Supplementary Information

Direct measurement of N_2O_5 heterogeneous uptake coefficients on atmospheric aerosols in southwestern China and evaluation of current parameterizations

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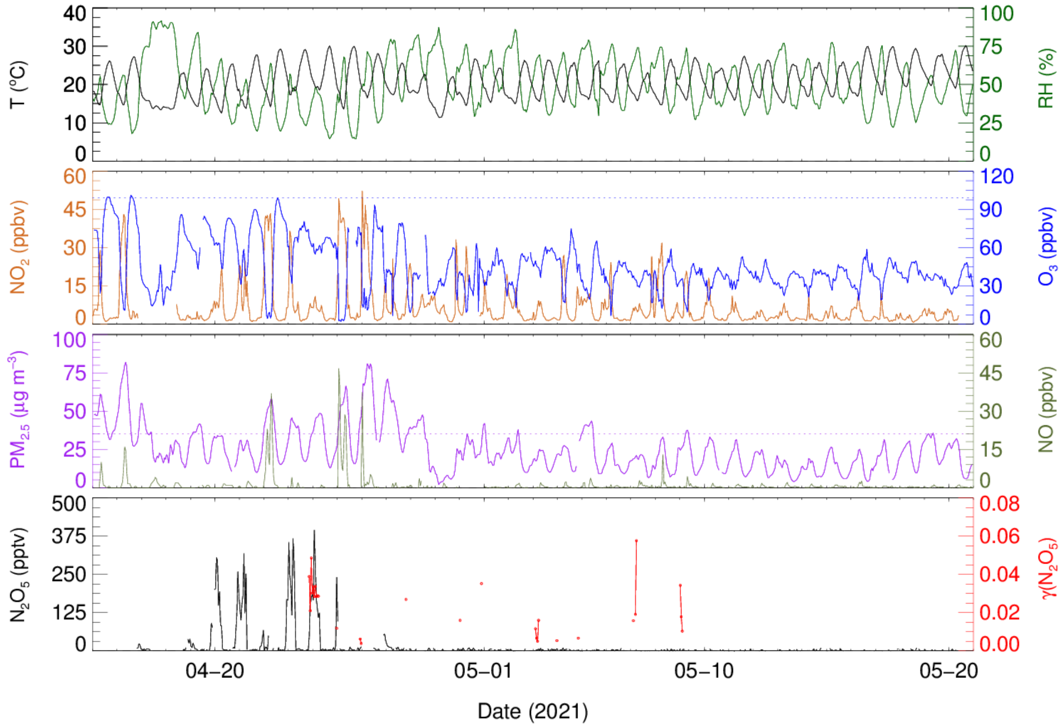

Figure S1. Time series of measured concentrations of NO_2, O_3, NO, $PM_{2.5}$ and N_2O_5, the values of $\gamma(N_2O_5)$, and meteorological parameters of RH and T during the campaign. The blue line and the purple line represent Chinese national air quality standards for O_3 and $PM_{2.5}$, respectively.

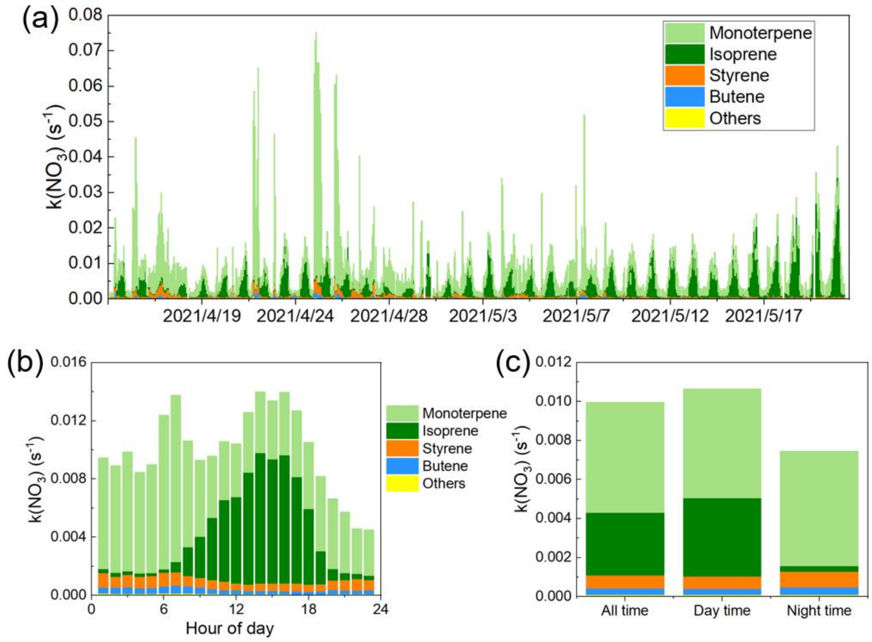

Figure S2. NO_3 reactivity with VOCs. (a) Time series of VOCs contributions for $k(NO_3)$. (b) Mean diurnal profiles of $k(NO_3)$. (c) The contribution of VOCs categories for k(NO_3).

