Response to interactive comment on “Atmospheric oxidation of isoprene and 1,3-butadiene: influence of aerosol acidity and relative humidity on secondary organic aerosol” by M. Lewandowski, M. Jaoui, J.H. Offenberg, J.D. Krug, and T.E. Kleindienst

Commentator A. Nenes

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The interpretation of the experimental results relies heavily on the ability of $[H_+]_{air}$ to capture the in-situ pH of atmospheric particles. The methodology of Surrat et al.(2007) involves extracting filter samples in water, measuring its pH and then back-calculating the amount of H_+ in the original aerosol (assuming that H_+ is conserved). This is largely equivalent to an “ion balance” method, because the H_+ measured corresponds to an aerosol sample diluted by orders of magnitude, so that the ions present are largely dissociated (this is affected by the degree of dilution used, but does not change the inherent nature of the methodology). However, two studies currently in discussion in ACPD (Guo et al., 2014; Hennigan et al., 2014) raise doubts on whether such methods can be used as a proxy for in-situ aerosol pH, as it is shown that H_+ from ion balance is not correlated with in-situ aerosol pH for a wide range of aerosol conditions. This is especially relevant for this study as chamber RH is varied; the latter affects the amount of in-situ aerosol liquid water (hence pH) in a way that is not reflected in $[H_+]_{air}$. Even if a constant RH were used as in Surrat et al.(2007), the variable chemical composition (and potentially phase state) of the particles across experiments can still have a nontrivial effect on aerosol liquid water content, hence in-situ pH.

With the above said, we are not implying that the study here is fundamentally flawed. However, it would be good to see the acidity interpretation accompanied by both $[H_+]_{air}$ and pH calculations from a thermodynamic model (e.g., AIM, ISORROPIA, MESA) applied to the chamber conditions. Guo et al.(2014) and Hennigan et al.(2014) have shown that models applied to complex SE US and Mexico City aerosol, even at relatively low RH, can provide a much better representation of aerosol pH than ion-balance methods, provided that they are applied in “forward mode”. This is what we recommend here as well to be done. In the absence of gas-phase inorganic component measurements, one can still apply thermodynamic models in a useful manner (e.g.,Guo et al.,2014).

> We generally agree with the reviewer’s assessment of the limitations of the $[H^+]_{air}$ measurement. Although we believe that the limitations inherent in the measurement may not be as pronounced under the controlled conditions of a laboratory experiment as they are under ambient sampling conditions, it remains at best an indirect measurement of the aerosol properties of interest. We have retained the $[H^+]_{air}$ metric in the early part of the paper's results (isoprene/SO_2 and 1,3-butadiene vs $[H^+]$) in part for consistency with previous studies, especially the isoprene/SO_2 comparison to Surratt et al 2007. While these experiments could certainly benefit from additional information regarding the actual aerosol pH levels, we do not believe that this information is vital to the comparisons presented.
>
> In the varied RH experiments, where $[H^+]_{air}$ measurements are of limited value (since the maximum dissociated H^+ in the extracts remains unchanged, but actual aerosol pH is expected to change with liquid water content), we agree with the reviewer that aerosol pH levels or aerosol liquid water concentrations would be of tremendous value to the interpretation of the results. Unfortunately, we do not have sufficient composition information to do the modeling with ISORROPIA or AIM appropriately. While chamber temperature, RH, and particle sulfate loading are known for each reaction step, particle phase ammonium and nitrate were not measured in these experiments. And, although not strictly necessary, no gas-phase ammonia or

nitric acid concentrations are available (and, as high-NOx experiments, nitric acid concentrations should be non-trivial), further complicating model predictions. Additionally, as with the SOAS field measurements reported in Guo et al (2014), we have a significant aerosol fraction composed of isoprene-related organic aerosol to contend with, which can further contribute to aerosol phase water content, but is not accounted for in the models.

Given these limitations, we believe that any modeled pH levels or aerosol liquid water concentrations that we could generate from our existing data would be suspect and potentially counterproductive to the analysis (due more to our under-analysis of the aerosol composition than to any limitations inherent in the models). While we readily admit that humidity provides, at best, an indirect measure of the physically important aerosol parameters of interest in these comparisons, it is nevertheless the most reliable measurement surrogate that we have to work with in this data set. As such, we have retained it in the comparisons, but have added additional text to the Methods section further clarifying the limitations of both $[H^+]_{air}$ measurement in lieu of aerosol pH, and the use of humidity level as a surrogate for aerosol liquid water content (Line 165):

> "While this method provides a simple, easily repeatable measure of bulk acidity, it does not fully capture the actual acidity of individual aerosol particles, which is more likely to be of physical significance in these chemical systems. It is also of limited value in experiments where the relative humidity is varied, as the extraction of the collected aerosol effectively masks the effects of changing particulate liquid water concentrations. Further limitations of the $[H^+]_{air}$ measurement techniques have be described in detail in Hennigan et al. (2014). While a number of methods have been developed to measure aerosol liquid water content directly or estimate it through the use of thermodynamic models such as ISORROPIA (Fountoukis and Nenes, 2007) or AIM (Wexler and Clegg, 2002), liquid water measurements were not available for this study, and insufficient aerosol compositional information was collected for accurate use of thermodynamic modeling."

We have also added a Summary section which includes an additional review of the limitations of the experiments presented in the paper, including areas requiring additional investigation in future work, which includes discussion of the need for aerosol liquid water or pH assessments in future work (line 470):

> "While these experiments are suggestive, they also include a number of shortcomings that need to be addressed in future work. Perhaps the most significant is the use of absolute humidity and $[H^+]_{air}$ as surrogate measures of aerosol liquid water content and aerosol pH. Determination of the effective pH in the aerosol particles through the application of thermodynamic models, such as ISORROPIA or AIM, should provide a more realistic assessment of actual acidity than the $[H^+]_{air}$ approach, provided adequate gas and particle composition data is obtained experimentally. However, even these models generally account for only the influence of inorganic species, while the presence of isoprene SOA products has been reported to also contribute significantly to water uptake on ambient aerosols (Guo et al., 2014). This suggests that for laboratory experiments with high organic aerosol concentrations, particularly from isoprene-related parent hydrocarbons, direct measurements of aerosol liquid water content may be required."

Anonymous Referee #1
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Do the authors think that water vapour plays a role in the VOC oxidation chemistry leading to a lower SOC yield at an elevated humidity level or is it more related to particle phase chemistry such as a lower yield organosulfates, enhanced hydrolysis or reduced absorptive partitioning of organic compounds due to lower organic mass? Can the authors discuss this in the manuscript?

> Given the relatively limited organic compositional analysis available in these experiments, it is difficult to assess the potential changes in VOC chemistry occurring as RH is varied. As no significant changes in NOx or ozone concentrations were observed, and that the delta hydrocarbon remained essentially constant at all RH levels, it would appear that at least the early generations of VOC oxidation chemistry remained essentially unchanged (in contrast, the changes in the yield of the SO_2 to sulfate reactions with changing RH did result in observable changes in NO_X, O_3, and delta SO_2 concentrations, although this data was not presented in detail in the paper). Reductions in the formation of oligomeric species or organosulfates in a more water-rich environment seem plausible, but we currently lack the detailed organic analyses needed to back up these ideas. Further experiments are pending on these topics. Additional discussion added to the manuscript at Line 371:
>
> > "The reason for this reduction in SOC formation is not entirely clear. Gas-phase NO_x and O_3 concentrations do not appear to change significantly as a function of humidity level, as does the concentration of isoprene consumed in the reactions. This suggests that early-generation gas-phase oxidation reactions are probably not altered significantly by changing humidification. Changes in the aerosol liquid water content may affect the gas-particle partitioning of later-generation isoprene oxidation products, or increased water content may affect particle-phase organosulfate formation or the formation of oligomeric species (Pye et al., 2013). Further analysis of gas- and particle-phase organic constituents is required to further investigate this effect."

Pp. 29441 Line 21 onwards: Is the sulfate acidity effect purely related to the reactivity of oxidation products to acidic sulfate? I imagine that the layer of SOA formed on the seed particle likely hinders acid catalysed accretion reactions and absorptive partitioning largely controls the subsequent SOA formation. In other words, VOCs with higher ΔM_{SOA} may not show a strong acidity effect. How do the placements of these VOC relate to ΔM_{SOA} from neutral seed experiments?

> Although interface and/or transport effects may impose limits on acid catalyzed reactions at some concentration level, no clear indications were observed in these experiments. As noted in Section 3.1, variations in the particulate sulfate loading in the isoprene/SO_2 experiments (due to the concentration of SO_2 employed in different stages) produced linear OC vs $[H^+]$ behavior essentially identical to previous experiments conducted with constant sulfate concentrations generated with nebulized sulfate aerosol. In addition, Offenberg et al (2009) previously considered different organic loading with a-pinene SOC with no obvious differences in the results. It is possible that the organic to sulfate ratios used in these experiments simply do not reach a critical threshold at which interface effects would become limiting. However, it is also possible that there are additional factors, such as aerosol phase and/or mixing state, which would negate the limiting interface conditions of the core/shell structure suggested by the reviewer. The need for further examination of the physical characteristics of the particle phase are now included in the Summary section (Line 486):
>
> > "Further examination of the mixing state and phase of the generated aerosols would also like be of value, given that the available interfacial area could affect interactions

> between H^+, sulfate, and SOA, which may in turn affect organosulfate formation or other pathways to increased SOA yield."

Pp. 29442 Line 19 onwards: Temperature data should be given in Tables 1 and 2. How large was the temperature differences between these experiments? If the temperature had a significant impact on the RH, it is likely that the temperature also had an influence on the ΔM_{SOA}. Can the authors discuss about this in the manuscript?

The referenced text applies to the relative humidity variation experiments, which are detailed in Figure 4 (not Figures 1 and 2). Figure 4 has been modified to include temperature and relative humidity ranges for the described experiments, in addition to the absolute humidity ranges already provided.

Pp. 29442 Line 25 and Pp. 29443 Line 21 onwards: There are several thermodynamic models available to calculate aerosol water content and pH values. The authors may want to use one of these tools to estimate the values for these experiments and add them to Tables 1 and 2, and discuss if these parameters had an influence on acid catalysed accretion reactions or not.

