Semi-quantitative understanding of source contribution to nitrous acid (HONO) based on 1-year continuous observation at the SORPES station in eastern China

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Abstract

Nitrous acid (HONO), an important precursor of the hydroxyl radical (OH), has been long-standing recognized to be of significance to atmospheric chemistry, but its sources are still debate. In this study, we conducted continuous measurement of HONO from November 2017 to November 2018 at the SORPES station in Nanjing of eastern China. The yearly average mixing ratio of observed HONO was 0.69 ±0.58 ppb, showing a larger contribution to OH relative to ozone with a mean net OH production rate of 0.59 ppb/h. To estimate the effect of combustion emissions of HONO, the emitted ratios of HONO and NO_x were derived from 55 fresh plumes ($NO/NO_x > 0.85$), with a mean value of 0.79%. During the nighttime, the chemistry of HONO was found to depend on RH, and heterogeneous reaction of NO_2 on aerosol surface was presumably responsible for HONO production. The average nighttime NO_2-to-HONO conversion frequency (C_{HONO}) was determined to be 0.0055 ± 0.0032 h^{-1} from 137 HONO formation cases. The missing source of HONO around noontime seemed to be photo-induced with an average $P_{unknown}$ of 1.02 ppb h^{-1}, based on a semiquantitative HONO budget analysis. An over-determined system of equations was applied to obtain the monthly variations in nocturnal HONO sources. Except for burning-emitted HONO (approximately 23% of total measured HONO), the contribution of heterogeneous formation on ground surfaces was an approximately

constant proportion of 36% throughout the year. The soil emission revealed clear seasonal variation, and contributed up to 40% of observed HONO in July and August. A higher propensity for generating HONO on aerosol surface occurred in heavily polluted period (about 40% of HONO in January). Our results highlight ever-changing contributions of HONO sources, and encourage more long-term observations to evaluate the contributions from varied sources.

1. Introduction

Nitrous acid (HONO) is a vital constituent of nitrogen cycle in the atmosphere, first observed in the field by Perner and Platt (1979). The concentrations of HONO varied from dozens of ppt in remote regions (Villena et al., 2011b;Meusel et al., 2016) to several ppb in polluted urban regions (Yu et al., 2009;Tong et al., 2015). The photolysis of HONO (R1) has been long standing as a momentous source of the hydroxyl radicals (OH) especially during the early morning when other OH sources are minor (Platt et al., 1980;Alicke, 2002, 2003). Even during the daytime, recent studies have recognized the photolysis of HONO as a potentially stronger contributor to daytime OH radicals than that of O_3 (Kleffmann, 2005;Elshorbany et al., 2009;Li et al., 2018). Meanwhile, HONO has been found to affect adversely human heath (Jarvis et al., 2005;Sleiman et al., 2010).

Although the significance of HONO has been given much weight, the sources of ambient HONO are complicated and have been debated for decades. HONO can be emitted from combustion, including vehicle exhaust, industrial exhaust and biomass burning (Table 1).Tunnel experiments with tests for different engine types have determined an emission ratio of HONO/NO_x for traffic source, ranged in 0.3-0.8% (Kirchstetter et al., 1996;Kurtenbach et al., 2001). The release from soil nitrite through acidification reaction and partitioning is considered to be another primary source of atmospheric HONO (Su et al., 2011). Soil nitrite could come from biological nitrification and denitrification processes (Canfield et al., 2010;Oswald et al., 2013), or be enriched via reactive uptake of HONO from the atmosphere

(VandenBoer et al., 2014a;VandenBoer et al., 2014b). In addition to direct emissions, the vast majority of HONO is produced chemically. The recombination of NO and OH (R3) is the main homogeneous reaction for supplying HONO (Pagsberg et al., 1997;Atkinson, 2000), whose contribution may be significant under conditions of sufficient reactants at daytime. During the nighttime, with low OH concentrations, other larger sources, i.e. heterogeneous reactions of NO_2 on various surfaces, are required to explain elevated mixing levels of HONO. Laboratory studies indicate that NO_2 can be converted to HONO on humid surfaces (R4), being first order in NO_2 and depending on various parameters including the gas phase NO_2 concentration, the surface water content, and the surface area density (Kleffmann et al., 1998;Finlayson-Pitts et al., 2003). Besides, heterogeneous reduction of NO_2 with surface organics (R5) is proposed to be another effective pathway to generate HONO (Ammann et al., 1998;Ammann et al., 2005;Aubin and Abbatt, 2007), observed in freshly emitted plumes with high concentrations of NO_x and BC (Xu et al., 2015). Notably this reaction rate is drastically reduced after the first few seconds due to consumption of the reactive surfaces (Kalberer et al., 1999;Kleffmann et al., 1999), but this reaction could be strongly enhanced by light on photo-activated surface (George et al., 2005;Stemmler et al., 2006;Stemmler et al., 2007). During the daytime, heterogeneous HONO formation from the photolysis of adsorbed nitric acid (HNO_3) and particulate nitrate (NO_3^-) at UV wavelengths has been found in experiments and observations (Zhou et al., 2003;Zhou et al., 2011;Ye et al., 2016;Ye et al., 2017). Heterogeneous processes are typically considered as the primary sources of HONO in many regions yet are the most poorly understood. For NO_2 conversion to HONO on surfaces (R4,R5), the uptake coefficients of NO_2 derived from different experiments vary from 10^{-9} to 10^{-2} (Ammann et al., 1998;Kirchner et al., 2000;Underwood et al., 2001;Aubin and Abbatt, 2007;Zhou et al., 2015). The key step to determine the uptake of NO_2 or the reaction rate is still ill-defined, and we are also not certain if and how the ambient natural surfaces can be reactivated by radiation. Furthermore, it has become a main concern to compare the contributions of ground and aerosol surfaces to HONO formation. It is so far, not well explained for the observed HONO,

especially during daytime. Large unknown sources of HONO were identified by many studies (Su et al., 2008b;Sörgel et al., 2011;Michoud et al., 2014;Lee et al., 2016).

Benefitting from more and more studies, particularly the observations under different environments (Lammel and Cape, 1996;Li et al., 2012), understanding of HONO chemistry in the atmosphere has been greatly improved during the last decade. However, most HONO observations were short-term campaigns with studies ranging from several weeks to several months. For example, Reisinger (2000) found a linear correlation between the HONO/NO_2 ratio and aerosol surface density in the polluted winter atmosphere; and Nie et al. (2015) showed the influence of biomass burning plumes on HONO chemistry, according to observed data during late April–June 2012; while Wong et al. (2011) believed that NO_2 to HONO conversion on the ground was the dominant source of HONO by analyzing vertical profiles from 15 August to 20 September in 2006. Moreover, a theory that HONO from soil emission explained the strength and diurnal variations of the missing source has been presented by Su et al. (2011) based on data measured from 23 to 30 October 2004. In case the HONO sources possibly exhibit temporal variability, especially seasonal differences, it is challenging to draw a full picture on the basis of these short-term observations. More than a year of continuous observation is needed, yet rather limited.

The Yangtze River Delta (YRD) is one of the most developed regions in eastern China. Rapid urbanization and industrialization have induced severe air pollution over the last three decades, particularly high concentrations of reactive nitrogen (Richter et al., 2005;Rohde and Muller, 2015), including HONO (Wang et al., 2013;Nie et al., 2015). In this study, we conducted HONO observations continuously from November 2017 to November 2018, at the Station for Observation Regional Processes and the Earth System (SORPES), located in the western part of the YRD, a place that can be influenced by air masses from different source regions of anthropogenic emissions, biomass burning, dust and biogenic emissions (Ding et al., 2013;Ding et al., 2016). Our one-year observation showed well-defined diurnal patterns and obvious season

variations of HONO concentrations at relatively high levels. We discussed the potential mechanism of HONO production based upon semiquantitative analysis and correlation studies, and paying special attention to changes in major sources of HONO during different seasons.

2. Methodology

2.1. Study site and instrumentation

Continuously observations was conducted at the SORPES station at the Xianlin Campus of Nanjing University (118°57′E, 32°07′N), located in the northeast suburb of Nanjing, China, from November 2017 to November 2018 (Fig. S1). The easterly prevailing wind and synoptic condition makes it a representative background site of Nanjing and a regional downwind site of the city cluster in the YRD region. Detailed descriptions for the station can be found in previous studies (Ding et al., 2013;Ding et al., 2016).

HONO was measured with a commercial long path absorption photometer instrument (QUMA, Model LOPAP-03). The ambient air was sampled in two similar temperature controlled stripping coils in series using a mixture reagent of 100 g sulfanilamide and 1 L HCl (37% volume fraction) in 9 L pure water. In the first stripping coil, all of the HONO and a fraction of interfering substances were absorbed into solution, and the remaining interfering species (NO_2, HNO_3, HO_2NO_2, PAN, etc.) were absorbed in the second stripping coil. After adding a reagent of 0.8 g N-naphtylethylendiamine-dihydrochloride in 8 L pure water to both coils, colored azo dye was formed in the solutions from 2 stripping coils, which were then separately detected via long path absorption in special Teflon tubing. The real HONO signal was the difference between the signals in the two channels to minimize the measurement interferences. Further details can be found in (Heland et al., 2001;Kleffmann et al., 2006). To correct for the small drifts in instrument's baseline, compressed air was sampled every 12 h (flow rate: 1 L/min) to make zero measurement. A span check

was made using 0.04 mg/m^3 nitrite (NO_2^-) solution each two weeks with a flow rate of 0.28 ml/min. The time resolution, detection limit, accuracy of the measurement was 10 min, 10 pptv, and 10%, respectively.

The NO and NO_2 levels were measured using a chemiluminescence instrument (TEI, model 42i) coupled with a highly selective photolytic converter (Droplet Measurement Technologies, model BLC), and the analyzer had a detection limit of 50 pptv for an integration time of 5 min, with precision of 4% and an uncertainty of 10% (Xu et al., 2013). O_3 and CO were measured continuously using Thermo-Fisher Scientific TEI 49i and TEI 48i. The fine particle mass concentration ($PM_{2.5}$) was continuously measured with a combined technique of light scattering photometry and beta radiation attenuation (Thermo Scientific SHARP Monitor Model 5030). Water soluble aerosol ions (NO_3^-, SO_4^{2-}, NH_4^+ etc.) and ammonia (NH_3) were measured by a Monitor for Aerosols and Gases in ambient Air (designed and manufactured by Applikon Analytical B.V., the Netherlands) with a $PM_{2.5}$ cyclone inlet, in a time resolution of 1 hr. The size distribution of submicron particles (6-820 nm) is measured with a DMPS (differential mobility particle sizer) constructed at the University of Helsinki in Finland. Meteorological measurements including relative humidity (RH), wind speed, wind direction, and air temperature were recorded by Automatic Weather Station (CAMPEEL co., AG1000). UVB total radiation was measured by UVB radiometer (UVS-B-T UV Radiometer, KIPP &ZONEN).

