A laboratory investigation of the relative humidity dependence of light extinction by organic compounds from lignin combustion

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Abstract

Light extinction by atmospheric particles is strongly dependent on the size, chemical composition, and water content of the aerosol. Since light extinction by particles directly impacts climate and visibility, measurements of the extinction at various relative humidities (RHs) are needed. In this work, the optical growth factors, $f_{\text{RH,ext}}$ (80\%RH, Dry) have been measured using cavity ring-down aerosol extinction spectroscopy at 532 nm for particles of varying organic/sulfate compositions. Specifically, slightly soluble, multifunctional aromatic compounds resulting from biomass burning have been investigated. In general, the organic compounds studied exhibit much smaller optical growth than inorganic compounds such as ammonium sulfate. Also, a linear relationship between mass fraction organic and optical growth has been observed for most organic compounds studied, in agreement with previous studies of more water-soluble organics. The role of particle density for mixtures that do not follow a linear relationship is also explored.

Keywords: aerosol optical properties, relative humidity, biomass burning

1. Introduction

Atmospheric particulate matter affects Earth’s climate and local visibility through the direct interaction of the particles with incoming solar radiation. Light extinction, the sum of scattering and absorption, is dependent on the particle size, composition, and shape. Ambient relative humidity affects extinction by causing changes in particle size due to hygroscopic growth. Laboratory quantification of the optical growth of particles of varying composition is necessary for inclusion into radiative transfer calculations, and is also useful for comparison with particle growth factors measured using other techniques.
The atmospheric aerosol composition varies spatially and temporally; however, most submicron particles contain a large fraction of organic carbon compounds (Murphy et al. 2006, Saxena and Hildemann 1996). The atmospheric organic aerosol mass is made up from a combination of primary sources and secondary conversion processes. Biomass burning, both anthropogenic along with natural, constitutes a large fraction of primary atmospheric organic matter (Yamasoe et al. 2000, Andreae and Merlet 2001). The chemical composition of aerosol mass resulting from biomass burning is quite complicated and depends on the combustion fuel and burning conditions (Reid et al. 2005). Water-soluble organic carbon compounds from biomass burning have been studied and include chemical classes ranging from anhydrosugars (e.g., levoglucosan) to aromatic compounds (Graham et al. 2002, Nolte et al. 2001).

Previous work has investigated the optical growth factors of relatively water-soluble organic compounds such as dicarboxylic acids, sugars, and amino acids, as well as complex internal mixtures of the organics with ammonium sulfate (Baynard et al. 2006, Garland et al. 2007). These studies found a linear relationship between optical growth factors and the organic mass fraction of the particles. The growth thus appears to follow a ZSR relationship (Stokes and Robinson 1966), which assumes that each component of the mixture acts independently, that no interaction between components occurs, and that the optical growth is additive.

In the present work, multifunctional aromatic acids (phthalic acid, pyromellitic acid, and 4-hydroxybenzoic acid) have been investigated. These compounds result from lignin combustion, and have limited water solubility (Graham et al. 2002, Nolte et al. 2001). The present experiments thus test if the linear relationship found between organic mass fraction and optical growth is also appropriate for organics of very low water solubility.

2. Experimental details

The dependence of aerosol extinction, at 532 nm, on relative humidity (RH) has been studied with a tandem cavity ring-down aerosol extinction spectrometer (CRD-AES) and is shown schematically in figure 1 (Baynard et al. 2007, Pettersson et al. 2004, Garland et al. 2007). The system used in the present work was newly constructed at the University of Colorado and is patterned after that used by Garland et al. (2007). The second harmonic of a pulsed Nd:YAG laser was used as the photon source. The extinction, $\sigma_e$ ($\text{cm}^{-1}$), within the cavity is related to the ratio of the cavity optical length to the sample length, $R_L$, the speed of light, $c$, and the ring-down time constants with, $\tau$, and without, $\tau_0$, the sample present, according to equation (1) (Pettersson et al. 2004). Typical $\tau_0$ values were 100 µs in each cell, yielding an effective path length of approximately 30 km.

$$\sigma_e = \frac{R_L}{c} \left( \frac{1}{\tau} - \frac{1}{\tau_0} \right)$$  (1)

