Atmospheric Changes and Ozone Increase in Mexico City during 2020 Lockdown Period

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Abstract

Atmospheric pollutant (NO_2, SO_2, CO, O_3 and $PM_{2.5}$) variations during the COVID-19 pandemic (during 2020) have been studied from Mexico City in Central America. Meteorological factors (i.e) rainfall, temperature along with relative humidity played an important role in increasing the photochemical reaction for the formation of O_3 and $PM_{2.5}$. Concentration pattern of O_3 and $PM_{2.5}$ were higher in all the stations in spite of the reduced primary pollutants. However, higher level of O_3 and $PM_{2.5}$ during the lockdown period in 2020 is mainly due to the air-mass exchange which happened through the broader channel in the north (Tenango del Aire Pass) and in the southeast (Cuautla-Cuernavaca valley). The higher values of particulate matter are compensated by domestic heating ("*Quédate en Casa*"/ *Stay at Home*), whereas the increase of O_3 is supported by the higher solar radiation and household activities (both indoor/ outdoor). Monitoring stations (BJ, GAM, UAM, SFE) in Mexico City indicate that the level of pollutants (except GAM) were within the WHO guidelines. Comparison of pollutants with other countries indicate a spike in NO_2, O_3 and $PM_{2.5}$ levels. Overall results indicate that the anthropogenic activities which is influenced by the meteorological parameters has affected the air quality in Mexico City and it persisted during the lockdown period.

Introduction

The COVID-19 is a worldwide ongoing pandemic, initially chronicled in Wuhan, capital of Hubei province in China (Raibhandari et al., 2020) during late December 2019. This contagious disease created chaos across the globe affecting 208 countries including the developed countries like USA, UK, Australia, Europe, Japan, Germany, Africa, Mexico, India, Singapore, Malaysia, Canada and several other Latin American countries with a total affected human cases of 44 million (as of 30th October, 2020).

Without any exception, Mexico also reported its first case during mid-January, 2020 in the state of Nayarit and Tabasco and gradually all over the country totaling 1,957,889 cases and deaths were upto 167,760 persons (as of 10th February, 2020). Among the different states in Mexico, the most affected cases was detected in Mexico City (as of 10th February, 2020). The Mexican government initiated the lockdown slowly during mid-March 2020 by ceasing all high activities and closing schools, movie theaters, restaurants, public malls to avoid large people gatherings for social distancing. Recently, air pollution is the most important environmental problem labelled in most of megacities posing threats for human health due to the presence of primary and secondary pollutants resulted from anthropogenic activities and in-situ atmospheric reactions. Mexico City, renowned as one of the five largest populated cities in the world is bustled with heavy human activities and residents > 22 million habitants (United Nations, 2018). On this context, Mexico City always pinpointed for the air pollution since 1940, the era of industrial activities and gradual rise in pollution (Lezama, 2000). There are numerous studies which reported the strangling air problems in Mexico City Metropolitan Area (MCMA) especially the high ozone (O_3) and $PM_{2.5}$ concentrations making this the most polluted City in North America (Molina et al. 2007). Despite the huge population, the Mexico City host a large vehicular fleet available as taxi cab, passenger car, ride hauling services, light duty vehicles and heavy vehicles for cargo system. After a very serious episodes of severe air pollution for several years, the Mexican government introduced Bus Rapid Transit (BRT) system as an initiative to minimize the air pollution. Since the epoch of industrialization, there was a regular increase in vehicles for freight systems considered as an important source for emitting pollutants in interurban areas and general vehicle fleet in urban areas (Bel, 2018).

Most of the megacities faces air pollution risking human health (Holgate, 2017), in recent decades, Mexico City has reported major air pollution calamity due to the high concentrations of air pollutants such as NO_2, SO_2, CO, $O_{3,}$ $PM_{2.5}$ which was high compared to the permissible Air Quality Standards guidelines (WHO, 2019). The majority of these pollutants are emitted through urban road transport containing massive vehicle fleet (metro, metro bus, microbus) and simultaneous traffic congestion, which is generally used by 12 million people (INEGI, 2018). Besides the immense use of this public transit, a study conducted on vehicle pollutant measurements discloses the commuter exposure to $PM_{2.5}$, CO and benzene especially in microbuses, buses and metro in Mexico City, which causes carcinogenic health problems (Gomez-Perales et al., 2004; Shiohara et al., 2005).

Since 1940, the Mexico City Metropolitan Area experienced a major air pollution due to urbanization and industrial activities, hence the Mexican government steps into implementing several strategies during the late 20th century to control and reduce the emissions triggering air pollution by restraining the emissions from industries also for the transport sector such as driving restrictions called "*No Driving Day*" (*Hoy No Circula* program in Spanish) in 1989. Implementing the control measures, it brought down significant changes in improving the air quality, which also happened due to the change in composition of gasoline and verification of vehicle engine (Davis, 2008; INEGI, 1988). However, particulate matter (PM) were a major pollutant emitted from the industrial areas present in the City which has happened due to in-house hold activities and different chemical additives from various sector (Soto-Coloballes, 2017; Sicard et al., 2020).

The immediate lockdown period announced across the globe made a substantial difference in the environment and the atmosphere, which was well documented through many research articles and social media. We made use of this period (upto June 2020) to identify and understand the causes, processes accountable for persisting air pollution in Mexico City Metropolitan Area. The main objective of the present study was to document and understand the changes due to the lock down which happened through industrial and transport sectors and the direct effect on the changes in the atmospheric conditions in Mexico City.

Materials And Methods

Geographical information of the Study area

Mexico City is an inland basin located at elevated position of 2240 m above mean sea level (MSL) enclosed with high mountains of Ajusco and Sierra Chicchinautzin in the south, Iztaccíhuatl- Popocatépetl dormant volcanic mountains in the east bordering the State of Mexico and Puebla (Fig. 1). Mexico City Metropolitan Area consists of 16 localities formerly known as “*Mexico City*”, comprising 59 metropolises in State of Mexico and 1 metropolis in State of Hidalgo. The topography of Mexico City indicates that it is surrounded with high mountains. In addition, a board opening in the north and a narrow passage in the south-south east at the border of the basin formerly called “*Tenango del Aire*” acts as natural ventilators for the City between the Mexico City basin and Cuautla- Cuernavaca Valley in the State of Morelos. Since 2000, the drastic transformation in the Mexico City caused urbanization and it expanded over some municipalities bordering the basin from the states of Mexico, Puebla, Tlaxcala, Morelos and Hidalgo which are under increasing population growth forming a grand urban complex in Mexico “*Mexico City Megalopolis*” as the most polluted City in the World (Fig. 1).

