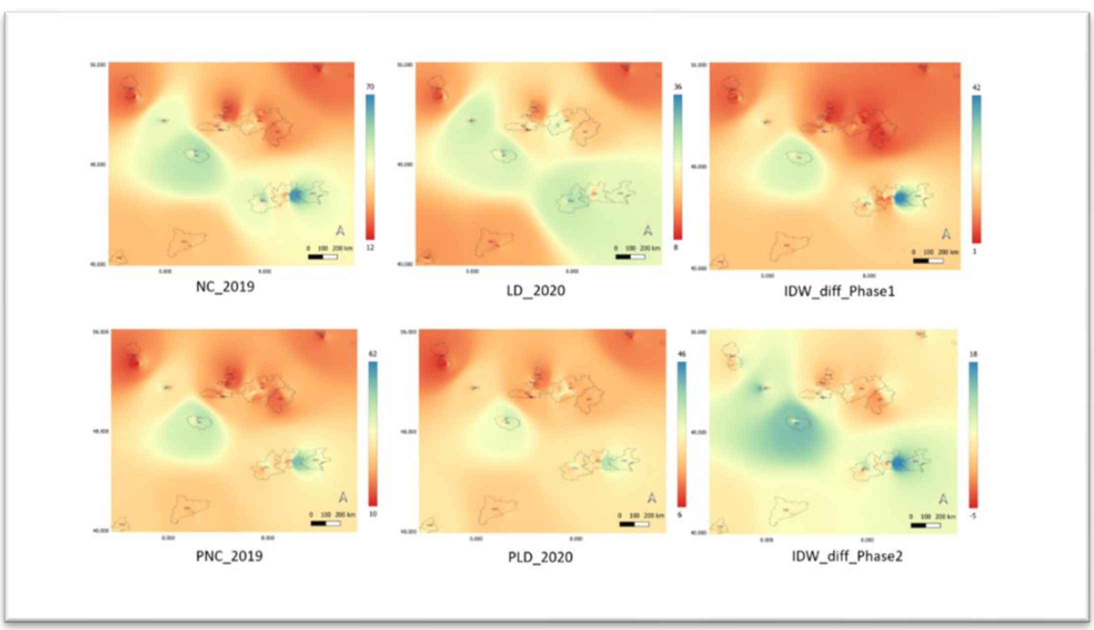


Figure-12 ground NO_2 concentration interpolated results using IDW for study extent.

Interpolation results help us to estimate the values of the unknown points using the Inverse distance technique which makes use of the available points and estimate the rest, even though there was limited data available for ground stations interpolated results highlighted those spots which were of interest and a considerable amount of NO2 concentration reduction was expected, results were not used for validating the satellite-based regional analysis.

A correlation analysis was performed between the data collected in 2019 (two timeframes) and 2020 (two timeframes) to see how related the data is under two scenarios, since there was limited ground data was available for each region, correlation results are shown below:

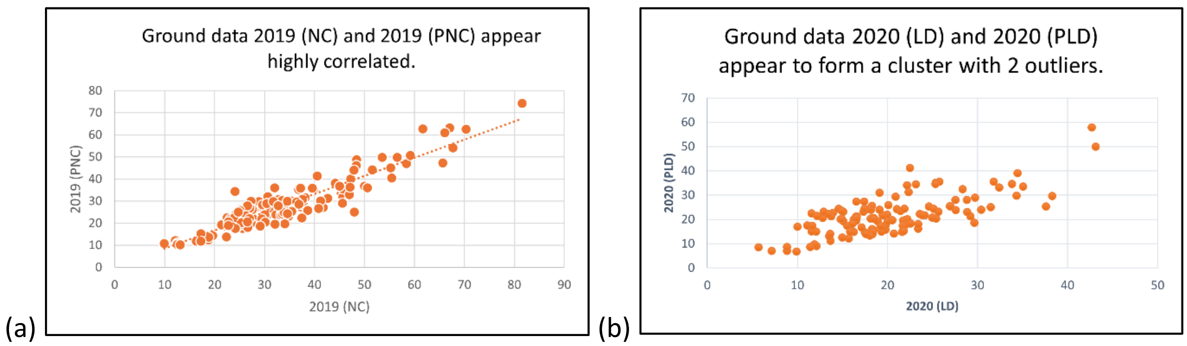


Figure 13 (a) Ground station data correlation (2019), (b) Ground data correlation (2020)

Ground station data correlation results demonstrate that data is highly correlated in 2019 while in 2020 it appears in clusters when considers all regions apart from two ground station in FR1regions with exceptional higher NO2 concentration recorded even under lockdown measures.