2.2. TUV model and OH estimate

The Tropospheric Ultraviolet and Visible (TUV) Radiation Model (http://www.acd.ucar.edu/TUV) was adopted to compute the photolysis frequencies, which is most probably accurate in clean and cloudless days. The pivotal parameters of this model were inputted as follows: the ozone density was measured by Total Ozone Mapping Spectrometer (http://toms.gsfc.nasa.gov/teacher/ozoneoverhead.html); the typical single scattering albedo (SSA) and Ångström exponent (Alpha) were 0.93 and 1.04 (Shen et al., 2018); The mean value of optical depth (AOD) at 550nm was

0.640, derived following an empirical relationship with $PM_{2.5}$ in Nanjing (Shao et al., 2017). To reduce the error of model, we used observed UVB to correct simulated results (J_{mod}) by Eq. (1). The daytime OH concentration was calculated by applying the linear fitting formula (Eq. 2) that obtained from correlations of measured OH concentrations with simultaneously observed $J(O^1D)$, suggested by Rohrer and Berresheim (2006). The coefficient a reflects the general chemical conditions (e.g. NO_x or VOCs) at the selected place for research, the exponent b represents the combined effects of all photolytic processes on OH, and the parameter c counts the light-independent OH sources. The values of a and b in Eq. (2) are adopted from the study in the Pearl River Delta (Lu et al., 2012). The value of c is set to 1.0×10^6 cm^{-3}, a typical nighttime OH concentration in urban areas of China (Li et al., 2012;Lu et al., 2014). The calculated OH concentrations around noon were in the range of 0.15-1.6×10^7 cm^{-3}, comparable to observations in Chinese urban atmospheres (Lu et al., 2012;Lu et al., 2013).

$$J = \frac{UVB_{obs}}{UVB_{mod}} J_{mod} \quad (1)$$

$$[OH] = a \times (J(O^1D) / 10^{-5} s^{-1})^b + c \quad (a = 5.6\times10^6 cm^{-3}, b = 0.68, c = 1.0\times10^6 cm^{-3}) \quad (2)$$

3. Results

3.1. Observation overview

We carried out continuous measurements for HONO at SORPES station in the northeast suburb of Nanjing from November 2017 to November 2018 with a mean measured ambient HONO mixing level of 0.69 ±0.58 ppb (Fig. S2), within the range of those in or in the vicinity of mega cities (Table 2). Fig.1 shows the seasonal pattern of HONO and related parameters. The highest concentration of HONO was found in winter (1.04 ± 0.75 ppb), followed by spring (0.68 ± 0.48 ppb), autumn (0.66 ±0.53 ppb) and summer (0.45 ± 0.37 ppb). Such seasonal variations in Nanjing are aligned with that in Beijing (Hendrick et al., 2014), and are somewhat similar to those in Jinan

(Li et al., 2018), where the highest levels occurred in winter and the lowest levels occurred in autumn, but these variations are different from those in Hongkong (Xu et al., 2015) where the highest and lowest values of HONO appeared in autumn and spring, respectively. The important point is that the seasonality of HONO coincides with that of NO_x (or NO_2), which is believed to be the main precursor of HONO, in current studies.

The HONO to NO_x ratio or the HONO to NO_2 ratio has been used extensively in previous researches to characterize the HONO levels and to indicate the extent of heterogeneous conversion of NO_2 to HONO, since it is less influenced by convection or transport processes than the individual concentration (Lammel and Cape, 1996;Stutz et al., 2002). When a large proportion of HONO comes from direct emissions, the value of $HONO/NO_2$ usually becomes larger, falsely implying the strong formation of HONO from NO_2, however, the freshly emitted air masses generally have the lowest $HONO/NO_x$ ratio, meaning that $HONO/NO_x$ behaves better than $HONO/NO_2$ in a way. As shown in Fig. 1(b), the low value of $HONO/NO_x$ in winter is attributed to heavy emissions because we see high mixing ratios of NO during this cold season (Fig. 1c), the reasons for two peaks of $HONO/NO_x$ in spring and summer will be discussed in sections 3.3, 3.4 and 4.

All daily changes of HONO concentration in different seasons closely resemble a cycle where HONO peaks in the early morning, and then decreases to the minimum in the late afternoon, following the diurnal trend of NO_x (Fig. 2).The daily variations of HONO in Nanjing are like those seen in other urban areas (Villena et al., 2011a;Wang et al., 2013;Michoud et al., 2014;Lee et al., 2016), but differ from observations on the roadside (Rappenglück et al., 2013;Xu et al., 2015). At night, the mixing ratio of HONO increases rapidly in the first few hours and then stabilizes (in spring and summer) or gradually climbs to its peak in the morning rush hour (in winter and autumn). The accumulation during nighttime hours suggests a significant production of HONO exceeding the dry deposition of HONO. As the sun rises, the HONO sink

will be strengthened by photolysis and the vertical mixing processes, resulting that the peak times of the diurnal patterns of HONO concentration varies in different seasons. During the daytime, the rate of HONO abatement is rapid before noon and then becomes progressively until HONO concentration falling to the minimum. Given that the photolytic lifetime of HONO is about 10-20 min at the midday (Stutz et al., 2000), the considerable HONO concentration during daytime indicates the existence of strong production of HONO.

From the daily variations of the HONO to NO_x ratio, we can further understand the behavior of HONO in the atmosphere. HONO/NO_x is regularly enhanced quickly before midnight then reaches a maximum during the latter half of the night. According to Stutz et al. (2002), the highest HONO/NO_x (or HONO/NO_2) is defined by the balance between production and loss of HONO at each night, the conditions affecting the highest achievable ratio at nighttime will be discussed in section 3.3. What's interesting here is the peak of the HONO/NO_x ratio in the midday sun in spring, summer and autumn, and even in winter, the ratio doesn't decline but remains stationary before and at noon. If the HONO sources during daytime are consistent with those at night, the minimum HONO/NO_x ratios should occur at noon due to the intense photochemical loss of HONO. Therefore, there must be additional sources of HONO during daytime (e.g. R3). The increase of HONO/NO_x with solar radiation (e.g., UVB) is found in both diurnal and seasonal variations, indicating that these daytime sources have a relationship with the intensity of solar radiation. We will further discuss the potential daytime sources of HONO in section 3.4.

The elevated mixing ratio of HONO presents an efficient source of OH radicals during daytime in Nanjing. We calculate the net OH production rate from HONO, i.e. P_{OH}(HONO), using Eq. (3) (Li et al., 2018). For comparison, the OH production rate from ozone photolysis, $P_{OH}(O_3)$, is derived from Eq. (4). Based on Alicke et al. (2002) and Alicke (2003), only part of the $O(^1D)$ atoms, formed by the photolysis of O_3 at wavelengths below 320 nm (R7), can produce OH radicals by reacting with water (R8)

in the atmosphere, so we use the absolute water concentration, which can be derived from relative humidity and temperature, to calculate the branching ratio of $O(^1D)$ (ϕ_{OH}) between R8 and R9. The reaction rate of $O(^1D)$ with O_2 is 4.0×10^{-11} cm^3 $molecules^{-1}$ s^{-1} and the reaction rate of $O(^1D)$ with N_2 is 3.1×10^{-11} cm^3 $molecules^{-1}$ s^{-1} (Seinfeld and Pandis, 2016). In addition to the two mechanisms mentioned above, there are other pathways to generate primary OH radicals: the photolysis of aldehydes, mainly HCHO, can form HO_2 radicals, and then converting to OH radicals by reacting with NO; the reactions of ozone with alkenes produce OH radicals directly; the ozonolysis of alkenes and nighttime reactions of NO_3 radicals with alkenes can also be net sources of OH radicals (Finlayson-Pitts and Pitts, 2000;Seinfeld and Pandis, 2016).

$$P_{OH}(HONO) = J(HONO)[HONO] - k_{NO+OH}[NO][OH] - k_{HONO+OH}[HONO][OH] \quad (3)$$

$$P_{OH}(O_3) = 2J(O^1D)[O_3]\phi_{OH}, \quad \phi_{OH} = k_8[H_2O]/(k_8[H_2O]+k_9[M]) \quad (4)$$

$$O_3 + h\upsilon \rightarrow O(^1D) + O_2(\lambda < 320nm) \quad (R7)$$

$$O(^1D) + H_2O \rightarrow 2OH \quad (R8)$$

$$O(^1D) + M \rightarrow O(^3P) + M \ \ (M \text{ is } N_2 \text{ or } O_2) \quad (R9)$$

Fig. 3 shows that the diurnal peak of OH production rate from HONO is usually found in the late morning, caused by the combined effects of HONO concentration and its photolysis frequency and the seasonal peak of $P_{OH}(HONO)$ occurs in spring for the same reason. $P_{OH}(O_3)$, coinciding with the trend of $J(O^1D)$, is highest around noon at daily time scale and is highest in summer at seasonal time scale, respectively. Significantly, the photolysis of HONO produce more OH than that of ozone throughout the daytime in winter, spring. In summer and autumn, the contribution of HONO to OH is greater in the early morning, and although the photolysis of ozone contributes more OH at noon, the role of HONO is considerable. Overall, the average

302 P_{OH}(HONO) during 8:00-16:00 LT is 0.59 ppb/h, and the mean value of $P_{OH}(O_3)$ is
303 0.41 ppb/h. The impressive role of HONO in the atmospheric oxidizing capacity
304 should benefit photochemical ozone production (Ding et al., 2013;Xu et al., 2017;Xu
305 et al., 2018), new particle formation (Qi et al., 2015) and secondary aerosol formation
306 (Xie et al., 2015;Sun et al., 2018) in Nanjing, the western YRD region.
307
308 ***3.2. Direct emissions of HONO from Combustion***
309
310 As mentioned above, the good correlation of HONO with NO_x (Fig. 4a) and the
311 similar patterns of HONO and NO_x, particularly sharply increasing together in the
312 fresh plumes, in which the NO/NO_x ratios are usually very high (Fig. S1), indicate the
313 presence of direct combustion emission of HONO, which need to be deducted when
314 analyzing the secondary formation of HONO. The SORPES station are influenced by
315 air masses from both industries and vehicles (Ding et al., 2016), the traffic emission
316 factor investigated in other experiments cannot be used straightly; thus, we derive the
317 emitted HONO/NO_x ratio according the method of Xu et al. (2015), and the following
318 criteria are adopted to select fresh plumes: (a) NO_x>40ppbv; (b) $\triangle NO/\triangle NO_x$>0.85;
319 (c) good correlation between HONO and NO_x (r>0.9); (d) short duration of plumes
320 (<=2h); and (e) UVB<=0.01 W/m^2. Then, the slopes of HONO to NO_x in selected
321 plumes were considered as the emission ratios in our study.
322
323 Within the one-year dataset, we select 55 freshly emitted plumes satisfying the criteria
324 above (Table S1), of which 20 air masses were found in the morning and evening rush
325 hours; the derived $\triangle HONO/\triangle NO_x$ ratios vary from 0.26% to 1.91% with a mean
326 value of 0.79%±0.36%. Many factors, such as the amount of excess oxygen; the types
327 of fuel used (gasoline, diesel, coal); if engines are catalyst-equipped, and if engines
328 are well-maintained, could result in variances in these ratios. Additionally, the rapid
329 heterogeneous reduction of NO_2 on synchronously emitted BC can also raise the value
330 of $\triangle HONO/\triangle NO_x$ (Xu et al., 2015). For our study, an average emission factor of
331 0.79% is deployed to evaluate the emission contribution of HONO (Eq.5), which is
332 abbreviated as $HONO_{emis}$.

