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Hygroscopicity of Isoprene-Derived Secondary Organic Aerosol Mixture Proxies: The Importance of Solute Diffusion and Salting-In Effects

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Abstract. Isoprene-derived secondary organic aerosol (SOA) components, such as the 2-methyltetrols (2-MT) and 2-methyltetrol sulfates (2-MTS), have been readily detected in atmospheric aerosols. Isoprene-derived SOA compounds commonly exist in aerosol mixtures containing inorganic salts, such as ammonium sulfate (AS). Despite its prevalence in the atmosphere, the water uptake of 2-MT, 2-MTS, and their mixtures are not well understood. In this study, we determine the physicochemical properties of 2-MT, 2-MTS, and their mixtures with AS. 2-MT and 2-MTS are viscous and dynamic surface tension measurements were taken to determine organic diffusion coefficients. The droplet growth was measured and both subsaturated and supersaturated hygroscopicity are parameterized by the single hygroscopicity parameter κ. Furthermore, aerosol phase state and morphology were analysed using atomic force microscopy. Results show that solute diffusion and salting-in influence the water uptake of 2-MT and 2-MTS with AS. The organic diffusion for 2-MTS/AS becomes an order of magnitude greater than for the organic solute alone but 2-MT diffusivity remains unchanged in the presence of AS. 2-MT/AS aerosols present a plateau in sub- and supersaturated κ-values close to pure AS; 2-MTS/AS aerosols exhibit a similar behavior under subsaturated conditions. However, under supersaturated conditions, 2-MTS/AS behaves as an ideal well-mixed aerosol that can be described by traditional κ-Köhler theory. Isoprene-derived SOA such as 2-MT and 2-MTS are abundant globally, and thus the impact from biogenic sources and non-ideal droplet activation properties must be considered in aerosol-cloud interactions.

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1. Introduction

Fine aerosol particles ($PM_{2.5}$) suspended within our atmosphere are a major contributor to Earth's radiative forcing and uncertainties in global temperature projections (Intergovernmental Panel on Climate, 2023). Aerosol-cloud radiative forcing uncertainty is attributed to aerosols' ability to form and modify cloud properties, known as aerosol-cloud interactions or the "aerosol indirect effect" (Köhler, 1936; Twomey, 1959, 1974; Albrecht, 1989; Intergovernmental Panel on Climate, 2023). An aerosol's ability to alter droplet formation is dependent on its hygroscopicity or water uptake behavior under supersaturated conditions (RH > 100%). Aerosols present a surface for condensation in the presence of water vapor and droplet activation depends on aerosol particle chemical composition and size (Seinfeld & Pandis, 1998; Petters & Kreidenweis, 2007). The aerosol droplets can then reach a point of unstable and uncontrollable growth, thereby acting as cloud condensation nuclei (CCN) (Köhler, 1936; Seinfeld & Pandis, 1998).

Köhler theory can estimate aerosol droplet growth and CCN activity (Köhler, 1936). In traditional Köhler theory, it is assumed that all aerosol solutes instantaneously dissolve and contribute to water uptake (Petters & Kreidenweis, 2007). Aerosol hygroscopicity is thus parameterized by Köhler theory through the single hygroscopicity parameter κ. κ of mixed composition is often estimated by the Zdanovskii-Stokes-Robinson (ZSR) mixing rule and it is assumed that an individual solute's contribution to hygroscopicity is scaled by its volume fraction (Petters & Kreidenweis, 2007). Thus, knowing aerosol internal physical and chemical composition is critical for understanding CCN formation. However, traditional κ-Köhler predictions of aerosol CCN activity neglect solute physicochemical properties that may alter droplet growth. Previous studies have shown that droplet-altering properties may be present within aerosols, such as the presence of complex morphologies (e.g., inner core-outer layer), surface-activity, or salting in/salting out effects; as a result, discrepancies between experimentally-determined κ and κ-Köhler predictions may occur, leading to uncertainties in the climate effects of aerosols (e.g., but not limited to Asa-Awuku & Nenes, 2007; Bertram et al., 2011; Song et al., 2013; Prisle & Mølgaard, 2018; Riemer et al., 2019; Ott et al., 2020; Malek et al., 2023).

Field studies have observed the presence of internally mixed aerosols containing both inorganic and organic compounds (Saxena, 1995; Murphy et al., 1998; Pratt & Prather, 2010). Inorganic aerosols, primarily composed of salts like ammonium sulfate (AS) and sodium chloride have well-defined hygroscopic properties. The ionic behavior of inorganic compounds promotes instantaneous dissolution in water and contributes to CCN activation (Cziczo et al., 1997; Seinfeld, 2003; Rose et al., 2008; Laskina et al., 2015). However, fine organic aerosols (OA) pose a greater challenge to aerosol hygroscopicity predictions. OA constitute 20-50% of atmospheric fine aerosol mass and are diverse in composition. OA can be directly emitted into the atmosphere, referred to as primary organic aerosols (POA) (Kanakidou et al., 2005). POA can originate from anthropogenic (e.g., biomass burning and coal combustion) and biogenic (e.g., pollen) sources (Seinfeld & Pandis, 1998; Kanakidou et al., 2005). In addition to POA, secondary organic aerosol (SOA) can be formed through multigeneration gas-phase oxidation reactions of volatile organic compounds (VOCs) or multiphase reactions of semi-/low-volatility organic compounds (SVOCs/LVOCs) (Kanakidou et al., 2005). SOA is ubiquitous in the atmosphere, forming a major component of fine OA mass (Zhang et al., 2007; Srivastava et al., 2022). For example, a study by Zhang et al. (2007) found that SOA contributed 65% to 95% of OA mass in urban and remote regions. Furthermore, SOA have been readily detected in mixtures with inorganic

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components, such as AS (Yang et al., 2009; Zhu et al., 2017); indeed, a study by Zhu et al. (2017) estimated 66% of SOA as being internally mixed with sulfate. Thus, the organic-inorganic interactions can significantly impact aerosol composition and climate properties.

Previous studies have determined that a significant contributor to SOA is the aqueous-phase chemical processing of isoprene-derived oxidation products (Claeys et al., 2004; Kanakidou et al., 2005). Isoprene is a type of biogenic volatile organic compound emission (BVOCs) and is considered one of the most abundant non-methane VOCs. Isoprene emissions have been estimated to be ~ 500 Tg C $year^{-1}$, rivaling that of methane emissions (Guenther et al., 2012; Sindelarova et al., 2014). Under alkyl peroxy radical (RO_2•) + hydroperoxy radical (HO_2•) dominant conditions, isoprene is photochemically oxidized by gas-phase hydroxyl radicals (•OH) to form large quantities of isoprene-derived epoxydiols (IEPOX) (Paulot et al., 2009). IEPOX is then able to partition into acidic sulfate-containing aerosol particles to produce isoprene-derived SOA (Surratt et al., 2010; Lin et al., 2012; Gaston et al., 2014; Riva et al., 2019), which mostly consists of 2-methyltetrols (2-MT) and 2-methyltetrol sulfates (2-MTS).

Both 2-MT and 2-MTS have been previously detected in atmospheric $PM_{2.5}$. For example, a study by Claeys et al. (2004) found that 2-MT contributed 2% of organic carbon detected in $PM_{2.5}$ collected from the Amazon rainforest. Additional field studies have also found that 2-MTS can contribute 0.3-16.5% of total organic carbon in both the Amazon rainforest and Southeast US (Chan et al., 2010; Froyd et al., 2010; Hettiyadura et al., 2019; Riva et al., 2019; Chen et al., 2021; Hughes et al., 2021). The formation of both compounds can also alter aerosol particle composition and phase state (Zhang, Chen, et al., 2019; Zhang, Nichman, et al., 2019). For example, 2-MT and 2-MTS have been observed to be in a semisolid or glassy state in aerosol particles (Chen et al., 2023). Particle glassy state is a result of highly viscous SOA; SOA viscosities can range from 10^2 to 10^{12} Pa·s for ultraviscous liquids or $>10^{12}$ Pa·s for amorphous solid state compounds (Virtanen et al., 2010; Renbaum-Wolff et al., 2013; Zhang et al., 2015). Viscosity can influence organic solute dissolution in droplets by slowing diffusion through the aqueous phase (Renbaum-Wolff et al., 2013). As a result, slower organic diffusion rates can influence gas partitioning, particle shape, chemical aging, multiphase reactions, and aerosol droplet growth (Riipinen et al., 2011; Shiraiwa & Seinfeld, 2012; Zhang et al., 2015). Furthermore, studies incorporating SOA viscosity and phase state into larger, global-scale models have observed changes to CCN and ice nuclei (IN) formation predictions (Riipinen et al., 2011; Shiraiwa et al., 2017; Wolf et al., 2021). Thus, probing the viscosity and resulting diffusion limitations of 2-MT and 2-MTS may affect their water uptake properties (Chen et al., 2023).

