

Production of N₂O₅ and ClNO₂ in summer in urban Beijing, China

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Abstract. The heterogeneous hydrolysis of dinitrogen pentoxide (N_2O_5) has a significant impact on both nocturnal particulate nitrate formation and photochemistry on the following day through photolysis of nitryl chloride (ClNO_2), yet these processes in highly polluted urban areas remain poorly understood. Here we present measurements of gas-phase N_2O_5 and ClNO_2 by high-resolution time-of-flight chemical ionization mass spectrometers (ToF-CIMS) during summer in urban Beijing, China as part of the Air Pollution and Human Health (APHH) campaign. N_2O_5 and ClNO_2 show large day-to-day variations with average ($\pm 1\sigma$) mixing ratios of 79.2 ± 157.1 and 174.3 ± 262.0 pptv, respectively. High reactivity of N_2O_5 , with $\tau(\text{N}_2\text{O}_5)^{-1}$ ranging from 0.20×10^{-2} to $1.46 \times 10^{-2} \text{ s}^{-1}$, suggests active nocturnal chemistry and a large nocturnal nitrate formation potential via N_2O_5 heterogeneous uptake. The life time of N_2O_5 , $\tau(\text{N}_2\text{O}_5)$, decreases rapidly as the increase of aerosol surface area, yet it varies differently as a function of relative humidity with the highest value peaking at $\sim 40\%$. The N_2O_5 uptake coefficients estimated from the product formation rates of ClNO_2 and particulate nitrate are in the range of 0.017-0.19, corresponding to direct N_2O_5 loss rates of 0.00044-0.0034 s^{-1} . Further analysis indicates that the fast N_2O_5 loss in the nocturnal boundary layer in urban Beijing is mainly attributed to its indirect loss via NO_3 , for example through the reactions with volatile organic compounds and NO , while the contribution of heterogeneous uptake of N_2O_5 is comparably small (7-33%). High ClNO_2 yields ranging from 0.10 to 0.35 were also observed which might have important implications for air quality by affecting nitrate and ozone formation.

1 Introduction

Dinitrogen pentoxide (N_2O_5) is an efficient nocturnal sink for nitrogen oxides (NO_x) (Dentener and Crutzen, 1993; Brown et al., 2006). N_2O_5 exists in a rapid temperature-dependent thermal equilibrium with nitrate radical (NO_3) – one of the most important oxidants at night-time (Wayne et al., 1991). Although NO_3 and N_2O_5 levels can be suppressed by rapid titration of NO_3 against NO and volatile organic compounds (VOCs) in urban areas (Brown et al., 2003b), heterogeneous uptake by aerosol particles, fog and cloud droplets is often found to be the major pathway for direct N_2O_5 removal (Bertram and Thornton, 2009; Wagner et al., 2013; Brown et al., 2006; Chang et al., 2011; Thornton et al., 2003). N_2O_5 can produce nitryl chloride (ClNO_2) on chloride-containing aerosols which serves as an important reservoir of NO_x (Finlayson-Pitts et al., 1989; Thornton et al., 2010; Phillips et al., 2012). It has been found that levels of particulate nitrate formed through hydrolysis of N_2O_5 at night-time were comparable to those produced from the reaction of NO_2 with OH radical during daytime (Geyer et al., 2001). Furthermore ClNO_2 can be photolyzed into NO_2 and atomic chlorine (Cl) after sunrise, resulting in significant impacts on daytime photochemistry, for example trace gas degradation and ozone formation (Osthoff et al., 2008; Sarwar et al., 2014; Riedel et al., 2012; Mielke et al., 2013). Thus, it is of great importance to understand N_2O_5 and ClNO_2 chemistry in the nocturnal boundary layer of various environments.

The heterogeneous reaction of N_2O_5 and activation of ClNO_2 are parameterized by the N_2O_5 uptake coefficient ($\gamma_{\text{N}_2\text{O}_5}$) and ClNO_2 product yield (ϕ), which are defined as the reaction probability of N_2O_5 upon its collision on an aerosol surface and the number of ClNO_2 molecules formed per lost N_2O_5 molecule upon uptake, respectively (Wagner et al., 2013; Brown, 2006; Roberts et al., 2009). Previous laboratory studies have shown a large variability of $\gamma_{\text{N}_2\text{O}_5}$ (0.0002 – 0.3) depending on the physical characteristics of the substrates (e.g., aerosol surfaces, water droplets, and ice/crystal surfaces), environmental conditions (e.g., acidity, relative humidity and temperature), and chemical composition of aerosol particles (e.g., nitrate, sulfate, black carbon and organic coating) (Sander et al., 2006; Chang et al., 2011; Anttila et al., 2006; Cosman et al., 2008; Thornton and Abbatt, 2005; McNeill et al., 2006). To reveal the effects of each factor on $\text{N}_2\text{O}_5/\text{ClNO}_2$ chemistry, several parameterizations of $\gamma_{\text{N}_2\text{O}_5}$ and ϕ have been proposed during the last decade (Riemer et al., 2003; Evans and Jacob, 2005; Anttila et al., 2006; Davis et al., 2008; Riemer et al., 2009; Griffiths et al., 2009). For example, Bertram and Thornton (2009) constructed

a parameterization of $\gamma_{\text{N}_2\text{O}_5}$ as a function of aerosol liquid water, nitrate, and chloride content based on the measurements of laboratory-generated internally mixed chloride-nitrate particles. Similarly, σ was parameterized as a function of aerosol liquid water content and aerosol chloride (Roberts et al., 2009). These results have great implications for regional/global chemical transport models which aim to improve the simulations of nitrate and ozone (Evans and Jacob, 2005; Sarwar et al., 2014).
5 However, the field-derived values of $\gamma_{\text{N}_2\text{O}_5}$ and σ often exhibit large inconsistencies with laboratory results, suggesting a more complex nature of heterogeneous N_2O_5 uptake in the ambient atmosphere (Brown et al., 2006; Chang et al., 2011).

N_2O_5 and NO_3 can be measured by various different techniques which have been summarized in Chang et al. (2011). For example, N_2O_5 can be derived from the thermal equilibrium with NO_2 and NO_3 that are simultaneously measured by differential optical absorption spectroscopy (DOAS) (Platt and Stutz, 2008; Stutz et al., 2004). Another indirect measurement of N_2O_5 is
10 subtracting ambient NO_3 from the total measured NO_3 after converting N_2O_5 to NO_3 in a heated inlet and then detected by Cavity Ring-Down Spectroscopy (CRDS), Cavity-Enhanced Absorption Spectroscopy (CEAS) or Laser-Induced Fluorescence (LIF) (O’Keefe and Deacon, 1988; Brown et al., 2001; Smith et al., 1995; Wood et al., 2003; Stutz et al., 2010). The simultaneous indirect measurements of N_2O_5 and NO_3 can be implemented using thermal dissociation – chemical ionization mass spectrometer (TD – CIMS) with high sensitivity and time resolution (Stutz et al., 2004), although the interference of m/z 62
15 (NO_3^-) from thermal decomposition of peroxy acetyl nitrate (PAN) and other related species need to be considered (Wang et al., 2014). Recently, the CIMS using iodide reagent ions (I-CIMS) with an unheated inlet configuration allowed the direct measurements of N_2O_5 (Kercher et al., 2009; Tham et al., 2014; Tham et al., 2016; Wang et al., 2016). The I-CIMS is also widely used to measure ClNO_2 in both laboratory and field studies (Thornton and Abbatt, 2005; McNeill et al., 2006; Osthoff et al., 2008; Tham et al., 2014; Tham et al., 2016; Wang et al., 2016). A large amount of ClNO_2 was first observed in polluted coastal
20 regions owing to the abundant chloride from sea salt aerosol, for example, the Gulf of Mexico and the Los Angeles basin (Osthoff et al., 2008; Riedel et al., 2012; Kercher et al., 2009). High levels of ClNO_2 from anthropogenic chloride sources were also reported in some inland areas (Thornton et al., 2010; Mielke et al., 2011; Phillips et al., 2012; Phillips et al., 2016; Bannan et al., 2015). More recently, some studies in Hong Kong (Tham et al., 2014; Brown et al., 2016a; Wang et al., 2016) and in the North China Plain (NCP) (Tham et al., 2016; Wang et al., 2017b; Wang et al., 2017c; Wang et al., 2018) observed consistently
25 high mixing ratios of N_2O_5 and ClNO_2 . In particular, ClNO_2 can be rapidly formed in the plumes of coal-fired power plants in

the NCP, which serves as an important source of chloride in non-ocean regions. Besides these measurement efforts, recently, some modeling studies have also evaluated the impacts of N_2O_5 and ClNO_2 chemistry on the ozone formation and regional air quality in China (Xue et al., 2015; Wang et al., 2016; Li et al., 2016). Despite this, our understanding of N_2O_5 and ClNO_2 chemistry in highly polluted urban regions with high levels of NO_x , O_3 , and high particulate matter is far from complete.

5 Beijing has been suffering from severe haze pollution during the last two decades (Chan and Yao, 2008). As a result, extensive studies have been conducted to characterize the sources and formation mechanisms of haze episodes (Huang et al., 2014; Guo et al., 2014; Li et al., 2017). The results show that nitrate and its precursors have been playing increasingly important roles in pollution events since 2006 mainly due to the continuous decrease in SO_2 (van der A et al., 2017). While the formation mechanisms of nitrate are relatively well known, the relative contributions of different mechanisms can have large variability and uncertainties. Pathak et al. (2009) found that heterogeneous hydrolysis of N_2O_5 contributed 50-100% of the nighttime enhancement of nitrate concentration in Beijing. WRF-Chem model simulations showed only 21% enhancement of nitrate during highly polluted days (Su et al., 2016). A recent study also observed a large nocturnal nitrate formation potential from N_2O_5 heterogeneous uptake, which is comparable to and even higher than that from the partitioning of HNO_3 in rural Beijing in autumn (Wang et al., 2017a). A large contribution of heterogeneous hydrolysis of N_2O_5 to the high $\text{PM}_{2.5}$ nitrate even in the daytime, due to persistently high NO_2 , was also reported in Hong Kong (Xue et al., 2014a). All these results highlight that N_2O_5 heterogeneous uptake might be an important pathway of nitrate formation in Beijing. A recent modeling study has evaluated the impacts of heterogeneous ClNO_2 formation on the next-day ozone formation in Beijing (Xue et al., 2014b). However, the roles of N_2O_5 in nitrate formation, and of N_2O_5 and ClNO_2 in night- and day-time chemistry in summer in urban Beijing during field campaign are not characterized yet, except for one measurement in suburban Beijing in the summer of 2016 (Wang et al., 2018).