$$HONO_{emis} = NO_x \times 0.0079 \quad (5)$$

$$HONO_{corr} = HONO - HONO_{emis} \quad (6)$$

Combustion emissions contribute an average of 23% of total measured HONO concentrations at night (Fig. 4b), with a maximum $HONO_{emis}$/HONO value of 32% in winter and a minimum $HONO_{emis}$/HONO value of 18% in summer. We then get the corrected observed HONO ($HONO_{corr}$) by Eq.(6) for further analysis. The slope of the fitted line for HONO and NO_x is 1.62%, higher than emission ratio 0.79% (Fig. 4a), and almost 80% of HONO is from $HONO_{corr}$ that is not affected by emissions (Fig. 4b).These imply significant secondary formation of HONO in the atmosphere.

3.3. Heterogeneous conversion of NO_2 to HONO during nighttime

3.3.1. The NO_2-to-HONO conversion rate (C_{HONO})

In addition to emissions, heterogeneous reaction of NO_2 on surfaces (R4, R5) is believed to be the major formation pathways of nocturnal HONO. Thus, the NO_2-to-HONO conversion rate is calculated from Eq. (5) (Alicke et al., 2002;Alicke, 2003;Wentzell et al., 2010), where NO_2 is adopted to scale HONO to reduce the dilution influence according to Su et al. (2008a). Similar to HONO/NO_x (Fig. 2), the nighttime $HONO_{corr}/NO_2$ ratio rises from the lowest value and then reaches a quasi-stable state, meaning that C_{HONO} can actually be used to assess how quickly $HONO_{corr}/NO_2$ can increase to its equilibrium.

$$C_{HONO} = \frac{\frac{[HONO_{corr}]_{(t_2)}}{[NO_2]_{(t_2)}} - \frac{[HONO_{corr}]_{(t_1)}}{[NO_2]_{(t_1)}}}{t_2 - t_1} \quad (7)$$

Following the method of Xu et al. (2015) and Li et al. (2018), 137 cases in which $HONO_{corr}/NO_2$ increased almost linearly from 18:00 to 24:00 each night are selected, and the slope fitted by the least linear regression for $HONO_{corr}/NO_2$ against time is

just the conversion frequency of NO_2 to HONO. The derived values of C_{HONO} vary from 0.0043±0.0017 h^{-1} in winter to 0.0066±0.0040 h^{-1} in summer, with an average value of 0.0055±0.0032 h^{-1}, which is in the range (0.044-0.014 h^{-1}) shown by other studies in urban and suburban sites (Fig. 5). Noting that C_{HONO} assumes all the increase of $HONO_{corr}/NO_2$ is caused by the conversion of NO_2, excluding other possible sources of HONO (e.g. soil nitrite); and the computed C_{HONO} is the net NO_2-to-HONO conversion rate since the measured $HONO_{corr}$ has already taken the sinks of HONO (mainly deposition) into account. Considering the uncertainties of C_{HONO}, utilizing C_{HONO} directly to analyze the mechanism of HONO formation thoroughly may not be appropriate, but it could be attemptable to facilitate the parameterizations for HONO production in air quality models by C_{HONO} when the chemical mechanisms are not clear yet.

3.3.2. RH dependence of HONO chemistry

It appears that NO_2 hydrolysis on humid surfaces (R4), having a first order dependence on NO_2 (Jenkin et al., 1988;Ackermann, 2000;Finlayson-Pitts et al., 2003), is influenced by the surface absorbed water (Kleffmann et al., 1998;Finlayson-Pitts et al., 2003), although the exact mechanisms are still unknown. In the studies of Stutz et al. (2002) and Stutz et al. (2004), the pseudo steady state of $HONO/NO_2$, where this ratio is at a maximum at nighttime, is presumed to be a balance between the production of HONO from NO_2 and the loss of HONO on surfaces, and the highest $HONO/NO_2$ is determined by the ratio of the reactive uptake coefficients for each process. Scatter plot of $HONO_{corr}/NO_2$ against relative humidity in our study are illustrated in Fig. 6. To eliminate as much influence of other factors as possible, the average of the 6 highest $HONO_{corr}/NO_2$ values in each 5% RH interval is calculated, according to Stutz et al. (2004). The phenomenon that $HONO_{corr}/NO_2$ first increases and then decreases with an increasing RH in Fig. 6(a) was also observed by other studies (Hao et al., 2006;Yu et al., 2009;Li et al., 2012;Wang et al., 2013). The dependencies of $HONO_{corr}/NO_2$ on RH and the possible reasons or mechanisms are discussed as follows. Even at the lowest measured RH of 18%, the

absolute moisture content in the atmosphere is still greater than 10^3 ppm in our study, which is quite abundant to react with NO_2, but the $HONO_{corr}/NO_2$ ratio is quite small and remains unchanged when RH is below 45%, indicating that the NO_2 to HONO conversion efficiency should be determined by water covering the surfaces, rather than by the amount of water in the air.

It has been reported that surfaced absorbed water depends on RH values, and the dependences vary for different material surfaces of the ground, but generally follow the shape of a BET isotherm (Lammel, 1999;Saliba et al., 2001;Sumner et al., 2004). The number of mono-layers of water increases slowly from zero to 2-4, accompanied by RH from zero to a turning point, and the water coverage grows dramatically (up to 10-100 mono-layers) once RH exceeds the turning point (Finlayson-Pitts et al., 2003). Fig. 6(a) shows the case where the surface for NO_2 converting to HONO is dominated by the ground, the $HONO_{corr}/NO_2$ increases along with RH when RH is less than 75%, which can be explained by the reaction of NO_2 to generate HONO on wet surfaces. However, a negative correlation between $HONO_{corr}/NO_2$ and RH is found when RH is over 75%, presumably because the rapidly growing aqueous layers of the ground surface lead to efficient uptake of HONO and make the surface less accessible or less reactive for NO_2. Hence, the RH turning point for absorbed water on ground surfaces is perhaps around 75% for our observation, within the range of results from experiments on various surfaces (70-80% RH) (Lammel, 1999;Saliba et al., 2001;Sumner et al., 2004). Once RH exceeds 95%, the reaction surface is asymptotically approaching the state of water droplet, where the quite limited formation of HONO and the extremely impactful loss of HONO will result in a dramatic decline of the $HONO_{corr}/NO_2$ ratio (Fig. 6(a) and Fig. 6(b)).

Notably, the constant $HONO_{corr}/NO_2$ value at RH between 75-95% under the condition of high $PM_{2.5}$ mass loading (Fig. 6(b)), compared to the downward trend of $HONO_{corr}/NO_2$ within the same humidity range in low $PM_{2.5}$ mass concentration (Fig. 6(a)), implies a contribution of aerosol surfaces to the NO_2-HONO conversion. Since

both $HONO_{corr}/NO_2$ in Fig. 6(a) and Fig. 6(b) are affected by the ground surfaces, we can use the difference of $HONO_{corr}/NO_2$ between the two figures to represent the influence of aerosol. As the area of shadow showed in Fig. 6(b), the aerosol-affected $HONO_{corr}/NO_2$ is positively related to RH before RH reaches 95%. With the increase of RH, the hygroscopic growth of aerosol particles should provide larger surface area. When RH is higher than 75%, which has exceeded the mutual deliquescence relative humidity of inorganic salts (Fountoukis and Nenes, 2007), aerosols will transfer to aqueous phase gradually, and then promoting multiphase or heterogeneous chemistry processes (Herrmann et al., 2015). For example, the oxidation of SO_2 by NO_2 on aqueous aerosol surface may produce NO_2^-/HONO efficiently under polluted condition (Xie et al., 2015;Wang et al., 2016). In addtion, the enhancement NO_2 uptake on micro-droplets by anions has been reported in experiments (Yabushita et al., 2009)

3.3.3. Impact of aerosols on HONO formation

To further understand the heterogeneous formation of HONO on aerosol, we carry out a correlation analysis when $HONO_{corr}/NO_2$ reaches the pseudo steady state at each night (3:00-6:00 LT). The convergence or diffusion processes of gases and particles caused by the decrease or increase of the boundary layer height can also lead to a consistent trend of $HONO_{corr}$ and $PM_{2.5}$ (Fig. 7a), while the ratio of $HONO_{corr}$ and NO_2 can not only reduce this physical effect but also represent the conversion degree of NO_2 to HONO, so a moderate positive correlation between $HONO_{corr}/NO_2$ and $PM_{2.5}$ ($r=0.35$, $p=0.01$) throughout the observation period could be more convincible (Fig. 7b). As shown by larger triangles with gray borders in Fig. 7(b), $HONO_{corr}/NO_2$ is better correlated with $PM_{2.5}$ in the months when the mass concentrations of $PM_{2.5}$ are higher during this 1-year measurement, generally occurring from November to May (Fig. 1d). This finding can be explained with a law that greater contributions of NO_2 heterogeneously reacting on aerosol surface to HONO cause better correlations between $HONO_{corr}/NO_2$ and $PM_{2.5}$. Interestingly, this relationship can also be divided approximately into two groups by NH_3/CO; the correlation is good when the value of

NH_3/CO is lower than 2‰, but when NH_3/CO is higher than 2‰, a poor correlation is found. We will discuss this phenomenon further in section 4. The evidence of HONO formation on aerosol were also found in other observations (Reisinger, 2000;Wang, 2003;Li et al., 2012;Nie et al., 2015;Hou et al., 2016;Cui et al., 2018).