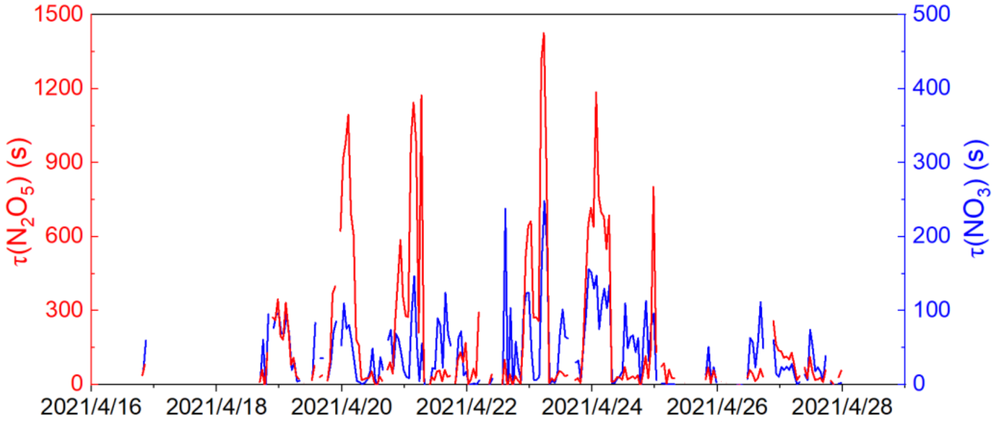

Figure S3. Time series of N_2O_5 and NO_3 lifetime during the campaign.

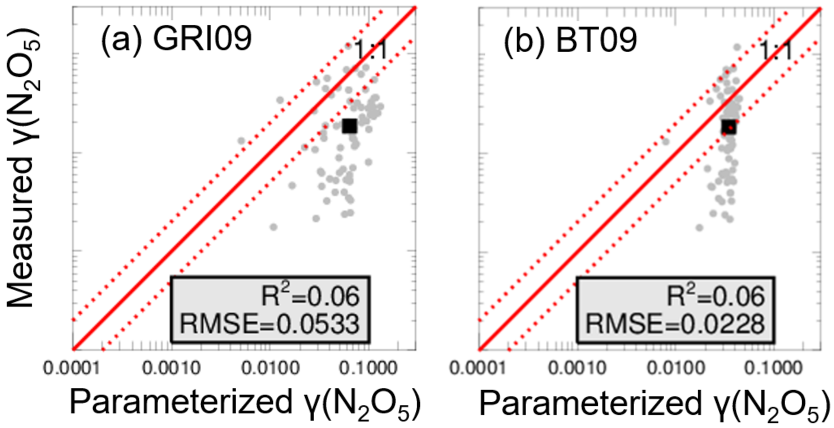

Figure S4. The distribution of parameterized $\gamma(N_2O_5)$ values of GRI09 (a) and BT09 (b).

Table S1. Summary of field observation results of nocturnal NO_3 and N_2O_5 concentrations, P(NO_3), and $\tau(N_2O_5)$ from various regions around the world in recent years.

Location	Site type	Period	NO_3 (pptv) (night)	N_2O_5 (pptv) (night)	P(NO_3) (ppbv/h)	$\tau(N_2O_5)$ (s)	Reference
Kunming, China	Suburban	2021.04	5.7±3.2	33.4±75.2 (395.1)	0.6± 0.1	185±294	This work
Beijing, China	Rural	2016.05	27	73±90 (937)	1.2 ± 0.9	270±240	(Wang et al., 2018)
Bejing, China	Urban	2016.09	-	36.7	1.4 ± 1.7	-	(Wang et al., 2017a)

Bejing, China	Suburban	2016.02	-	~1400	-	-	(Wang et al., 2020b)
Wangdu, China	Rural	2014.07	-	~200 (430)	1.7±0.6	76.9	(Tham et al., 2016)
Mountain Tai, China	Suburban	2014.07	-	6.8±7.7	0.5±0.4	74	(Wang et al., 2017c)
Jinan, China	Urban	2014.08	-	22±12 (278)	-	-	(Wang et al., 2017b)
Shanghai, China	Urban	2011.08	16±9	310±380	1.1±1.1	-	(Wang et al., 2013)
Taizhou, China	Rural	2018.05	4.4±2.2	26.0±35.7 (492)	1.0×0.5	43 ± 52	(Wang et al., 2020a)
Taizhou, China	Suburban	2018.05	4.4±2.2	26.0 ± 35.7	1.2±0.4	55±68	(Li et al., 2020)
Changzhou, China	Suburban	2019.05	-	61.0 ± 63.1 (477.2)	2.8 ± 1.6	-	(Zhai et al., 2023)
Hongkong, China	Island	2012.08	7 ±12	17±33 (336)	-	76±61	(Yan et al., 2019)
Hongkong, China	Coastal	2013.11	-	~11800	0.26	~13 h	(Brown et al., 2016)
Shenzhen, China	Coastal	2019.09	-	56±89 (1420)	2.9±0.5	-	(Niu et al., 2022)
Heshan, China	Urban	2019.09	~90	64±145	2.5±2.1	-	(Wang et al., 2022)
South China Sea	Island	2021.11	10 ±13	120±129	1.4±0.7	30±42	(Wang et al., 2024)
Seoul, Korea	Urban, tower	2015.05	-	4100±1200, 2600±1600 (5000)	1.3	1800	(Brown et al., 2017)
Southern Spain	Coastal	2008.11	-	~500	-	-	(Crowley et al., 2011)
Northwestern, Europe	Coastal, airborne	2010.07	-	670	-	15~120 min	(Morgan et al., 2015)
Taunus Observatory, Germany	Rural	2011.08	-	~800	~1.8	-	(Phillips et al., 2016)
East coast USA	Coastal	2002.06	17	84	-	-	(Brown et al., 2004)
California,	Coastal	2004.01	-	~200	-	~30 min	(Wood et

USA							al., 2005)
Salt Lake Valley, USA	Airborne	2017.01	-	0~2	0~2	-	(McDuffie et al., 2019)
Lower Fraser Valley, Canada	Suburban	2012.07	-	1.4 (23)	-	-	(Osthoff et al., 2018)

The values in brackets are the maximum of N_2O_5 concentration.

Table S2. Summary of global field observation results of $\gamma(N_2O_5)$.