Meteorological settings

The Mexico City basin falls under sub-tropical highland climate, which is classified into three patterns: 1) dry winter (November to March); 2) dry summer (April to May and 3) rainy season (June to October) mainly to understand the changes. The summer is the driest season in Mexico adjoined by the presence of clear skies with low humidity and high pressure system with an average ambient temperature of 12 to 24 ˚C. The driest month have westerly current experiencing the anti-cyclonic flow along with strong thermal inversion at night (Collins and Scott, 1993). This (flow) that often lasts after the sunrise due to turbulent mixing and the strong heating by the sun enhances the photochemical reaction of the ozone (O_3) recording higher values of pollutants in Mexico City. In contrary, the rainy season have easterly winds prevailing over the mountains surrounding the Mexico City basin, which is due to convection and the thermal inversions of high moisture concentration. However, during early morning the turbulent eddies are generated from the heat from the sun causing severe vertical mixing of the pollutants (Giovanni et al., 2017).

The average annual rainfall in Mexico City is about 820 mm, which is intense from July to September. The diverse meteorological condition in Mexico city is responsible for the persisting air pollution, triggering activities in the photochemical ozone production and other secondary pollutants such as aerosol loadings and particulate matter ($PM_{2.5}$ & PM_{10}) (Garrido-Perez et al., 2018).

Mexico City suffer several episodes of ozone pollution since the last few decades especially during summer season, which is found higher than permissible limits of Mexican Air Quality Standards and WHO guidelines. The summer seasons are suspected to have UV radiations boosting the photochemical reactions. However, in the rainy season after precipitation by mid-day the ozone pollution is happening throughout the year (Molina., 2002). The low wind velocity prevailing in Mexico City with high ozone concentration during summer and low during winter (1994–2014) is very well correlated with the particulate matter contents with similar changes (Barrett and Raga, 2016). Hence, the meteorological variables were considered as most important factor towards understanding the air quality and pollution in Mexico City.

Pollutant data collection

This study was carried out by analyzing various set of data which is considered as important for determining and the understanding the discrepancies of air quality in Mexico City Megalopolis during the lockdown period. We used the meteorological data such as 1) temperature (in °C); 2) relative humidity (in %); 3) wind speed (in m/s); 4) precipitation (in mm) and air pollutant data (i.e) NO_2, SO_2, CO, O_3, $PM_{2.5}$ (in $\mu g/m^3$ expect for CO measured in mg/m^3) from a real time monitoring stations.

In this article, we have limited our data by mentioning only the diurnal average concentrations of the pollutants from January – May 2020 compared along with the annual average concentration for 2017, 2018 and 2019. The selection of the data and period was selected primarily to identify the periods which is considered as regular movements in the city limits during the past years. The open data was obtained from government network called "*Red Autómatico de Monitoreo Atmosférico*" (RAMA, 2020). This network comprises 34 stations in Mexico City and State of Mexico with regular maintenance of the laboratories and the monitoring equipment. Among the 34 stations, we selected only 5 stations for the study based on importance with massive human activities and vehicular congestions in Mexico city limits. The selected stations are as follow as: a) Benito Juarez (BJ) (Alt. 2250 MSL); b) Coyoacán (COY) (Alt. 2280 MSL); c) Gustavo A. Madero (GAM) (Alt. 2227 MSL); d) Sante Fe (SFE) (Alt. 2599 MSL) and e) UAM Xochimilco (UAM) (Alt. 2246 MSL) respectively. The studied pollutants NO_2, SO_2, CO and $PM_{2.5}$ were obtained as hourly average concentration and O_3 was obtained on average for 8 hrs to comply the standard quality.

Satellite- borne data

The primary data of pollutants concentrations were cross referred with the satellite image through spatial and temporal analysis of the pollutants. The satellite images were procured from the open access platform from NASA, which is officially available as "*NASA GIOVANNI V4.34*". The data obtained were manipulated with the aid of Geographical Information System (GIS) for the above mentioned pollutants for the period of 2018 to 2020 (January- May). The spatial distribution of each pollutant were obtained and specified for our area of interest. We have collected different atmospheric pollutants (CO, NO_2, O_3, $PM_{2.5}$, and SO_2) satellite data from 2018 to 2020 for Mexico City. The data accessed from the GIOVANNI (Goddard Earth Sciences Data and Information Services Center, or GES DISC), indicates various Geo science data from NASA satellites directly on the web portal (https://earthdata.nasa.gov/), without any disturbances of traditional data acquisition and analysis methods. The pollutants CO, SO_2, and $PM_{2.5}$ were obtained from the source MERRA 2model (GMAO 2015) and NO_2, and O_3 from the source OMDOAO3e (Veefkind et al., 2012) with a spatial resolution of 0.25°. The data were available as vector files obtained data as a vector file which can be opened in Arc GIS software (Arc Map 10.3) and further the data was classified into four groups which was used to reclassify for the pollutants.

Mexican legislatures for air quality

The Mexico City megalopolis had a great history of air pollution because of economic and demographic growth. Hence the Mexican government made a remarkable advance in improving air quality since 1990s by initiating numerous regulations in transport and industrial sectors. The Secretariat of Environment (SEDEMA) is in authority for organizing Mexico City Environmental Programs towards air quality and other environmental problems in Mexico City megalopolis and other surrounding municipalities in states of Mexico, Puebla, Tlaxcala, Morelos and Hidalgo. Moreover, Mexico City have many other governmental officialdoms for the environmental policies and problems. The Mexican Secretariat of the Environment and Natural Resources (SEMERNAT) for the protection and management of natural resources through some environmental standards known as "Official Mexican Standards" (Norma Oficial Mexicana). The abrupt actions taken by Mexican government through these environmental agencies were executing the air quality standards, monitoring the stations in majority of the municipalities, regulating vehicle engines verifications for their emission inventories, modifying the composition in the gasoline and supporting newer technologies through scientific research. In 1994, the Mexican government imposed its air quality standards for major air pollutants especially for nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), ozone (O_3) and particulate matter ($PM_{2.5}$). The above parameters were used in this study as a quality guideline for determining air quality pertained to human health and the changes during the lockdown periods.

Results And Discussion

Spatial & temporal distribution of air pollutants in Mexico City

The average concentrations of air pollutants (NO_2, SO_2, CO, O_3, $PM_{2.5}$) from five studied monitoring stations in Mexico City is shown in Table 1. Likewise, satellite images for the months of January to May 2020 (Fig. 2) were used to observe the changes in the air pollutants along with the three previous years (2017, 2018 & 2019) (Suppl. Fig. F1).

