INFLUENCE ON AIR QUALITY OF MOVING FROM DIESEL TO ELECTRIC BUSES: THE CASE OF THE CITY OF CUENCA, ECUADOR

RENE PARRA[1], CLAUDIA ESPINOZA[2], CRISTIAN CAGUANA[2] & EMILIO HEREDIA[2]
[1]Instituto de Simulación Computacional (ISC-USFQ) and Departamento de Ingeniería Ambiental, Universidad San Francisco de Quito, USFQ, Ecuador
[2]Red de Monitoreo de Calidad del Aire de Cuenca, Empresa Pública de Movilidad, Tránsito and Transporte de Cuenca, EMOV EP, Cuenca, Ecuador

ABSTRACT

Diesel vehicles are essential sources of nitrogen oxides ($NO_x = NO + NO_2$) and fine particulate matter ($PM_{2.5}$) in Cuenca (2,500 metres above sea level (masl)), an Andean city located in southern Ecuador. According to the recent emission inventory, during 2021, diesel buses, which currently operate as part of the public transportation system, contributed 1,115 t/y and 98 t/y of NO_x and $PM_{2.5}$, corresponding to 16.4% and 18.3% of the on-road atmospheric emissions, respectively. To promote efficient and sustainable energy use in the country, the Organic Law on Energy Efficiency, in force since 2019, provides that from 2025, all vehicles incorporated into the urban and inter-parish public transport service must be electric. We assessed the effects on air quality of this shift, modelling the dispersion and photochemical reactions of air pollutants during October 2021, with the Weather Research and Forecasting with Chemistry (WRF-Chem) model under two scenarios: (1) the reference scenario (RS) using the emissions from all the sources of the emission inventory; and (2) the future scenario (FS) with electric buses replacing the current diesel bus fleet. The difference RS minus FS results at the historic centre of the city indicated benefits in terms of reduction of the daily maximum 1 h mean NO_2 (between 0.4 to 8.1 µg/m^3, median 2.9 µg/m^3) and 24 h mean $PM_{2.5}$ (0.3 to 2.3 µg/m^3, median 1.4 µg/m^3) levels. However, the daily maximum 8 h mean ozone (O_3) increased (1.0 to 3.6 µg/m^3, median 2.3 µg/m^3). This increase of O_3 levels in the urban area of Cuenca is explained by a volatile organic compounds (VOC)-limited regime for O_3 production, suggesting that the future shift from diesel to electric buses needs to be accompanied by controls for decreasing VOC emissions, especially those coming from gasoline cars, service stations and the use of solvents.

Keywords: ozone, VOC-limited regime, weekend effect, COVID-19 lockdown.

1 INTRODUCTION

On-road traffic, particularly diesel buses, plays a significant in the atmospheric pollution of Cuenca, an Andean city in southern Ecuador (Fig. 1). The latest atmospheric emission inventory for the city, based on 2021 data, reveals that the total emission of nitrogen oxides ($NO_x = NO + NO_2$) was 7,554 t/y, with 89.9% originating from on-road traffic. The total emissions of volatile organic compounds (VOCs) and fine particulate matter ($PM_{2.5}$) were 13,214 t/y and 822 t/y, respectively, with on-road traffic contributing 31.8% and 65.0%. Diesel buses, currently part of the public transportation system, were responsible for 1,115 t/y and 95 t/y of NO_x and $PM_{2.5}$, accounting for 16.4% and 18.3% of the on-road atmospheric emissions, respectively (Table 1).

Some factors are behind the high contribution of on-road traffic to atmospheric pollution. One factor is the height of the city (2,500 metres above sea level (masl)), which implies lower levels of O_2 in the atmosphere, implying, in general, increased emissions from all combustion sources compared to places at sea level [1]. Another important factor is the poor quality of fuels, mainly due to their high sulphur content, which vehicles currently use.

