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Remote sensing in the analysis of the behavior of CO associated with confinement due to COVID-19, in the city of Manizales

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ABSTRACT

This article analyzed the behavior of carbon monoxide (CO) levels in Manizales during pre-lockdown, lockdown, and post-lockdown, as a response to the coronavirus disease (COVID-19) pandemic. The analysis focuses on the data of CO levels obtained from the tropospheric monitoring instrument (TROPOMI), precipitation, and temperature (T) recorded by the network of stations of Caldas. The data allowed us to find that during the lockdown, the average value of CO was 9.92% lower than the value registered before the lockdown, and it was 11.75% lower after the lockdown. On the other hand, the correlation between CO levels and population density during the three periods was analyzed, obtaining an $R^2 = 0.816$ after lockdown. Finally, considering other possible variables that can affect the CO levels, an analysis of the behavior of CO was carried out concerning the temperature and precipitation of the city registered before, during, and after the lockdown. Regarding CO and temperature, the correlation was inverse with Pearson's $r = -0.599$ (Fisher's $z = -0.692$), which also supports the decreasing trend of the value measured, and that the variation of CO levels does not depend only on lockdown but also on other factors. Regarding CO and precipitation, a positive correlation of Pearson's $r = 0.165$ (Fisher's $z = 0.167$) was obtained.

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1. INTRODUCTION

In late 2019, the sudden outbreak of coronavirus disease (COVID-19), which originated in the city of Wuhan, China, required the implementation of containment and mitigation measures that brought the world's most populous country and second-largest economy to a halt [1], [2]. Despite the efforts adopted, the virus spread worldwide, becoming a pandemic, which, according to studies, had a significant impact on areas with a high multidimensional poverty index (MPI) [3]. Given the above, many governments opted to generate measures to mitigate or contain the spread of the virus, which led to having populations under strict lockdown protocols. These measures halted productivity, mobility, and numerous economic sectors to the extent that certain cities had completely desolate streets. This generated substantial financial costs, which some countries could not absorb [4]. Therefore, a reactivation or economic recovery process was urgently required, during which, according to de Lara-Tuprio *et al.* [5], governments faced the dilemma of continuing to control the spread of the virus without negatively affecting their economies or collapsing their health systems.

During the COVID-19 lockdown, several anthropogenic activities, including biomass burning, which are sources of greenhouse gases (carbon dioxide (CO_2), methane (CH_4), and carbon monoxide (CO)), were halted [6]. As a result, it is reasonable to assume that the levels of these gases may have varied during the lockdown periods. According to Khan *et al.* [7], in Pakistan, there were reductions in CO and other pollutant concentrations, which were attributed to the decrease in activities during the lockdown and environmental factors such as temperature (T) and relative humidity variations between 2019 and 2020. According to Liang *et al.* [8], greenhouse gas levels decreased significantly during the lockdown over the Yangtze River Delta of China. On the other hand, Lopez-Coto *et al.* [9] reported that the levels of CO in the Washington, District of Columbia (DC), and Baltimore metropolitan areas decreased by 16% in 2020 and the reduction was more significant in April than in May. Kumar *et al.* [10] reported that greenhouse gases had a collective global decrease of 7.1% by November 2020. They also state that in a post-lockdown cycle, to improve the economy due to the worldwide pandemic, most countries could consume more energy than in pre-lockdown and thus increase emission levels, as is the case in China and other countries. In India, satellite data analysis determined that tropospheric CO levels increased during the lockdown season, due to the strong vertical transport and weakening of the horizontal wind during the lockdown [11]. Another study in India revealed reduced CO levels during lockdown [12]. As a local case, in Colombia [13] estimated the variations of different gases based on data from five air quality traffic stations and determined a 21% decrease in CO levels during the lockdown, with a maximum value in April and from this month until June, which is the last month reported, an increase was observed. A much broader geographic study that analyzed the variations of CO and other gases in 20 cities around the world was carried out by Sannigrahi *et al.* [14], concluding that the CO reduction was 28 tons as a sum of the 20 cities. Still, some cities, such as Cologne and Denver, had an increase in CO levels. On the other hand, according to Sokhi *et al.* [15], an increase in CO levels was registered in some cities due to environmental conditions that can inhibit the dispersion of CO. In China, a temporal analysis was carried out in which it was possible to conclude that although CO decreased in some areas, in others, there were increases that could be related to use of heating systems and human behavior [16].

