

Supplement of

Resolving the complex responses of ozone transport and chemistry to typhoons in South China: Insights from process-level analysis

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Text S1. Contributions of specific VOC species or sub-categories to OH reactivity

In addition to five VOC groups (biogenic VOCs, alkanes, alkenes, aromatics and OVOCs), contributions from specific VOC species or sub-categories, as listed in Table S4, to k_{OH} were further examined under different scenarios. The following discussion focuses on the results at 500 m (representing the mid-ABL) for the urban and regional sites (Daxuecheng and Xijiao), as shown in Fig. S7. Results at 50 m and 1000 m (Figs. S8 and S9) exhibit consistent patterns as those at 500 m, and results at the suburban site (Heshan; Fig. S10) are similar as those in the urban areas; thus, they are not discussed in detail.

Under typhoon influence, the composition of VOCs-related k_{OH} at the urban site (Daxuecheng) remained generally consistent, with only limited changes in specific species. Among hydrocarbon groups, alkanes and aromatic dominated VOCs-related k_{OH} under all scenarios, accounting for 13-18% and 7-13%, respectively, at 500 m. Methane contributions decreased slightly under typhoons, whereas those from other alkane species remained largely unchanged in both seasons. Aromatic VOC contributions also showed limited variability: BTX (benzene, toluene and xylene) and trimethylbenzene together contributed 5-6% and 3-4% to k_{OH} in autumn and summer, respectively, while other more complex aromatics accounted for ~7% in autumn and ~4% in summer. In contrast, biogenic VOCs, dominated by isoprene, exhibited the largest typhoon-related variability among hydrocarbon species, with their contribution in summer reducing from 12% to 6% under typhoon influence. Among OVOC species, carbonyl compounds were the dominant contributors to k_{OH} under various scenarios, accounting for over 30%, with formaldehyde and acetaldehyde contributing 15-19% and 9-13%, respectively. Typhoons tended to enhance the overall contributions of carbonyl species, but only slightly. In addition, organic hydroperoxides and isoprene oxidation products also substantially contributed to k_{OH} : the latter remained stable at ~10% across scenarios, whereas the former generally increased under typhoon influence. Contributions from alcohols, phenols and carboxylic acids remained negligible to k_{OH} in all cases. Overall, the relatively stable contributions of VOC species to k_{OH} suggests that OH oxidation is primarily controlled by local VOC emissions, limiting the influence of typhoon-driven changes in transported VOCs.

At the regional site (Xijiao), typhoon impacts on VOC contributions to k_{OH} were more pronounced, reflecting a stronger influence from enhanced cross-regional transport. Isoprene, the major hydrocarbon species in terms of k_{OH} contribution, accounted for over 20% of k_{OH} under all conditions. Typhoons led to a notable increase in isoprene contribution, particularly in summer, when it rose from 21% to 37%. Alkanes represent another important hydrocarbon group, with methane contributing more than other alkanes in total. Along with enhanced biogenic VOC contributions, the relative contributions of other hydrocarbon species, including alkanes, alkenes and aromatics, generally decreased. Similar to the urban site, OVOC contributions at Xijiao were dominated by carbonyl compounds, generally exceeding 30%, with considerable additional contributions from organic hydroperoxides and isoprene oxidation products; in contrast, alcohols, phenols and carboxylic acids contributed negligibly to k_{OH} . Under typhoon influence, carbonyl contributions decreased while organic hydroperoxide

contributions increased, with these changes being more pronounced in summer. The enhancement in organic hydroperoxide contributions, together with reduced contributions from more reactive hydrocarbon species and carbonyl compounds, was indicative of stronger atmospheric aging, consistent with the decrease in the NO_x/NO_y ratio discussed in the previous section. These variations in k_{OH} composition in rural areas agree well with enhanced transport of more aged air masses into the PRD under typhoon influence, highlighting the greater sensitivity of rural photochemistry to typhoon-driven transport.

