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Contribution of Organic Nitrates to Organic Aerosol over South Korea during KORUS-AQ

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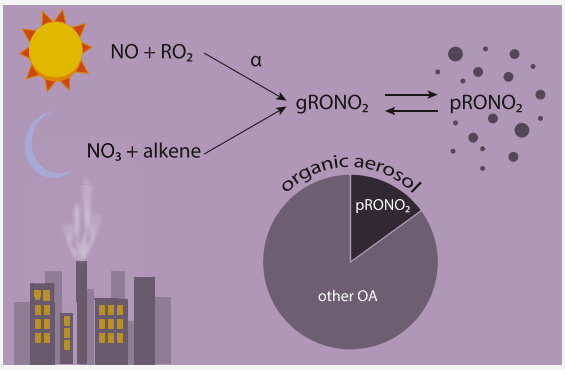
ABSTRACT: The role of anthropogenic NO_x emissions in secondary organic aerosol (SOA) production is not fully understood but is important for understanding the contribution of emissions to air quality. Here, we examine the role of organic nitrates ($RONO_2$) in SOA formation over the Korean Peninsula during the Korea−United States Air Quality field study in Spring 2016 as a model for $RONO_2$ aerosol in cities worldwide. We use aircraft-based measurements of the particle phase and total (gas + particle) $RONO_2$ to explore $RONO_2$ phase partitioning. These measurements show that, on average, one-fourth of $RONO_2$ are in the condensed phase, and we estimate that ≈15% of the organic aerosol (OA) mass can be attributed to $RONO_2$. Furthermore, we observe that the fraction of $RONO_2$ in the condensed phase increases with OA concentration, evidencing that equilibrium absorptive partitioning controls the $RONO_2$ phase distribution. Lastly, we model $RONO_2$ chemistry and phase partitioning in the Community Multiscale Air Quality modeling system. We find that known chemistry can account for one-third of the observed $RONO_2$, but there is a large missing source of semivolatile, anthropogenically derived $RONO_2$. We propose that this missing source may result from the oxidation of semi- and intermediate-volatility organic compounds and/or from anthropogenic molecules that undergo autoxidation or multiple generations of OH-initiated oxidation.



KEYWORDS: *organic nitrates, organic aerosol, urban air quality, aerosols, particulate matter, volatile organic compounds, nitrogen oxides, absorptive partitioning theory*

1. INTRODUCTION

Organic aerosol (OA) constitutes a large, and often dominant, fraction of tropospheric aerosol mass.[1−3] Much of this OA is secondary (secondary OA, SOA), produced from volatile organic compounds (VOCs) that are sufficiently oxidized in the atmosphere to be condensable and/or water-soluble.[4−8] The chemical and physical processes that control SOA production, however, are complex and currently highly uncertain.[1,9−16]

Particle-phase organic nitrates ($pRONO_2$) have recently emerged as a significant component of SOA in areas dominated by biogenic emissions, including in the Southeast United States,[17−22] in the Rocky Mountains,[23] across Europe,[24] in the boreal forest,[25] in the California Central Valley,[26,27] and in rural areas of both northern and southern China.[28−30] A number of studies have also found significant contributions of $pRONO_2$ to SOA in regions of oil and gas production, including in the Alberta Oil Sands[31] and in the Uintah Basin.[32] Recent observations have shown that organic nitrates are a significant contributor to OA in Chinese cities.[33,34] Specifically, Yu et al.[34] found that organic nitrates make up 9−25% of OA during spring-autumn in urban Shenzhen, and the dominant precursors to $pRONO_2$ included both biogenic (α-pinene, limonene, and camphene) and anthropogenic (styrene) VOCs.

Organic nitrates are produced from the oxidation of VOCs in the presence of NO_x(≡NO + NO_2), as shown in Figure 1. During the daytime when photochemistry is active, the OH oxidation of VOCs generates RO_2 radicals (R1). The minor products (branching ratio α) of the reaction of NO with RO_2 radicals are gas-phase organic nitrates ($gRONO_2$, R2). In the nocturnal residual layer away from fresh NO emissions, NO_3 radicals can add to the double bonds of alkenes to generate $gRONO_2$ (R3), for example, ref 35.

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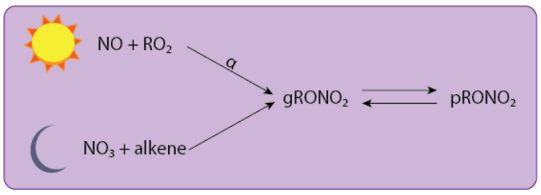

Figure 1. Schematic of $RONO_2$ production and phase partitioning.

$$RH + OH \rightarrow RO_2 + H_2O \quad (R1)$$

$$RO_2 + NO \xrightarrow{a} RONO_2 \quad (R2)$$

$$NO_3 + R_1 = R_2 \rightarrow R_1(ONO_2) - R_2 \quad (R3)$$

If an $RONO_2$ molecule generated from either the OH-initiated or NO_3-initiated reaction pathways has sufficiently low volatility, it may partition into the aerosol phase as a particle-phase organic nitrate, $pRONO_2$ (Figure 1). At 273 K, the addition of a nitrate functional group reduces the saturation concentration of a given molecule by 2.23 orders of magnitude,[36] thereby generating a lower volatility compound that may condense to form SOA.

In this study, we examine the contribution of $pRONO_2$ to OA in Seoul, Korea. As a megacity, Seoul has a complex mixture of urban emissions, including from a number of chemical facilities and from the transport of emissions from China, that contribute to the aerosol burden,[37,38] although the dominant precursors for SOA production in Seoul are locally emitted VOCs.[37] To better understand the sources of SOA in Seoul, here we aim to quantify the contribution of $pRONO_2$ to the total OA mass and determine the precursors and processes that control the production of $pRONO_2$ in Korea using observations from the 2016 Korea−United States Air Quality (KORUS-AQ) measurement campaign.

