# VERTICAL CONCENTRATION PROFILES OF URBAN AIR POLLUTANTS: A BRIEF OVERVIEW

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ABSTRACT

Understanding the vertical distribution of air pollutants in urban environments is essential for accurate exposure assessment, model validation and effective air quality management. This review synthesises current knowledge on vertical concentration profiles of urban pollutants, examining measurement techniques, observed patterns, controlling factors and practical applications. Traditional ground-based profiling systems, including tall towers and tethered balloons, have been complemented by advanced remote sensing technologies such as light detection and ranging technology, and unmanned aerial vehicles, enabling comprehensive characterisation of three-dimensional pollutant distributions. Primary pollutants from ground-level sources typically exhibit exponential decay with height, while secondary pollutants such as ozone display inverse gradients due to surface titration reactions. Particulate matter shows size-dependent vertical behaviour, with fine particles relatively well-mixed during convective conditions and coarse particles displaying steep gradients due to gravitational settling. Atmospheric boundary layer dynamics, urban morphology, emission source characteristics and chemical transformations fundamentally control vertical pollutant distributions. Applications include improved exposure assessment for epidemiological studies, air quality model evaluation, monitoring network optimisation and source apportionment. As cities expand vertically and climate change alters atmospheric dynamics, understanding pollutant distributions throughout the urban atmospheric column becomes increasingly critical for protecting public health and managing air quality in the growing global urban population.

*Keywords: vertical concentration profiles, air pollution, concentration gradients.*

## 1 INTRODUCTION

The vertical distribution of air pollutants in urban environments represents a critical dimension of air quality science that has implications for human health, environmental management, and regulatory policy. While horizontal dispersion patterns have been extensively documented over decades of research, the vertical structure of pollutant concentrations reveals fundamental insights into the complex interplay between emission sources, atmospheric dynamics, urban morphology, and chemical transformation processes. Understanding these vertical profiles is essential for accurate exposure assessment, as the majority of the global population now resides in urban areas where pollutant concentrations can vary dramatically with height above ground level [1].

Traditional air quality monitoring networks typically deploy sensors at fixed heights, often on rooftops or at standardised elevations, potentially missing the full complexity of pollutant distributions experienced by urban populations [2]. The growing recognition that concentrations at breathing height may differ substantially from those measured at monitoring stations has catalysed increased interest in three-dimensional characterisation of urban air quality. This review synthesises current understanding of vertical concentration profiles in cities, examining measurement methodologies, observed patterns for different pollutant species, physical and chemical processes controlling vertical distributions, and practical applications of this knowledge for air quality management and public health protection.



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It is worth noting that the literature reviewed in this paper was identified through systematic searches of major scientific databases including Web of Science, Scopus, and Google Scholar, using combinations of keywords such as ‘vertical concentration profile’, ‘urban air pollution’, ‘boundary layer’, ‘vertical distribution’ and ‘particulate matter’. The search focused primarily on peer-reviewed journal articles published within the last decade (2014–2024), with particular emphasis on field measurement studies in urban environments rather than purely modelling investigations. Priority was given to studies employing direct vertical profiling techniques and those reporting empirical observations of pollutant gradients within the urban boundary layer. While regional-scale chemical transport modelling studies were considered for their insights into boundary layer dynamics and process understanding, the review emphasises observational evidence and measurement methodologies applicable to urban air quality characterisation. Key journals including *Atmospheric Chemistry and Physics*, *Atmospheric Measurement Techniques*, *Boundary-Layer Meteorology*, and *Aerosol and Air Quality Research* provided substantial relevant literature. The selection excluded laboratory studies, wind tunnel experiments, and purely theoretical investigations to maintain focus on real-world urban applications.

## 2 MEASUREMENT TECHNIQUES AND TECHNOLOGIES

Vertical profiling of concentration of urban air pollutants employs diverse methodologies, each offering distinct capabilities and facing specific limitations. Table 1 summarises the more salient methodologies, while the following sections briefly discuss some of these techniques.

Table 1: Summary of measurement techniques for vertical pollutant profiling in urban areas.

| **Method** | **Typical vertical range** | **Temporal resolution** | **Major strengths** | **Main limitations** |
|---|---|---|---|---|
| Fixed towers/ gradient towers | 0–300 m | Minutes-hours | Continuous, accurate in-situ profiles; long-term capability | Limited spatial coverage; high cost |
| Mobile towers/ lifts | 0–50 m | Minutes-hours | Captures façade and canyon gradients | Difficult deployment; short duration |
| UAVs and tethered balloons | 0–1,000 m | Seconds-minutes | Flexible, high vertical resolution | Payload, aspiration, and legal constraints |
| Lidar and ceilometers | 50–2,000 m | Seconds-minutes | Continuous aerosol profiles; BL height detection | Indirect mass retrieval; requires calibration |
| MAX-DOAS and multi-axis optical systems | 0–3,000 m | Minutes-hours | Vertical sensitivity for gases ($NO_2$, HCHO, $SO_2$) | Limited near-surface sensitivity; inversion assumptions |
| Satellite remote sensing | >100 m | Hours-days | Regional context | Coarse resolution near surface |


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### 2.1 Ground-based profiling systems

Traditional ground-based approaches include instrumentation deployed on tall towers, which provide direct sampling at multiple discrete heights. These systems enable high-precision measurements of pollutant concentrations, meteorological parameters, and turbulent fluxes throughout the lower urban boundary layer [3]. Furthermore, tall-tower networks have been established in several major cities worldwide, providing long-term datasets that capture diurnal, seasonal, and interannual variations in the vertical structure [4], [5].

