Climate-driven unprecedented events: impacts on Monterrey urban air pollution

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Abstract

Extreme weather episodes have increased in frequency and intensity due to climate change. Record-breaking temperatures, prolonged tropical or subtropical storms, and drought have greatly impacted many large urban areas, changing air pollutants. The present work analyzes the pollutant concentrations affected by the passage of unprecedented events such as Hurricane Hanna, cold fronts, wildfires, and African dust clouds over the Monterrey urban area in the period 2015-2022. The average percentage changes with respect to the baseline of the primary and secondary pollutants during the most strict pandemic lockdown were mainly attributed to exceptional climate phenomena. The PM_{10} percentage differences calculated with the random forest deweather method as well as the anomalies formula had opposite changes to raw data without the presence of extraordinary occurrences. These findings are of particular interest in establishing methods for further quantifying the influence factors and formulating a better air quality policy in large cities facing new climate challenges.

Keywords: Extreme weather events, Air pollutants, Deseasonalized, Deweather, Climate change

1 Introduction

The World Health Organization (WHO) recognizes that the disease burden associated with air pollution is similar to that of the biggest health threats in large metropolitan areas [1]. Moreover, assessing the changes in atmospheric photochemistry, meteorology, and pollution is essential for proposing effective policies on air quality. The COVID-19 pandemic provided an opportunity to study nitrogen dioxide (NO_2), ozone (O_3), particulate matter (PM), and sulfur dioxide (SO_2) worldwide [2], as most countries implemented a mandatory lockdown to stop infection, unintentionally benefiting the environment [3, 4]. The reduction in vehicle traffic and the closure of industrial operations led to a drop in atmospheric pollution [5–8], especially in the major metropolises [9, 10]. In particular, NO_2 decreased along the full lockdown period in at least 63 cities around the world [11]. In a similar way, the low $PM_{2.5}$ values reflected some degree of the partial and total activity shutdown in most cities [9, 12], such as a decrease ranging from 5.93% [13] up to 46.5% [14] in China and nearly 200% in India [15]. These changes were generally much lower in some urban areas of Europe than in Asia [6, 16] and a slight increase in some US cities [17, 18]. Since the COVID-19 disease was identified, China, India, and the USA lead the list of countries with publications about lockdown and air pollution, while Mexico is one of the most underexplored [19]. Comparative studies with respect to prior periods have predominated, but few have examined the meteorological and environmental causes [20–22], and even less in the post-pandemic period [23]. Although the pandemic restrictions provided great data to fill the knowledge gap about air pollutants, there are still unresolved questions about cities where the reduction was not significant. Monterrey Metropolitan Area (MMA) is an industrial development hub in northeastern Mexico, with more than 4000 foreign-capitalized companies accelerating urban growth [24]. Furthermore, its proximity to the United States border maintains one of the principal commercial routes and an intense flow of heavy transportation [25]. The Pan American Health Organization has recognized PM_{10} in MMA as one of the highest in Latin America [26]. Its particle composition includes black carbon (BC) [27] sulfates, organic carbon (OC) [28] and Volatile Organic Compounds (VOCs), with a seasonal dependence on maximum photolysis and temperature [29]. Carbonyl compounds increase in the morning and decrease in the afternoon [30], which are sensitive to the NO_x–O_3 relationship [31]. Likewise O_3 has a sensitive response to the changes in NO_x and VOCs emissions, meteorology, and photochemistry [32]. Mobile sources are the main regional source of $PM_{2.5}$ and its precursors (NO_x, VOCs, and NH_3) [33]. The state vehicle register enlists about 2 million, 700 thousand auto motors [34], that substantially contribute to metropolitan emissions. Recently, Tesla announced the construction of its largest plant in the world on the Monterrey outskirts [35]. This urban area is a key point for the investigation of economic growth, increasing emissions, and the energy transition. Consequently, the aim of this work is to analyze eight years (2015-2022) of air pollutant observations affected by unprecedented events in Monterrey, one of the largest cities in the Western Hemisphere [36].