Similar to other complex organic mixtures, the water uptake ability of isoprene-derived SOA can be further complicated when mixed with inorganic components, such as AS. Previous studies have observed the presence of internally-mixed SOA/AS aerosols in both the southeast US and Amazon; in which a strong presence of 2-MT and 2-MTS has been observed (Chan et al., 2010; Froyd et al., 2010; Bondy et al., 2018; Riva et al., 2019; Wu et al., 2019). The presence of inorganic salts in aerosol mixtures can influence phase state based on organic physicochemical properties (Topping, 2010; Ruehl et al., 2012; Ruehl et al., 2016; Malek et al., 2023). In particular, inorganic compounds can result in water solubility-limited and/or surface-active organics partitioning out (Ruehl et al., 2012; Ruehl et al., 2016; Freedman,

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2017; Kang et al., 2020). As a result, the partitioned aerosols can exhibit a phase separated morphology (Ruehl et al., 2012; Ruehl et al., 2016; Freedman, 2017; Kang et al., 2020; Malek et al., 2023). However, inorganic salts may also enhance organic dissolution, known as "salting in" (Riva et al., 2019). For instance, studies have observed enhanced diffusion rates in viscous SOA particles through the aqueous droplet phase in the presence of inorganic salts (Reid et al., 2018; Jeong et al., 2022; Sheldon et al., 2023). Increased diffusion is a result of salts disrupting the hydrogen bonding network between neighboring organic molecules (Reid et al., 2018; Jeong et al., 2022; Sheldon et al., 2023). Therefore, organic physicochemical properties (surface-activity, viscosity) of SOA, such as 2-MT and 2-MTS, must be better defined to better predict the droplet formation of mixed SOA/AS aerosol CCN activity. To our knowledge there are no studies to date that investigate 2-MT and 2-MTS aerosol water uptake, water uptake of mixtures with AS, and the potential effect of physicochemical properties on CCN activity predictions.

In this study, we investigated the surface activity, solute diffusivity, droplet growth and water uptake of 2-MT, 2-MTS, and its mixtures with AS. 2-MT and 2-MTS surface tension values were experimentally determined. A previous study by Ekström et al. (2009) found 2-MT to be moderately surface-active. However, the surface activity of 2-MTS has not been characterized and potential organic surface tension depression in the presence of AS has not been explored for both organics. In tandem with surface tension measurements, this study estimated diffusion coefficients of both compounds to explore the effects of viscosity and diffusivity on aerosol water uptake. Aerosol κ-hygroscopicity for pure organic and organic-AS mixtures were experimentally determined under both subsaturated conditions (< 100% RH) and supersaturated (> 100% RH) conditions to observe both droplet growth and CCN activity, respectively. κ-hygroscopicity measurements were then compared to κ-Köhler hygroscopicity theory to evaluate the efficacy of traditional full dissolution and negligible viscosity assumptions in predicting the CCN activity of both compounds and their mixtures. Lastly, Atomic Force Microscopy (AFM) measurements on mixed particles were conducted to further understand particle morphology. The following work provides a comprehensive analysis of the wide range of physicochemical properties that may influence the droplet growth of 2-MT and 2-MTS mixed with AS.

2. Experimental Methods

2.1. Experimental Chemicals

For this study, ammonium sulfate (AS, $(NH_4)_2SO_4$; Thermo Fisher Scientific, >99.0%), was purchased and used without further purification. 2-methyltetrol (2-MT) and 2-methyltetrol sulfate (2-MTS) samples were synthesized using the published process of Cui et al. (2018). 2-MT was determined to be > 98% pure. The purity of 2-MTS was determined to be ~73 wt%, with remaining sample mass estimated to be 3 wt% AS and 24 wt% sodium methyl sulfate (SMS).

2.2. Surface Tension Measurements

For this study, surface tension of 2-MT, 2-MTS, and their mixtures with AS were measured at atmospherically relevant aqueous phase concentrations. Due to the limited amounts of synthesized sample, mixed amounts were judiciously selected to mimic mixture ratios previously reported in the literature. Specifically, a previous study by Cope et al.

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(2021) found that 2-MT concentrations in the atmosphere reached an upper bound of 300 mM. Therefore, stock solutions of 300 mM 2-MT and 2-MTS were prepared using deionized (DI) water. Furthermore, it is assumed that surface tension measurements at dilutions higher than 300 mM are also relevant for droplet growth. A previous study by Bain et al. (2023) found that aerosol surface tension can be approximated from surface tension measurements of bulk mixtures composed of < 100 mM organic component. Additionally, recent studies (Mikhailov et al., 2024; Ferdousi-Rokib et al., (in review)) also support the application of more dilute concentration regimes to predict droplet growth. A recent study by Mikhailov et al. (2024) found that surface tension depression observed in bulk dilute surface tension measurements was reflective of aerosol properties. Ferdousi-Rokib et al. (in review) also found that salting out effects can be approximated within mixtures < 100 mM organic component. Thus, in this work, the stock solutions were diluted to a 3-94 mM range; each stock solution and subsequent dilution concentrations are provided in Supplemental Tables S1-S5.

Droplet surface tension ($\sigma_{s/a}$) was measured using a pendant drop tensiometer with a modified profile analysis tensiometer (SINTERFACE Inc.); the experimental set up has been previously described in Fertil et al. (2025). Briefly described here, the pendant drop tensiometer generates a droplet of solution (< 10 µL) suspended from a 0.9-mm diameter needle (Beier et al., 2019; Fertil et al., 2025). Droplets remain suspended for 300 s to reach equilibrium; at each time step (~1 s), the droplet $\sigma_{s/a}$ was obtained from fitting the droplet curvature to the Young-Laplace Equation (Fordham & Freeth, 1948; Spelt, 1996; Padró et al., 2010). Surface tension measurements were run in triplicate; prior to each measurement, the tensiometer was flushed with DI water and ~ 2 mL of solution.

As the droplet equilibrates, surface tension changes, which is attributed to the accumulation of solute diffusing to the droplet surface (Joos & Rillaerts, 1981; Eastoe et al., 1998; Chernyshev & Skliar, 2015). As the solute saturates the surface, surface tension reaches equilibrium (Ross, 1945). The accumulation of solute at the surface and resulting concentration gradient within the droplet can be described by Fick's Second Law:

$$\frac{\partial C}{\partial t} = D_s \frac{\partial^2 C}{\partial x^2}, \quad (1)$$

where concentration over time $\frac{\partial C}{\partial t}$ is proportional to the second derivative concentration over position $\frac{\partial^2 C}{\partial x^2}$ and the diffusion coefficient D_s ($m^2\ s^{-1}$). The dynamic surface tension can be correlated with solute diffusion over time as (Joos & Rillaerts, 1981):

$$\sigma_t = \sigma_0 - 2RTC\left(\frac{D_s t}{\pi}\right)^{0.5}, \quad (2)$$

where σ_0 is the starting surface tension, σ_t is the surface tension at specified time t, R is the universal gas constant, T is temperature, and C is organic molar concentration. Eq. 2 can then be rearranged to solve for D_s using dynamic surface tension measurements.

2.3. Aerosol Experimental Methods

2.3.1. Aerosol Generation

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Solutions of 0.1 g L^{-1} total solute (2-MT, 2-MTS, and mixtures with AS) were prepared using ultra-purified Millipore water (18 MΩ·cm). Mixtures compositions are provided in Table S6. Polydisperse aerosols were then generated by passing each aqueous solution through a constant output Collison Nebulizer (Atomizer, TSI 3076); the generated aerosols were then dried to < 5% RH using two silica gel dyers in series. Aerosols were then analyzed for their water uptake properties under sub- and supersaturated conditions. To determine aerosol phase morphology, atomic force microscopy (AFM) images were also obtained. In addition to water uptake and AFM measurements, organic density and shape factor were measured; for details on density and shape factor measurements, see Armstrong et al. (2025).