As is known, producing HONO is not the dominant sink of NO_2 at night, but it seems that more NO_2 can be converted to HONO under conditions of heavy pollution (Fig. 7b). We discuss whether heterogeneous reactions of NO_2 on aerosols are able to provide comparable HONO with our measurement by Eq. (8), only considering HONO formation on particle surfaces and assuming that HONO principally settles on the ground surface, neglecting HONO loss on aerosol. c_{NO_2} is the mean molecular velocity of NO_2 (370m/s); $[\frac{S}{V}]_{aer}$ is the surface area to volume ratio (m^{-1}) of aerosol; ν_{HONO} is the deposition velocity of HONO, which is considered to be close to the deposition velocity of NO_2 at night (Stutz et al., 2002;Su et al., 2008a); and a approximate value of 0.1cm/s is used based on the measurements from Coe and Gallagher (1992) and Stutz et al. (2002); H is the boundary layer mixing depth, and a value of 100m is assumed for nighttime (Su et al., 2008a).

$$C_{HONO} = \frac{1}{4}\gamma_{NO_2\rightarrow HONO} c_{NO_2} [\frac{S}{V}]_{aer} - \frac{\nu_{HONO}}{H}\frac{[HONO]}{[NO_2]} \quad (8)$$

Considering at nighttime period with severe haze in winter, the aerosol surface density calculated from the particle number size distributions between 6 nm and 800 nm is about 1.2×10^{-3} m^{-1}, matched by 200 μg/m^3 of $PM_{2.5}$ from our observations, and the averaged mixing ratios of HONO and NO_2 are 1.15 ppb and 28.4 ppb, respectively (Table 2). For 30%-100% of the measured mean C_{HONO} (0.0043 h^{-1}) in winter, the uptake coefficient of NO_2-to-HONO ($\gamma_{NO_2\rightarrow HONO}$) calculated from Eq. (8) is in the range of 6.9×10^{-6} to 1.44×10^{-5}, consistent with the results from many laboratory studies

which demonstrate that the uptake coefficients of NO_2 (γ_{NO_2}) on multiple aerosol surfaces or wet surfaces are mainly distributed around 10^{-5} with the HONO yield varying from 0.1 to 0.9 (Grassian, 2002;Aubin and Abbatt, 2007;Khalizov et al., 2010;Han et al., 2017). It is necessary to elaborate that: (1) the ambient particles were dried with silica gel before measuring their number size distributions, and the mass concentrations of $PM_{2.5}$ were also measured under a system where the temperature was maintained at 30℃, usually above ambient temperature; (2) the aerosol surface was calculated by assuming that all particles are spherically shaped, but the particles could in fact have irregular bodies and porous structure; (3) the particle size of both $PM_{2.5}$ and derived $[\frac{S}{V}]_{aer}$ is just a part of the total suspended particulate matter. As described, the aerosol surface in the atmosphere is actually underestimated in our study, thus the $\gamma_{NO_2\rightarrow HONO}$ we derived could be the upper limit of the uptake coefficient for NO_2 conversion to HONO on aerosol. In addition to particles surfaces, other aerosol parameters such as surface water content, chemical composition, pH value, and phase state of surfaces may also influence the heterogeneous formation of HONO.

3.4. Missing daytime HONO source

After discussing the nocturnal formation mechanism of HONO, we now focus on the chemistry of daytime HONO whose concentrations are still about 0.25-0.6 ppb at noon with a lifetime of only 10-20 min (Fig. 2). We are not certain if the observed HONO can be provided by known mechanisms (gas phase reaction (R4) and emissions) to date, so a budget equation of daytime HONO (Eq. 9) is utilized to analyze its source and sinks (Su et al., 2008b;Sörgel et al., 2011). Here, dHONO/dt is the change rate of the observed HONO. The sources rates of HONO contain the homogeneous formation rate (P_{NO+OH}, R4); the combustion emission rate (P_{emis}); and the unknown HONO daytime source ($P_{unknown}$). The sink rates of HONO consist of the photolysis rate (L_{phot}, R1); the reaction rate of HONO with OH ($L_{HONO+OH}$, R2); and

511 the dry deposition rate (L_{dep}). T_V and T_h represent the vertical (T_V) and horizontal (T_h)
512 transport processes of HONO, which are thought to be negligible for intense radiation
513 and relatively homogeneous atmospheres with generally calm winds (Dillon, 2002;Su
514 et al., 2008b;Sörgel et al., 2011).
515

516 $$\frac{dHONO}{dt} = (P_{NO+OH} + P_{emis} + P_{unknown}) - (L_{phot} + L_{HONO+OH} + L_{dep}) + T_v + T_h \quad (9)$$

517

518 Therefore, the undiscovered daytime source of HONO ($P_{unknown}$) can be derived by Eq.
519 (10), which is a deformation of Eq. (9) without minor terms (T_v and T_h) and where
520 dHONO/dt is substituted by $\Delta HONO/\Delta t$ that is counted as difference between
521 observed HONO at two time points. The reaction rate constants of reaction 2
522 ($k_{HONO+OH}$) and reaction 4 (k_{NO+OH}) are 6.0×10^{-12} cm^3 $molecules^{-1}$ s^{-1} and 9.8×10^{-12}
523 cm^3 $molecules^{-1}$ s^{-1}, respectively (Atkinson et al., 2004). The emission ratio of
524 HONO and NO_x ($HONO/NO_x$ = 0.79%) obtained in section 3.2, is used to estimate
525 P_{emis}. For L_{dep}, the dry deposition velocity of diurnal HONO (ν_{HONO}) is measured as 2
526 cm/s in the work of Harrison et al. (1996), and a practical mixing height of 200 m is
527 adopted, considering that most of the HONO cannot rise above this altitude due to
528 rapid photolysis (Alicke et al., 2002).
529

530 $$P_{unknown} = J(HONO)[HONO] + k_{HONO+OH}[HONO][OH] + \frac{\nu_{HONO}}{H}[HONO] + \frac{\Delta HONO}{\Delta t} - k_{NO+OH}[NO][OH] - \frac{0.79\% \times \Delta NO_x}{\Delta t} \quad (10)$$

531

532 Fig. 8 shows the average daytime HONO budget from 8:00 LT to 16:00 LT during
533 different seasons. The major loss route of HONO is photodecomposition (L_{phot}) with
534 an average value of 1.48 ppb/h at noontime (10:00-14:00 LT) during this observation
535 period, next to dry deposition (L_{dep}) whose mean value at the same time is 0.2 ppb/h,
536 and by $L_{HONO+OH}$ which is less than 6% of that of L_{phot}. For the sources of HONO
537 around noon, the average homogeneous reaction rate between NO and OH (P_{NO+OH}) is

0.71 ppb/h and P_{emis} just gives a tiny part of HONO at a rate of 0.02 ppb/h, meaning that most of HONO comes from an unknown source whose average rate ($P_{unknown}$) is 1.02 ppb/h, contributing about 58% of the production of HONO. Comparing summer data, the mean unknown daytime source strength of HONO in Nanjing is almost at the upper-middle level of those reported in the existing literature: 0.22 ppb/h at a rural site of New York state, USA (Zhou et al., 2002); 0.5 ppb/h in a forest near Jülich, Germany (Kleffmann, 2005); 0.77 ppb/h in a polluted rural area of the Pearl River Delta, China (Li et al., 2012); 0.98 ppb/h at an urban site in Xi'an, China (Huang et al., 2017); 1.7 ppb/h in an urban area of Santiago, Chile (Elshorbany et al., 2009); 2.95 ppb/h in the urban atmosphere of Jinan, China (Li et al., 2018). In our study, the OH production rate from the missing HONO accounts for about 78% of total P_{OH}(HONO) (Fig. S2), suggesting that the unconventional source of HONO is of significance to atmospheric oxidation.

Hence, we perform a correlation analysis to explore the potential unknown daytime mechanisms of HONO (Table 3). $P_{unknown}$ is better correlated with NO_2*UVB than with NO_2 or UVB alone in spring and autumn (p=0.05), perhaps associated with the photo-enhanced conversion from NO_2 to HONO (George et al., 2005;Stemmler et al., 2006;Stemmler et al., 2007). The average value of $P_{unknown}$ normalized by NO_2 is 0.1 h^{-1}, over 18 times greater than the nighttime conversion rate (0.0055 h^{-1}), also implying that $P_{unknown}$ cannot be explained by the nocturnal mechanism of NO_2-to-HONO. Assuming that the height of a well-mixed boundary layer around noon remains constant for each day, UVB*NO_2 and UVB*NO_2*$PM_{2.5}$ could be proxies for photo-induced heterogeneous reactions of NO_2 on ground and aerosol surfaces, respectively. We do not have any solid evidence to identify which surfaces (ground or aerosol) are more important to the hypothetical photo-heterogeneous reaction of NO_2 based on the present analysis. For the same reason, the photolysis of particulate nitrates (NO_3^-) as a source of HONO (Ye et al., 2016;Ye et al., 2017) cannot be determined whether it is momentous in our study. The comparisons of correlation coefficients showed above follow the method provided by Meng et al.

(1992).

Our study suggest that the missing source of HONO should be considered in the air quality forecasting or regional models to characterize atmospheric oxidizing capacity better, especially in warm seasons (spring and summer). Based on the measurement (Fig. S3), the light-induced heterogeneous conversion of NO_2 to HONO on aerosol surfaces and ground surface can been included in simulation works probably, as what did in Lee et al. (2016).

4. Semi-quantitative estimation of the contribution from different sources

From this and previous studies, we can conclude that not only the concentration of ambient HONO but also the sources of HONO have temporal and spatial patterns, which is supposed to be considered in model studies. Nocturnal HONO is selected to discuss the monthly variations of HONO sources in detail without the uncertainties of daytime HONO formation, the influences of HONO photolysis, and the mixing effect of boundary layer. The heterogeneous reaction of NO_2 on aerosol produces a considerable portion of HONO in relatively polluted months (Dec.-May), but contributes very little less than nothing in clean months (Jun.-Oct.), as seen in section 3.3.3. Coincidentally, direct emissions from burning processes of HONO decrease from their peak values from winter to summer (section 3.2). However, the monthly averaged ratios of HONO and NO_x are highest in summer, which conflicts with two sources mentioned above.

As is known, higher NO_2-to-HONO conversion level or other NO_x-independent sources can cause an increase in the HONO/NO_x ratio. For the case of a mostly constant surface with low reactivity due to the long-term exposure to oxidizing gases and radiation, the yield of nighttime HONO from NO_2 reacting on ground surfaces could be imprecisely assumed to be unchanged. Thus, soil nitrite formed through microbial activities, especially nitrification by ammonia-oxidizing bacteria ($NH_4^+ \rightarrow NO_2^-$) (Su et al., 2011;Oswald et al., 2013), is adopted to be an source for

atmospheric HONO in this study, considering the nearby presence of some grassland and natural vegetation mosaics. Although we do not directly measure HONO emissions from soil, the observed ammonia can represent its monthly average intensity, based on the following hypothesis: the dominant source of NH_3 is from soil, especially from fertilizers ($NH_4^+ \rightarrow NH_3$) for a good correlation between ammonia and temperature in the site (r=0.63, p=0.01), omitting the contributions of livestock to NH_3 since there is only a small poultry facility within 10 km of this site (Meng et al., 2011;Huang et al., 2012;Behera et al., 2013). Combustion sources (vehicles, industry, biomass burning) should contribute only a fraction of NH_3 seeing that NH_3 is not related to NOx or CO in our study. Moreover, the release of both HONO and NH_3 depend on the strength of microbial activities, fertilizing amount, and soil properties (e.g., temperature, acidity and water content of soil). Although the processes of HONO and NH_3 emission from soil may not be completely synchronized, the seasonal patterns for each should be consistent.