4.2 Discussion

Rapid industrial growth and reliance on fossil fuels are continually wrecking our atmosphere with elevated levels of harmful pollutants. Covid-19 pandemic lockdown which forced the communities around the globe to go in hibernation to curtail the infection rate, allowed us to evaluate the relationship between human mobility and air pollution. The results mentioned in section 4.1 indicate that lockdown measures adopted by the EU member states have significantly improved the air quality due to reduced pollutants emission from anthropogenic sources, also observed by many researchers globally using a related approach [6], [8], [12], [16], [23], [85]. Even though a sudden reduction in air pollutants was observed due to lockdown but the study also revealed that these variations are swiftly turning back to their prior state with lockdown lifting.

Firstly, to investigate the impact of lockdowns on the air quality through satellite data and ground data, NO_2 concentrations for 15 regions of EU member states were considered for analysis during the lockdown and post-lockdown phases of 2020 with 2019 as a baseline, which is shown in Table.3.The results indicate that due to lockdown measures the mean NO_2 concentration range decreased in phase1 from 28-124µmol/m^2 to 22-86 µmol/m^2 for all regions and further reduction was observed in phase2 from 25-101µmol/m^2 to 23-68 µmol/m^2, Sentinel-5P data was used for Satellite-based analysis. The collective mean percentage variation of NO_2 concentrations when quantified for Phase1 was 26% and for phase2 it was down to 13% as derived from Figure.6.

This analysis supports the theory that a substantial reduction of NO2 concentration under the strict lockdown period may have been influenced by restricted human mobility, reduced industrial production and transportation controls which were observed throughout the Covid-19 pandemic lockdown around Europe. In the post-lockdown phase (phase2) with lockdown easing measures, it is evident that the air quality achieved during lockdown is reduced to half, which could be associated with the resumption of anthropogenic activities as supported by other studies [8], [18]. Ground station measurements also demonstrated a similar trend, overall NO_2 level in Phase1was measured at 37.7% which reduced to 23.8% in Phase2 (derived from Figure.11) and similar studies also predict that ground station measurements are influenced by meteorological conditions and type of ground station [6]. This study also highlighted that NO_2 concentration which is mainly associated with anthropogenic activities can participate in Ozone (O_3) formation and particulate matter under high temperature, so seasonal variation of NO2 level cannot be ignored which could have led to reduced NO_2 concentration in post-normal (PNC) 2019 and Post-lockdown (PLD) 2020 [86], [87]. By analysing the research data from Statista for the three most populated cities of Europe, it was observed that NO_2 concentration indicates a descending trend between March-August (Summer season) and a considerably higher level between September-February (Winter season) as shown below:

