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Research Paper

Impact of Aerosol Hygroscopicity on Pollution and Haze Formation in Delhi, India

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ABSTRACT: *Delhi, one of the world's most polluted megacities, experiences severe haze and fog episodes, especially in winter, critically impacted by aerosol hygroscopicity. This study analyzes aerosol hygroscopic growth and composition with a focus on the dominant role of ammonium chloride in enhancing aerosol liquid water content (ALWC), thereby exacerbating particulate pollution, reducing visibility, and affecting atmospheric processes. Utilizing detailed field measurements from winter campaigns, the research highlights how chloride-rich aerosols influence Delhi's air quality and outlines implications for pollution mitigation [Mandariya et al., 2024; Chen et al., 2022; Gunthe et al., 2021].*

KEYWORDS: *Aerosol hygroscopicity, ammonium chloride, aerosol liquid water content, haze formation, Delhi air pollution, secondary aerosol chemistry.*

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I. INTRODUCTION

Air pollution poses substantial threats to public health and the environment in megacities such as Delhi. Particulate matter (PM), especially fine particles below 1 micrometer (PM1), largely determines visibility impairment and respiratory risks. Aerosol hygroscopicity—the ability of particles to absorb water vapour—plays a key role in atmospheric chemistry, aerosol growth, and haze formation. Recent studies identify ammonium chloride aerosols as a major driver of high aerosol liquid water content in Delhi, promoting haze development and visibility reduction during polluted winter episodes [Mandariya et al., 2024; Chen et al., 2022; Gani et al., 2019; Rai et al., 2020].

II. BACKGROUND AND MOTIVATION

Atmospheric aerosols interact with water vapor, resulting in particle swelling and enhanced light scattering, crucial for haze and fog genesis [Tang and Munkelwitz, 1994; Petters and Kreidenweis, 2007]. Unlike sulfate and nitrate aerosols, ammonium chloride exhibits exceptionally high hygroscopicity [Mandariya et al., 2024; Hu et al., 2011]. Previous models suggested chloride's influence on Delhi's aerosol water content [Chen et al., 2022], but recent direct measurement studies have confirmed this effect by linking chloride-rich particle modes to elevated hygroscopic growth factors and aerosol liquid water content. This is further supported by observations of elevated aerosol chloride during winter from biomass and waste burning [Rai et al., 2020; Shukla et al., 2021].

III. METHODS

Field measurements during winter seasons employed sophisticated instruments, including Hygroscopic Tandem Differential Mobility Analyzer (HTDMA), Aerosol Chemical Speciation Monitor (ACSM), and mobility particle size spectrometers at IIT Delhi. Particle hygroscopic growth factors (HGFs) were measured at 90% relative humidity (RH) for aerosols sized 20–200 nm. Chemical composition data from ACSM with Positive Matrix Factorization identified organic aerosols (OA), ammonium, sulfate, nitrate, and chloride fractions. Thermodynamic modeling (ISORROPIA v2.1) was used to estimate aerosol liquid water content and detailed ion pairing including ammonium chloride contributions [Mandariya et al., 2024; Fountoukis and Nenes, 2007; Ng et al., 2011; Patel et al., 2021].

IV. RESULTS

- Aerosol hygroscopicity increases with particle size, with kappa (κ) values reaching up to 0.35 during high chloride (NH_4Cl) periods compared to ~0.18 during biomass burning and hydrocarbon-like organic aerosol episodes [Mandariya et al., 2024].
- Ammonium chloride contributes roughly 40–45% to aerosol liquid water content during Delhi's winter, despite chloride being only about 10% of the dry PM1 mass [Chen et al., 2022; Mandariya et al., 2024].
- Observed aerosol liquid water content (ALWC) peaks at 740 µg/m³, exceeding maxima reported for urban areas globally, e.g., Beijing reported around 210 µg/m³ [Chen et al., 2022].
- Elevated ALWC enhances secondary inorganic aerosol formation such as nitrate and sulfate, increasing particle mass and haze intensity [Mandariya et al., 2024; Jimenez et al., 2009].
- High ALWC correlates with diminished planetary boundary layer height and decreased surface solar radiation by about 50 W/m², causing pollution confinement and enhanced morning haze peaks [Chen et al., 2022; Gani et al., 2019].
- Organic aerosols negatively correlate with aerosol hygroscopicity due to their lower water affinity, while ammonium chloride strongly elevates water uptake capacity and CCN activity [Mandariya et al., 2024; Bhattu et al., 2016].
- Seasonal and diurnal variations show winter mornings as periods of peak aerosol hygroscopicity, driven by high RH and suppressed mixing [Mandariya et al., 2024; Fan et al., 2020].

V. DISCUSSION

This study reaffirms the significant role of chloride aerosols, primarily ammonium chloride formed from biomass burning, waste incineration, and industrial emissions, in Delhi's severe winter haze episodes [Chen et al., 2022; Mandariya et al., 2024; Gunthe et al., 2021]. The co-condensation of semivolatile ammonium chloride with water vapor creates a feedback loop intensifying aerosol growth and haze persistence. Results align with global observations of chloride aerosol influence in polluted urban atmospheres [Zhao et al., 2020; Hu et al., 2011]. The strong inverse relationship between organic aerosol loading and hygroscopicity underlines the complexity of aerosol composition effects. Mitigation efforts should thus prioritize controlling chloride precursor emissions, notably open waste burning and coal combustion, alongside ammonia management [Rai et al., 2020; Tobler et al., 2020].

VI. POLICY IMPLICATIONS AND RECOMMENDATIONS

Effective pollution control strategies must integrate chloride and ammonia precursor reduction, targeting major sources like biomass and municipal waste burning and industrial activities. Enhanced emission inventories and regional cooperation on air quality management are vital. Improved source apportionment and real-time monitoring can support policies to reduce severe haze and associated public health burdens [Chen et al., 2022; Gani et al., 2019; Shukla et al., 2021].

VII. CONCLUSION

The dominant influence of ammonium chloride on aerosol hygroscopic growth and liquid water content during Delhi's winter pollution events is conclusively demonstrated. This impact significantly drives haze formation, alters secondary aerosol chemistry, and suppresses the planetary boundary layer, reinforcing the need to incorporate chloride aerosol dynamics into comprehensive air quality management frameworks. Targeted reduction of chloride emissions could reduce haze frequency and intensity, improving air quality and health outcomes markedly in Delhi and similar megacities [Mandariya et al., 2024; Chen et al., 2022; Gunthe et al., 2021].

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