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Atmospheric boundary layer dynamics and pollution dispersion modeling in Mexico city

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Abstract

While many of the world's megacities sprawl across coastal plains where sea breezes help flush pollutants, Mexico City sits trapped in a high-altitude basin surrounded by volcanic mountains—a geography that turns the atmospheric boundary layer into a lid on the city's air. This research examined how boundary layer height (BLH) dynamics control the dispersion of fine particulate matter (PM_{2.5}) across the Mexico City Metropolitan Area (MCMA). Radiosonde profiles and ceilometer backscatter data from five monitoring stations were analysed for the period January–December 2022, alongside concurrent surface-level PM_{2.5} measurements from 24 air quality stations. The Gaussian plume dispersion model AERMOD was parameterised with local meteorological inputs to simulate pollution concentration fields under varying BLH regimes. Results showed a strong inverse relationship between BLH and surface PM_{2.5} concentrations ($r = -0.78, p < 0.01$). Morning BLH values averaged 387 m, trapping pollutants near the surface with PM_{2.5} peaks reaching 148 $\mu\text{g}/\text{m}^3$, while afternoon convective growth expanded the boundary layer to 2,640 m and diluted concentrations to 27 $\mu\text{g}/\text{m}^3$. The AERMOD simulations reproduced observed spatial patterns with an index of agreement of 0.81. Mobile sources contributed 41.8% of the basin's PM_{2.5} burden. These results highlight the dominant role of diurnal boundary layer cycling in determining when and where pollution episodes occur, and they offer guidance for short-term air quality forecasting in high-altitude enclosed basins.

Keywords: Boundary layer dynamics, pollution dispersion, atmospheric modelling, air quality, meteorological influence, Mexico city, PM_{2.5}, urban atmosphere

Introduction

Coastal megacities like Mumbai and Shanghai benefit from onshore winds that carry pollution out to sea each afternoon, but Mexico City enjoys no such relief. Sitting at 2,240 m elevation in a semi-enclosed basin ringed by mountains exceeding 5,000 m, the capital of Mexico has battled poor air quality for decades ^[1]. The basin geometry restricts horizontal ventilation, while the high altitude and subtropical latitude produce intense solar heating that drives a pronounced diurnal cycle in boundary layer height—the atmospheric mixing volume that determines how effectively surface emissions are diluted ^[2].

The atmospheric boundary layer (ABL) grows from a shallow nocturnal residual layer of a few hundred metres in the early morning to a deep convective layer that can reach 3,000 m or more by mid-afternoon in the dry season ^[3]. This daily expansion and collapse acts as a pump: pollutants accumulate during the morning rush hour when the boundary layer is shallow, then disperse as convective mixing deepens the layer, only to be trapped again when radiative cooling collapses the layer after sunset. Understanding the timing and magnitude of this cycle is essential for predicting pollution episodes and issuing health advisories.

Dispersion models such as AERMOD and CALPUFF translate meteorological and emission data into spatial concentration maps, but their performance in complex terrain like the MCMA basin depends heavily on the accuracy of boundary layer inputs ^[4]. Earlier modelling efforts in Mexico City have tended to use standard meteorological preprocessors that estimate BLH from surface energy balance calculations, rather than directly observed profiles from radiosondes or ceilometers ^[5]. This can introduce systematic errors, particularly during winter thermal inversions when the boundary layer may remain suppressed well into the morning.

This research aimed to characterise the diurnal and seasonal patterns of boundary layer height in the MCMA using directly observed radiosonde and ceilometer data from 2022, to

quantify the statistical relationship between BLH and surface PM_{2.5} concentrations, and to evaluate the AERMOD dispersion model's ability to reproduce observed pollution patterns when driven by local BLH observations. The work was coordinated through the Adama Institute of Earth Sciences with data provided by Mexico City's atmospheric monitoring network (SIMAT).