Tethered balloon systems and aerostat platforms represent another classical approach, offering vertical mobility and the ability to profile the entire boundary layer. These systems can carry instrument packages to heights of several hundred metres, though operations are constrained by weather conditions and require significant logistical support. Tethered systems have proven particularly valuable for intensive field campaigns targeting specific research questions about boundary layer structure and pollutant evolution [6].

### 2.2 Remote sensing technologies

Light detection and ranging (LiDAR) technology has revolutionized vertical profiling capabilities by enabling continuous, high-resolution monitoring of aerosol vertical structure. Elastic backscatter LiDAR systems provide range-resolved information about aerosol distributions, while more sophisticated differential absorption LiDAR (DIAL) can measure specific gaseous pollutants. These remote sensing instruments offer temporal resolutions of seconds to minutes and vertical resolutions of tens of metres, capturing the dynamic evolution of pollutant layers and mixing processes [7], [8]. The primary limitation is that LiDAR provides optical properties rather than direct mass concentrations, requiring calibration with in-situ measurements [9].

Doppler LiDAR systems complement aerosol LiDAR by measuring wind velocity profiles, enabling investigation of the coupling between atmospheric dynamics and pollutant distributions. These systems have been successfully deployed in various urban environments to characterise boundary layer dynamics and turbulent mixing processes [4].

### 2.3 Mobile and unmanned platforms

Unmanned aerial vehicles (UAVs) have emerged as flexible, cost-effective platforms for vertical profiling in recent years. Equipped with miniaturised sensors, UAVs can measure pollutant concentrations, meteorological parameters, and aerosol properties throughout the lower atmosphere with high spatial resolution. Their mobility enables profiling at multiple locations during single missions, facilitating investigation of horizontal and vertical variability, simultaneously [10]. However, payload limitations restrict the number and sophistication of instruments that can be deployed, and regulatory constraints on urban UAV operations present practical challenges.

Research has demonstrated that the location of sensor placement on UAVs significantly affects measurement accuracy due to propeller downwash and upwash effects. Optimal mounting positions alongside the UAV body minimise interference from rotor-generated airflows [10]. Sensor packages deployed on building facades or elevator systems in tall structures provide alternative approaches to vertical profiling, particularly valuable for characterising concentration distributions within the urban canopy layer.


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## 3 VERTICAL DISTRIBUTION PATTERNS OF MAJOR AIR POLLUTANTS

### 3.1 Primary gaseous pollutants

Primary pollutants emitted directly from ground-level sources typically exhibit characteristic vertical profiles with maximum concentrations near the surface, decreasing with height. For example, reactive nitrogen oxides ($NO_X$), which originate largely from vehicular traffic, often show a steep gradient, with concentrations that decline rapidly with altitude under stable conditions [11]. The strength of this $NO_X$ gradient is highly sensitive to atmospheric stability, consistent with observations of strong accumulation near the ground during nocturnal inversions.

Within street canyons, these pollutants can accumulate to concentrations that are multiple times higher at street level than at rooftop height during stable atmospheric conditions, when vertical mixing is suppressed. The vertical gradient strength varies substantially with atmospheric stability, time of day, and urban morphology. During unstable daytime conditions with vigorous convective mixing, vertical gradients weaken considerably, sometimes approaching uniform mixing throughout the lower boundary layer. Conversely, nocturnal stable stratification produces steep concentration gradients, with pollutants confined to shallow layers near the surface. Traffic-related pollutants often exhibit distinctive morning and evening rush-hour peaks that propagate upward as the mixing layer develops, creating time-varying vertical structure [12].

Volatile organic compounds (VOCs) display varied vertical behaviour depending on their sources and atmospheric lifetimes. Short-lived reactive VOCs show steep vertical gradients similar to $NO_X$, while longer-lived species may be more uniformly mixed or even increase aloft due to photochemical aging. For instance, tower-based measurements reveal that many non-methane hydrocarbons decrease with height whereas oxidised VOCs can increase, pointing to in-situ chemical transformation and vertical mixing processes [13].

### 3.2 Particulate matter

Particulate matter (PM) exhibits complex vertical distributions that depend strongly on particle size, composition, and formation mechanisms. Fine particles ($PM_{2.5}$) often display relatively uniform mixing within the boundary layer during daytime convective conditions, reflecting their small settling velocities and the dominance of turbulent diffusion over gravitational settling [14]. However, significant vertical structure can develop during stable conditions or when distinct air-mass layers are present. For example, measurements from a meteorological tower in Shenyang showed that $PM_{2.5}$ and $PM_1$ drop off more slowly with height during the day than at night, with near-surface concentrations rise sharply during stable nocturnal conditions [15].

Moreover, source apportionment studies reveal that $PM_{2.5}$ composition also varies with height. In a vertically stratified sampling campaign in a high-rise building, components associated with traffic emissions (e.g., elemental carbon) were significantly higher at lower floors, while other chemical species were more uniformly distributed with height, suggesting that sources of coarse particles dominate near ground level [2].