In this work, two high-resolution time-of-flight CIMSs using the same iodide ionization system operated by the Institute of Atmospheric Physics (IAP-CIMS) and University of Manchester (UoM-CIMS), respectively, were deployed in urban Beijing for real-time measurements of gas phase N_2O_5 and ClNO_2 . A broadband cavity enhanced absorption spectrometer (BBCEAS) operated by the University of Cambridge was also deployed synchronously for the inter-comparison of N_2O_5 . The temporal variations of N_2O_5 and ClNO_2 in summer and their relationships are characterized. The heterogeneous N_2O_5 uptake

coefficients and ClNO₂ production yields are estimated, and their implications in nitrate formation are elucidated.

2 Experimental methods

2.1 Field campaign site and meteorology

The measurements were conducted during the Air Pollution and Human Health (APHH) summer campaign from 11 to 16 June, 2017 at the Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences (39°58'28"N, 116°22'16"E, ASL: 49 m), which is an urban site located between the north 3rd and 4th ring roads in Beijing. The meteorological variables including wind direction (WD), wind speed (WS), relative humidity (RH), and temperature (*T*) at 15 m and 100 m were obtained from the Beijing 325 m Meteorological Tower (BMT) at the sampling site. The hourly average RH ranged from 12.9% to 82.8%, with an average value of $36.8 \pm 15.9\%$, and the hourly average temperature ranged from 17.9°C to 38.7°C, averaged at $26.7 \pm 4.9^\circ\text{C}$. All IAP instruments were deployed on the roof of a two-storey building (~10 m) while those of UoM-CIMS and BBCEAS were housed in two containers at ground level (~4 m) which are approximately 20 m away. More details about the sampling site can be found in previous studies (Sun et al., 2012).

2.2 Instruments

2.2.1 IAP-CIMS

Ambient air was drawn into the sampling room through a ~2 m Teflon perfluoroalkoxy tubing (PFA, ¼ inch inner diameters) at a flow rate of 10 standard liters per minute (slm), from which ~2 slm was sub-sampled into the CIMS. Methyl iodide gas (CH₃I) from a heated CH₃I permeation tube cylinder (VICI, 170-015-4600-U50) was ionized by flowing through a soft X-ray ionization source (Tofwerk AG, type P) under an ultra-high purity nitrogen (N₂, 99.999%) flow (2.5 slm). This flow enters an ion molecule reaction (IMR) chamber which was maintained at a pressure of 200 mbar using an SH-112 pump fitted with a Tofwerk blue pressure control box to account for changes in ambient pressure. A short segmented quadrupole (SSQ) positioned behind the IMR was held at a pressure of 2 mbar using a Tri scroll 600 pump. Note that the voltage settings used for the guidance of ions were carefully tuned to avoid declustering as much as possible (Lopez-Hilfiker et al., 2016). The gas phase background was determined once during the campaign by passing dry N₂ into inlet for 5 minutes.

2.2.2 UoM-CIMS

The UoM-CIMS setup has been described elsewhere (Priestley et al., 2018) except a Filter Inlet for Gases and AEROsols (FIGAERO) (Lopez-Hilfiker et al., 2014) was used in this study. The gas phase inlet of UoM-CIMS consisted of 5 m ¼" I.D. PFA tubing connected to a fast inlet pump with a total flow rate of 13 slm from which the ToF-CIMS sub-sampled 2 slm. CH₃I gas mixtures in N₂ were made in the field using a custom-made manifold (Bannan et al., 2014). 20 standard cubic centimetres per minute (sccm) of the CH₃I mixture was diluted in 4 slm N₂ and ionized by flowing through a ToFwerk x-ray ionization source. This flow enters into the IMR which was maintained at a pressure of 400 mbar using an SSH-112 pump also fitted with a ToFwerk blue pressure control box, while the subsequent SSQ was held at a pressure of 2 mbar using a Tri scroll 600 pump. During the campaign, gas phase backgrounds were established through regularly overflowing the inlet with dry N₂ for 5 continuous minutes every 45 minutes as has been performed previously.

The ambient target molecules were first ionized by reagent ions in the IMR, and then detected as adduction products with iodide, for instance, ClNO₂ as I•ClNO₂⁻ at *m/z* 208 and *m/z* 210 (I•³⁷ClNO₂⁻), and N₂O₅ as I•N₂O₅⁻ at *m/z* 235 (Slusher et al., 2004; Kercher et al., 2009) at a time resolution of 1 s. Data analysis is performed using the "Tofware" package (version 2.5.11) running in Igor Pro (WaveMetrics, OR, USA) environment. The mass axis of UoM-CIMS was calibrated using I⁻, I₂⁻ and I₃⁻, while that of IAP-CIMS was calibrated using NO₃⁻, I⁻, I•H₂O⁻, I•CH₂O₂⁻, I•HNO₃⁻, and I₃⁻, covering a wide range from *m/z* 62 to 381. Examples of high resolution peak fittings of *m/z* 208, 210 and 235 for IAP-CIMS are presented in Fig. S1.

2.2.3 Broadband cavity enhanced absorption spectrometer (BBCEAS)

A detailed description of BBCEAS has been given in Kennedy et al. (2011). Briefly, ambient air is first heated to 140 °C to thermally dissociate N₂O₅ into NO₃ and then enters the observational cavity that consists of two high-reflectivity mirrors. The sum of N₂O₅ and NO₃ is determined using the measured optical absorption of NO₃ in the wavelength of 640-680 nm. The temperature of the cavity is kept at 85 ± 1 °C to prohibit the recombination of NO₃ and NO₂ and to maintain the stability of the optical transmission signal. A very fast flow rate of 20 lpm is adopted to minimize the residence time of gases through PFA tubes. The loss of NO₃ through the system was estimated to be approximately 10%.

Considering that the relatively high aerosol loadings in Beijing can attenuate the intracavity light intensity and thus

deteriorate instrument sensitivity, a poly tetrafluoroethylene (PTFE) filter of pore size 1 μm was used to remove aerosol particles from the air stream. This filter acts also a point loss ($\sim 10\%$) for NO_3 but has a negligible impact on N_2O_5 (Dube et al., 2006). Because the mixing ratio of N_2O_5 is higher than NO_3 by a factor of >10 during APHH summer campaign, the influence of filter loss on the measurements of $\text{N}_2\text{O}_5 + \text{NO}_3$ is expected to be small. Aging of aerosol particles on the filter may potentially introduce uncertainties for the transmission efficiencies of NO_3 and N_2O_5 , but was found to be insignificant in this study.

2.3 Calibrations and inter-comparisons

During the campaign, field calibrations for UoM-CIMS were regularly carried out using known concentration formic acid gas mixtures made in the custom-made manifold. A range of other species were calibrated after the campaign, and relative calibration factors were derived using the measured formic acid sensitivity during these calibrations as has been performed previously (Le Breton et al., 2014, 2017; Bannan et al., 2014, 2015).

The UoM-CIMS was calibrated post campaign for both N_2O_5 and ClNO_2 , relative to formic acid that was calibrated and measured throughout the campaign. This is completed assuming that the ratio between formic acid and ClNO_2 sensitivity remains constant. ClNO_2 was calibrated using the method described in Kercher et al. (2009). Briefly, a stable source of N_2O_5 is generated and passed over a salt slurry where excess chloride reacts to produce gaseous ClNO_2 . The N_2O_5 for this process was synthesised based on the methodology described by Le Breton et al. (2014). Excess O_3 is generated through flowing 200 sccm O_2 (BOC) through an ozone generator (BMT, 802N) into a 5 litre glass volume containing NO_2 (Sigma, $>99.5\%$). The outflow from this reaction vessel is cooled in a cold trap held at -78°C (195K) by a dry ice/glycerol mixture where N_2O_5 is condensed and frozen. The trap is allowed to reach room temperature and the flow is reversed where it is then condensed in a second trap held at 220 K. This process is repeated several times to purify the mixture. The system is first purged by flowing O_3 for ten minutes before usage. To ascertain the N_2O_5 concentration in the line, the flow is diverted through heated line to decompose the N_2O_5 and into to a Thermo Scientific 42i NO_x analyser where it is detected as NO_2 . According to the inter-comparisons with the BBCEAS, including this study and others (e.g., Le Breton et al. (2014); Bannan et al. (2017)), the possible interference of NO_y on the NO_x analyser is not deemed important in terms of our reported N_2O_5 concentrations.

CINO₂ was produced by flowing a known concentration of N₂O₅ in dry N₂ through a wetted NaCl scrubber. Conversion of N₂O₅ to CINO₂ can be as efficient as 100% on sea salt, but it can also be lower, for example if CINO₂ is converted to Cl₂ (Roberts et al., 2008). In this calibration we have followed the accepted methods of Osthoff et al. (2008) and Kercher et al. (2009) that show a conversion yield of 100% and have assumed this yield in the calibrations of this study.