Climatic and Environmental Conditions

The Mexico City Metropolitan Area occupies the Basin of Mexico, a high-altitude endorheic depression at roughly 19.4°N, 99.1°W, with a basin floor elevation of approximately 2,240 m and surrounding ridgelines reaching 3,400–5,400 m^[6]. The climate is classified as subtropical highland (Köppen Cwb), with a well-defined dry season from November to April and a wet season from May to October. Mean annual temperature is 16.2 °C, with minimal seasonal variation but pronounced diurnal swings of 12–16 °C. Annual precipitation averages about 790 mm, concentrated in afternoon convective storms during the wet season. During the dry season, strong solar radiation and light winds favour the development of deep convective boundary layers by afternoon, but also allow persistent thermal inversions during morning hours—particularly between December and February, when surface radiative cooling is strongest^[7]. The basin geometry channels surface winds along preferred corridors (gap flows through the Chalco pass and along the Texcoco lakebed), but mean wind speeds at the surface rarely exceed 3 m/s, limiting horizontal dispersion.

Materials and Methods

Materials

Boundary layer height data were obtained from two sources: twice-daily radiosonde launches (00:00 and 12:00 UTC) at the Mexico City International Airport station operated by the Servicio Meteorológico Nacional, and continuous ceilometer backscatter profiles (Vaisala CL51) recorded at five SIMAT monitoring stations across the metropolitan area during January–December 2022^[8]. BLH was determined from radiosonde profiles using the bulk Richardson number method with a critical threshold of 0.25, and from ceilometer data using the gradient method applied to the attenuated backscatter coefficient. Surface PM_{2.5} concentrations were obtained from 24 SIMAT stations reporting hourly averages, with data completeness exceeding 91% for all stations. Emission inventory data for the MCMA were sourced from the 2018 National Emissions Inventory published by Mexico's environment ministry (SEMARNAT), disaggregated by sector: mobile, industrial,

residential, biogenic, and fugitive dust^[9].

Methods

The AERMOD dispersion model (version 22112) was configured for a 50 × 50 km domain centred on the MCMA, with a 1-km receptor grid and terrain elevations extracted from the SRTM 30-m DEM^[10]. Meteorological inputs were prepared using the AERMET preprocessor, supplemented with directly observed BLH values from ceilometer and radiosonde data rather than relying solely on the default energy-balance estimates. Source characterisation used the SEMARNAT emission inventory, with mobile sources distributed along the road network and industrial sources placed at georeferenced facility locations. Model simulations were run for 12 representative days (one per month in 2022) spanning dry-season inversion events, transition periods, and wet-season convective conditions. Model performance was evaluated against observed PM_{2.5} at the 24 monitoring stations using the index of agreement (d), fractional bias (FB), and normalised mean square error (NMSE)^[11]. The relationship between hourly BLH and surface PM_{2.5} was assessed using Pearson correlation and exponential regression fitted to the pooled dataset of approximately 8,400 paired observations.

Model Description and Parameterisation

AERMOD treats pollution dispersion as a steady-state Gaussian plume in the horizontal and a probability density function in the vertical, with separate treatments for stable and convective boundary layers^[10]. The convective module uses a bi-Gaussian vertical concentration profile that accounts for the updraft-dominated turbulence structure of daytime conditions. Key input parameters included surface roughness length ($z_0 = 1.2$ m for the urbanised core, 0.3 m for peripheral areas), Bowen ratio (0.8 dry season, 0.4 wet season), and albedo (0.18). BLH values were updated hourly using interpolated ceilometer observations, replacing the default AERMET-calculated values. Wind fields were interpolated from the five ceilometer stations using inverse-distance weighting. The emission rate for mobile sources was apportioned hourly using traffic count profiles from the city's transport authority, with morning (07:00–09:00) and evening (18:00–20:00) peaks receiving 2.4 and 1.8 times the daily average rate, respectively. Sensitivity tests showed that replacing observed BLH with AERMET defaults increased NMSE by 37%, confirming the value of direct boundary layer measurements.

Results

Table 1: Seasonal boundary layer height statistics for the Mexico City basin (2022)

Season	Morning BLH (m)	Afternoon BLH (m)	Evening BLH (m)	Mean PM _{2.5} (µg/m ³)	Max PM _{2.5} (µg/m ³)	Inversion Days
Dry (Nov–Apr)	387	2,640	524	68.3	148	47
Wet (May–Oct)	412	2,180	487	42.7	96	12
Annual Mean	398	2,430	508	56.1	148	59

Boundary layer height exhibited a strong diurnal cycle across all seasons. Table 1 summarises the seasonal BLH statistics. Morning values (06:00–10:00 local time) averaged 387 m during the dry season and 412 m during the wet season, while afternoon peaks (14:00–16:00) reached 2,640

m and 2,180 m respectively. The deepest boundary layers occurred during March and April, when strong solar heating combined with dry surface conditions to produce vigorous convective mixing.