Particles are generated via atomization from aqueous solutions (~0.5 wt% organic) and then dried to an RH < 10% with two diffusion driers in series with a combined residence time of approximately 75 s. The dry particles are size selected using a differential mobility analyzer, DMA (TSI 3080), to produce a near monodispersed aerosol. The dry, size selected, particles enter the first cell of the CRD-AES where the reference extinction coefficient due to particles, $\sigma_{e\text{p}}$ (Dry) is measured at 24°C. The particle flow then enters a temperature-controlled humidifier, typically set to 95% RH. The humidifier consists of a water vapor permeable membrane surrounded by liquid water, generally held at 30°C, allowing the aerosol flow to be exposed to 95% RH. The liquid particles then enter the second cell of the tandem CRD-AES where the $\sigma_{e\text{p}}$ (RH), RH (typically 80%), and temperature (typically 27°C) are measured. The temperature and RH are measured with Vaisala Humitter 50Y probes (accuracy ±3%). The two extinction values are then used to calculate $f_{RH}$ defined in equation (2).

$$f_{RH_{\text{ext}}}(80\%\text{RH}, \text{Dry}) = \frac{\sigma_{e\text{p}}(80\%\text{RH})}{\sigma_{e\text{p}}(\text{Dry})}$$  (2)

to describe the relative humidity dependence of light extinction. Finally, the particle concentration is measured with a condensation particle counter, CPC (TSI 3022A). With simultaneous measurements of particle extinction, $\sigma_{e\text{p}}$ ($\text{cm}^{-1}$), and particle concentration, $N$ ($\text{cm}^{-3}$), we can also determine the particle extinction cross-sections $C_{e\text{p}}$ ($\text{cm}^2$) = $\sigma_{e\text{p}} / N$. Errors in reported $f_{RH_{\text{ext}}}$ values are given as the experimental standard deviation of at least fifty 10 s data averages, collected over at least two different experiments.

Three organic compounds of limited water solubility (each containing at least one carboxylic acid substituent on an aromatic carbon ring) were studied: phthalic acid, 4-hydroxybenzoic acid, and pyromellitic acid. Each was
Table 1. Structures, water solubility, measured and calculated growth factors and \(f_{\text{RH}_{\text{ext}}}\) (80%RH, Dry) for the compounds studied. References include (a) (Yalkowsky and He 2003), (b) (Brooks et al. 2004), (c) (Hartz et al. 2006) and (d) (Mochida and Kawamura 2004). 

| Organic compound | Water solubility \((5^\circ \text{C})^a\) | Growth factor \((80\% \text{RH})^b\) | \(f_{\text{RH}_{\text{ext}}}\) \((80\% \text{RH, Dry})^c\) | \(D_{\text{eff}}\) | \(n\) |
|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Phthalic acid | 0.6 wt\% | 1.19 ± 0.04 | 1.27 ± 0.07 | 1.59 ± 0.11 | 1.11 |
| Pyromellitic acid | N/A | N/A | 1.10 ± 0.02 | | |
| 4-Hydroxybenzoic acid | 0.5 wt\% | 0.97 \(d\) | 0.92 ± 0.03 | | |

\(a\) Yalkowsky and He (2003).
\(b\) Brooks et al (2004).
\(c\) Hartz et al (2006).
\(d\) Mochida and Kawamura (2004).

obtained in the highest purity available (99% or higher) from Sigma-Aldrich. Due to the low water solubility of these organic compounds, aqueous solutions of 0.5 weight per cent (in HPLC grade water) were used for atomization. These organic compounds are assumed to be non-absorbing at 532 nm, therefore all extinction by the particles is purely scattering. The chemical structures and water solubility information of the organic compounds studied are given in table 1.

Since the extinction was measured as a function of particle size, particles that achieved multiple charges in the bipolar neutralizer of the DMA must be considered when reporting data as a function of particle diameter. Determination of the optical effective diameter, \(D_{\text{eff}}\), was performed empirically using dry ammonium sulfate particles as in Baynard et al (2006) and Garland et al (2007). Briefly, the extinction (cm\(^{-1}\)) and particle concentration (cm\(^{-3}\)) were used to calculate the per particle extinction cross-section (cm\(^2\)). Then, using Mie theory and the literature value for the refractive index of ammonium sulfate, 1.53, the experimental extinction cross-sections were compared with calculated extinction cross-sections (Lide 1994). The particle diameter where the experimental and calculated cross-sections were equal was used as the effective optical diameter. For sizes selected from the DMA of 100–450 nm, the corresponding effective optical diameters were 150–501 nm. The effective optical diameters were determined for ammonium sulfate and applied to the other compounds and mixtures studied. This method of accounting for the contribution of multiply charged particles to extinction assumes spherical particles and similar behaviors of ammonium sulfate and organic compounds in the DMA.