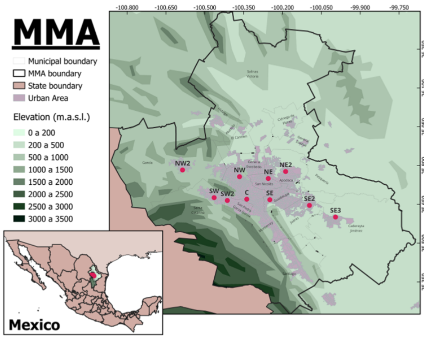
2 Materials and Methods

2.1 Mobility and COVID-19 cases

The *Healthy Distance Program* was a countrywide strategy in Mexico based on social distancing measures and the closure of all non-essential activities [37]. From the beginning of the pandemic, some local governments disagreed with the national recommendations, as was in the MMA [38]. It implemented a mixture of measures from March 2020 to October 2021 (Table S1). Social media information was widely used as a measure of mobility during the lockdown. Figure S1 shows the COVID-19 cases [39], the mobility from a *Python* library [40], and the Unified Mobility Index (MIU) [41].

2.2 Ground data

The Integral Environmental Monitoring System (SIMA) records in the MMA the criteria pollutants $PM_{2.5}$, PM_{10}, NO_2, O_3, SO_2, and CO. Additionally, this network also collected meteorological data on humidity, temperature, global solar irradiance, precipitation, wind speed and direction. The available data for the period 2015–2022 were analyzed, except for the SE3 station that started operations in 2017. The CO measurements were not included because of a lack of calibration from 2016 to 2021. Figure 1 shows and lists the selected stations that comply with at least 75% of the available monthly measurements per pollutant [42].



Code	Municipality	Environment
C	Monterrey	downtown
NE	San Nicolás	urban
SE	Guadalupe	residential
NW	Monterrey	urban
SW	Santa Catarina	urban-quarries
NE2	Apodaca	urban
SE2	Juárez	rural-industrial
SE3	Cadereyta	rural-refinery
NW2	García	rural-quarries
SW2	San Pedro	ecological park

Fig. 1 SIMA stations (red dots) in the MMA.

2.2.1 Deseasonalized air pollutants data and anomaly calculation

A function derived from the linear term and truncated Fourier series was fitted with a frequency of $K = 2$, and its coefficients were obtained [20] for the baseline (January 2015 to December 2019). The air pollution anomalies $A(t)$ were calculated as follows:

$$A(t) = D(t) - \left[c_0 + c_1 t + \sum_{k=1}^{K} \left(a_k \cos(2\pi tk) + b_k \sin(2\pi tk) \right) \right] \quad (1)$$

By subtracting the linear trend $(c_0 + c_1 t)$ and the Fourier fitting from the original air pollutant measurements $D(t)$, the influence of seasonality and long-term trends were reduced. Considering meteorological conditions, the pollutant measurements in the presence of daily accumulated precipitation of 10 mm and wind speed values of 60 km/h were filtered.

2.3 Deweather model for PM_{10} data

Machine learning methods to determine changes in air quality have gained popularity over the past decades. Random Forest (RF) is a regression model that has been implemented to extract meteorological influences in air pollution [43–45]. It involves applying a normalization technique to meteorology based on pollutant emissions [46–48]. The RF model was trained using measurements in the period 2015-2022, with resampling for each monitoring station. The algorithm inputs were the meteorological (relative humidity, temperature, pressure, direction, and velocity wind) and temporal (hour and Julian day) variables to predict the PM_{10}. The RF process repeats hundreds to thousands of times until it obtains an average regression called Deweather. In this work, the Deweather model was a method to evaluate the monthly changes in PM_{10} during lockdown, comparing the results with anomalies analysis.

2.4 Satellite data

2.4.1 OMI

The Total Ozone Column (TOC) [49], NO_2 Vertical Column Density (VCD) [50], and maps of Aerosol Optical Depth at 500nm (AOD_{500}) are provided by the Ozone Monitoring Instrument (OMI) on board the AURA-NASA satellite. The satellite overpass time is between 13:00 and 14:00 h CST for the coordinates of Monterrey downtown (25.40°N, 100.28°W, and 560m asl). The products used were OMTO3 (L2) v8.5 for TOC, OMNO2 (L2) v4.0 for VCD, and OMAERUVd (L3) v3 for AOD_{500}. Gases information was utilized to determine concentration patterns. For maps of the incoming aerosols from Africa, the Giovanni platform was employed [51].

