Remote Sensing Based Analysis Of Disparity In Tropospheric NO2 During COVID-19

Nasru Minallah, M. Nouman Khan, Waleed khan, Khurram S. Khattak, Atif Sardar Khan

Abstract: Satellite based remote sensing technology is one of the emerging fields due to their proven significance. This work proposes a sophisticated satellite-based remote sensing system for analyzing tropospheric NO_2, that spans from surface up to 10km. The major source of tropospheric NO_2 is the anthropogenic activities, such as the combustion of fossil fuels including coal, gas and oil and natural processes comprising lightning and soil processes. NO_2 is one of the major air pollutant and source of acute health effects. In this article, we propose a satellite-based CPS along with the Google Earth Engine (GEE) as our data processing engine. Sentinel-5 Precursor (Sentinel-5p) satellite of European Space Agency (ESA) was utilized to remotely sense temporal atmospheric NO_2 concentration. In order to investigate the utility of our proposed CPS, we focus on Pakistan as our study region. In order to analyze the disparity in tropospheric NO_2 during COVID-19 using our proposed satellite-based CPS, we consider pre lockdown period from 10th February 2020 to 21st March 2020, while the observed lockdown period spans from 22nd March 2020 to 12th April 2020. Most of the anthropogenic activities such as public transport, industrial operations were halted due to COVID-19 lockdown in Pakistan. This resulted in a very drastic decrease in the observed atmospheric NO_2 concentration. This article analyzes the NO_2 concentrations in Pre-lockdown and during-lockdown in all the major cities of Pakistan. The obtained results show a drastic decrease in NO_2 concentration, especially 83% reduction in the case of Karachi and the lowest decrease of 51.2% in Gujranwala. Furthermore, our pre-lockdown and during-lockdown analysis show a decrease of 43.3% in the target pollution in the whole country. We also analyzed China and Italy tropospheric NO_2 using deployed CPS and detected a total decrease of 63.8% in China and 36.9% in Italy tropospheric NO_2, respectively.

Index Terms: Pakistan; NO_2, COVID19; Cyber-Physical System; troposphere; anthropogenic

1 INTRODUCTION

Since December 2019, the word CORONA had created fear between everyone[1]. Almost entire world was familiar from the name COVID-19. COVID-19 stands for COrona VIrus Disease outbreak in 2019, on 17th November 2019 from Wuhan[2]. Later it spread exponentially in nearby cities of Wuhan[2]. In order to avoid spreading of COVID-19, the central government of China imposed a lockdown in Wuhan and other cities in Hubei province on 23rd January 2020[3]. Due to COVID19 lockdown in China and Italy a tremendous decrease in tropospheric NO_2 occurred. Following China and Italy, COVID19 also started hitting other countries. In Pakistan, the very first case of COVID19 pandemic was reported on 26th February[4]. In order to control the spread of the virus, Pakistan also declared country wide lockdown due to which the human anthropogenic activities were halted dramatically. NO_2 exists in troposphere due to anthropogenic activities and natural sources. Figure 1 shows sources of NO_2 concentration. Numerous human anthropogenic activities like combustion of fossil fuels[5] have adverse impact on the environment. These anthropogenic activities involve emission of hazardous gases like NO_2[5, 6]. Furthermore, major sources of NO_2 in Pakistan are anthropogenic activities. Lightning also contribute to the production of NO_2 in the troposphere. The accelerated cooling and heating of gasses within lightning bolt produces nitric oxide, which further converts to NO_2 by combining with oxygen in troposphere[7].

One of the pollutants that can severely affect living beings health is nitrogen dioxide NO_2[8]. The NO_2 is red-brown acidic and one of highly reactive gas [9]. Excess of NO_2 in troposphere have a negative impact on the human health. It also accelerates the formation of tropospheric ozone (O_3), fine particle pollution, summer smog and acid rain[10]. Previous studies claimed that exposure of NO_2 to crops can alter their growth rate, especially of the fungal pathogens and herbivorous insects [11]. Among many sources of NO_2, major contributing sources are natural lightening, soil emissions, biomass fuel burning, industrial burning processes, and crop residue burning [12]. According to environmental specialists, the climate conditions variability is mostly linked with the concentration of NO_2 [13].

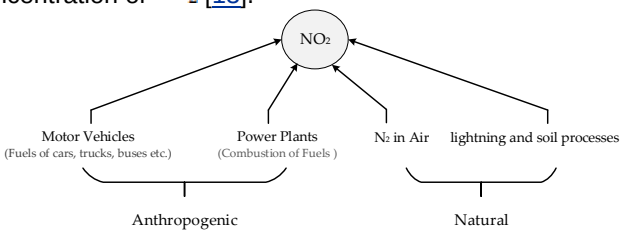

Figure 1 Sources of NO_2

Traditionally, embedded sensors such as Mics 2714 and PM2 are used to sense different atmospheric pollutants but these sensors cannot cover larger area as they can be installed in a limited area and are costly[14]. Satellite-based remote sensing is a process to monitor physical characteristics of a specific area of earth surface with the help of the reflected or emitted Electromagnetic Radiations [15]. Electromagnetic radiations performs as a main source for information communication in satellite-based cyber physical system (CPS)[16]. Using the concept of satellite-based CPS, useful characteristics of electromagnetic radiations can be exploited beyond the range of visible spectrum. In [17], Khokhar et al. used data products of SCIAMACHY (SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY) to investigate tropospheric NO_2 over Pakistan during the time period of 2002 to 2012. A seasonal cycle of maximum in winter, while a minimum Summer was detected. Authors used Sentinel-5P and OMI(Ozone Monitoring Instrument) data during COVID-19 pandemic (January – April 2020) and detected a drastic decrease in tropospheric NO_2 in China, South Korea, Italy, Spain, France, Germany, Iran, and the United States.