Until now, we can separate the sources of HONO into four parts: (1) combustion emissions from vehicles and industries ($HONO_{emi}$) with a constant emitted HONO/NOx ratio of 0.79%; (2) conversion of NO_2 to HONO on the ground surfaces ($HONO_{grd}$) with a constant but unknown yield x_1; (3) conversion of NO_2 to HONO on aerosol surfaces ($HONO_{aer}$) with a $PM_{2.5}$-dependent yield ($HONO_{aer}/NO_2$); and (4) emission from soil ($HONO_{soi}$), expressed by corrected NH_3 multiplied by an unknown coefficient x_2. The corrected NH_3 is obtained by subtracting combustion emission from total observed ammonia. Ammonia from combustion is found to be proportional to simultaneous CO (Meng et al., 2011;Chang et al., 2016), and a proportion of 0.3%, which is in the lower quantile of the NH_3/CO ratios in fresh air masses (for hourly data: $NO/NO_x > 0.75$; UVB = 0; temperature < 5 ℃) is used from our measurements. Substituting monthly average values of measured HONO, NO_2, $PM_{2.5}$, NH_3, and CO into Eq.(11) by assuming that $HONO_{tot}$ is equal to $HONO_{obs}$, we can get an overdetermined system of equations, which have 11 equations with 2 unknowns (excluding mean values of related parameters from February), and then we derive an

approximate solution (x_1=1.89%, x_2=1.62%) by the method of ordinary least squares.

Fig. 9 shows that an average of 36% of HONO is produced heterogeneously on ground surfaces without perceptible temporal variations, but the contribution of this source is overtaken by NO_2 converting to HONO on aerosols in January (approximately 40% of HONO), and was exceeded by soil emission in July and August (approximately 40% of HONO).The seasonal variations of HONO from different pathways at night indicate that short-term observations may just capture a small part of the total picture when exploring the source mechanisms of HONO. The total HONO concentration ($HONO_{tot}$) is the sum of derived HONO from the four sources listed above. The good correlation between $HONO_{tot}$ and $HONO_{obs}$ and the low mean normalized error of $HONO_{tot}$ to $HONO_{obs}$ reveal that our assumption on nocturnal HONO sources is reasonable. It should be noted that the slope of the linearly fitted line between $HONO_{corr}/NO_2$ and $PM_{2.5}$ in spring (r=0.74, slope=0.68‰) is much higher than that in winter (r=0.60, slope=0.20‰), but we just use a mean slope of 0.26‰ to evaluate aerosol effects throughout the year, this may be why our method underestimates HONO in March and April and overestimates HONO in January, and indicating that the mass concentration of $PM_{2.5}$ is not the only factor affecting formation of HONO on aerosols. Besides, lacking considerations of the impact of RH and temperature on NO_2-to-HONO conversion and of seasonal variations in ground surface properties, uncertainties of NO_2-to-HONO conversion mechanisms and of combustion HONO emissions, and lacking direct observation for soil emitted HONO, could all result in the bias between $HONO_{tot}$ and $HONO_{obs}$, so more studies on the detailed mechanism of various HONO sources need to be performed.

$$\frac{[HONO_{grd}]}{[NO_2]} = x_1$$
$$\frac{[HONO_{aer}]}{[NO_2]} = 0.26‰ \times [PM_{2.5}]$$
$$\frac{[HONO_{emi}]}{[NO_x]} = 0.79\% \quad (11)$$
$$\frac{[HONO_{soi}]}{[NH_3] - 0.3\% \times [CO]} = x_2$$
$$HONO_{tot} = HONO_{emi} + HONO_{soi} + HONO_{grd} + HONO_{aer}$$

5. Conclusions

Continuous field measurement of HONO over 1 year was conducted at the SORPES station in Nanjing in the western YRD, China, from December 2017 to December 2018. The observed seasonal average concentrations of HONO are in the range of 0.45-1.04 ppb, which are comparable to those in other urban or suburban regions and appears to be of vital importance to atmospheric oxidation as the net OH production rate of HONO is about 1.5 times as that of ozone at daytime. HONO and NO_x have coincident monthly variations peaking in December and decreasing to the lowest value in August, and have similar diurnal pattern with the highest value in the early morning and a low point in the late afternoon, both indicating that NO_x is a crucial precursor of HONO.

Combustion emissions contribute an average of 23% to nocturnal HONO concentrations, with an average emission ratio $\triangle HONO/\triangle NO_x$ of 0.79%. During the nighttime, the dominant source of RH-dependent HONO could be the heterogeneous reaction of NO_2 on wet ground or aerosol surfaces with a mean estimated conversion rate of 0.0055 h^{-1}. During the daytime, a missing HONO source with an average strength of 1.02 ppb/h was identified around noon, contributing about 58% of the production of HONO and seeming to be photo-enhanced. HONO released from soil is adopted to discuss the seasonal changes of nocturnal HONO, and can contribute 40% to HONO during summer. Ground formation provides a major part of HONO at a

roughly constant proportion of 36%. The uptake of NO_2 on aerosol surface could generate the greatest amount of HONO during heavily polluted periods (e.g. January). Our results draw a complete picture of the sources of HONO during different seasons, and demonstrated the needs of long-term and comprehensive observations to improve the understanding of HONO chemistry.

Author contribution

W.N. and A.D. designed the study; Y.L. and W.N. wrote the manuscript; Y.L., Z.X. and R.X. collected the HONO data and contributed to the data analysis; T.W., Y.L., L.W. and X.C. collected other related data, e.g. NH_3, NO_x and $PM_{2.5}$.

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Tables

Table 1. Sources and sinks for nitrous acid (HONO) in the troposphere.

Budget	Occurrence	Pathways	Abbr.
Sinks	Only daytime	$HONO + h\upsilon \xrightarrow{320-400nm} OH + NO$	R1
	Mainly daytime	$HONO + OH \rightarrow NO_2 + H_2O$	R2
	All day	Deposition / heterogeneous loss on aerosol	/
Sources	Mainly daytime	$NO + OH \xrightarrow{M} HONO$	R3
	Mainly nighttime	$2NO_{2(g)} + H_2O_{(ads)} \xrightarrow{surf} HONO_{(g)} + HNO_{3(ads)}$	R4
	Mainly daytime	$NO_{2(g)} + HC_{red} \xrightarrow{surf} HONO_{(g)} + HC_{ox}$	R5
	Only daytime	$HNO_3 / NO_3^- + h\upsilon \xrightarrow{surf} HONO / NO_2^- + O$	R6
	All day	Release of soil nitrite	/
	All day	Combustion emission (fossil and biomass)	/

Table 2. Overview of the measured HONO and NOx levels in Nanjing and comparison with other urban or suburban sites.

Location	Date	HONO(ppb)		NO_2(ppb)		NOx(ppb)		HONO/NO2		HONO/NOx		Ref
		Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	
Rome(Italy)	May-Jun 2001	1.00	0.15	27.2	4.0	51.2	4.2	0.037	0.038	0.020	0.036	1
Kathmandu(Nepal)	Jan-Feb 2003	1.74	0.35	17.9	8.6	20.1	13.0	0.097	0.041	0.087	0.027	2
Tokto(Japan)	Jan-Feb 2004	0.80	0.05	31.8	18.2	37.4	26.3	0.025	0.003	0.021	0.002	3
Santiago(Chile)	Mar 2005	3.00	1.50	30.0	20.0	200.0	40.0	0.100	0.075	0.015	0.038	4
Mexico City(Mexico)	Mar 2006	/	0.43	/	28.4	/	44.8	/	0.015	/.	0.010	5
Houston(USA)	Sep 2006	0.50	0.10	20.0	10.0	/	/	0.025	0.010	/	/	6
Shanghai(China)	Oct 2009	1.50	1.00	41.9	30.0	/	/	0.038	0.032	/	/	7
Hongkong(China)	Aug 2011	0.66	0.70	21.8	18.1	29.3	29.3	0.031	0.042	0.025	0.028	8
	Nov 2011	0.95	0.89	27.2	29.0	37.2	40.6	0.034	0.030	0.028	0.021	
	Feb 2012	0.88	0.92	22.2	25.8	37.8	48.3	0.036	0.035	0.025	0.020	
	May 2012	0.33	0.40	14.7	15.0	19.1	21.1	0.022	0.030	0.019	0.022	
Beijing(China)	Oct–Nov 2014	1.75	0.93	37.6	35.3	94.5	53.4	0.047	0.026	0.019	0.017	9
Xi'an(China)	Jul–Aug 2015	0.51	1.57	15.4	24.7	/	/	0.033	0.062	/	/	10
Jinan(China)	Sep–Nov 2015	0.87	0.66	25.4	23.2	38.0	37.5	0.049	0.034	0.034	0.022	11
	Dec 2015-Feb 2016	2.15	1.35	41.1	34.6	78.5	64.8	0.056	0.047	0.034	0.031	
	Mar–May 2016	1.24	1.04	35.8	25.8	47.3	36.0	0.046	0.052	0.035	0.041	
	Jun–Aug 2016	1.20	1.01	22.5	19.0	29.1	25.8	0.106	0.079	0.060	0.049	
Nanjing(China)	Nov 2017-Nov 2018	0.80	0.57	18.9	13.9	24.9	19.3	0.045	0.044	0.041	0.036	this
	Dec-Feb(winter)	1.15	0.92	28.4	23.1	45.5	37.7	0.040	0.038	0.029	0.025	study
	Mar–May(spring)	0.76	0.59	17.4	12.9	19.1	15.9	0.048	0.049	0.046	0.042	
	Jun–Aug(summer)	0.56	0.34	12.5	7.7	13.5	9.1	0.048	0.051	0.046	0.045	
	Sep–Nov(autumn)	0.81	0.51	18.9	13.4	25.1	17.7	0.044	0.035	0.039	0.029	

1: Acker et al. (2006); 2: Yu et al. (2009); 3: Kanaya et al. (2007); 4: Elshorbany et al. (2009); 5: Dusanter et al. (2009); 6: Wong et al. (2011); 7: Bernard et al. (2016); 8: Xu et al. (2015); 9: Tong et al. (2015); 10: Huang et al. (2017); 11: Li et al. (2018)

Table 3. Correlations of $P_{unknown}$ against various parameters.