2.4.2 VIIRS

The satellite instrument of the Visible Infrared Imaging Radiometer Suite (VIIRS) [52] was used for tracking wildfires. Near Real-Time NOAA-20 (formally JPSS-1) VIIRS Active Fire detection product is derived collaboratively by NASA and National

Oceanic and Atmospheric Administration (NOAA). VIIRS has local overpass times of approximately 01:30 -13:30 h with a spatial resolution of 375 m. The data product Fire Radiative Power [53] was processed to localize the active fire and estimate the number of hotspots related to wildfires on the mountain range (the Sierra Madre Oriental, henceforth SMO) nearby MMA.

2.5 HYSPLIT model

The Hybrid-Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model from NOAA - Air Resources Laboratory (ARL) [54] was executed on the Realtime Environmental Applications and Display System website to demonstrate dust transport. Data from reanalysis 2015–2022, stored on the HYSPLIT website, were applied for wind backward-trajectories simulations during African dust events.

3 Results and Discussion

3.1 Unprecedented events

Affected pollutant concentrations from the passage of an unprecedented cold front, large African dust clouds, a hurricane, record wildfires, an atypical drought, the COVID-19 lockdown, and even controls prior were analyzed.

3.1.1 Cold fronts

The frontal systems crossing the northern hemisphere considerably affect the air quality along their transport pathways. As the cold front enters an urban area, the contaminated airmass from other regions can cause a sharp increase in PM_{10} [55]. Figure S2 shows an extreme PM_{10} value of $430\mu gm^{-3}$ after cold front arrival. At the end of 2019 and the beginning of 2020, the long persistence of the jet stream with westerly winds and widespread displacement toward Mexican territory increased the number of cold fronts [56]. This phenomenon caused low raw averages of PM_{10}, $PM_{2.5}$, and NO_2 (Figures S3 and S4). Mexico City also recorded this decline in January and February 2020, prior to the pandemic restrictions [57]. In mid-February 2021, an unprecedented winter storm crossed the United States, causing failures in the electricity system supply in Texas [58, 59] at the same time as a new closure (L2) in the MMA. The cold snap whipped as far as northeastern Mexico, decreasing temperatures by below 10°C along with particle matter (Figure S2). The air pollutants measured during the passage of the cold fronts were filtered for the analysis of anomalies.

3.1.2 African dust

In June 2020, the strongest dust storm over the last two decades (dubbed *Godzilla*) transported massive amounts of dust from Africa to the Americas [60]. The origin, transport, and deposition of dust associated with the PM_{10} increase can be identified by comparing the AOD_{500} and HYSPLIT model [61]. Figure S5 illustrates the back trajectories from HYSPLIT about the main dust transportation routes from northwest Africa to the southeast part of the MMA. This was aligned with the AOD_{500} records from the OMI satellite before and during the COVID-19 lockdown. Part of the satellite grid cells cover a mountain bend that acts as a barrier by accumulating particles [62, 63]. On the other hand, SIMA sensors registered the arrival of the dust storm modeled by HYSPLIT, exhibiting ridges on 16 July 2018 and 17 July 2020 (Figure S6). The dusty episodes during the June-July period have also been recorded in Puerto Rico (18.22°N, 66.52°W) [64] and Houston (667 km northeast of Monterrey) coincident with the large-scale Saharan dust intrusion [65] when the dry deposition peak over the eastern Gulf of Mexico [66]. The dust is present year-round due to erosion of soil, unpaved roads, particle resuspension, and quarry activities. Notwithstanding, PM_{10} values rise midyear when African dust arrives, exceeding the WHO air quality guidelines [67]. As at other sites affected by Saharan dust outbreaks, these PM_{10} measurements were removed [68] before applying the anomaly formula.