Location	Period	Site type	$\gamma(N_2O_5)$	Method	Reference
Kunming, China	2021.04	Suburban	0.0018~0.12 (0.23±0.21)	AFTS	This work
Beijing, China	2016.02	Suburban	0.001-0.02 (0.0046)	Box model	(Wang et al., 2020b)
Beijing, China	2016.05	Rural	0.012-0.055 (0.034)	Products	(Wang et al., 2018)
Beijing, China	2016.09	Urban	0.025-0.072 (0.048)	Steady-state	(Wang et al., 2017a)
Beijing, China	2018.1	Urban	0.0075-0.0149	Steady-state	(Xia et al., 2021)
Beijing, China	2019.01	Tower	0.0005-0.2 (0.05)	Box model	(Chen et al., 2020)
Beijing, China	2020.12	Urban	0.0045-0.12 (0.042±0.026)	AFTS	(Chen et al., 2022)
Wangdu, China	2014.06	Rural	0.005-0.039	Products	(Tham et al., 2018)
Wangdu, China	2014.06	Rural	0.0012-0.072	Steady-state	(Lu et al., 2022)
Wangdu, China	2017.12	Rural	0.006-0.015	Steady-state	(Xia et al., 2021)
Mountain Tai, China	2014.07	Suburban	0.021-0.102 (0.061)	Steady-state	(Wang et al., 2017c)
Mountain Tai, China	2018.03	Suburban	0.001-0.019 (0.01)	AFTS	(Yu et al., 2020)
Jinan, China	2014.08	Urban	0.042-0.092 (0.069)	Steady-state	(Wang et al., 2017b)
Taizhou, China	2018.06	Suburban	0.027-0.107 (0.08)	Steady-state	(Li et al., 2020)

Location	Period	Site type	γ(N_2O_5)	Method	Reference
Changzhou, China	2019.06	Suburban	0.057-0.123 0.001-0.024	Steady-state Parameterization	(Zhai et al., 2023)
Hongkong, China	2013.11	Suburban	0.004-0.029 (0.014)	Steady-state	(Brown et al., 2016)
Hongkong, China	2013.11	Suburban	0.0005-0.016 (0.004)	Box model	(Yun et al., 2018)
Heshan, China	2017.03	Suburban	0.002-0.067 (0.02)	AFTS	(Yu et al., 2020)
Heshan, China	2019.10	Urban	0.0019-0.077 (0.0317)	Products	(Wang et al., 2022)
Shenzhen, China	2019.10	Coastal	0.002-0.068 (0.027±0.02) 0.005-0.08 (0.031±0.02)	Products Box model	(Niu et al., 2022)
New England, USA	2002.08	Ship	0.03-0.04	Steady-state	(Aldener et al., 2006)
New England, USA	2004.02	Airborne	0.0016-0.02	Steady-state	(Brown et al., 2006)
Texas, USA	2006.10	Airborne	0.0005-0.006 (0.0039)	Steady-state	(Brown et al., 2009)
Boulder, USA	2008.07	Tower	0.0009-0.012 (0.003)	AFTS	(Bertram et al., 2009)
Seattle, USA	2008.08	Coastal	0.005-0.04	AFTS	(Bertram et al., 2009)
California, USA	2009.09	Coastal	0.00003-0.029 (0.0054)	AFTS	(Riedel et al., 2012)
Los Angeles, USA	2010.05	Airborne	0.001-0.01	Steady-state	(Chang et al., 2016)
Colorade, USA	2011.02	Tower	0.002-0.1 (0.04)	Box model	(Wagner et al., 2013)
Eastern，USA	2015.02	Airborne	0.00002-0.175 (0.014)	Box model	(McDuffie et al., 2018)
Salt Lake Valley, USA	2017.01	Airborne	0.001-0.1 (0.076)	Box model	(McDuffie et al., 2019)
NW Europe/UK	2010.06	Airborne	0.0076-0.03	Steady-state	(Morgan et al.,

Location	Period	Site type	$\gamma(N_2O_5)$	Method	Reference
					2015)
SW Germany	2011.08	Suburban	0.004-0.11 (0.028)	Products, Steady-state	(Phillips et al., 2016)

The values in brackets are mean values of $\gamma(N_2O_5)$.
AFTS: aerosol flow tube system;
Steady-state: steady state approximation;
Products: products formation rate analysis;
Box model: inverse iterative box model simulation.

Table S3. Summary of the details and performances of the parameterizations discussed in this study.

Parameterization name	Factors considered	Parameterization	Reference	R^2	RMSE	Median
RIE03	Mass concentration of aerosol sulfate and nitrate (μg/m^3)	$\boldsymbol{\gamma = f \times r_1 + (1-f) \times r_2}$ where, $r_1=0.02$ $r_1=0.002$ f= mass SO_4^{2-}/(mass SO_4^{2-}+ mass NO_3^-)	(Riemer et al., 2003)	0	0.0223	0.017
DAV08	[SO_4^{2-}], [NO_3^-], [NH_4^+], RH, T	$\boldsymbol{\gamma = x_1 \times \gamma_1^* + x_2 \times \gamma_2^* + x_3 \times \gamma_3^*}$ where, $\lambda_1=-4.10612+0.02386 \times RH - 0.23771 \times \max((T-291),0)$ $\gamma_1=1/(1+e^{-\lambda 1})$ $\gamma_1^*=\min(\gamma_1, 0.08585)$ $\lambda_2=(-4.10612-0.80570)+0.02386 \times RH+(-0.23771+0.10225) \times \max((T-291),0)$ $\gamma_2=1/(1+e^{-\lambda 2})$ $\gamma_2^*=\min(\gamma_2, 0.053)$ $\lambda_3=-8.10774+0.04902 \times RH$ $\gamma_3=1/(1+e^{-\lambda 3})$ $\gamma_3^*=\min(\gamma_3, 0.0154)$ $x_3=[NO_3^-]/([NO_3^-]+[SO_4^{2-}])$ $x_2=\max(0, \min(1-x_3, [NH_4^+]/([NO_3^-]+[SO_4^{2-}])-1))$ $x_1=1-x_2-x_3$	(Davis et al., 2008)	0.02	00317	0.034