2. METHODS

Here, we introduce the KORUS-AQ campaign (Section 2.1), the UC Berkeley thermal dissociation laser-induced fluorescence (TD-LIF) measurements of $pRONO_2$ (Section 2.2), the University of Colorado Boulder high-resolution time-of-flight aerosol mass spectrometer (CU-AMS) measurements of $pRONO_2$ and OA (Section 2.3), and our Community Multiscale Air Quality (CMAQ) modeling system simulations of $RONO_2$ over Northeast Asia during the time period of the KORUS-AQ campaign (Section 2.4).

2.1. KORUS-AQ. The KORUS-AQ campaign took place during May and June 2016 over the Korean Peninsula and the Yellow Sea.[39] Seoul, Korea, is bordered to the west by the Yellow Sea and Gyeonggi Bay and bordered to the north, east, and south by forested and mountainous regions.[40] During KORUS-AQ, winds were typically from the west or northwest, meaning that air over the Yellow Sea can be considered "background" air for Seoul.[41] There are a number of large industrial facilities along the northwest coast of South Korea, including the Daesan petrochemical complex which produces large amounts of VOC emissions.[42]

This analysis uses observations from the NASA DC-8 which flew 20 research flights out of Pyeongtaek, South Korea (≈60 km south of Seoul). Flights typically began around 08:00 LT (KST). During a typical flight, three missed approaches were performed over the Seoul Air Base (within 15 km of the Seoul city center): one soon after takeoff around 08:00 LT, one around 12:00 LT, and one prior to landing around 15:00 LT. Each missed approach included 15−45 min of observations within the boundary layer in the Seoul metropolitan area. Flights also consisted of transects west of Seoul over the Yellow Sea, south of Seoul to Jeju, and/or southeast of Seoul to Busan at varying altitudes, as shown in Figure 2. We use 60 s measurement averages in this analysis.

During KORUS-AQ, the NASA DC-8 was equipped with the only two currently aircraft certified techniques to measure total $pRONO_2$: the UC Berkeley TD-LIF instrument and the University of Colorado Boulder CU-AMS. Although some other measurement techniques exist to measure certain specific $RONO_2$ species, for example, refs 43 and 44, the TD-LIF and CU-AMS measurement schemes allow for measurements of the sum of all $pRONO_2$ species.

2.2. TD-LIF Measurements of $tRONO_2$ and $pRONO_2$. Measurements of $tRONO_2$ (gas + particle) were made using the UC Berkeley TD-LIF instrument.[45,46] Briefly, one channel of the instrument measures NO_2 by LIF. In two other channels, air flows through a heated quartz oven prior to LIF

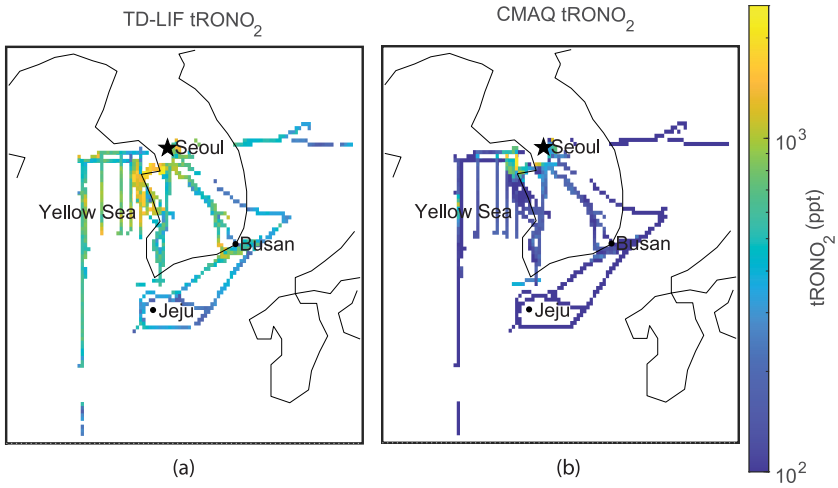

Figure 2. Maps of average (a) TD-LIF measured and (b) CMAQ-modeled $tRONO_2$ on a log scale, gridded to 0.1°. Seoul, Jeju, Busan, and the Yellow Sea are labeled for reference. Note that the modeling domain is larger than the domain of the map plotted here and covers much of Northeast Asia (17.4−47.2° N and 93.2−147.4° E).

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detection of NO_2. One channel's oven is set at 180 °C, the temperature at which peroxy nitrates (RO_2NO_2) dissociate into RO_2 and NO_2. The second is set at 360 °C, the temperature at which $RONO_2$ dissociate into RO + NO_2. The difference in NO_2 detected in adjacent channels gives the mixing ratio for each class of compounds: the RO_2NO_2 mixing ratio corresponds to the difference between the 180 °C channel and the unheated channel, and the $RONO_2$ mixing ratio corresponds to the difference between the 360 °C channel and the 180 °C channel.

$pRONO_2$ concentrations were measured using a fourth channel configured as described in Rollins et al.[47] Before entering the heated section of the instrument, air passes through a 10 cm long activated carbon honeycomb denuder with an outer diameter of 2 cm, which removes gas-phase compounds (MAST Carbon International Ltd. carbon monolith with 89 cells cm^{-2} where each open square is 0.63 by 0.63 mm with 0.43 mm thick walls in between). The particles that remain are then rapidly heated to vaporize the aerosols and dissociate the $RONO_2$ molecules present into RO and NO_2. NO_2 is then detected via LIF, giving a measurement of $pRONO_2$. We estimate a limit of detection of 20 ppt of $pRONO_2$ or 0.055 $\mu g\ m^{-3}$ of NO_3. Although inorganic nitrate compounds will also be vaporized, volatile inorganic nitrate salts form HNO_3 when vaporized[48] and will therefore not interfere in this measurement. Empirical and theoretical studies confirm that NO_2, HNO_3, and gas-phase organic nitrates are all removed at nearly 100% efficiency in the charcoal denuder, while particles greater than 100 nm in diameter are transmitted with over 95% efficiency.[47] A recent work has shown that HONO is removed with near-100% efficiency in dry air and with 85% efficiency at an RH of 46% with a similar denuder.[49] Furthermore, during KORUS-AQ, the denuder could be bypassed with a pair of three-way valves, as shown in Figure S1. When bypassed, the NO_2 calibration mixture reached the $pRONO_2$ LIF cell. When not bypassed, the NO_2 calibration events served as checks for NO_2 breaking through the denuder. Compared to the 20 ppt limit stated above, no breakthroughs of the 12 or 24 ppb NO_2 calibration steps were detectable during the deployment, as shown in Figure S6.