5 The second method used to verify our CINO₂ calibration is by cross calibration with a turbulent flow tube chemical ionisation mass spectrometer (TF-CIMS) (Leather et al., 2012). A known concentration of 0-20 sccm Cl₂ (99.5% purity Cl₂ cylinder, Aldrich) from a diluted (in N₂) gas mix is flowed into an excess constant flow of 20 sccm NO₂ (99.5% purity NO₂ cylinder, Aldrich) from a diluted (in N₂) gas mix, to which the TF-CIMS has been calibrated. This flow is carried in 52 slm N₂ that is purified by flowing through two heated molecular sieve traps. This flow is sub-sampled by the ToF-CIMS where the
10 I•CINO₂⁻ adduct is observed. The TF-CIMS is able to quantify the concentration of CINO₂ generated in the flow tube as the equivalent drop in NO₂⁻ signal. This indirect measurement of CINO₂ is similar in its methodology to CINO₂ calibration by quantifying the loss of N₂O₅ reacted with Cl⁻ (e.g., Kercher et al. (2009)). The TF-CIMS method gives a calibration factor 58% greater than that of the N₂O₅ synthesis method therefore this is taken as our measurement uncertainty. This calibration was scaled to those in the field using formic acid calibrations carried out in the laboratory by overflowing the inlet with various
15 known concentrations of gas mixtures (Bannan et al., 2014).

The IAP-CIMS calibration for N₂O₅ was performed by comparing with the measurements from the BBCEAS. As shown in Fig. S2, the raw signals of N₂O₅ from the IAP-CIMS measurements were highly correlated with those from BBCEAS (R² = 0.84). Given that the inter-comparison between the two instruments was relatively constant throughout the study, the average regression slope of 0.54 was then applied to determine the mixing ratio of N₂O₅ for the IAP-CIMS. The estimated N₂O₅ mixing
20 ratios were then compared with those measured by UoM-CIMS. As shown in Fig. 1, the two N₂O₅ measurements tracked well with each other (R² = 0.84, slope = 1.42) although some differences at the midnight of 13 June were observed. The raw signals of CINO₂ given by the IAP-CIMS were first converted to mixing ratios by assuming the same sensitivity between CINO₂ and N₂O₅ (i.e., 0.54 cps pptv⁻¹). The results show that the estimated CINO₂ for the IAP-CIMS agrees well with that was measured by UoM-CIMS and calibrated post campaign (R² = 0.93, slope = 0.905, Fig. 1). Overall, the uncertainty is 17% and 58%,
25 detection limit is 1.7 pptv and 0.7 pptv for N₂O₅ and CINO₂ of IAP-CIMS, respectively. All the discussions below are based

on IAP-CIMS measurements unless otherwise stated.

2.3 Collocated measurements

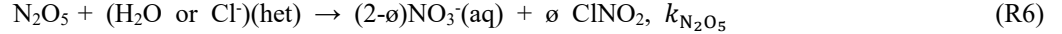
An Aerodyne High-Resolution Time-of-Flight Aerosol Mass Spectrometer (HR-AMS hereafter) and an Aethalometer (AE33, Magee Scientific Corp.) were deployed on the roof of the two-storey building to measure the size-resolved non-refractory submicron aerosol (NR-PM₁) species with a time resolution of 5 min, including organics (Org), sulfate (SO₄²⁻), nitrate (NO₃⁻), ammonium (NH₄⁺), and chloride (Cl⁻) (DeCarlo et al., 2006; Canagaratna et al., 2007), and black carbon (BC), respectively. A more detailed description of the operations and calibrations of this HR-AMS can be found in Xu et al. (2015); Sun et al. (2016). Other collocated measurements in two containers at ground level included gaseous species of O₃ (TEI 49C UV absorption analyzer), NO (TEI 42i TL NO analyzer), and NO₂ (CAPS NO₂ monitor, Aerodyne Research Inc.), and size-resolved particle number concentrations (11-550 nm) by a scanning mobility particle sizer (SMPS) equipped with a long Differential Mobility Analyzer (DMA, TSI, 3081A) and a Condensation Particle Counter (CPC, TSI, 3772).

2.4 Data analysis

2.4.1 Estimation of $\gamma_{\text{N}_2\text{O}_5}$ and ϕ

NO₃ is formed from the reaction of NO₂ with O₃ (R1) with a temperature-dependent reaction rate constant k_1 . NO₃ rapidly photolyzes during daytime, but at night it reacts with NO₂ to produce N₂O₅ (R2). N₂O₅ can thermally decompose back to NO₃ and NO₂, and the equilibrium rate coefficient K_{eq} is a function of ambient temperature. In this study, values of k_1 and K_{eq} recommended by Atkinson et al. (2004) and Brown and Stutz (2012) were used. The indirect loss of N₂O₅ is mainly through the reactions of NO₃ with either NO or VOCs (R3), while the direct N₂O₅ loss is predominantly from the heterogeneous hydrolysis on the surface of aerosol particles that contain water (R4) or chloride (R5). Note that het is an abbreviation of heterogeneous in the equations. The net reaction of R4 and R5 can be described as R6 where $k_{\text{N}_2\text{O}_5}$ is the heterogeneous uptake rate of N₂O₅, and ϕ is the ClNO₂ yield.





5 When the uptake reaction was not limited by gas-phase diffusion, $k_{\text{N}_2\text{O}_5}$ can be simplified as Eq. (1) (Riemer et al., 2003; Dentener and Crutzen, 1993):

$$k_{\text{N}_2\text{O}_5} = \frac{1}{4} \times c \times S_a \times \gamma_{\text{N}_2\text{O}_5} \quad (1)$$

Where c is the mean molecular speed of N_2O_5 (unit, m s^{-1}), and S_a is the aerosol surface area density calculated from the size-resolved particle number concentrations assuming spherical particles (unit, $\mu\text{m cm}^{-3}$). Note that S_a determined under dry
10 conditions was converted to that under ambient RH levels by using the hygroscopic growth factor in Liu et al. (2013).

The nocturnal mixing ratio of NO_3 can be derived from the simultaneous measurements of NO_2 and N_2O_5 (R2) assuming that the equilibrium between NO_3 and N_2O_5 is rapidly established after sunset (Brown et al., 2003a).

$$[\text{NO}_3(\text{cal})] = \frac{[\text{N}_2\text{O}_5]}{K_{eq}[\text{NO}_2]} \quad (2)$$

The nitrate radical production rate $p(\text{NO}_3)$ can be calculated from reaction R1 assuming that the nitrate radical is solely
15 from reaction R1.

$$p(\text{NO}_3) = k_1[\text{NO}_2][\text{O}_3] \quad (3)$$

With a steady-state assumption for NO_3 and N_2O_5 , the inverse N_2O_5 steady state lifetime, $\tau(\text{N}_2\text{O}_5)^{-1}$, which is defined as the ratio of $p(\text{NO}_3)$ to the N_2O_5 mixing ratios, can be expanded to Eq. (4) after the substitution of Eqs. (2) and (3) into the approximate time change rate for N_2O_5 (Brown et al., 2003a).

$$20 \quad \tau(\text{N}_2\text{O}_5)^{-1} = \frac{p(\text{NO}_3)}{[\text{N}_2\text{O}_5]} \approx \frac{k_{\text{NO}_3}}{K_{eq}[\text{NO}_2]} + k_{\text{N}_2\text{O}_5} \quad (4)$$

$\frac{k_{\text{NO}_3}}{K_{eq}[\text{NO}_2]}$ represents the contribution to $\tau(\text{N}_2\text{O}_5)^{-1}$ from the indirect N_2O_5 loss pathway, i.e. through the NO_3 reactions with VOCs and NO , while $k_{\text{N}_2\text{O}_5}$ indicates the direct loss of N_2O_5 through heterogeneous uptake.

Considering that the production of ClNO_2 is predominantly from the heterogeneous N_2O_5 uptake within stable air masses

and precursors, the production rate of ClNO_2 ($p\text{ClNO}_2$) can be related to the heterogeneous loss rate of N_2O_5 by:

$$p\text{ClNO}_2 = \frac{d\text{ClNO}_2}{dt} = \emptyset \times \left(\frac{1}{4} \times c \times S_a \times \gamma_{\text{N}_2\text{O}_5}\right) \quad (5)$$

The production rate of particulate nitrate ($p\text{NO}_3^-$) was obtained from HR-AMS measurements assuming that the measured $p\text{NO}_3^-$ was totally from production of nitrate by reaction R4 (Phillips et al., 2016). Note that the formation of particulate nitrate

5 from regional transport or via the net uptake of HNO_3 to aerosol is not taken into consideration.

$$p\text{NO}_3^- = \frac{d\text{NO}_3^-}{dt} = (2 - \emptyset) \times \left(\frac{1}{4} \times c \times S_a \times \gamma_{\text{N}_2\text{O}_5}\right) \quad (6)$$

Only periods with concurrent nighttime formation of ClNO_2 and NO_3^- meet the requirements that both of them are produced only from the heterogeneous N_2O_5 uptake. By combining Eq. (5) with Eq. (6), $\gamma_{\text{N}_2\text{O}_5}$ and $\emptyset$ can be represented as:

$$\gamma_{\text{N}_2\text{O}_5} = \frac{2(p\text{ClNO}_2 + p\text{NO}_3^-)}{c \times S_a \times [\text{N}_2\text{O}_5]} \quad (7)$$

$$\emptyset = 2 \left(\frac{p\text{NO}_3^-}{p\text{ClNO}_2} + 1 \right)^{-1} \quad (8)$$

2.4.2 Parameterization of $\gamma_{\text{N}_2\text{O}_5}$ and $\emptyset$

Aerosol liquid water content associated with inorganic species was estimated using the ISORROPIA-II thermodynamic equilibrium model (Nenes et al., 1998; Fountoukis and Nenes, 2007), with input data of ambient NR- PM_{10} species, and RH and T at 15 m. The N_2O_5 uptake coefficient and ClNO_2 yield can also be calculated by the parameterization proposed by Bertram

15 and Thornton (2009).

$$\gamma_{\text{N}_2\text{O}_5} = Ak \left(1 - \frac{1}{1 + \frac{29[\text{Cl}^-]}{[\text{NO}_3^-]} + \frac{0.06[\text{H}_2\text{O}]}{[\text{NO}_3^-]}} \right) \quad (9)$$

$$\emptyset = \left(1 + \frac{[\text{H}_2\text{O}]}{483[\text{Cl}^-]} \right)^{-1} \quad (10)$$

Where $[\text{H}_2\text{O}]$, $[\text{NO}_3^-]$ and $[\text{Cl}^-]$ are molar concentrations of liquid water, particle nitrate and chloride, respectively, and the empirical parameters $A = 3.2 \times 10^{-8}$, and $k = 1.15 \times 10^6 \times (1 - e^{-0.13[\text{H}_2\text{O}]})$ are used.