See response to comments from A. Nenes, above.

Pp. 29444 Line 27: I would like the authors to discuss a bit deeper about the structural differences of oxidation products here. What sort of oxidation products do the authors expect when there is an additional methyl group in a precursor VOC? Does this lead to more reactive intermediate oxidation products towards acidic sulfate?

Given the current length of the paper, and the additional analytical techniques (GC-MS and/or LC-MS) that would need to be incorporated in order to provide a detailed discussion of the organic compositions of the isoprene and 1,3-butadiene systems, we have chosen to not include a more detailed discussion of the oxidation products here. We have instead qualified that this proposed pathway is speculative at this time, included a recent reference to 1,3-butadiene reaction mechanisms in general, and have suggested that this topic will need further discussion in a future manuscript. See Line 334 in Results and Discussion:

> "This could represent a substituent effect which influences the sensitivity of the gas-phase precursors to reaction by the acidic sulfate nucleophile, but further organic analysis of the aerosol phase constituents would be required to examine this possibility in detail. Although recent studies have compared the reaction pathways and products formed for 1,3-butadiene oxidation versus isoprene oxidation (Jaoui et al., 2014), these studies did not focus on acid-influenced reactions or organosulfate formation."

and line 493 in the Summary:

> "A further examination of the similarities and differences between acid-influenced OC formation in the isoprene and 1,3-butadiene systems would also likely be valuable. A more rigorous organic analysis of product distributions may help reveal why isoprene appears to be significantly more sensitive to acidic conditions than 1,3-butadiene at low humidity levels, and whether this difference is due to structural effects related to the additional methyl group affecting gas-phase chemistry, particle-phase organosulfate formation, or due to other phenomena, such as differences in volatility and partitioning of oxidized intermediates. A more detailed comparison of isoprene and 1,3-butadiene

organic chemistry under acidic conditional may help with the development of more accurate mechanisms for inclusion in air quality models."

As other reviewer commented, the authors should discuss their findings in atmospheric relevant context at the end of the manuscript.

A Summary section has been added to the paper, which incorporates a discussion of the relevance of these studies to atmospheric conditions, as well as a through assessments of the current limitations of the experiments presented (Lines 445-469):

"These experiments support previous studies suggesting that acidic aerosol can lead to increased SOA formation from the photooxidation of isoprene under laboratory conditions. Changing the source of the acidity from nebulized inorganic aerosol to a more atmospherically relevant photochemical conversion of SO_2 into acidic sulfate aerosol nearly identical results as previous nebulized sulfate aerosol experiments. In addition, 1,3-butadiene, a chemically similar compound released from primarily anthropogenic sources, was also demonstrated to produce higher concentrations of SOA under acidic conditions, albeit to a lesser extent than was seen with isoprene. The humidity experiments further suggest that aerosol liquid water content can have a substantial effect on SOA formation from isoprene and 1,3-butadiene. Increasing humidity produces a notable reduction in SOC formation in both the isoprene and 1,3-butadiene photochemical systems, which is more pronounced in both systems in the presence of acidic inorganic aerosols, and was most pronounced for the acidified isoprene/NO system.

In the isoprene/NO photochemical systems examined in this study, SOC enhancement due to the presence of acidic inorganic aerosol was observed to be negligible at absolute humidity levels above approximately 11 g H_2O m^{-3}. This lower SOC enhancement at elevated humidities may explain, in part, the difficulties in detecting increased SOA formation under acidic conditions in field studies of ambient air masses, particularly in humid climates like the southeastern US. This work suggests that a more detailed understanding of the role of humidity and of aerosol liquid water content is likely required in order to accurately predict the impact of acidity-influenced oxidation chemistry on overall SOA yields. While the data presented here may suggest that enhanced SOA formation via acid-influenced pathways is more constrained than previous studies may have suggested, it does still appear to represent a viable pathway for additional SOA formation from a number of precursor hydrocarbons, which may need to be incorporated into air quality models in order to accurately estimate secondary PM concentrations in certain locations.

While these experiments are suggestive, they also include a number of shortcomings that need to be addressed in future work. Perhaps the most significant is the use of absolute humidity and $[H^+]_{air}$ as surrogate measures of aerosol liquid water content and aerosol pH. Determination of the effective pH in the aerosol particles through the application of thermodynamic models, such as ISORROPIA or AIM, should provide a more realistic assessment of actual acidity than the $[H^+]_{air}$ approach, provided adequate gas and particle composition data is obtained experimentally. However, even these models generally account for only the influence of inorganic species, while the presence of isoprene SOA products has been reported to also contribute significantly to water uptake on ambient aerosols (Guo et al., 2014). This suggests that for laboratory experiments with high organic aerosol concentrations, particularly from isoprene-related parent hydrocarbons, direct measurements of aerosol liquid water content may be required.

Additionally, the relative humidity experiments presented here consider predominantly systematic increases in relative humidity. As some phenomena related to aerosol liquid water content are known to display hysteresis, such as deliquescence of sulfate aerosols, further testing. Experiments incorporating descending relative humidities and larger humidity steps are warranted, particularly along with the inclusion of liquid water content measurements. Further examination of the mixing state and phase of the generated aerosols would also like be of value, given that the available interfacial area could affect interactions between H^+, sulfate, and SOA, which may in turn affect organosulfate formation or other pathways to increased SOA yield.

Finally, further research is needed to examine changes in organic composition triggered by the effects considered in this work. In particular, the mechanism through which humidity level affects OC production from isoprene, even under non-acidified conditions, could be important to the selection of appropriate SOC yields in air quality models. A further examination of the similarities and differences between acid-influenced OC formation in the isoprene and 1,3-butadiene systems would also likely be valuable. A more rigorous organic analysis of product distributions may help reveal why isoprene appears to be significantly more sensitive to acidic conditions than 1,3-butadiene at low humidity levels, and whether this difference is due to structural effects related to the additional methyl group affecting gas-phase chemistry, particle-phase organosulfate formation, or due to other phenomena, such as differences in volatility and partitioning of oxidized intermediates. A more detailed comparison of isoprene and 1,3-butadiene organic chemistry under acidic conditional may help with the development of more accurate mechanisms for inclusion in air quality models."

Pp. 29432 Line 2 and elsewhere: I feel that $[H_3O_+]_{seed}$ or $[H_3O_+]_{aerosol}$ is more appropriate for expressing the aerosol acidity. It is very unlikely that free H_+ exists in the air under the experimental conditions used by the authors.

Although we agree that the $[H^+]_{air}$ terminology, generally defined as the dissociable H^+ in the aerosol per cubic meter of air sampled, can be misleading and subject to misinterpretation, it does have prior established use in the literature. In order to maintain consistency with these prior publications, the terminology has been retained here.

Anonymous Referee #2

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1) A major point of concern in this manuscript, as identified by the authors and further detailed in the short comment by A. Nenes, is the measurement of [H+] and its relationship with particle acidity and relative humidity. While the method used provides a valid bulk measurement, it is not clear whether bulk [H+] is particularly atmospherically relevant when other factors (e.g. particle water content) can influence acidity. In light of these concerns, I would suggest that the authors find addition methods, such as calculating particle acidity with a thermodynamic model, for approaching this intractable issue. As A. Nenes describes, such models have been shown to give reasonable estimates of aerosol pH, and when used in conjunction with measured bulk [H+], these estimates will provide a clearer interpretation of acidity in the particle phase. Of particular concern, in light of the difficulty of measuring particle acidity, are experiments in which multiple factors influencing acidity change together, such as the relative humidity experiments detailed in this manuscript. For reasons discussed in the manuscript, it can be hard to know how much the change in SOC yield reflects variations in humidity directly, or indirectly by changes in particle acidity, which may be changing despite a constant [H+] due to differences in particle water content. Employing thermodynamic models to estimate particle pH would be particularly useful for these experiments.

See response to comments from A. Nenes, above.

Additionally, considering the difficulty of separating the effects of humidity and acidity in these experiments, discussion of further controls would be beneficial in Section 3.3. For example, the authors mention temperature differences between experiments (L320); could these temperature differences also have an effect on SOC yields? Also, when the relative humidity was stepped up and down in these experiments, could hysteresis effects influence SOC yield, by which particles formed at one humidity and then brought to another humidity have different organic content than particles formed at the second humidity level (e.g. by irreversible particle-phase reactions)? A discussion of these temperature and hysteresis effects, and particularly any control experiments run to investigate these effects, would provide valuable insight into the many factors at play in these humidity experiments.

Although it is difficult to say with certainty how strongly the SOC yields may be impacted by temperature variations, we believe that the effects should be relatively small in the directly compared data sets presented in the paper. In the 1,3-butadiene/humidity experiments, the temperature differences between the two runs are approximately 3^{o}C, with the seed experiment having the higher temperature. In the isoprene/humidity experiments, the overall temperatures were higher than the 1,3-butadiene experiments (by approximately 2 and 5 degrees C), but consistent with one another to within about 1^{o}C. This may account for some of the differences in the observed behavior of the two systems, such as the greater separation of the butadiene curves at elevated humidity levels, but other sources of experimental error are likely to have a greater overall effect (as suggested by the scatter in the OC and yield plots) than the temperature differences. However, since converting from relative to absolute humidity could correct for the roughly 10-15% difference in water concentrations produced by these temperature differences, we felt that incorporating this correction improve the comparability of the datasets. We have adjusted the text to more directly provide the temperatures at which the different experiments have been conducted (in various locations), and have included an explicit mention of the possibility of temperature differences affecting the 1,3-butadiene RH experiments (Line 436):

> "Additionally, the temperature difference between the two experiments, although relatively small (approximately 3 ^{o}C on average) may be sufficient to introduce differences in the gas-particle partitioning between the two experiments."

With regards to hysteresis effect, in all described experiments the chamber system was allowed to equilibrate for at least 4 residence times following any change to the reaction conditions. This should allow for near-complete (>95%) turnover of all products formed under the previous conditions, which should minimize or eliminate any hysteresis effects from the causes suggested by the reviewer. However, other sources of hysteresis, such as deliquescence behavior of the inorganic sulfate, are more difficult to rule out. A limited number of additional data points were collected to attempt to test for hysteresis due to the direction or magnitude of the RH changes. However, due to the challenges of these long-running experiments, not enough data was obtained to produce a statistically significant assessment. Text has been added to the Summary section identifying this as an outstanding experimental issue warranting further study (Line 482):

> "Additionally, the relative humidity experiments presented here consider predominantly systematic increases in relative humidity. As some phenomena related to aerosol liquid water content are known to display hysteresis, such as deliquescence of sulfate aerosols, further testing. Experiments incorporating descending relative humidities and larger humidity steps are warranted, particularly along with the inclusion of liquid water content measurements."