Table 1
Mean concentration of major air pollutants of five municipalities in Mexico City during lockdown and its comparisons

Locations	**Year**	**NO_2 (µg/m^3)**	**SO_2 (µg/m^3)**	**CO (mg/m^3)**	**O_3 (µg/m^3)**	**$PM_{2.5}$ (µg/m^3)**
Benito Juárez	Annual Avg. 2018	-	42.25	1.78	163.45	22.37
Coyoacán		-	-	-	-	-
Gustavo A. Madero		12.78	-	-	131.70	23.69
Santa Fe		41.65	26.19	0.89	142.79	14.74
UAM Xochimilco		68.81	37.28	1.27	138.24	19.90
Avg.		41.03	35.24	1.31	144.05	20.18
Benito Juárez	Annual Avg. 2019	59.86	11.93	0.96	137.87	15.36
Coyoacán		-	-	-	-	-
Gustavo A. Madero		83.44	0.76	-	157.39	39.34
Santa Fe		63.32	19.62	0.16	123.66	30.63
UAM Xochimilco		55.86	14.08	0.86	144.20	27.47
Avg.		65.62	11.60	0.66	140.78	28.20
Benito Juárez	2020*	76.06	31.37	13.5	148.91	30.43
Coyoacán		-	-	-	-	-
Gustavo A. Madero		83.23	-	-	169.06	16.95
Santa Fe		65.27	16.43	7.11	148.60	36.13
UAM Xochimilco		60.53	21.51	8.37	171.69	39.23
Avg.		71.27	23.10	9.66	159.57	35.26
NOM-023-SSA1-1994		400/hr	-	-	-	-
NOM-022-SSAI-2010		-	290/24 hr	-	-	-
NOM-021-SSAI-1993		-	-	12.5/8 hr	-	-
NOM-020-SSAI-2014		-	-	-	137/8 hr	-
NOM-025-SSAI-2014		-	-	-	-	45/24 hr
WHO Guidelines		200/ hr	20/24 hr	-	100/8 hr	25/24 hr

*Mean concentration for January to May

Based on the available data set compared to the annual average of 2018, 2019 and 2020 (January to May) the pollutants were seen in the concentrated in the following order: NO_2: 2020 > 2019 > 2018; SO_2: 2018 > 2020 > 2019; CO: 2020 > 2018 > 2019; O_3: 2020 > 2018 > 2019 and $PM_{2.5}$: 2020 > 2019 > 2018. Compared to the WHO values for SO_2 (20/24 hr µg/m^3), O_3 (100/8hr µg/m^3) and $PM_{2.5}$ (25/24 hr µg/m^3) the present local values indicates higher values during the lockdown period of March to May 2020. The significant reduction in SO_2, CO, O_3 during 2019 period indicate that they were mainly seen during the fuel scarcity period (García-Franco, 2019). It should also be observed that nearly 70 explosions (January to May 2020) occurred in the volcano Popocatepetl emitting approximately 2500 tons/day load of SO_2 into the atmosphere (CENAPRED, 2020). This is very well supported by the plume and wind direction which is NW-W-NNE during the months of March, April and May 2020 (Suppl. Table T1) (de Foy et al., 2009; Martin Del-Pozzo, 2009; Schiavo, 2020; SEDEMA-CDMX, 2018). In addition, the higher NO_2, CO, SO_2 values during the January, February period of 2020 is also attributed to the smoke plumes released from the fireworks used during the festival seasons during the end of the year releasing high quantity of sulfate nitrate, ammonium and potassium, which is responsible for the 50% of total particulate matter (García-Franco, 2019; Retama et al., 2019).

Carbon monoxide values in Mexico City varied from 7.11 to 13.5 mg/m^3 in the five studied locations. However, overall calculated values were well below the permissible limits of NOM-021-SSAI-1993 (Mexican Norm.). Comparing the previous two years (2018-19) data on CO in Mexico City, the values indicate a five to seven-fold increase during the lockdown period. Higher values of CO during the lockdown period in Mexico City is mainly due to the indoor emission of CO mainly due to low grade solid fuel, biofuels clogged chimneys, gas burners, home cooking, wood-burning fire places, decorative fire places etc., could vent CO into indoor spaces and subsequently to the main route (Howard et al., 1991; Buchholz et al., 2016; Murphy et al., 2007; Wolff et al., 2013). In contrast, the lower values during the two previous years (2018-19) indicate that the major population in the City limits are often out in the streets due to the various workload as individuals and are well stretched in industrial sectors (Levesque et al., 2001; Maroni et a., 2002). The above distribution of personal in different work places also reduces the use of individual emission of CO mainly in indoor conditions. In addition, the presence of road side restaurants and food stalls, which is often popular in developing mega cities like Mexico also increases the presence of CO and its subsequent reduction in CO in April-May 2020 (Velasco et al., 2019).

Higher values of $PM_{2.5}$ in the lockdown period is mainly due to the presence of secondary pollutants, which is generated through photochemical reaction through NO_2, SO_2 and CO (Garcia-Franco, 2020). This is also supported by the temperatures (18–22°C) during the months of April and May 2020, where the photochemical reaction is triggered. Earlier report on $PM_{2.5}$ concentrations in Mexico indicates that high values are found in areas close to metro stations and rapid transit system, which includes the metro and metrobuses (Velasco et al., 2019). Moreover, in congested cities and high traffic zones the high presence of $PM_{2.5}$ suggest that the majority of $PM_{2.5}$ is due to the transport sector, which are trapped during morning and evening periods (Hernandez-Paniagua, 2018). Recent studies during the lockdown periods in different countries also suggest that the increase in particulate matter was counter balanced by domestic heating (Sicard et al., 2020). Likewise, the higher values of SO_2, $PM_{2.5}$ combine during the lockdown period is not associated to the reduction of vehicles rather than the volcanic explosions from Popocatepetl during the latter half of the lockdown period (March to May 2020) (Suppl. Table T1).

Role of wind in transporting pollutants

Mexico City have three types of seasons namely dry summer, dry winter and rainy season. During the dry summer (April and May) the photochemical reactions of VOC, NO_2 and SO_2 often causes smog, aerosol loadings (values in μg/m^3) with high O_3 (159.57) and $PM_{2.5}$ (35.26) (Cohen et al., 2018; Salcedo et al., 2012). Higher concentrations (values in μg/m^3) of NO_x (71.27) and O_3 (148.60) during early morning are from the vehicle rush during the peak hours (8 to 10 am) is directly linked to the photochemical reaction. Moreover, the pollutants have a tendency to circulate through synoptic pattern throughout the year due to their regional settings of high latitudes and altitude (Edgerton, 1999). In addition, the topography of Mexico City basin shows it is surrounded by high elevated mountain causing a circulation pattern effectively promoting the diurnal movement of airborne particles of O_3 and $PM_{2.5}$ within the basin, causing a persistent O_3 enrichment (de Foy et al., 2006). Despite the (in central Mexico region) circulation pattern, the pressure system which prevails in the basin creates a great difference in distribution of pollutants inside the basin. This is supported by the broader opening in the north of the basin which acts as a natural window of the City providing ventilation and in the south the "*Tenango del aire pass* (TAP)". The natural openings/ channels transmit the polluted air by northerly and southerly winds from TAP with high O_3 (110 μg/m^3) towards MCMA. The enriched values (μg/m^3) of NO_x (71.27), O_3 (159.57) is mainly through the corridors of Cuautla – Cuernavaca valley under high pressure system (S-SSE-SE wind direction) (Fig. 3). Meanwhile, the Cuautla – Cuernavaca valley in the south transmits the clean air from Amecameca prevailed with southerly winds under low pressure system (LPS) with lowest ozone concentration (80 μg/m^3) due to the air mass exchange event which happened in a circular manner inbetween the mountain openings (Garcia-Reynoso et al., 2009; Salcedo et al., 2012; Garcia-Yee et al., 2018). Moreover, the increase of O_3 is also due to the reduction in particulate matter content (compared to before lockdown), which also leads to surface O_3 levels through higher solar radiation and possibly through house hold garden related activities (Deng et al., 2010; Li et al., 2013; Su et al., 2003).