KORUS-AQ is the first time $pRONO_2$ measurements have been made with TD-LIF on aircraft. Previous ground-based measurements of $pRONO_2$ by TD-LIF were made in the Rocky Mountains during BEACHON-RoMBAS in 2011,[23] in the Uintah Basin during the 2012 Uintah Basin Winter Ozone Study (UBWOS),[32] in the Southeast United States during Southern Oxidant and Aerosol Study (SOAS) in 2013,[21] and in the California Central Valley during CalNex in 2010.[27]

We apply a small correction for the loss of charged particles to TD-LIF measurements of $tRONO_2$ and $pRONO_2$. In the TD-LIF inlet configuration during KORUS-AQ, air for all channels goes through 10−20 cm of PFA Teflon before heating. We performed a series of laboratory experiments (detailed in Section S1) to determine the loss of charged particles in these lengths of PFA Teflon tubing. Taking into account the ambient distribution of charged particles[50] and the observed aerosol size distribution measured during KORUS-AQ, there is less than 20% loss for charged particles with diameters less than 280 nm in the TD-LIF inlet.

We also apply a correction for inertial losses of particles in the TD-LIF inlet. We model the inertial losses on the two bends (90 and 98°) in the inlet (see Section S1) for varying particle sizes. We apply the size-dependent modeled losses to the aerosol volume distribution measured by a laser aerosol spectrometer (Langley LARGE Group). On average, we estimate that TD-LIF observes ≈60% of the particles observed by laser aerosol spectrometry. We apply both particle loss corrections (charged and inertial) to both the $pRONO_2$ and $tRONO_2$ TD-LIF measurements.

2.3. CU-AMS Measurements of $pRONO_2$. A second measurement of $pRONO_2$ was made by CU-AMS (Aerodyne Research, Inc.). CU-AMS also measured OA concentrations. A description of the CU-AMS aircraft sampling can be found in DeCarlo et al.,[51] Canagaratna et al.,[52] and Nault et al.[37]

The CU-AMS uses NO_x ion ratios (NO_2^+/NO^+) to differentiate between inorganic nitrate (NH_4NO_3) and organic nitrate ($pRONO_2$),[23,53] described further in Section S2. Uncertainties in this method are greatest when $pRONO_2$ < 20% of the total measured aerosol nitrate; those CU-AMS measurements have been removed from this analysis. This ion ratio technique has been used previously in rural environments where VOCs are dominantly biogenic and $RONO_2$ concentrations are relatively small.[17,23,54] However, the high NH_4NO_3 loadings in the urban environment measured during KORUS-AQ create uncertainty for the CU-AMS measurement of $pRONO_2$.

Although we applied a series of corrections for particle loss in the TD-LIF inlet (described in Section 2.2), we could not entirely reconcile the differences between the two measurements. Since the two measurements may be prone to larger uncertainties under different aerosol size and composition conditions, we conduct the following analyses using both the TD-LIF and CU-AMS $pRONO_2$ measurements separately and treat them as upper and lower bounds. A comparison of the TD-LIF and CU-AMS measurements, both before and after applied corrections, can be seen in Figure S9.

Because the TD-LIF and CU-AMS $pRONO_2$ measurements do not agree perfectly, we also use a CU-AMS-adjusted $tRONO_2$ to ensure a consistent comparison. In the following calculations that use CU-AMS $pRONO_2$, we subtract the TD-LIF $pRONO_2$ measurement from the TD-LIF $tRONO_2$ measurement to give an estimate of the $gRONO_2$ measured by TD-LIF. We then add the CU-AMS $pRONO_2$ to the estimated TD-LIF $gRONO_2$ to generate the CU-AMS-adjusted $tRONO_2$.

2.4. CMAQ Modeling of $RONO_2$ Chemistry and Phase Partitioning. We ran the CMAQ model v5.2[55,56] with the RACM2_Berkeley2.1 chemical mechanism[22,57] over Northeast Asia with a 15 km horizontal grid (17.4−47.2° N and 93.2−147.4° E) and 27 vertical layers. Meteorological fields were generated by WRF v3.8.1 and processed for use in CMAQ by MCIP v4.5.[58] The simulation period was April 17, 2016−June 12, 2016, with the first 14 days as a spin-up period to minimize the impact of initial conditions.

We used the KORUSv5.0 anthropogenic emission inventory developed at Konkuk University based on the CREATE emission inventory[59] which includes area, point, mobile, and ship emissions, MEGANv2.1 biogenic emissions,[60] and FINNv1.5 fire emissions,[61] all processed through the Sparse Matrix Operator Kernel Emission (SMOKE) system.[62] The KORUSv5.0 emission inventory was prepared using the SAPRC07T AERO6 mechanism, which we then converted to RACM2_Berkeley2.1 (detailed in Table S1).