2) Some discussion is needed at the end of the manuscript about the atmospheric relevance and implications of the results. Do these experiments provide any insight into field observations, and their persistent disparities from chamber experiments regarding the dependence of SOC yield on particle acidity? What effects might these humidity and acidity dependencies have on particle SOC yields in atmospheric conditions where isoprene and 1,3-butadiene are found?

A Summary section has been added to better summarize outstanding experimental issues related to this study and potential atmospheric implications for ambient SOA formation, particularly for isoprene (Lines 445-469). The text is provided above in the response to Reviewer #1.

3) Minor clarification questions about methods and instrumentation:
L151 – In the discussion of measuring [H+], some detail on the subject of uncertainty (e.g. the error bars shown on Figures 1, 2, 3, and 5) would be useful. How are these errors estimated, and what factors are (and are not) included?
L165 – A similar treatment of uncertainty in the discussion of particle organic carbon measurements would be useful as well.

Error bars for [H^+] were based on the rated variability of the pH probe used, converted into [H^+] units. Error bars on the OC concentrations were based on the variability in the replicate semi-continuous OC measurements conducted during each sampling period (typically, n>20). Error bars on yield values (requested below) incorporate variability in replicated hydrocarbon measurements and OC measurements during each sampling period. Error bars on absolute humidity were based on variability in the measured temperature and RH data, converted to absolute humidity on a 5-minute basis throughout each sampling period (n>200). Text has been added following the presentation of Figure 1 (Line 253), Figure 3 (Line 363), and Figure 4 (Line 387) clarifying the basis for the error bars presented.

L214 – What is the [SO2] background?

As given in Table 1, a background SO_2 concentration of 11 ppb was detected in the absence of SO_2 addition to the chamber. This reading was likely due to a small hydrocarbon interference on the SO_2 monitor, as this stage of the experiment was conducted last and the monitor's scrubbers had been subjected to significant hydrocarbon, SO_2, and aerosol concentrations in prior stages.

L579 – I believe figure 4 should have error bars similar to those in Figures 1,2,3 and 5.

Figure 4 has been revised to include error bars on both axes.

General – additional details that would provide useful insight include how SO2 and particle sulfate were measured; the temperatures at which experiments were conducted; and whether any oxidant source was added (and how much) to initiate the oxidation of the hydrocarbons.

Additional clarification has been added to the methods section to identify the SO_2 monitor employed (Line 147):

> "NO and NO_Y were measured with a TECO model 42C (Franklin, MA) oxides of nitrogen chemiluminescent analyzer, SO_2 was monitored by pulsed fluorescence detection (TECO, Model 43A), and O_3 was measured with a chemiluminescent ozone monitor (Bendix Model 8002, Lewisburg, WV)."

and the measurement of particle sulfate (Line 157):

> "Extracts were analyzed for sulfate (SO_4^{2-}) ions using a Dionex DX500 Ion Chromatography system equipped with an electrical conductivity detector. Anion analysis was conducted using a Dionex IonPac AS14A column and an isocratic 4 mM sodium carbonate/0.5 mM sodium bicarbonate eluent."

Clarification of experiment temperatures for the isoprene/SO_2 experiment and the 1,3-butadiene vs. [H^+] experiment have been added to the text, while Table 4 has been updated to include temperature ranges for the RH experiments, as requested above by Reviewer #1. Only NO was used as an oxidant in the experiments.

Technical corrections: The manuscript is largely free of typographical and grammatical errors.

L90 – an extra space in "by anthropogenic"

Corrected

L109 – "of" should be "in"

Corrected

Edited Manuscript: All changes made to the text of the manuscript have been highlighted in yellow.

Atmospheric Oxidation of Isoprene and 1,3-Butadiene: Influence of Aerosol Acidity and Relative Humidity on Secondary Organic Aerosol

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Abstract

The effects of acidic seed aerosols on the formation of secondary organic aerosol (SOA) have been examined in a number of previous studies, several of which have observed strong linear correlations between the aerosol acidity (measured as nmol H^+ per m^3 air sample volume) and the percent change of secondary organic carbon (SOC). The measurements have used several precursor compounds representative of different classes of biogenic hydrocarbons including isoprene, monoterpenes, and sesquiterpenes. To date, isoprene has displayed the most pronounced increase in SOC, although few measurements have been conducted with anthropogenic hydrocarbons. In the present study, we examine several aspects of the effect of aerosol acidity on the secondary organic carbon formation from the photooxidation of 1,3-butadiene, as well as extending the previous analysis of isoprene.

The photooxidation products measured in the absence and presence of acidic sulfate aerosols were generated either through photochemical oxidation of SO_2 or by nebulizing mixtures of ammonium sulfate and sulfuric acid into a 14.5 m^3 smog chamber system. The results showed that, like isoprene and β-caryophyllene, 1,3-butadiene SOC yields linearly correlate with increasing acidic sulfate aerosol. The observed acid sensitivity of 0.11 %SOC increase per nmol m^{-3} increase in H^+ was approximately a factor of three less than that measured for isoprene. The results also showed that the aerosol yield decreased with increasing humidity for both isoprene and 1,3-butadiene, although to different degrees. Increasing the absolute humidity from 2 to 12 g m^{-3} reduced the 1,3-butadiene yield by 45% and the isoprene yield by 85%.

1. Introduction

The role of aerosol acidity to increase formation of secondary organic aerosol (SOA) in the atmosphere continues to be a topic of considerable debate. Field studies at ground level have indicated that increases in ambient secondary organic carbon (SOC) due to ambient acidity are likely subtle. Zhang et al. (2007) examined increases of SOA species in the Pittsburgh area under acidic conditions, found at most a 25% increase in ambient SOA from the Pittsburgh area that could be attributed to acid catalyzed effects. In another study from the SEARCH network, Tanner et al. (2009) report low apparent impacts to aerosol acidity at the rural sites at Yorkville, GA and Centreville, AL, where biogenic hydrocarbons and anthropogenic oxidants from nearby urban centers might be expected to produce relatively high levels of aerosol acidity in the presence of the oxidation products of biogenic hydrocarbons.

Most laboratory studies aimed at addressing the impact of aerosol acidity on SOA concentrations have focused on isoprene. Emissions of isoprene (C_5H_8) from vegetation constitute the greatest worldwide source of nonmethane hydrocarbons (Guenther et al., 1995). SOC formation from isoprene has been shown to increase in the presence of sulfate acidity in smog chamber experiments (Edney et al., 2005; Surratt et al., 2007), with a variety of organosulfate compounds detected in the aerosol phase (Surratt et al., 2008; Surratt et al., 2010).

The effect of acidity to produce organosulfates has been studied mainly for aerosols with strong biogenic inputs. Surratt et al. (2007) initially showed that sulfate esters were formed in the aerosol products from photooxidations of isoprene and α-pinene in the presence of acidic seed aerosol. These products were then compared to those found in ambient aerosol collected at ground sites in the Southeast U.S. (i.e., the SEARCH network) and found to be similar to the laboratory aerosol (Jaoui et al., 2008). Additional studies (Froyd et al., 2010) showed that products of isoprene oxidation could render a single organosulfate compound (IEPOX-sulfate), which comprised up to 3% of the organic aerosol mass under some conditions in the free troposphere.

On a broader basis, laboratory studies have readily shown that acidic sulfate aerosol produces increased organic aerosol yields from the products of biogenic and anthropogenic oxidation systems (e.g., Jang et al., 2002). Since the initial studies, efforts have been undertaken to quantify the magnitude of the aerosol acidity effect. Surratt et al. (2007) investigated the effect of sulfate acidity on photooxidation products from the isoprene/NO_X system. They found that secondary organic carbon increases linearly with aerosol acidity, $[H^+]_{air}$, an acidity measure that gives its air concentration (nmol m^{-3}) rather than an aerosol pH. Offenberg et al. (2009) extended this same analysis to examine the acidity effects on monoterpenes (α-pinene) and sesquiterpenes (β-caryophyllene). For α-pinene aerosol products, the effect of acidity was found to be independent of organic carbon mass present and was a factor of eight lower than the effect for isoprene. The β-caryophyllene aerosol products, by contrast, showed an effect similar to that for isoprene and a factor of five higher than that for α-pinene. Analysis by Chan et al. (2011) confirmed the presence of organosulfate compounds in β-caryophyllene SOA formed under these conditions. Zhang et al. (2012) performed acidity experiments for 2-methyl-3-buten-2-ol (MBO), a compound structurally related to isoprene. MBO was shown to be less influenced by acidity than isoprene or β-caryophyllene, but more affected than α-pinene. However, this comparison is complicated by the fact that the MBO experiments were conducted under dry conditions using the photolysis of hydrogen peroxide to generate OH radicals; in contrast, Surratt et al. (2007) and Offenberg et al. (2009) relied upon NO_x photochemistry conducted at 30% relative humidity to generate their data.

Concentrations of the isoprene SOA tracer products, 2-methylthreitol and 2-methylerythritol, have also been found to rise with increased aerosol sulfate acidity. These results suggested that particle phase reactions could contribute to the increased isoprene aerosol yields and compound concentrations. Mechanisms for C_5 and C_{10} organosulfate formation in the atmosphere have been proposed (Surratt et al., 2008). Subsequent studies by Paulot et al. (2009) gave strong evidence that the atmospheric formation of isoprene sulfates under conditions of low nitrogen oxides involved a stable gas-phase C_5-hydroperoxide epoxide. Once uptake of the epoxide into acidified aerosol occurs, inorganic sulfate nucleophiles were able to convert the epoxide to organosulfates, and hydrolysis led to the formation of the 2-methyl tetrols, depending on the competitive rates of different nucleophiles in the aerosol. However, a recent study by Lin et al. (2013) reports measurements made in Chapel Hill, NC, an area impacted by anthropogenic oxidant emissions, that show epoxide formation also occurs through NO_X channel reactions. In these reactions, methylacryloylperoxy nitrate (MPAN), an intermediate stable product from isoprene oxidation, reacts with OH radicals leading to methyl acrylic epoxide (MAE).