20 3 Results and discussion

3.1 Overview of N_2O_5 and ClNO_2 measurements

Figure 1 shows the time series of N_2O_5 and ClNO_2 , gaseous species of NO , NO_2 and O_3 , and meteorological parameters during the field campaign. Both N_2O_5 and ClNO_2 exhibited large day-to-day variability with the 5-min average ($\pm 1\sigma$) mixing ratios being 79.2 ± 157.1 pptv and 174.3 ± 262.0 pptv, respectively. Such dramatic variations of N_2O_5 and ClNO_2 are consistent with previous observations in various environments, for example, ground sites in Colorado and London (Bannan et al., 2015; Thornton et al., 2010) and the residual layer at Mt. Tai (Wang et al., 2017c). Four nights (i.e., P1, P2, P3 and P4 from 20:00 to 04:30) were selected to investigate nocturnal chemistry of N_2O_5 and ClNO_2 in this study. The first two nights (P1 and P2) showed much higher mixing ratios of N_2O_5 and ClNO_2 than those during P3 and P4, although the NO_x and O_3 levels during P4 were comparable to those during P2 (Table 1).

The highest N_2O_5 mixing ratio (1.10 ppbv, 5-minute average) was observed at 2:15 on 13 June (P2), which is comparable to the previous observation in urban Beijing (1.3 ppbv) (Wang et al., 2017a), but much lower than that in the aged air masses in Hong Kong ~ 7.8 ppbv (Brown et al., 2016b). A recent measurement at a suburban site in Beijing impacted by the outflow of urban Beijing air masses also reported consistently high N_2O_5 (1-minute maxima 937 pptv) (Wang et al., 2018). The mixing ratio of N_2O_5 was also much higher than that in the nocturnal residual boundary layer at Mt. Tai (167 pptv) (Wang et al., 2017c), indicating potentially significant nighttime N_2O_5 chemistry in highly polluted urban areas. One of the reasons for this could be due to the high mixing ratios of precursors, for instance, the average O_3 mixing ratios at night-time were as high as 18-56 ppbv. Besides, the maximal N_2O_5 occurred during P2 other than the rest nights was likely due to the insignificant titration of NO during P2, e.g., 0.5 vs. 2.3-15.6 ppbv. The lowest nighttime average of N_2O_5 (~ 37.8 pptv) was observed during P3 although the NO_2 showed much higher concentration than those during P2 and P4, indicating the joint influences of precursors (NO_2 and O_3). Fast heterogeneous hydrolysis of N_2O_5 under high RH ($\sim 60.5\%$) conditions during P3 could be another reason, which was supported by the higher ClNO_2 during P3 than P4.

Similar to N_2O_5 , ClNO_2 presented the highest value (1.44 ppbv, 5-minute average) before sunrise on 13 June (P2), yet it is lower than the maximum of 2.1 ppbv (1-minute average) observed at a rural site located to the southwest of Beijing (Tham et al., 2016), and also the ClNO_2 peak of 2.9 ppbv (1-minute average) in suburban Beijing (Wang et al., 2018). These results indicated ubiquitously observed ClNO_2 in the NCP, although high ClNO_2 mixing ratios have been also observed previously in both marine and continental environments in North America, Europe and Asia (Osthoff et al., 2008; Mielke et al.,

2011;Thornton et al., 2010;Phillips et al., 2012;Tham et al., 2014). The average nitrate radical production rate $p(\text{NO}_3)$ was 2.8 ppbv h^{-1} and 3.6 ppbv h^{-1} during P1 and P2, respectively, which are both higher than those during P3 and P4 (1.7-2.6) (Table 1). This result supports a higher production potential for N_2O_5 during P1 and P2. On average, $p(\text{NO}_3)$ was 2.6 ± 2.4 ppbv h^{-1} at night-time, indicating more active nocturnal chemistry than previous studies in NCP in terms of radical production rates, for example, 1.2 ± 0.9 ppbv h^{-1} in suburban Beijing, 1.7 ± 0.6 ppbv h^{-1} in Wangdu, and 0.45 ± 0.40 ppbv h^{-1} at Mt. Tai (Tham et al., 2016;Wang et al., 2017c;Wang et al., 2018). We also note that the $p(\text{NO}_3)$ was comparable between P4 and P2 (2.6 pptv vs. 2.8 pptv), yet the N_2O_5 and ClNO_2 mixing ratios during P4 were much lower, likely due to the difference in NO levels, i.e., 0.5 vs. 7.1 ppbv. The favorable dispersing meteorological conditions with higher wind speed and lower relative humidity in P4 than those in P2 might also be an explanation (Table 1). Our results illustrate that precursors levels, reaction rates, and meteorological conditions can all affect the variability of N_2O_5 and ClNO_2 .

The average diurnal variations of trace gases, N_2O_5 , ClNO_2 and submicron nitrate and chloride are depicted in Fig. 2. O_3 showed a pronounced peak of 93.3 ppbv between 14:00 and 16:00 corresponding to a minimum mixing ratio of NO_2 (9.1 ppbv). As a consequence, $p(\text{NO}_3)$ showed relatively high values around noon with a decrease in the middle of the afternoon owing to the depletion of NO_2 and then reached a maximum of 5.9 ppbv h^{-1} before sunset. A similar diurnal pattern of $p(\text{NO}_3)$ was also observed at a rural site in the autumn of Beijing (Wang et al., 2017a). Both NO and NO_2 showed pronounced diurnal cycles with lowest concentrations in the afternoon. In addition to the rising boundary layer, the formation of NO_z is another important reason for the low levels of NO_x during this time period in urban Beijing (Sun et al., 2011). Nitrate and chloride also showed lowest concentrations in the late afternoon, mainly due to the evaporative loss under high temperature conditions (Sun et al., 2012).

N_2O_5 was rapidly formed after sunset. The mixing ratio of N_2O_5 peaked approximately at 22:00 and then remained at a consistently high level (~ 200 -300 pptv) until 3:00. After that, N_2O_5 showed a rapid decrease due to the significant titration by NO. Similar loss of N_2O_5 due to the injection of NO-containing air was also reported at sites near urban areas (Brown et al., 2003b). Because NO is predominantly from local emissions as supported by the tight correlation ($R^2 = 0.64$ -0.73, Fig. S3) with black carbon, a tracer for combustion emissions, our results demonstrated that the local NO emissions serve as an important scavenger of N_2O_5 before sunrise in urban Beijing. In comparison, the decrease in N_2O_5 due to the NO titration only occurred

during the second half of the night with low O₃ in suburban Beijing (Wang et al., 2018). This study also found high N₂O₅ after midnight due to the incomplete titration of O₃, for instance, ~52.9 ppbv after midnight on 13 June, which is different from previous findings that high N₂O₅ mixing ratios were typically observed before midnight due to the rapid depletion of O₃ (Wang et al., 2017a; Wang et al., 2017c). The high nocturnal mixing ratios of O₃ and NO₂ (Fig. 2) highlight much higher oxidative capacity at night in summer in urban Beijing compared to the other seasons and/or rural locations.

ClNO₂ showed clear nocturnal formation from heterogeneous processing and decreased rapidly after sunrise mainly due to photolysis (Fig. 2). Note that ClNO₂ peaked at a similar time (21:00-22:00) as that of N₂O₅ without showing a time lag of 1-3 h as previously observed in Jinan (Wang et al., 2017b), indicating that either particulate Cl⁻ was sufficient for the heterogeneous reactions or other chlorine sources (e.g., HCl) contributed to the formation of ClNO₂ in urban Beijing. According to previous studies, the partitioning of HCl to particulate Cl⁻ could contribute to ClNO₂ formation substantially at urban sites (Thornton et al., 2010; Riedel et al., 2012). In addition, Wang et al. (2018) also speculated that large particulate chloride during the campaign was possibly replenished by gas-phase HCl due to the high emissions from human activities. We also found that ClNO₂ was well correlated with chlorine (Cl₂) derived from IAP-CIMS (R² = 0.90-0.99) rather than particulate chloride (Cl⁻) (R² = 0.01-0.44) at the night-time, indicating that ClNO₂ might act as an intermediate during the formation of Cl₂ under sufficient chloride conditions (Roberts et al., 2008). Indeed, the much lower particulate Cl⁻ than ClNO₂ also indicated other chlorine sources. Therefore, we need simultaneous measurements for further supporting this conclusion in this study, e.g., HCl.