Parameters	Winter		Spring		Summer		Autumn	
	r	N	r	N	r	N	r	N
NO_2	0.24	167	0.30	275	0.02	379	0.06	339
$PM_{2.5}$	0.21	167	0.40	275	0.16	379	0.20	339
NO_3^-	0.20	160	0.37	266	-0.05	366	0.12	336
SO_4^{2-}	0.16	154	0.27	266	0.07	370	0.19	329
NH_4^+	0.18	160	0.34	268	0.01	374	0.16	324
RH	0.00	167	-0.32	275	-0.33	379	-0.22	339
UVB	0.21	167	0.41	275	0.45	379	0.50	339
NO_2*$PM_{2.5}$	0.19	167	0.39	275	0.04	379	0.15	339
NO_2*NO_3^-	0.19	160	0.37	266	-0.08	366	0.11	336
NO_2*SO_4^{2-}	0.19	154	0.33	266	0.02	370	0.16	329
NO_2*NH_4^+	0.19	160	0.37	268	-0.02	374	0.13	324
UVB*NO_2	0.33	167	0.62	275	0.41	379	0.59	339
UVB*$PM_{2.5}$	0.29	167	0.60	275	0.45	379	0.62	339
UVB*NO_3^-	0.26	160	0.51	266	0.18	366	0.41	336
UVB*SO_4^{2-}	0.19	154	0.46	266	0.36	370	0.54	329
UVB*NH_4^+	0.23	160	0.49	268	0.27	374	0.49	324
NO_2*UVB*$PM_{2.5}$	0.24	167	0.58	275	0.30	379	0.48	339

Figures

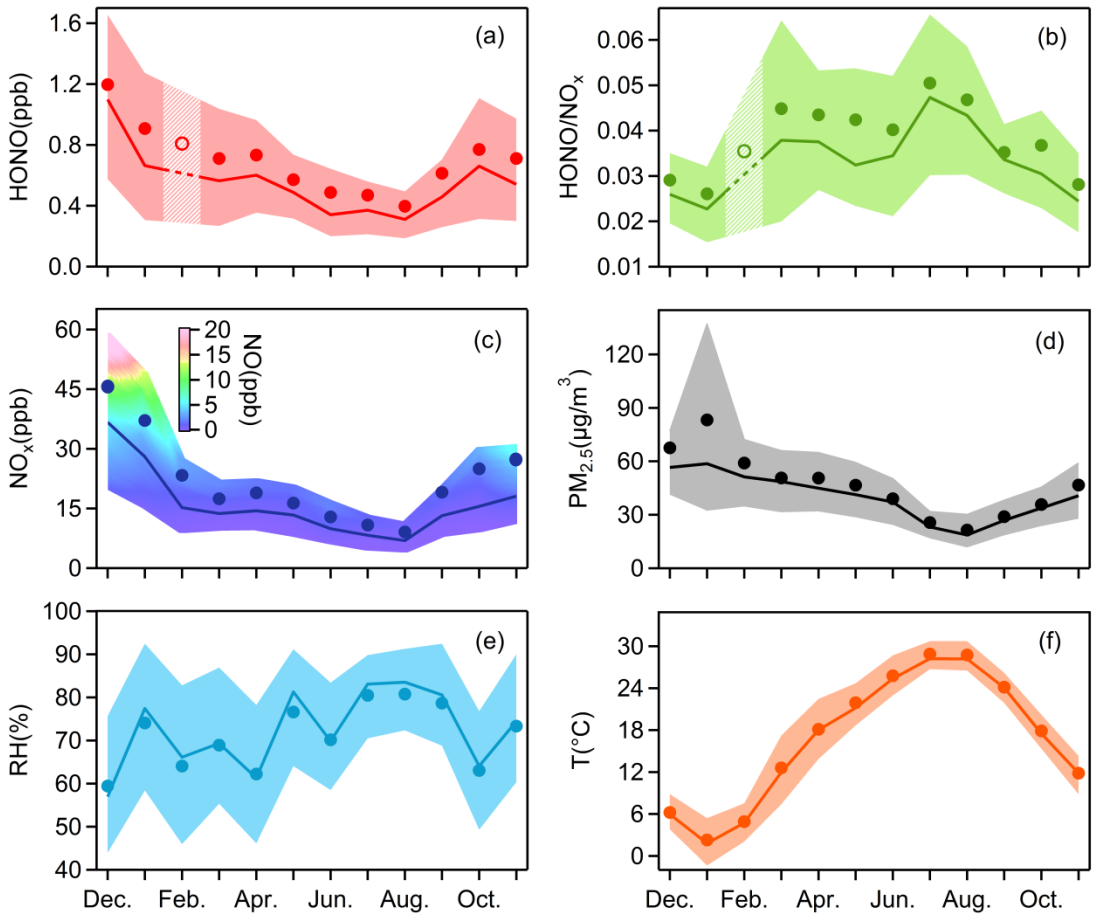

Fig. 1. Monthly variations of (a) HONO, (b) HONO/NO_x, (c) NO_x, (d) $PM_{2.5}$, (e) RH and (f) T. The solid bold lines are median values, the markers indicate mean values, and the shaded areas represent percentiles of 75% and 25%. In (a) and (b), values in February are linearly interpolated based on the data from the months before and after, since there were only few days when HONO was observed in February. In (c), the shaded area is colored by the 25_{th} to the 75_{th} percentiles of NO.

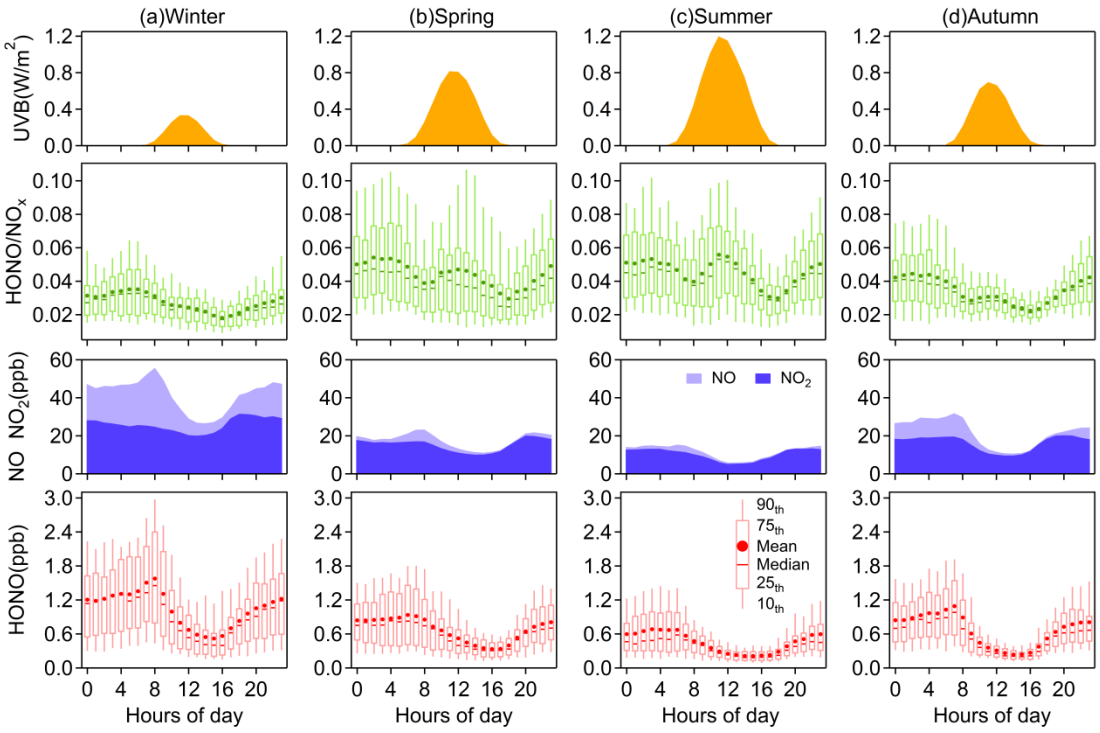

Fig. 2. Diurnal variations of HONO, NO, NO_2, HONO/NO_x, UVB in (a) winter, (b) spring, (c) summer, (d) autumn. NO, NO_2 and UVB values are displayed as their mean concentrations.

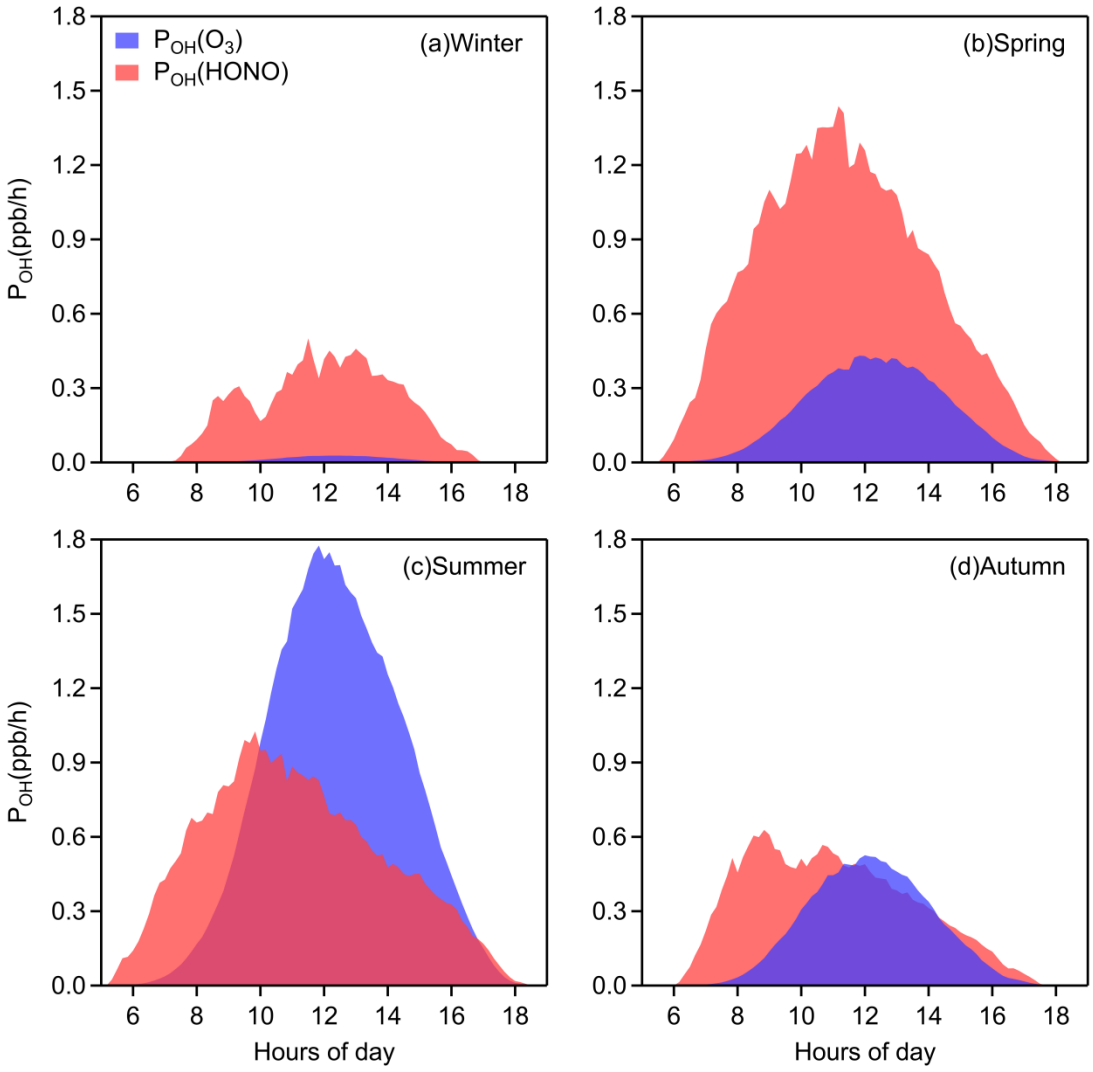

Fig. 3. Averaged OH production rates from photolysis of HONO and ozone in (a) winter, (b) spring, (c) summer, and (d) autumn. The P_{OH}(HONO) here is actually the net OH production rate, by subtracting the consumption of OH radicals by R2 and R3. The mean values of P_{OH}(HONO) at daytime (08:00-16:00 LT) are: 0.29 ppb/h in winter, 0.97 ppb/h in spring, 0.68 ppb/h in summer, 0.42 ppb/h in autumn.