2.3.2 Water Uptake Measurements

A humidified tandem differential mobility analyzer (H-TDMA) measured droplet growth under subsaturated conditions. Dry, polydisperse aerosols were size selected at 100, 150, and 200 nm by an electrostatic classifier (DMA 1, TSI 3082; flow rate = 0.3 L min^{-1}) and humidified using a Nafion humidification line (PermaPure M.H. series); particles were humidified at 88.2% ± 1.5% RH. Selected dry diameters are traditionally assumed to be spherical, thus having a shape factor (χ) of 1 (DeCarlo et al., 2004). Aerodynamic aerosol classifier (AAC) shape factor measurements confirmed 2-MT and 2-MTS sphericity (Armstrong et al., 2025). The wet diameter (D_w) was measured using a second electrostatic classifier (DMA 2, TSI 3082; flow rate = 0.3 L min^{-1}); the ratio of D_w to the dry-size selected diameter (D_d) is equal to the growth factor (G_F). The experimental set up is provided in Fig. S1. To calibrate the H-TDMA, a 0.1 g L^{-1} solution of AS was aerosolized; dried AS aerosols were size selected at 100 and 150 nm. Dried AS aerosol G_F and instrument RH was measured, with calibration measurements repeated multiple times as reported in Table S7. The experimental solutions were then aerosolized, and G_F was obtained for each solution; G_F is used to calculate the hygroscopicity parameter under subsaturated conditions, $\kappa_{H\text{-}TDMA}$. In addition to subsaturated conditions, water uptake was measured under supersaturated (*SS*) conditions using a CCNC-100 (Droplet Measurement Technologies); the experimental set up is provided in Fig. S2. The theory and operation of the CCNC has been previously described (Roberts & Nenes, 2005; Lance et al., 2006; Rose et al., 2008). For this study, the Scanning Mobility CCN Analysis (SMCA) protocol was used to measure droplet activation (Moore et al., 2010). Briefly described here, the dried polydisperse aerosols were passed through an electrostatic classifier (TSI 3080) in scanning mode and charged; scanning mode operated from 8-352 nm for 135 s. The DMA operated at a sheath-to-aerosol flow rate ratio of 10:1, and aerosol sample flow rate of 0.8 L min^{-1}. The monodisperse, size-selected aerosol stream was then sampled by a condensation particle counter (CPC, TSI 3776, flow rate = 0.3 L min^{-1}) and the CCNC-100 (flow rate = 0.5 L min^{-1}) in parallel series. The CPC counted the number concentration of dry particles at a given particle size (condensation nuclei, N_{CN}). The CCNC exposed the particles to 0.3-1.4%SS and the number concentration of particles activated (N_{CCN}) were measured. The instrument set up was calibrated using AS (Rose et al., 2008) and the calibration data are provided in Table S8 and Fig. S3.

CCN data of AS and experimental solutions was analyzed using the Python-based CCN Analysis Toolkit (PyCAT 1.0) (Gohil, 2022; Gohil & Asa-Awuku, 2022). PyCAT is a Python version of SMCA and is available on GitHub for public use. The analysis toolkit calculated the activation ratio of N_{CCN}/N_{CN} for each dry particle size. The activation ratios were

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fit using a sigmoid curve and the critical diameter ($D_{p,50}$) was found, where ~50% of the dry particles activate. A charge correction is applied in PyCAT using the multi-charge correction algorithm previously described (Fuchs, 1963; Wiedensohler, 1988). The obtained critical diameter of each solution is then used to calculate the single hygroscopicity parameter under supersaturated conditions, κ_{CCN}.

2.3.3. Atomic Force Microscopy (AFM) Morphology

Atomic force microscopy (AFM) measurements were utilized to characterize aerosol phase morphology. 2-MTS, 2-MTS/AS, and 2-MT/AS particles were collected onto silicon substrates (Silson Ltd) using a cascade impactor (Sioutas Cascade Impactor, flow rate = 9 L min^{-1} and stored at room temperature and relative humidity (40-50% RH) prior to analysis. Imaging followed the procedure of Zhang et al. (2018). Briefly, particles were imaged in a 5 x 5 μm region using a Dimension ICON® AFM (Bruker) in tapping mode with resonant frequency of 150 kHz and spring constant of 5.4 N m^{-1}.

2.3.4 Viscosity and Diffusion Calculation

The viscosity and the diffusion coefficient of the 2-MT and 2-MTS aerosols were calculated using a modified Vogel-Tammann-Fulcher (VTF) equation (DeRieux et al., 2018). The dry glass transition temperature values were obtained to be 226 K and 276 K from a previous study by Zhang, Nichman, et al. (2019). The Gordon-Taylor coefficient and the fragility coefficient were assigned to be 2.5 and 20, respectively. The hygroscopicity values were used from the measurement of H-TDMA of this study.

3. Traditional κ-Köhler theory

Traditionally, water uptake of aerosol particles has been calculated using κ-Köhler theory (Köhler, 1936; Petters & Kreidenweis, 2007). Köhler theory considers aerosol physicochemical properties (e.g., solute density, molecular weight) to describe the equilibrium water vapor saturation ratio at a droplet's surface (S_{eq}). The equilibrium relationship encompasses two competing effects. The Kelvin effect describes the increase of water vapor saturation as a result of the curvature of the droplet; the Kelvin effect is represented by droplet surface tension $\sigma_{s/a}$. The Raoult (solute) effect competes by decreasing vapor pressure due to the presence of solute in the aqueous droplet; the solute effect is represented by the water activity term, a_w (Seinfeld & Pandis, 1998; Wex et al., 2008). For compounds dissolved in water, water activity can be parameterized by the single hygroscopicity parameter, κ, as follows (Petters & Kreidenweis, 2007; Sullivan et al., 2009):

$$\frac{1}{a_w} = 1 + \kappa \frac{V_s}{V_w}, \quad (3)$$

where V_w and V_s are the volume of water and dry solute, respectively. Therefore, the equilibrium saturation ratio (S_{eq}) over the droplet is described as:

$$S_{eq} = \left(1 + \kappa \frac{{D_d}^3}{{D_w}^3 - {D_d}^3}\right)^{-1} exp\left(\frac{4\sigma_{s/a} M_w}{RT\rho_w D_w}\right), \quad (4)$$

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where ρ_w is the density of water, M_w is the molecular weight of water, R is the universal gas constant and T is the temperature.

κ describes ability of an aerosol to uptake water assuming full dissolution, and can be calculated from the intrinsic properties of the solute as κ_{int} (Sullivan et al., 2009):

$$\kappa_{\text{int}} = \frac{\nu_s \rho_s M_w}{\rho_w M_s}, \quad (5)$$

where M_s is the molecular weight of solute, ν_s is the van't Hoff factor, and ρ_s is the density of the solute; Armstrong et al. (2025) found 2-MT and 2-MTS density to be 1.4 g cm^{-3} and 2.46 g cm^{-3}, respectively. To estimate κ-hygroscopicity of aerosols containing more than one compound, the Zdanovskii, Stokes, and Robinson (ZSR) mixing rule can be applied to estimate (Petters & Kreidenweis, 2007):

$$\kappa_{\text{ZSR}} = \sum_i \varepsilon_i \kappa_i, \quad (6)$$

where ε_i is the volume fraction of the individual solute component, i.