The densities of the individual, solid, organic compounds (phthalic acid, pyromellitic acid, 4-hydroxybenzoic acid), ammonium sulfate, and some mixtures were also measured in this work. The densities of these compounds were measured as received from the manufacturer (before processing) and after being dissolved in water, and the water evaporated, to simulate the aerosol density after the atomization and drying process (after processing). A pycnometer was used to measure the densities of the solid materials through a liquid displacement method. Measurements were made using both acetone and water as the liquid displaced. To minimize the error in the measurement, relatively large sample masses (>0.5 g) were used in a 25 mL displacement volume. The mass of the solid sample, the difference in mass of the liquid with and without sample present, and the density of the liquid were used to calculate the density of the solid material. Results from the measurements along with comparisons to literature values are given in table 2.

Table 2. Comparison of density results before and after processing with the literature values at 25 °C (Lide 1994). All units are g cm\(^{-3}\), and measurements were performed at 22 °C.

| Organic compound | No processing | Literature value\(^a\) | With processing |
|------------------|---------------|----------------------|-----------------|
| Ammonium sulfate | 1.75          | 1.77                 | 1.79            |
| Phthalic acid    | 1.57          | 1.59                 | 1.45            |
| Pyromellitic acid| 1.65          | N/A                  | 1.51            |
| 4-Hydroxybenzoic acid | 1.44 | 1.46                 | 1.22            |

\(^a\) Lide (1994) at 25 °C.

3. Results and discussion

In order to validate the new experimental system, optical growth factors, \(f_{\text{RH}_{\text{ext}}}\) (80%RH, Dry), were measured for ammonium sulfate, and compared with other studies. These comparisons over the size range of 200–540 nm are shown in figure 2. Error bars on the measurement account for the effect on extinction of the uncertainty in the relative humidity probes. It can be seen that the present results agree well with those of Garland et al (2007), obtained using a similar technique. Another useful comparison for these measurements is to compare them to hygroscopic growth factor, \(G_f\), measurements. Generally, hygroscopic growth factors are measurements of a diameter change upon humidification \((G_f = D_{\text{wet}} / D_{\text{dry}})\). The Tang (1996) \(G_f\) measurement, of 1.48, at 80%RH was converted to \(f_{\text{RH}_{\text{ext}}}\) (80%RH, Dry) using Mie theory. Literature values for the refractive indices of ammonium sulfate (1.53) and water (1.333) were used to determine a volume weighted average refractive index for the humidified particle \((n = 1.39)\). The Mie calculation assumed a size distribution standard deviation of ±10 nm. To investigate another refractive index mixing rule, the refractive index for the humidified ammonium sulfate particles was also calculated according to a partial molar refraction average (Stelson 1990, Riziq et al 2007). Using
this method, the humidified particle refractive index was also calculated to be 1.39. Assumptions involved in the conversion of the Gf measurement to $f_{RH_{ext}}$ (80%RH, Dry) include spherical particles as well as no dependence of the growth factor on particle size. Overall, the $f_{RH_{ext}}$ (80%RH, Dry) measurements from both optical studies agree reasonably well with Gf measurements for ammonium sulfate.

The optical growth, $f_{RH_{ext}}$ (80%RH, Dry) was investigated for the three pure organic compounds over the size range from 150 to 501 nm. The results from these studies are shown in figure 3. For each of the organic compounds studied, no abrupt phase transition was observed. Overall, each organic studied in this work exhibits far less optical growth than ammonium sulfate. For example, $f_{RH_{ext}}$ (80%RH, Dry) values for phthalic acid and pyromellitic acid are 1.3 and 1.1, respectively, for 335 nm particles compared with 3.0 for ammonium sulfate. The organic 4-hydroxybenzoic acid exhibited $f_{RH_{ext}}$ (80%RH, Dry) values slightly below unity at all sizes, with the smallest particle size probed ($D_{eff} = 150$ nm) having the lowest $f_{RH_{ext}}$ (80%RH, Dry) of 0.85. An optical growth factor less than unity means that the light extinction by an ensemble of dry particles was larger than the light extinction by the particles at 80%RH. This could be due to a dry particle shape that is more non-spherical than the humidified particle, a lower dry particle density than humidified density, or a larger refractive index for the dry particle. A similar trend was seen in hygroscopic growth factor measurements for 4-hydroxybenzoic acid conducted by Mochida and Kawamura (2004) using HTDMA. This HTDMA study also concluded that the less than unity growth factor ($Gf \sim 0.97$ at 80%RH) must be due to a rearrangement of the particle structure upon humidification (Gysel et al 2002, Mochida and Kawamura 2004).

