An experimental and modelling analysis of cloud droplet growth from vehicular emissions with non-ideal microphysics over an Asian mega-city

Siddharth Gumber | Satyajit Ghosh

Abstract

Large cities in the developing world have unregulated traffic with dysfunctional diesel operated vehicles spewing out copious amounts of micron to sub-micron sized soot and black carbon particles. These particles mix with other aerosol particles as they are lifted by buoyant eddies. It is shown that the particles are rendered partly soluble as they get coated with soluble sulphate to activate into cloud droplets. This multi-component aerosol mixture thus comprises of fully soluble as well as partially soluble components so that mass accommodation and diffusional mass transfer considerations need to be carefully quantified over small non-planar surfaces of aerosol particles sourced from such emissions. The emitted soot and black carbon particles have number concentrations comparable to the sulphate mode and are small enough that the assumption of an infinitely dilute solution droplet is untenable. An X-ray fluorescence spectrometry indicates the presence of inorganic ions confirming the validity of non-ideal solution effects warranting a closer look at the osmotic coefficients. Additionally, laboratory values of the binary diffusion coefficients of water vapour cannot be applied to processes operating over the cloud base located several kilometres above where the pressure and temperature are different. A full Lennard-Jones diffusivity model is used with an accounting of the dipole moment of water vapour which most models ignore. This first study, combining these micro-scale enhancements are included in a Weather Research and Forecasting (WRF) case study over an Asian city. Not only are significant differences obtained in the cloud morphology when compared to a baseline case, but modelled cloud optical depths agree better with observations.

KEYWORDS

application/context, clouds, geophysical sphere, microphysics, microscale, physical phenomenon, scale, transport, urban
1 | INTRODUCTION

As overpopulated Asian cities continue to grow, they grapple with the menace of vehicular pollution. Many are from developing countries where regulatory mechanisms are not enforced stringently. Recent studies have found that a substantial fraction of soot and black carbon particles are generated from diesel-operated vehicles (mainly state-run buses, auto-rickshaws, and cars) in the Indian city of Chennai, a manufacturing hub (Kabirdoss, 2012; Safai et al., 2012). Since these minute aerosol particles have sub-micron radii, they stay aloft for several days within the city’s boundary layer with low descent-speeds. Owing to their enduring residence times they accrete soluble inorganic substances (mainly soluble sulphates) on their surfaces (Harris et al., 2013; Hegg & Hobbs, 1981). They can also accrete moisture enabling them to become active Cloud Condensation Nuclei (CCN). Rönkkö et al. (2017) have reported the significance of traffic-generated sub-micron sized aerosol clusters in modulating terrestrial cloud cover through tropospheric aerosol formation. Some others have even suggested that such particles have the propensity to affect tropical cyclones often requiring prior alerting (Evans et al., 2011; Ghosh et al., 2014). Fan et al. (2018) have explored the activation and condensational growth of water droplets from ultra-fine particles generated from pollution plumes. Although, some recent papers over comparable Asian cities have studied urban haze (classifying it as ultra-fine particles) generated from road vehicles and their potential roles as cloud condensation nuclei (Ding et al., 2016; Guo et al., 2020; Kwon et al., 2020), none have explored how solution non-ideality affects activation and growth processes.

One of the objectives of this paper is to quantify the extent to which soot and black carbon particles released from vehicular pollution (we shall call this ‘the transient mode’ hereafter) along with the two other main background modes, the sulphate and sea salt modes, affect the local cloud microphysics over large cities when such processes operate. This has not been undertaken and is important because the atmospheric burden of such particles is projected to increase exponentially over the coming decades.