Experimental data can be used to derive aerosol κ. Under subsaturated (< 100% RH) conditions, G_F is related to hygroscopicity as follows (Kreidenweis & Asa-Awuku, 2014):

$$\kappa_{\text{H-TDMA}} = \frac{\left(G_F^3 - 1\right)}{\frac{RH}{exp\left(\frac{4\sigma_{s/a} M_w}{RT\rho_w D_d G_F}\right)}} - G_F^3 + 1, \quad (7)$$

Where $\kappa_{\text{H-TDMA}}$ is subsaturated hygroscopicity and RH is the relative humidity of the H-TDMA instrument as a decimal. Similarly, for supersaturated (>100% RH), the critical diameter correlates to κ as follows (Petters & Kreidenweis, 2007):

$$\kappa_{\text{CCN}} = \frac{4\left(\frac{4\sigma_{s/a} M_w}{RT\rho_w}\right)^3}{27 D_{p,50}^3 ln^2 SS}. \quad (8)$$

Where κ_{CCN} is supersaturated hygroscopicity. Traditionally, it is assumed that droplet surface tension $\sigma_{s/a}$ is equivalent to that of the surface tension of water ~ 72 mN m^{-1}. Köhler theory also assumes that all solutes are well mixed within the aqueous phase. The Köhler/ZSR model does not account for potential viscosity and diffusivity limitations due to inorganic-organic mixing in the aqueous phase. Therefore, in this study, traditional κ- Köhler values are predicted assuming both 2-MT and 2-MTS are well mixed within the aqueous phase and fully contribute to droplet growth. The applicability of these assumptions are discussed in the later sections. Additionally, a list of variable abbreviations are provided in Table S9.

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4. Results

4.1. Surface Tension and Diffusion

4.1.1. Organic Samples

Dynamic pendant drop tensiometer measurements were taken for 2-MT and 2-MTS samples; measurements were performed by hanging droplets < 10 μL over a period of 300 s. The droplet curvature was measured every 1 s. Average surface tension values were obtained for 2-MT and 2-MTS when droplet surface tension values remained constant (at equilibrium) and are listed in Table S10 and shown in Fig. 1.

In the dilute bulk measurement regime, 2-MT (Fig. 1, orange squares) and 2-MTS (Fig. 1, purple closed circles) $\sigma_{s/a}$ values are close to pure water (~ 72 mN m^{-1}, Fig. 1, blue dashed line). For solutions < 53 mM organic concentration, 2-MT and 2-MTS exhibit little to no surface-activity. Surface-activity is similar to the dilute surface tension of pure AS, a non-surface-active compound, which remains ~ 72 mN m^{-1}(Fig. 1, red circles, Pruppacher et al., 1997). However, for organic solutions > 53 mM, minimal surface tension depression is observed with $\sigma_{s/a}$ values between ~68–70 mN m^{-1} (Fig. 1 and Table S10); in comparison, AS surface tension increases with concentration, as observed in Fig. 1 and previous studies (Pruppacher et al., 1997; Hyvärinen et al., 2005; Mikhailov et al., 2024). Therefore, both synthesized 2-MT and 2-MTS can be classified as weakly surface-active. A previous study by Riva et al. (2019) observed greater surface tension depression for IEPOX SOA/sulfate mixtures. In particular, enhanced surface tension depression was attributed to organic partitioning and formation of 2-MT and 2-MTS oligomers (Riva et al., 2019).

In comparison to the surface tension of other short-chained particulate organosulfates, such as sodium ethyl sulfate (Fig.1, black triangles) and sodium methyl sulfate (Fig. 1, grey triangles), 2-MT and 2-MTS have lower dilute surface values (Peng et al., 2021). However, similar to other surface-active organosulfates (sodium ethyl sulfate and sodium octyl sulfate), neither 2-MT and 2-MTS surface tension significantly depress aerosol surface tension (Table S11 and S14). For example, Mikhailov et al. (2024) observed surface tension depression as low as ~ 56 mN m^{-1} for dilute D-glucose/AS mixtures. Furthermore, moderately surface-active compounds, such as 2-methylglutaric acid (2-MGA, Fig. 1, green squares) and sodium octyl sulfate (Fig. 1, grey diamonds) exhibit surface tension depression in the range of ~ 64-68 mN m^{-1} for concentrations ≤ 22 mM (Tables S13-S14). Additionally, stronger surface-active organics (surfactants), such as sodium dodecyl sulfate (SDS) show surface tension at the droplet surface can be depressed in the dilute regime. SDS reaches $\sigma_{s/a}$ of ~ 39 mN m^{-1} at 9 mM organic (Fig. 1 and Table S15). Sodium octyl sulfate, SDS, and 2-MGA present noticeable surface tension depression in the dilute bulk measurement regime (Fig. 1) that affect aerosol properties (Vepsäläinen et al., 2023; Zhang et al., 2023; Kleinheins et al., 2025). However, in comparison to previously studied organics, 2-MT and 2-MTS $\sigma_{s/a}$ remains close to pure water in the dilute bulk regime (Fig. 1). Thus, 2-MT and 2-MTS surface activity is negligible for droplet activation.

It should be noted that the synthesized 2-MTS sample is 73% pure 2-MTS and is likely mixed with AS and SMS. Both SMS and AS (Fig.1, red circles; Table S16) have surface tension values, > 72 mN m^{-1} in the dilute regime. However, despite the presence of impurities in the mixture, synthesized 2-MTS surface tension reaches values ~ 68 mN m^{-1}. Therefore, the presence of these additional compounds may counteract possible further surface tension depression

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exhibited by 2-MTS. Future surface tension modeling studies for synthesized 2-MTS data may be needed to probe the surface depressing abilities of the pure organosulfate component (e.g., multicomponent models of Topping et al., 2007).

Both 2-MT and 2-MTS are considered viscous compounds and may diffuse slowly through the measured droplets (Reid et al., 2018; Zhang, Chen, et al., 2019; Chen et al., 2023). As a result, equilibrium surface tension is reached after a period of time, *t.* The rate of diffusion of the organic through water, also known as the diffusion coefficient D_s, can be calculated from dynamic surface tension measurements (Eq. 1-2). Diffusion coefficient values for synthesized 2-MT and 2-MTS samples range between 10^{-9} to 10^{-11} m^2 s^{-1}, with diffusion slowing with increasing sample concentration. Specifically, D_s for the 2-MT and 2-MTS samples are estimated to be 10^{-9} to 10^{-11} m^2 s^{-1} and 10^{-9} to 10^{-10} m^2 s^{-1}, respectively (Table S17). Additionally, the viscosity-based diffusion coefficient was calculated and shown in Table S19. 2-MT and 2-MTS diffusion rates are comparable to rates observed for other previously investigated viscous components in aqueous solution (Curry et al., 2018; Tandon et al., 2019). For example, methylglyoxal, a known viscous component, has an aqueous phase diffusion rate ~ 10^{-9} m^{-2} s^{-1} (Curry et al., 2018). In addition to the diffusion coefficients in aqueous solution, a study by Chenyakin et al. (2017) average diffusion coefficients between 10^{-13} and 10^{-14} m^2 s^{-1} for organic molecules in a sucrose-water proxy for SOA. A study by Renbaum-Wolff et al. (2013) reported diffusion coefficients ranging from 10^{-13} and 10^{-15} m^2 s^{-1} for α-pinene-derived SOA between 70-90% RH. Indeed, 2-MT and 2-MTS have been previously observed to be highly viscous, resulting in slow diffusivity (Wang et al., 2011; Chenyakin et al., 2017; Tandon et al., 2019; Zhang, Chen, et al., 2019; Chen et al., 2023). Furthermore, at higher viscosity and lower diffusion rates, the diffusion of solute molecules fails to follow the Stokes-Einstein relationship describing the self-diffusion of solute molecules through a liquid phase (Einstein, 1905; Chenyakin et al., 2017; Tandon et al., 2019). For viscous material, such as 2-MT and 2-MTS, diffusion in water is self-limited (Chenyakin et al., 2017). Slow diffusion correlates with the longer time scales are needed to reach equilibrium surface tension for more concentrated sample solutions; the solute molecules are limited in their ability to accumulate to the surface; thus time is an important factor in the surface tension measurements. This effect is more prominent in 2-MT than 2-MTS, as evident in its slower diffusion rates for concentrations >30 mM (Table S17).

4.1.2. AS and Synthesized Organic Mixture

Previous studies have observed that inorganic compounds, such as AS, mixed with organics can enhance surface tension effects (Topping, 2010; El Haber et al., 2023). Additionally, AS can result in the partitioning of organics to the to the surface (i.e., the movement of organics to the surface is commonly referred to as salting-out). To determine if partitioning effects are present in organic/AS mixtures, 2-MT and 2-MTS were mixed with 500 mM AS and dynamic surface tension measurements were taken; mixture dynamic surface tension measurements are shown in Fig. 2. Average mixed surface tension values are listed in Table S10.