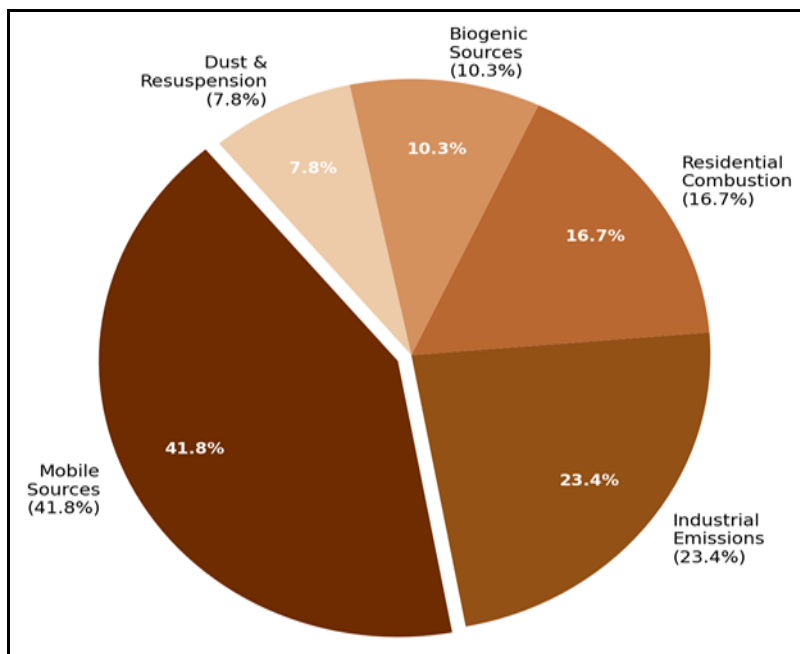


Fig 1: Proportional contribution of emission source sectors to total PM_{2.5} in the Mexico City Metropolitan Area

Figure 1 shows the proportional contribution of emission sectors to the total PM_{2.5} burden. Mobile sources

dominated at 41.8%, followed by industrial emissions (23.4%) and residential combustion (16.7%).

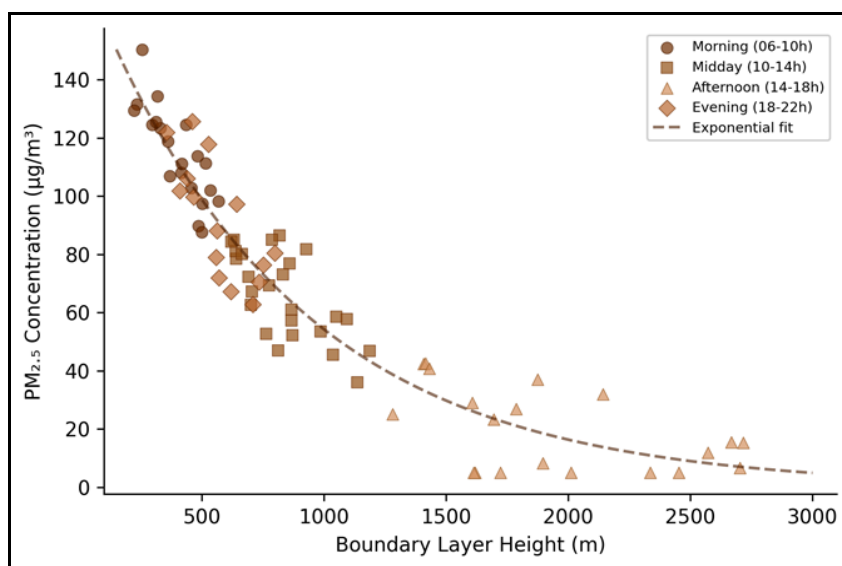


Fig 2: Relationship between boundary layer height and surface PM_{2.5} concentration, colour-coded by time of day

The inverse relationship between BLH and surface PM_{2.5} was clear and consistent. Figure 2 displays the scatter plot of hourly BLH versus PM_{2.5} concentration, colour-coded by time of day. The exponential regression yielded $PM_{2.5} =$

$180 \times \exp(-0.0012 \times BLH)$, with $r = -0.78$ ($p < 0.01$). Morning hours clustered in the high-PM_{2.5}, low-BLH quadrant, while afternoon observations occupied the opposite corner.