There is an important micro-scale effect relating to the chosen values of the mass accommodation coefficient ($\alpha$). Current models prescribe a uniform value of this coefficient ($-1$) assuming that all particles are fully soluble, and the impinging water vapour molecules apprehend a planar liquid water surface (partly valid for only very large droplets) (Lim & Hong, 2010; Morrison et al., 2005). Soot and black carbon particles are partially soluble so that the resultant cloud droplets are small and therefore non-planar. A recent estimate indicates a solubility range varying from 0.1–0.4 for aged black carbon particles (Ghosh et al., 2007; Yamasoe et al., 2000). A recent paper by Duan et al. (2019) have undertaken sensitivity experiments on the effect of condensation coefficient on droplet activation and growth in polluted environments using a cloud parcel model. However, studies related to understanding additional microscale enhancements vis a vis solution non-ideal consideration along with variable diffusivity values and their implications on cloud morphology are still scanty.

With this background, we can summarize the main microphysical enhancements that this paper shall address:

1. Detailed physico-chemical modelling of soot and black carbon aerosol growth with an accurate prescription of the diffusivity profile of water vapour over these particle surfaces.
2. Incorporating a size-dependent osmotic coefficient ($\Phi$) and non-unity mass accommodation coefficient ($\alpha$). Large scale models (such as the WRF) prescribe a uniform value of unity for both coefficients assuming a planar surface for all sizes—this is an oversimplification for all the modes.
3. Integrating both these microphysical enhancements into large scale models.

2 | MATERIALS AND METHODS

2.1 | Synoptic conditions and the studied area

The city of Chennai is located along the Bay of Bengal in the southern peninsular region of the Indian Sub-continent (13.0827°N, 80.2707°E). Because it is a coastal city, it receives both land as well as sea breeze with changes in wind directions, sometimes more than 180° (Garratt, 1994; Thara et al., 2002). A date early during December 2015 was chosen when a north-westward moving low-pressure trough induced upper-level wind divergence and eventually deluged the study region, that is, Chennai (Chakraborty, 2016; IMD, 2015; Jayaraman, 2015) (see Data S1). The subsequent analyses are based on 1st December 2015 when distinct cloud activity was observed.

2.2 | Experimental characterisation of vehicle-generated black carbon particles

A major thrust of this study was first to get a handle on the typical particle size distribution of the soot and black carbon (BC) particles emitted from a diesel engine. The city's traffic volume count at specific road junctions
approached nearly 45,000 vehicles during a 24 h period comprising of light and heavy-duty vehicles, two-wheelers, and auto rickshaws—all these vehicle types run on four-stroke petrol and diesel engines yielding copious amounts of PM particles particularly from malfunctioning vehicles—a common occurrence in the

FIGURE 1  (a) Schematic diagram illustrating how soot and black carbon from vehicular emissions affect cloud formation. Morphological changes are observed when microscale corrections are included. (b) Schematic diagram illustrating the coupling of various boundary layer, cloud-scale as well as microscale processes
sub-continent (Senathipathi et al., 2005). The paper explores emissions, atmospheric mixing and dilution and importantly cloud microphysical implications of the emitted particles. A concept diagram (Figure 1) illustrates these processes.

2.2.1 | Vehicular exhaust collection

Our laboratory study involved the measurement of all emitted particles with diameters less than 10 μm, that is, PM_{10} emissions. A four-stroke, water-cooled, Kirloskar Diesel engine (Rated power: 3.7 kW, 1500 rpm) was coupled to an eddy current dynamometer (Make: Powermag) which ensured a stable braking torque during typical engine half-load conditions. It was found that the maximum amounts of emissions were observed when vehicles operated at half loads around congested thoroughfares around traffic junctions (Gumber et al., 2018; Senathipathi et al., 2005). The diesel engine configuration coupled with the brake dynamometer is shown in Figure S1 (see Data S1).