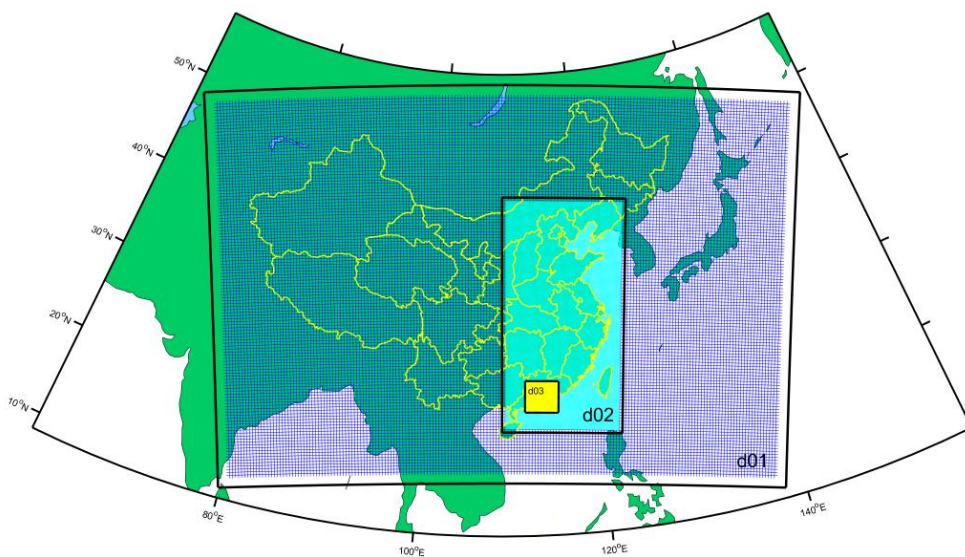


Figure S1. Simulation domains. The black bold rectangles denote the WRF modeling domains, and the shaded areas are the CMAQ modeling domains. d01, d02, the first and second simulation domains with the horizontal resolutions of 36 and 12 km, respectively; d03, the subdomain with the resolution of 12 km used for sensitivity studies.

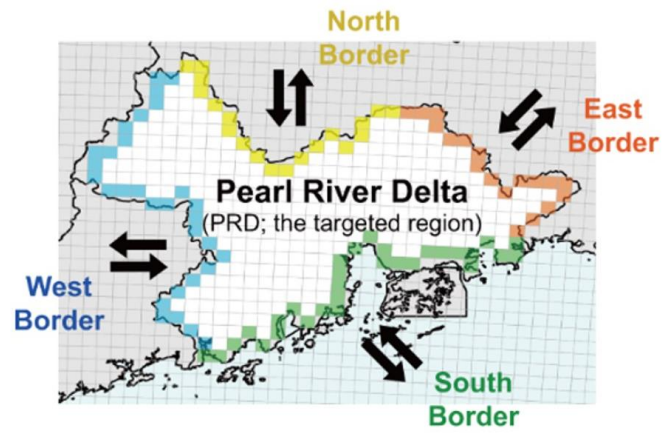


Figure S2. North, south, west, east borders of the PRD in the budget analysis (originated from Qu et al. (2023)).

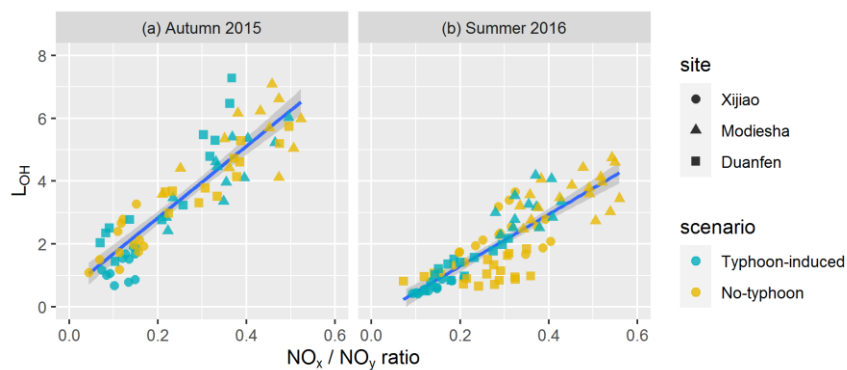


Figure S3. Correlations between simulated daytime (9:00–17:00 LT) NO_x/NO_y ratios and L_{OH} on O_3 pollution days of (a) autumn 2015 and (b) summer 2016 at three representative sites: Xijiao (regional, northeast PRD), Modiesha (urban, central PRD) and Duanfen (regional, southwest PRD). The locations of three sites are shown as the sites o, d and k, respectively, in Fig. S1b of Part I of this paper (Qu et al., 2021).