This article addresses the solution to the question: is it possible that in Manizales, Colombia, a city located in the middle of large green areas and near an active volcano, there is a reduction in CO levels? to respond to the problem posed in this research, the behavior of CO levels at the tropospheric level in Manizales, Colombia, was analyzed in a multi-temporal manner. The CO data used were obtained from the tropospheric monitoring instrument (TROPOMI) on board the sentinel-5 precursor (S5P) satellite [17]. The results of this research will provide insight into the behavior of CO levels in a scenario of total mobility restriction and will serve as input for the city's environmental agencies to plan public policies regarding sustainable mobility. Additionally, while there are studies that have addressed the behavior of CO levels during the lockdown, there are no such studies in the city of Manizales. These results would allow us to address this gap and contribute to the understanding of the behavior of CO levels in Andean cities such as Manizales. The hypothesis on which this study is based is that CO levels in the city decreased during the lockdown. This article defines three phases to perform a multitemporal analysis: pre-lockdown, lockdown, and post-lockdown. Each step is divided into two sub-phases based on the level of mobility restriction, ranging from no mobility restriction to full mobility restriction and then to removal of the restriction. Finally, the study analyzes the behavior of CO levels, population density, and climatological variables such as temperature and precipitation during each phase.

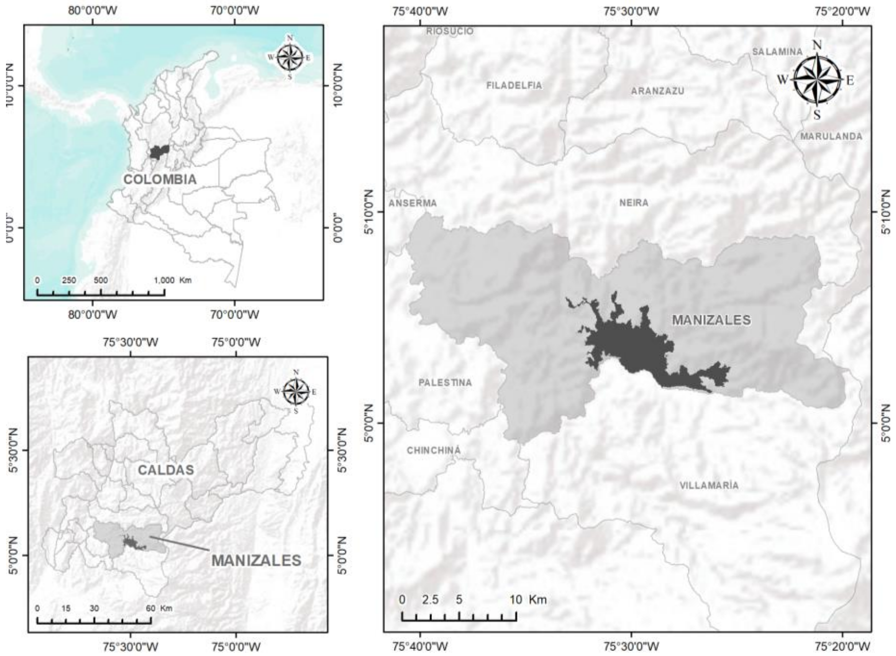
2. METHOD

2.1. Study area

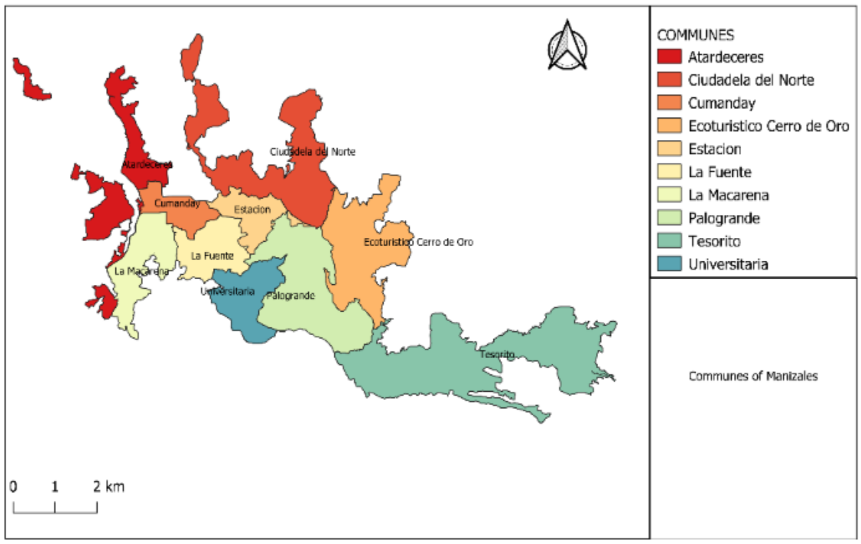
The study was conducted in Manizales, located in the Caldas department of central Colombia (see Figure 1(a)). The city is situated to the west of the Cordillera Central and close to the Nevado del Ruiz volcano, which has resulted in the soil having a high content of ashes [18]. According to National Administrative Department of Statistics (DANE) projections and information from the planning secretariat of the municipality, the city has approximately 400,000 inhabitants distributed in 10 zones called communes (see Figure 1(b)) each one with its own demographic characteristics recorded in Table 1. To mitigate the impact of COVID-19, the city administration implemented a lockdown with a total restriction of mobility on March 16, 2020, during the pandemic.