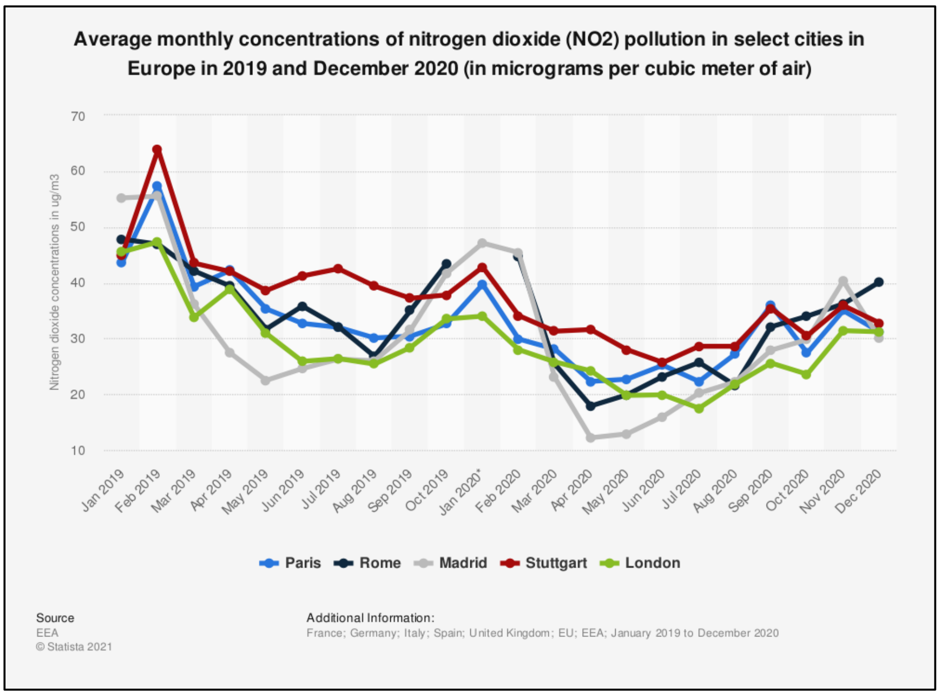
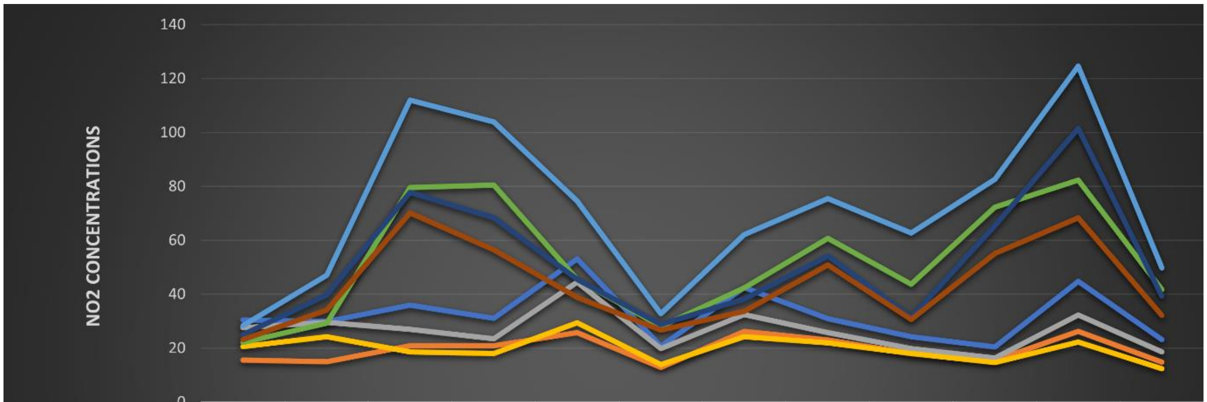


Figure 14 Average monthly NO2 concentration in selected cities for 2019 and 2020 [88]

It is apparent from the above analysis that, as illustrated by satellite-based analysis (Figure.8) and ground station measurements (Figure.9) a considerable positive air quality impact was seen not only in the lockdown phase but also in the post-lockdown phase, even though there is a gradual shift to the previous NO_2 level as visualized in the time-series, which demonstrate that first research question raised in section 1.1 is responded (Figure.8, and Figure.9). A comparative analysis of NO_2 variation in both Satellite-based data (SD) and ground-based data (GD) is shown in the figure below:



	ES51	ES30	BE1	BE2	FR1	DK01	IT	DEA	DE7	NL	UKI	UKD
NC_2019 (GD)	30.44	29.87	35.91	31.14	53.15	20.73	42.49	30.91	24.21	20.38	44.79	23.17
LD_2020 (GD)	15.52	14.96	20.84	20.95	25.8	12.89	26.19	23	18.04	15.37	26.16	14.82
PNC_2019 (GD)	27.65	29.49	27	23.42	44.42	19.8	32.45	25.81	19.81	16.32	32.25	18.67
PLD_2020 (GD)	20.61	24.16	18.56	18.02	29.47	13.93	24.24	21.96	17.98	14.58	22.3	12.36
NC_2019 (SD)	28.39	47.03	111.98	103.99	74.62	32.72	62.13	75.5	62.7	82.69	124.55	49.78
LD_2020 (SD)	22.15	29.2	79.65	80.47	45.55	28.01	42.39	60.8	43.68	72.33	82.34	41.67
PNC_2019 (SD)	25	39.7	77.8	68.4	45.5	28.8	38.19	54.2	31.39	65.48	101.45	39.27
PLD_2020 (SD)	23.2	34.14	70.1	56.52	38.78	26.6	33.71	50.8	30.59	55.16	68.26	32.12

Figure 15 Comparative analysis of Satellite and ground NO2 observations in different selected lockdown phases

For a more detailed air quality gain in lockdown phases, the behaviour of other associated pollutants with NO_2 will enhance the extent of the study.

Google Earth Engine platform was used to collect Sentinel-5P data for this study which proved to be very convenient in data storage, assessment, and analysis, it saves data pre-processing time, and all analytical tools were available under one umbrella. Sentinel-5P is the latest addition by European Space Agency (ESA) to monitor the atmosphere and climatic variations, which provides imagery with high spatial resolution. In this study where NO_2 concentration data was required to analyse at the regional scale, it was inevitable to use satellite-based data with higher Spatio-temporal resolution. Atmospheric pollutant's ability to disperse under climatic conditions and variability emphasized data collection through a platform that has a global coverage to track the fumes further away from the boundaries. This study demonstrates the importance of TROPOMI data for air quality monitoring over ground-station data and this question was raised in section1.1.

Satellite sensor such as TROPOMI from Sentinel-5P with a global coverage provided consistent results instead of ground stations which were suitable for small-scale analysis. Ground stations always require expensive equipment to install, and data required to be processed through climatic models and for better coverage a large number of stations are required. In this study, Sentinel-5P provided detailed Tropospheric NO_2 concentrations for all the selected regions which made it much convenient to analyse the air quality during the lockdown and post-lockdown phases, on the other hand, ground stations were limited to a specific part of the region's incomplete observation for the years 2019 and 2020.

It was acknowledged while collecting the ground data observations that, cities such as London (UKI), Paris (FR1), Barcelona (ES51), Madrid (ES30), Brussels (BE1), Copenhagen (DK01) have a sufficient amount of ground stations available to take observations from Urban/traffic sources which provide more accurate observation as compared to Amsterdam (NL32) where there is only one ground station and even that was not fully functional to provide data for the year 2020 and correlation results exposed outliers in data belong to NL region (Figure.13b), similar situations were exposed for other cities too. Partial data sets for 2020 make it much difficult to correlate with satellite-based data for analysis, eventually, it was interpolated to highlight some patterns in data and to get an overall situation.

The most challenging question which was raised at the start of this study was to investigate how it is possible to avoid lockdown to achieve better air quality by making use of a sustainable approach to gain the NO2 level as observed under strict lockdown and to answer this spatial distribution of NO2 concentration was observed over the regions and a clustering pattern was highlighted through an established link with the big cities situated in those regions as shown in Table.2.

To support the above discussion, the spatial distribution of NO_2 concentrations in different regions as illustrated in Figure-7 and Figure-10 from satellite sensor and ground stations respectively is analysed. In both sensors' observations, each region is underlining some clusters of measurements with the highest NO_2 concentrations which were more likely the dense urban areas with more prominent air quality variations. These highly dense urban areas are London (UKI), Paris (FR1), Brussels (BE1), Barcelona (ES51), Madrid (ES30), Rotterdam (NL33), Dusseldorf (DEA) and Milan (ITC4) which has shown a considerable reduction of NO_2 because of restricted mobility in lockdowns (Figure.6 & Figure.11) These above-mentioned cities are economic hubs of their countries where it is not easy to foresee if the air quality level can be maintained, this study is predicting that, even though the highest amount of air quality was achieved due to lockdown but it is not an everlasting situation, the post-lockdown observations are expressing an entirely different trend, where lockdown can simply be understood as an environmental experience to evaluate our policies towards air quality in dense urban areas through implementation of sustainable approaches and stringent actions.