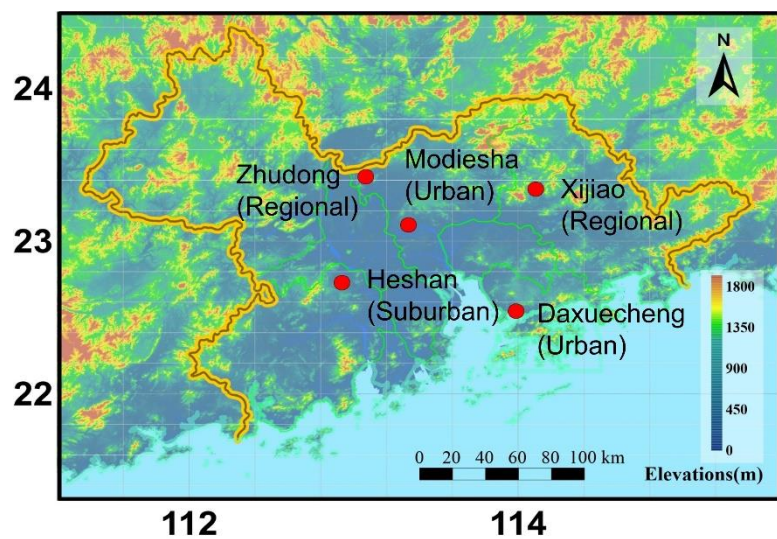


Figure S4. Locations of five representative sites with VOCs measurements.

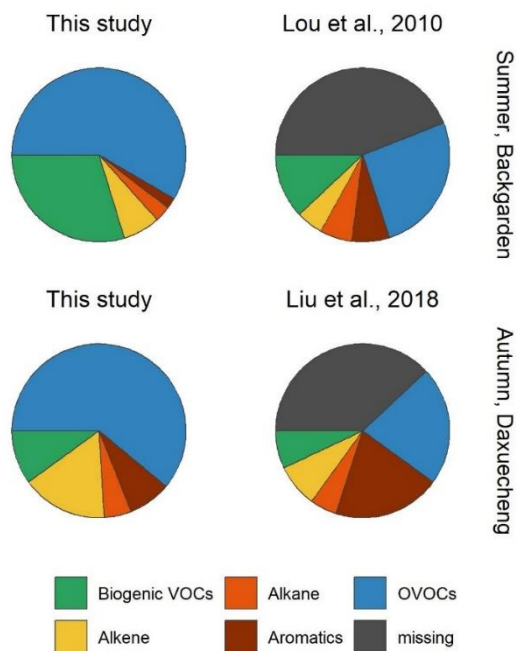


Figure S5. Comparisons between simulated proportional VOCs contributions to k_{OH} and observational results in the PRD from previous publications.