Coarse particles ($PM_{10-2.5}$) exhibit steeper vertical gradients due to more rapid gravitational settling. These larger particles, often derived from mechanical processes such as road dust resuspension and construction activities, tend to remain concentrated near their surface sources. The vertical profile of $PM_{10}$ typically represents a combination of the relatively uniform fine fraction and the more stratified coarse fraction [15].


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Ultrafine particles (UFP or $PM_{0.1}$, diameter < 100 nm), primarily emitted from combustion processes, show strong vertical gradients near major roadways, with concentrations decreasing rapidly with height and distance from sources. These particles have significant health implications due to their ability to penetrate deep into the respiratory system, yet their vertical distributions remain less comprehensively characterised than larger particles [16].

### 3.3 Black carbon and absorbing aerosols

Black carbon (BC), a key component of combustion-derived aerosols and an important climate-forcing agent, typically displays enhanced concentrations near the surface with exponential decay aloft, reflecting its predominantly ground-level (traffic) sources [17]. Vertical profiles of BC measured using various platforms have documented concentration patterns that vary with atmospheric conditions and source distributions.

The vertical structure of BC provides valuable information for source apportionment, as different combustion sources (traffic, residential heating, industrial emissions, etc.) may have characteristic emission heights. Measurements in urban areas have shown that BC concentrations can decrease by 30–50% between ground level and heights of 100–200 m, though the exact vertical profile shape depends on mixing conditions and source strength [18].

### 3.4 Secondary pollutants: Ozone

Ozone ($O_3$) presents a distinctive vertical profile pattern that contrasts markedly with primary pollutants. In urban environments, $O_3$ concentrations frequently increase with height in the lower boundary layer, creating a characteristic '$O_3$-deficit' within the urban canopy. This phenomenon results from rapid $O_3$ titration by nitric oxide (NO) emitted from traffic sources near the surface [19]. Above the immediate influence of surface NO emissions, $O_3$ concentrations recover and may exceed those in the urban canopy by 10–30 ppb.

The vertical $O_3$ structure varies diurnally and seasonally. During nighttime, $O_3$ destruction near the surface continues while aloft $O_3$ may persist due to reduced mixing with surface air. Daytime photochemical production can modify vertical profiles, particularly downwind of urban centres where secondary $O_3$ formation is enhanced. Regional-scale transport of $O_3$-rich air masses aloft can create elevated layers with concentrations exceeding surface values, affecting overall boundary layer composition as these layers mix downward.

Understanding, $O_3$ vertical profiles is crucial for interpreting surface monitoring data and assessing population exposure, as elevated $O_3$ concentrations aloft can represent a reservoir that impacts surface air quality as the boundary layer evolves [20].

### 3.5 Secondary aerosols

Secondary aerosols formed through gas-to-particle conversion processes, including sulphate, nitrate, and secondary organic aerosols (SOA), exhibit vertical distributions influenced by both their formation mechanisms and mixing processes. Sulphate aerosols, formed from sulphur dioxide ($SO_2$) oxidation, may show relatively uniform vertical mixing when formation occurs throughout the boundary layer. However, aqueous-phase processing in clouds or fog layers can create elevated layers of enhanced sulphate concentrations [14].

Ammonium nitrate aerosol, a major component of $PM_{2.5}$ in many urban areas, displays temperature-dependent partitioning between gas and particle phases. This thermodynamic behaviour can produce distinctive vertical structure, with preferential partitioning to the particle phase at cooler temperatures aloft. Measurements have documented cases where


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nitrate concentrations increase with height despite decreasing total $NO_X$ concentrations, reflecting temperature effects on gas-particle equilibrium [14].

Secondary organic aerosol formation and evolution involve complex chemical processes that may occur throughout the boundary layer, leading to varied vertical patterns depending on precursor distributions, oxidant availability, and atmospheric conditions [21].

### 3.6 Summary of the vertical concentration profile patterns of major air pollutants

Vertical concentration profile patterns are pollutant-dependent, as indicated in the previous subsections. Table 2 summarises the discussion in Section 3.

Table 2: Summary of the vertical concentration profile patterns of major air pollutants.

| Pollutant | Profile type | Gradient strength | Primary driver |
|---|---|---|---|
| $NO_X$, BC | Exponential decay from surface | Strong | Ground-level traffic emissions |
| $O_3$ | Inverse (increases with height) | Moderate | Surface NO titration |
| $PM_{2.5}$ | Well-mixed (day), stratified (night) | Weak to moderate | Atmospheric stability |
| $PM_{10\text{-}2.5}$ | Steep decay from surface | Very strong | Gravitational settling |
| UFP | Rapid decay near sources | Very strong | Source proximity |

## 4 CONTROLLING FACTORS: PHYSICAL AND CHEMICAL PROCESSES

### 4.1 Atmospheric boundary layer dynamics

Atmospheric stability exerts fundamental control over vertical pollutant dispersion. The boundary layer evolves through a characteristic diurnal cycle in response to surface heating and cooling, profoundly affecting pollutant vertical distributions. During daytime, solar heating creates an unstable boundary layer with turbulent mixing that can extend to heights of 1–2 km or more. This convective mixing promotes vertical homogenisation, reducing concentration gradients and diluting surface pollutants through a large vertical volume [4].