Parameterization name	Factors considered	Parameterization	Reference	R^2	RMSE	Median
		(1=NH_4HSO_4, 2=$(NH_4)_2SO_4$, 3=NH_4NO_3)				
BT09	ALWC, $[NO_3^-]$, $[Cl^-]$, V_a, S_a	$\gamma = \frac{4}{c}\frac{V_a}{S_a}K_H k'_{2f}\left(1 - \frac{1}{\left(\frac{k_3[\mathrm{H_2O}]}{k_{2b}[\mathrm{NO_3}^-]}\right) + 1 + \left(\frac{k_4[Cl^-]}{k_{2b}[\mathrm{NO_3}^-]}\right)}\right)$ where, K_H=51, Henry's Law Coefficient (Fried et al., 1994) k'_{2f}=$\beta - \beta_e{}^{(-\delta[\mathrm{H_2O}])}$ β=1.15×10^6 (s^{-1}) δ=0.13 (M^{-1}) $\frac{k_3}{k_{2b}}$=0.06 $\frac{k_4}{k_{2b}}$=29	(Bertram and Thornton, 2009)	0.06	0.0228	0.034
BT09 w/o Cl	ALWC, $[NO_3^-]$, V_a, S_a	$\gamma = \frac{4}{c}\frac{V_a}{S_a}K_H k'_{2f}\left(1 - \frac{1}{\left(\frac{k_3[\mathrm{H_2O}]}{k_{2b}[\mathrm{NO_3}^-]}\right) + 1}\right)$ parameters are same as BT09.	(Bertram and Thornton, 2009)	0.07	0.0202	0.020
GRI09	ALWC, $[NO_3^-]$, V_a, S_a	$\gamma = \frac{4}{c}\frac{V_a}{S_a}K_H k'_{2f}\left(1 - \frac{1}{\left(\frac{k_3[\mathrm{H_2O}]}{k_{2b}[\mathrm{NO_3}^-]}\right) + 1}\right)$	(Griffiths et al., 2009)	0.06	0.0533	0.063

Parameterization name	Factors considered	Parameterization	Reference	R^2	RMSE	Median
		Where, K_H=51 $\frac{k_3}{k_{2b}}$=1/30 k'_{2f}=5×10^6				
YU20	ALWC, [NO_3^-], [Cl^-], V_a, S_a	$\gamma = \frac{4}{c}\frac{V_a}{S_a}K_H k'_{2f}\left(1 - \frac{1}{\left(\frac{k_3[\mathrm{H_2O}]}{k_{2b}[\mathrm{NO_3}^-]}\right) + 1 + \left(\frac{k_4[Cl^-]}{k_{2b}[\mathrm{NO_3}^-]}\right)}\right)$ where, K_H=51 k'_{2f}=[H_2O]×3×10^4 $\frac{k_3}{k_{2b}}$=0.033 $\frac{k_4}{k_{2b}}$=3.4	(Yu et al., 2020)	0.09	0.02	0.019
EJ05	Mass fraction of aerosol sulfate and organic, RH,	**γ=mass SO_4^{2-}/dry mass×γ_1+mass organic/dry mass×γ_2** where, $\gamma_1=\alpha\times10^{\beta}$ $\alpha=2.79\times10^{-4}+1.3\times10^{-4}\times RH-3.43\times10^{-6}\times RH^2+7.52\times10^{-8}\times RH^3$	(Evans and Jacob, 2005)	0	0.0228	0.019

Parameterization name	Factors considered	Parameterization	Reference	R^2	RMSE	Median
	T	$\beta=4\times10^{-2}\times(T-294)$, $(T\geq282K)$ $\beta=-0.48$, $(T<282K)$ $\gamma_2=RH\times5.2\times10^{-4}$, $(RH<57\%)$ $\gamma_2=0.03$, $(RH\geq57\%)$				
BT09+Rie09	ALWC, $[NO_3^-]$, $[Cl^-]$, V_a, S_a, organic coating	$\frac{1}{\gamma}=\frac{1}{\gamma_{core}}+\frac{1}{\gamma_{org.coat}}$ where, γ_{core}=BT09 $\gamma_{org.coat}=\frac{4RTD_{org}H_{org}R_c}{clR_p}$ R, gas constant (atm·m^3/mol·K) T, temperature (K) $D_{org}H_{org}=\varepsilon D_{aq}H_{aq}$ $\varepsilon=0.03$ $H_{aq}=5000$, Henry's Law Coefficient in aqueous core (mol m^{-3} atm^{-1}) $D_{aq}=1\times10^{-9}$, N_2O_5 Liquid Diffusion Coefficient (m^2 s^{-1}) R_p, median particle total radius, (m) $R_c=R_p-l$, particle core radius (m) $l=R_p\times(1-\beta^{1/3})$, organic coating thickness (m) $\beta=V_{inorganic}/(V_{organic}+V_{inorganic})$	(Bertram and Thornton, 2009;Anttila et al., 2006;Riemer et al., 2009)	0.03	0.0278	0.012
BT09+Rie09(wG14)	ALWC, $[NO_3^-]$, $[Cl^-]$,	$\frac{1}{\gamma}=\frac{1}{\gamma_{core}}+\frac{1}{\gamma_{org.coat}}$	(Gaston et al., 2014)	0.07 (O/C=0.8);	0.0201 (O/C=0.8);	0.019 (O/C=0.8);