2.2.2 | Ascertaining particle size distribution

The methodology for ascertaining particle size distribution includes a two-step process:

(a) Collection at source: As is evident from Figure 1 dense plumes of soot and black carbon are found along major thoroughfares and arterial roads which at the ground level are often only a few metres wide horizontally. The exhaust emissions from identical four-stroke diesel engines were sampled for a preliminary size assessment using SEM and the details are included in Data S1. From the SEM micrograph (Figure 2a,c,d), one also observes numerous sub-micron radii particles with only a few large particles to the tune of 1 μm. (b) Open-air collection: The near source pollutant plume is further diluted in the lowest part of the atmospheric boundary layer (ABL)—this happens a few metres above the ground level. The collection procedure was repeated at 3 m vertical height (standard reference height in accordance with the pollution control board norms) with the plume diverted to the open air outside proxying particle release in the ambient as happens in many droplet-driven flows (Ghosh et al., 1991). Higher wind speeds at this higher altitude enabled representative dilution effects and therefore samples collected from this procedure were subjected to Dynamical Light Scattering (DLS) size characterisation techniques described later. As stipulated by the Bureau of Indian Standard the following points were considered (Kumar, 2021):

i. Maintaining a density difference between the dispersed particles and the dispersing medium.

ii. Using established vortexing methods followed by a segregation of over-sized particles \((r > 5 \, \mu \text{m})\) using standard wet sieving techniques (Fauzie & Venkataramana, 2017; Kumar, 2021; Pecora, 2000). In this instance, the

![FIGURE 2](image-url)
collected soot particles were ultra-sonicated (Make: SONICS Vibra Cell) in double-distilled water at a fixed pulse duration of 30 s lasting up to 10 min.

The particle size distribution analysis of the suspended soot emissions was then undertaken using DLS. The particle sizer (Make: HORIBA SZ 100) employed for estimating the particle size works on the principle of light scattering from particles in the size range 0.3 nm–8 μm (ancillary information in Data S1). The modal radius \( r_m \) of the suspended soot particles from the above methodology was found to be 0.14 μm (see Figures 2b and 2 in Data S1). The corresponding particle numbers were estimated based on smoke meter (Make: AVL) readings and this was found to be ~5,00,000 particles cm\(^{-3}\) (reduced to ~1000 particles cm\(^{-3}\) based on AERMOD; see Figure S4 in Data S1). The ascertained modal size and numbers are largely in agreement with the results from established procedures (Kittleson, 1998; Lepperhoff, 2001; Xue et al., 2015; Zhu et al., 2002). Seasonal pollutant variability mainly impacts aerosol spectral distributions by altered number concentrations alone with not much change in the spreads and the modal size in conformity with previous studies (Patade et al., 2015). The modelled seasonal variability for this study is shown in Figure S4.

The presence of inorganic pollutant vapours, that is, \( \text{SO}_x \) and \( \text{NO}_x \) always present in Chennai are expected to aid activation (Ayers & Larson, 1990; Che et al., 2016; Ghosh et al., 2000; Kolb et al., 2010; Kulmala et al., 1998; Pierce & Adams, 2006; Spracklen et al., 2005; Varun Raj et al., 2009). The effects of \( \text{SO}_x \) and \( \text{NO}_x \) are interconnected and are included in the intermediate stage (see Figure 1b).

It is also important to quantify solution non-ideal effects when metal ions (\( \text{Fe}^{2+} \), \( \text{Mn}^{2+} \), \( \text{Zn}^{2+} \), \( \text{Cu}^{2+} \)) from malfunctioning metallic exhaust pipes are present along with soot and black carbon particles inducing electrolytic effects and consequently lowering the solution osmotic coefficient (Charron et al., 2019; Deguillaume et al., 2005)—current large-scale models assume pure water droplets ignoring these effects. A chemical speciation analysis of the collected PM\(_{10}\) particles was thus undertaken to ascertain the relative proportions of elements.