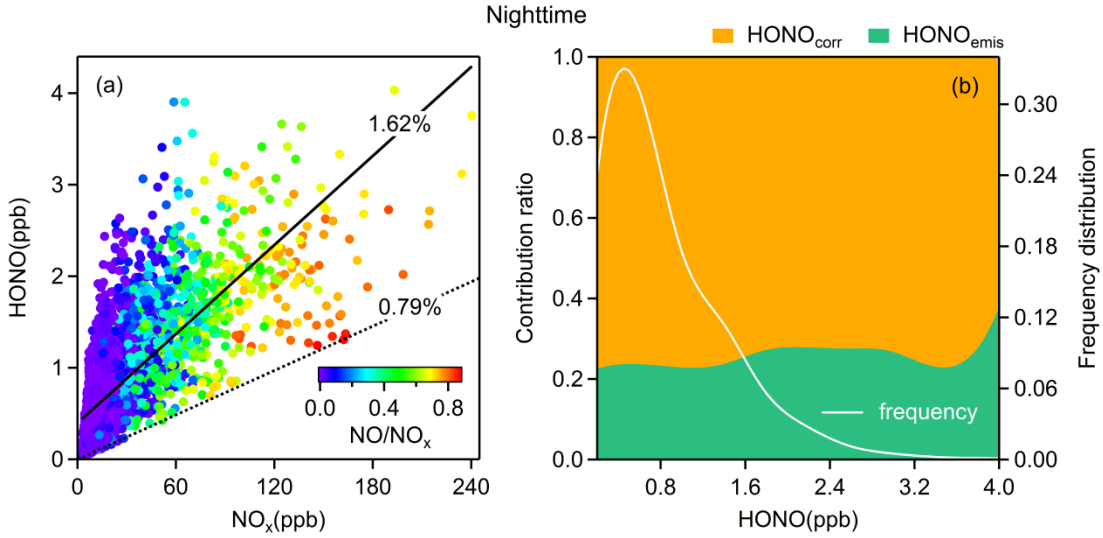

Fig. 4. (a) The relationship between HONO and NO_x colored by NO/NO_x. The dotted line is the emission ratio derived in this study and the solid line is obtained from simple linear fitting; (b) average emission contribution ratios for different concentrations of HONO and the frequency distribution of HONO concentrations. Both (a) and (b) are nighttime values.

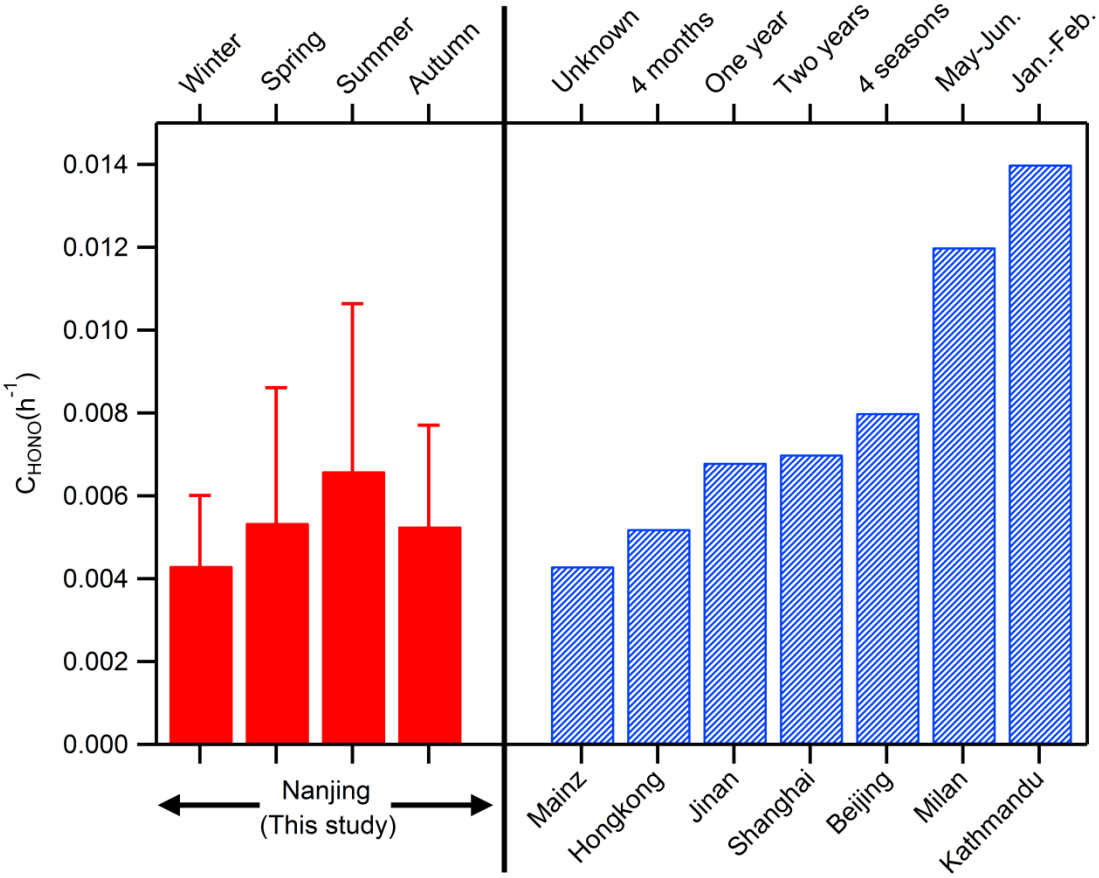

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Fig. 5. Comparison of observed NO_2 to HONO conversion rates in cities: Nanjing (this study); Mainz (Lammel, 1999); Hongkong (Xu et al., 2015); Jinan (Li et al., 2018); Shanghai (Wang et al., 2013); Beijing (Wang et al., 2017); Milan (Alicke et al., 2002); and Kathmandu (Yu et al., 2009).

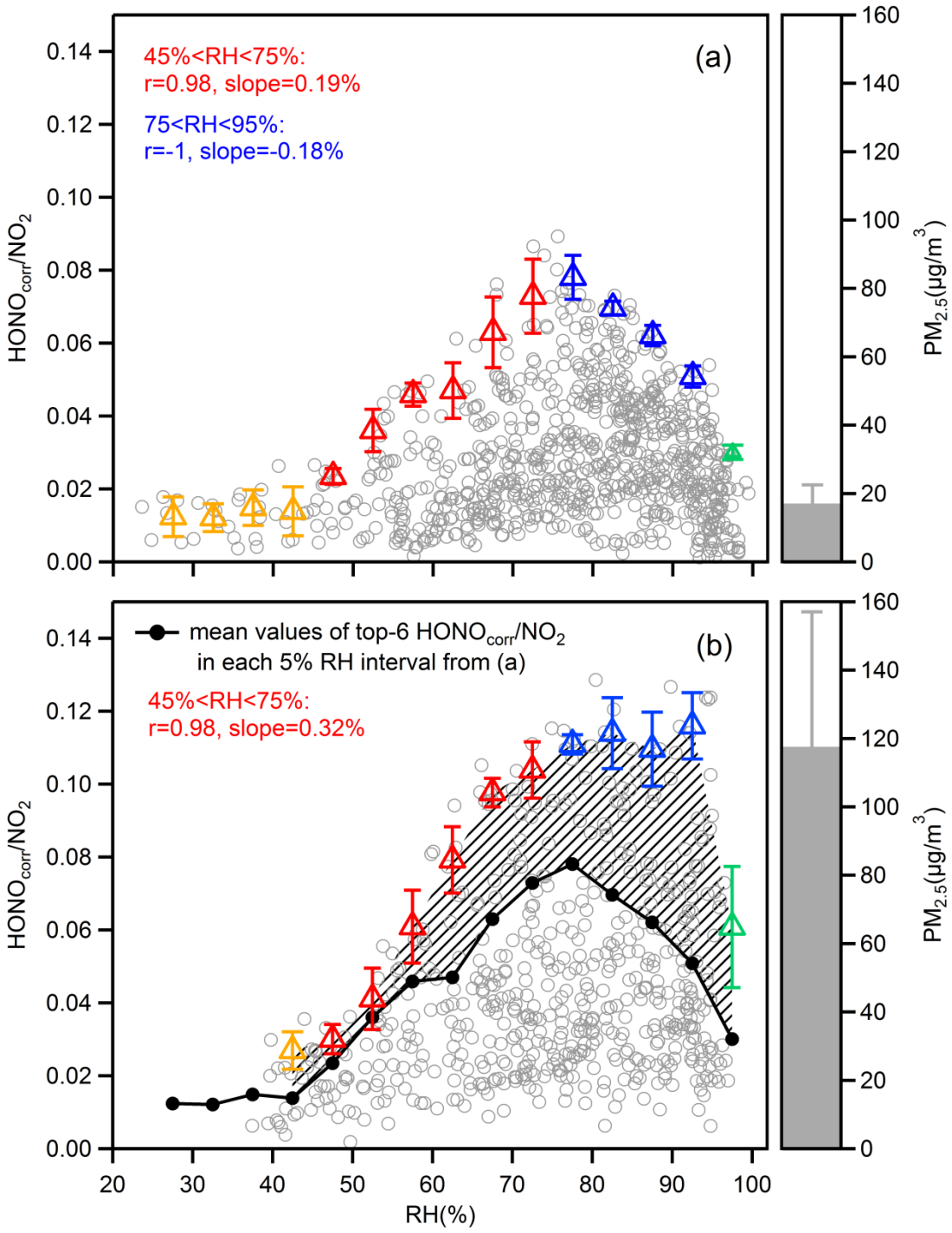

Fig. 6. Scatter plot of $HONO_{corr}/NO_2$ and RH during nighttime, separating the data into (a) clean hours (hourly mean $PM_{2.5}$<25μg/m^3) and (b) polluted hours (hourly mean $PM_{2.5}$>75μg/m^3). Triangles are the averaged top-6 $HONO_{corr}$/NO2 in each 5% RH interval, and the error bars are the standard deviations. The overall average concentrations of $PM_{2.5}$ in (a) and (b) are shown to the right of the figures.