Parameterization name	Factors considered	Parameterization	Reference	R^2	RMSE	Median
	V_a, S_a, organic coating, O/C, RH	same as BT09+Rie09 except, ε=0.06, (RH≤30% and O/C≥0.7) ε=0.008, (RH≤30% and O/C≤0.7) ε=0.3, (30%≤RH≤70% and O/C≥0.7) ε=0.05, (30%≤RH≤70% and O/C≤0.7) ε=1.0, (70%≤RH and O/C≥0.7) ε=0.8, (70%≤RH and O/C≤0.7)		0.07 (O/C=0.5)	0.0248 (O/C=0.5)	0.006 (O/C=0.5)
MD18	ALWC, $[NO_3^-]$, $[Cl^-]$, V_a, S_a, organic coating, O/C, RH	$\frac{1}{\gamma}=\frac{1}{\gamma_{core}}+\frac{1}{\gamma_{org.coat}}$ same as BT09+Rie09 except, γ_{core}=BT09 w/o Cl k'_{2f}=$[H_2O]\times 2.14\times 10^5$ $\frac{k_3}{k_{2b}}$=0.04 ε=0.15×O/C+0.0016×RH	(McDuffie et al., 2018)	0.05 (O/C=0.8); 0.04 (O/C=0.5)	0.0205 (O/C=0.8); 0.0208 (O/C=0.5)	0.022 (O/C=0.8); 0.018 (O/C=0.5)

References:

Aldener, M., Brown, S. S., Stark, H., Williams, E. J., Lerner, B. M., Kuster, W. C., Goldan, P. D., Quinn, P. K., Bates, T. S., Fehsenfeld, F. C., and Ravishankara, A. R.: Reactivity and loss mechanisms of NO_3 and N_2O_5 in a polluted marine environment: Results from in situ measurements during New England Air Quality Study 2002, Journal of Geophysical Research-Atmospheres, 111, 10.1029/2006jd007252, 2006.

Anttila, T., Kiendler-Scharr, A., Tillmann, R., and Mentel, T. F.: On the reactive uptake of gaseous compounds by organic-coated aqueous aerosols: Theoretical analysis and application to the heterogeneous hydrolysis of N_2O_5, Journal of Physical Chemistry A, 110, 10435-10443, 10.1021/jp062403c, 2006.

Bertram, T. H., and Thornton, J. A.: Toward a general parameterization of N_2O_5 reactivity on aqueous particles: the competing effects of particle liquid water, nitrate and chloride, Atmospheric Chemistry and Physics, 9, 8351-8363, 10.5194/acp-9-8351-2009, 2009.

Bertram, T. H., Thornton, J. A., and Riedel, T. P.: An experimental technique for the direct measurement of N_2O_5 reactivity on ambient particles, Atmospheric Measurement Techniques, 2, 231-242, 10.5194/amt-2-231-2009, 2009.

Brown, S. S., Dibb, J. E., Stark, H., Aldener, M., Vozella, M., Whitlow, S., Williams, E. J., Lerner, B. M., Jakoubek, R., Middlebrook, A. M., DeGouw, J. A., Warneke, C., Goldan, P. D., Kuster, W. C., Angevine, W. M., Sueper, D. T., Quinn, P. K., Bates, T. S., Meagher, J. F., Fehsenfeld, F. C., and Ravishankara, A. R.: Nighttime removal of NOx in the summer marine boundary layer, Geophysical Research Letters, 31, 10.1029/2004gl019412, 2004.

Brown, S. S., Ryerson, T. B., Wollny, A. G., Brock, C. A., Peltier, R., Sullivan, A. P., Weber, R. J., Dube, W. P., Trainer, M., Meagher, J. F., Fehsenfeld, F. C., and Ravishankara, A. R.: Variability in nocturnal nitrogen oxide processing and its role in regional air quality, Science, 311, 67-70, 10.1126/science.1120120, 2006.

Brown, S. S., Dube, W. P., Fuchs, H., Ryerson, T. B., Wollny, A. G., Brock, C. A., Bahreini, R., Middlebrook, A. M., Neuman, J. A., Atlas, E., Roberts, J. M., Osthoff, H. D., Trainer, M., Fehsenfeld, F. C., and Ravishankara, A. R.: Reactive uptake coefficients for N_2O_5 determined from aircraft measurements during the Second Texas Air Quality Study: Comparison to current model parameterizations, Journal of Geophysical Research-Atmospheres, 114, 10.1029/2008jd011679, 2009.

Brown, S. S., Dube, W. P., Tham, Y. J., Zha, Q. Z., Xue, L. K., Poon, S., Wang, Z., Blake, D. R., Tsui, W., Parrish, D. D., and Wang, T.: Nighttime chemistry at a high altitude site above Hong Kong, Journal of Geophysical Research-Atmospheres, 121, 2457-2475, 10.1002/2015jd024566, 2016.

Brown, S. S., An, H., Lee, M., Park, J. H., Lee, S. D., Fibiger, D. L., McDuffie, E. E., Dube, W. P., Wagner, N. L., and Min, K. E.: Cavity enhanced spectroscopy for measurement of nitrogen oxides in the Anthropocene: results from the Seoul tower during MAPS 2015, Faraday Discussions, 200, 529-557, 10.1039/c7fd00001d, 2017.