www.witpress.com, ISSN 1743-3541 (on-line)
doi:10.2495/SDP240551

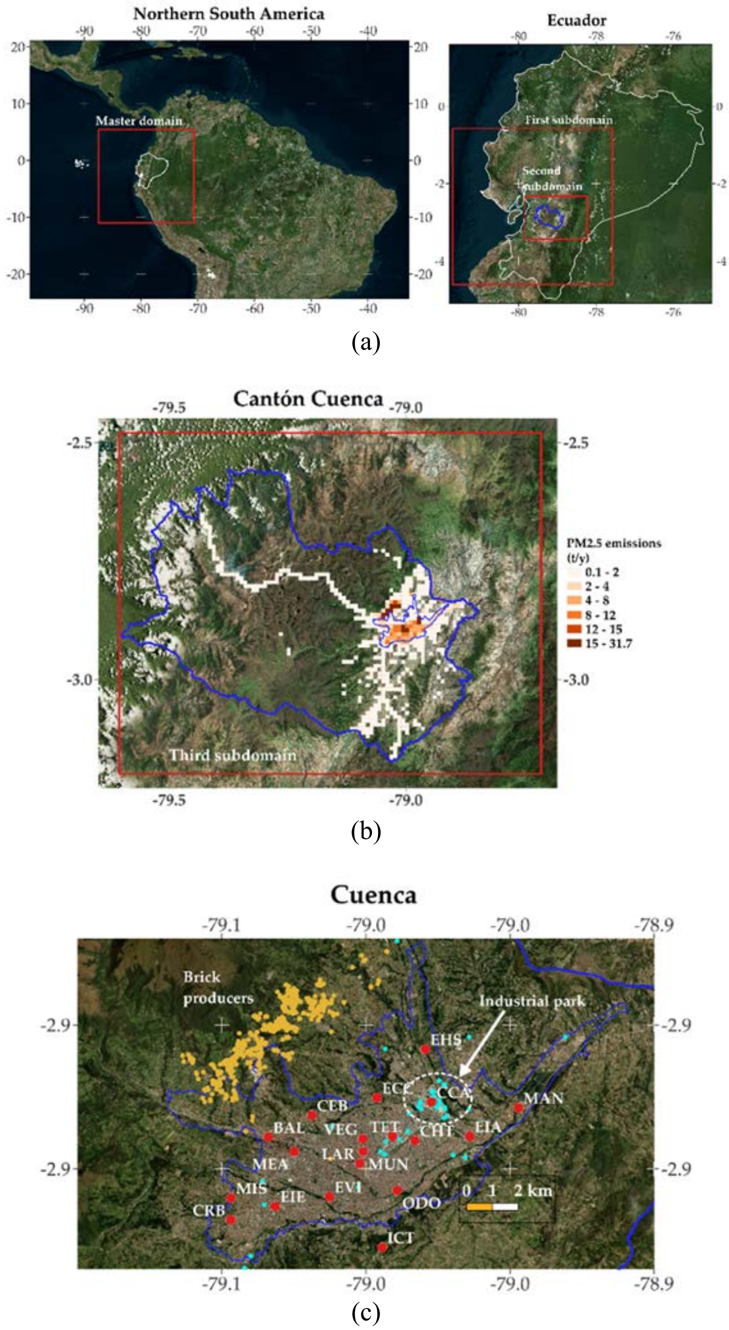


Figure 1: (a) Location of Ecuador; (b) Cantón Cuenca and $PM_{2.5}$ emissions of 2021 (t/y); and (c) The urban area of Cuenca (blue border) and the air quality network (red dots). Orange dots (northwest) indicate the artisanal brick producers. Cyan dots indicate industries. MUN is the automatic station located at the historic centre. Other red dots are passive stations.

www.witpress.com, ISSN 1743-3541 (on-line)

Table 1: Emission inventory of primary pollutants in Cuenca from on-road traffic in 2021 [2].

	NO_x		CO		VOCs		PM_{10}		$PM_{2.5}$	
Category	t/y	%	t/y	%	t/y	%	t/y	%	t/y	%
Gasoline vehicles										
Automobile	927.2	13.7	19 472.7	51.8	2274.0	54.1	174.6	20.3	19.1	3.6
Hybrids	0.8	0.0	2.2	0.0	0.1	0.0	3.2	0.4	0.2	0.0
Pickup, van	407.6	6.0	7471.5	19.9	367.6	8.7	33.8	3.9	4.0	0.7
Taxi	42.7	0.6	990.0	2.6	54.1	1.3	33.0	3.8	3.6	0.7
Heavy	1.4	0.0	113.4	0.3	2.0	0.0	0.1	0.0	0.0	0.0
Motorcycle	57.8	0.9	4626.2	12.3	441.5	10.5	32.4	3.8	3.0	0.6
Diesel vehicles										
Automobile	4.7	0.1	11.4	0.0	3.3	0.1	3.8	0.4	2.7	0.5
Pickup, van	181.1	2.7	344.1	0.9	86.9	2.1	91.8	10.7	64.6	12.1
Bus	1115.3	16.4	824.7	2.2	358.8	8.5	108.9	12.7	97.7	18.3
Microbus	253.7	3.7	214.1	0.6	80.0	1.9	24.1	2.8	21.6	4.0
Heavy	3790.3	55.9	3554.1	9.4	533.0	12.7	354.3	41.2	317.9	59.5
Total	6782.4	100.0	37624.3	100.0	4201.2	100.0	860.1	100.0	534.3	100.0

The estimated total fleet was 167,703 vehicles, of which 89.9% were gasoline-powered and the remaining 10.1% were diesel-powered. Gasoline cars produced 74.6% of on-road VOC emissions, while diesel cars contributed 78.8% and 94.4% of NO_x and $PM_{2.5}$ from on-road traffic, respectively. The city's vehicle park configuration has a marginal presence of hybrid and electric vehicles. The estimated number of diesel buses was about 1,800 vehicles.

From 2012 to 2022, at the historic centre (MUN station), the yearly mean $PM_{2.5}$ concentrations ranged between 5.7 and 14.5 µg/m^3 [3], all of them higher than the current World Health Organization (WHO) guideline (5.0 µg/m^3) [4]. Ozone (O_3), a secondary pollutant produced by photochemical reactions between VOCs and NO_x, typically shows higher levels in Cuenca around September, in part due to the levels of solar radiation. For 7 days in 2022, the O_3 levels exceeded the WHO guideline (100 µg/m^3, maximum daily 8 h mean).