As evening approaches and surface cooling begins, the boundary layer transitions to stable stratification. A residual layer aloft retains the previous day's mixed pollutants, while a shallow stable layer forms near the surface, capping vertical mixing. Pollutants emitted into this stable nocturnal boundary layer accumulate in a confined volume, producing high surface concentrations and steep vertical gradients. The nocturnal boundary layer height may be only 50–200 m, compared to 1–2 km during daytime [22].

Doppler LiDAR observations have shown that mixing height derived from turbulence measurements and aerosol layer height from backscatter profiles generally show similar diurnal cycles, in the range 300–800 m, with variations depending on sky conditions and atmospheric stability. Morning transition represents a critical period when the growing convective boundary layer entrains pollutants from the residual layer aloft, potentially causing secondary maxima in surface concentrations [4].

Mechanical turbulence generated by wind shear contributes to vertical mixing independently of buoyancy effects, particularly important during neutral stability conditions or within the urban canopy where building roughness enhances turbulence generation. The


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coupling between thermal and mechanical turbulence production determines overall mixing efficiency and pollutant dilution rates [23].

### 4.2 Urban morphology and microscale flows

Building geometry fundamentally modifies airflow patterns and pollutant dispersion within the urban canopy layer. Street canyon aspect (building height to street width) ratios control the formation and strength of canyon vortices that can trap pollutants. High aspect ratio canyons (deep, narrow streets) often develop stable recirculation patterns that limit vertical ventilation, causing pollutant accumulation at street level [24].

The urban roughness sublayer, extending approximately two to three times the mean building height, represents a zone of complex three-dimensional flows where building-scale eddies dominate momentum and scalar transport [25]. Above this layer, in the inertial sublayer, flow becomes more horizontally homogeneous and traditional similarity theory becomes applicable. Pollutant concentrations transition from highly variable within the roughness sublayer to more horizontally uniform aloft.

High-rise buildings create distinctive flow patterns including downwash on windward faces and enhanced turbulence in building wakes, affecting pollutant dispersion over large volumes [26]. Building arrays with varying heights generate complex flow channelling and recirculation zones that influence vertical transport efficiency. The urban heat island effect, creating warmer temperatures in cities compared to surrounding rural areas, enhances buoyancy-driven vertical mixing, particularly during evening and nighttime hours when urban–rural temperature differences peak [25].

### 4.3 Emission source characteristics

The vertical location and temporal pattern of emission sources directly shape concentration profiles. Ground-level traffic emissions dominate pollutant inputs in most urban areas, producing maximum concentrations at the surface. However, the growing prevalence of high-rise buildings introduces elevated emission sources including rooftop ventilation systems, backup generators, and residential heating systems, complicating traditional assumptions about surface-dominated emissions [27].

Industrial point sources with tall stacks inject pollutants at elevated heights, often above the urban boundary layer, where different dispersion regimes govern their behaviour. Plume rise, determined by emission temperature and velocity, can carry pollutants to heights where they undergo different transport and transformation compared to surface emissions [28].

Temporal emission patterns interact with boundary layer evolution to modulate vertical profiles. Morning rush-hour emissions coinciding with a shallow, stable boundary layer produce different vertical structures than afternoon emissions released into a deep, well-mixed layer. Weekend–weekday differences in emission timing and magnitude create corresponding variations in vertical distribution patterns.

### 4.4 Chemical transformation and deposition

Chemical reactions modify pollutant vertical distributions by altering species concentrations at rates that vary with height. Photochemical processes depend on solar radiation intensity, which varies with altitude due to aerosol extinction and cloud effects. Enhanced photolysis rates aloft can accelerate $O_3$ formation and other photochemical transformations compared to near-surface levels [29].


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Gas-phase reaction rates depend on concentrations of reactants that may themselves exhibit vertical structure. The $O_3$–NO titration reaction creating vertical '$O_3$-deficits' exemplifies chemistry-transport interactions. Heterogeneous reactions on aerosol surfaces and cloud droplets represent additional pathways whose efficiency varies with altitude as particle concentrations and cloud occurrence change [14].

Dry deposition removes pollutants from the atmosphere at the surface, creating a sink that drives downward vertical flux and influences concentration profiles. Deposition velocities vary among species based on their physical and chemical properties and surface characteristics [30]. Gravitational settling contributes to coarse particle deposition, producing steeper vertical gradients for larger particles. Wet deposition during precipitation events can rapidly remove pollutants throughout the atmospheric column, temporarily altering vertical structure before rebuilding during subsequent emissions.

### 4.5 Summary of the controlling factors

Various factors have bearing on vertical concentration profile patterns of major air pollutants, as indicated in the previous subsections. Tables 3 and 4 summarise the discussion in Section 4.