3.2 Reactivity of N₂O₅ and NO₃

Considering the time needed for meeting the steady-state assumption, only the data two hour after sunset were used to calculate N₂O₅ steady-state lifetime via Eq. (4) (Wagner et al., 2013). High N₂O₅ reactivity was observed and the average $\tau(\text{N}_2\text{O}_5)^{-1}$ was $0.16\text{-}1.58 \times 10^{-2} \text{ s}^{-1}$ during these four nights corresponding to a short nighttime N₂O₅ lifetime between 1.1 and 10.7 minutes (Fig. 3), with $\tau(\text{N}_2\text{O}_5)^{-1}$ ranging from 0.20×10^{-2} to $1.46 \times 10^{-2} \text{ s}^{-1}$ throughout the campaign. Such values are overall consistent with those measured at surface sites and in the nocturnal residual layer in NCP, for example, $1.30 \times 10^{-2} \text{ s}^{-1}$ in Wangdu (Tham et al., 2016) and $1.30\text{-}1.40 \times 10^{-2} \text{ s}^{-1}$ at Mt. Tai (Wang et al., 2017c). In comparison, the N₂O₅ loss is much more rapid

than that previously reported in southern China (1-5 h) (Brown et al., 2016b) and the USA (a few hours) (Wagner et al., 2013), mainly due to the high aerosol loading in NCP leading to an enhanced N_2O_5 sink through both indirect and direct pathways. Correspondingly, the average $\tau(\text{NO}_3)^{-1}$ calculated from the inferred NO_3 were 0.02-0.62 s^{-1} during the four nights, indicating active NO_3 nighttime chemistry through reactions with NO and VOCs in the polluted nocturnal boundary. Note that P2 and P4 showed comparable $p(\text{NO}_3)$ (2.8 vs. 2.6 ppbv h^{-1}) (Table 1), yet the N_2O_5 reactivity during P4 ($1.58 \times 10^{-2} \text{ s}^{-1}$) was significantly higher than that during P2 ($0.16 \times 10^{-2} \text{ s}^{-1}$) likely due to the higher NO level, and the enhanced N_2O_5 heterogeneous loss might also be an explanation. Consistently, $\tau(\text{NO}_3)^{-1}$ showed similar patterns to those of $\tau(\text{N}_2\text{O}_5)^{-1}$. Indeed, the N_2O_5 reactivity presented a nonlinear dependence on aerosol surface area (S_a) and relative humidity (Figs. 3c and 3d). Although P3 showed much higher RH than P4 (60.5% vs. 28.0%), the N_2O_5 reactivity was comparable between P3 and P4 (0.014 vs. 0.016 s^{-1}), illustrating the complex heterogeneous process of N_2O_5 .

Figure 3c shows the N_2O_5 lifetime as a function of surface area density (S_a) with the data being binned according to the $50 \mu\text{m}^2 \text{ cm}^{-3}$ S_a increment. $\tau(\text{N}_2\text{O}_5)$ decreased rapidly from 11.8 minutes to 2.2 minutes as S_a increased up to $500 \mu\text{m}^2 \text{ cm}^{-3}$, and then remained at relatively constant levels at $S_a > 500 \mu\text{m}^2 \text{ cm}^{-3}$. Such an S_a dependence of $\tau(\text{N}_2\text{O}_5)$ is consistent with previous observations in Hong Kong (Brown et al., 2016b). Large variations in $\tau(\text{N}_2\text{O}_5)$ as a function of RH were also observed. As shown in Fig. 3d, the N_2O_5 lifetime decreased by nearly a factor of 5 from 11.3 to 2.2 minutes as RH increased from 40% to 50%. We noticed that the aerosol surface area exhibits an increase as a function of RH at RH > 40% (Fig. S4). These results suggested that the decrease in $\tau(\text{N}_2\text{O}_5)$ at high RH levels (RH > 40%) might be caused by increased N_2O_5 uptake rates due to the higher S_a . In addition, the increasing aerosol liquid water content at high RH might be another reason (Fig. S4). Comparatively, the N_2O_5 lifetime showed an increase as a function of RH at RH < 40%, while the variations in S_a were small, suggesting additional contributions from other factors, for example, aerosol loading and composition (Morgan et al., 2015). Considering that the period of this study is relatively short, long-term measurements are needed in future studies to better characterize the parameterizations of $\tau(\text{N}_2\text{O}_5)$ as a function of S_a and RH.

3.3 Relationship between N_2O_5 and ClNO_2

Previous studies have found that N_2O_5 and ClNO_2 were generally positively correlated in predominantly continental air

masses whereas they were negatively correlated in marine air masses with high chloride content (Bannan et al., 2015). Phillips et al. (2012) also reported large variability in N_2O_5 and ClNO_2 correlations and ClNO_2 -to- N_2O_5 ratios in air masses from continental or marine origins due to the changes in particle Cl⁻. In this study, ClNO_2 was well and positively correlated with N_2O_5 during all four nights (Fig. 4, $R^2 = 0.36 - 0.78$), and only slight changes in $\text{ClNO}_2/\text{N}_2\text{O}_5$ ratios were observed after sunset.

5 These results are different from previous observations showing large variability in the correlations (Osthoff et al., 2008), which indicates that there are sufficient chloride sources for the ClNO_2 formation during this study period. The differences in regression coefficients among the four nights can be explained by different air masses originating from different regions which were calculated using the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLOT, NOAA) model (Draxler and Hess, 1997) (Fig. S5). For example, ClNO_2 tracked much better with N_2O_5 after midnight ($R^2 = 0.69$) than that before midnight

10 ($R^2 = 0.16$) during P2 (Fig. S6), suggesting the influences of air masses from different regions (Fig. S5). Comparatively, P4 and P1 showed similar tight correlations between ClNO_2 and N_2O_5 before and after midnight, consistent with their similar back trajectories during the two different periods.

The $\text{ClNO}_2/\text{N}_2\text{O}_5$ ratios varied significantly throughout the study ranging from 0.3 to 95.5 (30 minute average). The average ($\pm 1\sigma$) ratio of $\text{ClNO}_2/\text{N}_2\text{O}_5$ was 6.9 ± 7.4 , consistent with the previous studies in NCP, for example, 0.4-131.3 in Jinan

15 and Wangdu (Wang et al., 2017b; Tham et al., 2016). However, the ratios are substantially higher than those measured in other megacities, e.g., Hong Kong (0.1-2.0) (Wang et al., 2016), London (0.02-2.4) (Bannan et al., 2015) and Los Angeles, California (0.2-10.0) (Mielke et al., 2013). These results indicate ubiquitously high $\text{ClNO}_2/\text{N}_2\text{O}_5$ ratios in the NCP, consistent with another measurement in suburban Beijing (Wang et al., 2018), which might result from the high ClNO_2 production rate due to high aerosol loadings. We also note that the relatively low N_2O_5 associated with high N_2O_5 reactivity might be another possible

20 explanation. Furthermore, we compared the $\text{ClNO}_2/\text{N}_2\text{O}_5$ ratios with particulate concentrations and compositions during the four nights (Fig. 5). P3 showed the highest median ratio of 9.4, which is much higher than those during the rest of three nights (1.0-3.2). This can be explained by the correspondingly high liquid water content that facilitated the N_2O_5 heterogeneous uptake (Morgan et al., 2015). In comparison, the particle chloride concentrations were relatively close during the four nights, with slightly lower concentrations during P4, further supporting that the $\text{ClNO}_2/\text{N}_2\text{O}_5$ ratios were independent of particle

25 chloride in this study due to the sufficient chloride source for the ClNO_2 production, e.g., HCl gas-particle partitioning. The

lower ClNO₂/N₂O₅ ratios during P2 compared with P1 can be explained by the “nitrate effect” which suppressed N₂O₅ uptake (Mentel and Wahner, 1999) as P2 showed much higher nitrate concentrations than P1 (4.2 vs. 1.4 μg m⁻³). Note that the ClNO₂/N₂O₅ ratios were also characterized with the dependence on Org/SO₄ ratios in our campaign, similar to other studies (Evans and Jacob, 2005; Riemer et al., 2009).

5 3.4 N₂O₅ uptake coefficient and ClNO₂ production yield

To quantify the relative contributions of different pathways to N₂O₅ loss, three periods with relatively stable air masses and concurrent increases in ClNO₂ and NO₃⁻ (Fig. 6, 20:00-23:00 on 12 June, 20:00-00:00 on 13 June, and 20:00-22:30 on 14 June) were selected for the calculations of $\gamma_{\text{N}_2\text{O}_5}$ and ϕ . The rigorous method as suggested by Phillips et al. (2016) was used in this study. Briefly, the predicted concentrations of ClNO₂ and NO₃⁻ were derived by integrating $p\text{ClNO}_2$ and $p\text{NO}_3^-$ with average S_a and N₂O₅ over each time step (~15 min) and initial estimations for $\gamma_{\text{N}_2\text{O}_5}$ and ϕ . Repeating the integration by changing $\gamma_{\text{N}_2\text{O}_5}$ and ϕ until good agreements between observed and predicted values of ClNO₂ and NO₃⁻ were reached. The derived heterogeneous uptake coefficient, ClNO₂ yield, and N₂O₅ loss rate k_d following this method are listed in Table 2.