GDP growth rate for EU states have experienced a decline up to -6.1 in 2020 as compared to 2019 which is a lot higher than the economic crisis in 2009 when it was down to -4.3, which is affecting the general public financially and socially due to restricted mobility [89]. Societies can certainly not afford lockdowns, just to breathe fresh air, anthropogenic NO_2 sources can be diminished by shifting our dependency on fossil fuel to electric vehicles or alternative fuels, green energy sources such as wind and solar could also help to minimize the powerhouse's contribution to pollutants in the atmosphere and all can be achieved through a shift in policies towards green energy.

4.3 Limitations and Future work

In this study, Sentinel-5P data was retrieved through Google Earth Engine, proved to be a useful tool when pre-processing the required data with access to data catalogue from various satellites but it was accompanied by some limitation; Firstly, large spatial extent visualization often ends up with an error stating memory limit exceeded which can only be waived by minimizing the spatial extent which does not support large spatial analysis, secondly, image analysis is restricted to tools already available in Docs section and thirdly web-based IDE does not support ImageCollection export which is dependent on Python API functionality through a batch process and direct export to the local machine is not possible which makes the data more open than private. Moreover, incomplete ground station data was also a limitation to perform a more robust approach in addressing the air quality issue at the regional scale.

This study attempted to address the impact of lockdown in improving the air quality at a regional scale and it provides a comparative analysis mainly focused on satellite-based and ground-based NO_2 concentration levels, but future work requires to consider meteorological conditions such as wind speed and direction, temperature, humidity, solar radiation and rainfall, which widely influence the NO_2 level in the atmosphere through dispersion [90]. To determine the air quality based on NO_2 in a particular area, it is also important to expand the analysis by correlating other pollutants which are associated with NO_2 e.g., Ozone (O_3) and Particulate Matters ($PM_{2.5}$, PM_{10}) and future work should look at these aspects too. NO_2 concentration shows a strong affiliation with economic activities such as transportation of goods, industrial production and people mobility which are mainly linked to fuel combustion, so future research should be focused on reducing the NO_2 level in the atmosphere without compromising economic development. In 2019 the contribution of alternative fuel vehicles was 11% which increase to 24% in 2020, so there is an opportunity to evaluate in future research that how clean our atmosphere will be if we moved 100% away from conventional fuel [91].

5. Conclusions

In this study, Spatio-temporal variations of Tropospheric NO_2 concentrations were analysed during the implementation of lockdown and post-lockdown phases due to the Covid-19 pandemic, and a detailed study was conducted on 15 regions across Europe with a comparative analysis of both satellite-based data and ground station data. The highest reduction obtained on Tropospheric NO_2 column number density measured through Sentinel-5P was 51% in ITC4 region accompanied by 14% in DK01 region the lowest reduction during lockdown phase, whereas in post lockdown phase the highest reduction of 33% was documented in UKI region and 2.5% in DE7 region was reported the lowest. NO_2 concentration recorded through ground stations demonstrated 51% reduction in FR1 region the highest and 24% reduction in NL region the lowest observed in lockdown phase, whereas 34% reduction in FR1 region and 9% reduction in DE7 region was recorded in post-lockdown phase.

This study indicates that the NO_2 reduction in both lockdown phases may be associated with restricted mobility and industrial activities which resulted in improved air quality linked to lockdown measures, but it also concludes that in determining the air quality based on NO_2 pollution other variables (temperature, wind speed, season etc.) and pollutant (O_3, Aerosols) associated with NO_2 reduction needs to be considered to support the results and long-term analysis.

Sentinel-5P provide free and open-source data, with high spatial resolution support to monitor air quality from local to global scales through the Google Earth Engine (GEE) platform, Spatio-temporal data availability with daily global coverage determine the authenticity of data when compared with ground station data.