While considerable effort has been expended studying acidic effects of biogenic precursors, far less effort has been made to examine such effects on hydrocarbons having an anthropogenic origin. An interesting anthropogenic compound for consideration is 1,3-butadiene (C_4H_6). The main source for this compound is from automotive exhaust emissions, although additional sources from cigarette smoke, evaporative emissions of gasoline, and from biomass combustion have been reported (Anttinen-Klemetti et al., 2006; Dollard et al., 2001; Eatough et al., 1990; Hurst, 2007; Pankow et al., 2004; Penn and Snyder, 1996; Sorsa et al., 1996; Thornton-

Manning et al., 1997; Ye et al., 1998). It has been classified as a hazardous compound in the 1990 Clean Air Act Amendments (US EPA, 1996), a carcinogenic and toxic pollutant, and a genotoxic chemical in humans and other mammals (Acquavella, 1996; US EPA, 2002). With respect to aerosol formation, 1,3-butadiene is also of interest as a structural analog for isoprene. SOA formation from 1,3-butadiene has been examined in a number of recent studies (Angove at al., 2006; Sato, 2008; Sato et al., 2011; Jaoui et al., 2014), although with only limited consideration of the effects of aerosol acidity.

The main focus of the present study is to explore some additional aspects of the role of acidic sulfate aerosol in the formation of SOA from isoprene and 1,3-butadiene. For isoprene, we examine the increase of SOA using acidic sulfate derived from the photooxidation of SO_2 to see if the results are consistent with those using nebulized acidic sulfate seed aerosol. In addition, we have measured the extent to which the isoprene analog – 1,3-butadiene – also shows an increase in SOA formation in the presence of acidic aerosol. The results are then compared to biogenic compounds previously studied to determine the relative magnitudes of the effect. In addition, this study attempts to extend the analysis over a broader range of humidities in an effort to assess the impact of aerosol water content on acidic influenced SOA formation. In the previous studies by Surratt et al. (2007) and Offenberg et al. (2009), all measurements were conducted at a single humidity level (30% relative humidity), while Zhang et al. (2012) examined only dry conditions. Extending these studies to a wider range of hydrocarbons and across a more realistic range of humidities should provide data of greater atmospheric relevance and contribute to further development of acidity-influenced SOA chemistry in air quality models.

2. Experimental

Secondary organic aerosol was generated in a 14.5 m^3 fixed-volume, Teflon-coated reaction chamber. The chamber used a combination of UV-fluorescent bulbs that provided radiation from 300-400 nm with a distribution similar to that of solar radiation to the extent that can be achieved with UV bulbs (Kleindienst et al., 2006). The reaction chamber was operated as a continuous stirred tank reactor having a residence time of 4 h, to produce a constant, steady-state aerosol distribution which could be repeatedly sampled at different seed aerosol acidities.

To supply isoprene and 1,3-butadiene, high concentration gas mixtures were produced in high-pressure cylinders diluted with nitrogen (N_2). Tank concentrations were approximately 2000 ppm for isoprene and 4500 ppm for 1,3-butadiene. The hydrocarbons, NO, and SO_2 (when used) were added through flow controllers into the inlet manifold, where they were diluted and mixed prior to introduction into the chamber. Inorganic aerosol was added to the chamber by nebulizing dilute aqueous solutions of ammonium sulfate and/or sulfuric acid (TSI, Model 9302, Shoreville, MN), with total sulfate concentration of the combined solution held constant in order to maintain stable inorganic concentrations in the chamber. The seed aerosol stream then passed through a ^{85}Kr neutralizer (TSI, Model 3077, Shoreville, MN) and equilibrated to the computer-controlled relative humidity designated for a particular experiment. To change the acidity of the seed aerosol, the ratio of the ammonium sulfate and sulfuric acid solutions was changed to produce a constant aerosol sulfate concentration (typically ~30 $\mu g\ m^{-3}$) across the range of acidities used.

Concentrations of isoprene and 1,3-butadiene in the inlet manifold and chamber were measured using a gas chromatograph with flame ionization detection (Hewlett-Packard, Model

5890 GC). NO and NO_Y were measured with a TECO model 42C (Franklin, MA) oxides of nitrogen chemiluminescent analyzer, SO_2 was monitored by pulsed fluorescence detection (TECO, Model 43A), and O_3 was measured with a chemiluminescent ozone monitor (Bendix Model 8002, Lewisburg, WV). Temperature and relative humidity were measured with an Omega Digital Thermo-Hydrometer (Model RH411, Omega Engineering, Inc., Stamford, CT).

Aerosol samples were collected on 47 mm Teflo membrane filters (Pall Corporation, Ann Arbor, MI) for determination of the particulate sulfate concentration (in select experiments) and the aerosol hydrogen ion concentration per unit volume of air sampled, or $[H^+]_{air}$, expressed as nmol H^+ m^{-3}. Aerosol produced in the chamber was collected at a rate 10 to 20 L min^{-1} over a period of approximately 4 h. Filters were extracted by sonication for 30 min using 10 mL of distilled, deionized water in a 50 mL polypropylene vial. Extracts were analyzed for sulfate (SO_4^{2-}) ions using a Dionex DX500 Ion Chromatography system equipped with an electrical conductivity detector. Anion analysis was conducted using a Dionex IonPac AS14A column and an isocratic 4 mM sodium carbonate/0.5 mM sodium bicarbonate eluent.

For $[H^+]_{air}$ determination, the extract were allowed to cool to room temperature and the pH of each extract was measured with a temperature-compensated Oakton 300 series pH/conductivity meter (OAKTON Instruments, Vernon Hills, IL). The $[H^+]_{air}$ was calculated by dividing the measured aqueous concentration of hydrogen ions by the volume of air collected, as described by Surratt et al. (2007). While this method provides a simple, easily repeatable measure of bulk acidity, it does not fully capture the actual acidity of individual aerosol particles, which is more likely to be of physical significance in these chemical systems. It is also of limited value in experiments where the relative humidity is varied, as the extraction of the collected aerosol effectively masks the effects of changing particulate liquid water concentrations. Further limitations of the $[H^+]_{air}$ measurement techniques have be described in detail in Hennigan et al. (2014). While a number of methods have been developed to measure aerosol liquid water content directly or estimate it through the use of thermodynamic models such as ISORROPIA (Fountoukis and Nenes, 2007) or AIM (Wexler and Clegg, 2002), liquid water measurements were not available for this study, and insufficient aerosol compositional information was collected for accurate use of thermodynamic modeling. Nevertheless, in the absence of a true aerosol pH measurement, the $[H^+]_{air}$ approach appears to provide a useful, if limited, surrogate measure under sufficiently constrained experimental conditions.

Measurements of particulate organic carbon were performed with an on-line thermal optical transmittance carbon analyzer using a parallel plate, carbon strip denuder (Sunset Laboratories, Tigard, OR; Birch and Cary, 1997) prior to aerosol collection on the quartz filter within the instrument. Other details of operation for the carbon analyzer on the photochemical reaction chamber are described elsewhere (Offenberg et al., 2007). The duty cycle for this measurement was 0.75 h (i.e., 0.5 h sampling and 0.25 h analysis times, respectively). All particulate carbon concentrations measured during the interval of aerosol acidity filter collections were averaged for comparison with the integrated measurements of aerosol acidity.

Four different sets of experiments were performed, each involving multiple stages: (1) an isoprene/NO experiment in which different concentrations of SO_2 were used to generate varied levels of aerosol acidity, (2) a 1,3-butadiene/NO experiment in which different nebulizer solutions were used to generate varied levels of aerosol acidity, (3) a pair of isoprene/NO experiments, one using a low concentration ammonium sulfate seed and the other using an acidic inorganic component, in which the inorganic compositions were held constant while the humidity levels were varied, and (4) a comparable pair of 1,3-butadiene/NO experiments in which humidity levels were systematically varied.

In the isoprene/NO experiment (ER370), the initial mixture of isoprene, NO, and SO_2 was irradiated in the chamber until the reaction mixture reached a steady-state concentration. For each of the three successive stages, the SO_2 concentration was progressively reduced and the reaction mixture was allowed to equilibrate. In the final stage, SO_2 was turned off to generate a "base case" aerosol from the isoprene/NO_X reaction alone. In all cases, filter measurements were conducted only after the steady-state condition was achieved.

For the 1,3-butadiene/NO experiment (ER444), an ammonium sulfate solution was used to generate approximately 35 $\mu g\ m^{-3}$ of inorganic aerosol to provide a base case. In subsequent stages, the seed aerosol was made progressively more acidic by reducing the proportion of ammonium sulfate and adding increasing fractions of sulfuric acid to the solution. This approach offers two main advantages over the SO_2 oxidation method described above. First, it provides a consistent level of inorganic sulfate aerosol at all stages; in contrast, the SO_2 oxidation produces variable inorganic concentrations, and effectively no inorganic content in the base case without SO_2 addition. Second, the addition of the seed aerosol should have a negligible effect on the gas-phase radical chemistry, which may otherwise be affected by the conversion of SO_2 to sulfuric acid.

For the humidity studies, each hydrocarbon was examined with two different experiments. First, each hydrocarbon/NO system was tested at multiple humidity levels using only a low concentration (1 $\mu g\ m^{-3}$) ammonium sulfate seed aerosol (ER666 for 1,3-butadiene; ER667 for isoprene). This provided a base case for exploring the changes in SOC formation and aerosol yield in the absence of significant aerosol acidity. Relative humidities were varied between roughly 10% and 60%, which corresponded to absolute humidities of approximately 2 to 14 g m^{-3}. For isoprene, this base case experiment was then repeated in the presence of a moderately acidic sulfate aerosol, which was held constant across the full range of humidities examined (ER662). For 1,3-butadiene, a more acidic inorganic aerosol, generated using a solution incorporating a higher fraction of sulfuric acid solution to ammonium sulfate solution, was employed (ER444).