### 2.3 Elemental composition analysis and implications

The presence of elemental Carbon in the collected deposits was estimated from an Energy-dispersive X-ray spectroscopy (EDAX) (see Figure S3). The samples contained 59% carbon (C) comparing favourably with earlier studies (Lai et al., 2016; Sielicki et al., 2012). Further details of the compositional inferences on the relative abundances of other metals resulting from break wear emissions are indicated in Data S1 which describes the use of a hand-held X-ray fluorescence spectrometer. This X-ray fluorescence (HH-XRF) spectrometer (Make: SPECTRO xSORT) was used for a rapid, non-destructive, in-situ chemical speciation of exhaust emissions. The sampled vehicular exhaust indeed contained transition metals including Fe (1.08%), Cu (<0.004%), Ti (2%), Zn (1.2%), and Mn (<0.006%). Additionally, remnants of the metal filter (Al 52.6%) used in the exhaust sampler along with borosilicate fibres (Si 42.5%) from the filter paper were also detected in high concentrations. Large scale models assume infinitely dilute solution droplets (osmotic coefficient \( \Phi = 1 \)), e.g., in Morrison et al. (2005) and Lim and Hong (2010), it is important to explore the induced effects on cloud microphysical developments when the assumption of solution ideal behaviour is not invoked.

### 2.4 Theoretical considerations

Having ascertained the modal attributes of vehicular emissions experimentally, it follows that water vapour deposition patterns are explored further through detailed process modelling procedures.

The first aerosol mode is a pure sulphate mode grown partially from gas to particle conversion (Koziel et al., 2006; Rap et al., 2009; Ghosh et al., 2007, 2018; also see Gumber et al., 2020). The focus of interest for this paper however is the subsequent mode comprised of vehicle-generated soot and black carbon particles.

The transient black carbon mode over Chennai, India shown in Figure 2b can be classed as ultra-fine particles (Guo et al., 2020). Published literature indicates analogous chemical signatures over Beijing, China (Kumar et al., 2014) but with no data on the extents of soluble sulphate on the transient mode. An earlier study by Yamasoe et al. (2000) estimated the amount of soluble sulphate coated over freshly emitted black carbon particles in South America and found a solubility fraction of 0.25 for slightly aged particles. We have prescribed this value for our subsequent modelling analysis. The partly soluble transient mode can be characterized with a density correction (Ghosh et al., 2007):

\[
\rho_t = \rho_s \times \frac{\rho_{\text{insol}}}{\rho_s - \epsilon(\rho_s - \rho_{\text{insol}})}
\]

Here, \( \rho_s \) is the density of soluble ammonium sulphate particles (1769 kg m\(^{-3}\)), \( \rho_{\text{insol}} \) the density of insoluble black carbon particles (1350 kg m\(^{-3}\)) and \( \epsilon \) the mass fraction of the accreted soluble ammonium sulphate.
Over the transient black carbon mode, the process of vapour mass transfer combines the effect of both mass accommodation along with the process of diffusive mass transport, with a larger contribution from the diffusion term.

2.4.1 Vapour accommodation and diffusional uptake corrections

From the measured spectrum (Figure 2b), the modal radius is submicron, and the mass accommodation is strongly curvature dependent, which in turn has a direct impact on the Köhler process. In essence, a single coefficient called the mass accommodation coefficient \( \alpha \) combines the effects of evaporative as well as condensational kinetics along the boundary layer of the liquid vapour interface. The partially soluble soot and BC particles grow by water vapour condensation characterized through an overall condensation coefficient \( (C_i) \):

\[
C_i = \frac{4\pi D_{AB} r}{4D_{AB} + \Delta \nu + \frac{r}{\Delta \nu}}
\]

Here, \( D_{AB} \) is the binary-diffusivity of \( \text{H}_2\text{O} - \text{air} \), \( \nu \) the mean thermal velocity of molecules, \( r \) the cloud droplet radius and \( \Delta \nu \) the vapour jump length (1.09 \times 10^{-7} \text{ m} (Abdul-Razzak et al., 1998)).