We made a few adjustments to the emission inventory informed by a series of comparisons between CMAQ-modeled VOC concentrations and aircraft VOC measurements made

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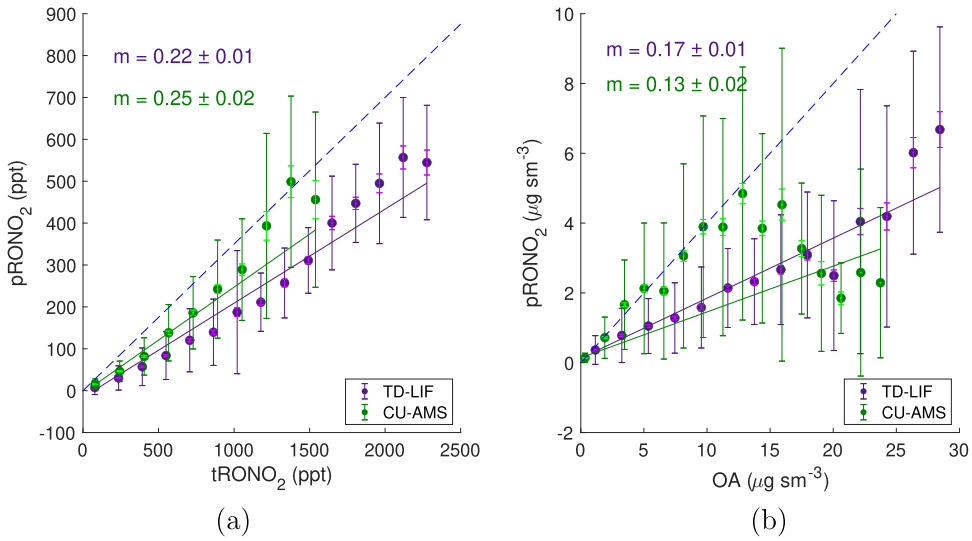

Figure 3. (a) Plot of $pRONO_2$ vs $tRONO_2$ mixing ratios as measured by TD-LIF and CU-AMS. Data are binned by the $tRONO_2$ mixing ratio, and the average $pRONO_2$ in each bin is plotted. The York fit shown corresponds to the average fraction of $RONO_2$ in the particle phase (F_p). We draw an estimated upper limit (≈35%) for the fraction of $RONO_2$ in the particle phase, as shown in the blue dashed line, drawn above the mean of most measurements. (b) Plot of $pRONO_2$ mass concentration (using an estimated average molecular weight of 300 g mol^{-1}) vs OA mass concentration. Data are binned by OA concentration, and the average $pRONO_2$ in each bin is plotted. The York fit shown corresponds to the average fraction OA mass that can be attributed to $pRONO_2$. Again, we draw an estimated upper limit (≈40%) for the fraction of OA mass attributable to $pRONO_2$, as shown in the blue dashed line, drawn above most measurement means. We do not understand why AMS data above 15 $\mu g\ m^{-3}$ deviate so strongly from the trend measured at lower OA concentrations. In both plots, the larger, dark-colored error bars correspond to the standard deviation of measurements within each bin to represent observed variability, whereas the smaller, light-colored error bars correspond to the standard error of measurements within each bin to represent measurement uncertainty. We apply a threshold requirement of 20 observations per bin to include in the plot.

with whole air samples analyzed with multicolumn gas chromatography.[63] We increased monoterpene emissions by a factor of 3 to improve the magnitude agreement between modeled and observed concentrations of monoterpenes (see Figure S12). Note that we expect monoterpenes in Korea to have both biogenic and anthropogenic sources.[64,65]

Comparison between modeled and observed BTEX (benzene, toluene, ethyl benzene, and xylenes) indicated that these species were also underestimated in the emission inventory (see Figure S12). We updated BTEX emissions over the Daesan petrochemical complex to match emission fluxes calculated from observations using a mass balance approach by Fried et al.[42] Elsewhere, we note that the spatial pattern of modeled TOL (defined as toluene and less-reactive aromatics, for measurement comparison purposes we approximate as the sum of toluene and ethyl benzene) corresponds well to the spatial pattern of the sum of measured toluene and ethyl benzene (see Figure S10). However, without any emission corrections, the model underestimates boundary layer TOL by a factor of 1.4. We also note that measurements of other reactive aromatics (xylenes and 1,2,4-trimethyl benzene) correlate well with the sum of measured toluene and ethyl benzene (see Figure S11). As such, we scale TOL emissions by 1.4 and define the emissions of the other reactive aromatics based on their measured ratios to the sum of toluene and ethyl benzene. We use measured *o*-xylene as a proxy for model species XYO, the sum of measured *m*-xylene and 1,2,4-trimethyl benzene as a proxy for model species XYM, and measured *p*-xylene as a proxy for model species XYP. This method results in setting XYO emissions as 0.05× TOL, XYM emissions as 0.08× TOL, and XYP emissions as 0.07× TOL, such that XYO, XYM, and XYP emissions all follow the same spatial pattern as TOL.

We use the default initial and boundary conditions from the ICON and BCON processors in CMAQ v5.2, respectively. However, measurements of isoprene-derived nitrates by Caltech's chemical ionization mass spectrometer (CIT-CIMS)[66] indicated that longer-lived propanone nitrate and ethanal nitrate were underestimated in CMAQ. Consequently, we increased the boundary and initial concentrations of propanone nitrate and ethanal nitrate to match the CIT-CIMS observations of both nitrates over the Yellow Sea (propanone nitrate = 21.5 ppt and ethanal nitrate = 4.1 ppt).

The original RACM2 (Regional Atmospheric Chemistry Mechanism) mechanism[67] is available in CMAQ v5.0.2 and later versions.[68] Browne et al.[69] modified the mechanism to RACM2_Berkeley to expand the organic nitrate chemistry. New species, along with their corresponding oxidation rates and branching ratios, were added to further classify anthropogenic nitrates[70−72] and to represent monoterpene nitrates.[73−76] The parameterization of OH-initiated isoprene oxidation was also updated.[77−79] RACM2_Berkeley was evaluated using aircraft observations over the Canadian boreal forest.[69]

RACM2_Berkeley was updated to RACM2_Berkeley2 in Zare et al.[57] to reflect recent advances in the representation of OH- and NO_3-initiated BVOC oxidation under both low- and high-NO_x conditions, with a focus on a detailed representation of nitrates derived from NO_3-initiated oxidation of isoprene and on the fate of the most important individual biogenically derived organic nitrates. Deposition rates were also updated.