- *The work has been carried out under the umbrella of National Center for Big data and Cloud Computing (NCBC), University of Engineering and Technology, Peshawar, Pakistan*
- *Corresponding Author: Narsu Minallah, Email: n.minallah@uetpeshawar.edu.pk*

Some specific uses of satellite-based CPS are [18, 19]:

- Can be used for weather forecasting.
- Remotely sense broad locales on the Earth's surface with the help of satellite sensors, empowering us to see significantly beyond what we can see on the ground.
- Employed Land Cover and Land Use analysis for an up-to-date change detection, which can further help in earth resource planning and management.
- Enables monitoring of temperature of oceans and variations in its trends
- Tracking of cloud to anticipate climatic variability and storms can be performed effectively

CPS is a system controlled and monitored through a computer-based algorithm, with physical and software parts deeply integrated and operational on different temporal and spatial scales. Though sharing same basic architecture as Internet-of-Things (IoT), CPS has higher coordination between physical and computational domains [20]. With technological advancement in embedded boards, sensors, computational algorithms and cloud platforms, CPS are revolutionizing diverse fields, such as smart cities, smart girds, intelligent transportation systems, industrial automation, health and environmental monitoring. In this contest, Satellite based Cyber-Physical Systems are emerging as the most optimum and cost effective solution for environmental pollution monitoring in general and atmospheric NO2 in particular [20]. In this work, a Sentinel-5 Precursor (Sentinel-5P) based CPS have been proposed for tropospheric NO2 monitoring. Specific contribution of our work are as following:

- Identification of the problem area
- Developed cyber physical system for the detection of NO_2 concentration during COVID-19 lockdown
- Change detection and comparison between the NO_2 concentration between pre- and during COVID-19
- Unveiled the percent increase anthropogenic activities due to rise in NO_2concentration

The rest of the paper is organized as follows. Section 2 sheds light on the focused cities in Pakistan. Section 3 discusses satellite data used for this work. After that section 3, Experimental Setup (section 4) states about strategy adopted for the development of proposed CPS. Section 5 covers the results and discussion, which shows pre-lockdown and during-lockdown NO_2 concentration over focused cities. Conclusion and future work summarizes our work.

2 Study Area

In this article, we focused on Pakistan as our focused study area with a latitude and longitude of $30.3753° N$ and $69.3451°E$, respectively. Pakistan is sharing border with Afghanistan, Iran China and India as shown in **Error! Reference source not found.**. According to a recent survey, Pakistan comprises a land cover of 881,913km2 with a population of 212.4 million[21]. Pakistan is divided into four provinces[22]:

(1) Punjab (31.1471° N, 75.3412° E) having a total area of 205,344km2 with 109.99 million population
(2) Sindh (25.8943° N, 68.5247° E) with an area of 140,914 km² with 47.88 million population
(3) Khyber Pakhtunkhwa (34.9526° N, 72.3311° E) covers a total area of 101,741 km² with 35.53 million population
(4) Baluchistan (31.1471° N, 75.3412° E) encompasses 205,344km2 of area with 12.34 million population

Pakistan counts in one of the most arid zone countries with higher temperature, low humidity and participation and high solar radian over most parts of Pakistan[23]. The overall average minimum temperature recorded varies from -26°C to 4°C and the highest temperature ranges from 28 °C to 52 °C. Keeping in view the discussed Geography and Meteorology of the country, this article, focuses on cities listed in **Error! Reference source not found.**. For the analysis of tropospheric NO_2 disparity during COVID-19, we use our proposed satellite-based CPS.

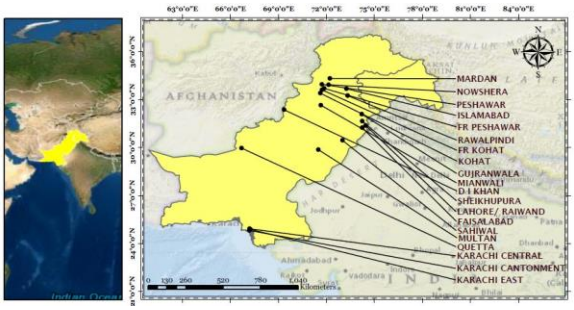

Figure 2 *Study Area(Pakistan)*

Table 1 Pakistan Cities under observation

S.No	City	Latitude , Longitude
1	Mardan	34.1989° N, 72.0231° E
2	Nowshera	34.0105° N, 71.9876° E
3	Peshawar	34.0151° N, 71.5249° E
4	DI Khan	31.8626° N, 70.9019° E
5	Kalabagh	32.9599° N, 71.5398° E
6	Kohat	33.5889° N, 71.4429° E
7	Quetta	30.1798° N, 66.9750° E
8	Karachi	24.8607° N, 67.0011° E
9	Taxila	33.7463° N, 72.8397° E
10	Islamabad	33.6844° N, 73.0479° E
11	Rawalpindi	33.5651° N, 73.0169° E
12	Srinagar	34.0837° N, 74.7973° E
13	Faisalabad	31.4504° N, 73.1350° E
14	Sahiwal	30.6682° N, 73.1114° E
15	Gujranwala	32.1877° N, 74.1945° E
16	Multan	30.1575° N, 71.5249° E
17	Sheikhupura	31.7167° N, 73.9850° E
18	Lahore	31.5204° N, 74.3587° E
19	Raiwind	31.2449° N, 74.2137° E

3. SATELLITE BASED CYBER PHYSICAL SYSTEM

The employed Satellite-based CPS in this study integrates Sentinel-5p satellite imagery and Google Earth Engine (GEE) in order to develop a situation-aware and detailed system for tropospheric temporal NO_2 monitoring. Sentinel-5p, developed by European Space Agency (ESA), is an earth observation satellite developed and launched in October 2017 [25]. The main objective was to perform high spatio-temporal resolution atmospheric measurements for monitoring air quality, UV radiations, ozone and climate forecasting. Built on a hexagonal Astrobus L 250 M, it is equipped with three with three solar panels of 1500 watts capacity and hydrazine thrusters respectively for power harvesting and station-keeping. Salient features of Sentinel-5P are detailed in Table 2.