2.2. Meteorological parameters of the study area

Temperature and relative humidity are known to be meteorological variables that can influence the behavior of CO levels [7], [19]. In the case of the city of Manizales, historical data from the Caldas environmental data and indicators center (CDIAC) [20] show that the average maximum temperature has been around 16.8 °C, which is typically recorded during February and March. The temperature trend in the city is that it increases during the first quarter of the year and then begins to decrease until its lowest point in October (Figure 2).



(a)



(b)

Figure 1. Study area; (a) location map of Manizales [3] and (b) communes of Manizales

Table 1. Demographic data by commune

Commune name	Population	Area (Ha)	Population density (residents/Ha)	% of the total population
Atardeceres	34800	266.344558	130.66	9.02
Cumanday	22859	81.688125	279.83	5.92
Estación	22794	105.397791	216.27	5.91
Ciudadela del Norte	86205	392.802781	219.46	22.34
Ecoturistico	31605	333.630853	94.73	8.19
Tesorito	22881	697.170875	32.82	5.93
Palogrande	27326	416.157338	65.66	7.08
Universitaria	33990	167.348575	203.11	8.81
Fuente	43206	139.190733	310.41	11.20
Macarena	35560	182.118156	195.26	9.22

The geography and climate of Colombia, particularly the orographic barrier of the Andes Mountain range, results in the country having 24 regions with distinct local and regional climates. Furthermore, the country has monomodal and bimodal rainfall regimes. Manizales is located in a bimodal region of Colombia, which means it experiences two dry and two rainy seasons. According to Mosquera *et al.* [21], 66% of the annual rainfall and 69% of erosive events in Manizales occur from March to May and September to November in response to the bimodal regime, while the dry seasons occur at the beginning and middle of the year (see Figure 3).

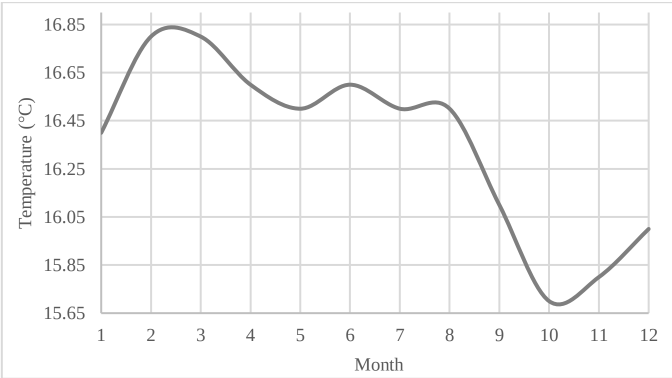


Figure 2. Historical average maximum temperature in Manizales during the year, data obtained from CDIAC [20]