3. Results and Discussion

The experiments presented here support previous studies suggesting that acidic aerosol can lead to increased SOA formation from the photooxidation of isoprene under laboratory conditions. Changing the source of the acidity from nebulized inorganic aerosol to a more atmospherically relevant photochemical conversion of SO_2 into acidic sulfate aerosol produced only a minor change in the resulting percent increase in SOC per unit increase in $[H^+]_{air}$. In addition, 1,3-butadiene, a chemically similar compound released from primarily anthropogenic sources, was also demonstrated to produce higher concentrations of SOA under acidic conditions. The humidity experiments further suggest that humidity level, and likely aerosol liquid water content, can have a substantial effect on SOA formation from isoprene and 1,3-butadiene. Increasing humidity produces a notable reduction in SOC formation in both the isoprene and 1,3-butadiene photochemical systems. However, this reduction is more pronounced in both systems in the presence of acidic inorganic aerosols, and was most pronounced for the isoprene/NO system.

3.1 Isoprene Acidity Variation

Data for the isoprene/SO_2 acidity experiment are provided in Table 1. For this experiment, the initial isoprene concentration was 8.4 ppmC, the initial NO was 0.37 ppm, and the relative humidity averaged 30% at 25 °C (6.5 g m^{-3} absolute humidity, on average). SO_2 ranged from near background to 0.23 ppm. Residual SO_2 might have contributed to the background $[H^+]_{air}$ of 54 nmol m^{-3}, although this value is more likely due to aerosol-phase organic products of isoprene oxidation, particularly organic acids. However, in terms of the relative changes of percent OC increase, this background value is of little consequence. Generating the acidity with SO_2 allows the $[H^+]_{air}$ to achieve values in excess of 1500 nmol m^{-3}, a value much greater than can be reliably maintained using nebulized solutions. However, unlike nebulized aerosol, the concentrations of inorganic sulfate in the product aerosol vary at each stage of the experiment, as shown in Table 1. Sulfate concentrations were measured by ion chromatography at each stage of this experiment.

With no added SO_2 (stage ER370-9), the organic carbon from the isoprene reaction resulted in 5.3 μgC m^{-3} of SOC formed (corrected for chamber losses). Percent increases over this base case value ranged from 62% to 459% at the highest acidity level (1524 nmol m^{-3}). Figure 1 provides a plot of the percent change in OC against the aerosol acidity. Error bars for $[H^+]_{air}$ are derived from the rated variability of the pH probe used, converted into nmol m^{-3} using the sampling and extraction volumes employed. Error bars on the OC concentrations are based on the variability in the replicate semi-continuous OC measurements conducted during each sampling period (typically, n>20). As seen in the figure, the relative increase in organic carbon correlated well with increasing acidity with an R^2 of 0.985. The negative intercept resulted from the small amount of acidity measured under the condition without SO_2, and the slope indicates a 0.31 %SOC increase per nmol m^{-3} of increased $[H^+]_{air}$.

Despite employing different mechanisms for generating the acidic aerosol, the agreement in the data between this study and Surratt et al. (2007) is excellent. The %SOC increase appears to be quite consistent (0.31 for SO_2 photooxidation vs. 0.32 via nebulization), suggesting both pathways lead to comparable acid enhancements. The results also suggest that variations in the inorganic aerosol loading do not strongly impact the observed %SOC increase, at least under the range of conditions considered, which is consistent with the results previously reported by

Offenberg et al. (2009) for α-pinene/NO acidity experiments conducted at different SOC concentrations.

Attempting to expand the SO_2 experiment to incorporate additional humidity conditions revealed a further challenge for the use of SO_2 versus nebulization of sulfate aerosols in these acidity experiments. Changes to the chamber humidification also resulted in changes in the amount of SO_2 converted to aerosol-phase acidic sulfate, with higher humidity resulting in lower aerosol sulfate concentrations. Nebulized sulfate aerosols, in contrast, appear to retain stable aerosol sulfate concentrations and $[H^+]_{air}$ levels under variable humidity conditions. This limitation could potentially be overcome through the use of a direct measure of acidity in aerosol particles. However, given the inherent limitations of the $[H^+]_{air}$ measurement, the nebulization approach provides a cleaner evaluation of the effects of humidity on SOC formation. For this reason, the remainder of the experiments presented will focus on nebulized inorganic sulfate for the generation of aerosol acidity.

3.2 1,3-Butadiene Acidity Variation

Data for the 1,3-butadiene acidity experiment are provided in Table 2. For these experiments, the initial 1,3-butadiene and NO concentrations were 6.8 ppmC and 0.34 ppm, respectively. The first acidity condition once the reaction started was the base case of pure ammonium sulfate, which rendered a $[H^+]_{air}$ of 48 nmol m^{-3}. The next condition used a nebulizer solution of nominally one-third sulfuric acid and two-thirds ammonium sulfate to give an $[H^+]_{air}$ of 259 nmol m^{-3}; the third case was a nominal one-third ammonium sulfate and two-thirds sulfuric acid giving an $[H^+]_{air}$ of 666 nmol m^{-3}; and the last case used sulfuric acid solution only for an $[H^+]_{air}$ of 963 nmol m^{-3}. The aerosol sulfate concentration was measured as approximately

35 µg m^{-3} for the ammonium sulfate nebulization prior to the start of photochemistry; previous measurements have shown that sulfate concentrations remain stable as the ammonium sulfate/sulfuric acid ratio of the nebulizer solution is varied. The 1,3-butadiene consumed by reaction ranged from 4.9 to 5.2 ppmC and averaged 5.03 ppmC.

Organic carbon concentrations increased with increasing acidity at the fixed relative humidity of 30% (at an average temperature of 22 °C) from the base case of 22.6 µgC m^{-3} to 44.7 µgC m^{-3} at the highest acidity condition. SOC concentrations and percent increases from the base case (ammonium sulfate) for the four stages are given in Table 2. The %SOC increases monotonically with sulfate acidity up to nearly a 100% increase at the highest acidity condition. The yield determined as [SOC] / Δ[1,3-butadiene$_{\text{carbon}}$] was calculated for each condition and found to increase from 0.009 at the lowest acidity condition to 0.019 at the highest. Since ΔHC remained nearly constant over the entire experiment, the increase in yield was essentially equivalent to the increase in SOC, that is, a factor of two.

Figure 2 provides a plot of the percent change in organic carbon versus the $[H^+]_{air}$ for 1,3-butadiene SOA at 30% relative humidity. As seen in the figure, the relative increase in organic carbon correlated well with increasing acidity with an R^2 of 0.967. The negative intercept resulted from the small amount of acidity measured in the base case with the ammonium sulfate nebulizer solution. The plot shows an increase of 0.112 %SOC for each nmol m^{-3} increase in $[H^+]_{air}$.

Figure 2 also compares the results from the 1,3-butadiene system with similar acidity measurements from this laboratory. Superimposed on the sulfate acidity effect from 1,3-butadiene SOA products are measurements made for three biogenic hydrocarbons previously studied: isoprene (Surratt et al., 2007), α-pinene, and β-caryophyllene (Offenberg et al., 2009).

In those studies, SOA formation from isoprene, β-caryophyllene, and α-pinene was found to correlate with aerosol acidity as linear relationships with different slopes. From the present work, the 1,3-butadiene case also follows the same trend with a slope larger than that of α-pinene and smaller than that of β-caryophyllene. In all five of these studies, a relative humidity of 30% was used.

Table 3 further summarizes all the data from these $[H^+]_{air}$ variation experiments. $[H^+]_{air}$ and absolute OC concentrations are given as ranges for the individual studies. For most of the experiments, Figure 2 shows the relationship between the percent change in SOC concentration compared to the "neutral" base case. All data from experiments with isoprene, α-pinene, and β-caryophyllene are from prior studies in this laboratory (Surratt et al., 2007; Offenberg et al. 2009) and use a chamber relative humidity of 30%. Table 3 also includes data for the MBO experiment described by Zhang et al. (2012) where SOA was produced under conditions of low NO_X with the aerosol generated through $RO_2 + HO_2$ and $RO_2 + RO_2$ reactions. Unlike the other experiments presented in Table 3, the MBO experiment was conducted under dry conditions (less than 3% relative humidity).

Overall, the sulfate acidity effect follows the order (from greatest to least effect): isoprene; β-caryophyllene; MBO; 1,3-butadiene; and α-pinene. However, the exact placement of MBO in this range is somewhat questionable given the dramatic differences in experimental conditions used in that study (low NO_x chemistry and dry conditions) compared to the others. In comparing the relative sensitivity of isoprene and 1,3-butadiene to sulfate acidity, there is about a factor of three difference in the %SOC response to increasing $[H^+]_{air}$ despite the general structural similarity of the compounds. This could represent a substituent effect which influences the sensitivity of the gas-phase precursors to reaction by the acidic sulfate nucleophile, but further organic analysis of the aerosol phase constituents would be required to examine this possibility in detail. Although recent studies have compared the reaction pathways and products formed for 1,3-butadiene oxidation versus isoprene oxidation (Jaoui et al., 2014), these studies did not focus on acid-influenced reactions or organosulfate formation.

3.3 Isoprene Humidity Variation

Table 4 provides the initial conditions for the two isoprene/NO experiments designed to examine changes in SOC formation and yield resulting from changes in humidity. In the base case experiment (ER667), the reaction was conducted in the presence of only a low concentration (~1 μg m^{-3}) of inorganic aerosol produced through the nebulization of a 10 mg L^{-1} ammonium sulfate solution. The relative humidity was then changed in stages from 9% to 49% in ~10% increments (at an overall average temperature of 28 °C). At each stage, the chamber was allowed to equilibrate before a complete set of $[H^+]_{air}$, SOC, and ΔHC measurements were made. Measured $[H^+]_{air}$ values averaged 54 nmol m^{-3} over the course of the experiment, a level consistent with previous non-acidified isoprene/NO systems (both Surratt et al., 2007, and ER370 reported above). In addition, a comparable experiment (ER662) was conducted using a moderately acidic inorganic aerosol generated via nebulization of a mixed ammonium sulfate and sulfuric acid solution. In this experiment, duplicate measurements were made at steady-state relative humidity levels of 8, 28, 44, and 18%. The overall average temperature over the course of the experiment was 27 °C. In this experiment, the measured $[H^+]_{air}$ values averaged 275 nmol m^{-3}. Based upon previous isoprene acidity experiments, this modest level of sulfate acidity would be expected to produce an increase in SOC of approximately 50-75% at a relative humidity of 30%.