Table 2 *Sentinel-5P satellite main characteristics*

Attitude control	three-axis stabilized with optional yaw steering
launch mass	820 kg. (including 82 kg hydrazine fuel and TROPOMI instrument 220 kg)
power	1 500 W (EOL), 430 W average power consumption
battery capacity	156 Ah
data storage capacity	480 Gbits memory storage to ensure loss-free communication needed for a single orbit pass.
Spatial sampling	7x7 km2
Dimensions	1.40 x 0.65 x 0.75 m
Design lifetime	7 years
Data generated	139 Gbits per full orbit
Communication links	S-band TT&C with 64 Kbit/s uplink and 128 Kbit/s-1Mbit/s downlink with ranging and coherency, X-band science data downlink at 310 Mbps OQPSK

Sentinel-5p satellite is equipped with TROPOspheric Monitoring Instrument (TROPOMI) as payload [25]. The total mass of TROPOMI is about 200 kg, consuming 170 watts of power on average and a data output of 140 Gbit per orbit. The TROPOMI is a spectrometer that can measure the UV, visible, near-infrared and short-wave infrared, which allows the retrieval of trace gas species. Sensed parameters range from carbon dioxide (CO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), ozone (O_3), sulfur dioxide (SO_2), formaldehyde ($HCHO$), particulate matter (PM) and aerosol aspects like the Aerosol Index as detailed in **Error! Reference source not found.** [24]. TROPOMI has a full global coverage with temporal resolution of 1 day, but with a much improved resolution of 3.5 x 7 km^2 as compared to the predecessor providing measurements since 2004 Compared to OMI [14] and GOME [25]. The data of TROPOMI contains quality assurance value higher than 0.5 and the value of cloud fraction is less than 40%. With TROPOMI specification, it is possible to estimate pollutant concentrations and emissions in smaller towns, individual power plants, wildfires and major infrastructures.

Table 3 *Data product of Sentinel-5p*

S.N0	S5-p Data Product [24]	Main Parameter	Spectral Range(nm) [24]
1	Ozone profiles	Total and tropospheric profiles	270-330
2	Sulphur Dioxide (SO_2)	Total column	308-325
3	Ozone (O_3)	Total column	325-337
4	UV Aerosol Index	aerosol Index	336-440
5	Formaldehyde (HCHO)	Total column	337-360
6	Nitrogen Dioxide (NO_2)	Total column	405-500
7	Aerosol Layer Height	mid-level pressure	440-460
8	Cloud	Fraction, albedo, top pressure	460-490
10	Methane (CH_4)	Total column	1590-1675
11	Carbon monoxide (CO)	Total column	2305-2385

In this work, Google Earth Engine (GEE) has been integrated with Sentinel-5p data to extract concentration of tropospheric NO_2. GEE is a cloud platform that provides large satellite imagery dataset and computational servers need for image processing. GEE, in collaboration with Google Cloud Storage has become a platform where scientist can collaborate using data, algorithms and visualizations. Requests to servers on the platform can be made through Python and JavaScript applications. GEE is an open source cloud-based processing engine[26] and it is widely used in the analysis of deforestation, drought, disaster, disease, food security, water management, climate monitoring and environmental protection [27]. **Error! Reference source not found.** shows the schematic of the deployed CPS. Using our deployed CPS, we analyze the troposphere of Pakistan before lock down and during-lockdown. We process pre-lockdown and amid-lockdown NO_2 datasets of Sentinel-5P using the developed CPS. Using our proposed satellite-based CPS, we investigate 19 cities of Pakistan, as shown Figure 2, and a drastic decreases in their tropospheric NO_2 is observed during COVID-19 lockdown.

