

## Author's Response

### Response to referee # 2:

We are grateful for the reviewer's comments. Those comments are all valuable and helpful for improving our paper. Our response to the comments and changes to the manuscript are included below. We repeat the specific points raised by the reviewer in bold font, followed by our response in italic font. The pages numbers and lines mentioned below are consistent with those in the Atmospheric Chemistry and Physics Discussions (ACPD) paper.

### Major comment:

**The authors mention that the chemical interactions between the species can affect the hygroscopic growth or phase transition of the mixed aerosols throughout the manuscript. For example, in the abstract, “For the internal mixture of oxalic acid with levoglucosan or succinic acid, there is enhanced water uptake at high RH due to positive chemical interactions between solutes.” It is not clear what kinds of chemical interactions are referred to and how these interactions enhance the hygroscopic growth of the mixed aerosols. The authors should explain and address how and what kinds of interactions between the species alter hygroscopicity of the mixed aerosols in details.**

*Reply: We appreciate the reviewer's comments. The chemical interactions mentioned in the manuscript are related to the ZSR assumption. The ZSR relation is based on the assumption that each component in the mixture takes up water independently without interactions between species. As a result, the ZSR rule could well describe the hygroscopic behaviors of mixtures if no obvious interactions between components exist. The discrepancies between ZSR predictions and measurements can be attributed to the significant interactions between components. Chan and Chan (2003) have introduced a parameter  $\xi_w'$  based on ZSR assumption to quantify the effect of chemical interaction between species on the water uptake of the mixtures. The enhancement ( $\xi_w' > 1$ , measurements greater than predictions) and reduction effects ( $\xi_w' < 1$ , measurements less than predictions) indicate that the water uptake of the mixture is larger and smaller than the sum of water uptake of individual component following the ZSR relation, respectively. This is likely due to the fact that the interactions between the species enhance ( $\xi_w' > 1$ ) or reduce ( $\xi_w' < 1$ ) water uptake of the mixtures compared to ZSR predictions. Neutral effect ( $\xi_w' \sim 1$ , measurements close to predictions)*

*indicates that the water uptake of the mixtures is close to the ZSR predictions, suggesting no interactions exist or the chemical interactions between species have no effect on the water uptake of the mixtures. It was found that the effect of chemical interactions on the water uptake of mixtures was related to the component type and RH (Chan and Chan, 2003). According to the method proposed by Chan and Chan (2003), we also attributed the large discrepancies between measurements and ZSR predictions to chemical interactions.*

*For organic compounds with polar functional groups such as OH and COOH, hydrogen bonding is the most probable interaction related to the hygroscopicity of organic aerosols. In present study, the hydrogen bonding interaction between organic mixtures containing oxalic acid with levoglucosan or other dicarboxylic acid could enhance the solubility of each organic composition, which may even make the organic fractions stay in liquid irrespective of various humidity (Hemming and Seinfeld, 2001; Marcolli et al., 2004). One previous study also suggests that the solubility of each component is enhanced in the fructose and citric acid mixture by some intermolecular interactions relevant to hydrogen bonding between the hydroxyl groups of the two components (Kwok et al., 2010).*

*These organic acids as well as levoglucosan molecules possess a large number of polar functional groups that promote the formation of hydrogen bonding with water molecules and enhance intra- and intermolecular interactions. UNIFAC does not account for hydrogen bonding interactions between the polar groups that can occur within the small, polyfunctional oxygenated organics, which often leads to underprediction of the water uptake by individual organics (Peng et al., 2001). It suggests that the polar functional groups promote formation of hydrogen bonding with water molecules may enhance the hygroscopic growth of some organic aerosols. Due to the technology and literature limitation, the detailed mechanism for the effects of chemical interactions on the hygroscopicity of the submicron mixed aerosols has not been well captured. In the future, measurement techniques with high size resolution are needed to explore the chemical interactions mechanism.*

***Related changes included in the revised manuscript:***

*Page 23365 line 12: We add some discussion after ZSR method description, “Due to its simple assumption that each component in the mixture takes up water independently without interactions between species, the ZSR rule could well describe the hygroscopic behaviors of*

*mixtures if no obvious interactions between components exist. Thus, the large discrepancies between ZSR predictions and measurements can be attributed to the significant interactions between components.”*

*The other changes related to interactions can be seen in response to minor comments. In addition, page 23358 line 17: “positive chemical interactions” is revised to “chemical interactions such as hydrogen bonding”. Page 23378 line 15: after the sentence “interactions between it and oxalic acid could induce significant water uptake after 70 % RH”, we add “The hydrogen bonding interaction between organic mixtures containing oxalic acid with levoglucosan or other dicarboxylic acid could enhance the solubility of each organic composition which may even make the organic fractions stay in liquid irrespective of various humidity. The polar functional groups can promote formation of hydrogen bonding with water molecules. It may enhance the hygroscopic growth of some organic aerosols at medium and high RH.” Page 23378 line 26: “positive chemical interactions” is revised to “chemical interactions such as hydrogen bonding”.*

#### **Minor comments**

**Page 23362, line 10, “The dry polydisperse aerosol particles were then charged and passed through the first differential mobility analyzer (DMA1), where nearly monodisperse aerosol particles with the desired initial particle diameter of 100 nm were selected.” Given that some species are non-crystallizing, how could the author ensure that initial dry aerosols are generated for all investigated systems?**

***Reply:** We agree with reviewer’s viewpoint. Some organic particles may always contain some residual water even under very low RH conditions. Hence the  $RH < 5\%$  in our study does not warrant that the initial organic particles are completely dried.*

#### ***Related changes included in the revised manuscript:***

*To avoid the misunderstanding, the word “dry” has been changed into “initial” in the revised manuscript.*

**Page 23362, line 15, “The residence time of aerosol particles at a given RH before entering into DMA2 was about 5 s in the humidification section.” How could the**

**authors ensure that the single component and multicomponent aerosols reach their equilibrium states within this timescale (5 s)?**

*Reply: Kerminen (1997) estimated the residence time for achievement of water equilibrium to be between  $8 \times 10^{-6}$  s and 0.1 s for 100 nm and 500 nm particles. Therefore, the typical residence time of a few seconds in the humidification section in DMA measurement is sufficient for most equilibrium hygroscopic measurements. In this study, the measured GFs for the single component at certain RH agree well with literature values within measurement uncertainty. In addition, the residence time (5 s) in our measurement is consistent with that reported in previous single component and multicomponent organic hygroscopic growth studies (Koehler et al., 2006; Moore and Raymond, 2008).*

**Page 23368, line 16 “Predictions from UNIFAC model based on MA liquid assumption have a good agreement with measured GF above 50% RH while slightly overestimate hygroscopic growth at lower RH.” Based on MA liquid assumption, what the composition of MA aerosols is predicted by the model? Does the model predict that MA aerosols retain water or have no residual water at low RH?**

*Reply: Based on MA liquid assumption, the model predictions indicate MA aerosols contain residual water at low RH.*

***Related changes included in the revised manuscript:***

*Page 23368 line 15: the sentence “Such hygroscopic behavior indicates MA particles are in a liquid state even at RH ~ 5 % (Peng et al., 2001).” is revised to “Such hygroscopic behavior indicates MA particles are in a liquid state and still retain some water even at RH ~ 5 % (Peng et al., 2001).”*

**Page 23370, line 18, “For the 1 : 1 mixed Lev/OA particles (Fig. 3a, b), no deliquescence behavior is observed and the continuous water uptake starting at low 20 RH ~ 10% indicates the initial particles appear to be in a liquid state.” What is the composition of the mixed Lev/OA particles at low RH? Any residual water present in the mixed particles?**

*Reply: The model predictions indicate 1 : 1 Lev/OA aerosols contain residual water at low*

*RH, which is also suggested by the continuous water uptake starting at low RH.*

***Related changes included in the revised manuscript:***

*Page 23369 line 18: the sentence “For the 1 : 1 mixed Lev/OA particles (Fig. 3a, b), no deliquescence behavior is observed and the continuous water uptake starting at low RH ~ 10 % indicates the initial particles appear to be in a liquid state.” is revised to “For the 1 : 1 mixed Lev/OA particles (Fig. 3a, b), no deliquescence behavior is observed and the continuous water uptake starting at low RH ~ 10 % indicates the initial particles appear to be in a liquid state and retain some water.”*

**Page 23372, line 17, “ Both ZSR and ideal solution model could well describe the hygroscopic behavior of this mixture within experiment uncertainty, indicating that no interactions related to hygroscopicity exist and the droplets behave like ideal solution” Please elaborate what is meaning of “there is no interactions related to hygroscopicity exist”.**

*Reply: As shown in Fig.5, the hygroscopic growth of Lev/PA mixture (1:1, mass) is well described by ZSR predicted-curve. According to the discussions in the major comment, this consistency indicates no interactions exist or the chemical interactions between species have no effect on the water uptake of the mixtures.*

***Related changes included in the revised manuscript:***

*To avoid confusion, Page 23372 line 18 “no interactions related to hygroscopicity exist and” will be deleted in the revised manuscript.*

**Page 23373, line 9, “Due to the influence of MA, the OA may also exist in a liquid state at low RH.” What is the composition of mixed particles at low RH? Do the mixed particles are completely dried? Any FTIR data or model results to support the presence of dry particles? If not, how the residual aerosol phase water at low RH affects the Gf calculation and the data analysis?**

*Reply: For the 1:1 OA/MA mixture, the model predictions indicate the mixed particles contain residual water at low RH, also suggested by the continuous water uptake starting at low RH. In other words, if the mixed particles are completely dried the deliquescence*

transition may occur during the humidification. Obviously, the 1:1 OA/MA mixed particles are not completely dried. In fact, the GFs reported from HTDMA measurements are effective growth factors based on particle diameter at the lowest RH (~4%) measured which need not to ensure the particles are completely dried. As for the model calculations, the predicted GFs are also obtained based on particle diameter at the same lowest RH as in the measurement. Both measured and predicted GFs are obtained based on the same calculation method. Thus the residual aerosol phase water at low RH has no obvious effects on the GF calculation and the data analysis. To explore the influence of residual aerosol phase water, we carefully checked the difference of predicted GF based on particle diameter at the lowest RH (~4%) and dry condition (0% RH). It was found that the residual water at the lowest RH (~4%) was so slight that it could hardly result in significant difference between the predicted GFs based on particle diameter at the lowest RH (~4%) and dry conditions (0% RH). Even at 90% RH, this difference is not larger than 0.02.

***Related changes included in the revised manuscript:***

Page 23373 line 9: the sentence “Due to the influence of MA, the OA may also exist in a liquid state at low RH.” is revised to “Due to the influence of MA, the OA may also exist in a liquid state at low RH thus the mixed particles still contain some water retained from these two components.”

Page 23366 line 2: after the sentence “Here the UNIFAC model with parameters modified by Peng et al. (2001) was used for WSOCs studied in this work.”, we add “Considering the measured GFs are calculated from the lowest RH~4%, the predicted GFs from E-AIM are also obtained from the same lowest RH. It should be noted that the residual water in the particles at the lowest RH~4% are so slight that it could hardly result in significant difference between the predicted GFs from the lowest RH(~4%) or dry condition (0% RH).”

**Page 23373, line 25, “The water uptake by the OA/SA mixture may be contributed to OA. It seems can be explained by the strong interactions among OA, SA and water molecules upon hydration.” Please elaborate what are the strong interactions among OA, SA and water molecules and how the interactions affect the hygroscopic growth.**

***Reply:*** It suggests that the polar functional groups within OA and SA may promote formation

*of hydrogen bonding with water molecules resulting in enhanced hygroscopic growth at high RH, indicated by the comparisons of measurements and ZSR predictions assuming OA and SA in a solid state.*

***Related changes included in the revised manuscript:***

*Page 23373 line 26: the sentence “It seems can be explained by the strong interactions among OA, SA and water molecules upon hydration.” is revised to “It seems to be explained by the hydrogen bonding interactions within polar functional groups of OA, SA and water molecules upon hydration which promote the water association with submicron OA/SA mixed particles at moderate RH.”*

**Page 23374, line 21, “It is clearly that phase behavior of OA is strongly influenced by the coexisting organic species, thus resulting in enhance of interactions between water and organic mixtures containing OA.” Please elaborate how strong interactions between the species enhance the hygroscopic growth.**

***Reply:*** *The hydrogen bonding interaction between organic mixtures containing oxalic acid with phthalic acid could enhance the solubility of each organic composition which may even make the organic fractions stay in liquid irrespective of various humidity. As a result, the organic mixtures show more water uptake compared to the solid counterparts.*

***Related changes included in the revised manuscript:***

*Page 23374 line 21: the sentence “It is clearly that phase behavior of OA is strongly influenced by the coexisting organic species, thus resulting in enhance of interactions between water and organic mixtures containing OA.” is revised to “It is clear that phase behavior of OA is strongly influenced by the coexisting organic species, thus resulting in enhanced hygroscopic growth of organic mixtures containing OA.” After this sentence, we add “The hydrogen bonding interaction between organic mixtures containing OA with PA could enhance the solubility of each organic composition which may even make the organic fractions stay in liquid irrespective of various humidity (Hemming and Seinfeld, 2001; Marcolli et al., 2004). Consequently, the organic mixtures show more water uptake compared to the solid counterparts, also suggested by model predictions based on various phase assumption.”*

**Page 23376, line 23, “The enhanced hygroscopicity of mixed particles may be attributed to the chemical interactions between levoglucosan and OA.” Please explain why interactions between levoglucosan and OA enhance the hygroscopic growth of mixed particles.**

*Reply: The polar functional groups within levoglucosan and OA may promote formation of hydrogen bonding with water molecules resulting in enhanced hygroscopic growth at high RH, which is indicated by comparisons of measurements and ZSR predictions at high RH.*

***Related changes included in the revised manuscript:***

*Page 23376 line 23: the sentence “The enhanced hygroscopicity of mixed particles may be attributed to the chemical interactions between levoglucosan and OA.” is revised to “The enhanced hygroscopicity of mixed particles is likely due to the fact that the polar functional groups within levoglucosan and OA may promote formation of hydrogen bonding with water molecules resulting in more water uptake at high RH, which is indicated by the comparisons of measurements and ZSR predictions.”*

#### **References:**

- Chan, M. N., and Chan, C. K.: Hygroscopic properties of two model humic-like substances and their mixtures with inorganics of atmospheric importance, *Environ. Sci. Technol.*, 37, 5109-5115, doi:10.1021/es034272o, 2003.
- Hemming, B. L., and Seinfeld, J. H.: On the hygroscopic behavior of atmospheric organic aerosols, *Ind. Eng. Chem. Res.*, 40, 4162-4171, doi:10.1021/ic000790l, 2001.
- Kerminen, V. M.: The effects of particle chemical character and atmospheric processes on particle hygroscopic properties, *J. Aerosol Sci.*, 28, 121-132, doi:10.1016/s0021-8502(96)00069-9, 1997.
- Koehler, K. A., Kreidenweis, S. M., DeMott, P. J., Prenni, A. J., Carrico, C. M., Ervens, B., and Feingold, G.: Water activity and activation diameters from hygroscopicity data - Part II: Application to organic species, *Atmos. Chem. Phys.*, 6, 795-809, 2006.
- Kwok, K., Mauer, L. J., and Taylor, L. S.: Phase behavior and moisture sorption of deliquescent powders, *Chem. Eng. Sci.*, 65, 5639-5650, doi:10.1016/j.ces.2010.06.012, 2010.
- Marcilli, C., Luo, B. P., and Peter, T.: Mixing of the organic aerosol fractions: Liquids as the thermodynamically stable phases, *J. Phys. Chem. A*, 108, 2216-2224, doi:10.1021/jp036080l, 2004.
- Moore, R. H., and Raymond, T. M.: HTDMA analysis of multicomponent dicarboxylic acid aerosols with comparison to UNIFAC and ZSR, *J. Geophys. Res.- Atmos.*, 113, doi:10.1029/2007jd008660, 2008.
- Peng, C., Chan, M. N., and Chan, C. K.: The hygroscopic properties of dicarboxylic and



multifunctional acids: Measurements and UNIFAC predictions, *Environ. Sci. Technol.*, 35, 4495-4501, doi:10.1021/es0107531, 2001.