Chang, W. L., Brown, S. S., Stutz, J., Middlebrook, A. M., Bahreini, R., Wagner, N. L., Dube, W. P., Pollack, I. B., Ryerson, T. B., and Riemer, N.: Evaluating N_2O_5 heterogeneous hydrolysis parameterizations for CalNex 2010, Journal of Geophysical Research-Atmospheres, 121, 5051-5070, 10.1002/2015jd024737, 2016.

Chen, X., Wang, H., Zhai, T., Li, C., and Lu, K.: Direct measurement of N_2O_5 heterogeneous uptake coefficients onambient aerosols via an aerosol flow tube system: design, characterizationand performance, Atmospheric Measurement Techniques, 15, 7019-7037, 10.5194/amt-15-7019-2022, 2022.

Chen, X. R., Wang, H. C., Lu, K. D., Li, C. M., Zhai, T. Y., Tan, Z. F., Ma, X. F., Yang, X. P., Liu, Y. H., Chen, S. Y., Dong, H. B., Li, X., Wu, Z. J., Hu, M., Zeng, L. M., and Zhang, Y. H.: Field Determination of Nitrate Formation Pathway in Winter Beijing, Environmental Science & Technology, 54, 9243-9253, 10.1021/acs.est.0c00972, 2020.

Crowley, J. N., Thieser, J., Tang, M. J., Schuster, G., Bozem, H., Beygi, Z. H., Fischer, H., Diesch, J. M., Drewnick, F., Borrmann, S., Song, W., Yassaa, N., Williams, J., Pohler, D., Platt, U., and Lelieveld, J.: Variable lifetimes and loss mechanisms for NO_3 and N_2O_5 during the DOMINO campaign: contrasts between marine, urban and continental air, Atmospheric Chemistry and Physics, 11, 10853-10870, 10.5194/acp-11-10853-2011, 2011.

Davis, J. M., Bhave, P. V., and Foley, K. M.: Parameterization of N_2O_5 reaction probabilities on the surface of particles containing ammonium, sulfate, and nitrate, Atmospheric Chemistry and Physics, 8, 5295-5311, 10.5194/acp-8-5295-2008, 2008.

Evans, M. J., and Jacob, D. J.: Impact of new laboratory studies of N_2O_5 hydrolysis on global model budgets of tropospheric nitrogen oxides, ozone, and OH, Geophysical Research Letters, 32, 10.1029/2005gl022469, 2005.

Fried, A., Henry, B. E., Calvert, J. G., and Mozurkewich, M.: The reaction probability of n_2o_5 with sulfuric-acid aerosols at stratospheric temperatures and compositions, Journal of Geophysical Research-Atmospheres, 99, 3517-3532, 10.1029/93jd01907, 1994.

Gaston, C. J., Thornton, J. A., and Ng, N. L.: Reactive uptake of N_2O_5 to internally mixed inorganic and organic particles: the role of organic carbon oxidation state and inferred organic phase separations, Atmospheric Chemistry and Physics, 14, 5693-5707, 10.5194/acp-14-5693-2014, 2014.

Griffiths, P. T., Badger, C. L., Cox, R. A., Folkers, M., Henk, H. H., and Mentel, T. F.: Reactive Uptake of N_2O_5 by Aerosols Containing Dicarboxylic Acids. Effect of Particle Phase, Composition, and Nitrate Content, Journal of Physical Chemistry A, 113, 5082-5090, 10.1021/jp8096814, 2009.

Li, Z. Y., Xie, P. H., Hu, R. Z., Wang, D., Jin, H. W., Chen, H., Lin, C., and Liu, W. Q.: Observations of N_2O_5 and NO_3 at a suburban environment in Yangtze river delta in China: Estimating heterogeneous N_2O_5 uptake coefficients, Journal of Environmental Sciences, 95, 248-255, 10.1016/j.jes.2020.04.041, 2020.

Lu, X., Qin, M., Xie, P. H., Duan, J., Fang, W., and Liu, W. Q.: Observation of ambient NO_3 radicals by LP-DOAS at a rural site in North China Plain, Science of the

Total Environment, 804, 10.1016/j.scitotenv.2021.149680, 2022.

McDuffie, E. E., Fibiger, D. L., Dube, W. P., Lopez-Hilfiker, F., Lee, B. H., Thornton, J. A., Shah, V., Jaegle, L., Guo, H. Y., Weber, R. J., Reeves, J. M., Weinheimer, A. J., Schroder, J. C., Campuzano-Jost, P., Jimenez, J. L., Dibb, J. E., Veres, P., Ebben, C., Sparks, T. L., Wooldridge, P. J., Cohen, R. C., Hornbrook, R. S., Apel, E. C., Campos, T., Hall, S. R., Ullmann, K., and Brown, S. S.: Heterogeneous N_2O_5 Uptake During Winter: Aircraft Measurements During the 2015 WINTER Campaign and Critical Evaluation of Current Parameterizations, Journal of Geophysical Research-Atmospheres, 123, 4345-4372, 10.1002/2018jd028336, 2018.

McDuffie, E. E., Womack, C. C., Fibiger, D. L., Dube, W. P., Franchin, A., Middlebrook, A. M., Goldberger, L., Lee, B., Thornton, J. A., Moravek, A., Murphy, J. G., Baasandorj, M., and Brown, S. S.: On the contribution of nocturnal heterogeneous reactive nitrogen chemistry to particulate matter formation during wintertime pollution events in Northern Utah, Atmospheric Chemistry and Physics, 19, 9287-9308, 10.5194/acp-19-9287-2019, 2019.

Morgan, W. T., Ouyang, B., Allan, J. D., Aruffo, E., Di Carlo, P., Kennedy, O. J., Lowe, D., Flynn, M. J., Rosenberg, P. D., Williams, P. I., Jones, R., McFiggans, G. B., and Coe, H.: Influence of aerosol chemical composition on N_2O_5 uptake: airborne regional measurements in northwestern Europe, Atmospheric Chemistry and Physics, 15, 973-990, 10.5194/acp-15-973-2015, 2015.