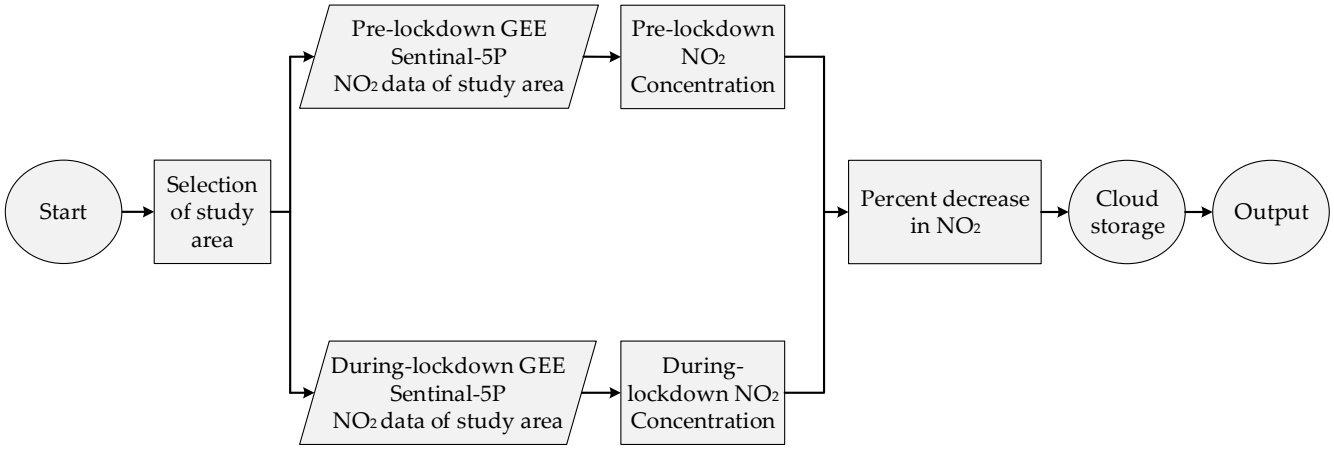

Figure 3 *Satellite based Cyber Physical system tropospheric* NO_2

3. RESULTS AND DISCUSSIONS

Our aim of this study is to detect the impact of COVID-19 lockdown on tropospheric NO_2 in the densely populated cities of Pakistan using our designed Satellite-based CPS. For the stated analysis, we consider the period before lockdown commencing from 10th February 2020 to 21st March 2020, while the duration of the amidst-lockdown period varied from 22th March 2020 to 12th April 2020. Figure presents a pictorial view of the averaged tropospheric NO_2 concentration before lockdown in the country. It can be observed that human activities were in progress before lockdown as obvious from Figure . As usual the cities of Karachi, Lahore and Rawalpindi have highest concentration of NO_2 in the troposphere. Similarly, Figure 2 presents the averaged tropospheric NO_2 concentration during-lockdown over Pakistan. It can be observed from Figure 3 and **Error! Reference source not found.** that a drastic decrease is evident in the tropospheric NO_2 over various cities of Pakistan during-lockdown. The detailed analysis of NO_2 before and during-lockdown over major cities of Pakistan are discussed as follows:

3.1 Impact Of Lockdown Period On Concentrations In The Target Cities Of Pakistan

3.1.1 MARDAN

Mardan is a city of Khyber Pakhtunkhwa Province in Pakistan. Figure shows Pre-lockdown averaged NO_2 over Mardan, which is estimated as $3.1 \times 10^{15} \mathrm{molec./cm^2}$. Similarly, Figure 2 shows NO_2 concentration over Mardan during lockdown. It can be observed from Figure 3 that through lockdown period, the NO_2 concentration is $1.2 \times 10^{15} \mathrm{molec./cm^2}$ with an average decrease of 61.3% in the city.

3.1.2 NOWSHERA

Nowshera is a district in Peshawar division of Khyber Pakhtunkhwa (KP) province in Pakistan. It is not very densely populated but industrialized city of KP province of Pakistan. Figure shows pre lockdown NO_2 in Nowshera troposphere, which has concentration of $5.5 \times 10^{15} \mathrm{molec./cm^2}$. Furthermore it can be observed from Figure 3 that during lockdown Nowshera tropospheric NO_2 concentration is decreased to $2 \times 10^{15} \mathrm{molec./cm^2}$, which is 63.7% decrease .

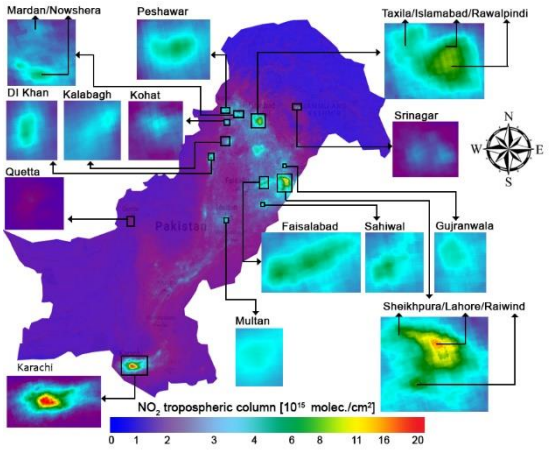

***Figure 4**. Before lockdown NO_2 (2020-02-10 to 2020-03-21) in Pakistan troposphere*

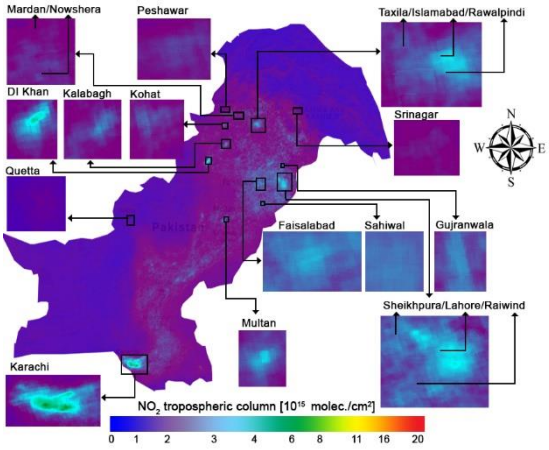

***Figure 2.** During-lockdown NO_2 (2020-03-22 to 2020-04-12) in Pakistan troposphere*

3.1.3 PESHAWAR

Peshawar is subdivision in Khyber Pakhtunkhwa and it is one of most populated (1.97 million) city in Pakistan. It also has some famous industries of Pakistan. Figure shows Pre-lockdown averaged NO_2 over Peshawar, which is estimated as $7.5 \times 10^{15} \mathrm{molec./cm^2}$. Similarly Figure 2 shows NO_2 concentration over Peshawar during lockdown. It can be observed from Figure 3 that during lockdown period, NO_2 concentration over Peshawar is $2.2 \times 10^{15} \mathrm{molec./cm^2}$, with an average decrease of 70.7% in the city.

3.1.4 KOHAT

Kohat is city in Khyber Pakhtunkhwa and it have cement and textile industries. Figure shows pre lockdown NO_2 in Kohat troposphere, which has concentration of $2.9 \times 10^{15} \mathrm{molec./cm^2}$. Furthermore it can be observed from Figure 3 that during lockdown, Kohat tropospheric NO_2 concentration is decreased to $0.8 \times 10^{15} \mathrm{molec./cm^2}$, which is 72.5% decrease.

3.1.5 DERA ISMAIL KHAN

Dera Ismail Khan (DI khan) is a city in Khyber Pakhtunkhwa(KP) and it have Sugar industries, concerts and bricks factories. Figure shows Pre-lockdown averaged NO_2 over DI Khan, which is estimated as $5.8 \times 10^{15} \mathrm{molec./cm^2}$.