# **Hygroscopic behavior of multicomponent organic aerosols and their internal mixtures with ammonium sulfate**

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## Abstract

Water soluble organic compounds (WSOCs) are important components of organics in the atmospheric fine particulate matter. Although WSOCs play an important role in the hygroscopicity of aerosols, water uptake behavior of internally mixed WSOC aerosols remains limited characterization. Here, the hygroscopic properties of single component such as levoglucosan, oxalic acid, malonic acid, succinic acid and phthalic acid and multicomponent WSOC aerosols mainly involving oxalic acid are investigated with the hygroscopicity tandem differential mobility analyzer (HTDMA). The coexisting hygroscopic species including levoglucosan, malonic acid and phthalic acid have strong influence on the hygroscopic growth and phase behavior of oxalic acid, even suppress its crystallization completely. The interactions between oxalic acid and levoglucosan are confirmed by infrared spectra. The discrepancies between measured growth factors and predictions from Extended Aerosol Inorganics Model (E-AIM) with UNIFAC method and Zdanovskii-Stokes-Robinson (ZSR) approach increase at medium and high relative humidity (RH) assuming oxalic acid in a solid state. For the internal mixture of oxalic acid with levoglucosan or succinic acid, there is enhanced water uptake at high RH due to **chemical interactions such as hydrogen bonding** between solutes. Organic mixture has more complex effect on the hygroscopicity of ammonium sulfate than single species. Although hygroscopic species such as levoglucosan accounts for a small fraction in the multicomponent aerosols, they may still strongly influence the hygroscopic behavior of ammonium sulfate by changing phase state of oxalic acid which plays the role of “intermediate” species. Considering the abundance of oxalic acid in the atmospheric aerosols, its mixtures with hygroscopic species may significantly promote water uptake under high RH conditions and thus affect the cloud condensation nuclei (CCN) activity, optical properties and chemical reactivity of atmospheric particles.

## 1 Introduction

Atmospheric aerosols can strongly affect the Earth's climate and atmospheric processes (Ramanathan et al., 2001). As one of the most important physicochemical properties, the hygroscopic properties determine the size, concentration, and phase state of aerosol particles and thus contribute to radiative forcing on the climate system, including both the direct forcing by absorbing or scattering light and indirect forcing through activation of cloud condensation nuclei (CCN) (Haywood and Boucher, 2000; Kanakidou et al., 2005). In addition, the water uptake of atmospheric aerosols influences their atmospheric lifetimes, reactivity, air quality and even human health (Pandis et al., 1995; Krueger et al., 2003; Chan and Yao, 2008; Poschl, 2005; Schneidemesser; et al., 2015).

For the atmospheric fine particulate matter, the organic components can usually occupy 20-90% by mass (Kanakidou et al., 2005; Zhang et al., 2007), a large fraction of which is composed of water soluble organic compounds (WSOCs) (Saxena and Hildemann, 1996; Graham et al., 2002; Decesari et al., 2005). Hygroscopic properties of aerosols are mainly affected by their chemical composition. Therefore, water soluble organic compounds can significantly alter aerosols' hygroscopicity (Saxena et al., 1995; Mircea et al., 2005). Compared with the thorough study on hygroscopic properties of atmospheric inorganic components, the knowledge on the hygroscopic behavior of WSOCs still remains relatively limited (Kanakidou et al., 2005; Jimenez et al., 2009; Hallquist et al., 2009). Due to complexity of organic matter, it is difficult to conduct a comprehensive investigation on the hygroscopic behavior of all the organic compounds. To solve this problem, a set of identified model organic compounds have been proposed to represent the WSOCs (Fuzzi et al., 2001; Mayol-Bracero, 2002; Decesari et al., 2006). According to the approach suggested by Fuzzi et al. (2001), the WSOCs can be generally separated into three categories based on acid/base character: (i) neutral compounds, (ii) mono-/di-carboxylic acids, and (iii) polycarboxylic acids such as humic-like organic polymers. Levoglucosan as a tracer of biomass burning products (Simoneit et al., 1999), is often selected to represent the neutral compounds (Decesari et al., 2006; Svenningsson et al., 2006). Dicarboxylic acids are ubiquitous in the atmosphere and have been identified as significant components of the organic matter in urban and remote atmospheric aerosols (Chebbi and Carlier, 1996; Mochida et al., 2003; Kundu et al., 2010).

Field measurements have shown that oxalic acid is usually the dominant dicarboxylic acid in aerosol particles, followed by malonic and succinic acids, phthalic acid (Hegde and Kawamura, 2012; Kawamura et al., 2013).

The hygroscopic properties of levoglucosan and the low molecular weight dicarboxylic acids have been investigated widely with different measurement methods in the past several years (Peng et al., 2001; Prenni et al., 2001; Brooks et al., 2002; Braban et al., 2003; Mochida and Kawamura, 2004; Parsons et al., 2004b; Chan et al., 2005; Yeung and Chan, 2010; Zamora et al., 2011; Ma et al., 2013; Minambres et al., 2013; Ghorai et al., 2014). Most studies have focused on hygroscopicity of aerosol particles containing only single organic component or its mixture with inorganic salt (Lightstone et al., 2000; Cruz and Pandis, 2000; Hameri et al., 2002; Prenni et al., 2003; Wise et al., 2003; Braban and Abbatt, 2004; Parsons et al., 2004a; Ling and Chan, 2008; Zardini et al., 2008; Pope et al., 2010; Peckhaus et al., 2012; Ghorai et al., 2014). It was found that water uptake and phase behavior of the organic aerosols has great uncertainty. Considering that WSOCs usually have flexible conformers, there are more complex interactions between WSOCs and water molecules (Wang et al., 2015), and thus hygroscopicity of WSOCs are more dependent on their composition, mixed state and phase state. Even for the same single component WSOC, differences still existed in measurement results of hygroscopic growth with various measurement technologies (Zamora et al., 2011). Previous HTDMA measurements showed that oxalic acid particles had significant water uptake upon hydration below 90% relative humidity (RH) while it was not observed in the electrodynamic balance (EDB) measurements (Prenni et al., 2001; Peng et al., 2001). This discrepancy could be attributed to initial physical state of aerosol particles, which has considerable influence on water uptake behaviors of atmospheric aerosols (Martin, 2000; Mikhailov et al., 2009). Due to complex interactions among organic mixtures, organic aerosol fractions are more likely to form liquid or amorphous rather than crystalline phases (Mikhailov et al., 2009; Marcolli et al., 2004; Cappa et al., 2008). Considering the potential impact of the interactions between organic species on their hygroscopicity, it needs further study on the hygroscopic behaviors of multicomponent organic aerosols and their mixtures with ammonium sulfate (Marcolli et al., 2004; Moore and Raymond, 2008). In addition, measurements for the hygroscopic growth of internally mixed organic aerosols can be used to

assess the prediction reliability of relevant thermodynamic models (Peng et al., 2001).

In this study, the hygroscopic behaviors of multicomponent organic aerosol particles were investigated with a hygroscopicity tandem differential mobility analyzers (HTDMA) system. Levoglucosan, oxalic acid, malonic acid, succinic acid, and phthalic acid were chosen as the surrogates of WSOC. The attenuated total reflectance Fourier transform infrared (ATR-FTIR) spectroscopy was used to reveal information about molecular interactions and phase transitions in the aerosol particles. Several model methods were applied to predict the water uptake of these organic aerosols including Extended Aerosol Inorganics Model (E-AIM, available at <http://www.aim.env.uea.ac.uk/aim/aim.php>) in combination with the UNIFAC (Universal Quasi-Chemical Functional Group Activity Coefficient) method, Zdanovskii-Stokes-Robinson (ZSR) method, and Ideal solution model. Additionally, the nonideality and CCN activity of WSOC aerosols were evaluated. Finally, the influence of organic mixture on the water uptake behavior of ammonium sulfate was determined.

## **2 Experiment and method**

### **2.1 Hygroscopic growth measurements**

The hygroscopicity tandem differential mobility analyzer (HTDMA) used here has been described in previous studies (Shi et al., 2012; Lei et al., 2014). The schematic of HTDMA system is shown in Fig. 1, mainly including three parts: (1) the aerosol particles generation and drying section; (2) the particles size selection and humidity control apparatus; (3) the detection system for number size distributions of the humidified aerosols. The wet aerosol particles were produced from a constant output atomizer (1500, MSP) containing aqueous solutions of the organic compounds. Chemical properties and mixture composition of the substances investigated were listed in Table 1 and 2. Each pure component or mixture was completely dissolved in ultrapure water (EASY Pure® II UF ultrapure water system, 18.2 MΩ cm) to form a dilute solution with concentration of around 0.1 wt %. The nebulized aerosols were subsequently dried to RH <5% in silica gel diffusion dryers coupled with a Nafion gas dryer (Perma Pure Inc., USA).

The **initial** polydisperse aerosol particles were then charged and passed through the first differential mobility analyzer (DMA1), where nearly monodisperse aerosol particles with the

desired initial particle diameter of 100 nm were selected. The size-selected particles then entered into a humidification system consisting of two Nafion conditioner tubes. The aerosols were prehumidified in the first Nafion conditioner tube and accomplished humidification in the second Nafion tube at a desired relative humidity. The residence time of aerosol particles at a given RH before entering into DMA2 was about 5 s in the humidification section. The size distribution of humidified aerosol particles was measured by the second differential mobility analyzer (DMA2) and a condensation particle counter (CPC, MSP 1500). The inversion of HTDMA measurement data was based on a log-normal size distribution approximation (Stolzenburg and McMurry, 2008). The ratio of sheath air to aerosol flow rate was maintained at 10:1 for both DMAs. In our system, sheath air flows were recirculated in a closed-loop arrangement to ensure relative humidity in the humidification section and DMA2 was equal. A dew point hygrometer (Michell, UK) was used to monitor the relative humidity of sheath flow in the DMA2, with an uncertainty of  $\pm 0.08$  % RH. All experiments were performed at ambient temperature ( $297\pm 1$  K). In our measurements for organic mixtures, no obvious reduction of particle diameter was observed during measurements in DMA2 at  $\text{RH} < 5\%$ , indicating the evaporation of organics was suppressed in the mixtures.

Hygroscopic growth factor (GF), indicating water uptake ability of aerosol particles, is defined as the ratio of particle mobility diameter at a specific RH to the mobility diameter measured in DMA2 at  $\text{RH} < 5\%$ . All results are the average of at least three measurements and uncertainty in our measured growth factors are within 0.02. The results of instrument performance evaluation can be seen in Fig. S1 in Supplement.

## **2.2 Infrared absorption measurements**

The attenuated total reflectance Fourier transform infrared (ATR-FTIR) spectroscopy is a valuable tool to probe the hygroscopic process of aerosol particles. The ATR horizontal cell apparatus (Pike Technologies) was similar to our previous studies (Zhang et al., 2014) and a Ge crystal instead of ZnSe was used as the substrate due to acidity of oxalic acid. Aerosol particles produced from aqueous samples (2.0 wt%) in a constant output atomizer passed through the silica gel diffusion dryer and then deposited on the Ge crystal substrate, resulting in a homogeneously dispersed sample. To obtain enough signal-to-noise level spectrum, the

aerosol particles used for infrared measurements did not experience size selection. The upper limit of particle size was below 2  $\mu\text{m}$ . The RH inside the ATR cell was controlled by a nitrogen flow which was mixed by dry nitrogen with nitrogen saturated with water vapor. A humidity probe accurate to  $\pm 2\%$  (HMP 237, Vaisala) was placed at the exit of the cell to monitor the RH. To ensure hygroscopic equilibration, each RH was maintained 30 min before making measurement. Infrared spectra at various RHs during humidification were measured in the spectral range from 4000 to 750  $\text{cm}^{-1}$  with 4  $\text{cm}^{-1}$  resolution by averaging 64 scans using a Thermo Nicolet 6700 FTIR spectrometer equipped with a high-sensitivity mercury cadmium telluride (MCT) detector. All spectra reported here were referenced to the background signal of the blank Ge crystal under dry conditions and gas water lines have been subtracted.

### 3 Modeling methods

#### 3.1 Hygroscopic growth treatment

To minimize the Kelvin curvature effect for submicron particles measured in the HTDMA, the relative humidity (RH) was converted to water activity ( $a_w$ ) by Köhler equation:

$$RH = a_w \exp\left(\frac{4\sigma_{sol}M_w}{RT\rho_w D_p}\right) \quad (1)$$

Here,  $\sigma_{sol}$  is the surface tension of droplet,  $M_w$  is the molar mass of water,  $R$  is the ideal gas constant,  $T$  is the temperature,  $\rho_w$  is the density of water,  $D_p$  is the droplet diameter. The surface tension of droplet is set to be that of pure water (0.072  $\text{J m}^{-2}$ ). Although organics in the droplet may reduce its surface tension,  $a_w$  error caused by approximation was negligible compared with the uncertainty of the RH measurement.

According to the expression proposed by Kreidenweis et al. (2005), continuous water uptake behavior of individual species can be well described with a polynomial fit equation:

$$GF = \left[1 + \left(a + b \cdot a_w + c \cdot a_w^2\right) \frac{a_w}{1 - a_w}\right]^{1/3} \quad (2)$$

The coefficients  $a$ ,  $b$  and  $c$  obtained by Eq. (2) fitting to GF- $a_w$  measurement data are given in Table 3.



### 3.2 Hygroscopic growth prediction

The ZSR method is widely used to estimate hygroscopic growth of internally mixed particles by assuming independent water uptake of the pure components in the particles at a given RH (Prenni et al., 2003; Brooks et al., 2004; Zamora and Jacobson, 2013). This method has been successfully applied to predict water uptake of various mixed systems containing inorganic salts and organic species in the atmosphere. The hygroscopic growth factor ( $GF_{mix}$ ) of the mixed particles can be calculated by ZSR relation (Stokes and Robinson, 1966; Malm and Kreidenweis, 1997), as following:

$$GF_{mix} = \left( \sum_k \varepsilon_k GF_k^3 \right)^{1/3} \quad (3)$$

Where  $GF_k$  is the hygroscopic growth factor of pure component  $k$ ,  $\varepsilon_k$  is the respective volume fraction in the dry mixture. This equation is derived by assumption that water content of mixture is equal to sum of water uptake of pure components. The volume fraction ( $\varepsilon_i$ ) of component  $i$  is calculated as:

$$\varepsilon_i = \frac{(w_i / \rho_i)}{\sum_k (w_k / \rho_k)} \quad (4)$$

Where  $w_i$  is the mass fraction of species  $i$ ,  $\rho_i$  is the respective density. Due to its simple assumption that each component in the mixture takes up water independently without interactions between species, the ZSR rule could well describe the hygroscopic behaviors of mixtures if no obvious interactions between components exist. Thus, the large discrepancies between ZSR predictions and measurements can be attributed to the significant interactions between components.