The moist adiabatic lapse rate was 6.5 \text{ C km}^{-1} for this case study with a cloud-base temperature \( T_{cb} \) of 15 \text{ C} approaching ~4.4 \text{ C} at the cloud top. This temperature variability is expected to greatly influence the value of \( \alpha \), particularly over partially soluble organic aerosols. Roy et al. (2020) showed that over the troposphere, \( \alpha \) was of the order of 0.02 at \( T \sim 309 \text{ K} \) in the lower portions of a cloud and increased to 0.21 at the upper reaches where \( T \sim 276 \text{ K} \).

For this present study, warm rain microphysics overwhelmed ice processes over the cloud depth of 3500 \text{ m} and over this large vertical extent \( \alpha \) values are expected to change. Past research indicates that the observed values differ by two orders of magnitude ranging from 0.03 (Van Dingenen & Raes, 1991) to 1 (Eisele & Tanner, 1993; Jefferson et al., 1997). In a much earlier, but a well-recognized study (Chodes et al., 1974) found \( \alpha \) values in the range of 0.02–0.05, with an average of 0.033. A similar value of \( \alpha \) (to the tune of 0.036) for warm clouds is also prescribed in other studies (Conant et al., 2004; Fountoukis et al., 2007; Meskhidze et al., 2005; Pruppacher & Klett, 2010). In this study, we have shown results for \( \alpha = 0.036 \) as well as \( \alpha = 1.0 \).

Whilst most models adopt only a standard temperature (\( T \)), pressure (\( p \)) correction to compute \( D_{\text{Air-}~\text{H}_2\text{O}} \) values, in this paper, we not only apply the \( T-P \) correction, but also add the finite dipole moment of water-vapour by using a modified collision integral \( (\Omega_p) \) in a 6–12 Lennard-Jones model (Reid et al., 1987) (see Data S1). When effects of both mass accommodation \( \alpha \) and vapour diffusion are combined one obtains a re-scaled binary diffusivity \( D_{\text{Air-}~\text{H}_2\text{O}}' \):

\[
D_{\text{Air-}~\text{H}_2\text{O}}' = \frac{0.0386 \times 10^{-4} \frac{\Omega_p^2}{p}}{\frac{r}{r + \Delta \nu} + \frac{0.0386 \times 10^{-4} \frac{\Omega_p^2}{p}}{\frac{r + \Delta \nu}{\alpha}} (\frac{2M_{\text{H}_2\text{O}}}{kT})} \]

One notices a temperature dependence given by \( -T^{-1.50} \), in contrast to \( -T^{-1.81} \) in the standard Chen and Othmer’s diffusivity correlation (without the dipole moment corrections) used in the WRF (Chen & Othmer, 1962; Morrison et al., 2005). It is found that within the cloud interior the average extent of over-prediction of \( D_{\text{Air-}~\text{H}_2\text{O}} \) in a standard formulation is about 25% as compared to the expected values.

With this background, we now proceed in a step-by-step fashion to compare test cases (along with baseline cases) to single out the impact of mass accommodation and diffusional uptake enhancements.
2.4.2 | Sensitivity analysis combining effects of both water vapour diffusion and mass accommodation

The aerosol spectrum shown in Figure 2b is allowed to ascend through two microphysical configurations.

1. The baseline case: ‘Standard microphysics’ includes a $T/p$ corrected diffusivity profile along with a mass accommodation coefficient $\alpha = 1.0$.

2. The enhanced case: ‘Enhanced microphysics’ includes a full Lennard-Jones diffusivity profile with a dipole moment correction along with a much lower value for $\alpha$ of 0.036, more representative of the partially soluble vehicle mode.

A sophisticated Lagrangian Chemical Parcel Model (CPM) is used enabling a bin-wise growth of dry aerosol particles into size-resolved cloud droplets. The model accounts for solution non-ideal effects and estimates accurate, height-dependent values for the osmotic coefficient ($\Phi$) through a detailed Pitzer module (O’Dowd et al., 2000). The model is initialized with temperature, pressure, updraft speed and RH below the cloud-base with respective values of 15°C, 823 hPa, 1.0 ms$^{-1}$, 91.0% (http://weather.uwyo.edu/upperair/sounding.html).