Currently, particulate matter in outdoor air pollution is part of the Group 1 (carcinogenic to humans) of agents classified by the International Agency for Research of Cancer [5]. Other carcinogenic agents directly linked to on-road emissions are the engine exhaust by diesel cars, benzene, and formaldehyde, the last VOCs emitted mainly by gasoline cars. Short-term acute effects from O_3 exposition include respiratory symptoms, pulmonary function changes, increased airway responsiveness, and inflammation [6].

Under the Sustainable Development Goals [7], a decrease in air pollution is necessary to improve health and well-being (SDG 3) through the promotion of affordable and clean energy (SDG 7) and to achieve sustainable cities and communities (SDG 11). Under the Ecuadorian energy efficiency law [8], all new vehicles added to the public transportation system must be electric by 2025.

The shift to electric buses will decrease the exhaust emissions from diesel buses, decreasing NO_x and $PM_{2.5}$ emissions. Therefore, this contribution aims to estimate the benefits of decreasing NO_x and $PM_{2.5}$ in the air quality in Cuenca.

2 METHOD

Based on the emission inventory of the year 2021 and the availability of air quality records, we modelled the air quality in Cuenca during October 2021, considering two scenarios:

- The reference scenario (RS) (diesel buses): Air quality was modelled, including all the sources from the emission inventory of 2021; and
- The future scenario (FS) (electric buses): Air quality was modelled, including all the sources, but the exhaust emissions from diesel buses were eliminated.

The emission inventory 2021 included the following sources: on-road traffic, vegetation, industries, use of solvents, service stations, combustion of liquid petroleum gas, air traffic, landfills, handcrafted brick production, dust erosion, and mining.

We used the Weather Research and Forecasting with Chemistry (WRF-Chem V3.2), a numerical and state-of-the-art chemical transport model, for research and forecasting purposes. This model read hourly maps of speciated emissions previously prepared from the 2021 emission inventory. The WRF-Chem V3.2 model validated the 2021 emission inventory 2021 with acceptable air quality modelling performance [2].

Initial and boundary conditions were generated through the final National Centers for Environmental Prediction (NCEP FNL) Operational Global Analysis data [9]. Meteorology was modelled using a master domain of 70 × 70 cells (27 × 27 km each cell) and three nested subdomains (Fig. 1). The third sub-domain (100 × 82 cells, 1 x 1 km each cell, 35 vertical levels) covered the territory of Canton Cuenca. For the third subdomain, the option for chemical dispersion was activated. We used the carbon bond mechanism–Z (CBMZ) [10] for the speciation emission of gases and MOSAIC for aerosols [11]. Table 2 indicates the options selected for modelling:

Table 2: WRF-Chem's configuration for atmospheric modelling in Cuenca [12].

Component and WRF-Chem option nomenclature	WRF-Chem option	Model
Microphysics	4	WRF single-moment 5-class
Longwave radiation	1	RRTM
Shortwave radiation	2	Goddard
Surface layer	1	MM5 similarity
Planetary boundary layer	1	Yonsei University
Cumulus parameterization	0	0 No cumulus scheme
Options of chemistry and aerosol modules	7	CBMZ and MOSAIC
Land surface	2	Noah
Urban surface	0	No urban physics

The modelling air quality performance was assessed through the percentages of records captured, based on the maximum deviation between the records and computed values of Table 3. For short-term air quality, we used the records from the MUN station to assess the performance for the NO_2 (maximum mean in 1 h per day), $PM_{2.5}$ (mean in 24 h per day), and O_3 (maximum mean in 8 h per day) concentrations during periods consistent with the WHO guidelines. For long-term air quality, the performance was assessed by the percentage of the passive stations, with a maximum difference of 30% between the modeled concentration and records.

Table 3: Accuracies for air quality modeling [13].

Variable	Accuracy
Short-term: Maximum 1 h NO_2 mean, 24 h $PM_{2.5}$ mean, maximum 8 h O_3 mean	± 50%
Long-term: NO_2 and O_3	± 30%

3 RESULTS

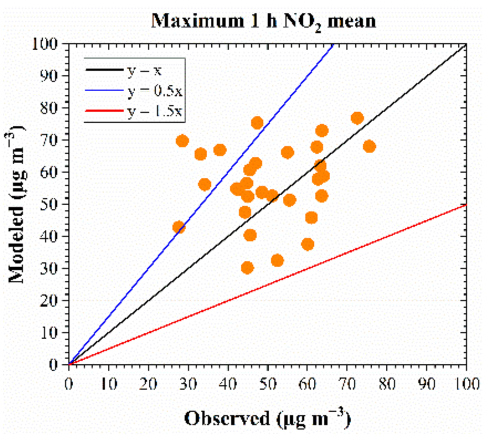
Table 4 shows the modelling performance. For short-term air quality parameters, the model captured 80.0% of the maximum 1 h NO_2 means, 70.0% of the 24 h $PM_{2.5}$ means, and 67.0% of the maximum 8 h O_3 means. The model captured the NO_2 and O_3 monthly mean concentrations for long-term air quality in 69.0% and 88.0% of the passive stations, respectively. Fig. 2 compares the records and computed values of these pollutants.