The Extended Aerosol Inorganics Model (E-AIM) developed by Wexler and Clegg (2002), can be used to treat the solution thermodynamics including prediction of the water activity, phase state, and equilibrium partitioning of the atmospheric inorganic aerosol systems. E-AIM was later extended to include organic components by combining with the widely applied Universal Quasi-Chemical Functional Group Activity Coefficient (UNIFAC) model (Fredenslund et al., 1975; Hansen et al., 1991; Wittig et al., 2003). The UNIFAC model based

on functional group contributions can predict water activity coefficients for aqueous organic mixtures with various composition. Due to hydrogen bonding interactions between polar groups, standard UNIFAC model is not suitable for organic compounds with two highly polar functional groups separated by less than three or four carbon atoms, especially low molecular weight dicarboxylic acids (Peng et al., 2001). Peng et al. (2001) had revised UNIFAC parameters involving interactions between hydroxyl/carboxyl groups and water to accurately predict water activity for several individual dicarboxylic acids. Here the UNIFAC model with parameters modified by Peng et al. (2001) was used for WSOCs studied in this work. Considering the measured GFs are calculated from the lowest RH~4%, the predicted GFs from E-AIM are also obtained from the same lowest RH. It should be noted that the residual water in the particles at the lowest RH~4% are so slight that it could hardly result in significant difference between the predicted GFs from the lowest RH(~4%) or dry condition (0% RH).

For the ideal solution, the water activity  $a_w$  is equal to the mole fraction of water in the solution (Raoult's law), seen in Eq. (5). Based on the ideal solution assumption, this model may fail to predict water activity of solutions containing electrolyte components or organic compounds with non-ideal interaction. Previous investigations have demonstrated the ideal solution model was a useful tool to predict the hygroscopic growth of atmospheric organics such as humic-like substances, levoglucosan and oxalic acid (Gysel et al., 2004; Mochida and Kawamura, 2004; Mikhailov et al., 2009).

$$a_w = \frac{n_w}{n_w + n_s} \quad (5)$$

where  $n_w$ ,  $n_s$  are the mole numbers of water and solute, respectively.

Considering aerosol droplets may be deviated from ideal solution due to large solute concentrations and complex interactions between solutes, the van't Hoff factor  $i$  was used to evaluate non-ideality of solution (Low, 1969; Pruppacher et al., 1998). The van't Hoff factor is equal to the numbers of dissociated ions per solute molecule, usually defined as following form:

$$a_w^{-1} = 1 + i \frac{n_s}{n_w} \quad (6)$$

where  $n_s$  is the sum of the mole number of all the solutes and  $n_w$  is the mole number of water in solution.

### 3.3 Single hygroscopicity parameter $\kappa$

According to  $\kappa$ -Köhler theory proposed by Petters and Kreidenweis (2007), a single hygroscopicity parameter  $\kappa$  for describing the hygroscopic growth ability of aerosol particles, can be obtained based on hygroscopic growth measurements under subsaturated conditions (Carrico et al., 2008):

$$\kappa = \frac{(GF^3 - 1)(1 - a_w)}{a_w} \quad (7)$$

Where  $a_w$  is the water activity and GF is the respective hygroscopic growth factor. For organic compounds with continuous water uptake under subsaturated conditions, it was found that the  $\kappa$ -value based on the GF measurements from HTDMA around 90% RH can be used to assess the CCN activity of aerosols (Petters and Kreidenweis, 2007; Chan et al., 2008).

## 4 Results and discussion

### 4.1 Hygroscopic growth of individual component aerosols

Hygroscopic behaviors of dicarboxylic acids including oxalic acid (OA), malonic acid (MA), succinic acid (SA) and phthalic acid (PA) for 100 nm **initial** aerosol particles are presented in Fig. 2. For MA and PA with significant hygroscopic growth, predictions from E-AIM and ideal solution model are also shown. As can be seen from Fig. 2a, the GF of OA particles does not increase below 30% RH and then keeps around 1.02 until 90% RH. The slight increase of GF suggests water absorption on the surface of OA particles. No significant hygroscopic growth or deliquescence behavior for OA is observed in the 5-90% RH range studied, consistent with previous studies by EDB and other methods (Peng et al., 2001; Brooks et al., 2002; Braban et al., 2003; Ma et al., 2013). Theory prediction and bulk measurements also show the deliquescence point of OA is greater than 97% RH (Peng et al., 2001; Zamora et al., 2011). Measurements using the HTDMA in early studies indicated

substantial water uptake by OA particles during hydration above 45% RH (Prenni et al., 2001; Mikhailov et al., 2009). The phase state of the particles can strongly influence their hygroscopic growth. Mikhailov et al. (2009) demonstrated that initial state of OA particles generated in their measurement should be amorphous, resulting in gradual water uptake at lower RH. OA aerosol particles generated in this study may be crystalline due to dry conditions and electric charge effects (Mikhailov et al., 2009), thus accounting for no significant water uptake prior to deliquescence point. Although OA has a high vapor pressure, no evaporation losses for OA particles are observed in agreement with earlier HTDMA studies, suggesting that the initial dry particles composed of OA dihydrate (Prenni et al., 2001; Mikhailov et al., 2009). It has been found that anhydrous OA particles could transform into OA dihydrate during hydration between 10-30% RH (Braban et al., 2003). If the initial particles are composed of anhydrous OA, a GF of 1.17 can be obtained based on the transition from anhydrous form to dihydrate one. Obviously, this is not the case in present study.

As shown in Fig. 2b, MA exhibits continuous water uptake with increasing RH and no phase transition is observed, consistent with previous EDB and HTDMA measurements (Peng et al., 2001; Prenni et al., 2001). Such hygroscopic behavior indicates MA particles are in a liquid state and still retain some water even at RH~5 % (Peng et al., 2001). Predictions from UNIFAC model based on MA liquid assumption have a good agreement with measured GF above 50% RH while slightly overestimate hygroscopic growth at lower RH. Contrarily, the ideal solution model underestimates the hygroscopic growth of MA above 40% RH. As for SA (Fig. 2c), no hygroscopic growth is observed even at 90% RH, similar behavior also reported by Prenni et al. (2001) and Svenningsson et al. (2006). According to EDB and bulk measurements, the deliquescence relative humidity (DRH) of SA can reach up to 99% RH due to its limited solubility (Peng et al., 2001; Zamora et al., 2011). The hygroscopic growth of submicron PA particles is given in Fig. 2d. The PA particles take up water gradually without phase changes in the RH range studied. Our results suggest initial PA particles may still retain water at the lowest RH, similar to other organic species such as citric acid and malic acid (Peng et al., 2001). The overall trend of the growth curve is consistent with measurements reported by Brooks et al. (2004) and Hartz et al. (2006). Considering the molecular structure of PA, the UNIFAC model with the parameters modified by Peng et al. (2001) was used here.

The UNIFAC model underestimates hygroscopic growth at the moderate and high RH while predictions from ideal solution model are close to the measured GFs. It should be noted that Peng et al. (2001) corrected UNIFAC model interaction parameters only based on water activity data for solutions of seven dicarboxylic acids, mainly straight chain carboxylic acids. Therefore, more water activity data for complex model organic compounds may be helpful for further UNIFAC parameter modification.

## 4.2 Hygroscopic growth of multicomponent organic aerosols

For organic aerosols containing OA, theoretical growth curves derived from E-AIM are based on various OA phase assumption, i.e., solid and liquid phase, indicated by solid and dashed lines, respectively. In the ZSR approach, the GFs of OA in a solid phase are set equal to 1 and hygroscopic growth curve of OA in a liquid phase is obtained from UNIFAC model (i.e. dehydration curve). To better reproduce the measured GFs, model calculations assuming OA dihydrate and anhydrous OA are presented in Figs. 3a, 5a-7a and 3b, 5b-7b, respectively.

### 4.2.1 Levoglucosan and oxalic acid (Lev/OA)

The hygroscopic behaviors of organic aerosols containing levoglucosan and OA at different mass ratios are shown in Fig. 3. For the 1:1 mixed Lev/OA particles (Fig. 3a, b), no deliquescence behavior is observed and the continuous water uptake starting at low RH~10 % indicates the initial particles appear to be in a liquid state and retain some water. Both ZSR relation and E-AIM based on OA solid phase assumption strongly underestimate the hygroscopic growth of Lev/OA particles in the whole RH range. ZSR approach assumes independent water uptake of components and no interactions exist in the mixtures. Thus, interactions between individual components of mixed particles can determine whether this simple method will deviate from measured GFs for multicomponent aerosols. The hygroscopic properties of levoglucosan have been studied with a variety of measurement methods. Measurements with the HTDMA have demonstrated that levoglucosan particles could retain water even at RH lower than 10% (Mochida and Kawamura, 2004; Mikhailov et al., 2009). The residual water retained by levoglucosan in the mixture may inhibit the formation of OA crystalline during the generation of initial particles. Parsons et al. also found that levoglucosan could reduce the deliquescence or crystallization relative humidity of

ammonium sulfate (Parsons et al., 2004a). OA in the initial mixed particles may exist in a liquid or amorphous semisolid state, thus strongly influencing its hygroscopic behavior in the subsequent humidification (Prenni et al., 2001; Mikhailov et al., 2009).

As shown in Fig. 3a, water uptake predictions from ZSR relation and E-AIM are obviously elevated, assuming OA exists in a liquid phase over the whole RH range studied. However, differences between measured GFs and predicted values are still outside the measurement uncertainty at high RH above 60%. In the early study by Prenni et al. (2003), it indicated that ZSR rule could well describe the hygroscopic growth of internally mixed particles containing ammonium sulfate and oxalic acid based on dihydrate assumption. The discrepancy in present study may be caused by the potential interactions between levoglucosan and oxalic acid in the droplets, which may promote hygroscopicity of particles at high RH. The influence of interactions between individual components on the hygroscopic growth has been quantified by Chan and Chan (2003), depending on chemical composition and RH. For comparison, predicted growth curves from three models according to anhydrous OA assumption are given in Fig. 3b. The ZSR method based on OA liquid phase assumption can well describe water uptake of Lev/OA mixtures (1:1, mass) in the 5-90% RH range. The predictions from E-AIM assuming OA present in a liquid phase, are close to measured GFs but still lower due to its underestimation for water contents of levoglucosan at high RH (Fig. S2, Supplement). The growth curves from ideal solution model differ from measurements regardless of OA composition assumption, caused by nonideality of solution.

To further explore the effects of composition on hygroscopicity, the hygroscopic growth of Lev/OA (1:3, 3:1, mass) mixtures with only ZSR predicted curves are shown in Figs. 3c, d. In the Lev/OA (1:3, mass) case, it can be observed that predictions based on liquid anhydrous OA assumption are in good agreement with measured GFs above 70% RH. Below 40% RH, the mixed particles show no obvious water uptake and the consistence of measurements with predictions based on OA inert mass assumption suggests OA in this mixture may exist in solid phase. Levoglucosan in the particles can take up water gradually with increasing RH, resulting in formation of aqueous solution. Solid OA can be partially dissolved in aqueous levoglucosan and contribute to water uptake at medium 40-70% RH. By compared with ZSR calculations, it can be concluded that OA finishes full deliquescence after 60% RH. As for the

Lev/OA (3:1, mass) case, it seems that OA keeps solid phase in the mixture below 50% RH and then partially deliquesced in the medium 60-70% RH, fully dissolved in the droplets at higher RH. Previous studies on aerosol particles containing binary components indicated that organic species such as malonic acid, citric acid contributing to water uptake at low RH could induce partial deliquescence of ammonium sulfate and lower its deliquescence point (Choi and Chan, 2002b; Prenni et al., 2003; Zardini et al., 2008). Svenningsson et al. (2006) have investigated the hygroscopic growth of organic mixtures composed of levoglucosan, succinic acid and fulvic acid and found that experimental values could be reproduced by ZSR approach as long as limited solubility of succinic acid was taken into consideration.

Infrared spectra of equal mass levoglucosan and oxalic acid mixture are used to confirm the interactions between species and phase transitions. The ATR-IR spectra of pure levoglucosan and OA particles, and of Lev/OA (1:1, mass) mixture recorded at various RHs are presented in Fig. 4. For levoglucosan aerosols, the spectrum at 2% RH shows a broad absorption between 3570 and 3050  $\text{cm}^{-1}$  assigned to O-H stretch. The absorbance of the O-H stretch increases at higher RH and a new infrared feature occurs at 1646  $\text{cm}^{-1}$  contributed by condensed phase water. The spectrum of OA particles at 2% RH shows an anhydrous feature with a sharp carbonyl stretching band at 1723  $\text{cm}^{-1}$ . When RH increases to 30%, the twin bands in the region 3600-3300  $\text{cm}^{-1}$  indicate the transformation of anhydrous form to dihydrate. No obvious liquid water uptake can be observed with further humidification up to 91% RH. Our infrared measurement for OA particles is consistent with observation by Braban et al. (2003) while deviate from the H-TDMA results in Fig. 2a. The possible reason may be caused by size effect considering the IR absorption in present study mainly from larger particles. As with the Lev/OA (1:1, mass) mixture, features from both levoglucosan and OA components are present. In the low 2% RH spectrum, the carbonyl stretching band from OA is obviously split into peaks at 1750  $\text{cm}^{-1}$  and 1724  $\text{cm}^{-1}$  which suggests strong interaction between OA and levoglucosan. Above 30% RH, the carbonyl stretching band shifts to 1743  $\text{cm}^{-1}$  in agreement with the C=O feature from aqueous OA (Hug and Bahnemann, 2006). Meanwhile, the increase of absorption between 3570-3050  $\text{cm}^{-1}$  and feature at 1646  $\text{cm}^{-1}$  confirm significant water uptake by mixture particles. The IR results also indicate levoglucosan could strongly influence phase state of OA, resulting in more water uptake at

low RH.

#### 4.2.2 Levoglucosan and phthalic acid (Lev/PA)

Figure 5 shows the hygroscopic growth of 100 nm **initial** particles containing levoglucosan and phthalic acid with equal mass ratio. Continuous water uptake without phase transition can be observed. Both ZSR and ideal solution model could well describe the hygroscopic behavior of this mixture within experiment uncertainty, indicating that **no interactions related to hygroscopicity exist and** the droplets behave like ideal solution. The E-AIM (UNIFAC) underestimates water uptake at high RH due to strong interactions between polar groups on the solute molecule (Peng et al., 2001). Choi and Chan (2002a) used the EDB to measurement the water activity of binary organic mixtures by equal molar ratio including maleic acid and malic acid, malonic acid and glutaric acid. They found that both ZSR and modified UNIFAC could accurately predict the measurements for these mixtures which did not experience phase transition, similar to results observed with the HTDMA by Moore and Raymond (2008).

#### 4.2.3 Oxalic acid and malonic acid (OA/MA)

Figure 6 shows the hygroscopic growth of 100 nm **initial** particles containing oxalic acid and malonic acid with equal mass ratio. In present study, the hygroscopic growth of OA/MA (1:1, mass) displays a smooth nature. Previous particle measurements showed that MA could strongly affect the deliquescence behavior of coexisting species like ammonium sulfate or glutaric acid (Choi and Chan, 2002a; Ling and Chan, 2008). It was reported that MA could substantially suppress the crystallization of glutaric acid in the equal molar mixed particles (Choi and Chan, 2002a). **Due to the influence of MA, the OA may also exist in a liquid state at low RH thus the mixed particles still contain some water retained from these two components.** Assuming the oxalic acid in the initial particles composed of dihydrate, predictions from ZSR and E-AIM based on OA liquid phase assumption are relatively consistent with measured hygroscopic growth while deviate a lot based on solid assumption (Fig. 6a). As for the anhydrous OA case, the deviations between predictions from ZSR and E-AIM based on OA liquid phase assumption and measurements increase at low RH while minimize at high RH. And the growth curve from ideal solution model is more close to the experiment data.