3.1.3 Hurricane Hanna

The number of systems that at least qualified as tropical or subtropical storms during the 2020 Atlantic hurricane season exceeded that of the previous record-holder (in 2005) [69, 70]. Tropical Storm Hanna was the earliest 8th storm on record, and becoming the season's first hurricane. The eye made landfall 500 km from Monterrey (Figure S7) with maximum sustained winds of 150 km/h and a minimum central pressure of 973 hPa [71]. It was the last significant rainfall in the MMA, crossing the region at the end of July 2020 and dropping the daily PM_{10} for four days (Figure S6). The maximum precipitation accumulated was 489 mm at SE3 station and 604 mm in the vicinity of NE station (25.73°N, 100.30°W). Table S2 shows the PM_{10} averages in July for the years 2020 and 2019, with the effects of African dust and Hurricane Hanna and without both events, respectively. The mean percentage relative differences (RD) without measurements affected by these episodes was -0.4%.

3.1.4 Wildfires

From March to May in the central region of Mexico, wildfires occur [72]. Early in the spring of 2021, one of the most devastating forest fires in the last decade raged over the SMO. Wildfires destroyed almost 1000 hectares and forced the evacuation of roughly 400 people. The VIIRS and the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Terra-NASA satellite detected at least eight clusters of hotspots (active fires) visible in the forested region, with smoke flowing northeast [73]. In 2022, a second historical record of wildfires was observed in the same area. Figure S8 depicts the daily number of hotspots between 2015-2022 detected by VIIRS and a map of active fires during the most critical period. For assessing impact, a weighted kernel function was applied to the PM_{10} and the wind speed and direction measurements in a specific radius [74–76]. Figure S9 shows the non-parametric regression for five stations from 13 to 18 March 2021. Wildfire increased the PM_{10} values higher than $100\mu gm^{-3}$ with the dominant southeast wind. Smoke is partially responsible for the increase of monthly average PM_{10} in March 2021 and 2022 (Figure S2). In Mexico City outskirts, it produces over 70% of the principal fine particle mass [77] and several trace gases in northeast Mexico [78]. This PM_{10} increase does not seem to have a relationship between O_3 monthly mean and the number of fire detections, as in other regions of Mexico [79].

3.1.5 COVID-19 lockdown

In general, the particle matter decline in the first two months of 2020 was due to the atypical number of cold fronts. Furthermore, the meteorological conditions led to high-ozone episodes and driven the dispersion and accumulation of pollutants during the lockdown period [80–82]. Despite 54.6% of the population using their own vehicles as the main mode of transportation to work [83] and more than 90% of them having mobile internet connection [84], PM and NO_2 did not show a proportional reduction to the MIU in 2020. This result was more in line with the transport of air masses and meteorological parameters than the vehicular flux reduction, similar to those of Rio de Janeiro [85] and Ireland [86]. The predominance of the decrease in pollutants without taking into account environmental and meteorological factors could be falsely attributed to the COVID-19 lockdown. The environmental episodes should be taken into account in lockstep [87] and they can help other cities identify natural and anthropogenic influences.

3.2 Satellite NO_2 and O_3 changes

The NO_2 VCD monthly averages derived from OMI data [50] were used to calculate the RD for Monterrey city (25.67°N and 100.30°W). The pixel size is 1°×1° with grid boxes drawn around the city coordinates. Figure S10 shows the main NO_2 VCD reductions in April and October 2020, around -21% and -19%, respectively. The values are lower than half of those reported in other large cities [88]. The lowest VCD was 31% in August 2022, during a total opening of activities. A deseasonalized analysis from platform Air Quality/NASA based on satellite data for Monterrey indicated a slight change from March to June 2020 during L1. Indeed, two months before the COVID-19 lockdown, the values were lower than in that period [89]. In the case of the O_3 column from OMI, peaks appeared on December 2021 and November 2022, within variations lower than ±10% along the period, implicating the main changes were in the tropospheric ozone.