Meteorological influence of wind over the pollutants (NO_2, SO_2, CO, O_3, $PM_{2.5}$, Wind speed) in the present study is analyzed for four stations (BJ, GAM, SFE, UAM) in the study area (Fig. 3a-x). Results from the northern monitoring station GAM indicates higher concentration (in μg/m^3) of NO_2 (83.23), O_3 (169.06), $PM_{2.5}$ (16.25), which also follows a NNE-NE-ENE direction. The wind velocity was 5.5 to 8.8 m/s causing pollutants to more a longer distance from north to south by the strong influence of wind (Fig. 3g, j-l) (Fast et al., 2007). No clear distribution pattern is observed in SO_2 and CO. The trajectory of the pollutants suggests that the ventilation of polluted air is transferred through the broad channel in the northern part of Mexico City and it is also depending on the velocity and air pressure (Fast et al., 2007). Data from the central monitoring station indicates elevated higher values (in μg/m^3) of NO_2 (71.27), CO (9.66), O_3 (159.27) and lower values of $PM_{2.5}$ (35.26) and SO_2 (23.10) respectively. The wind direction follows a S-SSE-SE and N-NNE-NE-ENE-E, where pollutants are carried away with a maximum velocity of 4.4 to 5.4 m/s (Fig. 3a-f).

The two southern monitoring stations UAM and SFE indicates that the concentration (values in μg/m^3) pattern is at the intermediate level: NO_2: 60.53, 65.27; SO_2: 21.51, 16.43; CO: 8.37, 7.11; O_3: 171.69, 148.60; $PM_{2.5}$: 39.23, 36.13 and wind speed (in m/s): 7.7, 8.8 indicating a SSE-SE-ESE direction respectively. The air mass exchange is mainly through the volcanic mountain series of Xaltepec used Teuhtli. Furthermore, it is evident that there is a presence of "*Rossby wave*" breaking event, which is an anticyclonic process where cold air passes towards equator and the warm air towards westward direction (Rodrigues and Wollings, 2017). This massive instability in the atmospheric conditions in Mexico City clearly affects the air quality conditions in the region (Silva-Quiroz et al., 2019).

Role of temperature in distribution of pollutants

Temperature is another important factor governing all the meteorological factors like rainfall and pressure. Like wind, temperature is also an important factor for the formation of secondary pollutants (values in μg/m^3) O_3 (UAM: 171.69), $PM_{2.5}$ (UAM: 39.23). However, the primary pollutants like NO_2 (GAM: 82.33); SO_2 (BJ: 31.37); CO (BJ: 13.5) are formed due to the photochemical reaction (Garcia-Franco, 2020; Sicard et al., 2020). The above results are very well supported by previous studies indicating a variability in the upper-troposphere circulation "*Madden-Julian Oscillation*", where low UV radiation and less ozone exists (Barret and Raga 2016). Ozone concentration studies in 2015 indicates that the temperature reaches higher values during the hot-dry seasons accompanied by a minimum boundary layer height (Garzon et al., 2015). The major correlation with the higher values (μg/m^3) of $PM_{2.5}$ (UAM: 39.25) and O_3 (UAM: 171.69) during the March to May period, where the temperature inversions occurs in the day and vertical mixing of air column happens during the night time (Whiteman et al., 2000; Garcia-Franco et al., 2020).

Changes in vehicle and industrial emission inventories

As this article mainly infers the origin of pollutants from the transport sector which was later affected by the meteorological influences. The record of the inventories of transport sector (including road & air) and industrial emissions where the reduction in emission ceased during February to May 2020.

General surface/ ground transportation movements in Mexico City involves 17 million commuting trips during week days (INEGI, 2017). The aviation movements for national/ international movements is documented in Table 2. Six different regions aviation movements were considered from the available data sets: a) Domestic & International (DL); b) American international (AI); c) Canadian International (CI); d) Central & Latin America (CL); e) European (E) and f) Asian (A). The movement of air traffic for the month of February and March 2020 were reduced from different routes were: February 2020 (in %): DI (11.22) > E (9.83) > A (7.56) > CL (7.26) > AI (6.65) > CI (2.78) and March 2020: CL (35.44) > DI (24.50) > CI (23.75) > AI (13.33) > A (11.46) > E (2.96) respectively. The data also infers that the movement of air traffic is based on the policies of each country and region. This is also inferring that CO_2 reduction takes place due to the reduction of air traffic (Le Quere et al., 2020).

Table 2 **Air carriers services and it's reduction during the initial lockdown period in Mexico**

Air Carriers	2020 (No. of flights)			Reduction in flights (%)		
	Jan	Feb	Mar	Jan$^+$	Feb	Mar
Domestic & International (DL)						
Aeromar	2163	1930	1860		89.23	85.99
Aeromexico	7307	6277	5225		85.90	71.51
Aeromexico Connect	10054	8953	7511		89.05	74.71
Aerounion*	291	236	263		81.10	90.38
Estafeta*	341	285	325	100	83.58	95.31
Interjet	10219	9081	6309		88.56	61.74
Mas Air*	126	104	110		82.54	87.30
Magnicharters	494	306	310		61.94	62.75
Vivaaerobus	6534	5809	5492		88.90	84.05
Volaris	11895	10899	9908		91.63	83.30
Total Services & CO_2	49424	43880	37313	100	88.78	75.50
American International (AI)						
Alaska Airlines	1139	1136	1228		99.74	107.81
American Airlines	3113	3141	2897		100.90	93.06
Amerijet International*	24	26	24		108.33	100.00
Atlas Air*	40	42	42		105.00	105.00
Compass Airlines	70	62	62		88.57	88.57
Continental Express	595	578	462		97.14	77.65
Delta Airlines	3115	2708	2271	100	86.93	72.91
Envoy Air, Inc	1086	1016	863		93.55	79.47
FEDEX*	167	161	166		96.41	99.40
Frontier	353	352	306		99.72	86.69
Jet Blue Air	324	274	263		84.57	81.17
Mesa Airlines	1783	1605	1549		90.02	86.88
Southwest Airlines	1070	962	904		89.91	84.49
United Airlines	2839	2609	2586		91.90	91.09
Total Services & CO_2	15718	14672	13623	100	93.35	86.67
Canadian International (CI)						
Air Canada	886	839	745		94.70	84.09
West Jet	1179	1182	930	100	100.25	78.88
Total Services & CO_2	2065	2021	1675	100	97.22	76.25
Central & Latin America (CL)						
Aerolineas Argentinas	52	50	40		96.15	76.82
Aerorepublica	59	41	24		69.49	40.68
Avianca	309	290	206		93.85	66.67
Copa	850	792	580	100	93.18	68.24
Lanperu	212	200	108		94.34	50.94
Volaris Costa Rica	115	108	73		93.91	63.48
Total Services & CO_2	1597	1481	1031	100	92.74	64.56
European (E)						
Air France	151	137	123		90.73	81.46
British Airways	88	84	86		95.45	97.73
Cargolux Airlines*	90	61	96		67.78	106.67
Iberia	126	122	114	100	96.83	90.48
KLM (Royal Dutch Airlines)	62	58	56		93.55	90.32
Lufthansa	120	116	90		96.67	75.00
Turkish Airlines	70	68	62		97.14	88.57
Total Services & CO_2	707	646	627	100	90.17	97.04
Asian (A)						
Emirates Arabes	155	150	112		96.77	72.26
Korean Air	20	24	24	100	120.00	120.00
Qatar Airlines	73	79	81		108.22	110.96
Total	248	253	217	100	92.44	88.54