#### 4.2.4 Oxalic acid and succinic acid (OA/SA)

Figure 7 displays the hygroscopic behavior of 100 nm initial particles containing oxalic acid and succinic acid with equal mass ratio. Based on ZSR assumption, it can be expected that no water uptake by this mixture would occur over the RH range, indicated by ZSR-calculated curve. However, obvious hygroscopic growth of OA/SA mixture after 70% RH can be observed and the GF is up to 1.28 at 90% RH. No model curves are in good agreement with experiment results within measurement uncertainty in the entire RH range. SA has been proved to be nonhygroscopic under subsaturation condition by various methods. Chemical interaction between the mixtures may enhance the water uptake under high humidity conditions (Chan and Chan, 2003). The water uptake by the OA/SA mixture may be contributed to OA. It seems to be explained by the hydrogen bonding interactions within polar functional groups of OA, SA and water molecules upon hydration which promote the water association with submicron OA/SA mixed particles at moderate RH. In a recent study with the HTDMA, it was observed that the SA could significantly decrease the DRH of ammonium sulfate from 80.4% RH to 73.2% RH for equal mass mixed submicron particles (Laskina et al., 2015). It has been revealed that ion-molecule interactions between the SA and ammonium sulfate can lead to water uptake of this equal mass mixture prior to the deliquescence point (Minambres et al., 2010).

Infrared spectra of equal mass oxalic acid and succinic acid mixture are used to explore the interactions between species. The ATR-IR spectra of pure OA and SA particles, and of OA/SA (1:1, mass) mixture recorded at various RHs are presented in Fig. 8. For pure SA aerosols, the spectra at various RHs show no difference and no liquid water feature can be observed. In the spectra of OA/SA (1:1, mass) mixture, the occurrence of absorption in the region 3600-3300  $\text{cm}^{-1}$  indicates the transformation of anhydrous form to dihydrate. However, no obvious condensed phase water feature is detected even at 90% RH. The difference between HTDMA and IR measurements may be caused by size effects which have influence on the hygroscopic behaviors of aerosols (Laskina et al., 2015; Cheng et al., 2015).

#### 4.2.5 Oxalic acid and phthalic acid (OA/PA)

Figure 9 shows the hygroscopic growth of 100 nm initial particles containing oxalic acid

and phthalic acid with equal mass ratio. Although PA is less hygroscopic than MA, the OA/PA mixed particles show a similar growth trend with that of OA/MA. It is obvious that the ZSR and E-AIM significantly underestimate the water content of particles at medium and high RH without taking deliquescence of OA into account. It is clear that phase behavior of OA is strongly influenced by the coexisting organic species, thus resulting in enhanced hygroscopic growth of organic mixtures containing OA. The hydrogen bonding interaction between organic mixtures containing OA with PA could enhance the solubility of each organic composition which may even make the organic fractions stay in liquid irrespective of various humidity (Hemming and Seinfeld, 2001; Marcolli et al., 2004). Consequently, the organic mixtures show more water uptake compared to the solid counterparts, also suggested by model predictions based on various phase assumption. We also measured hygroscopic growth of aerosols consisting of levoglucosan, oxalic acid and phthalic acid (Lev/OA/PA) with equal mass ratio and found the similar hygroscopic behavior with Lev/OA or OA/PA mixtures, shown in Fig. S3 in Supplement.

### 4.3 Evaluation of organic droplet nonideality

To describe the dissociation and nonideality of submicron organic aerosol droplets, the van't Hoff factor  $i$  is used to assess the degree of deviation from ideality. For the organics, a van't Hoff factor of 1 usually suggests that the solution behaves as an ideal solution. Based on the Eq. (6), van't Hoff factor  $i$  is obtained from the slope of the linear fit by  $a_w^{-1}$  versus  $n_s/n_w$  for each aerosol droplet. The calculated van't Hoff factor  $i$  as well as corresponding R-squared values are given in Fig. 8. For mixtures containing oxalic acid, van't Hoff factor  $i$  is calculated based on various OA composition assumption, OA dihydrate and anhydrous OA, shown in Fig. 10a, b respectively.

The van't Hoff factors for OA, SA and their mixture are not included since no obvious hygroscopic growth occurs in the measured RH range. The resulting  $i$  for levoglucosan, MA and PA is 1.35, 1.38 and 1.20 respectively, consistent with the literature values of 1.05, 1.29 for levoglucosan (Zamora and Jacobson, 2013; Mikhailov et al., 2009), and 1.37 for MA (Wise et al., 2003). It seems that the three single component aerosol droplets deviate slightly from ideal solution. Assuming OA dihydrate,  $i$  for most organic mixtures is close to 1 while

for Lev/OA with the mass ratio of 1:1, 1:3 it is obviously larger than 1, suggesting the mixtures deviate substantially from an ideal solution. For anhydrous OA assumption case, only  $i$  (0.62) for OA/PA mixture deviates a lot from 1. In the case of Lev/OA (1:1, 1:3 by mass),  $i$  for mixtures assuming OA dihydrate is 1.71, 1.58 respectively larger than their pure components,  $i$  for OA dihydrate is 0.98 (Mikhailov et al., 2009).

#### 4.4 CCN activity of multicomponent WSOC aerosols

Previous studies have confirmed organics may play important role in cloud formation by acting as cloud condensation nuclei (CCN) (Suda et al., 2014; Xu et al., 2014). Here we use the single hygroscopicity parameter  $\kappa$  to evaluate the hygroscopicity and CCN activity of WSOC aerosol particles (Petters and Kreidenweis, 2007). This parameter usually can be derived from hygroscopic growth measurements at RH~90% with the HTDMA or from critical supersaturation measurements under supersaturated conditions (Petters and Kreidenweis, 2007). It has been shown values of  $\kappa$  estimated from the two methods agree well within 30%, especially for organics with continuous hygroscopic growth (Petters and Kreidenweis, 2007; Chan et al., 2008; Petters et al., 2009). For aerosol particles containing OA, it is convenient to use the  $\kappa$  capturing all solute properties to describe the hygroscopicity without taking OA composition assumption into account, indicated by Eq. (7).

It has been found  $\kappa$  for organic aerosols may correlate with the ratio of oxygen to carbon atoms (O/C) in dry particles while deviations from this relationship also reported (Jimenez et al., 2009; Duplissy et al., 2011; Rickards et al., 2013). The single hygroscopicity parameter  $\kappa$  evaluated from our HTDMA data at 90% RH is plotted as a function of O/C ratio, shown in Fig. 11. The  $\kappa$ -values for SA and its mixture with OA are not included. For OA, the  $\kappa$ -value (0.484) is obtained from UNIFAC-predicted GF, consistent with literature values 0.48, 0.504 (Rickards et al., 2013; Kreidenweis et al., 2008). The  $\kappa$ -values for other pure components are also in good agreement with reported values. As shown in Fig. 11, the general trend indicates the possible relationship between  $\kappa$ -value and O/C ratio for WSOC aerosols. To further assess the effects of coexisting species on hygroscopicity of mixed particles, we compare the  $\kappa$ -values of pure levoglucosan, oxalic acid and their mixtures at various mass ratio with ZSR predictions assuming anhydrous OA or OA dihydrate, seen in Fig. 12. It can be observed that

the hygroscopicity of three Lev/OA mixtures is similar and more close to that of OA compared to levoglucosan. Predictions from ZSR rule significantly underestimate  $\kappa$ -values derived from GF measurements, regardless of OA composition assumption. The enhanced hygroscopicity of mixed particles is likely due to the fact that the polar functional groups within levoglucosan and OA may promote formation of hydrogen bonding with water molecules resulting in more water uptake at high RH, which is indicated by the comparisons of measurements and ZSR predictions. The similar enhancement effects were also observed in aerosol particles containing ammonium sulfate and fulvic acid due to complex chemical interactions (Chan and Chan, 2003).

#### **4.5 Effect of organic mixture on hygroscopicity of ammonium sulfate (AS)**

The organic mixture of oxalic acid with levoglucosan is selected to determine the influences of multicomponent organics on the hygroscopic properties of ammonium sulfate (AS). As shown in Fig. 13, the hygroscopic growth measurements for equal mass mixture of AS with OA are also presented for comparison. It can be seen that 1:1 AS/OA mixture does not show any hygroscopic growth until reaching its deliquescence point 77% RH consistent with literature values for eutonic mixtures (Brooks et al., 2002). Based on OA dihydrate assumption, the E-AIM predictions agree well with measured growth factors. It should be noted that the deliquescence point predicted by E-AIM is 73% RH slightly lower than the experiment result. The ZSR relation underestimates water uptake of AS/OA mixture after complete deliquescence without taking OA dissolution into consideration.

For the 2:1:1 AS/OA/Lev mixed aerosols, a smoothing of hygroscopic growth behavior can be observed without obvious phase transitions occurring. Both E-AIM and ZSR method underestimate the hygroscopic growth above 30% RH. In the previous study, the binary mixture containing AS and levoglucosan still showed phase transitions even when organic fraction accounted for up to 50% (Lei et al., 2014). A possible explanation for present phenomenon is that levoglucosan could suppress crystallization of OA resulting in more water uptake at low RH which enhances partial dissolution of AS. For both equal mass mixtures of AS/OA and AS/Lev, the hygroscopic growth of particles can be well described by E-AIM (seen in Fig.13a and Lei et al., 2014). However, this is not the case for AS/OA/Lev mixture. It

is obvious that the organic mixture has more complex effect on the hygroscopicity of ammonium sulfate than single organic species. Although levoglucosan only accounts for a small fraction in the mixture, it still strongly influences the hygroscopic behavior of AS by changing phase state of OA which plays the role of “intermediate” species.

## 5 Conclusion and Atmospheric Implications

In present study, the hygroscopic properties of single component and multicomponent water-soluble organic compounds mainly involving oxalic acid are investigated with the HTDMA. The hygroscopic behavior of oxalic acid in our measurements differs from previous HTDMA data but agrees with EDB and other methods results. The hygroscopic growth of other single component aerosol particles including levoglucosan, malonic acid, succinic acid and phthalic acid, are in good agreement with previous studies. The most of multicomponent organic aerosols show continuous water uptake behavior without obvious phase transition except for OA/SA mixture. For equal mass mixed organic aerosols containing oxalic acid, the coexisting hygroscopic species such as levoglucosan, malonic acid and phthalic acid have strong influence on the phase behavior of oxalic acid, even suppress its crystallization completely. The interactions between oxalic acid and levoglucosan at dry state are confirmed by infrared spectra. Although succinic acid is nonhygroscopic species under subsaturation conditions, interactions between it and oxalic acid could induce significant water uptake after 70% RH. The hydrogen bonding interaction between organic mixtures containing oxalic acid with levoglucosan or other dicarboxylic acid could enhance the solubility of each organic composition which may even make the organic fractions stay in liquid irrespective of various humidity. The polar functional groups can promote formation of hydrogen bonding with water molecules. It may enhance the hygroscopic growth of some organic aerosols at medium and high RH.

Model methods including E-AIM (UNIFAC), ZSR approach and ideal solution model are used to predict the hygroscopic growth of single component and multicomponent organic aerosol particles. The discrepancies between measurements and predictions from E-AIM and ZSR approach increase at medium and high RH assuming the OA in a solid state. For ZSR method, it can describe the hygroscopic growth of aerosol particles containing OA in a liquid

state at high RH based on anhydrous OA assumption except for OA/SA. However, it should be noted that the OA in the dry mixtures is more likely to exist in a dihydrate form rather than an anhydrous one due to residual water retained by coexisting species such as levoglucosan. As a result, the substantial underestimation of hygroscopic growth of Lev/OA mixtures at high RH by ZSR relation based on dihydrate assumption may be caused by the **chemical interactions such as hydrogen bonding** between solutes, also indicated by the van't Hoff factor  $i$  and the single hygroscopicity parameter  $\kappa$ -value. Comparisons between measurement results and thermodynamic predictions assess the reliability of the aerosol models for predicting hygroscopic properties of atmospheric WSOC with various chemical properties. Predictions from E-AIM (UNIFAC) significantly underestimated water content of most mixed aerosols at high RH, suggesting model parameters may need to be further modified so that it can more reliably predict thermodynamic properties of atmospheric organic aerosols. Due to low disassociation, most WSOC mixtures studied have a van't Hoff factor close to 1 except for Lev/OA (1:1,1:3 mass), influenced by OA composition assumption. By comparing the single hygroscopicity parameter  $\kappa$ -values with ZSR predictions, it indicates the hygroscopicity of mixtures containing oxalic acid and levoglucosan is significantly enhanced at high RH conditions.

These findings suggest that the presence of coexisting hygroscopic species has a significant impact on the phase behaviors and hygroscopic growth of oxalic acid which has a high deliquescence point. Organic mixture has more complex effect on the hygroscopicity of ammonium sulfate than single species. Although hygroscopic species such as levoglucosan account for a small fraction in the multicomponent aerosols, they may still strongly influence the hygroscopic behavior of AS by changing phase state of OA which plays the role of “intermediate” species. Considering the abundance of oxalic acid in the atmospheric aerosols, its mixtures with hygroscopic species may promote water uptake under high RH conditions and thus affect the cloud condensation nuclei (CCN) activity, optical properties and chemical reactivity of atmospheric particles.

**The Supplement related to this article is available online.**

*Author contributions.* B. Jing and S. R. Tong contribute equally to this work.