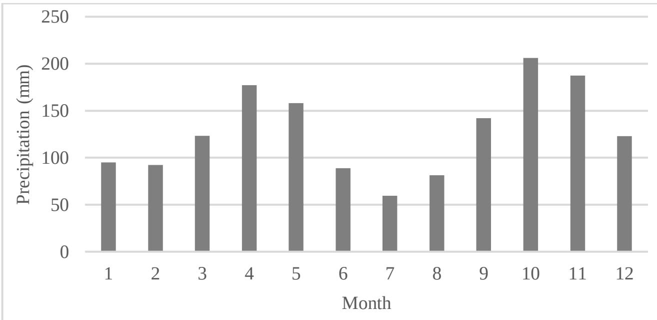


Figure 3. Bimodal rainfall behavior Manizales, precipitation data are taken from Institute of Hydrology, Meteorology and Environmental Studies, IDEAM [22]

2.3. Data sources

The OFF L3 product was utilized as a source of satellite data, specifically the CO_column_number_density obtained from the TROPOMI platform aboard the S5P satellite. The data was accessed from Google Earth Engine [23]. TROPOMI's algorithm allows it to derive CO values from the modified shortwave infrared, based on CO absorption spectral bands in the range of 2305-2385 nm [24]. The CO values are provided in units of mol/m^2 and have a spatial resolution of 1113.2 meters. The quality data warehouse of CDIAC [20] was used as a source of data from earth stations. Population data was obtained from the public innovation laboratory of the city of Manizales. Table 2 summarizes the data sources and time resolution used in the study.

Table 2. Data sources

Datatype	Source name	Temporal resolution	Variable
Satellite data	S5P TROPOMI	16/03/2019-01/08/2019 16/03/2020-01/08/2020 16/03/2021-01/08/2021	CO
Ground data	CDIAC	16/03/2019-01/08/2019 16/03/2020-01/08/2020 16/03/2021-01/08/2021	T and precipitation
Population	Public innovation laboratory of the city of Manizales	2019-2021	Population

2.4. Method

The behavior of CO levels in the city of Manizales before, during, and after the lockdown was analyzed by defining three phases: pre-lockdown, lockdown, and post-lockdown, each with their respective dates recorded in Table 3. The lower limit of each phase was selected as the date when the lockdown was implemented by the Colombian government (03/16/2019), and the upper limit was chosen as the date when the mobility restrictions imposed by the lockdown were lifted by the government (08/01/2019). During the lockdown phase, mobility restrictions were established by the Colombian government to contain the spread of COVID-19. The severity of the lockdown was modified depending on the behavior of the pandemic, with some dates having greater flexibility than others. As a result, sub-phases were created within each phase based on the varying characteristics of the lockdown severity, as recorded in Table 4.

After establishing the phases and sub-phases, the data from TROPOMI and CDIAC were downloaded and analyzed for the region that encompasses the city of Manizales to exclusively obtain the values of the variables: CO, T, and precipitation on the defined dates. Subsequently, a relational analysis was performed between the variables, and the results obtained were contextualized with the social reality experienced by the city during the lockdown and its sub-phases. Figure 4 provides a graphical representation of the aforementioned process.

Table 3. Analysis phases

Phase	Date
Pre-lockdown	16/03/2019-01/08/2019
Lockdown	16/03/2020-01/08/2020
Post-lockdown	16/03/2021-01/08/2021