TABLE 1  A comparison of modelled versus observational variables for the case study under consideration

| Parameter | Observed value | Modelled value (enhanced case) |
|-----------|----------------|-------------------------------|
| **Microphysical variables** | | |
| Liquid cloud optical depth (also see Figure S6 in Data S1) | 21 | 19.47 |
| Cloud liquid droplet effective radius ($r_e$) | 15.6–17.5 | 16.34 |
| Water vapour mixing ratio at the cloud-base (and cloud-top) ($g\,kg^{-1}$) | 11.39 (6.18) | 12.02 (6.0) |
| Cloud liquid water path (g m$^{-2}$) | 600 | –625 |
| **Dynamical variables** | | |
| Temperature at the cloud-base (and cloud-top) (°C) | 15 (4.4) | 15.5–16.5 (3–5) |
| U wind speed at the cloud-base (and cloud-top) (m s$^{-1}$) | –8.39 (–10.65) | –7.4 (–10.30) |
| V wind speed at the cloud-base (and cloud-top) (m s$^{-1}$) | –3.92 (9.0) | –3.45 (9.5) |

Note: Source of observations: Precipitation—multi-satellite precipitation estimate with climatological gauge calibration- late run half-hourly 0.1° [GPM GPM_3IMERGHHL v06] mm h$^{-1}$; cloud optical depth—MODIS atmosphere L3 monthly product (08_L3). NASA MODIS adaptive processing system, Goddard Space Flight Center https://doi.org/10.5067/MODIS/ MYD08_M3.006 (aqua) (Platnick et al., 2015); cloud liquid water effective particle radius—MODIS Terra MOD08 v6.1 0.1°; cloud liquid water path—daily mean daily 1° [MODIS-Terra MOD08_D3 v6.1] g m$^{-2}$. Region 79.0576E, 10.7886N, 81.0571E, 14.3701N; temperature/wind speeds/water vapour mixing ratio: http://weather.uwyo.edu/upperair/sounding.html.

3 | RESULTS AND DISCUSSIONS

3.1 | Comparing water-vapour supersaturation profiles from sensitivity tests

Vertical profiles of super-saturation yield an overall picture of how the aerosol particles within an air parcel (with a radius ~ 500 m) modulate the extent of hydration around an assortment of particles. Figure 3 shows the overall super-saturation profile for the black carbon mode along with background sulphate and sea-salt modes for the ‘enhanced’ and ‘standard’ microphysics cases. The peak super-saturation in the former case is
higher by 26% (at 0.0390%) compared with an 0.0310% obtained in the latter case (also see Figure S5).

We next explore the extent of non-ideal solution effects (when the osmotic coefficient $\Phi < 1$) within the cloud parcel.

### 3.2 Modelled vertical growth of cloud droplets and solution non-ideal effects

We show in Figure 4, the vertical growth profiles of a droplet bin grown from transient emissions along with the corresponding $\Phi$ profile indicating significant non-ideal behaviour.

In the next section, we show variations in the cloud and rain mixing ratios when these microscale effects are hard-wired within the LES mode of the WRF model.

### 3.3 Large Eddy simulation

To explicitly resolve the energy-containing eddies over the coastal metropolitan city of Chennai it was
required to configure the WRF in the Large Eddy mode in a manner outlined earlier by Bera and Prabha (2019). High resolution simulations were performed for two cases- the new enhanced case and a baseline scenario. The spatial resolution was held at 100 m × 100 m in the horizontal and 200 m in the vertical with a control volume dimension of 20 km × 20 km × 10 km. Sub-grid scale turbulence characterisation was done through an 1.5 order TKE closure scheme which used prognostic equations to characterize the eddy viscosity coefficients. The LEM was configured with weather soundings including potential temperature (θ), relative humidity, u and v winds over Chennai for 1st December 2015 00:00:00 (http://weather.uwyo.edu/upperair/sounding.html). A spin-up time of 5 h was sufficient and results were analysed only during the final 2 h window.