In the historic centre (MUN station), differences between the scenarios (RS − FS) showed decreases in the daily maximum 1 h mean NO_2 (between 0.4 and 8.1 $\mu g/m^3$, median 2.9 $\mu g/m^3$) and 24 h mean $PM_{2.5}$ (0.3 to 2.3 $\mu g/m^3$, median 1.4 $\mu g/m^3$) levels. However, the daily maximum 8 h mean ozone (O_3) increased (1.0 to 3.6 $\mu g/m^3$, median 2.3 $\mu g/m^3$) (Fig. 3).

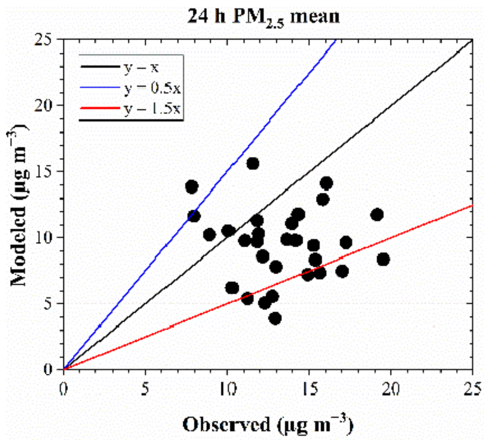
Consistently, the records at passive stations also showed decreases in the mean-monthly NO_2 (0.8 to 2.8 $\mu g/m^3$, median 1.7 $\mu g/m^3$) and increases in the mean-monthly O_3 (0.4 to

Table 4: Percentages of the air quality records captured by modelling.

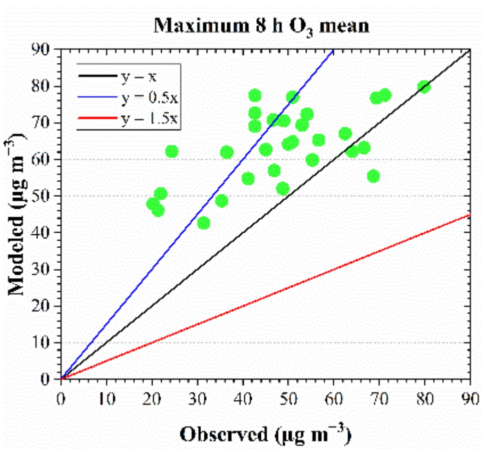
Short term:	
Maximum 1 h NO_2 mean	80.0
24 h $PM_{2.5}$ mean	70.0
Maximum 8 h O_3 mean	67.0
Long term:	
NO_2, monthly mean	69.0
O_3, monthly mean	88.0



(a)



(b)



(c)

Figure 2: Observed versus modelled (MUN station). (a) Maximum 1 h NO_2 mean; (b) 24 h $PM_{2.5}$ mean; and (c) Maximum 8 h O_3 mean.

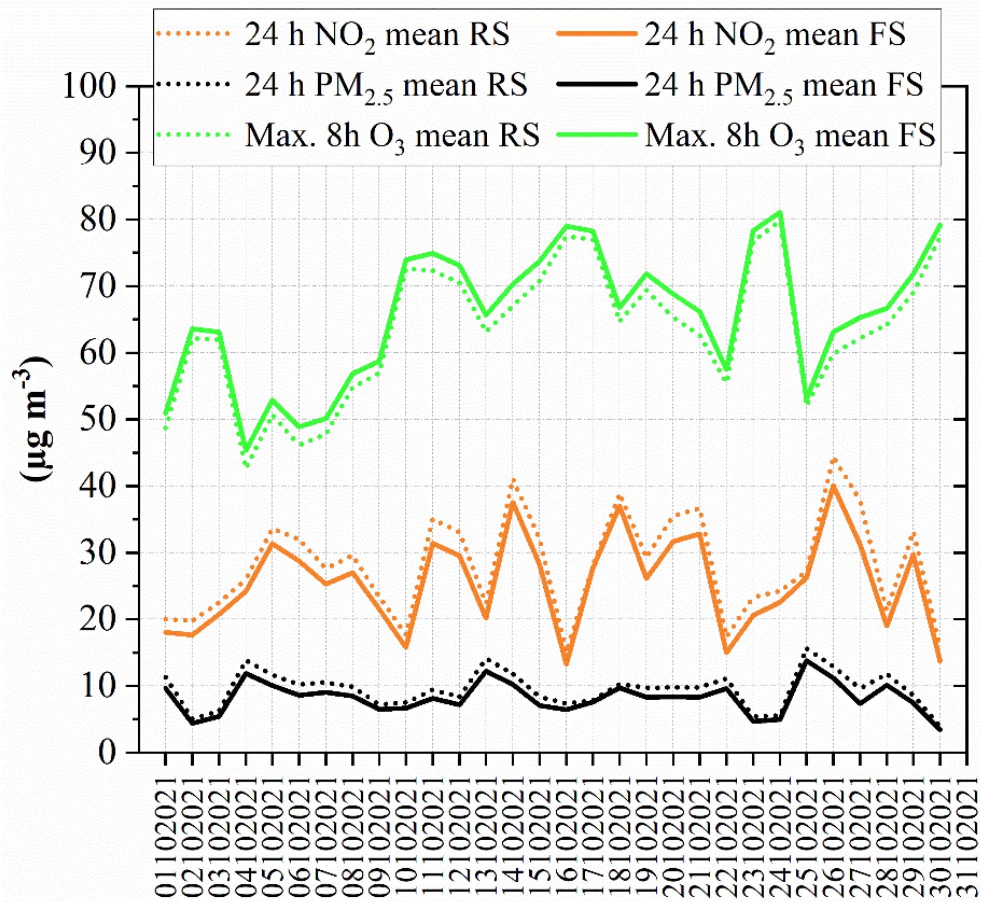
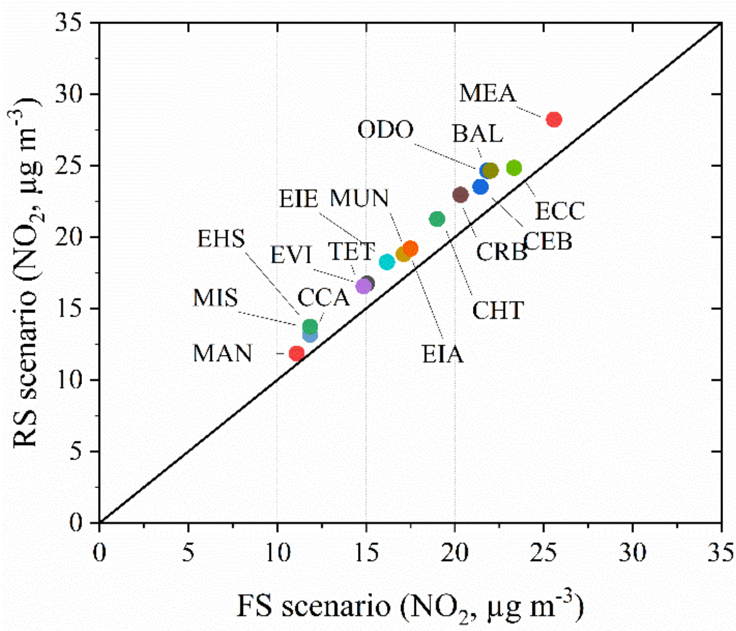