Zare et al.[22] revised RACM2_Berkeley2 to RACM2_Berkeley2.1 to include an explicit representation of multiphase organic nitrate formation and loss, including vapor-pressure-driven partitioning into OA, aqueous-phase uptake, and condensed-phase reactions. Further updates were also done

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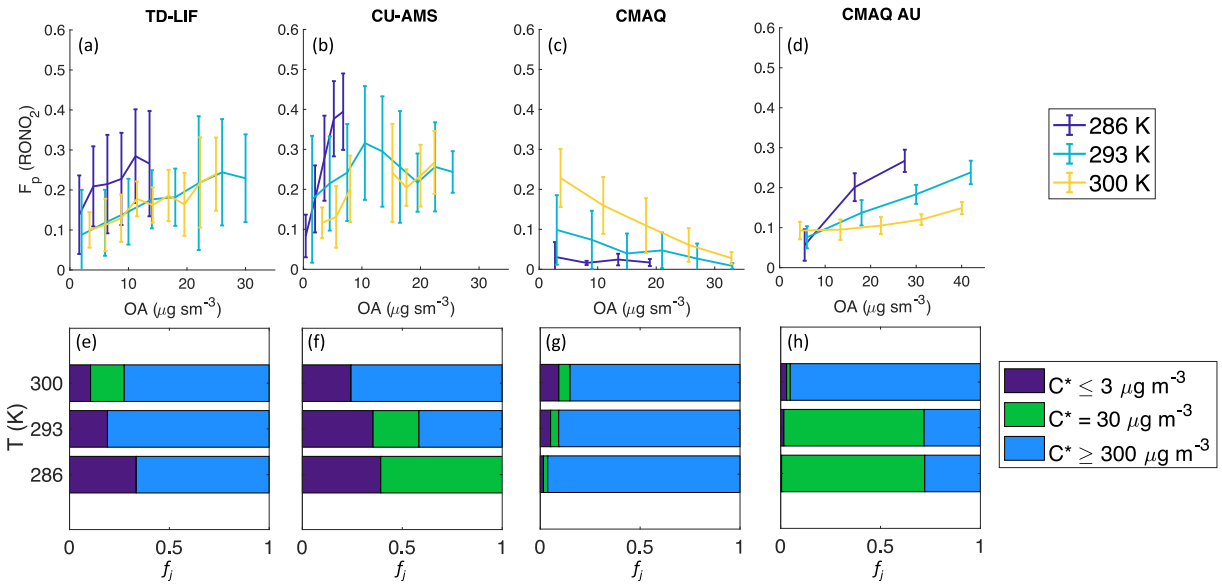

Figure 4. [Top] Plots of the fraction of $RONO_2$ in the particle phase (F_p) vs OA concentration. Data were separated into three temperature bins (centered at 286, 293, and 300 K) and binned by OA concentration. The average F_p in each OA bin is plotted, and error bars represent the standard deviation of F_p in each bin. As suggested by absorptive partitioning theory, measured F_p increases with the increasing available solvating aerosol (in this case, OA). [Bottom] Temperature-dependent fractional distribution (f_j) of saturation concentrations (C_j^*) fit to a volatility basis set. Each set of plots is shown for the TD-LIF measurements (a,e), the CU-AMS measurements (b,f), unmodified CMAQ output (c,g), and CMAQ output with an unknown source of $RONO_2$ added (d,h).

to explicitly represent isoprene nitrates from NO_3 oxidation that are subject to reactive uptake to the aerosol phase. As such, the RACM2_Berkeley2.1 mechanism represents our current understanding of $RONO_2$ chemistry and phase partitioning. Zare et al.[22] evaluated this mechanism (implemented in CMAQ) using observations from the SOAS campaign in the Southeast United States during Summer 2013. Inclusion of the particle-phase pathways for $RONO_2$ improved the model-measurement agreement for $tRONO_2$, and the modeled fraction of $tRONO_2$ in the particle phase (F_p) was within the range of observed F_p.

To compare modeled and measured concentrations, we sample CMAQ coincidentally in time (hourly resolution) and horizontal space with each observation. All comparisons in the following analysis use boundary-layer measurements (<1000 m) and the average of the bottom three model layers.

3. RESULTS

Maps of average TD-LIF measured and CMAQ modeled $tRONO_2$ used in the following analysis are shown in Figure 2. Both the measurements and model indicate that $tRONO_2$ concentrations are the highest in and around Seoul. However, the model consistently underpredicts $tRONO_2$ concentrations throughout the region. For reference, CMAQ predicts that >95% of $pRONO_2$ is derived from vapor-pressure-dependent partitioning into OA, whereas <5% of $pRONO_2$ enters the particle phase through aqueous pathways, similar to the study of Zare et al.[22] in the Southeast United States.

3.1. $RONO_2$ Partition into the Aerosol Phase and Can Be a Significant Contribution to SOA. We explore the average phase-partitioning behavior of $RONO_2$ during KORUS-AQ in Figure 3. Our observations from both TD-LIF and CU-AMS indicate that, on average, one-fourth of $tRONO_2$ is in the condensed phase and therefore contributes to the OA burden. We also consider a line, drawn above most measurement means in Figure 3, that represents a reasonable upper limit of 35% for the fraction of $tRONO_2$ in the particle phase.