3.3 Air Pollutants long term and anomalies

The air pollutants were not spatially homogeneous in the MMA due to the orography, urban sprawl, and a wide variety of anthropogenic sources. At least three years before the pandemic outbreak, PM_{10} $PM_{2.5}$ and NO_2 (at SE3) concentrations decreased. This fact could have caused the O_3 formation from increased UV radiation [90]. Figure 2 shows the truncated Fourier series and the linear trends for the monthly means of criteria pollutants in the period 2015–2022. The highest values for PM_{10}, $PM_{2.5}$ and NO_2 occur in wintertime when O_3 reaches the minimum values. By contrast, SO_2 had no clear annual pattern. The solar UV radiation is around two times higher in the summer than in the winter and it promotes the formation of ozone and the aging of organic aerosols. The PM_{10} and $PM_{2.5}$ trends exhibited clear decreases on practically all stations, following prior findings [91], attributed to the government's corresponding policy related to the 2017 controls on quarries and industries. Higher levels of particle concentration were recorded in the western zone, consistent with the predominant wind direction from east to west [62]. A drastic drop in SO_2 at SW station was caused by ceasing in a factory as the main source of emission. In the post-pandemic period (2021-2022), a regional extreme drought promoted severe pollution accumulation along with low wind speeds and the second opening stage (N2). Excluding ozone, an increase in the daily pollutant concentrations was noticed in the first half of 2022 at almost all stations. The downtown station (near the water supply service of Monterrey) recorded a significant increase in NO_2 linked to the passage of heavy trucks used as water pipes during the drought-related crisis.

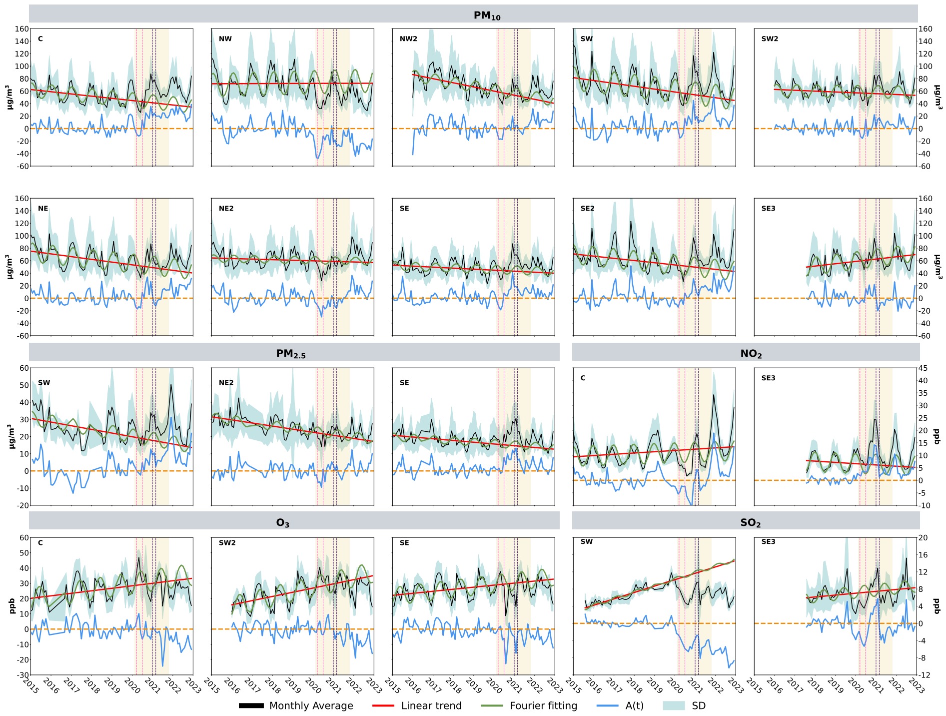


Fig. 2 Monthly averages of criteria pollutant concentrations recorded from 2015 to 2022 in the MMA, the linear trend, the Fourier fitting, and the anomaly A(t). The main lockdown were L1 (pink dotted line), L2 (violet dotted line), and the complete systematic phase (light yellow area).

The trends decreased on average up to 2019 for PM_{10} (-4 %/yr), $PM_{2.5}$ (-7 %/yr) and NO_2(-1 %/yr), while O_3 and SO_2 had an increase of approximately 8%/yr and 14%/yr, respectively (Table S3). The daily data set was filtered, considering meteorological and environmental factors. Subsequently, Equation 1 was applied to observe the net variation. The anomalies over the complete period exhibited values of $A\,(t) < 0$ not only in the lockdown context (Figure 2). The baseline anomaly and overlapping years of 2020, 2021, and 2022 revealed the most noticeable changes were in PM_{10} during L1, as shown in Figure 3. The lowest anomaly was at NW, near the subway, encompassing high mobility and unpaved roads.