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## References

- Braban, C. F., Carroll, M. F., Styler, S. A., and Abbatt, J. P. D.: Phase transitions of malonic and oxalic acid aerosols, *J. Phys. Chem. A*, 107, 6594-6602, doi:10.1021/jp034483f, 2003.
- Braban, C. F., and Abbatt, J. P. D.: A study of the phase transition behavior of internally mixed ammonium sulfate-malonic acid aerosols, *Atmos. Chem. Phys.*, 4, 1451-1459, doi:10.5194/acp-4-1451-2004, 2004.
- Brooks, S. D., Wise, M. E., Cushing, M., and Tolbert, M. A.: Deliquescence behavior of organic/ammonium sulfate aerosol, *Geophys. Res. Lett.*, 29, 1917, doi:10.1029/2002-gl014733, 2002.
- Brooks, S. D., DeMott, P. J., and Kreidenweis, S. M.: Water uptake by particles containing humic materials and mixtures of humic materials with ammonium sulfate, *Atmos. Environ.*, 38, 1859-1868, doi:10.1016/j.atmosenv.2004.01.009, 2004.
- Cappa, C. D., Lovejoy, E. R., and Ravishankara, A. R.: Evidence for liquid-like and nonideal behavior of a mixture of organic aerosol components, *Proc. Nat. Acad. Sci. U. S. A*, 105, 18687-18691, doi:10.1073/pnas.0802144105, 2008.
- Carrico, C. M., Petters, M. D., Kreidenweis, S. M., Collett, J. L., Jr., Engling, G., and Malm, W. C.: Aerosol hygroscopicity and cloud droplet activation of extracts of filters from biomass burning experiments, *J. Geophys. Res.- Atmos.*, 113, D08206, doi:10.1029/2007-jd009274, 2008.
- Chan, C. K., and Yao, X.: Air pollution in mega cities in China, *Atmos. Environ.*, 42, 1-42, doi:10.1016/j.atmosenv.2007.09.003, 2008.
- Chan, M. N., and Chan, C. K.: Hygroscopic properties of two model humic-like substances and their mixtures with inorganics of atmospheric importance, *Environ. Sci. Technol.*, 37, 5109-5115, doi:10.1021/es034272o, 2003.
- Chan, M. N., Choi, M. Y., Ng, N. L., and Chan, C. K.: Hygroscopicity of water-soluble organic compounds in atmospheric aerosols: Amino acids and biomass burning derived

- organic species, *Environ. Sci. Technol.*, 39, 1555-1562, doi:10.1021/es049584l, 2005.
- Chan, M. N., Kreidenweis, S. M., and Chan, C. K.: Measurements of the hygroscopic and deliquescence properties of organic compounds of different solubilities in water and their relationship with cloud condensation nuclei activities, *Environ. Sci. Technol.*, 42, 3602-3608, doi:10.1021/es7023252, 2008.
- Chebbi, A., and Carlier, P.: Carboxylic acids in the troposphere, occurrence, sources, and sinks: A review, *Atmos. Environ.*, 30, 4233-4249, doi:10.1016/1352-2310(96)00102-1, 1996.
- Cheng, Y., Su, H., Koop, T., Mikhailov, E., and Poeschl, U.: Size dependence of phase transitions in aerosol nanoparticles, *Nature Communications*, 6, doi:10.1038/ncomms6923, 2015.
- Choi, M. Y., and Chan, C. K.: Continuous measurements of the water activities of aqueous droplets of water-soluble organic compounds, *J. Phys. Chem. A*, 106, 4566-4572, doi:10.1021/jp013875o, 2002a.
- Choi, M. Y., and Chan, C. K.: The effects of organic species on the hygroscopic behaviors of inorganic aerosols, *Environ. Sci. Technol.*, 36, 2422-2428, doi:10.1021/es0113293, 2002b.
- Cruz, C. N., and Pandis, S. N.: Deliquescence and hygroscopic growth of mixed inorganic-organic atmospheric aerosol, *Environ. Sci. Technol.*, 34, 4313-4319, doi:10.1021/es9907109, 2000.
- Decesari, S., Facchini, M. C., Fuzzi, S., McFiggans, G. B., Coe, H., and Bower, K. N.: The water-soluble organic component of size-segregated aerosol, cloud water and wet depositions from Jeju Island during ACE-Asia, *Atmos. Environ.*, 39, 211-222, doi:10.1016/j.atmosenv.2004.09.049, 2005.
- Decesari, S., Fuzzi, S., Facchini, M. C., Mircea, M., Emblico, L., Cavalli, F., Maenhaut, W., Chi, X., Schkolnik, G., Falkovich, A., Rudich, Y., Claeys, M., Pashynska, V., Vas, G., Kourtchev, I., Vermeylen, R., Hoffer, A., Andreae, M. O., Tagliavini, E., Moretti, F., and Artaxo, P.: Characterization of the organic composition of aerosols from Rondonia, Brazil, during the LBA-SMOCC 2002 experiment and its representation through model compounds, *Atmos. Chem. Phys.*, 6, 375-402, doi:10.5194/acp-6-375-2006, 2006.
- Duplissy, J., DeCarlo, P. F., Dommen, J., Alfarra, M. R., Metzger, A., Barmapadimos, I., Prevot,



- A. S. H., Weingartner, E., Tritscher, T., Gysel, M., Aiken, A. C., Jimenez, J. L., Canagaratna, M. R., Worsnop, D. R., Collins, D. R., Tomlinson, J., and Baltensperger, U.: Relating hygroscopicity and composition of organic aerosol particulate matter, *Atmos. Chem. Phys.*, 11, 1155-1165, doi:10.5194/acp-11-1155-2011, 2011.
- Fredenslund, A., Jones, R. L., and Prausnitz, J. M.: Group-contribution estimation of activity-coefficients in nonideal liquid-mixtures, *Aiche J.*, 21, 1086-1099, doi:10.1002/aic.690210607, 1975.
- Fuzzi, S., Decesari, S., Facchini, M. C., Matta, E., Mircea, M., and Tagliavini, E.: A simplified model of the water soluble organic component of atmospheric aerosols, *Geophys. Res. Lett.*, 28, 4079-4082, doi:10.1029/2001gl013418, 2001.
- Ghorai, S., Wang, B., Tivanski, A., and Laskin, A.: Hygroscopic properties of internally mixed particles composed of NaCl and water-soluble organic acids, *Environ. Sci. Technol.*, 48, 2234-2241, doi:10.1021/es404727u, 2014.
- Graham, B., Mayol-Bracero, O. L., Guyon, P., Roberts, G. C., Decesari, S., Facchini, M. C., Artaxo, P., Maenhaut, W., Koll, P., and Andreae, M. O.: Water-soluble organic compounds in biomass burning aerosols over Amazonia - 1. Characterization by NMR and GC-MS, *J. Geophys. Res.- Atmos.*, 107, doi:10.1029/2001jd000336, 2002.
- Gysel, M., Weingartner, E., Nyeki, S., Paulsen, D., Baltensperger, U., Galambos, I., and Kiss, G.: Hygroscopic properties of water-soluble matter and humic-like organics in atmospheric fine aerosol, *Atmos. Chem. Phys.*, 4, 35-50, doi:10.5194/acp-4-35-2004, 2004.
- Hallquist, M., Wenger, J. C., Baltensperger, U., Rudich, Y., Simpson, D., Claeys, M., Dommen, J., Donahue, N. M., George, C., Goldstein, A. H., Hamilton, J. F., Herrmann, H., Hoffmann, T., Iinuma, Y., Jang, M., Jenkin, M. E., Jimenez, J. L., Kiendler-Scharr, A., Maenhaut, W., McFiggans, G., Mentel, T. F., Monod, A., Prevot, A. S. H., Seinfeld, J. H., Surratt, J. D., Szmigielski, R., and Wildt, J.: The formation, properties and impact of secondary organic aerosol: current and emerging issues, *Atmos. Chem. Phys.*, 9, 5155-5236, doi:10.5194/acp-9-5155-2009, 2009.
- Hameri, K., Charlson, R., and Hansson, H. C.: Hygroscopic properties of mixed ammonium sulfate and carboxylic acids particles, *Aiche J.*, 48, 1309-1316, doi:10.1002/aic.690480617, 2002.

Hansen, H. K., Rasmussen, P., Fredenslund, A., Schiller, M., and Gmehling, J.: Vapor-liquid-equilibria by UNIFAC group contribution .5. Revision and extension, *Ind. Eng. Chem. Res.*, 30, 2352-2355, doi:10.1021/ie00058a017, 1991.

Hartz, K. E. H., Tischuk, J. E., Chan, M. N., Chan, C. K., Donahue, N. M., and Pandis, S. N.: Cloud condensation nuclei activation of limited solubility organic aerosol, *Atmos. Environ.*, 40, 605-617, doi:10.1016/j.atmosenv.2005.09.076, 2006.

Haywood, J., and Boucher, O.: Estimates of the direct and indirect radiative forcing due to tropospheric aerosols: A review, *Rev. Geophys.*, 38, 513-543, doi:10.1029/1999rg000078, 2000.

Hegde, P., and Kawamura, K.: Seasonal variations of water-soluble organic carbon, dicarboxylic acids, ketocarboxylic acids, and alpha-dicarbonyls in Central Himalayan aerosols, *Atmos. Chem. Phys.*, 12, 6645-6665, doi:10.5194/acp-12-6645-2012, 2012.

Hemming, B. L., and Seinfeld, J. H.: On the hygroscopic behavior of atmospheric organic aerosols, *Ind. Eng. Chem. Res.*, 40, 4162-4171, doi:10.1021/ic000790l, 2001.

Hug, S. J., and Bahnemann, D.: Infrared spectra of oxalate, malonate and succinate adsorbed on the aqueous surface of rutile, anatase and lepidocrocite measured with in situ ATR-FTIR, *J. Electron. Spectrosc.*, 150, 208-219, doi:10.1016/j.elspec.2005.05.006, 2006.

Jimenez, J. L., Canagaratna, M. R., Donahue, N. M., Prevot, A. S., Zhang, Q., Kroll, J. H., DeCarlo, P. F., Allan, J. D., Coe, H., Ng, N. L., Aiken, A. C., Docherty, K. S., Ulbrich, I. M., Grieshop, A. P., Robinson, A. L., Duplissy, J., Smith, J. D., Wilson, K. R., Lanz, V. A., Hueglin, C., Sun, Y. L., Tian, J., Laaksonen, A., Raatikainen, T., Rautiainen, J., Vaattovaara, P., Ehn, M., Kulmala, M., Tomlinson, J. M., Collins, D. R., Cubison, M. J., Dunlea, E. J., Huffman, J. A., Onasch, T. B., Alfarra, M. R., Williams, P. I., Bower, K., Kondo, Y., Schneider, J., Drewnick, F., Borrmann, S., Weimer, S., Demerjian, K., Salcedo, D., Cottrell, L., Griffin, R., Takami, A., Miyoshi, T., Hatakeyama, S., Shimono, A., Sun, J. Y., Zhang, Y. M., Dzepina, K., Kimmel, J. R., Sueper, D., Jayne, J. T., Herndon, S. C., Trimborn, A. M., Williams, L. R., Wood, E. C., Middlebrook, A. M., Kolb, C. E., Baltensperger, U., and Worsnop, D. R.: Evolution of organic aerosols in the atmosphere, *Science*, 326, 1525-1529, doi:10.1126/science.1180353, 2009.

Kanakidou, M., Seinfeld, J. H., Pandis, S. N., Barnes, I., Dentener, F. J., Facchini, M. C., Van

- Dingenen, R., Ervens, B., Nenes, A., Nielsen, C. J., Swietlicki, E., Putaud, J. P., Balkanski, Y., Fuzzi, S., Horth, J., Moortgat, G. K., Winterhalter, R., Myhre, C. E. L., Tsigaridis, K., Vignati, E., Stephanou, E. G., and Wilson, J.: Organic aerosol and global climate modelling: a review, *Atmos. Chem. Phys.*, 5, 1053-1123, doi:10.5194/acp-5-1053-2005, 2005.
- Kawamura, K., Tachibana, E., Okuzawa, K., Aggarwal, S. G., Kanaya, Y., and Wang, Z. F.: High abundances of water-soluble dicarboxylic acids, ketocarboxylic acids and alpha-dicarbonyls in the mountaintop aerosols over the North China Plain during wheat burning season, *Atmos. Chem. Phys.*, 13, 8285-8302, doi:10.5194/acp-13-8285-2013, 2013.
- Kreidenweis, S. M., Koehler, K., DeMott, P. J., Prenni, A. J., Carrico, C., and Ervens, B.: Water activity and activation diameters from hygroscopicity data - Part I: Theory and application to inorganic salts, *Atmos. Chem. Phys.*, 5, 1357-1370, doi:10.5194/acp-5-1357-2005, 2005.
- Kreidenweis, S. M., Petters, M. D., and DeMott, P. J.: Single-parameter estimates of aerosol water content, *Environ. Res. Lett.*, 3, doi:10.1088/1748-9326/3/3/035002, 2008.
- Krueger, B. J., Grassian, V. H., Iedema, M. J., Cowin, J. P., and Laskin, A.: Probing heterogeneous chemistry of individual atmospheric particles using scanning electron microscopy and energy-dispersive X-ray analysis, *Anal. Chem.*, 75, 5170-5179, doi:10.1021/ac034455t, 2003.
- Kundu, S., Kawamura, K., Andreae, T. W., Hoffer, A., and Andreae, M. O.: Molecular distributions of dicarboxylic acids, ketocarboxylic acids and alpha-dicarbonyls in biomass burning aerosols: implications for photochemical production and degradation in smoke layers, *Atmos. Chem. Phys.*, 10, 2209-2225, doi:10.5194/acp-10-2209-2010, 2010.
- Laskina, O., Morris, H. S., Grandquist, J. R., Qiu, Z., Stone, E. A., Tivanski, A. V., and Grassian, V. H.: Size matters in the water uptake and hygroscopic growth of atmospherically relevant multicomponent aerosol particles, *J. Phys. Chem. A*, 119, 4489-4497, doi:10.1021/jp510268p, 2015.
- Lei, T., Zuend, A., Wang, W. G., Zhang, Y. H., and Ge, M. F.: Hygroscopicity of organic compounds from biomass burning and their influence on the water uptake of mixed organic ammonium sulfate aerosols, *Atmos. Chem. Phys.*, 14, 11165-11183, doi:10.5194/acp-14-11165-2014, 2014.

- Lightstone, J. M., Onasch, T. B., Imre, D., and Oatis, S.: Deliquescence, efflorescence, and water activity in ammonium nitrate and mixed ammonium nitrate/succinic acid microparticles, *J. Phys. Chem. A*, 104, 9337-9346, doi:10.1021/jp002137h, 2000.
- Ling, T. Y., and Chan, C. K.: Partial crystallization and deliquescence of particles containing ammonium sulfate and dicarboxylic acids, *J. Geophys. Res.- Atmos.*, 113, D14205, doi:10.1029/2008jd009779, 2008.
- Low, R. D.: A generalized equation for the solution effect in droplet growth, *J. Atmos. Sci.*, 26, 608-611, 1969.
- Ma, Q., Ma, J., Liu, C., Lai, C., and He, H.: Laboratory study on the hygroscopic behavior of external and internal C-2-C-4 dicarboxylic acid-NaCl mixtures, *Environ. Sci. Technol.*, 47, 10381-10388, doi:10.1021/es4023267, 2013.
- Malm, W. C., and Kreidenweis, S. M.: The effects of models of aerosol hygroscopicity on the apportionment of extinction, *Atmos. Environ.*, 31, 1965-1976, doi:10.1016/s1352-2310(96)00355-x, 1997.
- Marculli, C., Luo, B. P., and Peter, T.: Mixing of the organic aerosol fractions: Liquids as the thermodynamically stable phases, *J. Phys. Chem. A*, 108, 2216-2224, doi:10.1021/jp036080l, 2004.
- Martin, S. T.: Phase transitions of aqueous atmospheric particles, *Chem. Rev.*, 100, 3403-3453, doi:10.1021/cr990034t, 2000.
- Mayol-Bracero, O. L.: Water-soluble organic compounds in biomass burning aerosols over Amazonia 2. Apportionment of the chemical composition and importance of the polyacidic fraction, *J. Geophys. Res.*, 107, D20, 8091, doi:10.1029/2001jd000522, 2002.
- Mikhailov, E., Vlasenko, S., Martin, S. T., Koop, T., and Poeschl, U.: Amorphous and crystalline aerosol particles interacting with water vapor: conceptual framework and experimental evidence for restructuring, phase transitions and kinetic limitations, *Atmos. Chem. Phys.*, 9, 9491-9522, doi:10.5194/acp-9-9491-2009, 2009.
- Minambres, L., Sanchez, M. N., Castano, F., and Basterretxea, F. J.: Hygroscopic properties of internally mixed particles of ammonium sulfate and succinic acid studied by infrared spectroscopy, *J. Phys. Chem. A*, 114, 6124-6130, doi:10.1021/jp101149k, 2010.
- Minambres, L., Mendez, E., Sanchez, M. N., Castano, F., and Basterretxea, F. J.: Water uptake