Table 3: Summary of the main factors controlling vertical concentration profile patterns of major air pollutants.

| **Controlling factor** | **Key processes** | **Effect on vertical concentration profile** |
|---|---|---|
| Emissions | Traffic (ground-level), industrial (elevated), temporal patterns | Determines baseline concentration profile shape |
| Boundary layer dynamics | Atmospheric stability, mixing height, turbulent transport | Controls mixing efficiency and gradient strength |
| Urban morphology | Building geometry, street canyons, urban heat island | Modifies airflow and traps pollutants in canopy |
| Chemistry | Photochemical reactions, $O_3$–NO titration, secondary formation | Transforms species and creates inverse gradients |
| Deposition | Dry deposition, gravitational settling | Creates surface sink and downward flux |

Table 4: Summary of the effects of atmospheric conditions on vertical concentration profile patterns of major air pollutants.

| **Condition** | **Mixing height** | **Profile characteristic** |
|---|---|---|
| Daytime (unstable) | 1–2 km | Weak gradients, well-mixed |
| Nighttime (stable) | 50–200 m | Steep gradients, surface accumulation |
| Urban canopy | 0–150 m | Highly variable, canyon trapping |


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## 5 PRACTICAL APPLICATIONS AND IMPLICATIONS

### 5.1 Exposure assessment and health studies

Accurate characterisation of pollutant vertical distributions is essential for exposure assessment, as breathing-height concentrations may differ substantially from those measured at standard monitoring locations. Most regulatory monitoring stations sample air at rooftop locations 3–10 m above ground, potentially underestimating exposures in street canyons or overestimating exposures for elevated residences [16]. Vertical profile information enables correction factors relating rooftop measurements to street-level concentrations, improving exposure estimates for epidemiological studies and health impact assessments.

Population-weighted exposure calculations require integrating pollutant concentrations throughout the vertical extent of urban buildings where people reside and work. High-rise residential buildings house occupants at various heights experiencing different pollutant concentrations depending on their floor level, building ventilation systems, and external concentration profiles. Studies documenting vertical concentration gradients along building facades inform building design and ventilation strategies to minimize indoor pollutant infiltration [31].

Vulnerable populations including children in schools, elderly in care facilities, and patients in hospitals may experience different exposures depending on building height and ventilation configurations. Understanding vertical profiles enables targeted interventions to reduce exposures for these sensitive and vulnerable groups [2].

### 5.2 Air quality model evaluation

Vertical profile observations provide critical data for evaluating and improving air quality models. While surface concentration measurements offer limited constraints on model performance, vertical profiles test models' ability to represent boundary layer processes, turbulent mixing, and pollutant transport throughout the three-dimensional atmosphere. Comparison of modelled versus observed vertical profiles reveals deficiencies in planetary boundary layer schemes, emission height specifications, and dispersion parametrisations [32].

Chemical transport models rely on accurate representation of vertical mixing to simulate pollutant evolution, long-range transport, and surface-atmosphere exchange. Vertical profile data help constrain mixing heights, turbulent diffusion coefficients, and convective transport parametrisations [33]. Models that reproduce observed surface concentrations but fail to match vertical profiles may achieve correct results through compensating errors rather than proper representation of underlying processes.

Three-dimensional data assimilation systems increasingly incorporate vertical profile information from remote sensing and aircraft measurements to improve initial conditions and model forecasts. The growing availability of continuous LiDAR profiling enables operational data assimilation for air quality forecasting systems [34].

### 5.3 Air quality prediction and forecasting

Accurate air quality prediction and forecasting increasingly rely on integration of vertical profile information into both numerical and data-driven modelling frameworks. Operational chemical transport models require realistic representation of vertical pollutant distributions to initialise forecasts and to properly simulate dispersion, transport, and transformation processes throughout the atmospheric column.


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Boundary layer height, atmospheric stability parameters, and vertical mixing coefficients derived from profiling observations serve as critical inputs that constrain model physics and improve forecast skill. Recent advances in machine learning approaches for air quality prediction have demonstrated enhanced performance when incorporating features related to vertical structure, including mixing layer depth, stability indices, and three-dimensional urban morphology metrics. Hybrid modelling systems that assimilate real-time vertical profile data from LiDAR and remote sensing platforms into numerical models show particular promise for short-term forecasting in urban areas. The availability of continuous vertical profiling enables validation of predicted three-dimensional concentration fields rather than solely surface values, revealing model deficiencies in boundary layer representation that may remain hidden when evaluating only ground-level predictions.

As forecasting systems evolve toward higher spatial resolution and incorporation of building-scale effects, characterisation of pollutant vertical structure within the urban canopy layer becomes essential for predicting exposures across the full vertical extent of urban development.

### 5.4 Monitoring network design

Understanding vertical pollutant distributions informs optimal placement and interpretation of air quality monitoring stations. Rooftop monitoring locations provide measurements representative of the urban background above the immediate influence of street-level sources, while street canyon monitors capture maximum population exposures in traffic-impacted areas. Multi-level monitoring systems characterising vertical gradients enable estimation of area-wide concentrations from limited measurement locations through interpolation constrained by typical vertical profile shapes [35].

Remote sensing measurements of column-integrated pollutant abundances, including satellite retrievals and ground-based spectrum, require vertical profile information to relate column measurements to surface concentrations relevant for air quality standards and health protection. The relationship between surface and column amounts varies with atmospheric stability, boundary layer height, and pollutant source distributions. Climatological vertical profiles derived from long-term measurement programs provide transfer functions for operational satellite-based air quality monitoring systems [8].