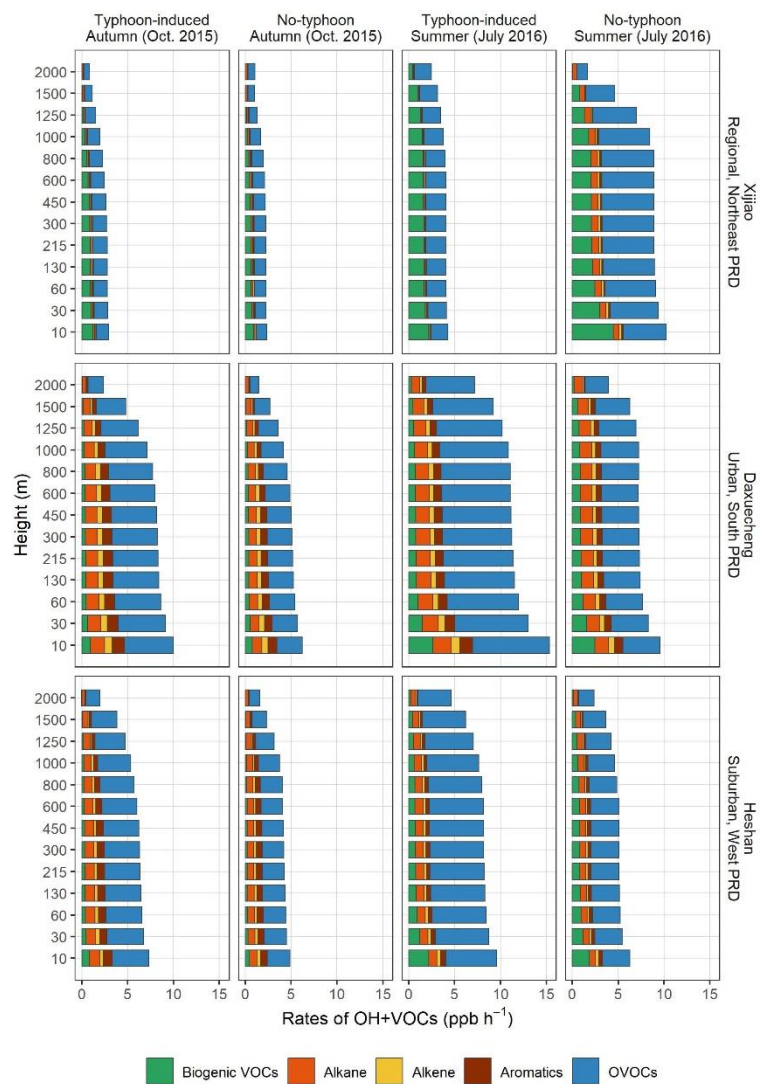


Figure S6. Contributions of five VOCs groups to daytime-mean (9:00–17:00 LT) OH+VOCs reaction rates (ppb h⁻¹) at the Xijiao, Daxuecheng and Heshan sites, shown for multiple heights on the typhoon-induced and no-typhoon O₃ pollution days of two seasons.