Table 4. Description of the phases and subphases defined in the study

Phase	Identifier phase	Identifier sub-phase	Date sub-phase	Lockdown severity characteristic
Pre-lockdown	PRL	A1	16/03/2019-26/04/2019	No restrictions, no COVID-19 pandemic exists yet
		B1	27/04/2019-01/08/2019	
Lockdown	L	A2	16/03/2020-26/04/2020	Restriction of mobility, only necessary personnel on the streets of Manizales
		B2	27/04/2020-01/08/2020	At the beginning of the flexibilization of restrictions, it is necessary to reactivate the country's economy. Authorization is given for circulating more personnel on the streets of Manizales
Post-lockdown	POL	A3	16/03/2021-26/04/2021	Restrictions have been eliminated, and economic reactivation in its entirety
		B3	27/04/2021-01/08/2021	Vaccine application progresses

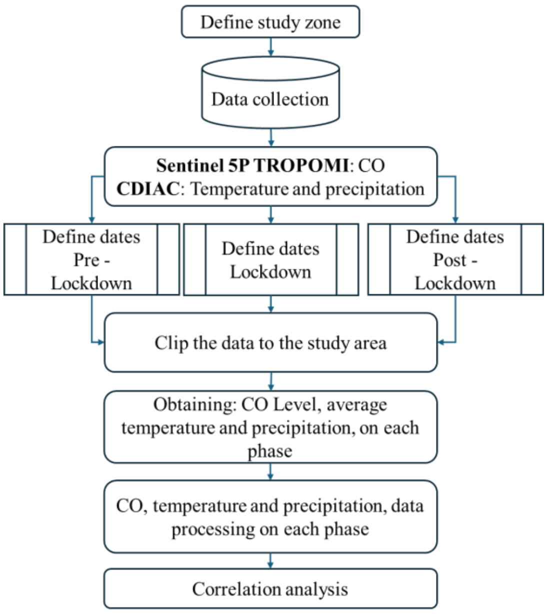


Figure 4. Method flowchart

3. RESULTS AND DISCUSSION

3.1. Variation of CO levels results

An analysis was performed on the variation of CO levels based on the CO data collected for the dates listed in Table 4. The CO levels obtained for each commune during subphases A2 and A3 were found to be lower than those obtained in A1 (refer to Figure 5). Conversely, the CO levels in subphases B2 and B3 were found to be higher than those in subphase B1 for some communes (refer to Figure 6).