### 5.5 Source apportionment

Vertical concentration profiles combined with chemical composition measurements provide constraints for source apportionment studies. Different source categories often have characteristic emission heights: traffic at ground level, industrial point sources at stack height, regional transport aloft. The vertical structure of pollutant concentrations and chemical tracers helps differentiate local versus regional contributions and identify dominant source types affecting particular altitude ranges [14].

Measurements showing enhanced concentrations of specific pollutants or tracers at elevated heights may indicate contributions from distant sources transported aloft, while strong surface enhancements suggest local ground-level sources. Time-resolved vertical profiling during source-specific events (e.g., rush hours, industrial releases and regional transport episodes) enables attribution of concentration variations to particular source categories [36].


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## 6 FUTURE RESEARCH DIRECTIONS AND EMERGING CHALLENGES

Despite substantial advances in vertical profiling capabilities and understanding of pollutant distributions within the lower boundary layer, critical knowledge gaps remain that warrant urgent research attention. UFP, which pose significant health risks due to their deep respiratory penetration and potential translocation to other organs, remain poorly characterised in terms of their vertical distributions, particularly beyond the immediate vicinity of emission sources. The vertical behaviour of emerging pollutants including microplastics, volatile chemical products from consumer goods, and novel combustion-derived compounds has received minimal investigation, despite their potential health and environmental significance. Furthermore, the proliferation of super-tall buildings exceeding 300–500 m in global megacities introduces unprecedented vertical scales for exposure assessment, yet pollutant distributions, infiltration patterns, and occupant exposures at these extreme heights remain largely undocumented. These knowledge gaps are particularly concerning given that populations residing and working in high-rise environments are rapidly expanding worldwide, and emerging pollutants may exhibit vertical distribution patterns fundamentally different from conventional pollutants due to their distinct physical–chemical properties and source characteristics.

Despite substantial progress in characterising urban pollutant vertical profiles, important knowledge gaps and emerging challenges remain. The increasing prevalence of high-rise development, reaching unprecedented heights in megacities worldwide, extends the vertical domain requiring characterisation. Pollutant distributions and exposure patterns in super-tall buildings exceeding 300–500 m altitude remain poorly documented, as do the influences of building ventilation systems drawing outside air from various heights.

Climate change may alter urban vertical dispersion patterns through changes in boundary layer dynamics, atmospheric stability, and urban heat island intensity. Understanding how vertical pollutant distributions respond to changing climate conditions is essential for projecting future air quality and developing adaptive management strategies.

The integration of vertical profile measurements with emerging high-resolution modelling capabilities, including large-eddy simulation approaches that explicitly resolve building-scale flows, offers opportunities to advance process-level understanding of urban pollutant transport. Machine learning techniques applied to large vertical profile datasets may reveal patterns and predictive relationships not apparent through traditional analysis/phenomenological methods.

Expanding vertical profiling capabilities to include a broader range of pollutants, particularly emerging contaminants such as ultrafine particles, microplastics, and volatile chemical products, will provide more comprehensive characterisation of urban air quality throughout the atmospheric column. Development of compact, low-cost sensors suitable for vertical profiling applications could enable widespread deployment of three-dimensional monitoring networks in cities globally [37].

## 7 CONCLUSION

Vertical concentration profiles reveal the complex three-dimensional structure of urban air quality, shaped by interactions between emission sources, atmospheric dynamics, urban morphology, and chemical processes. Advances in measurement technology, particularly remote sensing systems and unmanned platforms, have dramatically enhanced capabilities to characterise pollutant distributions with height. These measurements demonstrate substantial vertical variability, with important implications for exposure assessment, model evaluation, and air quality management.


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Primary pollutants from ground-level sources typically decrease with height following characteristic functions modulated by atmospheric stability and mixing processes. Secondary pollutants exhibit more complex patterns reflecting their formation mechanisms and precursor distributions. Boundary layer evolution drives diurnal cycles in vertical structure that fundamentally influence surface pollutant concentrations and population exposures.

As urban areas continue expanding vertically and horizontally, understanding pollutant distributions throughout the urban volume becomes increasingly critical for protecting public health and managing air quality effectively. Integration of vertical profile observations into operational monitoring networks, forecasting systems, and regulatory frameworks will enhance capabilities to characterise, predict, and mitigate urban air pollution impacts on the growing global urban population.

## REFERENCES

[1] Roostaei, V., Gharibzadeh, F., Shamsipour, M., Faridi, S. & Hassanvand, M.S., Vertical distribution of ambient air pollutants ($PM_{2.5}$, $PM_{10}$, $NO_X$, and $NO_2$): A systematic review. *Heliyon*, **10**(21), e39726, 2024. https://doi.org/10.1016/j.heliyon.2024.e39726.

[2] Liao, H.-T., Lai, Y.-C., Chao, H.J. & Wu, C.-F., Vertical characteristics of potential $PM_{2.5}$ sources in the urban environment. *Aerosol and Air Quality Research*, **23**(3), 220361, 2023. https://doi.org/10.4209/aaqr.220361.