Figure 3 provides a plot of the measured SOC levels as a function of humidity for these two isoprene systems. Due to temperature differences between these experiments (and, more importantly, the 1,3-butadiene experiments described below), measures of chamber relative humidity have been converted into absolute humidity (g H_2O m^{-3}) to provide a common basis for all four experiments. Error bars on the humidity axis are determined from the variability in absolute humidities calculated on a 5-minute basis throughout the sampling periods. It is unclear whether relative humidity or absolute humidity is of greater physical significance in the systems under consideration. A direct measure of aerosol liquid water content would likely be a more appropriate metric than either relative or absolute humidity for this study. However, no method for the analysis of aerosol liquid water content was available for these experiments.

For the base case experiment, the SOC values range from a high of 13.3 μgC m^{-3} at the lowest humidity level (2.6 g H_2O m^{-3}) to just over 3 μgC m^{-3} at the higher humidities (10.4 to 13.1 g m^{-3}). The reason for this reduction in SOC formation is not entirely clear. Gas-phase NO_x and O_3 concentrations do not appear to change significantly as a function of humidity level, as does the concentration of isoprene consumed in the reactions. This suggests that early-generation gas-phase oxidation reactions are probably not altered significantly by changing humidification. Changes in the aerosol liquid water content may affect the gas-particle partitioning of later-generation isoprene oxidation products, or increased water content may affect particle-phase organosulfate formation or the formation of oligomeric species (Pye et al., 2013). Further analysis of gas- and particle-phase organic constituents is required to further investigate this effect.

For the acidified experiment, SOC declined from above 30 μgC m^{-3} at the lowest humidity level (2.2 g m^{-3}) to around 4 μgC m^{-3} under the highest humidity condition (11.3 g m^{-3}).

Although the absolute humidities considered in the two experiments do not correspond precisely, the percent increase in SOC for the acidic experiment versus the base case ranges from approximately 140% at the lowest humidity levels, to approximately 65-75% in the mid-range (where these experiments best overlap with the previous SOC versus $[H^+]_{air}$ studies), to virtually no statistical difference between SOC levels above approximately 11 g H_2O m^{-3}. Figure 4 provides SOC yield curves for these two isoprene/NO scenarios. Error bars on the SOC yields incorporate variability in the replicate measurements of both the inlet and chamber hydrocarbon concentration as well as in the semi-continuous OC measurements throughout each sampling period. As in the experiments described in the previous sections, the humidity changes performed here had a minimal impact on the measured ΔHC. As a result, the isoprene/NO yield plots follow essentially the same pattern as that seen for SOC formation in Figure 3.

These results suggest that humidity can have a profound effect on the acid-derived enhancement of SOC formation from isoprene. Although the range of conditions explored is limited (only a single bulk acidity level; only a partial range of relative humidities; and only a comparatively narrow temperature range, by atmospheric standards), the data imply that under some circumstances, high humidity (or perhaps high aerosol water content) can essentially suppress enhanced SOC formation from isoprene photochemistry. These results also reinforce the fundamental weakness of the $[H^+]_{air}$ measurement as a surrogate for acidity levels in actual aerosol particles. Although the bulk acidic potential of the systems, as measured by $[H^+]_{air}$, does not change significantly over the range of humidities considered, the resulting changes in the SOC concentrations suggest that the pH in aerosol particles may be changing significantly due to variations in aerosol liquid water content, solution ionic strength, or other factors not effectively captured by the $[H^+]_{air}$ measurement.

3.4 1,3-Butadiene Humidity Variation

Conditions for the two 1,3-butadiene/NO experiments for examining changes due to humidity variations are presented in Table 4. As described above, the base case experiment (ER666) was conducted in the presence of ~1 µg m^{-3} of ammonium sulfate aerosol. The relative humidity was then changed in stages from 10% to 60% in increments of roughly 10% each, at an overall average temperature of 25 ºC. This was compared with an additional experiment (ER444) employing an acidic inorganic aerosol nebulized from solution, with measurements made at steady-state relative humidity levels of 31, 50, 10, and 62%, at an overall average temperature of 25 ºC. The nebulizer solutions used in ER444 used higher levels of sulfuric acid relative to ammonium sulfate that the isoprene experiment described above (ER662). This produced a more acidic inorganic aerosol, with measured $[H^+]_{air}$ values of 718 nmol m^{-3} on average observed for the 1,3-butadiene acidic aerosol experiment.

Figure 5 provides a plot of the measured SOC levels as a function of humidity for these two 1,3-butadiene systems. For the base case experiment, the SOC values range from a high of 45.1 µgC m^{-3} at the lowest humidity level (2.5 g H_2O m^{-3}) to 24.7 µgC m^{-3} at the higher humidity (13.6 g m^{-3}). For the acidified experiment, SOC declined from 60.3 µgC m^{-3} at the lowest humidity level (1.9 g m^{-3}) to 31.1 µgC m^{-3} under the highest humidity (12.3 g m^{-3}). The range in SOC enhancement from the base case to the acidified case is far lower than that observed in the isoprene system, ranging from approximately 35% at low humidity to 25% at high humidity. These enhancements are somewhat lower than would be expected for this level of acidity based on the data presented in Figure 2. SOC yield curves, provided in Figure 4, follow this same trend, as the ΔHC shows only minimal variation with humidity.

These results are markedly different from those seen for isoprene/NO, both in terms of the level of SOC enhancement under the acidic condition and the extent to which the SOC enhancement declines with increasing humidification. It is not clear what factors are driving this difference in behavior. Part of the difference likely derives from structural differences between the two molecules, as was described above with respect to the SOC versus $[H^+]_{air}$ studies. Additionally, the higher level of $[H^+]_{air}$ used for the 1,3-butadiene experiment may be partially offsetting the impact of increasing humidity, as more aerosol liquid water would be needed to reduce actual particle acidity under these conditions. Other factors, such as the relative hygroscopicity of isoprene and 1,3-butadiene SOA, may also be contributing. Additionally, the temperature difference between the two experiments, although relatively small (approximately 3 ºC on average) may be sufficient to introduce differences in the gas-particle partitioning between the two experiments. Further experimentation is needed to attempt to better understand which aspects of these aerosol systems are physically significant for activation or deactivation of these acid-influenced reaction pathways, in order to determine if these pathways are ultimately important to SOA formation in the ambient atmosphere.

4. Summary

These experiments support previous studies suggesting that acidic aerosol can lead to increased SOA formation from the photooxidation of isoprene under laboratory conditions. Changing the source of the acidity from nebulized inorganic aerosol to a more atmospherically relevant photochemical conversion of SO_2 into acidic sulfate aerosol nearly identical results as previous nebulized sulfate aerosol experiments. In addition, 1,3-butadiene, a chemically similar compound released from primarily anthropogenic sources, was also demonstrated to produce higher concentrations of SOA under acidic conditions, albeit to a lesser extent than was seen with isoprene. The humidity experiments further suggest that aerosol liquid water content can have a substantial effect on SOA formation from isoprene and 1,3-butadiene. Increasing humidity produces a notable reduction in SOC formation in both the isoprene and 1,3-butadiene photochemical systems, which is more pronounced in both systems in the presence of acidic inorganic aerosols, and was most pronounced for the acidified isoprene/NO system.

In the isoprene/NO photochemical systems examined in this study, SOC enhancement due to the presence of acidic inorganic aerosol was observed to be negligible at absolute humidity levels above approximately 11 g H_2O m^{-3}. This lower SOC enhancement at elevated humidities may explain, in part, the difficulties in detecting increased SOA formation under acidic conditions in field studies of ambient air masses, particularly in humid climates like the southeastern US. This work suggests that a more detailed understanding of the role of humidity and of aerosol liquid water content is likely required in order to accurately predict the impact of acidity-influenced oxidation chemistry on overall SOA yields. While the data presented here may suggest that enhanced SOA formation via acid-influenced pathways is more constrained than previous studies may have suggested, it does still appear to represent a viable pathway for additional SOA formation from a number of precursor hydrocarbons, which may need to be incorporated into air quality models in order to accurately estimate secondary PM concentrations in certain locations.

While these experiments are suggestive, they also include a number of shortcomings that need to be addressed in future work. Perhaps the most significant is the use of absolute humidity and $[H^+]_{air}$ as surrogate measures of aerosol liquid water content and aerosol pH. Determination of the effective pH in the aerosol particles through the application of thermodynamic models, such as ISORROPIA or AIM, should provide a more realistic assessment of actual acidity than the $[H^+]_{air}$ approach, provided adequate gas and particle composition data is obtained experimentally. However, even these models generally account for only the influence of inorganic species, while the presence of isoprene SOA products has been reported to also contribute significantly to water uptake on ambient aerosols (Guo et al., 2014). This suggests that for laboratory experiments with high organic aerosol concentrations, particularly from isoprene-related parent hydrocarbons, direct measurements of aerosol liquid water content may be required.

Additionally, the relative humidity experiments presented here consider predominantly systematic increases in relative humidity. As some phenomena related to aerosol liquid water content are known to display hysteresis, such as deliquescence of sulfate aerosols, further testing. Experiments incorporating descending relative humidities and larger humidity steps are warranted, particularly along with the inclusion of liquid water content measurements. Further examination of the mixing state and phase of the generated aerosols would also like be of value, given that the available interfacial area could affect interactions between H^+, sulfate, and SOA, which may in turn affect organosulfate formation or other pathways to increased SOA yield.

Finally, further research is needed to examine changes in organic composition triggered by the effects considered in this work. In particular, the mechanism through which humidity level affects OC production from isoprene, even under non-acidified conditions, could be important to the selection of appropriate SOC yields in air quality models. A further examination of the similarities and differences between acid-influenced OC formation in the isoprene and 1,3-butadiene systems would also likely be valuable. A more rigorous organic analysis of product distributions may help reveal why isoprene appears to be significantly more sensitive to acidic conditions than 1,3-butadiene at low humidity levels, and whether this difference is due to structural effects related to the additional methyl group affecting gas-phase chemistry, particle-phase organosulfate formation, or due to other phenomena, such as differences in volatility and partitioning of oxidized intermediates. A more detailed comparison of isoprene and 1,3-butadiene organic chemistry under acidic conditional may help with the development of more accurate mechanisms for inclusion in air quality models.