Table 1 shows a comparison of modelled versus observational dynamical as well as microphysical variables for the case study under consideration. It is very clear from Table 1 that model results agree remarkably well with the observed values.

3.3.1 | Contrasting cloud water amounts and cloud structure in a large-scale cloud model

Figure 5a shows the domain-averaged modelled cloud and rainwater amounts for the ‘enhanced microphysics case’ along with the results from the standard baseline test case. One notices that cloud and rain amounts are overpredicted significantly in the baseline case.

Whilst the layer-averaged profiles yield significant differences in the cloud and rain amounts, it is also necessary to explain variations in the cloud morphologies shown in Figure 5b,c.

Not only are the overall positioning of the cloud decks different, the cloud morphological developments are also very different. The ‘enhanced microphysics’ also impacts the cloud optical depths as is to be expected. A higher droplet concentration count (≈825 cm⁻³) with concomitantly reduced sizes contributes to the persistent cloudiness that was observed. In fact, the maximum drop effective radii (rₑ) in the ‘enhanced’ case was 16.34 μm, in contrast to an rₑ of 18.5 μm in the ‘baseline’ case. This has further ramifications- the large numbers of small droplet sizes scatter in-coming radiation over a longer-lasting cloud, reflected in the higher mean optical depth (τₑ) of 19.47. For the ‘standard baseline’ with a lower droplet number count (≈560 cm⁻³) yields a higher rₑ and a mean τ of 15.58. It must be pointed out in the absence of aircraft assisted in-situ observations, it was impossible to compare observed droplet numbers and radii. However, data was available to compare the modelled optical depths with satellite-based estimates (Platnick et al., 2015) with the average τₑ to the tune of 21 comparing better with the modelled τₑ in the ‘enhanced’ case.

4 | CONCLUSIONS

This first study shows that customising local emissions within cloud models should be done with caution. Unregulated vehicular emissions comprising of soot and black carbon (mainly from Asian megacities) are partially soluble and at sub-micron sizes yield highly concentrated aerosol solution droplets with dissolved ions, so that osmotic coefficients are less than unity. This non-ideal behaviour implies that the assumption of infinitely diluted solution droplets is untenable. This first study shows that by invoking a full Pitzer formulation, one can exactly calculate the actual osmotic coefficients which has a bearing on the condensational growth. With high number concentrations, the combined effects of vapour accommodation, diffusional uptake and solution non-ideal effects must be rigorously accounted for in extant models. This research shows that the extent of maximum supersaturation differs by 26% between the enhanced and the baseline case indicating that (i) even with partial solubility, vehicular pollution from diesel engines activates into small cloud droplets, (ii) median radius and the droplet spectral spreads at the cloud-base differ by 10% and 16%, respectively and this impacts cloud water auto-conversion rates (Ghosh & Jonas, 1998), (iii) when these microscale enhancements are included within a large-scale model (WRF), the extent of cloudiness and the cloud optical depths also agree better with observations.

ACKNOWLEDGEMENTS

The authors would like to acknowledge High Speed Computing facilities under the ERASMUS+ Capacity Building Scheme for Higher Education, the Automotive Research Centre (ARC), Metal Matrix Composite (MMC) Laboratory, and the School of Advanced Sciences (SAS) at Vellore Institute of Technology, Vellore for instrumentation support required for this study.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analysed in this study.
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**How to cite this article**: Gumber, S., & Ghosh, S. (2022). An experimental and modelling analysis of cloud droplet growth from vehicular emissions with non-ideal microphysics over an Asian mega-city. *Atmospheric Science Letters*, 23(5), e1081. https://doi.org/10.1002/asl.1081