Figure 3: Modelled concentrations of October 2021 for the reference scenario (RS: diesel buses) and future scenario (FS: electric buses).

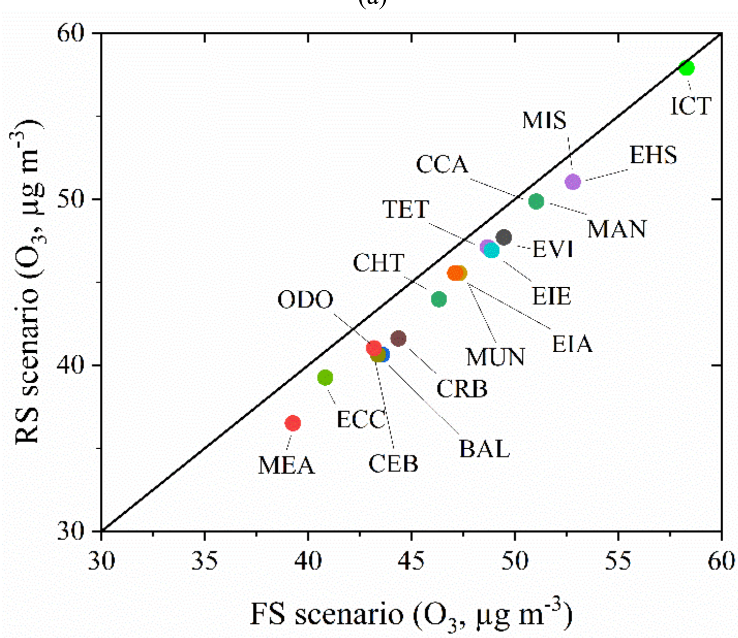
2.9 µg/m^3, median 1.8 µg/m^3) (Fig. 4). The lowest difference for NO_2 was modelled to Machángara (MAN), a passive station west of the city, with a low influence of NO_x on-road traffic. The lowest difference for O_3 was computed to Ictocruz (ICT), a station south and out of the urban area, with very low influence from on-road traffic emissions.

Fig. 5 shows the modelled map of 1 h NO_2 for 18 October 2021 at 07:00 for the RS and FS scenarios and the difference between them (RS − FS). All the values were positive, reaching differences up to 12 µg/m^3.

Fig. 6 depicts the computed map of 24 h $PM_{2.5}$ mean for 18 October 2021 for both scenarios and the difference (RS − FS). Similarly, all the values were positive, reaching differences up to 2 µg/m^3 in the urban area. Fig. 7 indicates the corresponding maps of the 8 h O_3 maximum for the same day. The difference (RS − FS) shows negative values (up to −6.5 µg/m^3) over the urban area and its northwest, highlighting that the shift from diesel to electric buses will increase the O_3 levels.



(a)



(b)

Figure 4: Modelled mean monthly concentrations for October 2021. Vertical axis: reference scenario (RS: diesel buses). Horizontal axis: future scenario (FS: electric buses). (a) NO_2; and (b) O_3. The nomenclature indicates the passive stations.