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Table 1. Isoprene SOA as a function of sulfate acidity from the photooxidation of SO_2.

Stage	Initial SO_2 (ppb)	SO_4^{-2} (μgC m^{-3})	$[H^+]_{air}$ (nmol m^{-3})	OC (μgC m^{-3})	OC Increase (%)	SOC Yield
ER370-9	11[a]	0	54	5.3	0.0	0.002
ER370-8	55	8.7	324	8.6	62	0.003
ER370-7	88	15.3	457	10.9	105	0.004
ER370-4	136	31.1	912	16.8	214	0.006
ER370-1	231	59.2	1524	29.8	459	0.011

[a] Measurement subject to possible HC interference. No SO_2 was added in stage ER370-9.

Table 2. Conditions and OC data for 1,3-butadiene photooxidation with the nebulized inorganic aerosol. For each stage, the initial 1,3-butadiene was 6.8 ppmC; initial NO was 0.34 ppm; and relative humidity was 30% (6.1 g m^{-3} absolute humidity).

Stage	$[H^+]_{air}$ (nmol m^{-3})	OC (μgC m^{-3})	OC % Increase	ΔHC (ppmC)	SOC Yield
ER444-1	48	22.6	0.0	5.0	0.009
ER444-2	259	28.3	25	5.0	0.012
ER444-3	666	41.6	84	5.2	0.016
ER444-4	963	44.7	98	4.9	0.019

Table 3. Summary of the normalized yields for sulfate acidity effect for precursor hydrocarbons studied to date. SOA formed in the presence of NO_X at 30% relative humidity, except where indicated.

SOA precursor	$[H^+]_{air}$ (nmol m^{-3})	[OC] (μgC m^{-3})	Normalized OC Change [a]	Reference
1,3-Butadiene	48 – 963	22.6 – 44.7	0.11	(this work)
Isoprene [b]	54 - 1524	5.3 – 29.8	0.31	(this work)
Isoprene	32 – 517	12.2 – 31.1	0.32	Surratt et al. (2007)
α-pinene (low OC)	68 – 1229	8.0 – 11.6	0.044	Offenberg et al. (2009)
α-pinene (high OC)	153 – 1014	40.5 – 55.3	0.039	Offenberg et al. (2009)
β-caryophyllene	112 – 1147	10.0 – 34.0	0.22	Offenberg et al. (2009)
2-Methyl-3-butene-2-ol (MBO) [c]	125 – 1590	6.5 – 21.9	0.14	Zhang et al. (2012)

[a] %SOC change per $[H^+]_{air}$; [b] acidity generated from SO_2 photooxidation; [c] experiment conducted in the absence of NO_x under dry conditions

Table 4. Reaction conditions for humidity variation experiments.

Exp	Hydrocarbon	Inorganic	HC (ppmC)	NO_x (ppm)	Temp (°C)	Humidity (%)	Humidity (g m^{-3})
ER667	Isoprene	Low Conc $(NH_4)_2SO_4$	8.2	0.35	28 – 29	9 – 49	2.6 – 13.1
ER662	Isoprene	1/2 $(NH_4)_2SO_4$, 1/2 H_2SO_4	7.0	0.29	27 – 28	8 – 44	2.2 – 11.3
ER666	1,3-Butadiene	Low Conc $(NH_4)_2SO_4$	7.1	0.42	25 – 26	11 - 60	2.5 – 13.6
ER444	1,3-Butadiene	1/3 $(NH_4)_2SO_4$, 2/3 H_2SO_4	6.9	0.34	22 – 23	10 - 62	1.9 – 12.3

Figure 1. A comparison of the sulfate acidity effect for isoprene SOA. For Surratt et al., 2007 (open circles), the acidity was derived from nebulized sulfate aerosol. In the present study (closed circles), the acidity was derived from the photooxidation of SO_2.

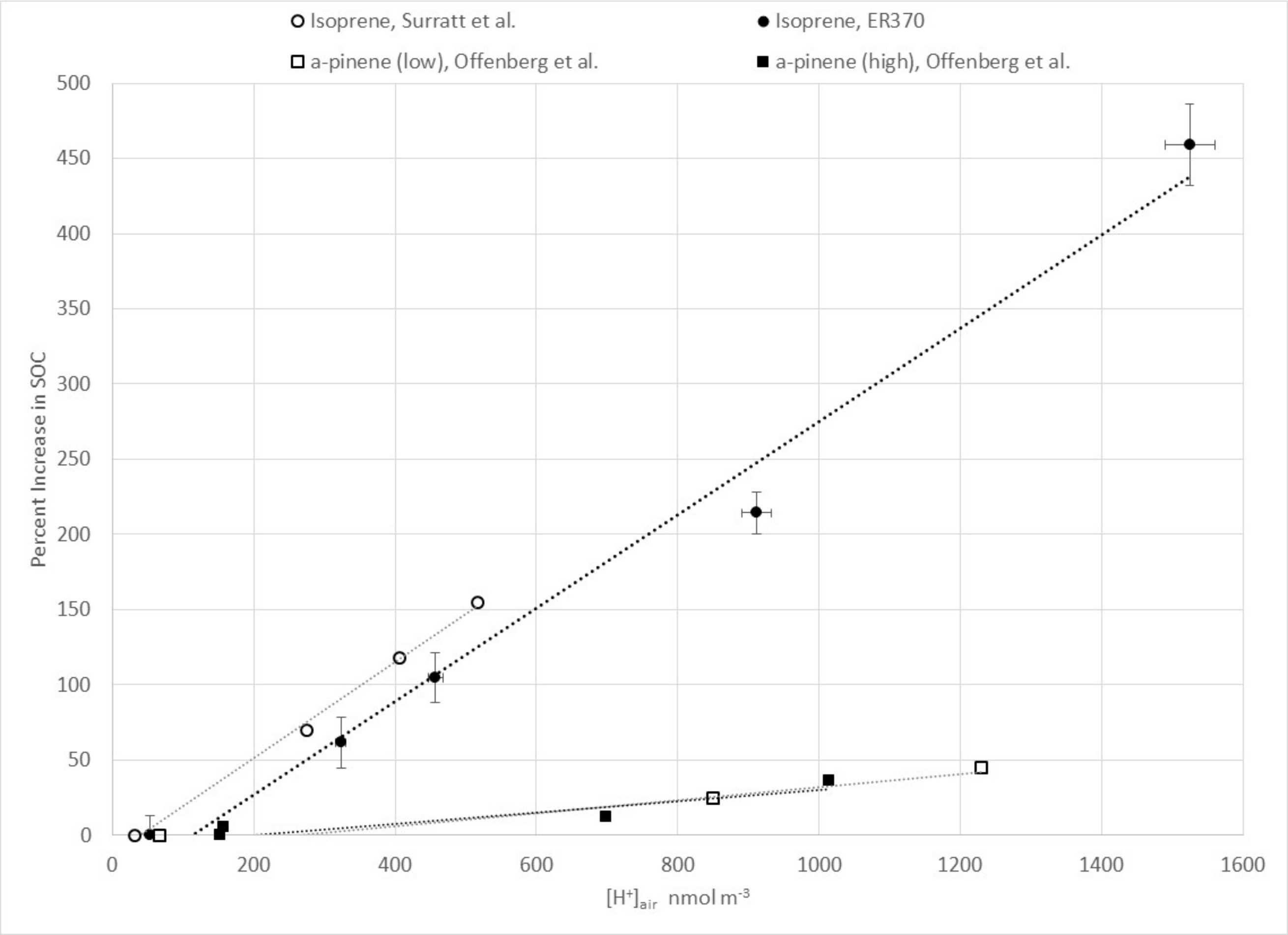

Figure 2. Aerosol acidity effect for 1,3-butadiene/NO, relative to previously published data (Surratt et al., 2007; Offenberg et al., 2009). All experiments were conducted with nebulized sulfate aerosol at 30% relative humidity.