- of internally mixed ammonium sulfate and dicarboxylic acid particles probed by infrared spectroscopy, *Atmos. Environ.*, 70, 108-116, doi:10.1016/j.atmosenv.2013.01.007, 2013.
- Mircea, M., Facchini, M. C., Decesari, S., Cavalli, F., Emblico, L., Fuzzi, S., Vestin, A., Rissler, J., Swietlicki, E., Frank, G., Andreae, M. O., Maenhaut, W., Rudich, Y., and Artaxo, P.: Importance of the organic aerosol fraction for modeling aerosol hygroscopic growth and activation: a case study in the Amazon Basin, *Atmos. Chem. Phys.*, 5, 3111-3126, doi:10.5194/acp-5-3111-2005, 2005.
- Mochida, M., Kawabata, A., Kawamura, K., Hatsushika, H., and Yamazaki, K.: Seasonal variation and origins of dicarboxylic acids in the marine atmosphere over the western North Pacific, *J. Geophys. Res.- Atmos.*, 108, 4193, doi:10.1029/2002jd002355, 2003.
- Mochida, M., and Kawamura, K.: Hygroscopic properties of levoglucosan and related organic compounds characteristic to biomass burning aerosol particles, *J. Geophys. Res.- Atmos.*, 109, D21202, doi:10.1029/2004jd004962, 2004.
- Moore, R. H., and Raymond, T. M.: HTDMA analysis of multicomponent dicarboxylic acid aerosols with comparison to UNIFAC and ZSR, *J. Geophys. Res.- Atmos.*, 113, D04206, doi:10.1029/2007jd008660, 2008.
- Pandis, S. N., Wexler, A. S., and Seinfeld, J. H.: Dynamics of tropospheric aerosols, *J. Phys. Chem.*, 99, 9646-9659, doi:10.1021/j100024a003, 1995.
- Parsons, M. T., Knopf, D. A., and Bertram, A. K.: Deliquescence and crystallization of ammonium sulfate particles internally mixed with water-soluble organic compounds, *J. Phys. Chem. A*, 108, 11600-11608, doi:10.1021/jp0462862, 2004a.
- Parsons, M. T., Mak, J., Lipetz, S. R., and Bertram, A. K.: Deliquescence of malonic, succinic, glutaric, and adipic acid particles, *J. Geophys. Res.- Atmos.*, 109, D06212, doi:10.1029/2003jd004075, 2004b.
- Peckhaus, A., Grass, S., Treuel, L., and Zellner, R.: Deliquescence and efflorescence behavior of ternary inorganic/organic/water aerosol particles, *J. Phys. Chem. A*, 116, 6199-6210, doi:10.1021/jp211522t, 2012.
- Peng, C., Chan, M. N., and Chan, C. K.: The hygroscopic properties of dicarboxylic and multifunctional acids: Measurements and UNIFAC predictions, *Environ. Sci. Technol.*, 35, 4495-4501, doi:10.1021/es0107531, 2001.

- Petters, M. D., and Kreidenweis, S. M.: A single parameter representation of hygroscopic growth and cloud condensation nucleus activity, *Atmos. Chem. Phys.*, 7, 1961-1971, doi:10.5194/acp-7-1961-2007, 2007.
- Petters, M. D., Carrico, C. M., Kreidenweis, S. M., Prenni, A. J., DeMott, P. J., Collett, J. L., Jr., and Moosmueller, H.: Cloud condensation nucleation activity of biomass burning aerosol, *J. Geophys. Res.- Atmos.*, 114, D22205, doi:10.1029/2009jd012353, 2009.
- Pope, F. D., Dennis-Smith, B. J., Griffiths, P. T., Clegg, S. L., and Cox, R. A.: Studies of single aerosol particles containing malonic acid, glutaric acid, and their mixtures with sodium chloride. I. Hygroscopic growth, *J. Phys. Chem. A*, 114, 5335-5341, doi:10.1021/jp100059k, 2010.
- Poschl, U.: Atmospheric aerosols: Composition, transformation, climate and health effects, *Angew. Chem. Int. Ed.*, 44, 7520-7540, doi:10.1002/anie.200501122, 2005.
- Prenni, A. J., DeMott, P. J., Kreidenweis, S. M., Sherman, D. E., Russell, L. M., and Ming, Y.: The effects of low molecular weight dicarboxylic acids on cloud formation, *J. Phys. Chem. A*, 105, 11240-11248, doi:10.1021/jp012427d, 2001.
- Prenni, A. J., De Mott, P. J., and Kreidenweis, S. M.: Water uptake of internally mixed particles containing ammonium sulfate and dicarboxylic acids, *Atmos. Environ.*, 37, 4243-4251, doi:10.1016/s1352-2310(03)00559-4, 2003.
- Pruppacher, H. R. and Klett, J. D.: *Microphysics of Clouds and Precipitation*, 2nd Ed., Springer Publications, New York, USA, 1997.
- Ramanathan, V., Crutzen, P. J., Kiehl, J. T., and Rosenfeld, D.: Atmosphere - aerosols, climate, and the hydrological cycle, *Science*, 294, 2119-2124, doi:10.1126/science.1064034, 2001.
- Rickards, A. M., Miles, R. E., Davies, J. F., Marshall, F. H., and Reid, J. P.: Measurements of the sensitivity of aerosol hygroscopicity and the kappa parameter to the O/C ratio, *J. Phys. Chem. A*, 117, 14120-14131, doi:10.1021/jp407991n, 2013.
- Saxena, P., Hildemann, L. M., McMurry, P. H., and Seinfeld, J. H.: Organics alter hygroscopic behavior of atmospheric particles, *J. Geophys. Res.- Atmos.*, 100, 18755-18770, doi:10.1029/95jd01835, 1995.
- Saxena, P., and Hildemann, L. M.: Water-soluble organics in atmospheric particles: A critical review of the literature and application of thermodynamics to identify candidate

- compounds, *J. Atmos. Chem.*, 24, 57-109, doi:10.1007/bf00053823, 1996.
- Schneidemesser, E. v., Monks, P. S., Allan, J. D., Bruhwiler, L., Forster, P., Fowler, D., Lauer, A., Morgan, W. T., Paasonen, P., Righi, M., Sindelarova, K., and Sutton, M. A.: Chemistry and the linkages between air quality and climate change, *Chem. Rev.*, 115, 3856-3897, doi:10.1021/acs.chemrev.5b00089, 2015.
- Shi, Y., Ge, M., and Wang, W.: Hygroscopicity of internally mixed aerosol particles containing benzoic acid and inorganic salts, *Atmos. Environ.*, 60, 9-17, doi:10.1016/j.atmosenv.2012.06.034, 2012.
- Simoneit, B. R. T., Schauer, J. J., Nolte, C. G., Oros, D. R., Elias, V. O., Fraser, M. P., Rogge, W. F., and Cass, G. R.: Levoglucosan, a tracer for cellulose in biomass burning and atmospheric particles, *Atmos. Environ.*, 33, 173-182, doi:10.1016/s1352-2310(98)00145-9, 1999.
- Stokes, R. H., and Robinson, R. A.: Interactions in aqueous nonelectrolyte solutions .I. Solute-solvent equilibria, *J. Phys. Chem.*, 70, 2126-2131, doi:10.1021/j100879a010, 1966.
- Stolzenburg, M. R., and McMurry, P. H.: Equations governing single and tandem DMA configurations and a new lognormal approximation to the transfer function, *Aerosol Sci. Technol.*, 42, 421-432, doi:10.1080/02786820802157823, 2008.
- Suda, S. R., Petters, M. D., Yeh, G. K., Strollo, C., Matsunaga, A., Faulhaber, A., Ziemann, P. J., Prenni, A. J., Carrico, C. M., Sullivan, R. C., and Kreidenweis, S. M.: Influence of functional groups on organic aerosol cloud condensation nucleus activity, *Environ. Sci. Technol.*, 48, 10182-10190, doi:10.1021/es502147y, 2014.
- Svenningsson, B., Rissler, J., Swietlicki, E., Mircea, M., Bilde, M., Facchini, M. C., Decesari, S., Fuzzi, S., Zhou, J., Monster, J., and Rosenorn, T.: Hygroscopic growth and critical supersaturations for mixed aerosol particles of inorganic and organic compounds of atmospheric relevance, *Atmos. Chem. Phys.*, 6, 1937-1952, doi:10.5194/acp-6-1937-2006, 2006.
- Wexler, A. S., and Clegg, S. L.: Atmospheric aerosol models for systems including the ions  $H^+$ ,  $NH_4^+$ ,  $Na^+$ ,  $SO_4^{2-}$ ,  $NO_3^-$ ,  $Cl^-$ ,  $Br^-$ , and  $H_2O$ , *J. Geophys. Res.- Atmos.*, 107, 4207, doi:10.1029/2001jd000451, 2002.
- Wise, M. E., Surratt, J. D., Curtis, D. B., Shilling, J. E., and Tolbert, M. A.: Hygroscopic

- growth of ammonium sulfate/dicarboxylic acids, *J. Geophys. Res.- Atmos.*, 108, 4638, doi:10.1029/2003jd003775, 2003.
- Wittig, R., Lohmann, J., and Gmehling, J.: Vapor-liquid equilibria by UNIFAC group contribution. 6. Revision and extension, *Ind. Eng. Chem. Res.*, 42, 183-188, doi:10.1021/ie020506l, 2003.
- Xu, W., Guo, S., Gomez-Hernandez, M., Zamora, M. L., Secret, J., Marrero-Ortiz, W., Zhang, A. L., Collins, D. R., and Zhang, R.: Cloud forming potential of oligomers relevant to secondary organic aerosols, *Geophys. Res. Lett.*, 41, 6538-6545, doi:10.1002/2014-gl061040, 2014.
- Wang, Y., Ma, J. B., Zhou, Q., Pang, S. F., and Zhang, Y. H.: Hygroscopicity of mixed glycerol/Mg(NO<sub>3</sub>)<sub>2</sub>/water droplets affected by the interaction between magnesium ions and glycerol molecules, *J. Phys. Chem. B*, 119 (17), 5558–5566, 2015.
- Yeung, M. C., and Chan, C. K.: Water content and phase transitions in particles of inorganic and organic species and their mixtures using micro-Raman spectroscopy, *Aerosol Sci. Technol.*, 44, 269-280, doi:10.1080/02786820903583786, 2010.
- Zamora, I. R., Tabazadeh, A., Golden, D. M., and Jacobson, M. Z.: Hygroscopic growth of common organic aerosol solutes, including humic substances, as derived from water activity measurements, *J. Geophys. Res.- Atmos.*, 116, D23207, doi:10.1029/2011jd016067, 2011.
- Zamora, I. R., and Jacobson, M. Z.: Measuring and modeling the hygroscopic growth of two humic substances in mixed aerosol particles of atmospheric relevance, *Atmos. Chem. Phys.*, 13, 8973-8989, doi:10.5194/acp-13-8973-2013, 2013.
- Zardini, A. A., Sjogren, S., Marcolli, C., Krieger, U. K., Gysel, M., Weingartner, E., Baltensperger, U., and Peter, T.: A combined particle trap/HTDMA hygroscopicity study of mixed inorganic/organic aerosol particles, *Atmos. Chem. Phys.*, 8, 5589-5601, doi:10.5194/acp-8-5589-2008, 2008.
- Zhang, Q. N., Zhang, Y., Cai, C., Guo, Y. C., Reid, J. P., and Zhang, Y. H.: In situ observation on the dynamic process of evaporation and crystallization of sodium nitrate droplets on a ZnSe substrate by FTIR-ATR, *J. Phys. Chem. A*, 118, 2728-2737, doi:10.1021/jp412073c, 2014.



Zhang, Q., Jimenez, J. L., Canagaratna, M. R., Allan, J. D., Coe, H., Ulbrich, I., Alfarra, M. R., Takami, A., Middlebrook, A. M., Sun, Y. L., Dzepina, K., Dunlea, E., Docherty, K., DeCarlo, P. F., Salcedo, D., Onasch, T., Jayne, J. T., Miyoshi, T., Shimojo, A., Hatakeyama, S., Takegawa, N., Kondo, Y., Schneider, J., Drewnick, F., Borrmann, S., Weimer, S., Demerjian, K., Williams, P., Bower, K., Bahreini, R., Cottrell, L., Griffin, R. J., Rautiainen, J., Sun, J. Y., Zhang, Y. M., and Worsnop, D. R.: Ubiquity and dominance of oxygenated species in organic aerosols in anthropogenically-influenced Northern Hemisphere midlatitudes, *Geophys. Res. Lett.*, 34, L13801, doi:10.1029/2007gl029979, 2007.

Table 1. Chemical properties of investigated organic species.

Substance	Chemical Formula	MW(g mol <sup>-1</sup> )	$\rho$ (g cm <sup>-3</sup> )	Supplier/Purity
Ammonium sulfate	(NH <sub>4</sub> ) <sub>2</sub> SO <sub>4</sub>	132.1	1.77	Alfa Aesar, 99.95%
Levoglucozan	C <sub>6</sub> H <sub>10</sub> O <sub>5</sub>	162.1	1.62	Aldrich, 99%
Oxalic acid	C <sub>2</sub> H <sub>2</sub> O <sub>4</sub>	90	1.9	Aldrich, 99.999%
Oxalic acid (dihydrate)	C <sub>2</sub> H <sub>2</sub> O <sub>4</sub> · 2H <sub>2</sub> O	126	1.65	-
Malonic acid	C <sub>3</sub> H <sub>4</sub> O <sub>4</sub>	104.1	1.62	Sigma-Aldrich, 99%
Succinic acid	C <sub>4</sub> H <sub>6</sub> O <sub>4</sub>	118.1	1.57	Sigma-Aldrich, ≥99.5%
Phthalic acid	C <sub>8</sub> H <sub>6</sub> O <sub>4</sub>	166.1	1.59	Sigma-Aldrich, ≥99.5%

Table 2. Chemical composition and O/C ratio of mixtures used in experiments.

Mixture	Mass ratio	O/C ratio
Levoglucozan (Lev) + oxalic acid (OA)	1:1	1.27
Levoglucozan (Lev) + oxalic acid (OA)	1:3	1.58
Levoglucozan (Lev) + oxalic acid (OA)	3:1	1.03
Levoglucozan (Lev) + phthalic acid (PA)	1:1	0.64
Oxalic acid (OA) + malonic acid (MA)	1:1	1.62
Oxalic acid (OA) + succinic acid (SA)	1:1	1.40
Oxalic acid (OA) + phthalic acid (PA)	1:1	0.97
Levoglucozan (Lev) + oxalic acid (OA) + phthalic acid (PA)	1:1:1	0.93

Table 3. The three-parameter fit values for the the hygroscopic growth of the investigated organic aerosol particles with the Eq. (2).

Substance	a	b	c	R <sup>2</sup>
Levoglucozan	0.4315	-0.4929	0.2789	0.9997
Malonic acid	0.2512	0.2493	-0.1236	0.9959
Phthalic acid	0.4368	-0.6003	0.2737	0.9910

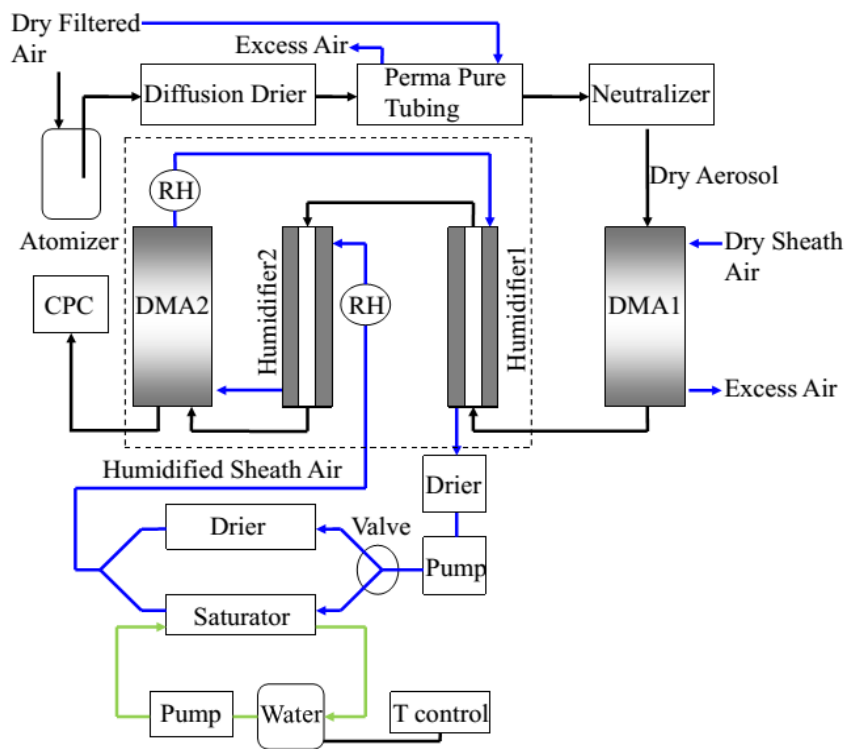


Figure 1. Schematic setup of the hygroscopicity tandem differential mobility analyzer (HTDMA) system.