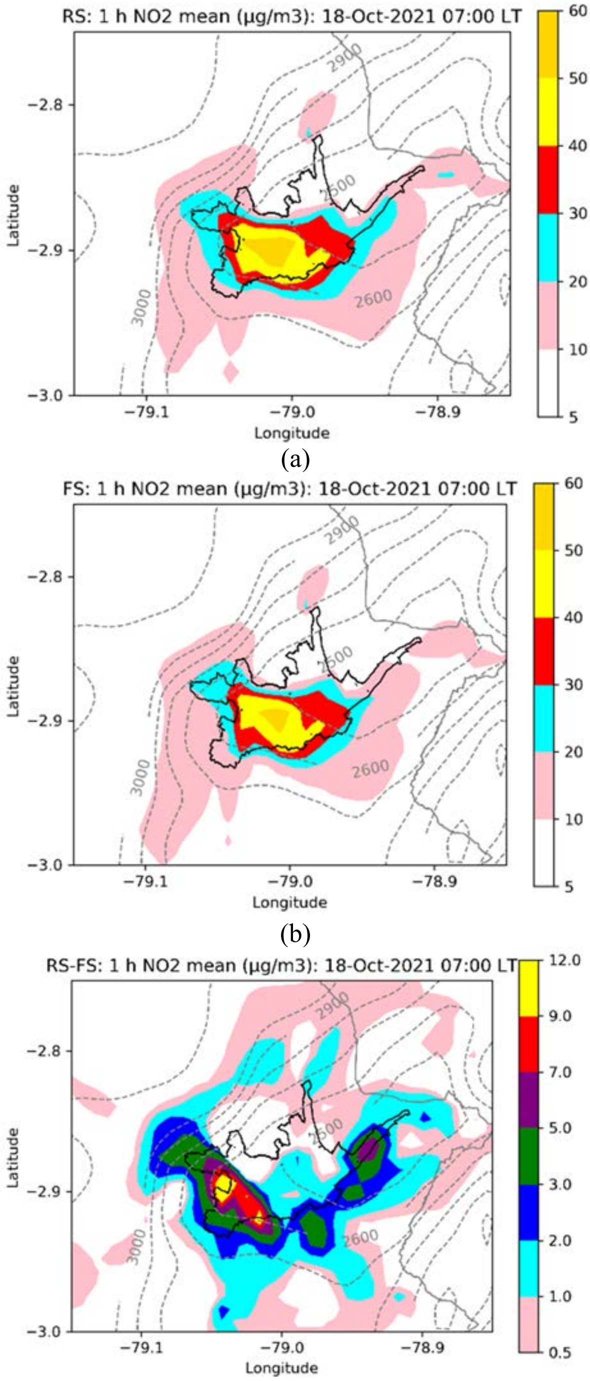
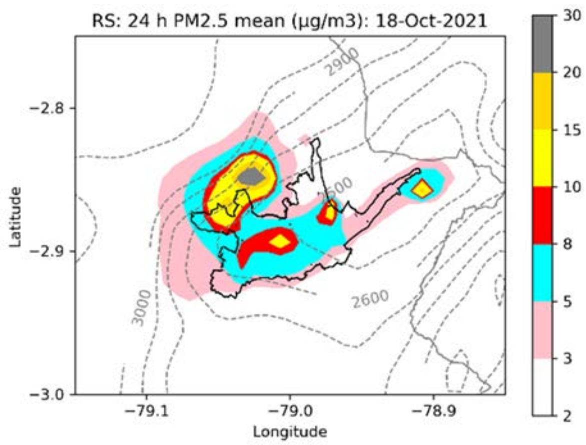
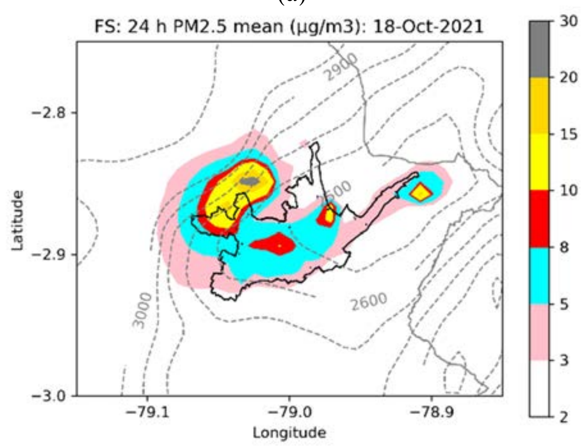


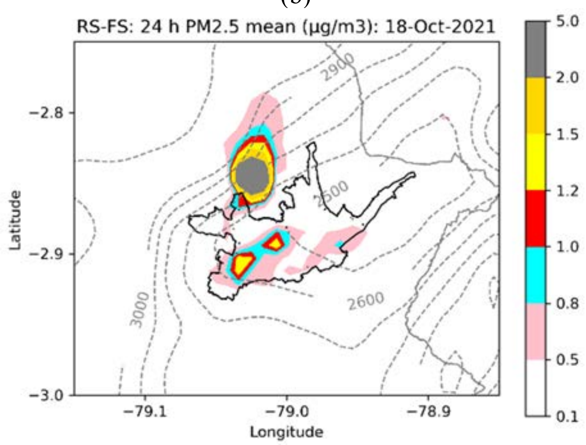
Figure 5: Modelled 1 h NO_2 at 07:00 LT for 18 October 2021. (a) RS scenario (diesel buses); (b) FS scenario (electric buses); and (c) Difference of RS minus FS.