To quantify the contribution of $pRONO_2$ to the total OA concentration, we assume an average molecular weight for $pRONO_2$ of 300 g mol^{-1}.[27] We expect condensable $RONO_2$ to be highly oxidized, to contain at least one nitrate group (molecular weight = 62 g mol^{-1}), and to therefore have relatively high masses. With this assumption, we estimate that ≈15% of the OA mass can be attributed to $pRONO_2$, as shown in Figure 3. Note that this estimate does not include CU-AMS measurements when $pRONO_2$ < 20% of the total measured aerosol nitrate. We again consider a reasonable upper limit, drawn above most measurement means, to estimate that a maximum of 40% of OA can be attributed to $pRONO_2$. This is within the range of $pRONO_2$ contributions to OA mass measured across Europe (42%),[24] in a suite of studies across the eastern United States, western United States, and Europe (5−73%)[80] and in recent studies in urban and rural China (9−28%).[34,81]

3.2. Observations Indicate That $RONO_2$ Phase Partitioning Is Controlled by Absorptive Partitioning into OA. Previous studies have shown that vapor pressure controls the phase of organic nitrates.[22,27] This equilibrium absorptive partitioning follows Raoult's law: the fraction of $RONO_2$ in the particle phase increases with increasing mass of the absorbing or solvating aerosol, namely, total OA.[82,83] Accordingly, the equilibrium fraction of an individual $RONO_2$ species i in the particle phase ($F_{p,i}$) is given by

$$F_{p,i} = \frac{C_{p,i}}{C_i} = \frac{C_{OA}/C_i^*(T)}{1 + C_{OA}/C_i^*(T)} = \left(1 + \frac{C_i^*(T)}{C_{OA}}\right)^{-1} \quad (1)$$

Here, $C_{p,i}$ and C_i are the particle phase and total concentrations of species i, respectively. $C_i^*(T)$ is the temperature-dependent saturation concentration (μ g m^{-3}) of species i and C_{OA} is the concentration of total OA.

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Table 1. Comparison of the York Fit Slopes between Measured (by TD-LIF and CU-AMS) and CMAQ Modeled Concentrations of $tRONO_2$, $pRONO_2$, and F_p[a]

	$tRONO_2$		$pRONO_2$		F_p	
	TD-LIF	CU-AMS	TD-LIF	CU-AMS	TD-LIF	CU-AMS
CMAQ	0.30	0.35	0.12	0.09	0.56	0.35
CMAQ add unknown	0.88	0.98	0.92	0.79	0.61	0.44

[a]Comparison is shown for both the unmodified CMAQ output and CMAQ output with an unknown source of condensable $RONO_2$ added. Scatter plots of these comparisons can be seen in Figure S14.

For both the TD-LIF and CU-AMS measurements of $pRONO_2$, the fraction of $RONO_2$ in the particle phase (F_p) increases with increasing OA concentration and increases with decreasing temperature, as shown in Figure 4. Assuming that the speciation of $RONO_2$ is invariant with temperature, these relationships between F_p, OA, and temperature indicate that the phase partitioning of $RONO_2$ during KORUS-AQ is indeed controlled by equilibrium absorptive partitioning.

To determine the volatility distribution of $RONO_2$ observed during KORUS-AQ, we define a saturation concentration basis set of $\{C_j^*\} = \{3, 30, 300\}$ $\mu g\ m^{-3}$, following the convention of Donahue et al.[82] Although we expect some $RONO_2$ species to have volatilities outside of this range, because the OA concentrations we observe during KORUS-AQ do not exceed 40 $\mu g\ m^{-3}$, we cannot reasonably constrain volatilities outside of this defined basis set. Given this basis set, the total fraction of organic nitrates in the particle phase ($F_{p,tot}$) can be represented as

$$F_{p,tot} = \frac{\sum_i C_i F_{p,i}}{\sum_i C_i} = \sum_{j=1}^{n} f_j \left(1 + \frac{C_j^*}{C_{OA}}\right)^{-1} \quad (2)$$

Here, f_j is the fraction of organic nitrates that can be classified as having saturation concentration C_j^* and $n = 3$ for the basis set defined earlier.

We solve for each f_j in eq 2 using our observations of $F_{p,tot}$ (=$pRONO_2/RONO_2$) and OA concentrations (C_{OA}). Moreover, because saturation concentration is dependent on temperature, we separate the observations into a series of temperature bins and solve for fitting parameters f_j in each temperature bin, as shown in Figure 4, for both TD-LIF and CU-AMS observations. As expected, organic nitrates become less volatile at lower temperatures. At all temperatures, 10−39% of organic nitrates can be represented with $C^* \leq 3$ $\mu g\ m^{-3}$, meaning that they will dominantly be condensed at the average observed OA concentrations of ≈9.8 $\mu g\ m^{-3}$. At high temperatures (≈300 K), 73−76% of organic nitrates can be represented with $C^* \geq 300$ $\mu g\ m^{-3}$, meaning that they will dominantly remain in the gas phase at observed OA concentrations. At low temperatures (≈286 K), the TD-LIF measurements suggest that 67% of organic nitrates can be represented with $C^* \geq 300$ $\mu g\ m^{-3}$ and the CU-AMS measurements suggest that 61% of organic nitrates can be represented with $C^* \geq 30$ $\mu g\ m^{-3}$.

We also fit the data to eq 2 using an empirical relationship between C^* and ΔH_{vap} from Epstein et al.[84] to examine the variation of $RONO_2$ volatilities observed at different temperatures but referenced to 300 K. Figure S15 shows the distribution of C^* (300 K) for $RONO_2$ during KORUS-AQ.

3.3. CMAQ Modeling Misses a Large Source of Semivolatile, Anthropogenically Derived $RONO_2$. To test the efficacy of our simulations, we compare modeled and measured NO_x, O_3, and O_x ($\equiv O_3 + NO_2$) mixing ratios at the Olympic Park ground site in Seoul, as shown in Figure S13. Our CMAQ simulation is able to capture the diurnal patterns in NO_x, O_3, and O_x and does not show a systematic under- or over-estimation. Additionally, we compare measured and modeled OA concentrations at KIST (Korea Institute of Science and Technology, Seoul) during the campaign (see Figure S13). The CMAQ simulation is able to accurately capture the regional OA background concentration and many of the episodic events with elevated OA. Moreover, a multimodel intercomparison study of air quality simulations for the KORUS-AQ campaign used comparisons of PM_1 to show that models, including CMAQ, were generally able to capture the synoptic meteorological patterns during the campaign.[85] We also include a comparison of measured and modeled temperature on the DC-8 in Figure S13, which shows that our CMAQ simulations are able to capture the observed variability in temperature.