For mixtures of 3-9 mM 2-MT and 500 mM AS, surface tension remains stable ~ 75 mN m^{-1} and is higher than pure 2-MT solution surface tension alone (Fig. 2A). Higher $\sigma_{s/a}$ values indicate a lack of salting out effects and organic surface partitioning; previous surface tension studies of organic/AS mixtures observed salting out effects through lower $\sigma_{s/a}$ values in comparison to pure organic solutions (Ferdousi-Rokib et al., 2025 (in review)). Thus, for 3-9 mM 2-MT

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with 500 mM AS mixtures, organic partitioning is not enhanced, and the droplet surface tension aligns with pure AS $\sigma_{s/a}$ (Fig.1. and Table S16). When organic concentration in the mixture is increased to 94 mM, a stronger time dependence for surface tension is observed (Fig. 2A); an equilibrium surface tension of ~71.2 mN m^{-1} is reached at ~300 s. This lower surface tension for 94 mM 2-MT with 500 mM AS compared to the previous 2-MT/AS mixture correlates with the higher concentration of organic in solution. However, the longer equilibrium time is indicative of a slow solute diffusion in the droplet.

Previous studies have observed diffusion effects within dynamic surface tension measurements and estimated solute diffusion (Eastoe et al., 1998; Bain et al., 2024). To determine organic diffusion within AS mixtures, the D_s was calculated using Eqs. 1-2. For 2-MT/AS mixtures, D_s ranged from 10^{-9} to 10^{-11}, with diffusion slowing as organic concentration increases (Fig. 2A, Table S17). 2-MT organic diffusion in AS mixtures is similar to that of the pure organic 2-MT solution D_s values. As a result, 2-MT organic diffusion remains relatively unaffected in the presence of AS. The organic 2-MT molecules do not diffuse fast enough to fully accumulate at the surface and substantially lower surface tension.

Similar to 2-MT/AS mixtures, 2-MTS/AS mixture surface tension was higher than 2-MTS solution surface tension alone. 2-MTS/AS mixture $\sigma_{s/a}$ values ranged from ~ 72.5 to 75 mN m^{-1} and remain similar to surface tension values of pure AS. Furthermore, $\sigma_{s/a}$ values remain constant as the 2-MTS organic concentration increases from 3 to 53 mM; the minimal correlation between organic concentration and surface tension implies that AS dominates droplet surface tension at the surface-air interface. In addition to being stable across organic concentrations. 2-MTS/AS $\sigma_{s/a}$ reaches equilibrium faster than 2-MT/AS; equilibrium is achieved across the mixtures at < 100 s (Fig. 2B). Indeed, based on the dynamic surface tension measurements, D_s for 2-MTS within AS mixtures remains ~10^{-9}, indicating slightly faster organic diffusivity through the droplet than 2-MT (Table S17). In the presence of AS, D_s increases by an order of magnitude. This suggests the presence of AS increases solubility and dispersion of 2-MTS molecules through the droplet, (Prisle et al., 2010; Toivola et al., 2017). A similar phenomenon has been observed in glyoxal/AS mixtures as the presence of the inorganic compound improves dissolution of the organic (Kampf et al., 2013). Therefore, the higher 2-MTS/AS surface tension values and diffusivity indicates that the organic is well dispersed within the droplet, but AS dominates droplet surface tension properties. Both 2-MT and 2-MTS present complex viscous properties that may affect droplet phase and potentially change in the presence of inorganic compounds, such as AS. As a result, 2-MT, 2-MTS, and AS-mixed aerosol water uptake properties may be influenced. Therefore, diffusion effects on synthesized organic and organic/AS aerosol mixtures were probed through water uptake measurements.

4.2. Water Uptake Measurements

In addition to the previous measurements, the droplet growth of 2-MT, 2-MTS samples, and their respective AS mixtures were measured; hygroscopicity was estimated under both subsaturated and supersaturated conditions. Mixtures were varied by sample wt% (Table S21); organic wt% of 2-MTS is estimated by accounting for impurities present in the sample and their respective properties (e.g., density, hygroscopicity, Table S20). The adjusted mass wt% for 2-MTS/AS mixtures are listed in Table S21. For subsaturated hygroscopicity, the H-TDMA instrument setup was

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used to measure G_F for all experimental solutions at 88.2% RH. Experimental growth factor values for 2-MT/AS and 2-MTS/AS mixtures are listed in Tables S20-S21. For supersaturated hygroscopicity, the CCNC instrument setup was used to obtain experimental $D_{p,50}$ values across multiple supersaturation conditions (0.31, 0.43, 0.65, 0.88, 1.10, 1.32, and 1.54 % SS); the critical diameter values for 2-MT/AS and 2-MTS/AS mixtures are listed in Tables S22-S23.

Under subsaturated conditions, both 2-MT and 2-MTS are moderately hygroscopic, with $\kappa_{H\text{-}TDMA}$ values of 0.103 and 0.276, respectively (Fig. 3A). For 2-MT/AS (Fig. 3A, orange open squares) and 2-MTS/AS (Fig. 3A, purple open circles) aerosol mixtures, subsaturated hygroscopicity values are similar. For 2-MT/AS mixtures ≤ 45 wt% organic, κ values plateau close to pure AS ($\kappa_{int} = 0.61$) at a $\kappa_{H\text{-}TDMA}$ ~ 0.56. For mixtures > 45 wt% organic, both 2-MT and 2-MTS exhibit lower $\kappa_{H\text{-}TDMA}$ values, ranging from 0.103-0.505 for 2-MT/AS mixtures and 0.276–0.433 for 2-MTS/AS mixtures. Previous studies by Malek et al. (2023) and Ferdousi-Rokib et al. (in review) have observed a plateau in hygroscopicity for AS-dominated organic mixtures prior to a drop in κ due to the presence of phase separated morphology; as a result of phase separation, the inorganic AS remains dissolved in the aqueous phase and drives hygroscopicity (Malek et al., 2023). After a threshold composition is reached (45 wt% organic), more organic solute contributes to the aqueous phase and thus hygroscopicity is lowered.

Under supersaturated conditions, 2-MT and 2-MTS remain moderately hygroscopic, with κ_{CCN} being 0.269 and 0.139, respectively. For 2-MT/AS mixtures (Fig. 3B, closed orange squares), supersaturated κ mimics the same trend as subsaturated 2-MT/AS κ; for mixtures ≤ 60 wt% 2-MT, κ_{CCN} also shows a plateau at ~ 0.53 and then decreases with increased organic aerosol composition. In comparison, the 2-MTS/AS mixtures (Fig. 3B, purple circles) present a linear hygroscopic trend; as organic wt% increases, κ_{CCN} drops in a linear fashion resembling ideal mixing and volume additivity (Petters & Kreidenweis, 2007). Indeed, 2-MTS/AS κ_{CCN} correlates with the hygroscopicity trend predicted by traditional κ_{ZSR} values (Eqs. 11-12)(Fig. 3B, purple line). 2-MTS/AS supersaturated hygroscopicity agrees well with traditional Köhler theory ($R^2 = 0.972$, Table S26), suggesting full 2-MTS dissolution and contribution to water uptake. By contrast, 2-MT/AS mixtures do not agree with traditional Köhler theory ($R^2 = 0.787$, Table S26), with the greatest discrepancy observed in the region between the κ experimental plateau and κ_{ZSR} (Fig. 3, orange line); additionally, subsaturated 2-MTS/AS mixtures deviate from κ_{ZSR} during the initial hygroscopic plateau (Fig. 3A, purple line). Thus, for 2-MT/AS mixtures and subsaturated 2-MTS/AS aerosols, the ideal mixing rule does not apply. This can once again be attributed to limitations to organic dissolution into the aqueous phase (Malek et al., 2023).