(a)



(b)



(c)

Figure 6: Modelled 24 h $PM_{2.5}$ mean for 18 October 2021. (a) RF scenario (diesel buses); (b) FS scenario (electric buses); and (c) Difference of RS minus FS.

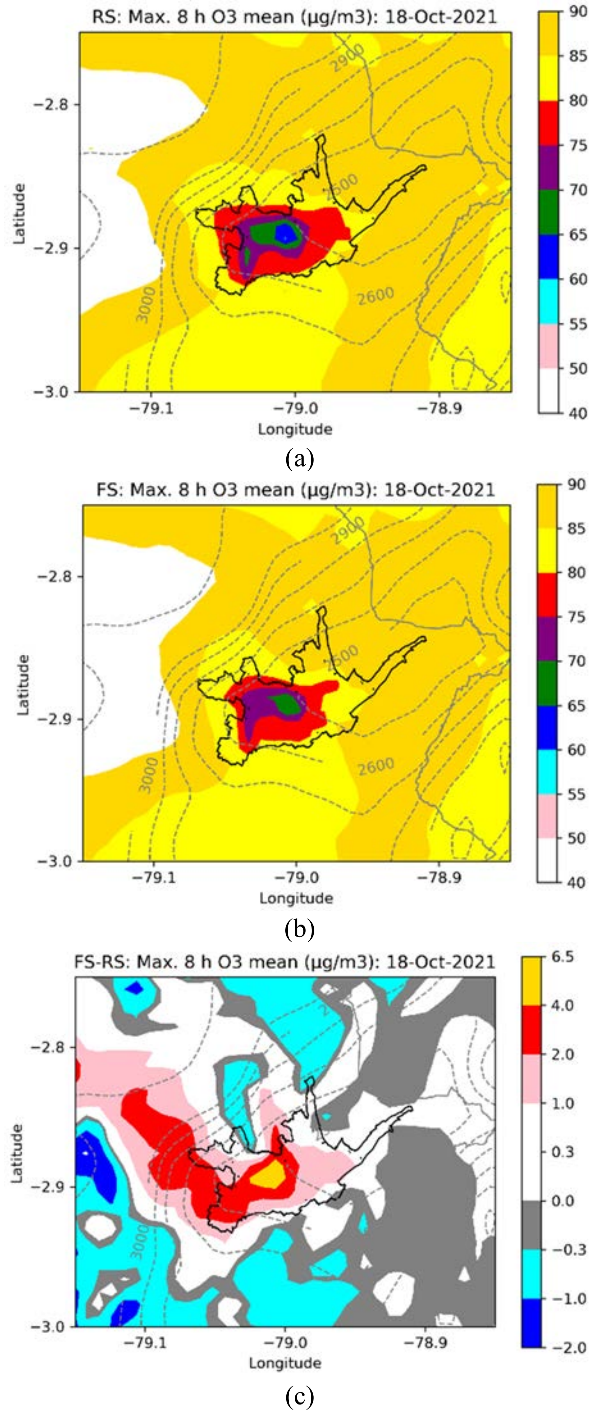


Figure 7: Modelled 8 h O_3 maximum for 18 October 2021. (a) RF scenario (diesel buses); (b) FS scenario (electric buses); and (c) Difference of FS minus RS.

4 DISCUSSION AND CONCLUSIONS

As expected, the modelled results indicated that the shift from diesel to electric buses in Cuenca will imply reductions in NO_2 and $PM_{2.5}$, pollutants that diesel cars emit to a high degree in this city. In particular, the decrease of 24 h mean $PM_{2.5}$ concentrations (0.3 to 2.3 $\mu g/m^3$, median 1.4 $\mu g/m^3$) is a significant benefit, considering that the current levels of this pollutant are higher than the recommended concentrations by the WHO. Even if the $PM_{2.5}$ and other carcinogenic levels were lower than the WHO guidelines, it is necessary to take action to decrease their abundance to reduce the air pollution's toll on public health.

However, modelled results suggested that the decrease of these two pollutants will be accompanied by an increase of the daily maximum 8 h mean O_3 (1.0 to 3.6 $\mu g/m^3$, median 2.3 $\mu g/m^3$), a secondary pollutant produced by photochemical reactions between NO_x and VOCs. The VOC-limited regime explains the unexpected behaviour for O_3 production in the urban area of Cuenca. Under this regime, the decrease of NO_2 emissions can promote the increase of O_3 due to the non-linear relationship between the O_3 and its precursors.

The decrease of NO_2 and $PM_{2.5}$, accompanied by an increase in O_3 was observed in Cuenca during the COVID-19 lockdown (16 March to 25 May 2020) [14]. During this period, on-road traffic and other activities reduced their activities. Specifically, the public transportation system, based on diesel buses, did not work, reducing the NO_x and $PM_{2.5}$ emissions. The air quality records during these periods showed consistent tendencies of the three pollutants compared to the results of this contribution.