Niu, Y. B., Zhu, B., He, L. Y., Wang, Z., Lin, X. Y., Tang, M. X., and Huang, X. F.: Fast Nocturnal Heterogeneous Chemistry in a Coastal Background Atmosphere and Its Implications for Daytime Photochemistry, Journal of Geophysical Research-Atmospheres, 127, 10.1029/2022jd036716, 2022.

Osthoff, H. D., Odame-Ankrah, C. A., Taha, Y. M., Tokarek, T. W., Schiller, C. L., Haga, D., Jones, K., and Vingarzan, R.: Low levels of nitryl chloride at ground level: nocturnal nitrogen oxides in the Lower Fraser Valley of British Columbia, Atmospheric Chemistry and Physics, 18, 6293-6315, 10.5194/acp-18-6293-2018, 2018.

Phillips, G. J., Thieser, J., Tang, M. J., Sobanski, N., Schuster, G., Fachinger, J., Drewnick, F., Borrmann, S., Bingemer, H., Lelieveld, J., and Crowley, J. N.: Estimating N_2O_5 uptake coefficients using ambient measurements of NO_3, N_2O_5, $ClNO_2$ and particle-phase nitrate, Atmospheric Chemistry and Physics, 16, 13231-13249, 10.5194/acp-16-13231-2016, 2016.

Riedel, T. P., Bertram, T. H., Ryder, O. S., Liu, S., Day, D. A., Russell, L. M., Gaston, C. J., Prather, K. A., and Thornton, J. A.: Direct N_2O_5 reactivity measurements at a polluted coastal site, Atmospheric Chemistry and Physics, 12, 2959-2968, 10.5194/acp-12-2959-2012, 2012.

Riemer, N., Vogel, H., Vogel, B., Schell, B., Ackermann, I., Kessler, C., and Hass, H.: Impact of the heterogeneous hydrolysis of N_2O_5 on chemistry and nitrate aerosol formation in the lower troposphere under photosmog conditions, Journal of Geophysical Research-Atmospheres, 108, 10.1029/2002jd002436, 2003.

Riemer, N., Vogel, H., Vogel, B., Anttila, T., Kiendler-Scharr, A., and Mentel, T.

F.: Relative importance of organic coatings for the heterogeneous hydrolysis of N_2O_5 during summer in Europe, Journal of Geophysical Research-Atmospheres, 114, 10.1029/2008jd011369, 2009.

Tham, Y. J., Wang, Z., Li, Q. Y., Yun, H., Wang, W. H., Wang, X. F., Xue, L. K., Lu, K. D., Ma, N., Bohn, B., Li, X., Kecorius, S., Gross, J., Shao, M., Wiedensohler, A., Zhang, Y. H., and Wang, T.: Significant concentrations of nitryl chloride sustained in the morning: investigations of the causes and impacts on ozone production in a polluted region of northern China, Atmospheric Chemistry and Physics, 16, 14959-14977, 10.5194/acp-16-14959-2016, 2016.

Tham, Y. J., Wang, Z., Li, Q. Y., Wang, W. H., Wang, X. F., Lu, K. D., Ma, N., Yan, C., Kecorius, S., Wiedensohler, A., Zhang, Y. H., and Wang, T.: Heterogeneous N_2O_5 uptake coefficient and production yield of $ClNO_2$ in polluted northern China: roles of aerosol water content and chemical composition, Atmospheric Chemistry and Physics, 18, 13155-13171, 10.5194/acp-18-13155-2018, 2018.

Wagner, N. L., Riedel, T. P., Young, C. J., Bahreini, R., Brock, C. A., Dube, W. P., Kim, S., Middlebrook, A. M., Ozturk, F., Roberts, J. M., Russo, R., Sive, B., Swarthout, R., Thornton, J. A., VandenBoer, T. C., Zhou, Y., and Brown, S. S.: N_2O_5 uptake coefficients and nocturnal NO_2 removal rates determined from ambient wintertime measurements, Journal of Geophysical Research-Atmospheres, 118, 9331-9350, 10.1002/jgrd.50653, 2013.

Wang, H. C., Lu, K. D., Chen, X. R., Zhu, Q. D., Chen, Q., Guo, S., Jiang, M. Q., Li, X., Shang, D. J., Tan, Z. F., Wu, Y. S., Wu, Z. J., Zou, Q., Zheng, Y., Zeng, L. M., Zhu, T., Hu, M., and Zhang, Y. H.: High N_2O_5 Concentrations Observed in Urban Beijing: Implications of a Large Nitrate Formation Pathway, Environmental Science & Technology Letters, 4, 416-420, 10.1021/acs.estlett.7b00341, 2017a.

Wang, H. C., Lu, K. D., Guo, S., Wu, Z. J., Shang, D. J., Tan, Z. F., Wang, Y. J., Le Breton, M., Lou, S. R., Tang, M. J., Wu, Y. S., Zhu, W. F., Zheng, J., Zeng, L. M., Hallquist, M., Hu, M., and Zhang, Y. H.: Efficient N_2O_5 uptake and NO_3 oxidation in the outflow of urban Beijing, Atmospheric Chemistry and Physics, 18, 9705-9721, 10.5194/acp-18-9705-2018, 2018.

Wang, H. C., Chen, X. R., Lu, K. D., Hu, R. Z., Li, Z. Y., Wang, H. L., Ma, X. F., Yang, X. P., Chen, S. Y., Dong, H. B., Liu, Y., Fang, X., Zeng, L. M., Hu, M., and Zhang, Y. H.: NO_3 and N_2O_5 chemistry at a suburban site during the EXPLORE-YRD campaign in 2018, Atmospheric Environment, 224, 10.1016/j.atmosenv.2019.117180, 2020a.