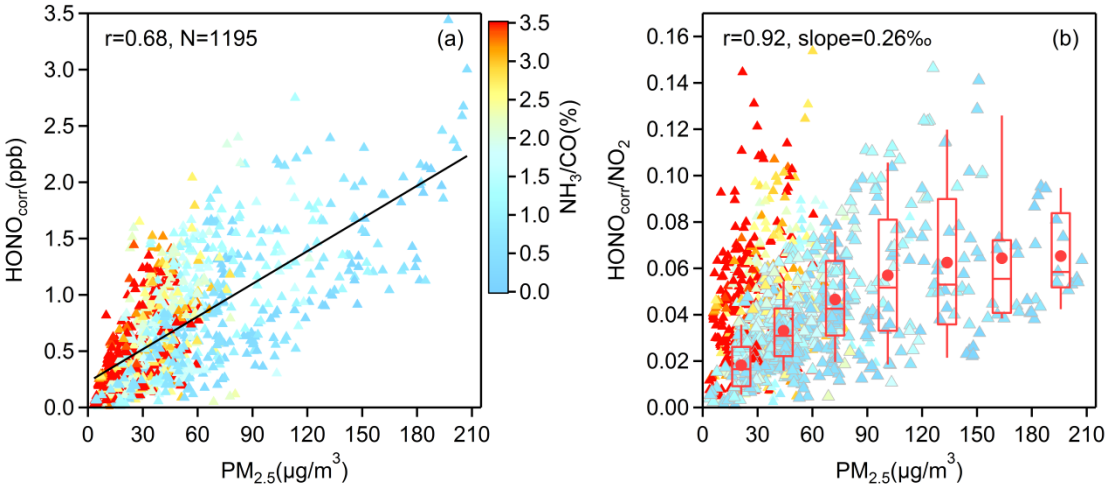

Fig. 7. (a) The correlation between $HONO_{corr}$ and $PM_{2.5}$, and (b) the correlation between $HONO_{corr}/NO_2$ and $PM_{2.5}$, all scatters come from the time (3:00-6:00 LT) when $HONO_{corr}/NO_2$ reaches the pseudo steady state at each night and are colored by NH_3/CO. In (b), the larger triangles with gray borders, depict the measured data from November to May, and the boxplot in each 30 μg/m^{3}interval of $PM_{2.5}$ is illustrated according to the same data, the red box boundaries represent interquartile range, the whiskers represent the 10%–90% percentile range, the horizontal red lines represent median values and the red markers represent mean values. The correlation coefficient and the slope of the linearly fitted line in (b) are derived from the average $HONO_{corr}/NO_2$ and average $PM_{2.5}$ in each box.

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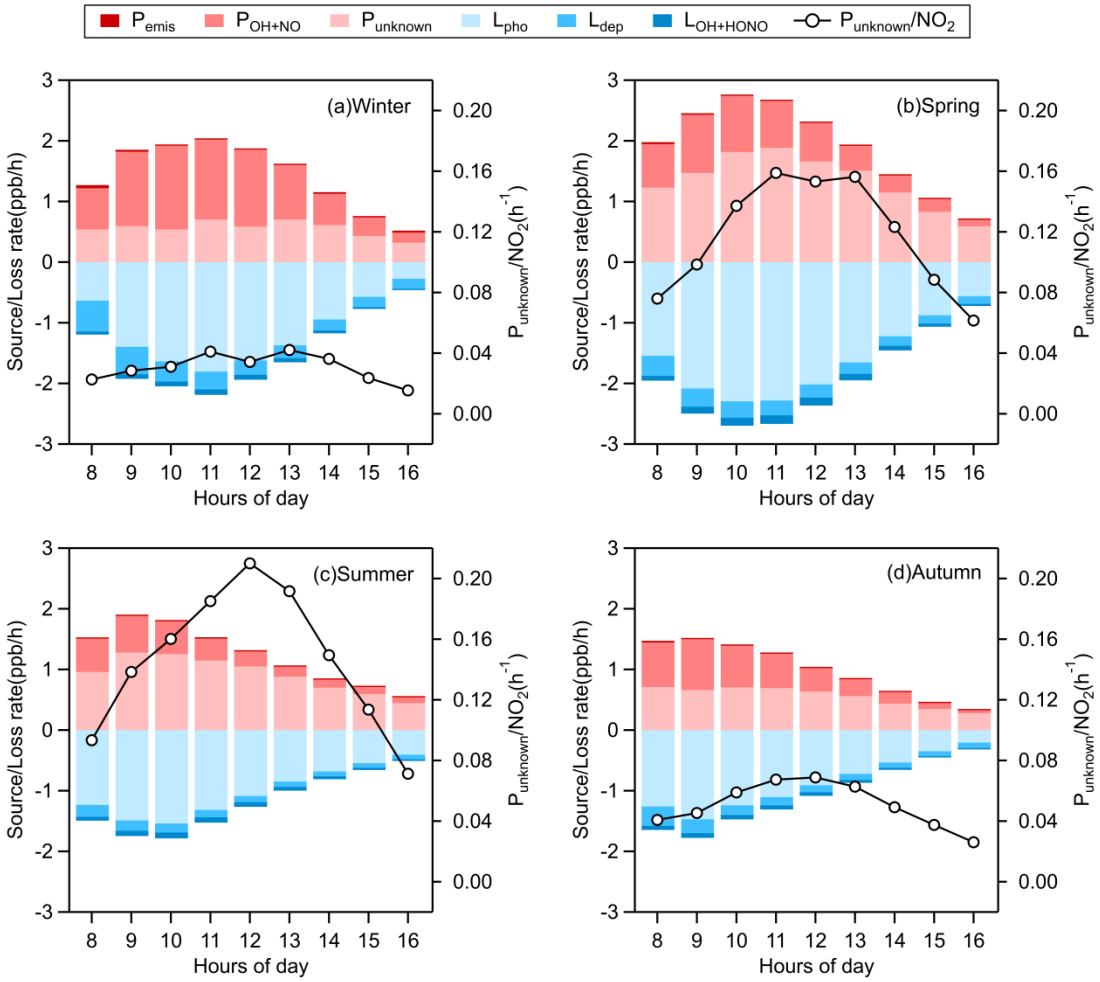

Fig. 8. Averaged daytime HONO budget and the missing source strength ($P_{unknown}$) normalized by NO_2 in (a) winter, (b) spring, (c) summer, and (d) autumn. The mean values of $P_{unknown}$ at noontime (10:00-14:00 LT) are: 0.58 ppb/h in winter, 1.72 ppb/h in Spring, 1.11 ppb/h in summer, 0.66 ppb/h in autumn.

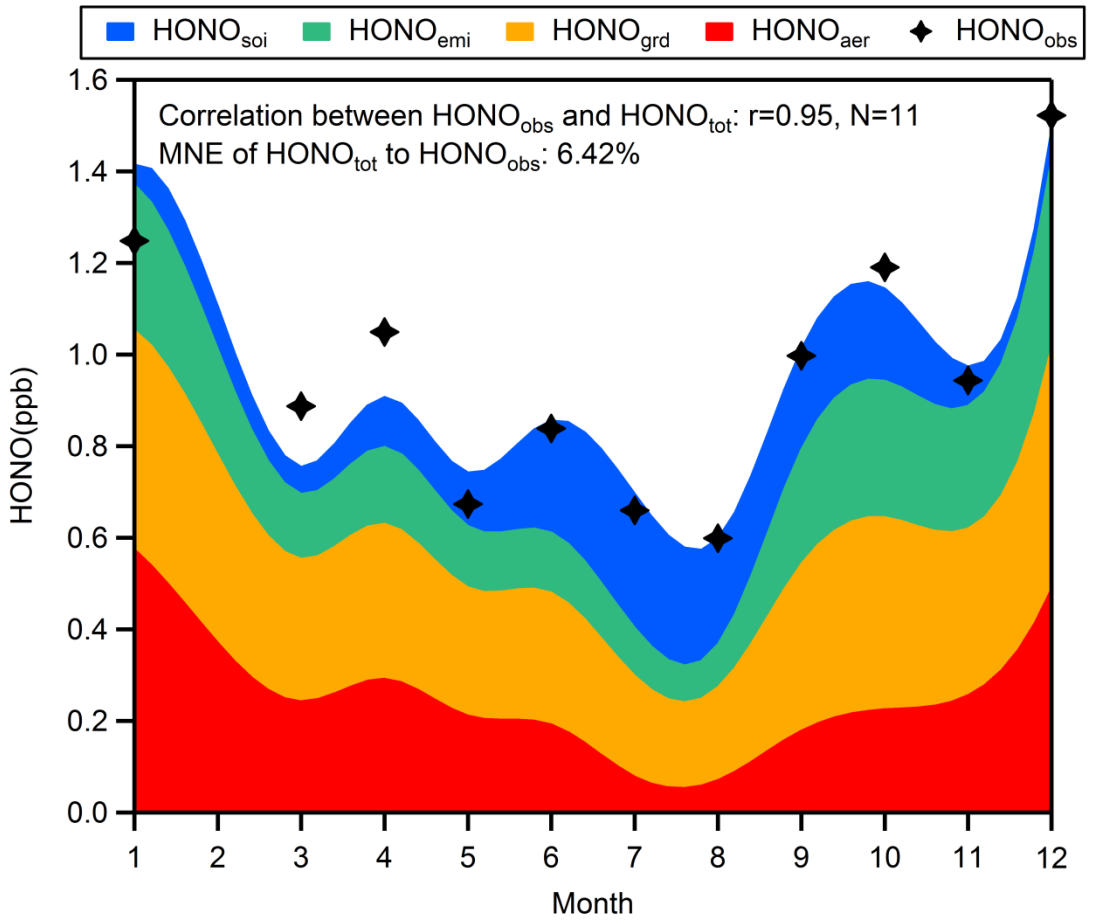

Fig. 9. Seasonal variations of 4 sources of mean HONO at night (3:00-6:00 LT).The mean normalized error (MNE) of $HONO_{tot}$ to $HONO_{obs}$ is 6.42%.