Similarly, Figure 2 shows NO_2 concentration during lockdown. It can be observed from Figure 3 that during lockdown NO_2 concentration over DI Khan is $2.3 \times 10^{15} molec./cm^2$, with an average decrease of 60.4% .

3.1.6 KALABAGH

Kalabagh is union council of Mianwali District in the Punjab province of Pakistan. One of the famous dam "Kalabagh Dam'' is located in Kalabagh. Figure shows pre lockdown NO_2 in kalabagh troposphere, which has concentration of $6.5 \times 10^{15} molec./cm^2$. Furthermore it can be observed from Figure 3 that during lockdown Kalabagh tropospheric NO_2 concentration is decreased to $1.5 \times 10^{15} molec./cm^2$, which is 77% decrease.

3.1.7 QUETTA

Quetta is the provincial capital and largest city of Baluchistan, Pakistan. It is also the 10th largest city of Pakistan. Figure shows Pre-lockdown averaged NO_2 over Quetta, which is estimated as $1.9 \times 10^{15} molec./cm^2$. Similarly, Figure 2 shows NO_2 concentration during lockdown. It can be observed from Figure 3 that during lockdown NO_2 concentration over Quetta is $0.9 \times 10^{15} molec./cm^2$, with an average decrease of 52.7%.

3.1.8 KARACHI

Karachi is the capital of the Pakistani province of Sindh. It is the largest city in Pakistan, and 7th largest city proper in the world. Ranked as a beta-global city, the city is Pakistan's premier industrial and financial center. Figure shows pre lockdown NO_2 in Karachi troposphere, which has concentration of $18.1 \times 10^{15} molec./cm^2$. Furthermore it can be observed from Figure 3 that during lockdown Karachi tropospheric NO_2 concentration is decreased to $3.1 \times 10^{15} molec./cm^2$, which is 82.9% decrease.

3.1.9 TAXILA

Taxila is located in Punjab and it have famous chemical industries. Figure shows Pre-lockdown averaged NO_2 over Taxila, which is estimated as $4.1 \times 10^{15} molec./cm^2$. Similarly, Figure 2 shows NO_2 concentration during lockdown. It can be observed from Figure 3 that during lockdown NO_2 concentration over Taxila is $1.0 \times 10^{15} molec./cm^2$, with an average decrease of 82.9%.

3.1.10 ISLAMABAD

Islamabad is the capital city of Pakistan, and is federally administered as part of the Islamabad Capital Territory. It is the ninth largest city in Pakistan. Figure shows pre lockdown NO_2 in Islamabad troposphere, which has concentration of $9.0 \times 10^{15} molec./cm^2$. Furthermore it can be observed from Figure 3 that during lockdown Islamabad tropospheric NO_2 concentration is decreased to $2.0 \times 10^{15} molec./cm^2$, which is 77.8% decrease.

3.1.11 RAWALPINDI

Rawalpindi, commonly known as Pindi, is a city in the Punjab province of Pakistan. It is adjacent to Pakistan's capital of Islamabad, and the two are jointly known as the "twin cities" on account of strong social and economic links between the cities. Figure shows Pre-lockdown averaged NO_2 over Rawalpindi, which is estimated as $15.6 \times 10^{15} molec./cm^2$. Similarly, Figure 2 shows during lockdown NO_2 concentration . It can be observed from Figure 3 that during lockdown NO_2 concentration over Rawalpindi is $3.9 \times 10^{15} molec./cm^2$, with an average decrease of 75%.

3.1.12 SRINAGAR

Srinagar is the largest city and the summer capital of the Indian union territory of Jammu and Kashmir. It lies in the Kashmir Valley on the banks of the Jhelum River, a tributary of the Indus, and Dal and Anchar lakes. Figure shows pre lockdown NO_2 in Srinagar troposphere, which has concentration of $2.2 \times 10^{15} molec./cm^2$. Furthermore it can be observed from Figure 3 that during lockdown Srinagar tropospheric NO_2 concentration is decreased to $1.5 \times 10^{15} molec./cm^2$, which is 31.9% decrease.

3.1.13 FAISALABAD

Faisalabad, formerly known as Lyallpur, is the third-most-populous city in Pakistan, and the second-largest in the eastern province of Punjab. Figure shows Pre-lockdown averaged NO_2 over Faisalabad, which is estimated as $7.5 \times 10^{15} molec./cm^2$. Similarly, Figure 2 shows during lockdown NO_2 concentration. It can be observed from Figure 3 that during lockdown NO_2 concentration over Faisalabad is $1.9 \times 10^{15} molec./cm^2$, with an average decrease of 74.7%

3.1.14 SAHIWAL

Sahiwal is the 14th largest city in Punjab and the 21st largest city in Pakistan. Sahiwal is also a hub of chemical industries. Figure shows pre lockdown NO_2 in Sahiwal troposphere, which has concentration of $6.6 \times 10^{15} molec./cm^2$. Furthermore it can be observed from Figure 3 that during lockdown Sahiwal tropospheric NO_2 concentration is decreased to $1.2 \times 10^{15} molec./cm^2$, which is 81.9% decrease

3.1.15 GUJRANWALA

Gujranwala is a city in Punjab and it also have famous industries of Pakistan. Figure shows Pre-lockdown averaged NO_2 over Gujranwala, which is estimated as $4.6 \times 10^{15} molec./cm^2$. Similarly, Figure 2 shows during lockdown NO_2 concentration. It can be observed from Figure 3 that during lockdown NO_2 concentration over Gujranwala is $2 \times 10^{15} molec./cm^2$, with an average decrease of 52.2%.