In addition to non-ideal hygroscopic trends, it is noted that overall, κ_{CCN} values remain lower than $\kappa_{H\text{-}TDMA}$ values for both 2-MT/AS and 2-MTS/AS, contrary to the traditional trend of $\kappa_{CCN} > \kappa_{H\text{-}TDMA}$ (Petters & Kreidenweis, 2007). The observed difference suggests greater organic dissolution and contribution to hygroscopicity in the supersaturated regime compared to subsaturated conditions. This suggests potential viscosity and diffusion limitations on hygroscopicity as RH transitions from sub- to supersaturated. Indeed, the viscosity of the 2-MT and 2-MTS changes under different conditions. Both compounds likely remain in the semi-solid phase state before entering the CCNC, and behave like liquids in the H-TDMA, as shown in Table S18. Additionally, Asa-Awuku and Nenes (2007) reported diffusivity limitation effects on aerosol water uptake for compounds with D_s values ≤ 2.5 x 10^{-10}, well within the range

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of D_s values for 2-MT, and 2-MT/AS. Water uptake was shown to be driven by the viscous organic phase slowly diffusing into the aqueous phase (Asa-Awuku & Nenes, 2007). Thus, it is believed that both 2-MT and 2-MTS organics slowly dissolve, and phase separate to form a relatively viscous phase under subsaturated conditions, corresponding to slow diffusion coefficients. AS is an inorganic compound that is assumed to instantaneously dissolve into the aqueous phase and thus drives hygroscopicity when the droplet is phase separated, such as for 2-MT/AS mixtures (Fig. 2). However, lower κ values at supersaturated conditions can be attributed to higher water content; previous studies have found greater water content correlating with reduced viscosity due to a plasticizing effect and resulting in enhanced organic mixing (O'Meara et al., 2016; Reid et al., 2018; Jeong et al., 2022). Thus, the organic viscous phase may experience "cracking" and may initially slow down the movement of organic molecules through the aqueous phase (Tandon et al., 2019). Therefore, phase behavior of the organic can have a strong influence on aerosol water uptake. Additionally, the non-ideal hygroscopic behavior of 2-MT/AS and subsaturated 2-MTS/AS mixtures versus the ideal hygroscopic behavior of supersaturated 2-MTS/AS aerosols can be probed through imaging of the aerosol mixture phase behavior.

4.3. Phase Morphology

To further understand the phase state and morphology of 2-MT and 2-MTS mixtures with AS, AFM images were taken at varied organic wt% (Fig. 4). Dried synthesized 2-MTS presents itself as a viscous, spherical particle, indicated by its smooth surface (Fig. S4); this agrees with both shape factor measurement of ~1 (Armstrong et al., 2025 (2025)) and diffusion coefficient values. As inorganic AS is mixed with 2-MTS, phase behavior changes. At 10 wt% 2-MTS (Fig. 4B), particle exhibits an engulfed core-shell morphology. A previous study by Cooke et al. (2022) observed a similar morphology for AS-seeded IEPOX-derived SOA particles; the study observed an organic shell, while the inorganic salt was observed to be present in the shell as well as within an aqueous core (Cooke et al., 2022). With AS dispersed on the outer shell as well as being present in an aqueous core, the inorganic salt in the shell will likely easily dissolve during water uptake and drive hygroscopicity, consistent with the results as observed in subsaturated hygroscopicity measurements. However, AS within the shell may introduce roughness in the outer edge and remain viscous in the initial water-uptake process, thus promoting "cracking" in the organic phase, which can result in full dissolution in the presence of higher water content and ideal mixing (Tandon et al., 2019).

As 2-MTS is increased to 45 wt%, the particle morphology shows greater inorganic phase dispersion, with AS protruding through the viscous organic phase (Fig. 4C). The visualized morphology and phase state of the particle agrees with behavior inferred from water-uptake and droplet measurements (Sect. 4.2). In particular, ~45 wt% is the observed threshold for the plateau in 2-MTS/AS $\kappa_{\text{H-TDMA}}$ values, prior to a linear decrease in $\kappa_{\text{H-TDMA}}$ values. The dispersion of AS disrupts the organic network within the viscous phase, giving rise to the observed roughness and promoting the "salting in" of 2-MTS. This phenomenon agrees with the results of previously published literature that show viscous organics mixed with AS; specifically, laboratory-generated SOA-AS and citric acid-AS mixtures (Saukko et al., 2012; Abramson et al., 2013). Previous studies have also observed increased diffusion within viscous SOA particles via a disruption of the hydrogen bonding network between the organic molecules that can promote solute

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movement in the droplet (Reid et al., 2018; Jeong et al., 2022; Sheldon et al., 2023). For this reason, it is likely that greater organic diffusion occurs above 45 wt% organic, resulting in decreasing $\kappa_{\text{H-TDMA}}$ values. Furthermore, the well dispersed AFM morphology is indicative of ideal mixing under supersaturated conditions, thereby agreeing with traditional Köhler theory of droplet growth.

In comparison, 2-MT mixtures present an engulfed core-shell morphology from 10 to 45 wt% organic (Fig. 4D-E). At 10 wt% 2-MT, the viscous organic phase dominates the particle morphology and AS remains dispersed at the surface edge, as shown in Fig. 4D. As organic wt% increases to 45 wt%, morphology remains unchanged and the organic phase stays intact. The intact core-shell morphology of 45 wt% 2-MT aerosol mimic contrasts with the well dispersed morphology observed for 45 wt% 2-MTS aerosol mimic. For 2-MT, the organic diffusion is relatively slow under both sub- and supersaturated conditions, likely due to the undissolved viscous organic phase (Fig. 4A). Thus, hygroscopicity of the 2-MT/AS mixture is dominated by AS dissolution from the core and outer shell, corresponding to the hygroscopic plateau observed for 2-MT/AS sub- and supersaturated water uptake measurements (Fig. 3). Therefore, particle morphology and viscosity influence the synthesized 2-MT's ability to diffuse through the aerosol droplet and can affect aerosol water uptake process. A previous study by Zhang et al. (2018) described the "self-limiting" effect of a core-shell morphology on IEPOX-SOA reactive uptake under sub-saturated conditions. Similar, the viscous organic core may limit the diffusion during the initial 2-MT/AS water uptake process. However, diffusion limitations can also result in the need for longer time periods to reach an "equilibrium" state, as observed by dynamic surface tension measurements. Consequently, current hygroscopicity measurements that occur at fast time scales may not capture the full water uptake process of the synthesized organics and their mixtures. For example, the residence of aerosols within DMT CCNC columns is ~ 10 s (Paramonov et al., 2015) while similar H-TDMA instrument set ups have a residence time ~ 6.5 s (Mikhailov & Vlasenko, 2020). However, a previous study by Chuang et al. (2003) found atmospheric droplet growth timescales range between 5 to 100 s, congruent with the timescale of 2-MT and 2-MTS dynamic surface tension change (Fig. 2. and Chuang, 2003). Therefore, hygroscopicity of viscous organic containing aerosols, such as 2-MT and 2-MTS, must be studied at greater residence times to observe any possible effects on hygroscopicity; understanding whether timescale effects CCN activity of organic-inorganic aerosol mixtures can greatly impact current global models that may assume instantaneous solute dissolution during the water uptake process. Furthermore, future studies should consider whether the hygroscopicity approximations of viscous 2-MT/AS and 2-MTS/AS mixtures are time dependent, as time-dependent droplet formation has been observed for biogenic aerosols (Vizenor & Asa-Awuku, 2018). Currently, traditional Köhler theory is unable to predict the water uptake of 2-MT/AS and subsaturated 2-MTS/AS aerosols and does not consider solute and droplet kinetic effects. However, by accounting for phase morphology and viscosity, κ predictions may be improved.

In addition, size-dependent morphology may also affect κ-hygroscopicity estimations. Several studies observe a relationship between particle size and aerosol phase transitions during water uptake (Veghte et al., 2013; Cheng et al., 2015; Altaf et al., 2016; Schmedding & Zuend, 2025). Specifically, Veghte et al. (2013) and Cheng et al. (2015) observe smaller AS-organic particles favoring a homogeneous liquid phase while larger particles remain in a partially engulfed morphology; this finding correlates with 2-MT/AS engulfed morphology for particles imaged ≥ 390 nm (Fig. 4).