*Cargo services. $^+$For the month of January 2020 for calculation purpose, the values are kept at 100.

Based on the surface transport movements in Mexico City from January to May 2020 indicates a wide variations and non-reduction of movements in some sectors. The usage (in millions) from January to May (2020) is as follows: metrosystem 130.709 (January) to 35.900 (May); public transport 12.4 (local and long distance buses) (in January) to 33.22 (May) and short transport system 44.16 (micro bus) (in January) to 11.61 (in May) (INEGI, 2020). Eventhough based on the above data there was a reduction in public transport movement during the lock down, other services were operating as it is during the normal conditions. This clearly contributes more towards emissions of NO_2, SO_2, CO, $PM_{2.5}$ and VOC as they are mostly perceived from the transport sector. The above inference is very well supported by earlier studies in Mexico City that apart from transport sector, industrial source (for NO_2, SO_2) and soil erosion (for $PM_{2.5}$) and solvent paints (for VOCs) are responsible for the presence of these pollutants (Molina et al., 2019). Likewise, the adaptations from MOBILE 6.2 - Mexico and Moves – Mexico found significant reduction in total emissions (in %) for NO_x by -37, CO by -52 and VOCs by 26 percent. However, there was an increase observed (in %) for O_3 by 6.6 due to the operations in urban traffic stations PM_{10} by + 8 and $PM_{2.5}$ by 6 mainly due to the contributions from gasoline based taxis and passenger cars (Guevara et al., 2017).

Industrial sector in Mexico City which has 26 different types (paper, manufacture, mining, fabrication, plastics, rubber) plays a major role in the emission and in transporting the pollutants. The "*Monthly industrial activity indice* (MIAI)" was calculated based on the data from 2019 (April-May). The calculated MIAI values for the construction industry indicates that it was 105, 99.5 (April, May 2019) and 64.7, 63.8 (April, May 2020) respectively. Likewise, for manufacturing industries it was 115.4, 114.9 (April, May 2019) and 74.3, 74.1 (April, May 2020). Overall, the reduction of industrial activity was between 35.7 to 40.3% (construction) and 40.8 to 41.1% in manufacturing sector. In the mining industry it is almost maintained the same way 70.3 to 73.1% (for April-May 2019) and 68.2 to 72.3% (for April-May 2020) for Mexico City (Suppl. Fig. F2a-j). Air quality/ emission studies from these industries often indicate that toxic metals (As, V, Fe, Cu) dominate due to the increase in $PM_{2.5}$ (Morales-García et al., 2014). The above MIAI values suggest that the main contributors exist due to the emissions which also has a direct effect on the higher values of VOCs that often has a direct impact on O_3 (Koupal and Palacios 2019).

Statistical Information

Statistical analysis was done with the available data as well as the meterological variables of temperature and rainfall for the year 2020. Dendrograms were generated which indicated two different clusters which high linkage distance (Fig. 4). The long linkage distance between O_3 and rainfall (avg. rainfall of 20.92 mm for March to May 2020) infers the presence of high O_3 and the production during the dry seasons (Velasco, 2017). The short linkage values of $PM_{2.5}$ and SO_2 indicates that the particulate matter contents are mainly due to the geothermal activity mixed with wind direction (NW) along with the vehicle emissions. The individual linkage of NO_2 with other parameters (O_3, $PM_{2.5}$, CO, SO_2) suggest that NO_2 is the controlling factor for the formation of O_3 and for the generation of $PM_{2.5}$ which also depends in the temperature and other pollutants (Murphy et a., 2007). The above inference is also supported by the notion "*Stay at Home*" (*Quédete en Casa*), where household heating has increased multiple times (Sicard et al., 2020). The short linkage distance between CO and temperature specifies the absorption of particular radiation where the generation of CO and temperature has a direct relationship.

Correlation matrix results ($p > 0.05$) clearly infers a negative value ($r^2 = -0.87$) with NO_2 indicate that the SO_2 in is from an external source mainly due to the explosions in volcan Popocateptl assisted by the wind direction. However, the strong association between O_3 *vs* NO_2 ($r^2 = 0.57$) and O_3 *vs* CO ($r^2 = 1.00$) indicates photochemical reaction and O_3 increase (Chin et al., 1994). Particulate matter indicates positive correlation with NO_2 ($r^2 = 0.94$) which is a governing factor, whereas the negative relationship with SO_2 ($r^2 = -0.98$) indicates the less conversion process responsible for the $PM_{2.5}$ particles. Positive correlation (r^2) of temperature with NO_2 (1.00), CO (0.54) and $PM_{2.5}$ (0.96) suggest that temperature is the dependent factor for the conversion of NO_2 and SO_2 for sulfate and nitrates (Eatough 1994; Khoder, 2002; Lin et al., 2019). The negative relationship (r^2) of rainfall with NO_2 (-0.84), CO (-0.93), $PM_{2.5}$ (-0.61) and temperature (-0.81) specifies the low reaction rate for the conversion of NO_2 and SO_2 to nitrate and sulfate during precipitation time. The moderate positive value for SO_2 *vs* rainfall (0.46) indicate the higher rate of conversion process due to the surface inversion during the night period (Lin et al., 2019). Overall results indicate that the distribution of pollutants is dependent on meteorological parameters, whereas the insignificant associations shows the independency of the factor for their fate and state in the atmosphere.

Comparative Studies

Based on the available data compared to the air pollutants reported from different countries during the present pandemia from January till date (Before the lockdown & After lockdown), we have collected the available data and it has been compared with reference to WHO guidelines (Table 3).