3.1.16. MULTAN

Multan is a city in Punjab and have famous industries of Pakistan, which is one of the main reason of excess NO_2 in Multan troposphere. Figure shows pre lockdown NO_2 in Multan troposphere, which has concentration of $4.3 \times 10^{15} molec./cm^2$. Furthermore it can be observed from Figure 3 that during lockdown Multan tropospheric NO_2 concentration is decreased to $2.1 \times 10^{15} molec./cm^2$, which is 51.2% decrease.

3.1.17. SHEIKHUPURA

Sheikhupura is located in Punjab and is the 16th largest city in Pakistan. Figure shows Pre-lockdown averaged NO_2 over Sheikhupura, which is estimated as $5.8 \times 10^{15} molec./cm^2$. Similarly, Figure 2 shows during lockdown NO_2 concentration. It can be observed from Figure 3 that during lockdown NO_2 concentration over Sheikhupura is $2.2 \times 10^{15} molec./cm^2$, with an average decrease of 62.1%.

3.1.18. LAHORE

Lahore is the capital of the Pakistani province of Punjab. It is the country's 2nd largest city after Karachi and 18th largest city proper in the world. Figure shows pre lockdown NO_2 in Lahore troposphere, which has concentration of $16 \times 10^{15} \text{molec./cm}^2$. Furthermore it can be observed from Figure 3 that during lockdown Lahore tropospheric NO_2 concentration is decreased to $3.5 \times 10^{15} \text{molec./cm}^2$, which is 78.2% decrease.

3.1.19 RAIWIND

Raiwind is an industrial hub located in Allama Iqbal Town of Lahore, Punjab, Pakistan. Figure shows Pre-lockdown averaged NO_2, which is estimated as $5.8 \times 10^{15} \text{molec./cm}^2$. Similarly, Figure 2 shows during lockdown NO_2 concentration. It can be observed from Figure 3 that during lockdown NO_2 concentration in Raiwind troposphere is $2.3 \times 10^{15} \text{molec./cm}^2$, with an average decrease of 60.4%.

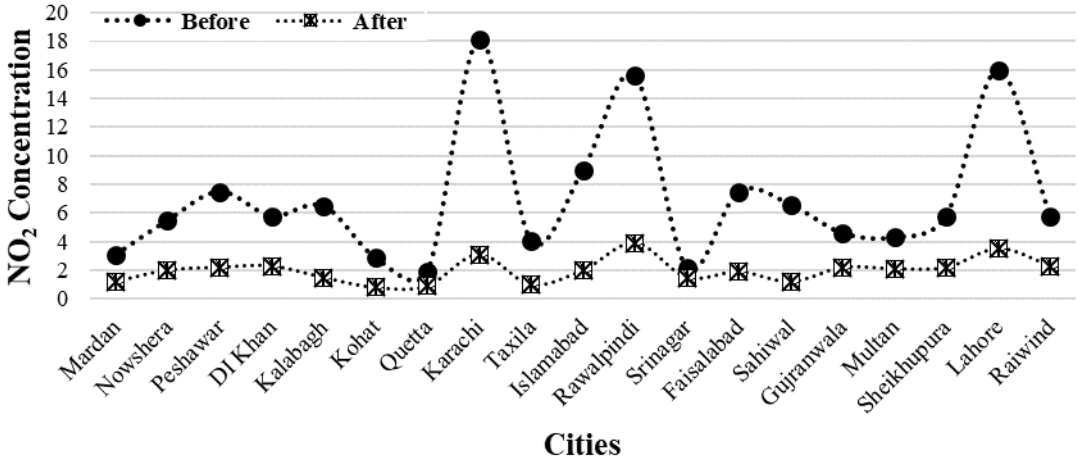

Figure 3. Pre-lockdown and during-lockdown NO_2 concentration($10^{15} molec./cm^2$) in Pakistan

Figure 4. Percent Decrease in NO_2 in Pakistan

4. COVID-19 LOCKDOWN EFFECT ON TROPOSPHERIC NO_2 OF CHINA AND ITALY

Furthermore using deployed CPS, we also analyzed China and Italy tropospheric NO_2 before COVID-19 and during COVID-19. On 23rd January 2020, the central government of China imposed a lockdown in Wuhan and other cities in Hubei province. The incident was commonly referred to in the media as the "Wuhan lockdown". **Error! Reference source not found.** shows Pre-COVID-19 and during COVID-19 NO_2 in troposphere of China. Using deployed CPS, we analyzed 10 most populated cities of China and estimated percent decrease of NO_2 due to COVID-19 as shown in **Error! Reference source not found.**. Before COVID-19 highest concentration of $20.0 \times 10^{15} \text{molec./cm}^2$ is estimated in Beijing , moderate concentration of $17.2 \times 10^{15} \text{molec./cm}^2$ is estimated in Chengdu and lowest concentration of $12.1 \times 10^{15} \text{molec./cm}^2$ is estimated in Shenyang troposphere. While processing during COVID-19

dataset (23rd January to 15th March) a drastic decrease in NO_2 in China troposphere is detected. **Error! Reference source not found.** shows percent decrease in NO_2 over 10 most populated cities of China. The highest decrease of 58.8% is in troposphere of Chongqing and lowest decreases of is recorded in Shenyang troposphere. Furthermore, our pre- lockdown and during-lockdown analysis show a decrease of 63.8% in the tropospheric NO_2 over China.