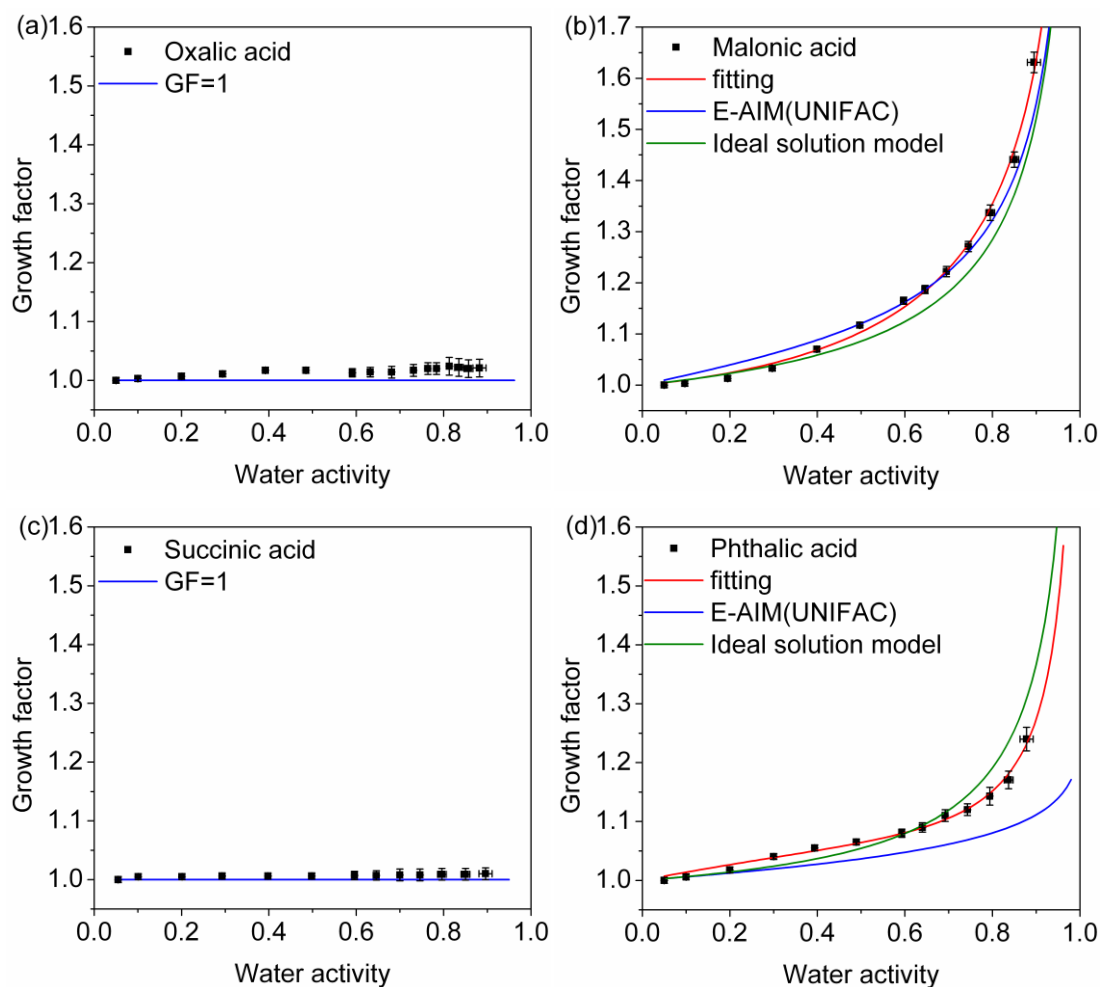


Figure 2. Hygroscopic growth factors of (a) oxalic acid, (b) malonic acid, (c) succinic acid and (d) phthalic acid particles as a function of water activity. **Initial** particle diameter is about 100 nm. For malonic acid and phthalic acid, the fit to the measurements with Eq. (2) is shown. Predictions from the E-AIM (UNIFAC) and ideal solution model are also included. The uncertainty in our measured growth factors is within 0.02.

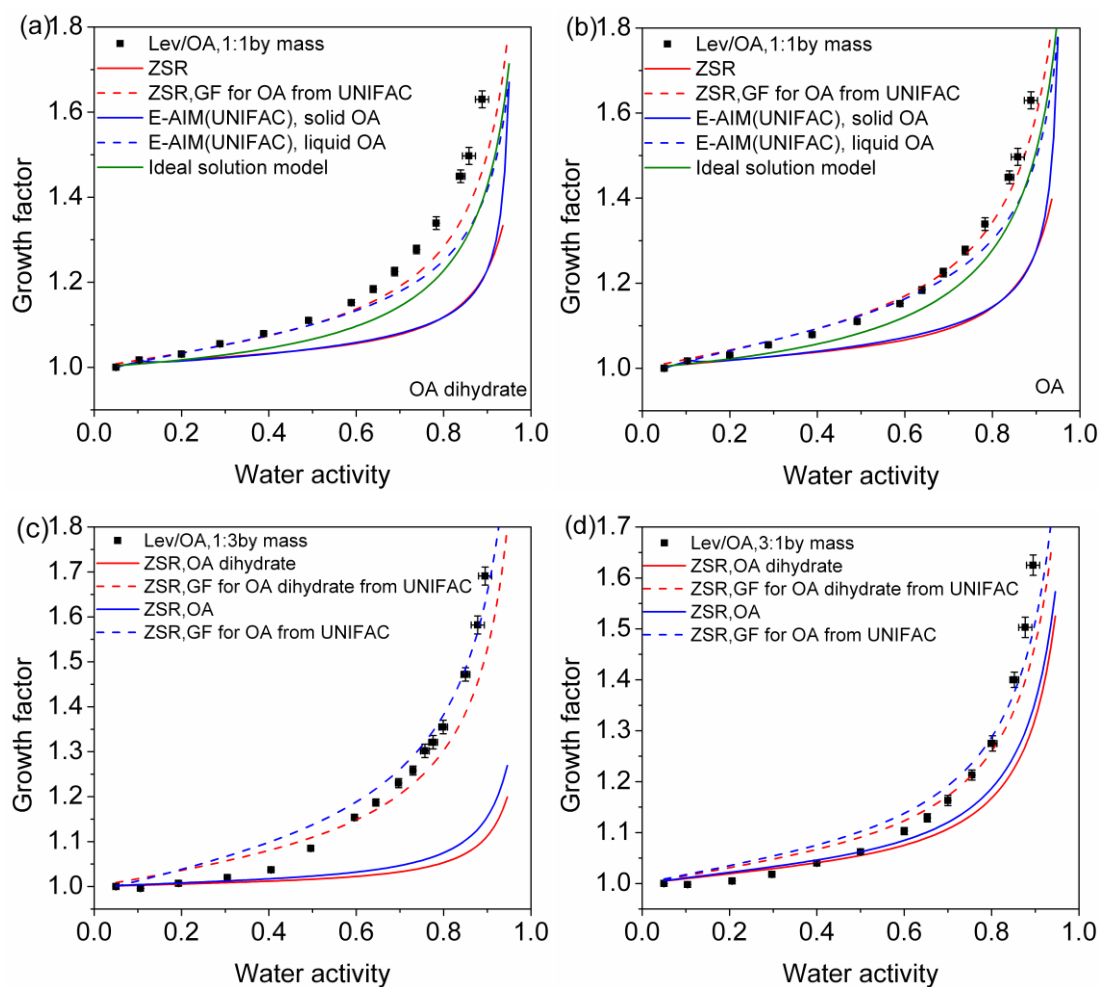


Figure 3. Hygroscopic growth factors of aerosols containing levoglucosan and oxalic acid (Lev/OA) with various mass ratio (a) and (b) 1:1, (c) 1:3, (d) 3:1 as a function of water activity. Initial particle diameter is about 100 nm. Predictions from the ZSR, E-AIM (UNIFAC) and ideal solution model are included in (a) and (b), assuming oxalic acid dihydrate and anhydrous oxalic acid in the initial dry particles, respectively. The dashed lines are calculated based on liquid oxalic acid (OA) assumption. For (c) 1:3, (d) 3:1 mass ratio, only ZSR-predicted curves are shown on the basis of different OA assumption. The uncertainty in our measured growth factors is within 0.02.

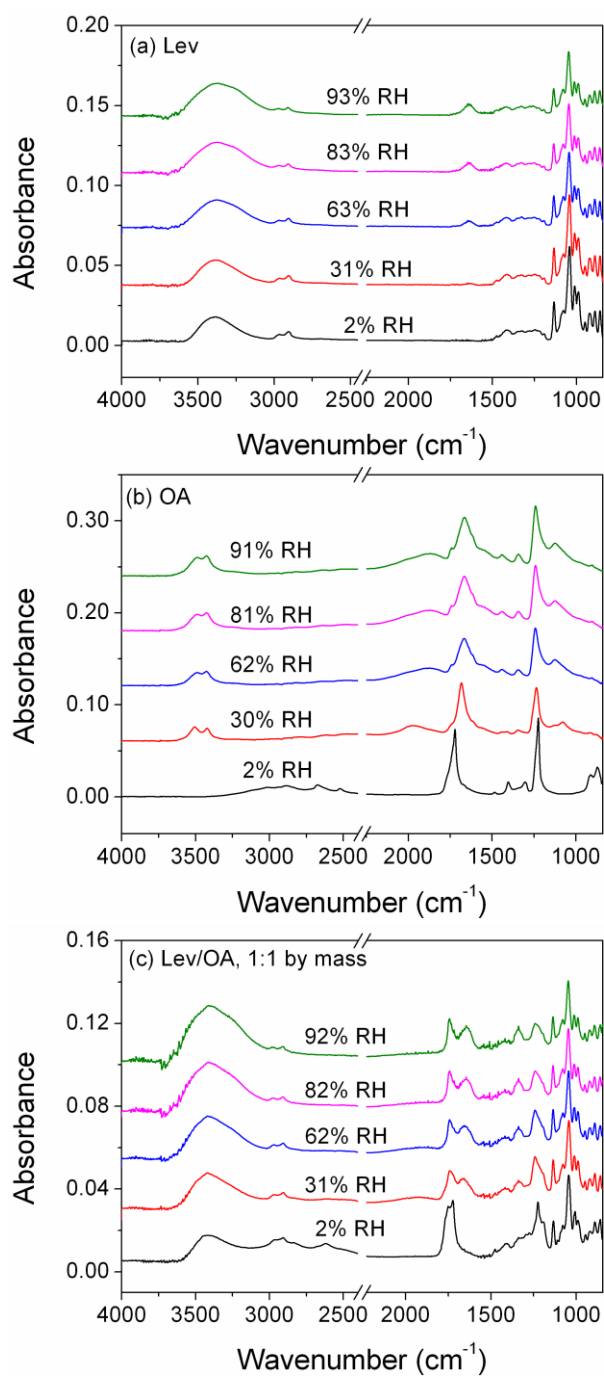


Figure 4. ATR-FTIR absorbance spectra of aerosol particles upon hydration with RH for (a) levoglucosan, (b) oxalic acid and (c) levoglucosan/oxalic acid mixture (1:1, by mass). Features from gas-phase water have been subtracted. Gas-phase CO<sub>2</sub> absorptions have been removed and the spectra have been offset for clarity.



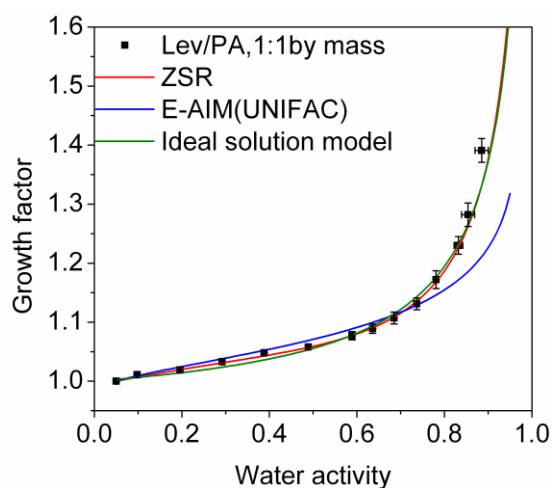


Figure 5. Hygroscopic growth factors of aerosols consisting of levoglucosan and phthalic acid (Lev/PA) at a mass ratio of 1:1 as a function of water activity. Initial particle diameter is about 100 nm. Predictions based on the ZSR, E-AIM (UNIFAC) and ideal solution model are also included. The uncertainty in our measured growth factors is within 0.02.

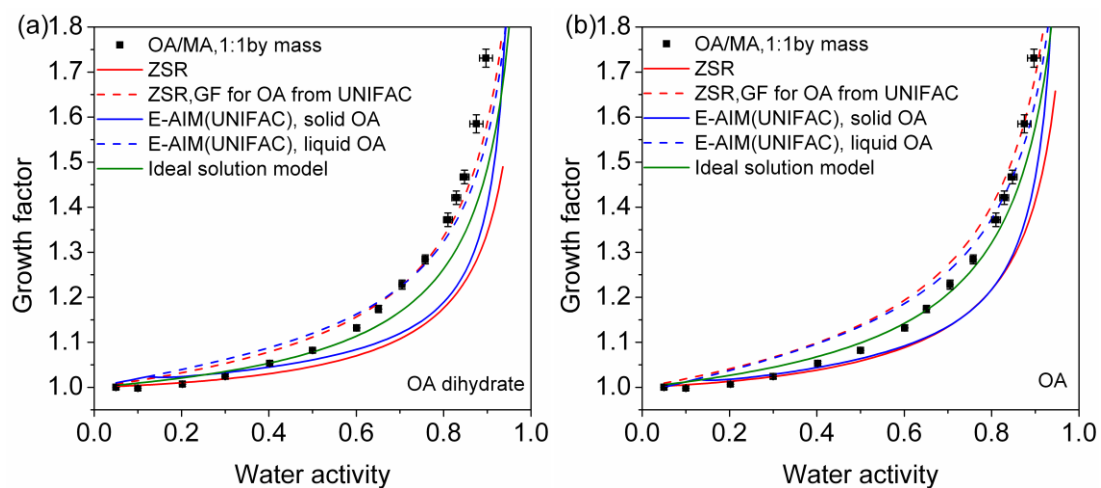


Figure 6. Hygroscopic growth factors of aerosols containing oxalic acid and malonic acid (OA/MA) at a mass ratio of 1:1 as a function of water activity. Initial particle diameter is about 100 nm. Predictions from the ZSR, E-AIM (UNIFAC) and ideal solution model are also included, assuming (a) oxalic acid dihydrate, (b) anhydrous oxalic acid in the initial dry particles. The dashed lines are calculated based on liquid oxalic acid (OA) assumption. The uncertainty in our measured growth factors is within 0.02.