[3] Haszpra, L., Barcza, Z., Haszpra, T., Pátkai, Z. & Davis, K.J., How well do tall-tower measurements characterize the $CO_2$ mole fraction distribution in the planetary boundary layer? *Atmospheric Measurement Techniques*, **8**(4), pp. 1657–1671, 2015. https://doi.org/10.5194/amt-8-1657-2015.

[4] Barlow, J.F. et al., Boundary layer dynamics over London, UK, as observed using Doppler lidar during REPARTEE-II. *Atmospheric Chemistry and Physics*, **11**(5), pp. 2111–2125, 2011. https://doi.org/10.5194/acp-11-2111-2011.

[5] Lan, C. et al., Intercomparison of eddy-covariance software for urban tall-tower sites. *Atmospheric Measurement Techniques*, **17**(9), pp. 2649–2669, 2024. https://doi.org/10.5194/amt-17-2649-2024.

[6] Renard, J.-B., Michoud, V. & Giacomoni, J., Vertical profiles of pollution particle concentrations in the boundary layer above Paris (France) from the optical aerosol counter LOAC onboard a touristic balloon. *Sensors*, **20**(4), p. 1111, 2020. https://doi.org/10.3390/s20041111.

[7] Zhang, H. et al., Comparison of scanning aerosol lidar and in situ measurements of aerosol physical properties and boundary layer heights. *Aerosol Research*, **2**(1), pp. 135–151, 2024. https://doi.org/10.5194/ar-2-135-2024.

[8] Schäfer, K., Emeis, S., Hoffmann, H. & Jahn, C., Influence of mixing layer height upon air pollution in urban and sub-urban areas. *Meteorologische Zeitschrift*, **15**(6), pp. 647–658, 2006. https://doi.org/10.1127/0941-2948/2006/0164.

[9] Lolli, S. et al., Climatological assessment of the vertically resolved optical and microphysical aerosol properties by lidar measurements, sun photometer, and in situ observations over 17 years at Universitat Politècnica de Catalunya (UPC) Barcelona. *Atmospheric Chemistry and Physics*, **23**(19), pp. 12887–12906, 2023. https://doi.org/10.5194/acp-23-12887-2023.

[10] Villa, T.F., Salimi, F., Morton, K., Morawska, L. & Gonzalez, F., Development and validation of a UAV based system for air pollution measurements. *Sensors*, **16**(12), p. 2202, 2016. https://doi.org/10.3390/s16122202.


© 2026 WIT Press
www.witpress.com, ISSN 1743-3541 (on-line)

[11] Zhang, Y. et al., Large vertical gradient of reactive nitrogen oxides in the boundary layer: Modeling analysis of DISCOVER-AQ 2011 observations. *Journal of Geophysical Research: Atmospheres*, **121**(4), pp. 1922–1934, 2016. https://doi.org/10.1002/2015JD024203.
[12] Song, X. et al., Elucidating key factors in regulating budgets of ozone and its precursors in atmospheric boundary layer. *NPJ Climate and Atmospheric Science*, **7**(1), p. 262, 2024. https://doi.org/10.1038/s41612-024-00818-8.
[13] Liu, Z., Zha, F., Wang, Y., Yuan, B., Liu, B. & Tang, G., Vertical evolution of the concentrations and sources of volatile organic compounds in the lower boundary layer in urban Beijing in summer. *Chemosphere*, **332**, 138767, 2023. https://doi.org/10.1016/j.chemosphere.2023.138767.
[14] Zhou, S. et al., Measurement report: Vertical distribution of atmospheric particulate matter within the urban boundary layer in southern China – Size-segregated chemical composition and secondary formation through cloud processing and heterogeneous reactions. *Atmospheric Chemistry and Physics*, **20**(11), pp. 6435–6453, 2020. https://doi.org/10.5194/acp-20-6435-2020.
[15] Li, X. et al., Vertical distribution of particulate matter and its relationship with planetary boundary layer structure in Shenyang, northeast China. *Aerosol and Air Quality Research*, **19**(11), pp. 2464–2476, 2019. https://doi.org/10.4209/aaqr.2019.06.0311.
[16] Quang, T.N., He, C., Morawska, L., Knibbs, L.D. & Falk, M., Vertical particle concentration profiles around urban office buildings. *Atmospheric Chemistry and Physics*, **12**(11), pp. 5017–5030, 2012. https://doi.org/10.5194/acp-12-5017-2012.
[17] Liu, H. et al., Vertical distribution of black carbon and its mixing state in the urban boundary layer in summer. *Atmospheric Chemistry and Physics*, **23**(12), pp. 7225–7239, 2023. https://doi.org/10.5194/acp-23-7225-2023.
[18] Chen, D., Liao, H., Yang, Y., Chen, L., Zhao, D. & Ding, D., Simulated impacts of vertical distributions of black carbon aerosol on meteorology and $PM_{2.5}$ concentrations in Beijing during severe haze events. *Atmospheric Chemistry and Physics*, **22**(3), pp. 1825–1844, 2022. https://doi.org/10.5194/acp-22-1825-2022.
[19] He, G. et al., Nighttime ozone in the lower boundary layer: Insights from 3-year tower-based measurements in south China and regional air quality modeling. *Atmospheric Chemistry and Physics*, **23**(20), pp. 13107–13124, 2023. https://doi.org/10.5194/acp-23-13107-2023.
[20] Li, L. et al., Ozone concentration at various heights near the surface layer in Shenyang, northeast China. *Frontiers in Environmental Science*, **10**, 1011508, 2022. https://doi.org/10.3389/fenvs.2022.1011508.
[21] Ren, H. et al., Measurement report: Vertical distribution of biogenic and anthropogenic secondary organic aerosols in the urban boundary layer over Beijing during late summer. *Atmospheric Chemistry and Physics*, **21**(17), pp. 12949–12963, 2021. https://doi.org/10.5194/acp-21-12949-2021.
[22] Melecio-Vázquez, D., Ramamurthy, P., Arend, M. & González-Cruz, J.E., Thermal structure of a coastal-urban boundary layer. *Boundary-Layer Meteorology*, **169**(1), pp. 151–161, 2018. https://doi.org/10.1007/s10546-018-0361-7.
[23] Barbano, F., Brattich, E. & Di Sabatino, S., Characteristic scales for turbulent exchange processes in a real urban canopy. *Boundary-Layer Meteorology*, **178**(1), pp. 119–142, 2021. https://doi.org/10.1007/s10546-020-00554-5.