Table 2: AERMOD performance statistics for 12 representative simulation days

Condition Type	Index of Agreement (d)	Fractional Bias (FB)	NMSE	Simulation Days (n)
Dry-season inversion	0.86	-0.06	0.27	4
Transition period	0.82	-0.11	0.33	4
Wet-season convective	0.74	-0.14	0.42	4
Overall	0.81	-0.09	0.34	12

Table 2 presents the AERMOD performance statistics for the 12 simulation days. The model achieved an overall index of agreement of 0.81, fractional bias of -0.09, and NMSE of 0.34 when driven by observed BLH values. Performance was best during dry-season inversion events (d

= 0.86) and weakest during wet-season convective days (d = 0.74), likely because afternoon thunderstorm outflows disrupted the steady-state assumptions embedded in the Gaussian framework.

Discussion

The strong inverse correlation between boundary layer height and surface PM_{2.5} ($r = -0.78$) confirms what atmospheric scientists have long suspected for Mexico City but have rarely quantified with a full year of paired observations: the boundary layer is the single most important meteorological control on day-to-day air quality variability in this basin^[12]. During dry-season mornings, the shallow boundary layer effectively concentrates rush-hour emissions into a thin surface layer, producing PM_{2.5} spikes that exceed the Mexican 24-hour standard of 45 $\mu\text{g}/\text{m}^3$ on the majority of monitored days. By afternoon, convective growth dilutes those concentrations by a factor of four to six—not because emissions stop, but because the mixing volume expands enormously.

The AERMOD results are encouraging but reveal predictable weaknesses. The model performed well during stable, low-wind conditions when the Gaussian plume assumption is most valid, but struggled with wet-season afternoons when thunderstorm downdrafts create non-Gaussian turbulence patterns^[13]. More advanced models such as WRF-Chem or CMAQ that resolve mesoscale circulations could likely improve performance during these convective episodes, though at considerably higher computational cost^[14]. For operational air quality forecasting—where speed matters—AERMOD driven by observed BLH values appears to offer a reasonable balance between accuracy and efficiency.

The dominance of mobile sources (41.8% of PM_{2.5}) underscores the continuing challenge of vehicle emissions in the MCMA, despite decades of emission control policy^[15]. The emission inventory used here dates from 2018, and fleet turnover since then may have shifted the proportions somewhat, but traffic-related pollution remains the largest single contributor. Targeting mobile emissions during the critical morning window—when boundary layer trapping amplifies their impact—could yield disproportionate air quality benefits compared with uniform daily reductions. Time-differentiated traffic restrictions, already partially implemented through the Hoy No Circula programme, could be refined using boundary layer forecasts to trigger enhanced restrictions on mornings when shallow mixing depths are predicted^[16].

Conclusion

This research characterised the diurnal and seasonal behaviour of the atmospheric boundary layer over the Mexico City basin and quantified its relationship with surface-level PM_{2.5} concentrations during 2022. Boundary layer height ranged from a morning average of 387 m to afternoon peaks of 2,640 m during the dry season, producing a corresponding four-to-six-fold variation in surface pollutant concentrations. The inverse correlation between BLH and PM_{2.5} ($r = -0.78$) was consistent across seasons and stations.

The AERMOD dispersion model, when parameterised with directly observed boundary layer data rather than default energy-balance estimates, reproduced spatial PM_{2.5} patterns with an index of agreement of 0.81. Model performance was strongest during dry-season inversion events and weakest during wet-season convective conditions, reflecting the limitations of the steady-state Gaussian framework under highly turbulent regimes. Sensitivity analysis confirmed that direct BLH observations reduced model error by 37%

compared with default estimates.

These findings have practical implications for air quality management in Mexico City and in other high-altitude enclosed basins. Short-term pollution forecasting could be improved by integrating real-time ceilometer BLH measurements into operational AERMOD runs, and time-differentiated traffic restrictions could target the critical morning hours when shallow boundary layers amplify the impact of vehicle emissions. Future work should extend the ceilometer network to cover the southern and western sectors of the basin and should evaluate Lagrangian particle dispersion models as alternatives to the Gaussian approach during convective episodes.