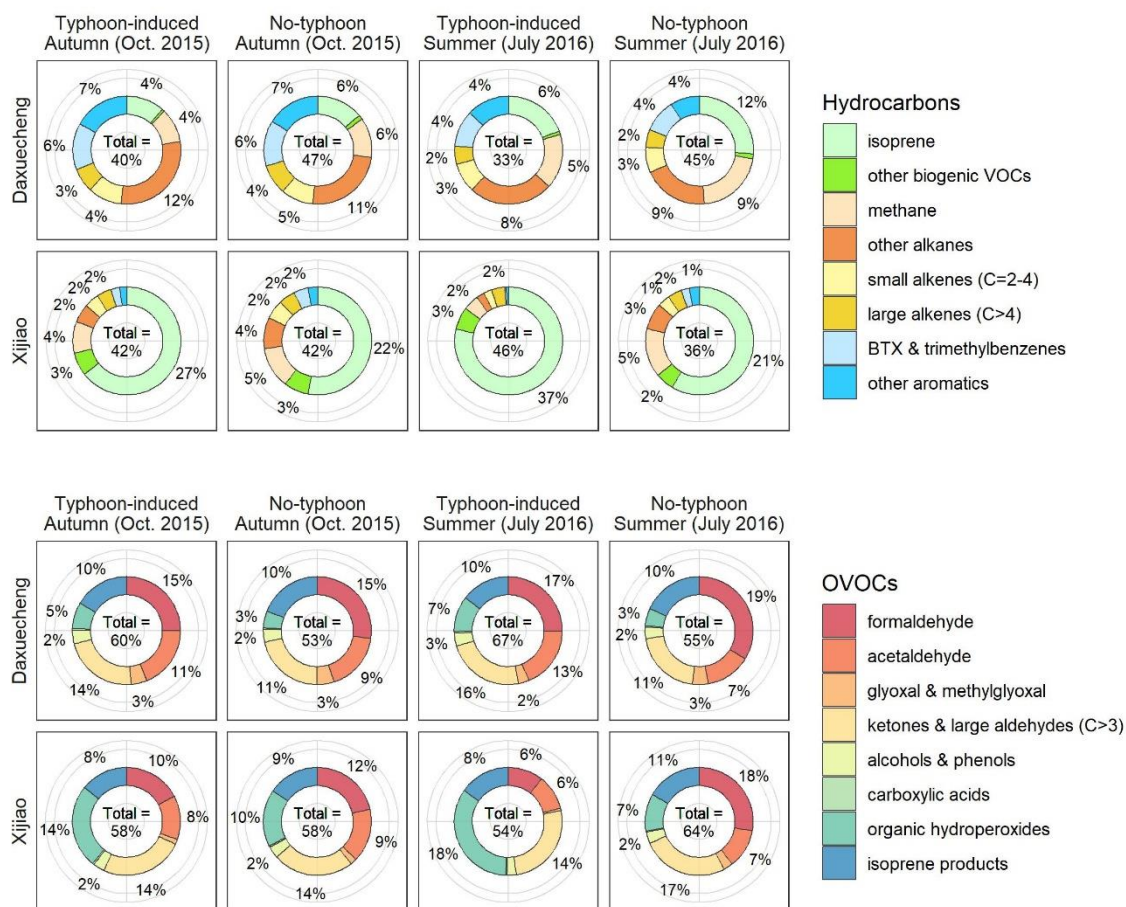


Figure S7. Proportional contributions of hydrocarbons and OVOC species or subcategories to daytime-mean (9:00–17:00 LT) k_{OH} (or $OH+VOCs$ reaction rates) at the Daxuecheng and Xijiao sites, shown at the height of ~ 500 m on the typhoon-induced and no-typhoon O_3 pollution days of two seasons. Detailed SAPRC07 species corresponding to the above species or subcategories are listed in Table S4.