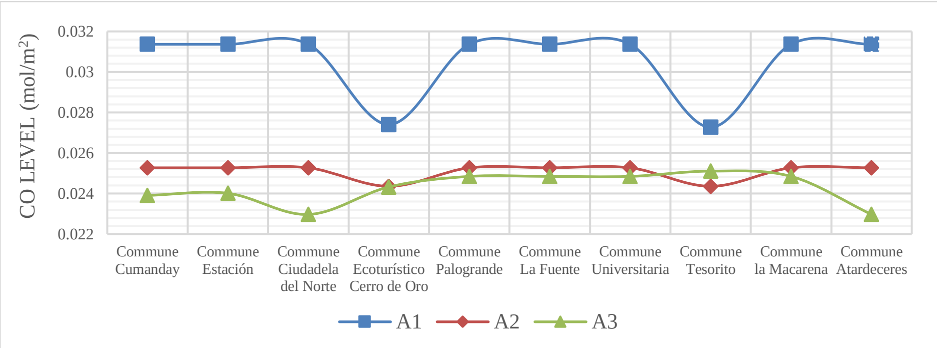


Figure 5. CO levels by commune during sub-phases: A1, A2, and A3

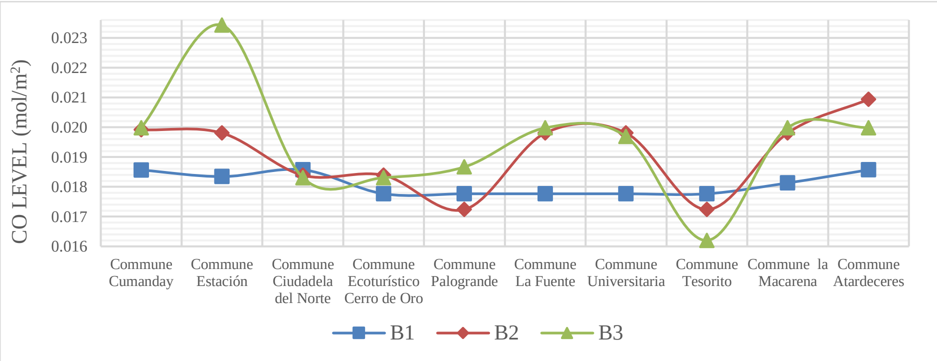


Figure 6. CO levels by commune during sub-phases: B1, B2, and B3

3.2. Temperature and precipitation behavior results

During the study period, temperature and precipitation were analyzed since, as mentioned earlier, these are meteorological variables that could influence the behavior of CO levels. The behavior can be observed in Figure 7. It should be noted that two data points could be defined as outliers, which deserve special attention since they may be due to damage to the measuring stations.

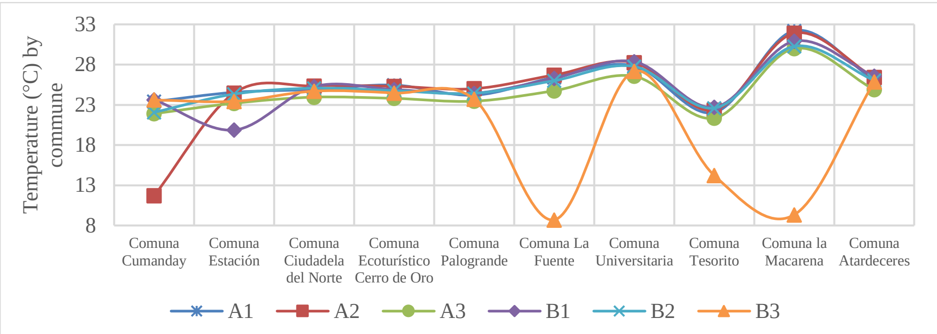


Figure 7. Temperature by commune during all sub-phases

3.3. CO levels and their relationship to population density results

The variation in CO levels across different communes may be linked to sociodemographic factors such as population density. Hence, Figure 8 is presented to explore the relationship between the population density of communes listed in Table 1 and CO levels. The figure shows the correlation levels listed in Table 5. Though the values do not demonstrate a significant correlation, except for B3, a positive correlation between population density and CO can be seen in Figure 8. This explains the trends observed in Figures 5 and 6, where downward kinks are observed in certain areas.

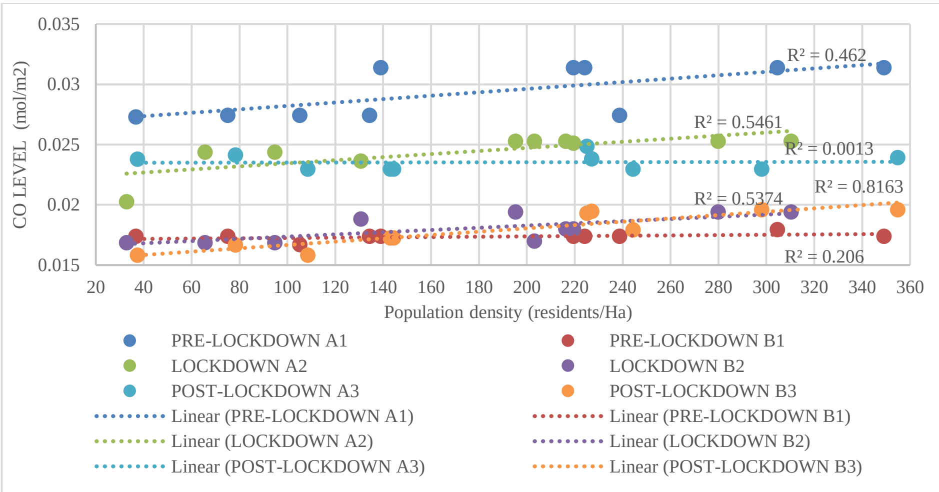
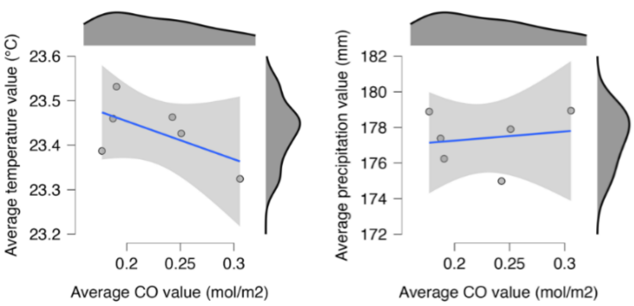