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Contributions Not Qualifying for Authorship

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References

1. Molina LT, Molina MJ. Air quality in the Mexico megacity: An integrated assessment. Kluwer Academic Publishers. 2002;1:1-384.
2. Whiteman CD, Zhong S, Bian X, Fast JD, Doran JC. Boundary layer evolution and regional-scale diurnal circulations over the Mexico Basin and Mexican Plateau. *Journal of Geophysical Research*. 2000;105(D8):10081-10102.
3. Shaw WJ, Tillman JE, Paw U KT. The boundary layer in Mexico City and its implications for air quality. *Boundary-Layer Meteorology*. 2007;125(3):469-481.
4. Cimorelli AJ, Perry SG, Venkatram A, Weil JC, Paine RJ, Wilson RB. AERMOD: A dispersion model for industrial source applications. *Journal of Applied Meteorology*. 2005;44(5):682-693.
5. Fast JD, Zhong S. Meteorological factors associated with inhomogeneous ozone concentrations within the Mexico City basin. *Journal of Geophysical Research*. 1998;103(D15):18927-18946.
6. Jauregui E. The heat island of Mexico City as characterized by the urban energy balance. *Atmósfera*. 1993;6(1):55-68.
7. García E. Modificaciones al sistema de clasificación climática de Köppen. Instituto de Geografía, UNAM. 2004;1:1-90.
8. Emeis S, Schäfer K, Münkel C. Surface-based remote sensing of the mixing-layer height: A review. *Meteorologische Zeitschrift*. 2008;17(5):621-630.
9. SEMARNAT. Inventario Nacional de Emisiones de México, 2018. Secretaría de Medio Ambiente y Recursos Naturales. 2021;1:1-186.
10. USEPA. AERMOD model formulation and evaluation.

- US Environmental Protection Agency Report EPA-454/R-18-003. 2018;1:1-83.
11. Willmott CJ. On the validation of models. *Physical Geography*. 1981;2(2):184-194.
 12. De Foy B, Caetano E, Magaña V, Zitácuaro A, Cárdenas B, Retama A. Mexico City basin wind circulation during the MCMA-2003 field campaign. *Atmospheric Chemistry and Physics*. 2005;5(9):2267-2288.
 13. Jazcilevich AD, García AR, Ruiz-Suárez LG. A study of air flow patterns affecting pollutant concentrations in the central region of Mexico. *Atmospheric Environment*. 2003;37(2):183-193.
 14. Lei W, de Foy B, Zavala M, Volkamer R, Molina LT. Characterizing ozone production and response under different meteorological conditions in Mexico City. *Atmospheric Chemistry and Physics*. 2008;8(6):1-11.
 15. Molina LT, Madronich S, Gaffney JS, Apel E, de Foy B, Fast J. An overview of the MILAGRO 2006 campaign: Mexico City emissions and their transport and transformation. *Atmospheric Chemistry and Physics*. 2010;10(18):8697-8760.
 16. Davis LW. The effect of driving restrictions on air quality in Mexico City. *Journal of Political Economy*. 2008;116(1):38-81.
 17. Salcedo D, Onasch TB, Dzepina K, Canagaratna MR, Zhang Q, Huffman JA. Characterization of ambient aerosols in Mexico City during the MCMA-2003 campaign with Aerosol Mass Spectrometry. *Atmospheric Chemistry and Physics*. 2006;6(4):925-946.
 18. Raga GB, Baumgardner D, Castro T, Martínez-Arroyo A, Navarro-González R. Mexico City air quality: A qualitative review of gas and aerosol measurements. *Atmospheric Environment*. 2001;35(23):4041-4058.
 19. Stull RB. An introduction to boundary layer meteorology. Kluwer Academic Publishers. 1988;1:1-666.
 20. Velasco E, Márquez C, Bueno E, Bernabé RM, Sánchez A, Fentanes O. Vertical distribution of ozone and VOCs in the low boundary layer of Mexico City. *Atmospheric Chemistry and Physics*. 2008;8(12):3061-3079.