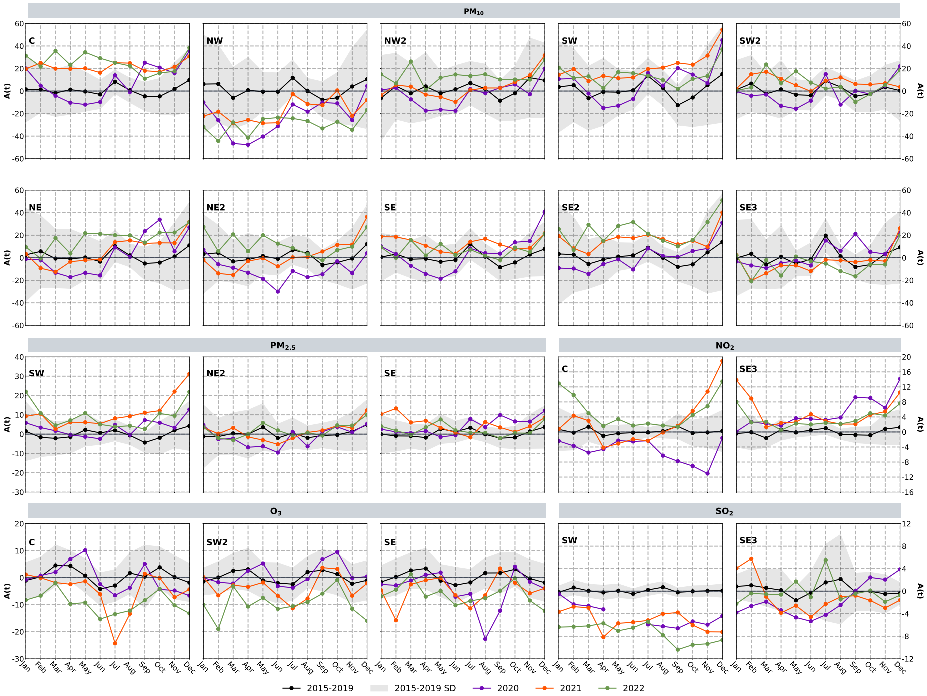


Fig. 3 Monthly average anomalies of PM_{10}, $PM_{2.5}$, NO_2, O_3, and SO_2 for the years 2020, 2021, and 2022, and the period 2015-2019 with its standard deviation.

The real average percentage changes during strict lockdown (L1) with respect to baseline in PM_{10}, $PM_{2.5}$ and SO_2 declined up to -14%, with an increase of 20% for O_3 and 10% for NO_2 (Table S4). The low reductions for PM_{10}, $PM_{2.5}$ and NO_2 are consistent with the uninterrupted passage of heavy transport, which was considered an essential activity along with most industries. The ascending behavior at the end of 2021 and 2022 was present in the majority of pollutants, due to an exceptional drought period. The O_3 reached their maximum in the spring, followed by a prolonged slump until the early autumn coincident with the maximum UV solar intensity. In the cold dry season, the low photolysis rate might lead to a low conversion of SO_2 to sulfate ions and thus accumulate higher concentrations [92]. At least since September 2020, the decreasing of SO_2 could be inferred from the fact that several companies and industries in Sta. Catarina (SW) did not work during L1. The Cadereyta refinery near SE3 station had SO_2 and NO_2 levels below the baseline between 2021 and 2022 due to an improvement in the refinery emissions system in spite of uninterrupted activity and an intense drought.

3.4 Deweather model performance

A special normalization of the meteorological effects on the PM_{10} concentrations was carried out by means of the deweather-RF method. The results of ten metrics (Table S5) used to evaluate the deweather model performance aligned with the PM_{10} values [48]. The non-linearity between predicted and observed values generated a mean Pearson correlation coefficient of 0.6, which is evidence of large differences due to extreme events. Figure S11 displays the behavior during the months involving relevant events.