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Indeed, for 2-MT/AS mixtures > 60 wt% 2-MT, κ_{CCN} decreases with increasing dry activation diameter before plateauing (Fig. S5). This trend may correlate to greater organic diffusion as particle size and morphology is changing before a dissolution limit is reached for > 60 wt% 2-MT/AS mixtures. For mixtures ≤ 60 wt% 2-MT, a similar decrease in κ_{CCN} is observed before hygroscopicity begins to increase; this may be attributed to the engulfed morphology in larger particles (Fig. 4D-E) promoting AS dissolution and water uptake contribution while 2-MT diffusion reaches a limit. However, the water uptake measurements performed in this study do not account for size-dependent phase morphology in its analysis. Therefore, future work may build upon the results of this study to better parameterize hygroscopicity based on initial particle size and size-dependent phase morphology affecting κ-hygroscopicity estimations. In particular, size-selected CCN measurements can be performed to better probe size-dependent morphology effects on aerosol activation. By doing so, global models can incorporate these influential physicochemical properties into predictions of aerosol-cloud interactions.

5. Summary and Implications

In this study, we investigated the influence of solute diffusivity and droplet phase morphology on the hygroscopicity of synthesized 2-MT, 2-MTS, and their mixtures with AS. Mixtures with AS were varied by organic wt%. Both 2-MT and 2-MTS were previously observed to be viscous and glassy, affecting solute diffusivity through water. To determine organic diffusivity and potential surface activity, dynamic surface tension measurements were taken for aqueous organic and mixed organic-inorganic solutions. 2-MT and 2-MTS were found to be weakly surface-active. Previous studies by Bain et al., 2023 and Mikhailov et al., 2024 determined that surface activity in the dilute bulk concentration range exhibit depressed aerosol surface tension relevant for droplet activation. However, neither 2-MT nor 2-MTS are sufficiently surface-active to depress droplet surface tension at the air-surface interface. 2-MT and 2-MTS solutes move slowly in droplets and have estimated diffusion rates (D_s) between 10^{-9} to 10^{-11} m^2 s^{-1}, with diffusion slowing as organic concentration is increased. When mixed with AS, 2-MT diffusivity remains relatively slow (10^{-10} m^2 s^{-1}) while 2-MTS diffusivity increases by an order of magnitude (10^{-9} m^2 s^{-1}); 2-MTS diffusion in aqueous AS-mixtures is similar to other quickly dissolving compounds, such as NaCl ($D_s = 10^{-9}$, Vitagliano & Lyons, 1956; Leaist & Hao, 1992) and can result in a well-mixed droplet.

Organic viscosity and diffusion known to affect aerosol water uptake (Asa-Awuku & Nenes, 2007; Bones et al., 2012; Tandon et al., 2019). For 2-MT, 2-MTS, and subsequent mixtures under both sub- and supersaturated conditions, droplet growth is modified by solute diffusion. Subsaturated droplet growth was measured using a H-TDMA at 88.2% RH and subsaturated hygroscopicity was parameterized by $\kappa_{H\text{-}TDMA}$. For supersaturated conditions, a CCNC determined the activation ratio of particles at varied supersaturations (0.3-1.4% SS) and water uptake was parameterized by κ_{CCN}. 2-MT/AS mixtures exhibit plateaued $\kappa_{H\text{-}TDMA}$ and κ_{CCN} values close to κ_{int} of AS (~0.61). A similar plateau behavior is observed for 2-MTS/AS $\kappa_{H\text{-}TDMA}$. However, for supersaturated conditions, 2-MTS/AS mixture κ_{CCN} follows ideal mixing behavior, represented by its proximity to κ-hygroscopicity predicted by traditional Köhler theory and volume additive ZSR. Additionally, $\kappa_{H\text{-}TDMA}$ remains higher than κ_{CCN}; this is a result of increased water content reducing viscosity and enhancing organic dissolution under supersaturated conditions.

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The κ-hygroscopicity plateau in Fig. 3 has been previously attributed to the presence of phase separation, resulting in the inorganic, more soluble, and ideal compound (AS) driving water uptake (Malek et al., 2023). However, for 2-MTS/AS ideal hygroscopic behavior is indicative of a well dissolved, homogeneous droplet (Petters & Kreidenweis, 2007). To better understand phase morphology of the synthesized organic-AS mixed particles, AFM measurements of synthesized 2-MTS, 2-MTS/AS mixtures, and 2-MT/AS mixtures were visualized. 2-MTS aerosols are smooth, spherical, viscous particles; when mixed with AS at 10 wt%, AS remains in the aqueous core and is dispersed on the side of the particle, introducing roughness on the aerosol outer shell. As organic concentration increases, the AS core is broken up through the particle. The less defined core-shell morphology may be the result of AS disrupting the interactions between neighboring 2-MTS particles in the viscous network; as a result, organic dissolution becomes faster as indicated by greater 2-MTS diffusion rates. Thus, 2-MTS/AS aerosols are well described by traditional full dissolution assumptions. In comparison, 2-MT/AS mixture AFM images show an engulfed core-shell morphology regardless of organic concentration. As a result, the viscous organic phase remains intact while aqueous AS in the core drives hygroscopicity and droplet growth.

This study demonstrates that viscosity can influence the initial organic diffusion through aqueous droplets, resulting in complex phase morphology and water uptake properties. Indeed, hygroscopicity from the subsaturated to supersaturated regime evolves due to the presence of increased water content. However, the hygroscopicity measurements performed in this study were on short time scales (6-10 s); in comparison, dynamic surface tension measurements showed droplet equilibrium being reached at 100-300 s for aqueous 2-MT, 2-MT/AS, and 2-MTS. Thus, current water uptake measurements may not fully capture a potentially evolving hygroscopicity over time. This is critical for a robust understanding biogenic aerosol influence on cloud formation. A previous study by Chuang (2003) found that droplet formation can occur within time scales of 5-100 s, well within evolving solute diffusion times observed in this study. Therefore, future work must investigate potentially dynamic water uptake of viscous biogenic aerosols, such as 2-MT, 2-MTS, and other SOA derived compounds. Furthermore, time dependent κ can be developed to better account for organic diffusion within larger scale cloud parcel and global models. In addition to time dependency, κ-hygroscopicity estimations may also be affected by size dependent phase morphology. A study by Veghte et al. (2013) found smaller aerosol particles preferring a homogenous state, while larger particles have an engulfed core-shell morphology similar to 2-MT/AS aerosols in this study. Therefore, particle size may influence viscous organic-AS water uptake due to diffusion and morphological influences. Future work may explore and parameterize the effect of size-dependent phase separated morphology on aerosol activation through step size-selected CCN measurements. Ultimately, it is crucial to understand how biogenic aerosol, such as 2-MT and 2-MTS, physicochemical properties such as aerosol viscosity, diffusivity, and phase morphology jointly alter cloud droplet formation. The results of this study demonstrate the co-dependency of these properties for two isoprene derived compounds and thus may improve our overall understanding of how biogenic aerosols and their mixtures affect aerosol-cloud interactions.

Data Availability. Data will be made available upon request.

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Author Contributions. NF designed, collected, analyzed all experimental data, and analyzed theoretical models. CA contributed to design and analysis of water uptake data. SJ contributed to design and collection of H-TDMA experimental data. AD contributed to design and analysis of AFM data. MA contributed to design and collection of AFM data. ERR contributed to collection of surface tension experimental data. ZZ and AG contributed to sample synthesis. JLW contributed to design, collection, and analysis of dynamic surface tension experimental data. YZ contributed to viscosity, diffusion, and AFM data analysis. JDS and AAA provided supervision and project administration for this work. All authors contributed to the writing and preparation of the manuscript.

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Figure Captions

Figure 1. Experimental average surface tension $\sigma_{s/a}$ values of compounds as a function of concentration. Average equilibrium surface tension of synthesized 2-MT and 2-MTS are shown as closed orange squares and closed purple circles, respectively. The surface tension of the organosulfates, including sodium ethyl sulfate (black open triangles), sodium methyl sulfate (grey closed triangles), and sodium octyl sulfate (grey closed diamonds) were obtained by Peng et al. (2016). 2-methylglutaric acid (green closed squares) and ammonium sulfate (red closed circles) $\sigma_{s/a}$ were obtained from Ferdousi-Rokib et al., 2025 (in review). Sodium dodecyl sulfate (SDS) $\sigma_{s/a}$ is shown as black diamonds. Pure water $\sigma_{s/a}$ at 25°C (~ 72 mN m^{-1}) is represented as a dashed blue line. Compounds can be categorized as weak to moderately surface active (65-65 mN m^{-1}) or surface-active (surfactants, < 65 mN m^{-1}) for compounds that can depress surface tension below that of pure water. Bain et al 2023 consider the dilute bulk measurement regime to be less than 100mM.