The estimated $\gamma_{\text{N}_2\text{O}_5}$ for the three selected periods were 0.017-0.09, which was generally comparable to previous values (0.014-0.092) derived from the steady-state assumption method in the NCP (Wang et al., 2017a; Wang et al., 2017b; Tham et al., 2016; Wang et al., 2017c), and also consistent with the recent measurements (0.012-0.055) using the same method in suburban Beijing (Wang et al., 2018). However, the $\gamma_{\text{N}_2\text{O}_5}$ determined in our campaign was 1-2 orders of magnitude higher than those obtained in laboratory (Thornton et al., 2003), and also much higher than those in Hong Kong and Germany (Brown et al., 2016b; Phillips et al., 2016). We also found that the parameterized $\gamma_{\text{N}_2\text{O}_5}$ values (0.0014-0.012) determined from Eq. (9) (the Bertram-Thornton parameterization) were significantly lower than the observed values, suggesting that more field measurements are needed to improve the parameterization schemes. Note that $\gamma_{\text{N}_2\text{O}_5}$ values appeared to increase with the rising relative humidity, which were also observed at other sites (Wang et al., 2017b; Thornton et al., 2003). For example, $\gamma_{\text{N}_2\text{O}_5}$ values increased from 0.019 to 0.090 when RH increased from 21.1% to 63.6%. However, the $\gamma_{\text{N}_2\text{O}_5}$ values were comparable at low RH levels (< 40%) (0.019 vs. 0.017 in Table 2) although RH differed by a factor of 2 (21% vs. 40%). These results further supported that the influences of hygroscopic growth on $\gamma_{\text{N}_2\text{O}_5}$ were mainly caused by increasing aerosol liquid

water content. The direct N_2O_5 loss rates estimated from the uptake coefficient were in the range of $0.00044\text{--}0.0034\text{ s}^{-1}$, which contributed 7–33% to the total N_2O_5 loss with the rest being indirect loss. The uncertainty of the direct N_2O_5 loss rates contributions is estimated to be $\sim 40\%$, associated from S_a ($\sim 30\%$), O_3 and NO_2 ($\sim 5\%$), and N_2O_5 ($\sim 17\%$). Our results indicated that the fast N_2O_5 loss in the nocturnal boundary in urban Beijing was predominantly from the indirect loss of NO_3 rather than the heterogeneous uptake of N_2O_5 , mainly due to active NO_3 reaction in summer. Such a conclusion was different from previous results in autumn Beijing that N_2O_5 loss was dominated by N_2O_5 heterogeneous hydrolysis (69.1%–98.8%) (Wang et al., 2017a). Several studies also revealed the importance of heterogeneous N_2O_5 uptake in N_2O_5 loss in the NCP by using the steady-state derived $\gamma_{\text{N}_2\text{O}_5}$ (Tham et al., 2016; Wang et al., 2017b; Wang et al., 2017c). While the uncertainties in different analysis methods, e.g., the product formation rates or steady-state assumption are one of the reasons, the high NO concentration could be the important reason for the dominant N_2O_5 loss pathway. The high VOC emissions, particularly biogenic emissions (e.g., isoprene and terpene) in summer than other seasons might be another reason for the differences in dominant N_2O_5 loss pathway. Indeed, the indirect N_2O_5 loss via $\text{NO}_3\text{+VOCs}$ was also found to dominate the total loss of N_2O_5 (67%) in summer in suburban Beijing (Wang et al., 2018). Our results highlight the significant nighttime NO_x loss through the reactions of NO_3 with VOCs in summer in urban Beijing.

The ClNO_2 yields ϕ derived for the three cases were 0.35, 0.10 and 0.15, respectively. The production yields in this study are substantially larger than those in urban Jinan (0.014–0.082) (Wang et al., 2017b), yet comparable to those reported at Mt. Tai (0.02–0.90) (Wang et al., 2017c) and continental Colorado (0.07–0.36) (Thornton et al., 2010). However, the significantly lower ϕ than that in suburban Beijing (0.50–1.0; (Wang et al., 2017b)) indicated more effective ClNO_2 production in suburban regions than urban regions to some extent. Indeed, the product of $\gamma_{\text{N}_2\text{O}_5}$ and ϕ ($\gamma_{\text{N}_2\text{O}_5} \times \phi$) in this study ranged from 0.006–0.009 and was much lower than those in (Wang et al., 2017b) (0.008–0.035). We noticed that ϕ were much lower than those parameterized from Eq. (10) (0.55–0.97), indicating that the Bertram-Thornton parameterization scheme might overestimate the ClNO_2 yield substantially. Note that $\gamma_{\text{N}_2\text{O}_5}$ might be overestimated associated with an underestimation of ϕ if assuming particulate nitrate is completely from the N_2O_5 heterogeneous uptake. Possible contribution from gas-phase HNO_3 repartitioning to the particulate phase was not considered mainly due to the lack of observational data for HNO_3 and NH_3 . Indeed, a recent study found that the nocturnal nitrate formation potential by N_2O_5 heterogeneous uptake was comparable to

that formed by gas-phase HNO_3 repartitioning in Beijing (Wang et al., 2017a). In addition, $\gamma_{\text{N}_2\text{O}_5} \times \emptyset$ was higher on 13 June than the other two days (e.g., 0.009 vs. 0.003-0.006), which might explain the correspondingly higher $\text{ClNO}_2/\text{N}_2\text{O}_5$ ratio in this day (on average 8.2 vs. 1.2-1.4). Our results overall suggest fast heterogeneous N_2O_5 uptake and high ClNO_2 production rate in summer in urban Beijing, which might have great implications for models to improve the simulations for nocturnal nitrate and daytime ozone.

4 Conclusions

We present the simultaneous measurement of gas-phase N_2O_5 and ClNO_2 by I-CIMS during the APHH summer campaign to investigate the nocturnal chemistry in urban Beijing. The average ($\pm 1\sigma$) mixing ratios of N_2O_5 and ClNO_2 were 79.2 ± 157.1 pptv and 174.3 ± 262.0 pptv, with maximum values of 1.17 ppbv and 1.44 ppbv, respectively. Differing from previous studies with negligible N_2O_5 after midnight at surface level, our measurements showed high nocturnal levels of N_2O_5 across the entire night, suggesting a high oxidative capacity in summer in urban Beijing. N_2O_5 and ClNO_2 exhibited clear diurnal variations with significant nocturnal formation due to heterogeneous uptake. The average nighttime nitrate radical production rate $p(\text{NO}_3)$ was 2.6 ± 2.4 ppbv h^{-1} , and the $\tau(\text{N}_2\text{O}_5)^{-1}$ was in the range of $0.20\text{-}1.46 \times 10^{-2} \text{ s}^{-1}$ corresponding to a nighttime N_2O_5 lifetime of 1.1-10.7 min. We also observed a decrease of $\tau(\text{N}_2\text{O}_5)$ under high relative humidity ($\text{RH} > 40\%$) conditions due to the higher N_2O_5 uptake rates with higher available surface area and liquid water content. N_2O_5 and ClNO_2 were positively correlated, although the $\text{ClNO}_2/\text{N}_2\text{O}_5$ ratios changed significantly from 0.3 to 95.5. The high $\text{ClNO}_2/\text{N}_2\text{O}_5$ ratios in this study might result from high ClNO_2 production rate and fast N_2O_5 loss due to the sufficient chloride source supply.

The N_2O_5 uptake coefficients estimated on basis of the product formation rates of ClNO_2 and NO_3^- were 0.017-0.09 in this study. Correspondingly, the direct N_2O_5 loss rates via the heterogeneous uptake were in the range of $0.00044\text{-}0.0034 \text{ s}^{-1}$, contributing 7%-33% to the total N_2O_5 loss. Our results indicated fast N_2O_5 loss in the nocturnal boundary in urban Beijing was mainly due to the indirect pathways through NO_3 reactions with NO/VOCs rather than the heterogeneous uptake of N_2O_5 . We also noticed that the derived ClNO_2 production yields (0.10-0.35) were substantially lower than those from the Bertram-Thornton parameterization, indicating that future studies are needed to address these discrepancies.

Data availability. The data in this study are available from the authors upon request (sunyele@mail.iap.ac.cn).

Competing interests. The authors declare that they have no conflict of interest.

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Table 1. Summary of average ($\pm 1\sigma$) meteorological parameters (RH, T , WS), CIMS species (N_2O_5 , ClNO_2 , the calculated NO_3 , nitrate radical production rate $p(\text{NO}_3)$, N_2O_5 reactivity ($\tau(\text{N}_2\text{O}_5)^{-1}$) and NO_3 reactivity ($\tau(\text{NO}_3)^{-1}$), trace gases (O_3 , NO_2 , NO), and NR- PM_{10} species (NO_3^- , Cl^-) for the entire study and four nighttime periods (i.e., P1, P2, P3 and P4).

	Entire	P1	P2	P3	P4
Meteorological parameters					
RH (%)	36.8 $\pm$ 15.9	36.3 $\pm$ 5.5	41.3 $\pm$ 2.5	60.5 $\pm$ 6.5	28.0 $\pm$ 7.0
T ($^{\circ}\text{C}$)	26.7 $\pm$ 4.9	24.5 $\pm$ 1.1	23.2 $\pm$ 0.7	23.2 $\pm$ 1.4	29.4 $\pm$ 2.4
WS (m s^{-1})	2.9 $\pm$ 1.4	1.9 $\pm$ 0.9	2.3 $\pm$ 0.7	1.9 $\pm$ 0.6	3.7 $\pm$ 1.7
CIMS species					
N_2O_5 (pptv)	79.2 $\pm$ 157.1	176.2 $\pm$ 137.2	515.8 $\pm$ 206.4	37.8 $\pm$ 29.0	88.3 $\pm$ 68.2
ClNO_2 (pptv)	174.3 $\pm$ 262.0	427.3 $\pm$ 222.5	748.3 $\pm$ 220.6	227.7 $\pm$ 103.7	57.2 $\pm$ 39.0
$\text{NO}_3(\text{cal})$ (pptv)	8.9 $\pm$ 15.7	7.2 $\pm$ 7.3	48.1 $\pm$ 26.2	2.0 $\pm$ 2.3	18.2 $\pm$ 15.2
$P(\text{NO}_3)$ (ppbv h^{-1})	3.2 $\pm$ 2.3	3.6 $\pm$ 4.2	2.8 $\pm$ 0.5	1.7 $\pm$ 1.2	2.6 $\pm$ 1.4
$\tau(\text{N}_2\text{O}_5)^{-1}$ (s^{-1})	0.011 $\pm$ 0.017	0.014 $\pm$ 0.028	0.0016 $\pm$ 0.0008	0.014 $\pm$ 0.0063	0.016 $\pm$ 0.011
$\tau(\text{NO}_3)^{-1}$ (s^{-1})	0.34 $\pm$ 0.87	0.62 $\pm$ 1.66	0.021 $\pm$ 0.017	0.42 $\pm$ 0.21	0.29 $\pm$ 0.30
Gaseous species					
O_3 (ppbv)	51.1 $\pm$ 35.4	23.4 $\pm$ 23.2	55.6 $\pm$ 5.3	17.8 $\pm$ 15.3	40.3 $\pm$ 28.0
NO_2 (ppbv)	28.1 $\pm$ 17.1	56.2 $\pm$ 22.4	16.9 $\pm$ 3.9	38.2 $\pm$ 9.9	28.7 $\pm$ 16.0
NO (ppbv)	8.7 $\pm$ 16.9	15.6 $\pm$ 14.6	0.5 $\pm$ 0.7	2.3 $\pm$ 3.5	7.1 $\pm$ 13.3
NR- PM_{10} species					
NO_3^-	2.7 $\pm$ 2.4	2.3 $\pm$ 1.5	4.3 $\pm$ 0.7	4.3 $\pm$ 1.6	0.6 $\pm$ 0.2
Cl^-	0.10 $\pm$ 0.16	0.13 $\pm$ 0.14	0.09 $\pm$ 0.02	0.08 $\pm$ 0.09	0.04 $\pm$ 0.07

Table 2. Estimated uptake coefficient of N_2O_5 , ClNO_2 production yield and related parameters for the selected periods at three nights.