Wang, H. C., Chen, X. R., Lu, K. D., Tan, Z. F., Ma, X. F., Wu, Z. J., Li, X., Liu, Y. H., Shang, D. J., Wu, Y. S., Zeng, L. M., Hu, M., Schmitt, S., Kiendler-Scharr, A., Wahner, A., and Zhang, Y. H.: Wintertime N_2O_5 uptake coefficients over the North China Plain, Science Bulletin, 65, 765-774, 10.1016/j.scib.2020.02.006, 2020b.

Wang, H. C., Yuan, B., Zheng, E., Zhang, X. X., Wang, J., Lu, K. D., Ye, C. S., Yang, L., Huang, S., Hu, W. W., Yang, S. X., Peng, Y. W., Qi, J. P., Wang, S. H., He, X. J., Chen, Y. B., Li, T. G., Wang, W. J., Huangfu, Y. B., Li, X. B., Cai, M. F., Wang, X.

M., and Shao, M.: Formation and impacts of nitryl chloride in Pearl River Delta, Atmospheric Chemistry and Physics, 22, 14837-14858, 10.5194/acp-22-14837-2022, 2022.

Wang, J., Wang, H. C., Tham, Y. J., Ming, L. L., Zheng, Z. L., Fang, G. Z., Sun, C. Z., Ling, Z. H., Zhao, J., and Fan, S. J.: Measurement report: Atmospheric nitrate radical chemistry in the South China Sea influenced by the urban outflow of the Pearl River Delta, Atmospheric Chemistry and Physics, 24, 977-992, 10.5194/acp-24-977-2024, 2024.

Wang, S. S., Shi, C. Z., Zhou, B., Zhao, H., Wang, Z. R., Yang, S. N., and Chen, L. M.: Observation of NO₃ radicals over Shanghai, China, Atmospheric Environment, 70, 401-409, 10.1016/j.atmosenv.2013.01.022, 2013.

Wang, X. F., Wang, H., Xue, L. K., Wang, T., Wang, L. W., Gu, R. R., Wang, W. H., Tham, Y. J., Wang, Z., Yang, L. X., Chen, J. M., and Wang, W. X.: Observations of N_2O_5 and $ClNO_2$ at a polluted urban surface site in North China: High N_2O_5 uptake coefficients and low $ClNO_2$ product yields, Atmospheric Environment, 156, 125-134, 10.1016/j.atmosenv.2017.02.035, 2017b.

Wang, Z., Wang, W. H., Tham, Y. J., Li, Q. Y., Wang, H., Wen, L., Wang, X. F., and Wang, T.: Fast heterogeneous N_2O_5 uptake and $ClNO_2$ production in power plant and industrial plumes observed in the nocturnal residual layer over the North China Plain, Atmospheric Chemistry and Physics, 17, 12361-12378, 10.5194/acp-17-12361-2017, 2017c.

Wood, E. C., Bertram, T. H., Wooldridge, P. J., and Cohen, R. C.: Measurements of N₂O₅, NO₂, and O₃ east of the San Francisco Bay, Atmospheric Chemistry and Physics, 5, 483-491, 10.5194/acp-5-483-2005, 2005.

Xia, M., Peng, X., Wang, W. H., Yu, C. A., Wang, Z., Tham, Y. J., Chen, J. M., Chen, H., Mu, Y. J., Zhang, C. L., Liu, P. F., Xue, L. K., Wang, X. F., Gao, J., Li, H., and Wang, T.: Winter $ClNO_2$ formation in the region of fresh anthropogenic emissions: seasonal variability and insights into daytime peaks in northern China, Atmospheric Chemistry and Physics, 21, 15985-16000, 10.5194/acp-21-15985-2021, 2021.

Yan, C., Tham, Y. J., Zha, Q., Wang, X., Xue, L., Dai, J., Wang, Z., and Wang, T.: Fast heterogeneous loss of N_2O_5 leads to significant nighttime NOx removal and nitrate aerosol formation at a coastal background environment of southern China, Science of the Total Environment, 677, 637-647, 10.1016/j.scitotenv.2019.04.389, 2019.

Yu, C., Wang, Z., Xia, M., Fu, X., Wang, W. H., Tham, Y. J., Chen, T. S., Zheng, P. G., Li, H. Y., Shan, Y., Wang, X. F., Xue, L. K., Zhou, Y., Yue, D. L., Ou, Y. B., Gao, J., Lu, K. D., Brown, S. S., Zhang, Y. H., and Wang, T.: Heterogeneous N_2O_5 reactions on atmospheric aerosols at four Chinese sites: improving model representation of uptake parameters, Atmospheric Chemistry and Physics, 20, 4367-4378, 10.5194/acp-20-4367-2020, 2020.

Yun, H., Wang, T., Wang, W. H., Tham, Y. J., Li, Q. Y., Wang, Z., and Poon, S. C. N.: Nighttime NOx loss and $ClNO_2$ formation in the residual layer of a polluted region:

Insights from field measurements and an iterative box model, Science of the Total Environment, 622, 727-734, 10.1016/j.scitotenv.2017.11.352, 2018.

Zhai, T. Y., Lu, K. D., Wang, H. C., Lou, S. R., Chen, X. R., Hu, R. Z., and Zhang, Y. H.: Elucidate the formation mechanism of particulate nitrate based on direct radical observations in the Yangtze River Delta summer 2019, Atmospheric Chemistry and Physics, 23, 2379-2391, 10.5194/acp-23-2379-2023, 2023.