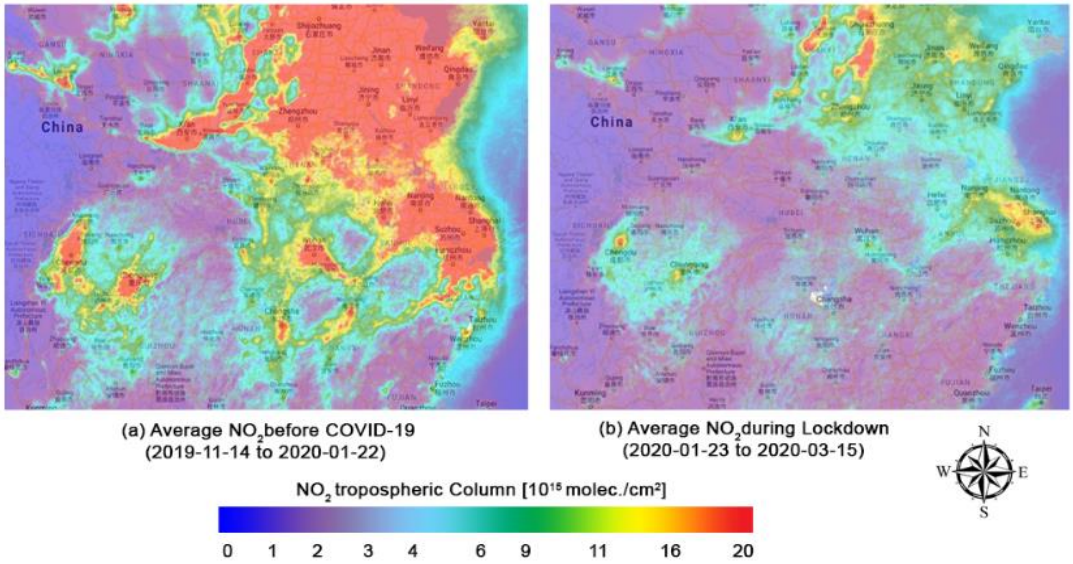

Figure 5. NO_2 *in China troposphere during 2019-11-14 to 2020-03-15*

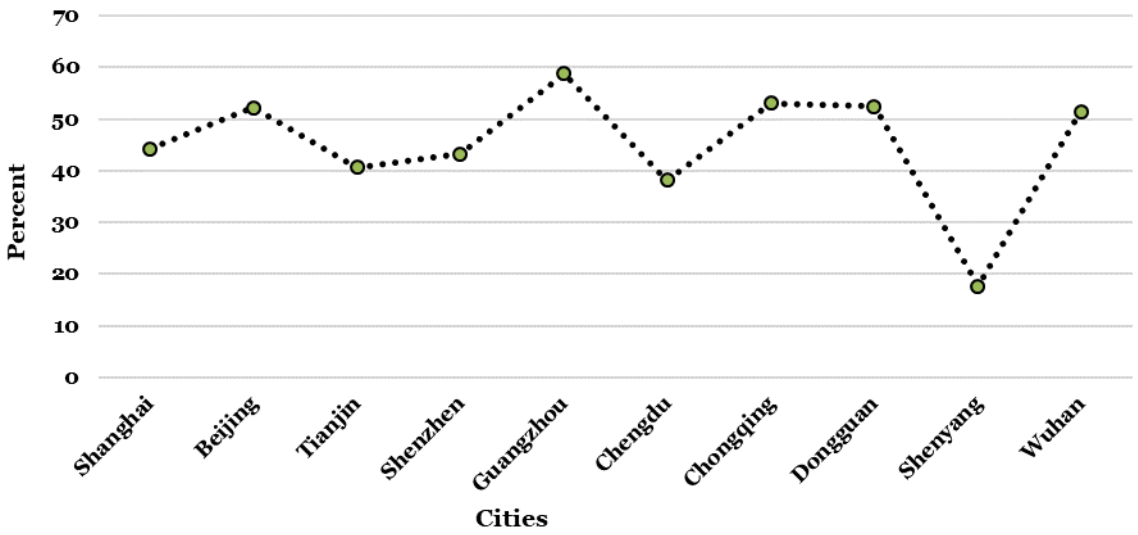

Figure 6*. Percent Decrease in* NO_2 *in China cities during 2019-11-14 to 2020-03-15*

After China, Italy was considered most affected country due to COVID-19. **Error! Reference source not found.** shows Pre-COVID-19 (1st February to 8th March of 2020) and during COVID-19(8th March to 25th May of 2020) average concentration of NO2 in Italy troposphere respectively. Before COVID-19 outbreak, highest averaged NO2 concentration of $20.0 \times 10^{15} \mathrm{molec./cm^2}$ is estimated in Milan troposphere and lowest concentration of $9.1 \times 10^{15} \mathrm{molec./cm^2}$ in Catania troposphere. On 9th March 2020, the government of Italy under Prime Minister Giuseppe Conte imposed a national quarantine, restricting the movement of the population except for necessity, work, and health circumstances, in response to the outbreak of COVID-19 in Italy. During the lockdown period (2020-03-09 to 2020-05-25), a drastic decrease in Italy troposphere is detected. **Error! Reference source not found.** shows percent decrease in NO2 over 8 most populated cities of Italy. The highest decrease of 58.8% is in troposphere of Chongqing and lowest decreases of 19.8% is recorded in Shenyang troposphere. Furthermore, our pre-lockdown and during-lockdown analysis show a decrease of 36.9% in the Italy tropospheric NO_2.