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[24] Gromke, C. & Ruck, B., Pollutant concentrations in street canyons of different aspect ratio with avenues of trees for various wind directions. *Boundary-Layer Meteorology*, **144**(1), pp. 41–64, 2012. https://doi.org/10.1007/s10546-012-9703-z.
[25] Barlow, J.F. & Coceal, O., *A Review of Urban Roughness Sublayer Turbulence*. Met Office, Meteorology Research and Development, Technical Report No. 527, Department of Meteorology, University of Reading, 2009. https://centaur.reading.ac.uk/38572/.
[26] Boppana, V.B.L., Xie, Z.-T. & Castro, I.P., Thermal stratification effects on flow over a generic urban canopy. *Boundary-Layer Meteorology*, **153**(1), pp. 141–162, 2014. https://doi.org/10.1007/s10546-014-9935-1.
[27] Guo, G.Z., Yu, Y., Kwok, K.C.S. & Zhang, Y., Air pollutant dispersion around high-rise buildings due to roof emissions. *Building and Environment*, **219**, 109215, 2022. https://doi.org/10.1016/j.buildenv.2022.109215.
[28] Akingunola, A. et al., A chemical transport model study of plume-rise and particle size distribution for the Athabasca oil sands. *Atmospheric Chemistry and Physics*, **18**(12), pp. 8667–8688, 2018. https://doi.org/10.5194/acp-18-8667-2018.
[29] Yan, S. et al., Impact of aerosol optics on vertical distribution of ozone in autumn over Yangtze River Delta. *Atmospheric Chemistry and Physics*, **23**(9), pp. 5177–5190, 2023. https://doi.org/10.5194/acp-23-5177-2023.
[30] Seinfeld, J.H. & Pandis, S.N., *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change* 2nd edn., John Wiley & Sons: New York, USA, 2006.
[31] Zhang, X., Fan, Y., Yu, W., Wang, H., Niu, B. & Li, M., Vertical distribution characteristics of outdoor particles concentrations in high-rise buildings. *Polish Journal of Environmental Studies*, **30**(2), pp. 1913–1922, 2021. https://doi.org/10.15244/pjoes/126320.
[32] Kukkonen, J. et al., A review of operational, regional-scale, chemical weather forecasting models in Europe. *Atmospheric Chemistry and Physics*, **12**(1), pp. 1–87, 2012. https://doi.org/10.5194/acp-12-1-2012.
[33] Pang, M. et al., The sensitivity of aerosol data assimilation to vertical profiles: Case study of dust storm assimilation with LOTOS-EUROS v2.2. *Geoscientific Model Development*, **18**(12), pp. 3781–3798, 2025. https://doi.org/10.5194/gmd-18-3781-2025.
[34] Zang, Z., Li, Z., Pan, X., Hao, Z. & You, W., Aerosol data assimilation and forecasting experiments using aircraft and surface observations during CalNex. *Tellus B: Chemical and Physical Meteorology*, **68**(1), 29812, 2016. https://doi.org/10.3402/tellusb.v68.29812.
[35] Santiago, J.L. et al., Indoor-outdoor pollutant concentration modelling: A comprehensive urban air quality and exposure assessment. *Air Quality, Atmosphere and Health*, **15**(9), pp. 1583–1608, 2022. https://doi.org/10.1007/s11869-022-01204-0.
[36] Liao, H.-T., Yen, C.-M., Chen, Y.-R., Wu, J.-D., Tsai, S.-W. & Wu, C.-F., Vertical variation of source-apportioned $PM_{2.5}$ and selected volatile organic compounds near an elevated expressway in an urban area. *Environmental Science and Pollution Research*, **31**(13), pp. 20477–20487, 2024. https://doi.org/10.1007/s11356-024-32480-1.
[37] Villa, T.F., Gonzalez, F., Miljievic, B., Ristovski, Z.D. & Morawska, L., An overview of small unmanned aerial vehicles for air quality measurements: Present applications and future prospectives. *Sensors*, **16**(7), p. 1072, 2016. https://doi.org/10.3390/s16071072.


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