The VOC-limited regime has been associated with the weekend effect, a phenomenon taking place in some urban areas, characterized by an increase in O_3 concentrations during weekends, even though accompanied by a reduction in emissions of its precursors compared to working days. The weekend effect (WE) was initially reported in New York and Baltimore in the 1970s [15], [16] and then was identified in other parts of the world, including the city of Cuenca [14], [17].

The WE in Cuenca and the modelled results of this contribution suggest that the future shift from diesel to electric buses needs to be accompanied by controls for decreasing VOC emissions, especially those coming from gasoline cars, service stations, and the use of solvents. On the other hand, promoting other electric vehicles, such as automobiles, motorcycles, and bikes, will reduce carbon monoxide and VOC emissions, avoiding or offset the increase of O_3 due to the weekend effect.

About 80% of Ecuador's electricity is produced from hydropower facilities, with other renewable sources contributing marginally. The rest is produced by power facilities using fossil fuels. Promoting electric vehicles reduces the emissions of primary pollutants (e.g., NO_2 and $PM_{2.5}$) directly in the places where they are being used. However, power facilities are affecting the air quality in their area of influence, which deserves a dedicated assessment.

ACKNOWLEDGEMENTS

This research is part of the 'Emisiones y Contaminación Atmosférica en el Ecuador 2024' project. Simulations were done at the Universidad San Francisco de Quito's high-performance computing system.

REFERENCES

[1] Molina, M.J. & Molina, L.T., Megacities and atmospheric pollution. *Journal of the Air and Waste Management Association*, **54**(6), pp. 644–680, 2004. https://doi.org/10.1080/10473289.2004.10470936.

[2] Parra, R., Molina, C., Caguana, C. & Heredia, E., *Inventario de Emisiones Atmosféricas Del Cantón Cuenca 2021*, 2023.

[3] Molina, C., Caguana, C., Heredia, E. & Parra, R., *Informe de La Calidad Aire Cuenca 2022*, 2023.
[4] World Health Organization, *WHO Global Air Quality Guidelines: Particulate Matter ($PM_{2.5}$ and PM_{10}), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide*, World Health Organization, 2021.
[5] International Agency for Research on Cancer, *List of Classifications*. https://monographs.iarc.who.int/list-of-classifications. Accessed on: 4 May 2024.
[6] World Health Organization, Regional Office for Europe, *Air Quality Guidelines for Europe*, World Health Organization, 2000.
[7] United Nations, *THE 17 GOALS | Sustainable Development*. https://sdgs.un.org/goals. Accessed on: 4 May 2024.
[8] Registro Oficial Órgano del Gobierno del Ecuador, Ley orgánica de eficiencia energética. https://www.recursosyenergia.gob.ec/wp-content/uploads/downloads/2019/03/Ley-Eficiencia-Energe%CC%81tica.pdf. Accessed 4 May 2024.
[9] NSF National Center for Atmospheric Research, *CISL RDA: NCEP FNL Operational Model Global Tropospheric Analyses, Continuing from July 1999*. https://rda.ucar.edu/datasets/ds083.2/. Accessed 20 Dec. 2022.
[10] Zaveri, R.A. & Peters, L.K., A new lumped structure photochemical mechanism for large-scale applications. *J. Geophys. Res.*, **104**(D23), pp. 30387–30415, 1999. https://doi.org/10.1029/1999JD900876.
[11] Zaveri, R.A., Easter, R.C., Fast, J.D. & Peters, L.K., Model for simulating aerosol interactions and chemistry (MOSAIC). *J. Geophys. Res.*, **113**(D13), D13204, 2008. https://doi.org/10.1029/2007JD008782.
[12] Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Barker, D.M., Duda, M.G., Huang, X.-Y., Wang, W. & Powers, J.G., A Description of the Advanced Research WRF Version 3.
[13] European Environment Agency, *The Application of Models under the European Union's Air Quality Directive: A Technical Reference Guide*. https://www.eea.europa.eu/publications/fairmode. Accessed on: 30 Dec. 2022.
[14] Parra, R. & Espinoza, C., Insights for air quality management from modeling and record studies in Cuenca, Ecuador. *Atmosphere*, **11**(9), p. 998, 2020. https://doi.org/10.3390/atmos11090998.
[15] Cleveland, W.S., Graedel, T.E., Kleiner, B. & Warner, J.L., Sunday and workday variations in photochemical air pollutants in New Jersey and New York. *Science*, **186**(4168), pp. 1037–1038, 1974. https://doi.org/10.1126/science.186.4168.1037.
[16] Lebron, F., A comparison of weekend-weekday ozone and hydrocarbon concentrations in the Baltimore-Washington Metropolitan Area. *Atmospheric Environment (1967)*, **9**(9), pp. 861–863, 1975. https://doi.org/10.1016/0004-6981(75)90046-3.
[17] Parra, R., Efecto fin de semana en la calidad del aire de la ciudad de Cuenca, Ecuador. *ACI Avances en Ciencias e Ingenierías*, **9**(1), 2018. https://doi.org/10.18272/aci.v9i15.291.

www.witpress.com, ISSN 1743-3541 (on-line)