Covid-19 pandemic lockdown proved to be an environmental experiment that is providing us with a unique opportunity to evaluate our policies towards climate change, with an emphasis that pollutant levels can be controlled. It is evident that NO_2 reduction and improved air quality due to lockdown are temporary and sooner or later we will be standing at the prior state with degraded air quality if we do not act now and implement resilient policies that support sustainable development and renewable energy sources.

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7. Appendix

7.1. Google Earth Engine Codes:

```
//Area of interest selection using ECDC_NUTS regions codes.
var Area_of_interest = ['BE1'];
// import the selected regions from feature collection already saved as in Asset.
var regions = ee.FeatureCollection('users/nvzafar/selected_regions');
// find the regions code from the ECDC_Nuts list.
var region = regions.filter(ee.Filter.inList('ECDC_NUTS', Area_of_interest));
// Get the geometry of the Area of Interest
var AOI = region.geometry();
var geometry = function(collection){
  return collection.clip(AOI);
};
Map.addLayer(AOI);
// Create the title label.
var title = ui.Label('Tropospheric NO2 column number density over BE1 region');
title.style().set('position', 'top-center');
Map.add(title);
//Define the Date of Interest which is the starting date of selected Timeframe.
var DOI = ee.Date('2019-03-18');
// Sentinel-5P NO2 data is selected from ImageCollection with filtered dates and cliped the collection with AOI geometry.
var NO2_BE1 = ee.ImageCollection('COPERNICUS/S5P/OFFL/L3_NO2')
  .select('tropospheric_NO2_column_number_density')
  .filterDate(DOI, DOI.advance(55, 'days'))
  .map(geometry);
print(NO2_BE1);
// Unit conversion from mole to micromole for better numerical analysis.
var mol_to_micromol = NO2_BE1.map(function (image) {
  return image.multiply(1000000).set('system:time_start', image.date().millis());
});
var BE1_NO2 = mol_to_micromol.mean().clip(AOI);
```

```

//Visualization parameters are selected
var band_viz = {
  opacity:0.55,
  min: 0,
  max: 300,
  palette: ['black', 'blue','purple', 'cyan', 'green', 'yellow', 'red']
};
Map.setOptions('hybrid');
Map.addLayer(BE1_NO2, band_viz, 'NO2_BE1');
Map.style().set('cursor', 'crosshair');

Map.setCenter(4.3531, 50.8377, 10);

// Mean calculation

var Stat_NO2_BE1= BE1_NO2.reduceRegion({
  reducer: ee.Reducer.mean(),
  geometry: AOI,
  scale: 1000,
  maxPixels: 1e9
});

// Standard deviation calculation
print(Stat_NO2_BE1);
var NO2_stdDev = BE1_NO2.reduceRegion({
  reducer: ee.Reducer.stdDev(),
  geometry: AOI,
  scale: 1000,
  maxPixels: 1e9
});
```

```
print(NO2_stdDev);

//Minimum and Maximun of data values calculation
var NO2_min_max = BE1_NO2.reduceRegion({
  reducer: ee.Reducer.minMax(),
  geometry: AOI,
  scale: 1000,
  maxPixels: 1e9
});
print(NO2_min_max);

//Median calculation
var NO2_median = BE1_NO2.reduceRegion({
  reducer: ee.Reducer.median(),
  geometry: AOI,
  scale: 1000,
  maxPixels: 1e9
});
print(NO2_median);
var histRegion = AOI;

// A time series is created for filtered dates and printed it to the console.
var time_series = ui.Chart.image
                  .doySeriesByYear({
                    imageCollection: mol_to_micromol,
                    bandName: 'tropospheric_NO2_column_number_density',
                    region: regions,
                    regionReducer: ee.Reducer.mean(),
                    scale: 1000,
                    sameDayReducer: ee.Reducer.mean(),
```

```
                  })
                  .setOptions({
                    interpolateNulls: true,
                    title: 'Average tropospheric_NO2_column_number_density Value by Day of Year BE1 region',
                    hAxis: {
                      title: 'Day of year',
                      titleTextStyle: {italic: false, bold: true}
                    },
                    vAxis: {
                      title: 'tropospheric_NO2_column_number_density',
                      titleTextStyle: {italic: false, bold: true}
                    },
                    lineWidth: 2,
                    colors: ['39a8a7', '9c4f97'],
                  });
print(time_series);



//  Chart for pixels and their associated NO2density, printed it to the console.
var Pixel_NO2_density =
    ui.Chart.image.histogram({image: BE1_NO2, region: histRegion, scale: 1000})
        .setOptions({
          title: 'Tropospheric_NO2_density Histogram',
          hAxis: {
            title: 'NO2 density',
            titleTextStyle: {italic: false, bold: true},
          },
          vAxis:
              {title: 'No. of pixels', titleTextStyle: {italic: false, bold: true}},
          colors: ['cf513e', '1d6b99', 'f0af07']
```

```
        });
print(Pixel_NO2_density);

// display of Colorbar and data filtered data
function ColorBar(palette) {
  return ui.Thumbnail({
    image: ee.Image.pixelLonLat().select(0),
    params: {
      bbox: [0, 60, 250, 300],
      dimensions: '200x15',
      format: 'png',
      min: 0,
      max: 300,
      palette: ['black', 'blue', 'purple', 'cyan', 'green', 'yellow', 'red'],
    },
    style: {stretch: 'horizontal', margin: '1px 2px'},
  });
}
function makeLegend(low, mid, high, palette) {
  var labelPanel = ui.Panel(
      [
        ui.Label(low, {margin: '8px 10px'}),
        ui.Label(mid, {margin: '8px 10px', textAlign: 'center', stretch: 'horizontal'}),
        ui.Label(high, {margin: '8px 10px'})
      ],
      ui.Panel.Layout.flow('horizontal'));
  return ui.Panel([ColorBar(palette), labelPanel]);
}
Map.add(makeLegend(0, 150, 300, ['black', 'blue','purple', 'cyan', 'green', 'yellow', 'red']));
var button = ui.Button('2019 JAN-DEC');
Map.add(button);
```