To investigate this observation, results from the density measurements made on the bulk compounds were used. As can be seen in table 2, the density of 4-hydroxybenzoic acid powder before being dissolved in water is 1.44 g cm$^{-3}$. After dissolving in water and evaporating the water, the density was measured to be 1.22 g cm$^{-3}$, becoming much less dense. Therefore, the low density of the dry aerosol composed of 4-hydroxybenzoic acid is likely responsible for the observed less than unity $f_{RH_{ext}}$ (80%RH, Dry). The other two organic compounds, phthalic acid and pyromellitic acid, were also
slightly less dense after processing, so it is possible that some of the optical growth of these compounds is masked by smaller differences in density.

After investigation of the pure organic compounds, internal mixtures of the organic compounds with ammonium sulfate were studied. In general, previous studies from our groups have found that an additive water uptake model, such as ZSR, is able to explain the water uptake behavior for complex internal mixtures of relatively water-soluble organics and ammonium sulfate based on mass additivity (Baynard et al. 2006, Garland et al. 2007). Results for the dependence of $f_{\text{RH}_{\text{ext}}}$ (80%RH, Dry) on mass per cent organic fraction for the low solubility aromatic acids are shown in figure 4 for particles with an effective optical diameter of 335 nm. As can be seen from the plot, there is a linear relationship between the mass fraction of organic in the particle and $f_{\text{RH}_{\text{ext}}}$ for internally mixed ammonium sulfate/phthalic acid particles as well as ammonium sulfate/pyromellitic acid. This is consistent with an additive model for water uptake. However, the particles that are internal mixtures of ammonium sulfate and 4-hydroxybenzoic acid deviate from the linear representation; thus the additive water uptake model cannot describe this system. Similar results were seen for all particles sizes (150–501 nm, not shown) investigated for these systems.

The measured $f_{\text{RH}_{\text{ext}}}$ (80%RH, Dry) values for the ammonium sulfate/4-hydroxybenzoic acid mixtures were smaller than predicted from the additive water uptake model, as well as smaller than that predicted assuming ammonium sulfate alone contributes to water uptake. Thus, it appears that 4-hydroxybenzoic acid is hindering water uptake. A similar deviation from additive water uptake was observed by Garland et al. (2007) for the individual amino acids glycine, threonine, and arginine mixed with ammonium sulfate. Additionally, in Garland et al. (2007), the internally mixed ammonium sulfate/arginine aerosol particles exhibited lower $f_{\text{RH}_{\text{ext}}}$ (80%RH, Dry) values than those predicted from ammonium sulfate alone. The authors concluded that a change in density upon humidification was responsible.

To investigate the apparent water uptake suppression, density measurements were performed on mixtures of 4-hydroxybenzoic acid with ammonium sulfate, and the results are shown in figure 5. The densities of the mixtures...
The solid line is the ZSR approximation for the ZSR approximation by a weighting according to mass fraction. The dash–dotted line is mixed with phthalic acid (circles), pyromellitic acid (triangles), and ammonium sulfate, 1. Both methods of prediction fit the data well. However, the density of 4-hydroxybenzoic acid, 1, is lower than that of the other organic compounds with ammonium sulfate. This suggests that a morphology change occurs when the dry particles are exposed to elevated relative humidities.

Humidified extinction measurements referenced to dry extinction measurements would be expected to exhibit the largest optical effect if the dry particle density is responsible for the deviation. To further test this hypothesis, extinction measurements were made at intermediate relative humidities (≈55%RH). More specifically, the extinction by the particles containing 4-hydroxybenzoic acid at 84%RH and 55%RH, after exposure to 95%RH, was measured. Results of the \( f_{\text{RH}_{\text{ext}}}(84\%\text{RH}, 55\%\text{RH}) \) measurements for 4-hydroxybenzoic acid mixed with ammonium sulfate are shown in figure 7. The \( f_{\text{RH}_{\text{ext}}}(84\%\text{RH}, 55\%\text{RH}) \) for pure 4-hydroxybenzoic acid is 0.97 ± 0.04, meaning that no optical growth by the pure compound occurs over these humidities. Also, the deviation from the additive water uptake model disappears for the mixtures of 4-hydroxybenzoic acid with ammonium sulfate. This suggests that a morphology change that occurs when the dry particles are exposed to elevated relative humidities is indeed responsible for the apparent suppression seen in figure 4 for particles containing 4-hydroxybenzoic acid. More specifically, the particles at intermediate relative humidities are more dense than the dry particles, resulting in \( f_{\text{RH}_{\text{ext}}}(84\%\text{RH}, 55\%\text{RH}) \) adhering to a mass additivity ZSR prediction.