Period	RH (%)	$\gamma_{\text{N}_2\text{O}_5}$	θ	K_d (s^{-1})	Percentage (%)
Case1	39.9	0.017	0.35	0.00044	32.6
Case2	63.6	0.090	0.10	0.0034	20.8
Case3	21.1	0.019	0.15	0.00055	6.9

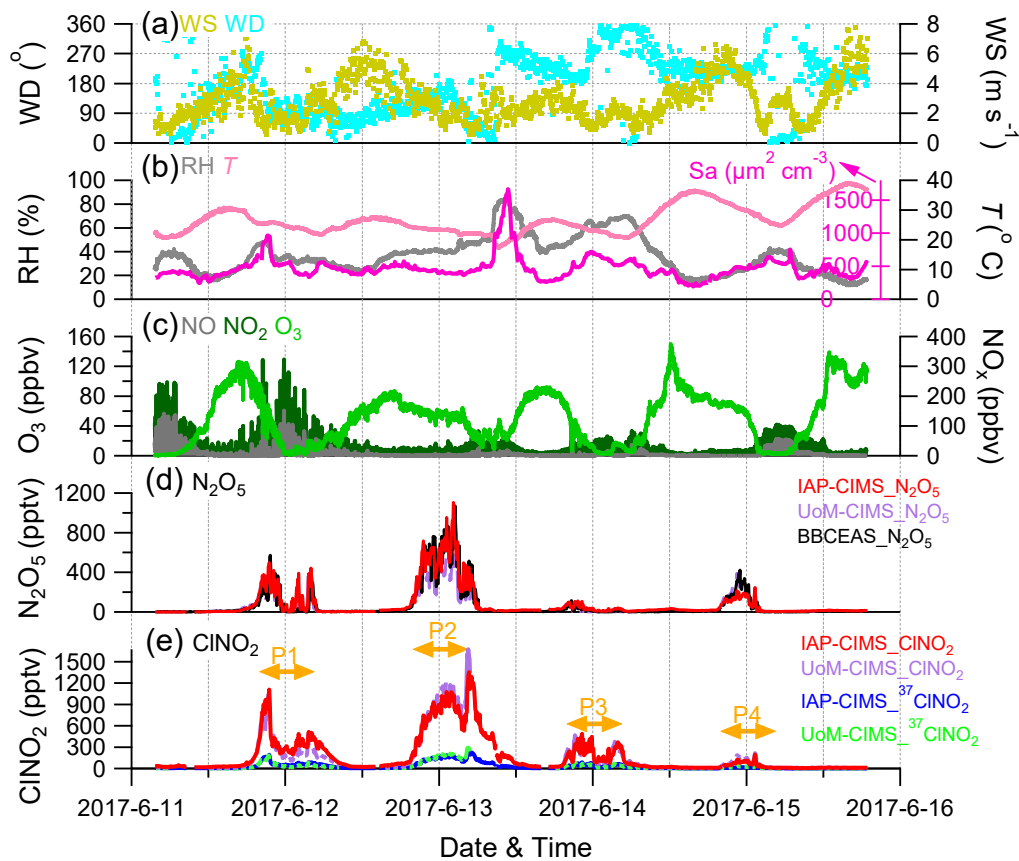


Figure 1. Time series of (a-b) meteorological parameters (WS, WD, RH, T) and surface area density (Sa), (c) trace gases (O₃, NO, NO₂), (d-e) IAP-CIMS species (N₂O₅, ClNO₂). The UoM-CIMS and BBCEAS measurements are also shown for inter-comparisons. The four nights (i.e., P1, P2, P3 and P4) are marked for further discussions.

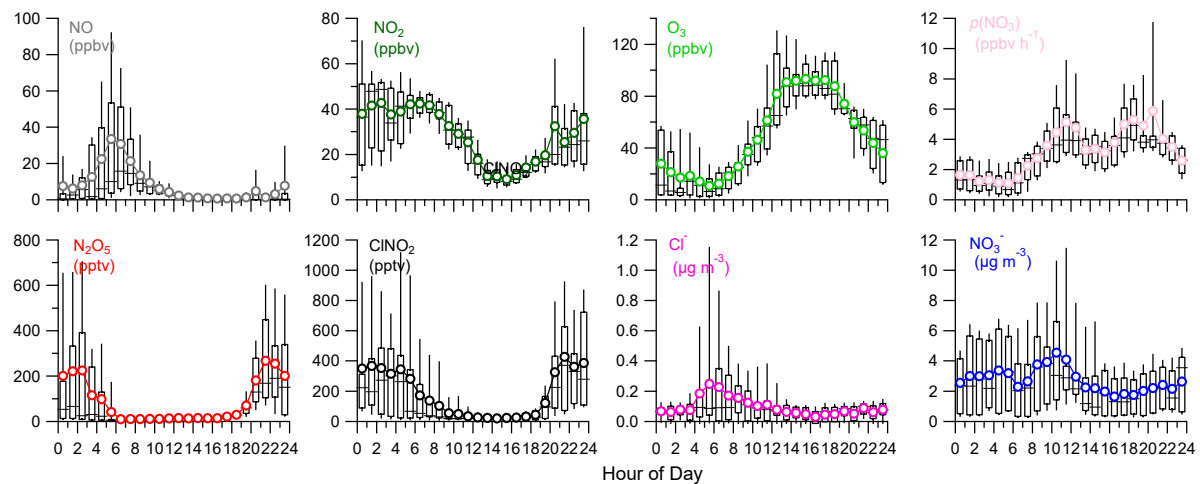


Figure 2. Diurnal variations of trace gases (NO, NO₂, O₃), IAP-CIMS species (N₂O₅, ClNO₂), nitrate radical production rate $p(\text{NO}_3)$, and NR-PM₁ species (Cl⁻, NO₃⁻).

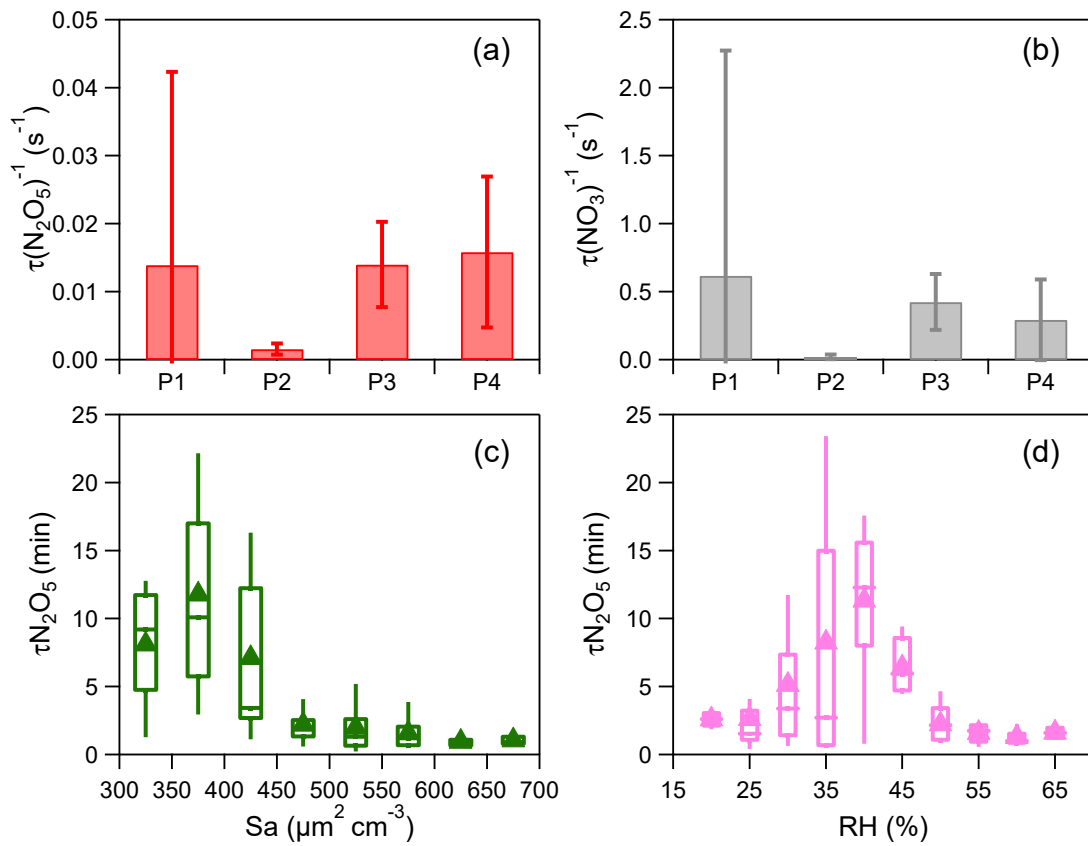


Figure 3. (a-b) Average reactivity of N_2O_5 ($\tau(\text{N}_2\text{O}_5)^{-1}$) and NO_3 ($\tau(\text{NO}_3)^{-1}$) for different nights (i.e., P1, P2, P3 and P4). The error bar represents the standard deviation, (c) Variations of the nocturnal $\tau(\text{N}_2\text{O}_5)$ as a function of aerosol surface area density (S_a), (d) Variations of the nocturnal $\tau(\text{N}_2\text{O}_5)$ as a function of relative humidity (RH). The data were binned according to S_a (50 $\mu\text{m}^2 \text{cm}^{-3}$ increment) or RH (5% increment). Mean (triangle), median (horizontal line), 25th and 75th percentiles (lower and upper box), and 10th and 90th percentiles (lower and upper whiskers) are shown for each bin.