Figure 2. Dynamic $\sigma_{s/a}$ measurements for (A) 3-94 mM 2-MT/500 mM AS and (B) 3-53 mM 2-MTS/500 mM AS mixtures. Dynamic $\sigma_{s/a}$ was recorded over a duration of 300 seconds.

Figure 3. Experimental κ-hygroscopicity measurements derived from (A) H-TDMA measurements and (B) CCNC measurements. Subsaturated hygroscopicity ($\kappa_{H\text{-}TDMA}$) of 2-MT/AS and 2-MTS/AS mixtures are represented as open orange squares and open purple circles, respectively. Supersaturated hygroscopicity (κ_{CCN}) for 2-MT/AS and 2-MTS/AS mixtures are represented as orange squares and purple circles, respectively. Traditional Köhler theory (κ_{ZSR}) was used to predict hygroscopicity of 2-MT/AS (solid orange line) and 2-MTS/AS (solid purple line) via Eq. 6. Organic κ_{int} was determined from 100 wt% κ_{CCN}. 2-MT κ_{int} (yellow dashed line) was determined to be 0.269. 2-MTS κ_{int} (blue dashed line) was determined to be 0.139.

Figure 4. (A) Schematic depicting aerosol droplet composed of a viscous organic core and aqueous phase layer and AFM images of (B) 10 wt% 2-MTS – 90 wt% AS (C) 45 wt% 2-MTS – 55 wt% AS (D) 10 wt% 2-MT – 90 wt% AS and (E) 45 wt% 2-MT – 90 wt% AS. AFM results show vertical particle height (left) and phase morphology (right) scale bars.

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Figures

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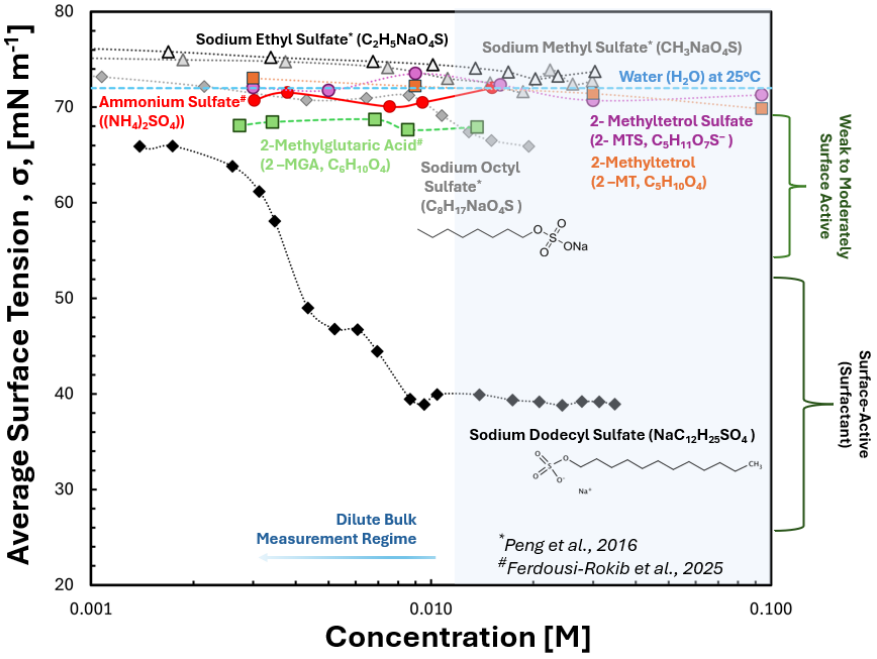

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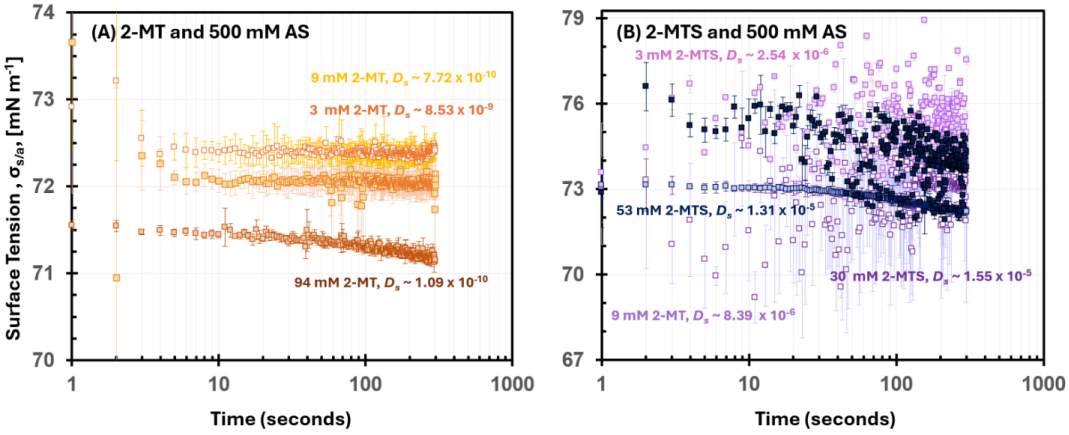

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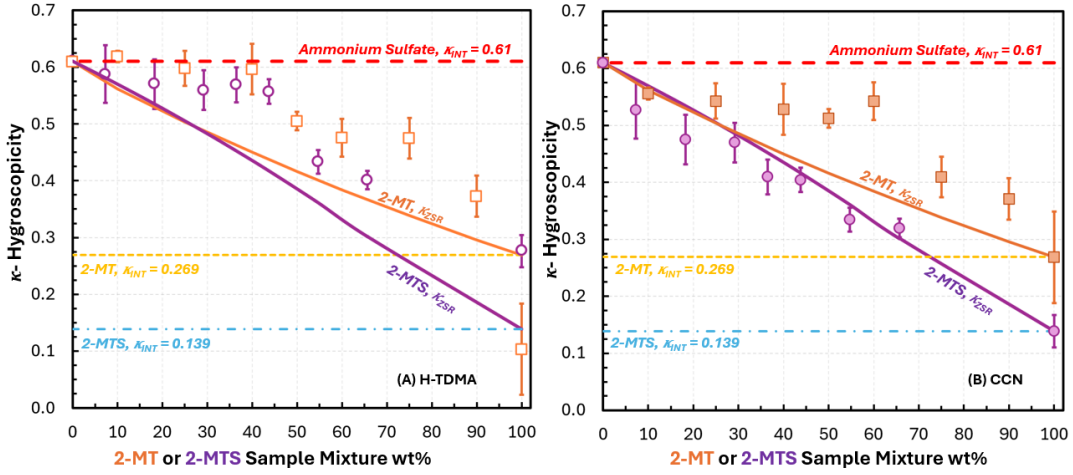

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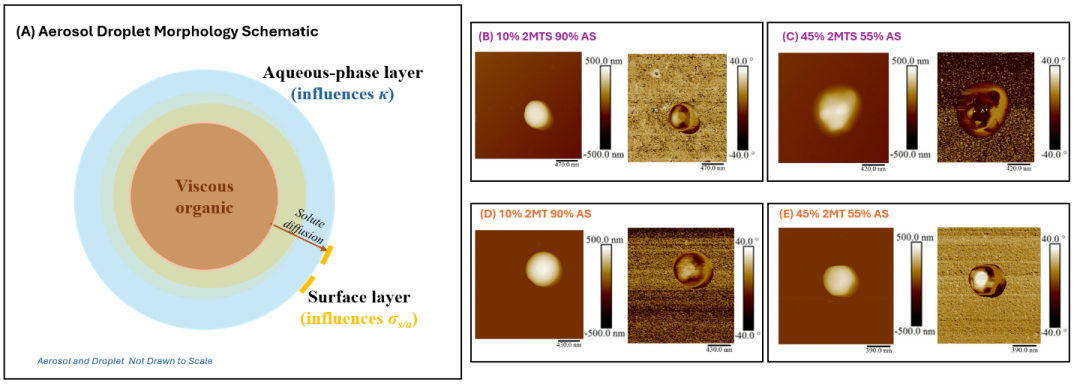

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