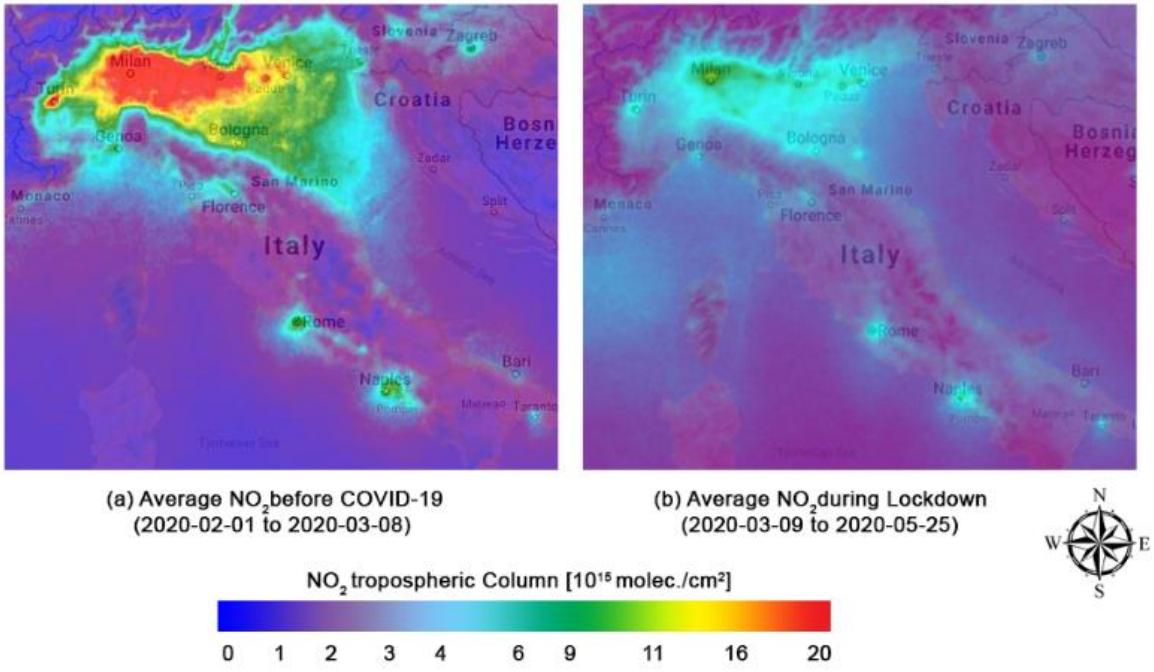

Figure 7. NO_2 *in Italy troposphere during 2020-02-01 to 2020-05-25*

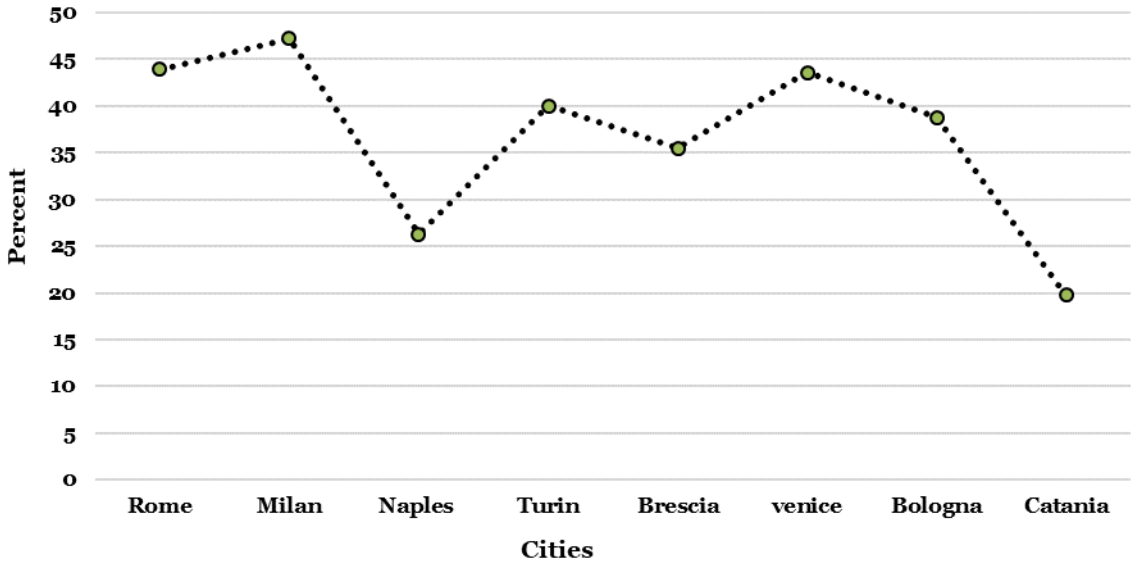

Figure 8. *Percent Decrease in* NO_2 *in Italy during 2020-02-01 to 2020-05-25*

4 CONCLUSION

In this study, we proposed a satellite based Cyber-Physical System for tropospheric NO_2 monitoring. The Proposed system integrated GEE algorithm with Sentinel-5P satellite data in order to extract concentration of NO_2 in Pakistan troposphere. We showed pre-lockdown and amid lockdown period of NO_2 concentration over 19 cities of Pakistan. These 19 cities are chosen because they have excess NO_2 in normal days. As currently there is spring season in Pakistan and we were expecting a moderate level of NO_2 in troposphere. But due to COVID-19 lockdown, their concentration in troposphere were recorded much lesser as compared to the previous spring season. Because lockdown is progress in Pakistan, all anthropogenic activities, like transport operation of industries and other anthropogenic activities, are halted. Such anthropogenic activities are the main reasons of NO_2 emissions. We also showed the percent decrease of NO_2 since 10th February to 4th April of 2020. The drastic decrease was found for Karachi, which was 83% and the lowest decrease was calculated for Gujranwala, which is 52.2%. Our analysis showed that almost 43.3 % decrease occurred in Pakistan troposphere due to COVID-19 lockdown. Furthermore, we also used our deployed CPS to investigate troposphere of China and Italy. We processed Sentinel-5p pre-lockdown dataset of pre-lockdown of China and Italy and estimates percent decrease in tropospheric NO_2 over most populated cities of china and Italy . According to obtained results, due to COVID-19 63.8% decrease in China tropospheric NO_2 and 36.9% in Italy tropospheric NO_2 is estimated.

ACKNOWLEDGMENT

The authors wish to thank A, B, C. This work was supported in part by a grant from XYZ.

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