However, our CMAQ simulation underpredicts measured $tRONO_2$ concentrations by a factor of ≈3, as shown by the slopes reported in Table 1 and plotted in Figure S14. Moreover, our CMAQ simulation underpredicts measured $pRONO_2$ concentrations by a factor of ≈10, indicating that the $RONO_2$ in CMAQ are too volatile. These underpredictions for both $tRONO_2$ and $pRONO_2$ indicate that our simulation is missing a large source of condensable $RONO_2$. We note that the RACM2_Berkeley2.1 mechanism does not include Cl-initiated oxidation of VOCs; however, based on observations, we estimate that the production rate of RO_2 radicals from Cl-oxidation is an order of magnitude slower than that from OH-initiated oxidation (see Section S6) and is therefore insufficient to explain the missing source of $RONO_2$.

To help determine the origin of the missing source of $RONO_2$, we examine the correlation between the model-measurement $RONO_2$ difference ($RONO_{2,\ diff}$) and measurements of various VOC classes. We find $R^2 < 0.05$ for the correlation between $RONO_{2,\ diff}$ and both isoprene and α-pinene, whereas there are relatively stronger correlations between $RONO_{2,\ diff}$ and anthropogenic alkanes ($R^2 = 0.15$), alkenes ($R^2 = 0.12$), aromatics ($R^2 = 0.23$), and aldehydes ($R^2 = 0.67$). The weak correlations between $RONO_{2,\ diff}$ and VOCs of biogenic origin and the relatively stronger correlations between $RONO_{2,\ diff}$ and VOCs of anthropogenic origin suggest that the missing source of condensable $RONO_2$ is derived from anthropogenic VOCs.

Note that the missing source of $RONO_2$ over the Korean Peninsula is likely derived from both the transport of $RONO_2$ produced in China and from locally produced $RONO_2$. As shown in Figure 2, CMAQ underpredicts $RONO_2$ over the Yellow Sea, a region influenced by the transport of air from China during parts of the KORUS-AQ campaign, as well as over the urban centers of the Korean peninsula where local chemistry contributes to the observed $RONO_2$.

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Furthermore, the RACM2_Berkeley2.1 mechanism was initially tested and validated on a regional scale over the Southeast United States, an area dominated by biogenic emissions.[22,57] Additionally, as described in Section 2.4, we adjusted the emissions of monoterpenes to improve the model-measurement agreement for biogenic VOCs. Though we expect some changes in the oxidation product distribution between low-NO_x environments (e.g., Southeast United States) and high-NO_x environments (e.g., Seoul), we are reasonably confident that our CMAQ simulation is accurately capturing the production and fate of $RONO_2$ derived from biogenic VOCs. We therefore attribute the missing source of $RONO_2$ in our simulations to $RONO_2$ of anthropogenic origin. The previous work evaluating RACM2_Berkeley2.1 in the Southeast United States[22,57] did not look at urban $RONO_2$ in the United States, but we have no reason to suspect that this missing source of condensable $RONO_2$ is not a general phenomenon.

The relationship between CMAQ modeled F_p ($RONO_2$), OA, and temperature is shown in Figure 4c. In contrast to the observations (Figure 4a,b) and in contrast with absorptive partitioning theory, the modeled F_p increases with increasing temperature and decreases with increasing OA. Exploration of the speciated distribution of modeled $RONO_2$ (shown in Figure S16) indicates that the increase in modeled F_p with temperature is driven largely by a temperature-dependent change in the $RONO_2$ speciation. The phase partitioning of each $RONO_2$ species is controlled by absorptive partitioning, meaning that the fraction of an individual $RONO_2$ species in the particle phase increases with decreasing temperature. However, the modeled increase in the total concentration of low-volatility monoterpene nitrates (HONIT) with temperature is larger than the modeled change in concentration of other higher-volatility nitrates with temperature. As a result, the concentration of $pRONO_2$ increases with increasing temperature faster than the concentration of $gRONO_2$ increases with increasing temperature, causing the total F_p to increase with increasing temperature. This modeled relationship between F_p and temperature stands in stark disagreement with the observations and therefore indicates that the species distribution of $RONO_2$ over Korea is incorrectly captured in our CMAQ simulation.

To test and quantify our hypothesis that our CMAQ simulation is missing a large source of condensable, anthropogenic $RONO_2$, we test the effect of adding an additional source of $RONO_2$. Because our CMAQ simulation underpredicts measured $tRONO_2$ concentrations by a factor of ≈3 (Table 1), we assign this additional source to have double the concentration of the existing simulated $RONO_2$. To determine the average volatility of this missing source of $RONO_2$, we iteratively vary its assigned C^* by an order of magnitude (C^* = 30, 300, and 3000 $\mu g\ m^{-3}$) and use an empirical relationship between C^* and ΔH_{vap} from Epstein et al.[84] We find the best agreement between modeled and measured $pRONO_2$ and F_p with $C^* = 300\ \mu g\ m^{-3}$, as shown in Table S2. Although comparison between modeled and measured $RONO_2$ remains relatively scattered (see Figure S14) and the missing source likely includes a variety of molecules with a range of volatilities, adding this missing semivolatile $RONO_2$ source improves the magnitude of the model-measurement agreement for $tRONO_2$, $pRONO_2$, and F_p, as shown in Table 1. Moreover, as shown in Figure 4, addition of this unknown source of relatively condensable $RONO_2$ results in an increase in F_p with decreasing temperature and increasing OA concentration. This relationship between F_p, temperature, and OA is in agreement with the observations and with the equilibrium absorptive partitioning theory.