3.5 PM_{10} changes in extraordinary events

The extraordinary events most significant were the COVID-19 restrictions (March 2020 to October 2021), storms (April 2020), hurricane Hanna, African dust (July 2020), cold fronts (February 2021), and wildfires (March 2021). Figure 4 shows the monthly mean PM_{10} changes with respect to the baseline using raw data, the deweather model and the anomaly formula in the absence of environmental and meteorological episodes. An apparent reduction occurred by subtracting only the absolute values, except in the month of wildfires. Instead, the net changes calculated by Eq.1 were minor compared to the raw data, with differences more than twice and even opposite. Despite the fact that the deweathering method did not account environmental phenomena such as wildfires and African dust, the results were more similar to anomalies with filtered data. It demonstrates the relevance of considering these factors because they can inverse the changes in air pollution.

4 Conclusion

This study seeks to provide a broader picture of changes in air pollution due to the impact of unprecedented events beyond the COVID-19 lockdown effects. In this region with an industrial heritage and continuous growth, the opening-closure of activities was not really more relevant than the extraordinary phenomena. There was no "background atmosphere" in the MMA due to the pandemic restrictions, as has been reported elsewhere. Since the heavy transport, the larger factories and companies worked as usual. PM_{10} assessing by three methods revealed that the main episodes in the context of the health crisis influenced the differences with respect to baseline and even produced opposite changes. Climate change could intensify extreme events and consequently have a growing impact on atmospheric pollution, to which a large number of people are exposed. It is important to consider in pollution models the long drought periods that increase the likelihood of wildfires and dust episodes. This analysis advances the understanding of the natural contributions needed to formulate better air quality policies in large cities.

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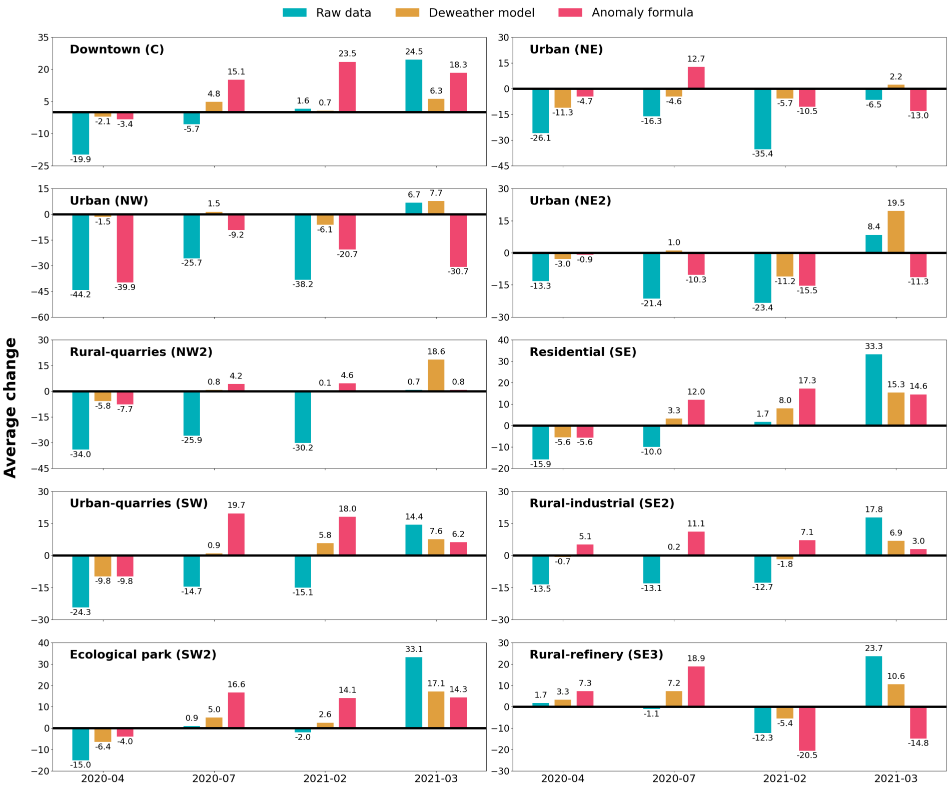

Fig. 4 Monthly mean changes of PM_{10} with respect to baseline using raw data, the deweather model, and the anomaly formula. The last two take into account the passage of storms (April 2020), hurricane Hanna and African dust (July 2020), cold fronts (February 2021), and wildfires (March 2021).

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