While 4-hydroxybenzoic acid did show a suppression of water uptake of ammonium sulfate, when present in a mixture of the three organic compounds with ammonium sulfate, there was no suppression. In this case, the complex mixture also adhered to the additive water uptake parameterization, included in figure 4. Thus, when 4-hydroxybenzoic acid is present in complex mixtures with other organic compounds and ammonium sulfate, no deviation, outside the error of the measurement, from linear water uptake is observed. Therefore, in a more atmospherically relevant particle surrogate, the deviation from the linear parameterization was not observed.

The data for all the organic/ammonium sulfate mixtures from this study (excluding 4-hydroxybenzoic acid) and from Garland et al (2007) (excluding amino acids) are shown for comparison in figure 8 at \( D_{\text{eff}} = 335 \text{ nm} \). The organic compounds shown range in water solubility from 0.5 wt%, this work, and up to 72.3 wt% water soluble, Garland et al (2007) data. The individual fits to the sugar and dicarboxylic acid can be found in Garland et al (2007). It can be seen that data from these studies on the optical growth factors of mixtures containing organic compounds of a wide range of water solubilities (from 0.5 to 72.3 wt%) can be represented with one linear parameterization. The fit is shown in figure 8, and is described by the equation \( f_{\text{RH}_{\text{ext}}}(80\%\text{RH}, \text{Dry}) = 2.96 - 0.0167 \times \text{(weight per cent organic)} \). Although there are subtle differences between the organic compounds studied, using

![Figure 6. Measured \( f_{\text{RH}_{\text{ext}}}(80\%\text{RH}, \text{Dry}) \) for ammonium sulfate mixed with phthalic acid (circles), pyromellitic acid (triangles), and 4-hydroxybenzoic acid (diamonds) for particles with \( D_{\text{eff}} = 335 \text{ nm} \). The solid line is the ZSR approximation for \( f_{\text{RH}_{\text{ext}}}(80\%\text{RH}, \text{Dry}) \) by a weighting according to mass fraction. The dash–dotted line is the ZSR approximation for \( f_{\text{RH}_{\text{ext}}}(80\%\text{RH}, \text{Dry}) \) by a volume fraction weighting, using the density measured in this work. The dotted line in the bottom panel is the ZSR prediction for 0.92 g cm\(^{-3}\) density, a better fit to the data.](image-url)

agree well with the densities calculated based on a weighted average of the density of the pure compounds. Thus it is possible to use the density of the pure compounds to calculate densities for mixtures. Using these measured densities, the ZSR relation based on volume additivity can be calculated. This calculation compared with the mass additivity ZSR and the \( f_{\text{RH}_{\text{ext}}}(80\%\text{RH}, \text{Dry}) \) data for mixtures of the three organic compounds with ammonium sulfate can be seen in figure 6. Since the densities of phthalic acid, 1.45 g cm\(^{-3}\) (circles), and pyromellitic acid, 1.51 g cm\(^{-3}\) (triangles), are closer to the density of ammonium sulfate, 1.79 g cm\(^{-3}\), both methods of prediction fit the data well. However, the density of 4-hydroxybenzoic acid, 1.22 g cm\(^{-3}\), was measured to be significantly lower than that of the other organic compounds and ammonium sulfate, thus the volume additivity ZSR prediction of \( f_{\text{RH}_{\text{ext}}}(80\%\text{RH}, \text{Dry}) \) is less than the mass additivity prediction. Also, since the volume additivity prediction fits the data better than the mass additivity ZSR prediction, density is assumed to be the primary factor responsible for the different behavior of 4-hydroxybenzoic acid when compared with phthalic acid and pyromellitic acid. A better fit to the data assumes a 4-hydroxybenzoic acid density of 0.92 g cm\(^{-3}\), and is also shown in the bottom panel of figure 6. Since our density measurements were made on bulk materials, it is possible that aerosol particles formed via atomization would have an even lower density due to the rapid drying process.
Figure 7. Measured $f_{RH_{ext}}$ (84%RH, 55%RH) for ammonium sulfate mixed with 4-hydroxybenzoic acid for particles with a diameter of 335 nm.