Table 3

Comparison of air pollutants reported before and after lockdown across the globe

Country	**Locations**	**Before Lockdown (before March 2020)**					**After Lockdown (after March 2020)**					**Reference**
		NO_2	**SO_2**	**CO**	**O_3**	**$PM_{2.5}$**	**NO_2**	**SO_2**	**CO**	**O_3**	**$PM_{2.5}$**	
India	Delhi	45.59	16.08	1.03	34.05	80.51	20.16	13.19	0.72	34.32	37.75	Mahato et al., 2020
China*	44 cities	-	-	-	-	-	13.66	6.76	4.58	-	5.93	Bao & Zhang., 2020
Brazil	Sao Paulo	24.4	-	0.4	40.2	12.4	19.2	-	0.1	44.6	12.4	Nakada & Urban., 2020
Rio de Janeiro[†]	Bangu	-1.8	-	-15.2	-	33.5	-16.8	-	-42.4	-7.8	-	Dantas et al., 2020
	Iraja	28.8	-	-	-	31.1	1.4	-	-	-2.7	-	Dantas et al., 2020
	Tijuca	-	-	12	-	63	-	-	-30.3	34	-	Dantas et al., 2020
Kazakhstan	Almaty	37	49	674	30	27	24	52	343	34	38	Kerimray et al., 2020
China	Yangtze River Delta	50	7	0.9	43	56	40	6	0.7	64	30	Li et al., 2020
Europe[a]	Nice	30.9	-	-	39.5	10.9	12.5	-	-	77.6	12.4	Sicard et al., 2020
	Rome	46.4			33.3	21.8	21.5			61.9	14.3	Sicard et al., 2020
	Turin	51.3			25.2	37.6	23.9			64.4	16.6	Sicard et al., 2020
	Valencia	27.8			31.6	18.8	8.3			65.8	10.7	Sicard et al., 2020
Mexico	2020	January to March					April to May					
	Benito Juárez	46.75	17.39	16.88	62.27	27.13	36.26	7.70	8.38	84.97	32.63	Present study
	Gustavo A. Madero	48.93	-	-	73.21	36.82	41.15	-	-	94.79	3.71	
	Santa Fe	39.01	9.79	9.63	72.10	29.33	31.81	3.94	3.94	78.16	34.28	
	UAM Xochimilco	28.36	11.64	9.41	73.60	33.83	34.74	5.94	5.91	96.76	39.62	
WHO Guidelines	-	200/hr	20/24 hr	-	100/8 hr	25/24 hr	200/hr	20/24 hr	-	100/8 hr	25/24 hr	

[a]Mean concentrations recorded at four station before and during lockdown; All values in µg/m^3 (except CO as mg/m^3); *Air Quality Index; [†]Variation in the air pollutants (%)

NO_2 values after the lockdown period in Mexico City is high compared to other countries, which is mainly due to the direct emissions from vehicles. Likewise, SO_2 and CO values indicate spike in some monitoring stations (especially in Benito Juárez), but it was lower than the permissible limits of WHO. The higher values in BJ alone is mainly due to topographical features of the station and the wind direction S-SSE-SE. Ozone values were well within the permissible limits of WHO, but it two to three fold higher than other countries. $PM_{2.5}$ values were higher in Mexico City when compared to other countries as well as WHO values which is mainly attributed to the photochemical reactions and solar radiations of the primary pollutants (Garcia-Yee et al., 2018; Sicard et al., 2020).

Conclusion

Mexico City is well known as one of the most polluted cities in North America and the present article focuses on the changes in the air quality status amid the present pandemic which has shook the whole world in one way or the other.

Primary and secondary data sets were generated to monitor the pollutants (NO_2, SO_2, CO, O_3 and $PM_{2.5}$) in four different monitoring stations located in the Mexico City area. The results indicate that higher values in GAM for all the pollutants which is two to three fold higher than the WHO permissible limits. The increase in pollutants were mainly due to the meteorological factors like rainfall, temperature, relative humidity, wind speed and its direction which foster the photochemical reaction. This is very well supported by the evaluation of statistical analysis indicating that the enrichment of pollutants (NO_2, SO_2, CO) were from vehicular fleet and industries. The higher temperatures often promote the intense photochemical reactions which enhances the formation of O_3 and $PM_{2.5}$ which is observed in all the stations despite the lockdown period which were are highly controlled by the wind direction and precipitation. It is clearly observed that Mexico City suffers severe air pollution through both natural as well as anthropogenic ways and the persistency of the pollutants happens via broad channel in the narrow passage (Tenango del Aire) and Cuautla-Cuernavaca Valley in the south. It is clear that the government should form strong strategies towards air quality management tools with updated technology for both transport vehicles and cars with changes in emissions standards, which will help cooperate restore the air quality standards.

Abbreviations

BJ: Benito Juárez; CO: Carbon monoxide; GAM: Gustavo A Madero; MCMA: Mexico City Metropolitan Area; MIAI: Monthly industrial activity índices; MOBILE 6.2: Mobile Source Emission Factor Model for Mexico; NO_2: Nitrogen dioxide, O_3: Ozone; $PM_{2.5}$: Particulate matter; SFE: Santa Fe; SO_2: Sulfur dioxide; UAM: Universidad Autónoma de Metropolitana; WHO: World Health Organization

Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

All data generated or analyzed during this study are included in this published article (and its supplementary information files)