4. DISCUSSION

The RACM2_Berkeley2.1 mechanism represents our state-of-the-science understanding of $RONO_2$ chemistry, where the only sources of semivolatile $RONO_2$ are biogenic. However, this mechanism only captures one-third of the $RONO_2$ production over the Korean Peninsula. Moreover, the unknown source of organic nitrates consists of $RONO_2$ that have lower volatility than most of the existing $RONO_2$ in the model. Consequently, our current understanding of $RONO_2$ chemistry is missing pathways for semivolatile $RONO_2$ production as a result of either missing oxidation pathways (first- or multi-generation, bimolecular or unimolecular) and/or an underestimation of $RONO_2$ yields.

Because the known chemistry can only account for one-third of the observed $RONO_2$, the missing source is approximately double in magnitude relative to the known sources. During KORUS-AQ, the average reactivity of all measured VOCs with OH was 2.4 s^{-1}, and the effective average $RONO_2$ yield (α), weighted by reactivity, was 1.3%. If the unknown source of $RONO_2$ has a low α of 1%, the missing reactivity must be ≈3 s^{-1}. On the other hand, if the unknown source of $RONO_2$ has a higher α of 20%, the missing reactivity must be ≈0.15 s^{-1}. For reference, during KORUS-AQ, the average isoprene reactivity was 0.051 s^{-1} and the average toluene reactivity was 0.054 s^{-1}.

We hypothesize three potential missing sources of semivolatile $RONO_2$: (1) missing source(s) of semi- and intermediate-volatility organic compounds (S/IVOCs) that are oxidized to $RONO_2$; (2) unrepresented autoxidation mechanisms that produce highly oxygenated organic peroxy radicals (RO_2) which could react with NO to form $RONO_2$; or (3) more generations of bimolecular oxidation that are currently represented.

S/IVOCs are considered major SOA precursors, for example, refs 12, 14, 37, and 86−93, but their concentrations are challenging to measure in the atmosphere due to condensation within instruments, for example, ref 94, and their chemistry is difficult to measure in chamber experiments due to wall loss, for example, ref 95. Nault et al.[37] concluded that during KORUS-AQ, S/IVOCs and reactive aromatics contributed to 70% of the total SOA over Seoul. Because they are emitted with relatively low volatility, the oxidation of S/IVOCs to form $RONO_2$ could contribute to the missing source of semivolatile $RONO_2$. The addition of a nitrate group decreases a molecule's volatility by ≈2.2 orders of magnitude,[36] meaning a missing $RONO_2$ source with a saturation concentration of 300 $\mu g\ m^{-3}$ implies a precursor with $C^* = 10^5\ \mu g\ m^{-3}$, namely, an IVOC. The contribution of S/IVOCs to $pRONO_2$ is not unprecedented; Lee et al.[31] showed that much of the $pRONO_2$ formation in the Alberta oil sands occurred via the photo-oxidation of IVOCs under high-NO_x conditions.

Autoxidation, a mechanism involving an intramolecular hydrogen shift followed by the addition of molecular oxygen in RO_2 radicals, can quickly (in seconds) generate highly oxygenated molecules or HOMs[96,97] and references therein. Because of their high oxygen content, HOMs have significantly

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reduced volatility compared to their parent VOCs, for example, refs 98−100. Although autoxidation becomes relatively more competitive with bimolecular oxidation pathways as NO_x decreases, absolute rates of autoxidation increase with increasing NO_x due to increased oxidant availability.[101] In Korea's high-NO_x environment, autoxidation may generate highly oxidized RO_2 which could produce $RONO_2$ via the reaction with NO (R2). While most previous studies of HOMs have focused on the autoxidation of RO_2 derived from biogenic VOCs, theoretical calculations by Wang et al.[102] indicate that substituted benzenes, which were measured in high abundance during KORUS-AQ,[42,63] may also produce HOMs through the autoxidation of bicyclic peroxy radicals. Beginning with a substituted benzene molecule with $C^* \approx 10^7$ $\mu g\ m^{-3}$, one hydrogen-shift reaction resulting in the addition of a hydroperoxide group would reduce the volatility by ≈2.5 orders of magnitude, and further addition of a nitrate group would reduce the volatility by ≈2.2 orders of magnitude,[36] resulting in a $C^* \approx 10^2$ $\mu g\ m^{-3}$ compound. Consequently, only one hydrogen-shift reaction is necessary to convert a substituted aromatic compound to a nitrate of the missing volatility.

Additionally, multiple recent studies have suggested that multigeneration OH oxidation of aromatics can lead to highly oxygenated oxidation products, many of which, particularly under high-NO_x conditions, contain nitrogen, for example, refs 103−105. Some of these nitrogen-containing products are likely organic nitrates, but the nitrogen-containing product distribution also includes peroxy nitrates and nitro aromatics. Because aromatics are a large contributor to total VOCs over Korea,[42,63] there could be significant production of semi-volatile, multifunctional, oxygenated organic nitrates from the multigeneration oxidation of aromatic VOCs.

In summary, exploration of the phase partitioning of $RONO_2$ over the Korean peninsula using our aircraft-based measurements of $pRONO_2$ and $tRONO_2$ during KORUS-AQ as an example of urban chemistry indicates that organic nitrates contribute ≈15% of the total OA. This significant contribution of organic nitrates to the OA burden, as has been observed elsewhere, reinforces the notion that a better understanding of the processes that control the production, loss, and phase partitioning of $RONO_2$ is crucial for understanding the processes that control SOA production and loss. Our current understanding of $RONO_2$ chemistry can only explain one-third of the observed $RONO_2$ in Korea and is therefore missing a source of semivolatile, anthropogenically derived $RONO_2$ in and around Seoul. We recommend further laboratory and field research to determine the source VOCs and mechanisms that drive the production of this missing source of organic nitrates.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.1c05521.

> Particle loss corrections applied to TD-LIF measurements, CU-AMS measurements of $pRONO_2$, comparison of TD-LIF and CU-AMS $pRONO_2$ measurements, CU-AMS measurements of OA, WAS measurements of VOCs, comparison of OH and Cl-oxidation of VOCs, CMAQ emissions, model-measurement comparison, and CMAQ-modeled $RONO_2$ speciation (PDF)

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Notes

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