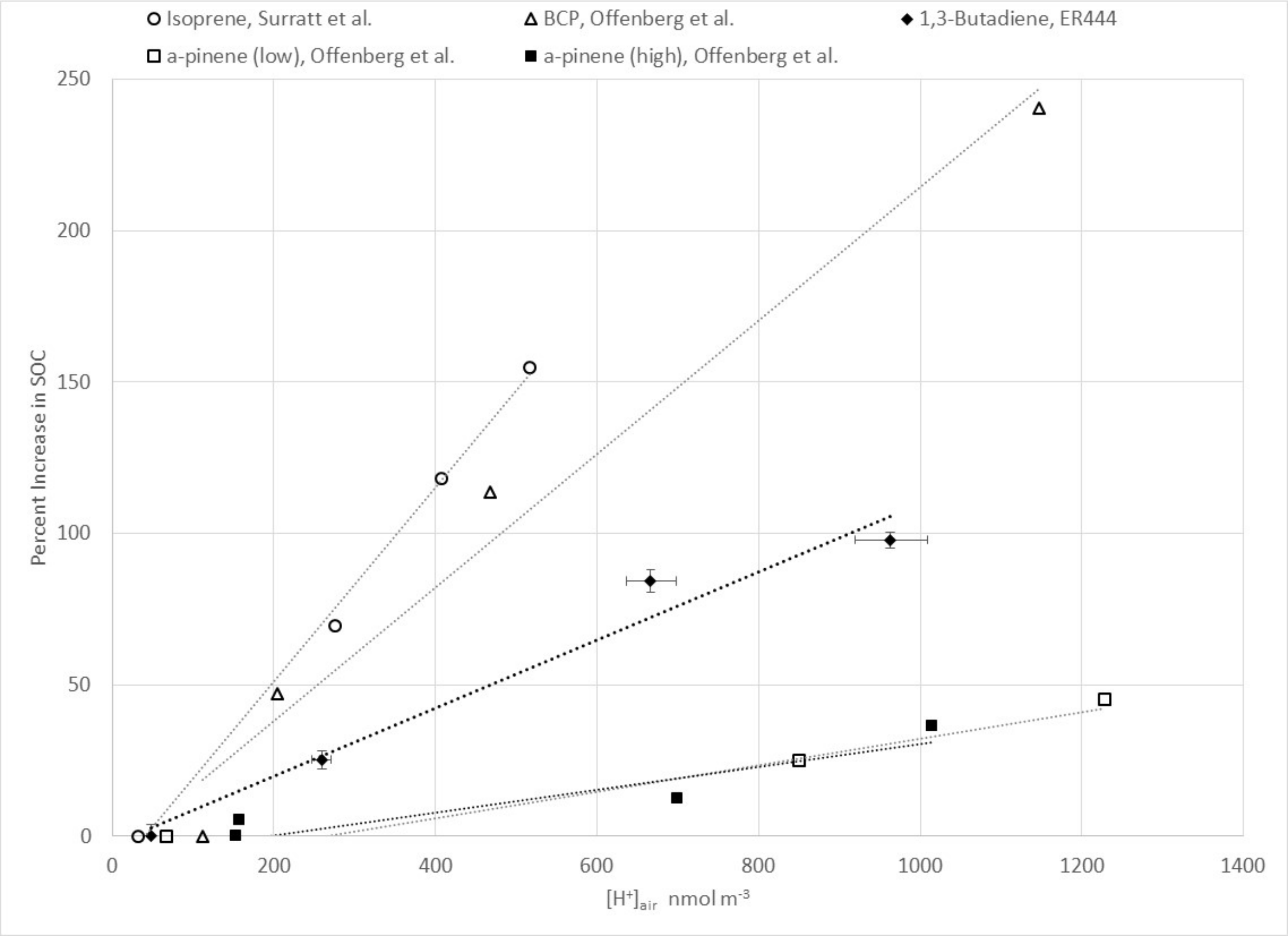

Figure 3. A comparison of the effects of humidity variation on isoprene/NO SOC formation. In ER667 (open circles), only a low concentration ammonium sulfate seed aerosol was present. In ER662 (closed circles), a moderately acidic sulfate aerosol was generated via nebulization.

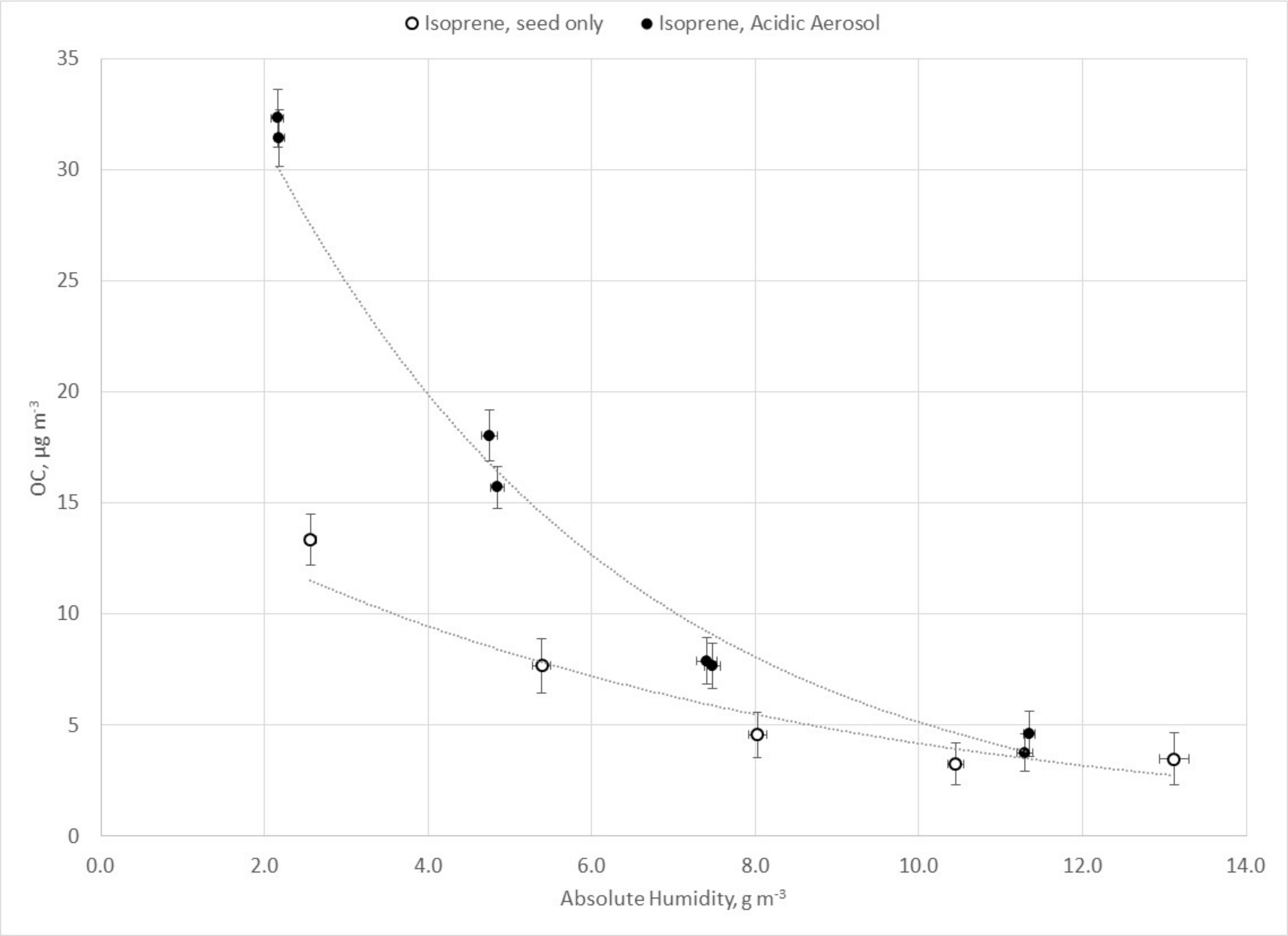

Figure 4. SOC yields for isoprene/NO and 1,3-butadiene/NO as a function of absolute humidity. In ER667 (isoprene, open circles) and ER666 (1,3-butadiene, open diamonds), only a low concentration ammonium sulfate seed aerosol was present. In ER662 (isoprene, closed circles) and ER444 (1,3-butadiene, closed diamonds), an acidic sulfate aerosol was present.

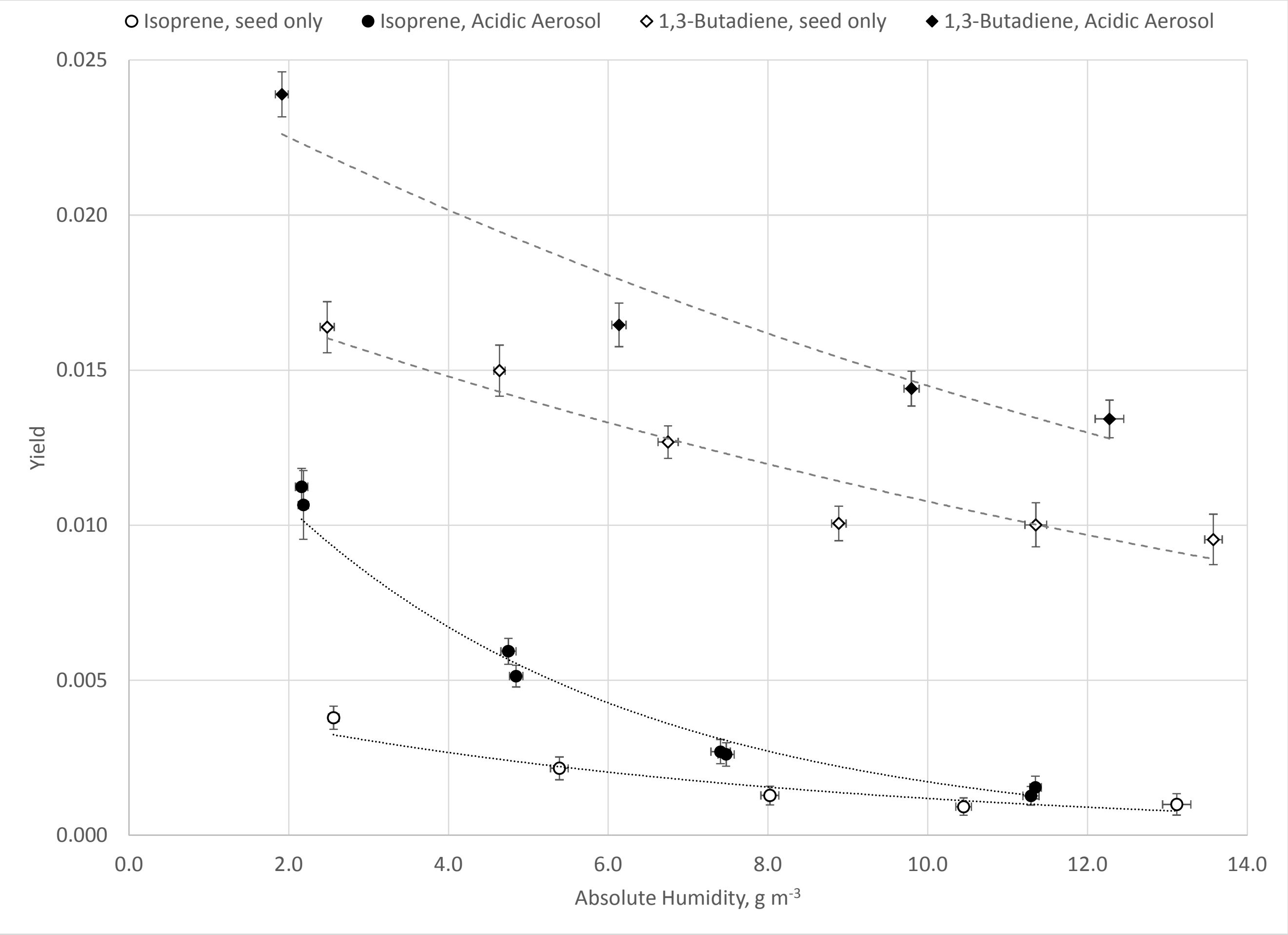

Figure 5. A comparison of the effects of humidity variation on isoprene/NO SOC formation. In ER666 (open diamonds), only a low concentration ammonium sulfate seed aerosol was present. In ER444 (closed diamonds), an acidic sulfate aerosol was generated via nebulization.