Competing interests

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Figures

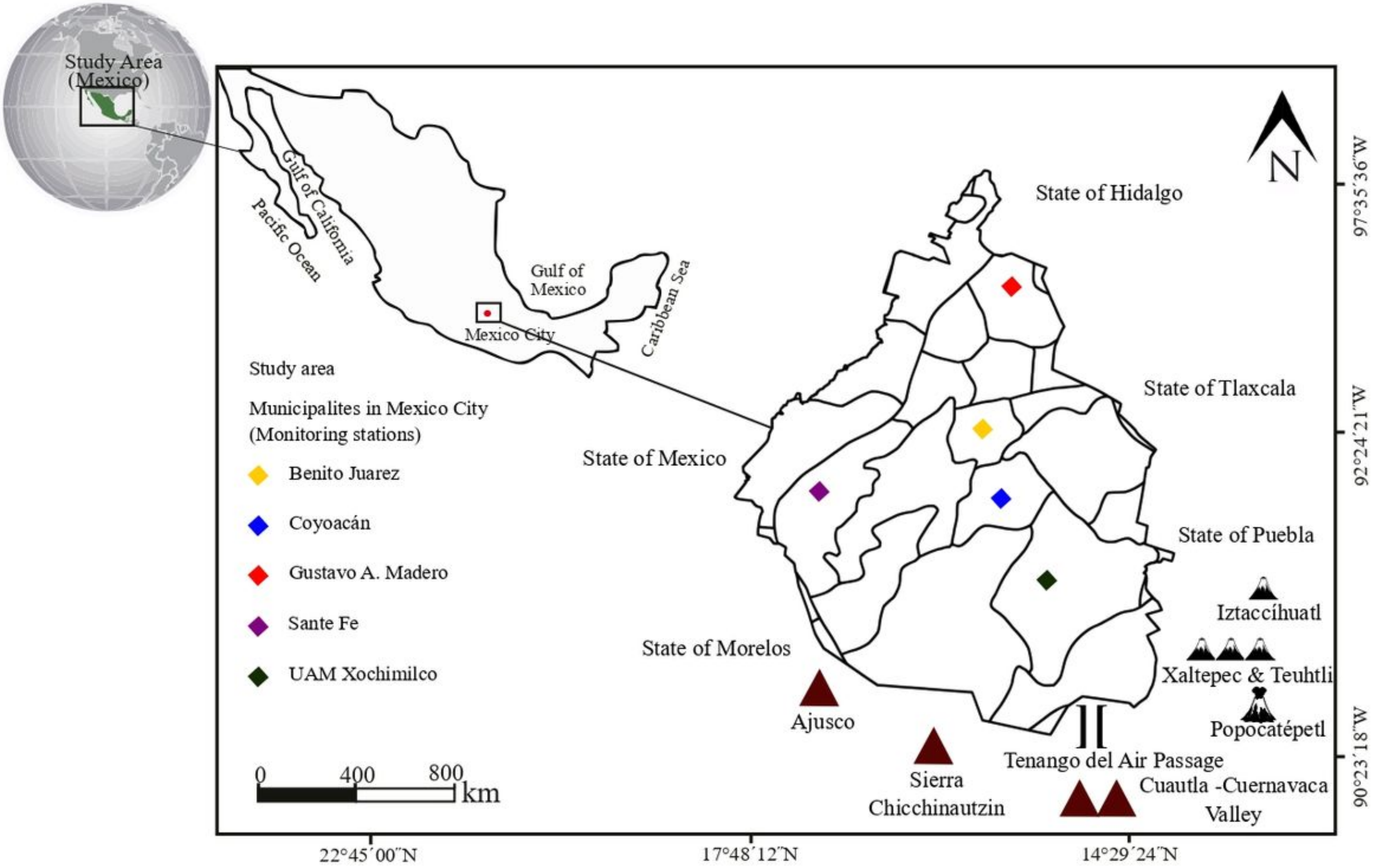

Figure 1

Map showing the Study area and other major Cities in Mexico. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

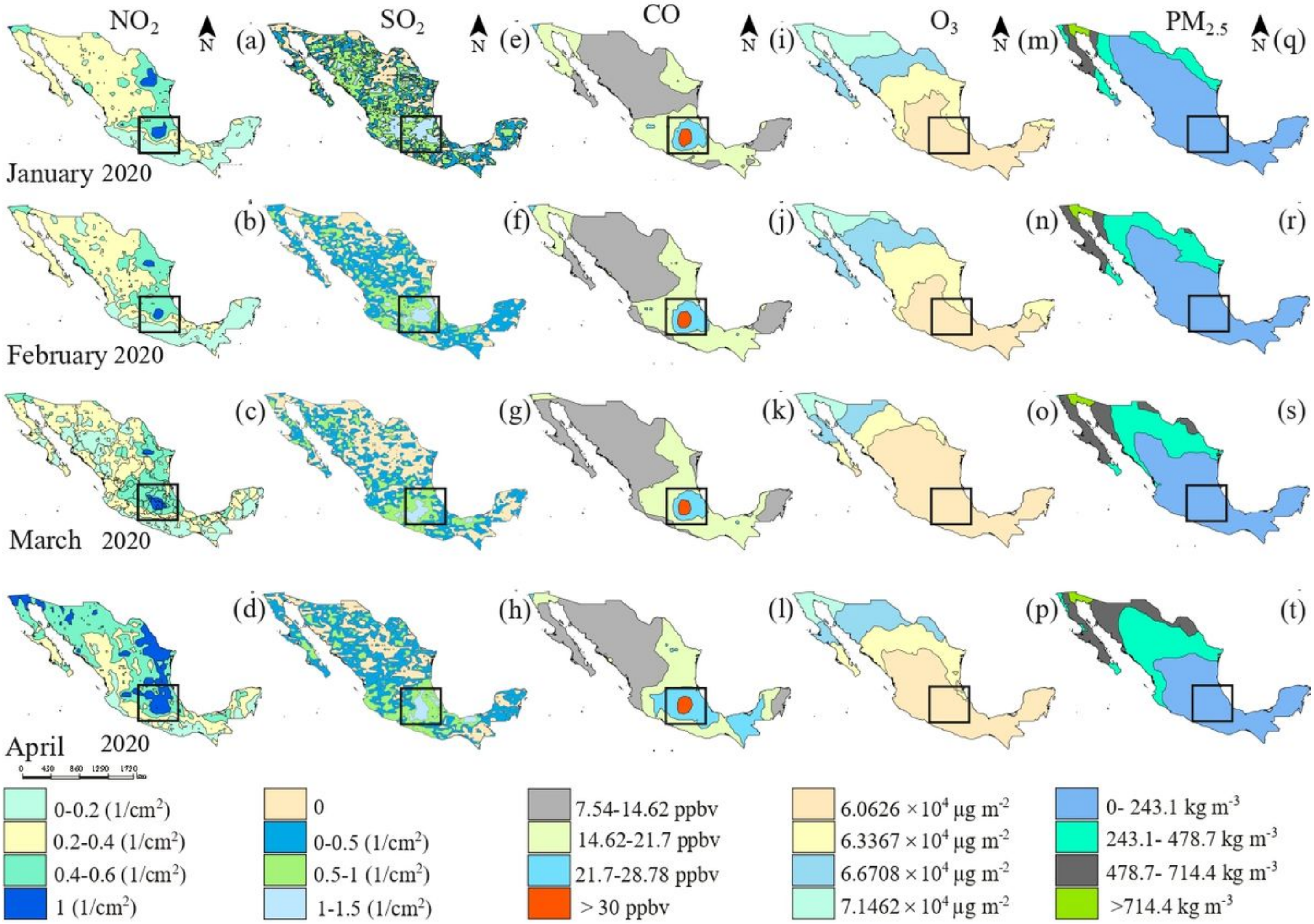

Figure 2

Concentrations of major air pollutants in Mexico from January-May, 2020 (In frame: Mexico City) Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