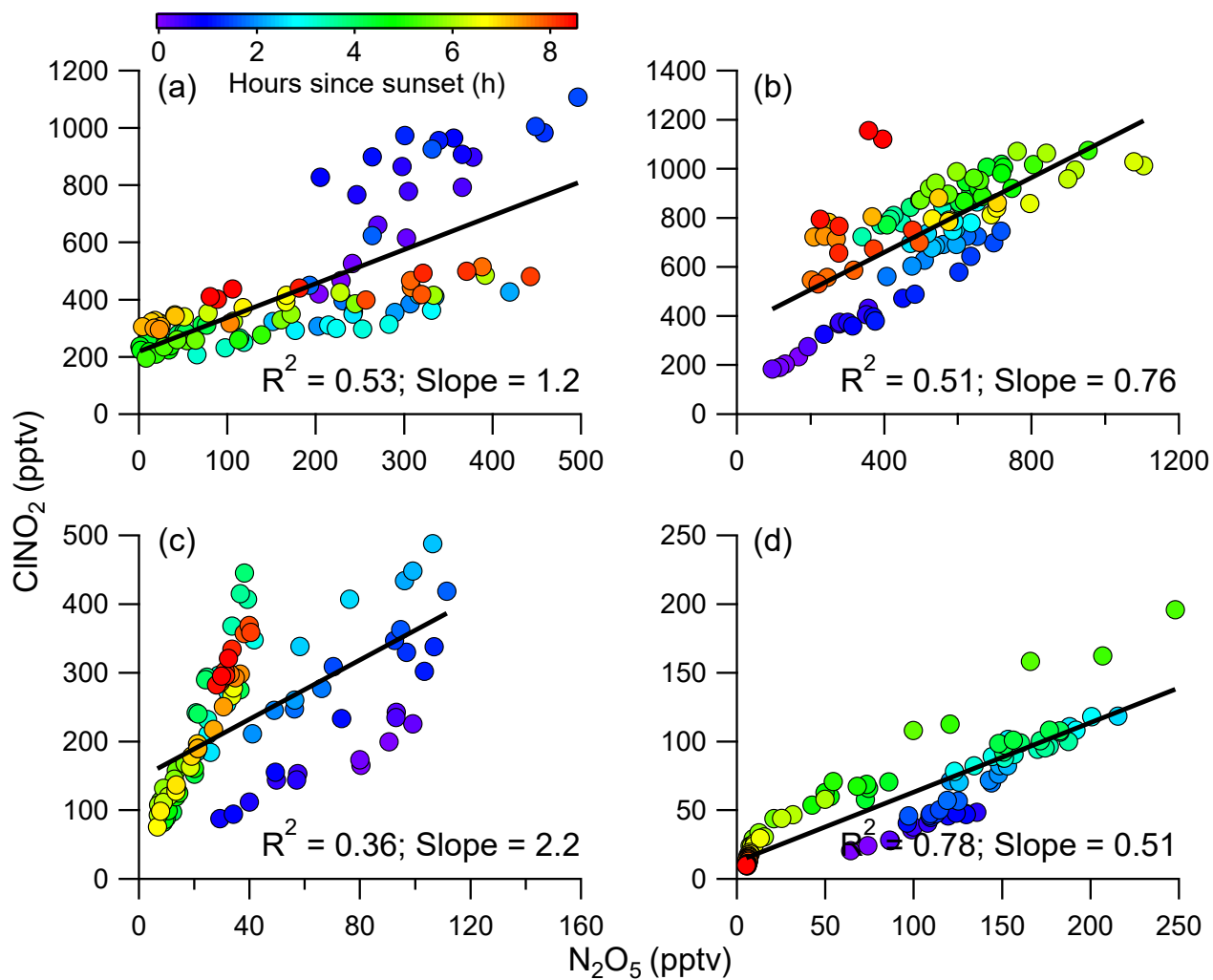


Figure 4. Correlations between ClNO_2 and N_2O_5 for four different nights, i.e., P1, P2, P3 and P4. The data are color-coded by the hours since sunset. Also shown are the correlation coefficients and slopes.

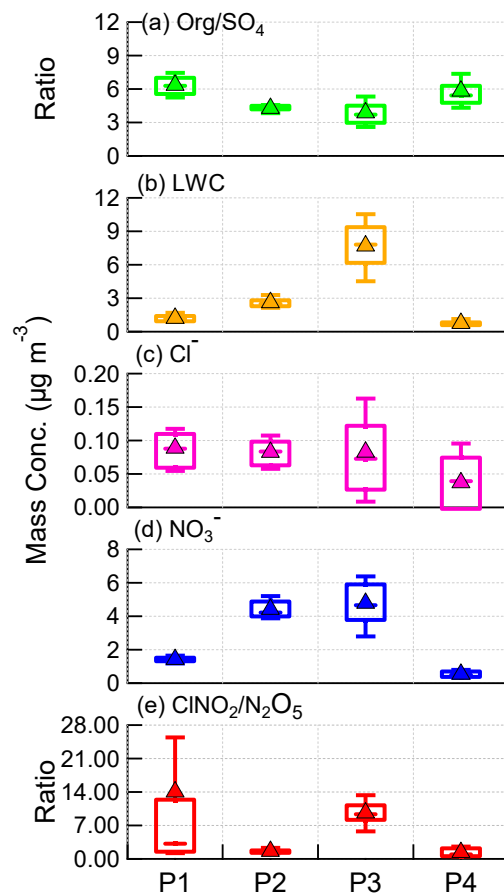


Figure 5. Box plots of (a) Org/SO₄ ratio, (b) LWC, (c) particulate chloride, (d) particulate nitrate, and (e) ClNO₂/N₂O₅ ratio for each night, i.e., P1, P2, P3 and P4. The mean (triangle), median (horizontal line), 25th and 75th percentiles (lower and upper box), and 10th and 90th percentiles (lower and upper whiskers) are shown.

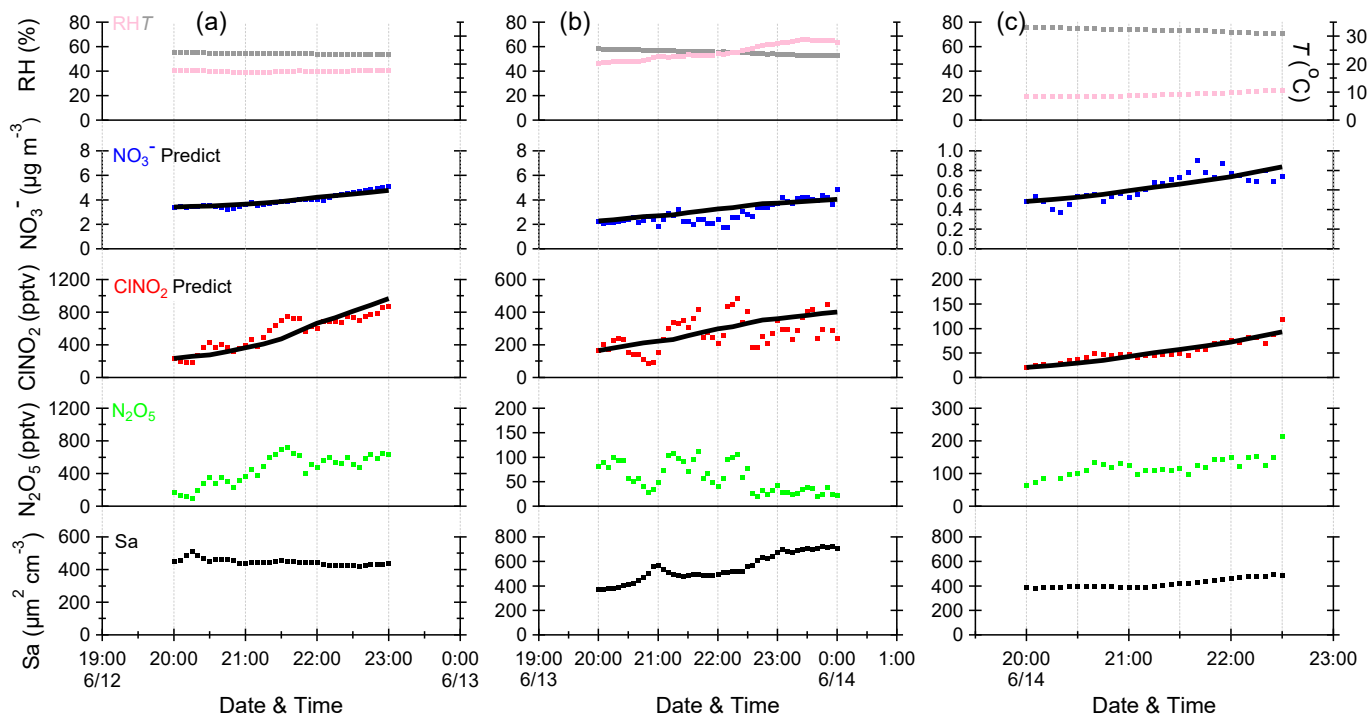


Figure 6. Time series of meteorological parameters (RH, T), particulate nitrate (NO_3^-), mixing ratios of N_2O_5 and ClNO_2 , and aerosol surface area density (S_a) for the selected periods at three nights. The black solid lines are the predicted, integration concentrations of NO_3^- and ClNO_2 calculated using the estimated method.