7.2. Jupyter Notebook codes

```
In [ ]: conda install -c conda-forge earthengine-api
        import ee
        # Initialize the Earth Engine module.
        ee.Initialize()
        pip install geemap
        import geemap
        DOI = ee.Date('2020-05-03')
        Map = geemap.Map()
        NO2 = ee.ImageCollection('COPERNICUS/S5P/OFFL/L3_NO2')\
                .select('tropospheric_NO2_column_number_density')\
                .filterDate(DOI, DOI.advance(46, 'days'))
        vis_params = {
            'opacity': 0.45,
            'min': 0,
            'max': 100,
            'palette': ['blue', 'purple', 'cyan', 'green', 'yellow', 'red']
        }
        image = NO2.sort('system:index', opt_ascending=False).mean()

        Area_of_interest = ['BE1']
        regions = ee.FeatureCollection('users/nvzafar/selected_regions')
        region = regions.filter(ee.Filter.inList('ECDC_NUTS', Area_of_interest))
        AOI = region.geometry()
        DOI = ee.Date('2020-05-03')
        Map = geemap.Map()
        NO2 = ee.ImageCollection('COPERNICUS/S5P/OFFL/L3_NO2')\
                .select('tropospheric_NO2_column_number_density')\
                .filterDate(DOI, DOI.advance(46, 'days'))
        vis_params = {
            'opacity': 0.45,
            'min': 0,
            'max': 100,
            'palette': ['blue', 'purple', 'cyan', 'green', 'yellow', 'red']
        }
        image = NO2.sort('system:index', opt_ascending=False).mean()
        task_config = {
            'region': AOI,
            'folder': 'Air_Quality',
            'scale': 1000,
            'crs': 'EPSG:4326',
            'description': 'NO2_DE7_PLD_2020'
        }
        # Export Image
        task = ee.batch.Export.image.toDrive(image, **task_config)
        task.start()
```