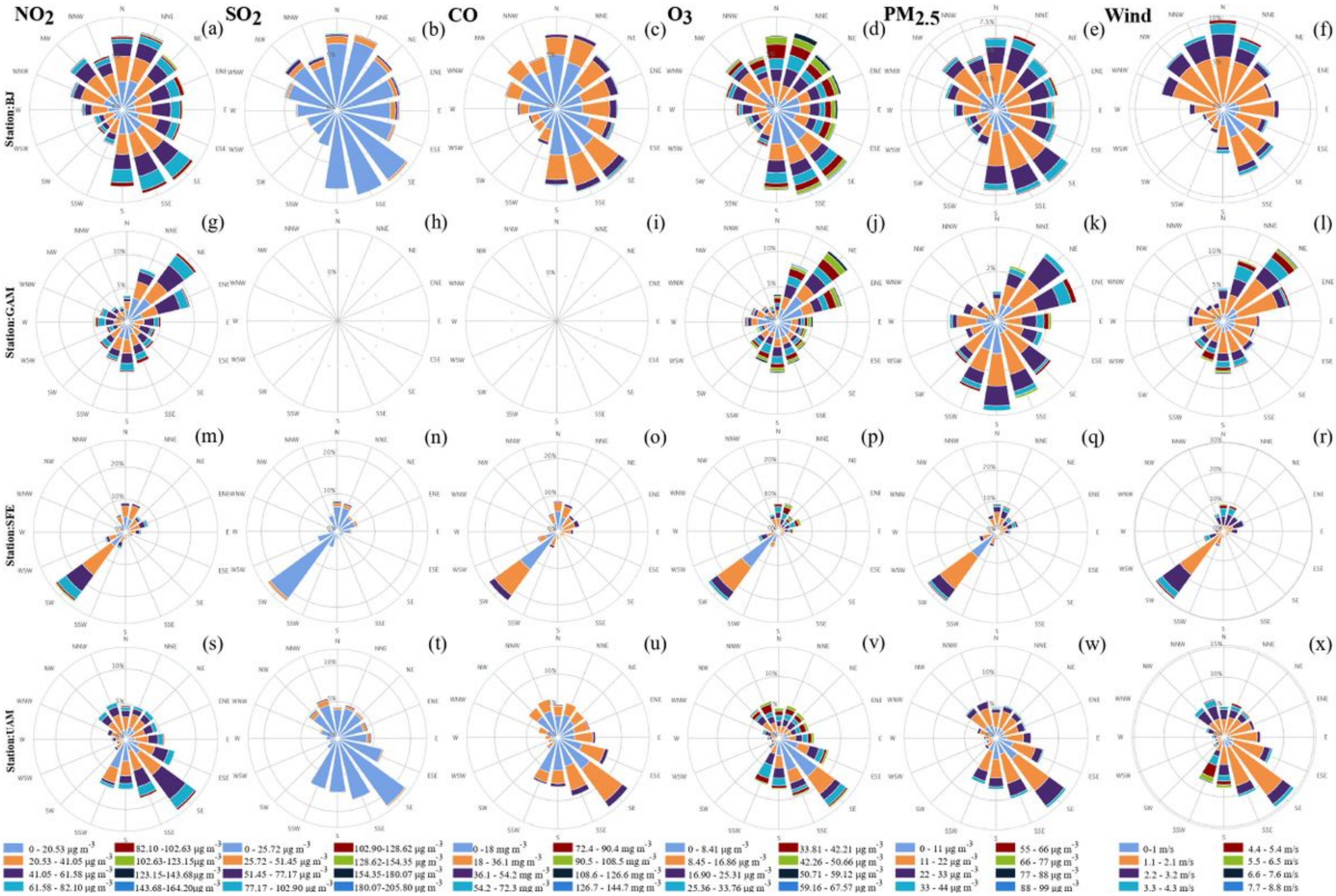

Figure 3

Diagram representing distribution of major air pollutants and wind Ross in four air monitoring stations in Mexico City, Mexico (January-May, 2020)

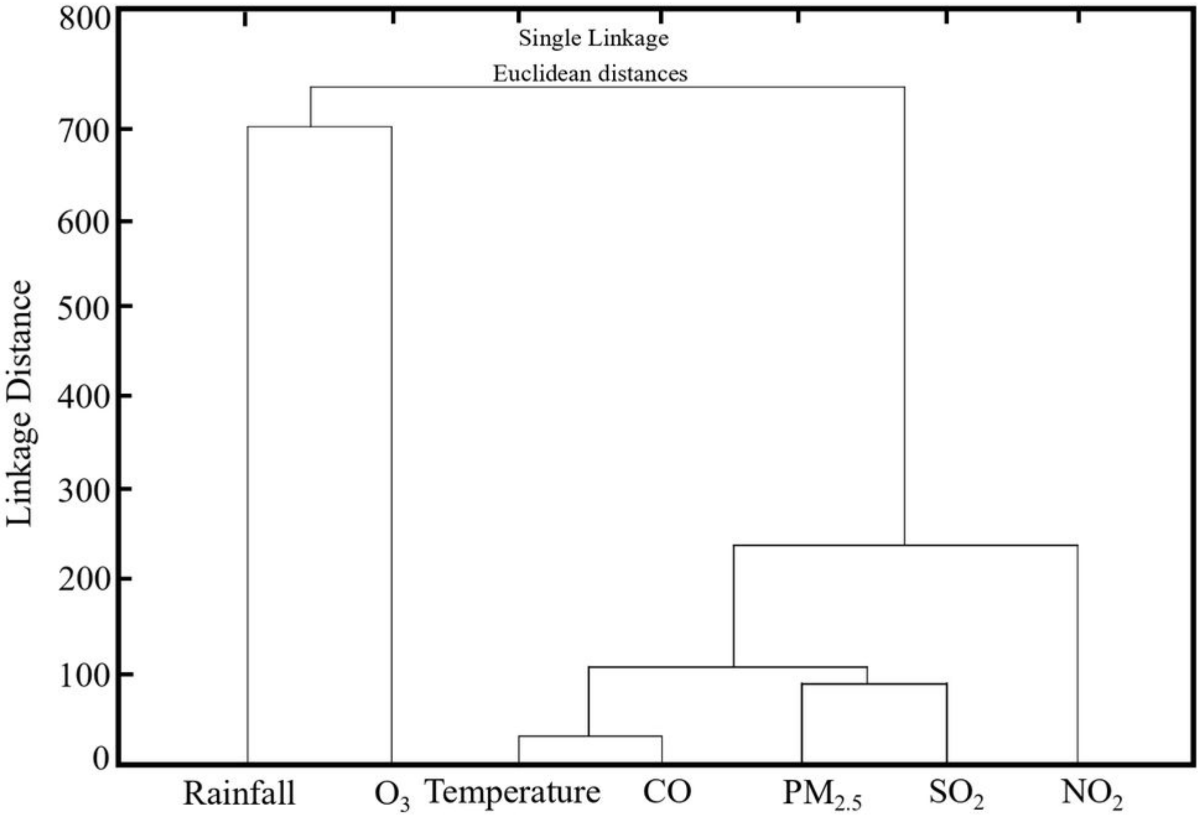

Figure 4

Dendrograms for major air pollutants and meteorological factors (January-May, 2020) from four air monitoring stations in Mexico City, Mexico

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