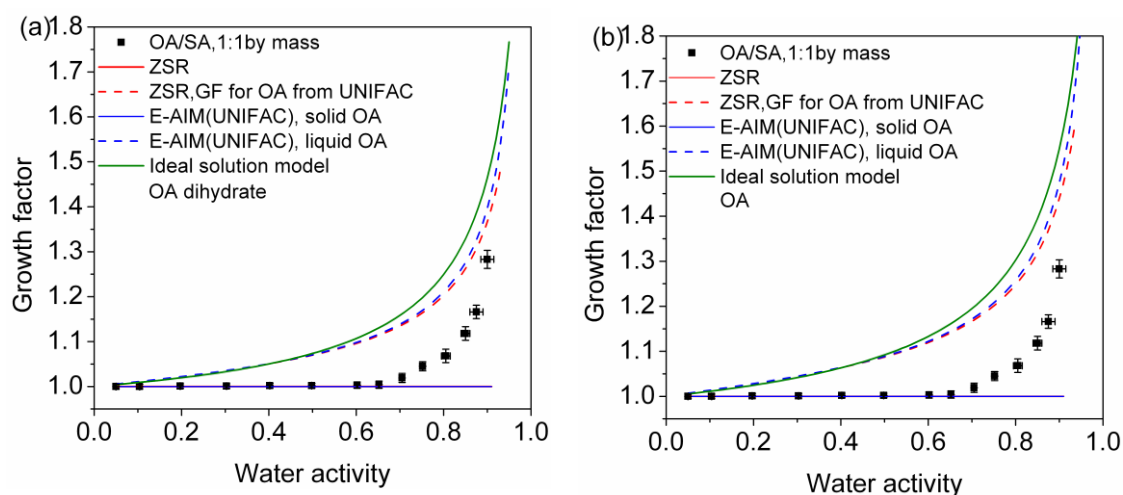


Figure 7. Hygroscopic growth factors of aerosols consisting of oxalic acid and succinic acid (OA/SA) at a mass ratio of 1:1 as a function of water activity. Initial particle diameter is about 100 nm. Predictions from the ZSR, E-AIM (UNIFAC) and ideal solution model are also included, assuming (a) oxalic acid dihydrate, (b) anhydrous oxalic acid in the initial dry particles. The dashed lines are calculated based on liquid oxalic acid (OA) assumption. The uncertainty in our measured growth factors is within 0.02.

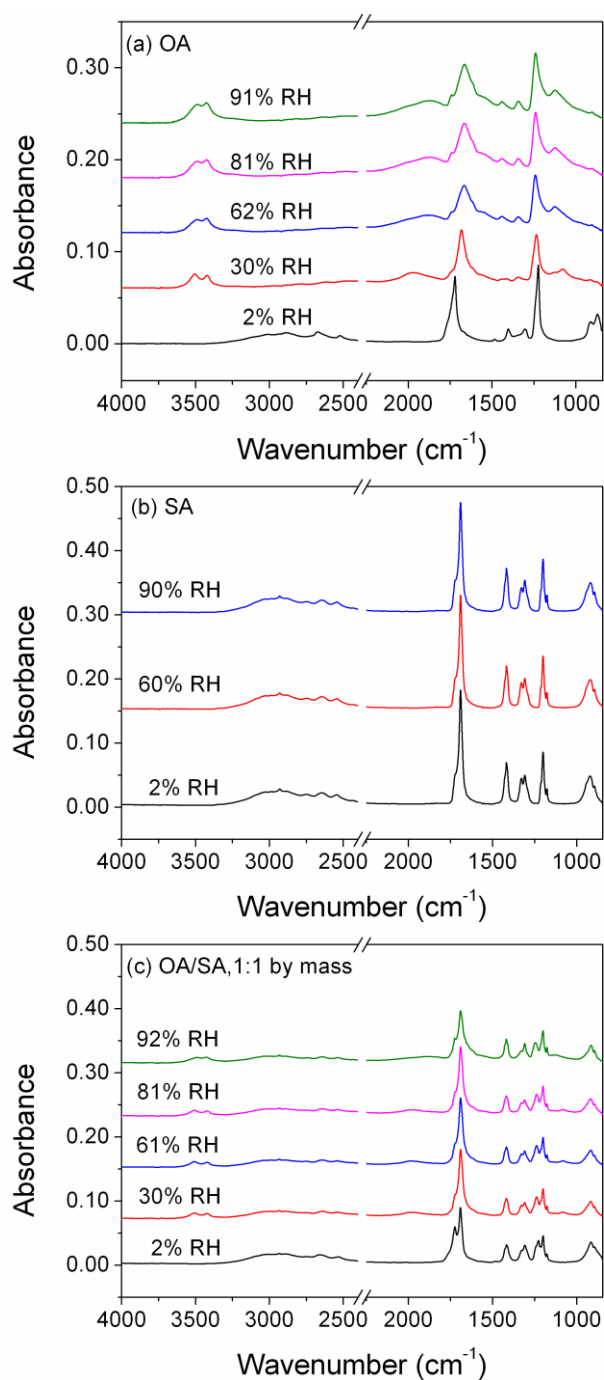


Figure 8. ATR-FTIR absorbance spectra of aerosol particles upon hydration with RH for (a) oxalic acid, (b) succinic acid and (c) oxalic acid/succinic acid mixture (1:1, by mass). Features from gas-phase water have been subtracted. Gas-phase CO<sub>2</sub> absorptions have been removed and the spectra have been offset for clarity.

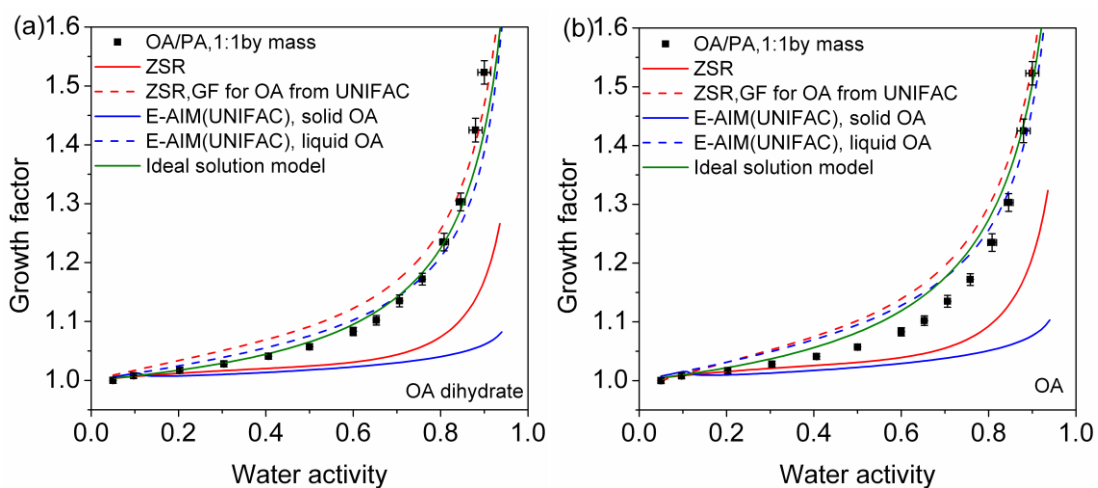


Figure 9. Hygroscopic growth factors of aerosols consisting of oxalic acid and phthalic acid (OA/PA) at a mass ratio of 1:1 as a function of water activity. **Initial** particle diameter is about 100 nm. Predictions from the ZSR, E-AIM (UNIFAC) and ideal solution model are also included, assuming (a) oxalic acid dihydrate, (b) anhydrous oxalic acid in the initial dry particles. The dashed lines are calculated based on liquid oxalic acid (OA) assumption. The uncertainty in our measured growth factors is within 0.02.

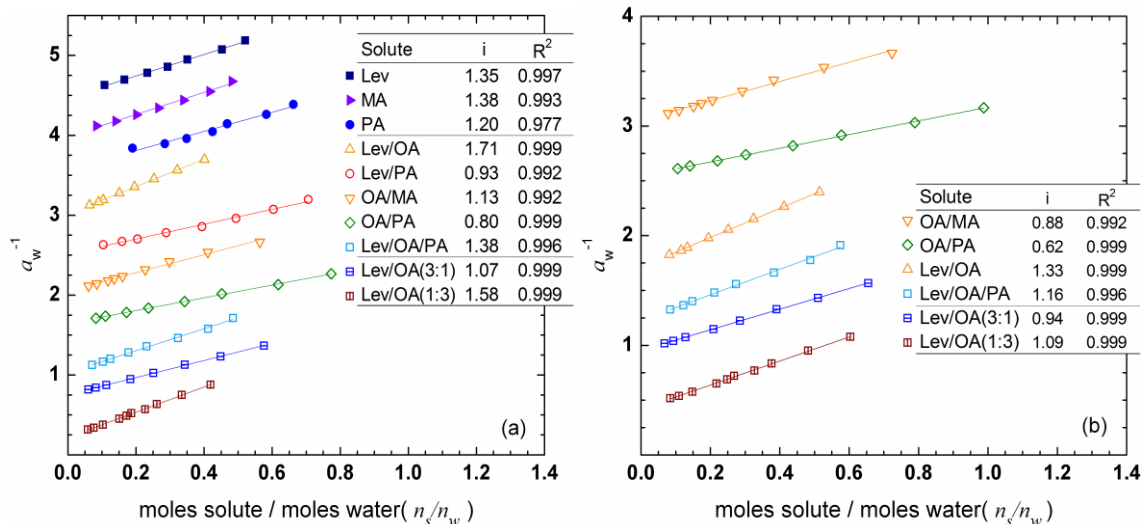


Figure 10. The inverse of the water activity ( $a_w^{-1}$ ) as a function of the ratio of mole number of total solute to mole number of water ( $n_s/n_w$ ) for all organic droplets. The slope of the fit line is equal to the van't Hoff factor ( $i$ ). The R-squared values for the fit are also listed. Each data set was offset by  $a_w^{-1} = 0.3$  from the previous one for clarity. Calculations for aerosols containing oxalic acid are based on assumption of (a) oxalic acid dihydrate and (b) anhydrous oxalic acid. All the mixtures are by equal mass composition except specially noted.

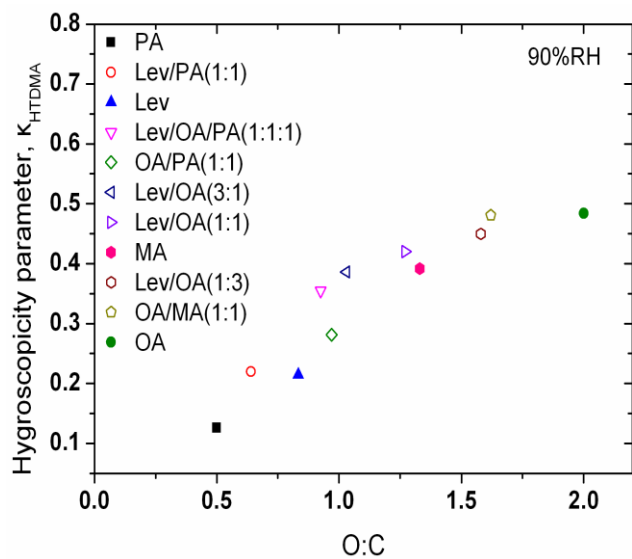


Figure 11. Relationship between O:C and hygroscopicity parameter  $\kappa$  derived from HTDMA measurements at 90% RH for all the organic aerosol particles in this study.

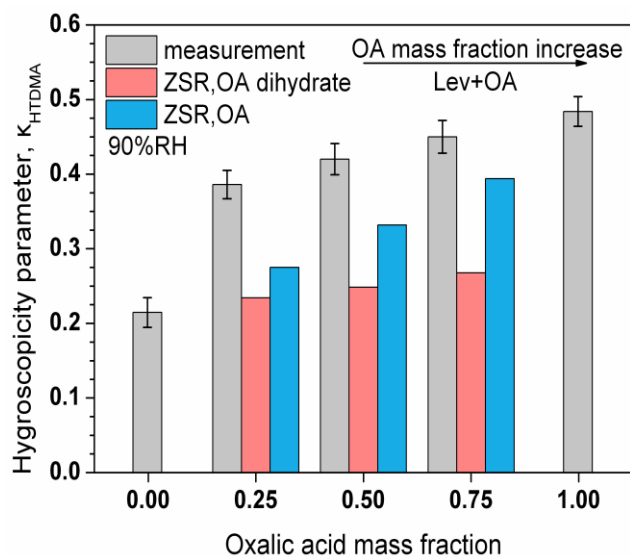


Figure 12. The  $\kappa$  results derived from HTDMA measurements at 90% RH for aerosols containing oxalic acid (OA) and levoglucosan (Lev) in varying mass proportions. ZSR-predicted  $\kappa$  values are also shown by assuming oxalic acid dihydrate or anhydrous oxalic acid in the **initial** mixtures. The  $\kappa$  value of oxalic acid is obtained from the UNIFAC.



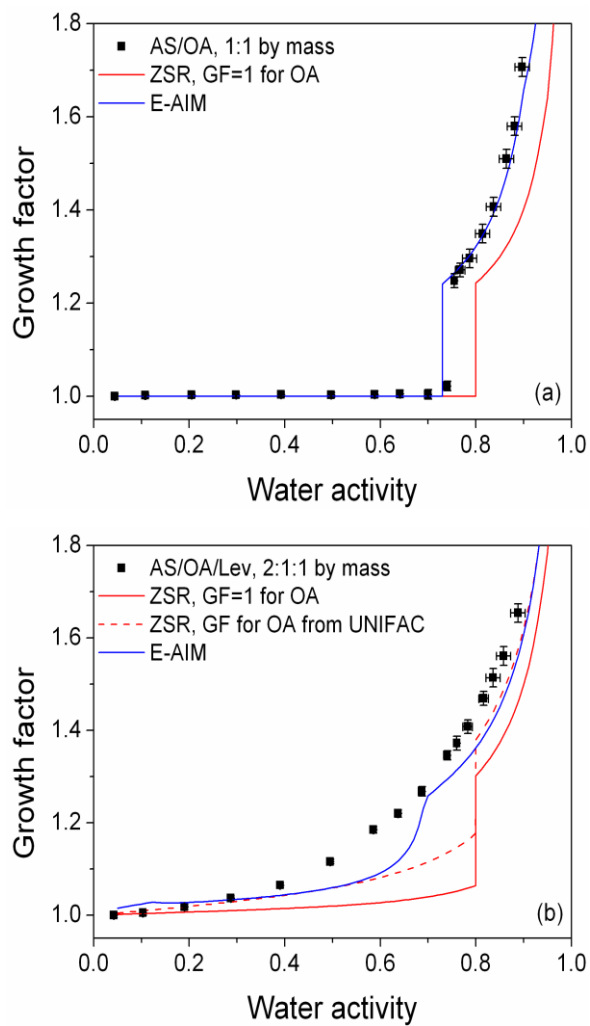


Figure 13. Hygroscopic growth factors of 1:1 AS/OA (a), 2:1:1 AS/OA/Lev (b) as a function of water activity. **Initial** particle diameter is about 100 nm. Predicted growth curves from the ZSR and E-AIM assuming oxalic acid dihydrate are indicated by red and blue lines respectively. The uncertainty in our measured growth factors is within 0.02.