Figure 8. Comparison of data from this study, for phthalic acid and pyromellitic acid, to results from Garland et al (2007), for sugars and dicarboxylic acids. The data for this range of organic compounds can be fit with the linear parameterization, $f_{RH_{ext}} (80\%RH, \text{Dry}) = 2.96 - 0.0167 \times \text{(mass fraction organic)}$. The gray dotted line shows the predicted $f_{RH_{ext}}$ if ammonium sulfate alone is responsible for the optical growth.

The hygroscopic growth factors of both phthalic (Brooks et al 2004, Hartz et al 2006) and 4-hydroxybenzoic acids (Mochida and Kawamura 2004) have been measured previously and values of the growth factor, Gf, reported. In order to use these measurements of Gf to predict the optical growth response, Mie scattering calculations, using known or assumed refractive indices and assuming spherical particles, must be employed. Since 4-hydroxybenzoic acid exhibited extremely minimal optical growth, we did not attempt to compare our results with the reported growth factor; however, a comparison with phthalic acid growth was performed. These conversions used a refractive index for phthalic acid of $n = 1.60$, similar to other aromatic compounds, such as toluene ($n = 1.50$) and phenol ($n = 1.54$). Volume weighted refractive indices based on the determined value for phthalic acid and $n = 1.33$ for water were used for the humidified particles’ refractive indices in these calculations. Dry and humidified extinction cross-sections were calculated at the dry and humidified diameters to calculate $f_{RH_{ext}}$. To calculate Gf from $f_{RH_{ext}}$, the same process was performed in reverse, iteratively. The results for these comparisons are given in table 1. For phthalic acid, the $f_{RH_{ext}} (80\%RH, \text{Dry})$ for 335 nm particles was determined as 1.27 ± 0.07. The Gf at 80%RH for 100 nm particles was determined using HTDMA by Brooks et al to be 1.12 ± 0.05 (Brooks et al 2004). Similarly, the Gf at 80%RH for 10 μm phthalic acid particles was determined by Hartz et al using an electrodynamic balance (2006) to be 1.10. The $f_{RH_{ext}} (80\%RH, \text{Dry})$ measurement from the
present work converted to Gf is 1.19 ± 0.04, similar to the values measured by HTDMA and electrodynamical balance. Additionally, when the Gf values of 1.12 ± 0.05 and 1.10 are converted to f/\text{RH}_{\text{ext}} (80\%\text{RH, Dry}) the values are 1.16 ± 0.11 and 1.11, respectively. Hameri et al. (2002) have measured the hygroscopic growth factor for particles composed of equal mass fractions of phthalic acid and ammonium sulfate using HTDMA. The reported Gf at 80\%RH for the mixed particles was 1.26 ± 0.03. To convert the Gf to f/\text{RH}_{\text{ext}}, a real refractive index of 1.56 (based on a volume weighted average of ammonium sulfate and phthalic acid) was used to calculate the dry particle extinction cross-section. When converted to f/\text{RH}_{\text{ext}}, the measured Gf corresponds to an f/\text{RH}_{\text{ext}} of 1.49 ± 0.10. The measured f/\text{RH}_{\text{ext}} from the current work was determined to be 2.11 ± 0.20. This optical growth factor corresponds to a Gf of 1.42 ± 0.05. Overall, reasonable agreement between measurements from the various techniques for pure compounds and mixtures was achieved.

4. Conclusions

In this work, the optical growth factors for polyfunctional aromatic acids have been measured for pure compounds as well as in mixtures with ammonium sulfate. The optical growth behavior at 80\%RH of these slightly soluble organic compounds was found to be very similar to the more water-soluble organic compounds studied previously by our groups, thereby adhering to previously determined parameterizations and thus expanding the classes of compounds these parameterizations can describe. Additionally, as both phthalic acid and pyromellitic acid as well as mixtures of all the organics do have an f/\text{RH}_{\text{ext}} (80\%\text{RH, Dry}) greater than unity, these results imply that a neglect of the optical growth of the organic mass fraction when modeling radiative forcing by atmospheric aerosols will underpredict the scattering effects of atmospheric aerosol populations.

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