Figure 8. Relation between CO level and population density

Table 5. Correlation values between CO levels and population density

Phase	Identifier sub-phase	R	R^2
Pre-lockdown	A1	0.5854	0.462
	B1	0.2025	0.206
Lockdown	A2	0.6420	0.546
	B2	0.6425	0.537
Post-lockdown	A3	0.0100	0.001
	B3	0.6539	0.816

For the city of Manizales, an analysis was conducted using available climatological data to investigate the relationship between CO levels, temperature, and precipitation, as shown in Figures 9(a) and (b) and in Table 6. The analysis results, which were generated using data collected during the phases, demonstrate that CO levels tend to increase as temperature decreases (as shown in Figure 9(a)). Furthermore, a positive correlation between CO levels and precipitation was observed, indicating that CO values tend to increase with increasing precipitation (see Figure 9(b)).



(a) (b)

Figure 9. Visual analysis of the behavior of CO, temperature, and precipitation; (a) analysis of the behavior of average values of CO and temperature and (b) analysis of the behavior of average values of CO and precipitation

Table 6. Precipitation, temperature, and CO values obtained in each subphase

Phase	Identifier sub-phase	Average precipitation value (mm)	Average temperature value (°C)	Average value of CO (mol/m^2)
Pre–lockdown	A1	178.94386	23.32	0.03063
	B1	178.88772	23.39	0.01774
Lockdown	A2	177.89674	23.43	0.02510
	B2	177.38446	23.46	0.01891
Post-lockdown	A3	174.98358	23.46	0.02415
	B3	176.24261	23.53	0.01910

Although the normality assumption was accepted for each variable independently (shapiro-wilk test, $p > 0.05$), the multivariate normality assumption was rejected ($p = 0.001$), as well as the bivariate normality assumption for the pair of variables average precipitation vs average temperature ($p = 0.02$). Therefore, Pearson's and Spearman's correlations, as well as Fisher's z-effect size, are reported since the p-value lacks interpretability in the correlation due to the sample size [25]. The effect size values obtained were more significant than 0.5. Table 7 shows the results of the correlation analysis between the variables.

Table 7. Correlation between CO, precipitation, and temperature

Variable		Average CO value (mol/m^2)	Average precipitation value (mm)
1. Average CO value (mol/m^2)	Pearson's r	-	
	Effect size (Fisher's z)	-	
	SE effect size	-	
	Spearman's rho	-	
	Effect size (Fisher's z)	-	
	SE effect size	-	
2. Average precipitation value (mm)	Pearson's r	0.165	-
	Effect size (Fisher's z)	0.167	-
	SE effect size	0.577	-
	Spearman's rho	0.200	-
	Effect size (Fisher's z)	0.203	-
	SE effect size	0.505	-
3. Average temperature value (°C)	Pearson's r	-0.599	-0.773
	Effect size (Fisher's z)	-0.692	-1.029
	SE effect size	0.577	0.577
	Spearman's rho	-0.257	-0.943*
	Effect size (Fisher's z)	-0.263	-1.763
	SE effect size	0.506	0.541

* $p < .05$, ** $p < .01$, *** $p < .001$

The present study reveals a decrease in CO levels during the COVID-19 lockdown in the city of Manizales. Additionally, the relationship between CO levels and meteorological variables, such as temperature and precipitation, and sociodemographic variables, such as population density, was explored. Descriptive statistical techniques were used to verify the relationship between the variables in question visually and numerically.

The city of Manizales has eight microclimates within its urban area, and according to Roncancio [26], due to its topography, geographical location, and anthropogenic activities, it may be affected by the urban heat island phenomenon. This phenomenon refers to the temperature elevation in urban areas compared to the surrounding rural areas due to human activities such as transportation, industrialization, and urbanization [27]. This behavior is reflected in the notable temperature differences between the communes of the city, with lower values observed in the Tesorito commune, which is close to a high Andean Forest that helps regulate the urban heat island effect experienced more markedly in the central and more urbanized areas of the city (communes: Macarena, Universitaria, and Fuente), as shown in Figure 7. In this figure, it can be observed that the average temperature in each district in subphase B1 was slightly higher than that recorded in the other two subphases. This situation could justify why the level of CO was higher in subphase B1. On the other hand, these results align with the correlation analysis (see Table 7), which indicates that CO levels tend to be higher when temperatures are lower, as observed in some of the analyzed communes.

During the analysis phases, the average value of CO generated in the city was 9.92% lower during lockdown and 11.85% lower during post-lockdown compared to pre-lockdown (Figure 10). This trend may be attributed to anthropogenic factors, such as the economic revival process that caused an increase in CO generation, according to [10], [16]. Additionally, the trend may be influenced by climatic factors, such as temperature and winds [11], [28], [29]. In Figure 10, a slight increase in CO levels was observed in B3, likely due to the dynamics of economic reactivation at that time, when there were no restrictions on the population and the vaccination process was advancing.

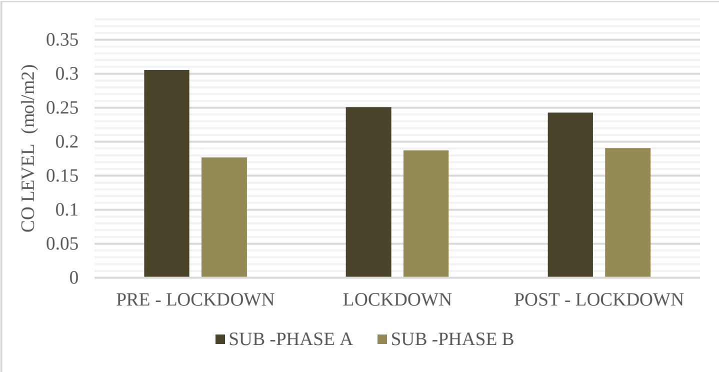


Figure 10. The average value of CO in Manizales during each subphase

Based on the obtained effect size, there was a strong negative correlation between the analyzed variables, temperature, and CO. As a result, high levels of CO were observed in some phases, possibly due to both anthropogenic factors and low temperatures facilitating the aggregation of particles by cooling air masses and promoting stagnation at low altitudes. This results in a negative correlation between temperature and CO levels [28], [29].

In addition to the results presented, it is essential to note that future research could explore factors such as reduced transportation and industrial activities, as well as changes in individual behaviors and consumption patterns during the pandemic, in greater detail to understand the observed changes in CO levels better. When analyzing air quality data, it is also important to consider the presence of microclimates within the urban area of Manizales. Further research on the specific characteristics and emission sources in each microclimate would be beneficial in developing specific mitigation strategies. Additionally, the observed differences in temperature and CO levels between municipalities emphasize the need for localized air quality monitoring and interventions rather than relying solely on city-wide measurements.

4. CONCLUSION

The study analyzed CO levels in Manizales during three periods: before, during, and after the lockdown imposed by health authorities to curb the spread of COVID-19. The results revealed CO levels were higher before the lockdown phase and decreased during the lockdown period. However, CO levels increased again during the post-lockdown phase, possibly due to the Colombian government's decision to ease mobility restrictions during the economic reactivation phase, leading to increased anthropogenic activities and CO generation, as predicted by some authors. Additionally, the study highlighted the relationship between CO levels and temperature and precipitation, where CO levels showed a negative correlation with temperature and a positive correlation with precipitation. Although the study was limited by the availability of CO data from the S5P-TROPOMI satellite platform due to the limited network of ground-based CO monitoring stations in the city, the results provide insights for the city government to plan campaigns and public policies for reducing CO generation. Future studies with more CO data from ground-based stations could improve the spatial resolution of the research and model the behavior of CO for the city. In summary, the results of this study can be a valuable tool for developing comprehensive public policies that address air quality issues in Manizales and contribute to a more sustainable and healthier city.

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