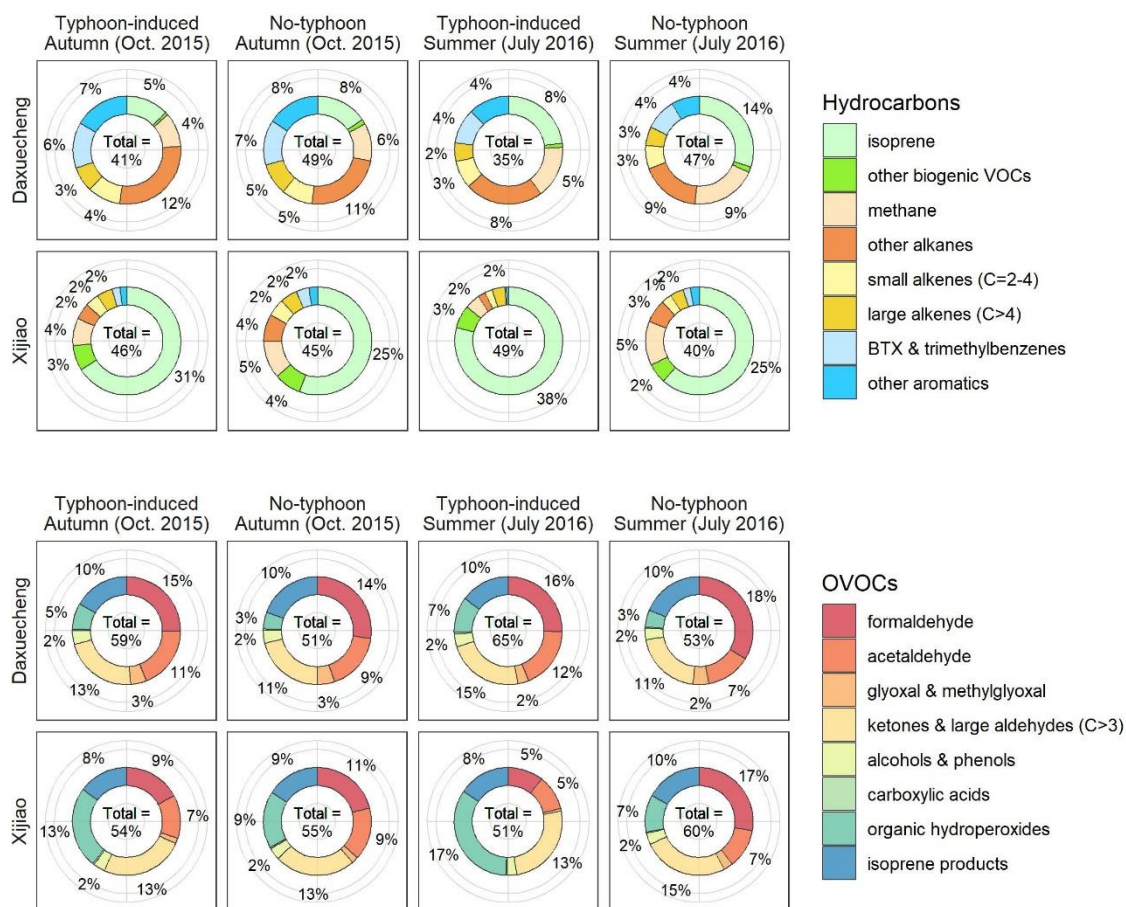


Figure S8. Same as Fig. S7 but for the height of ~50 m.

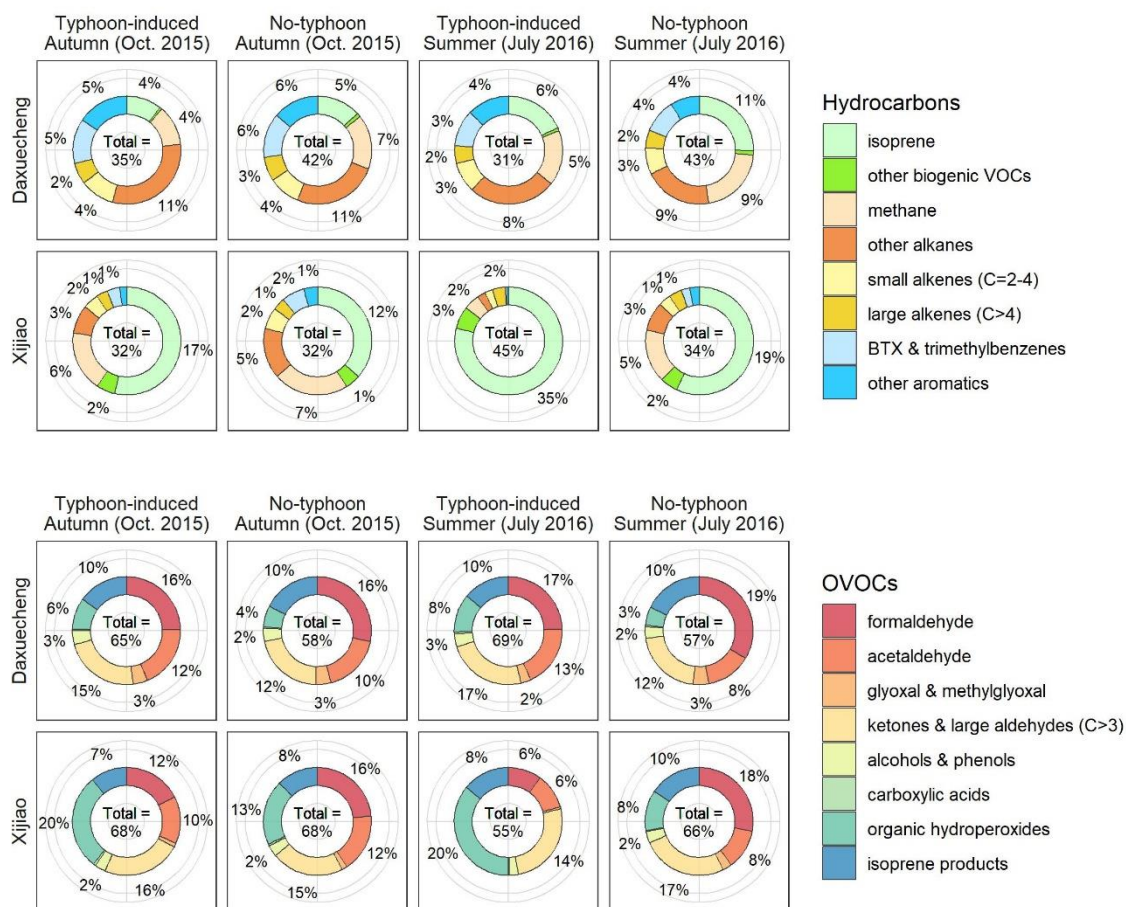


Figure S9. Same as Fig. S7 but for the height of ~1000 m.

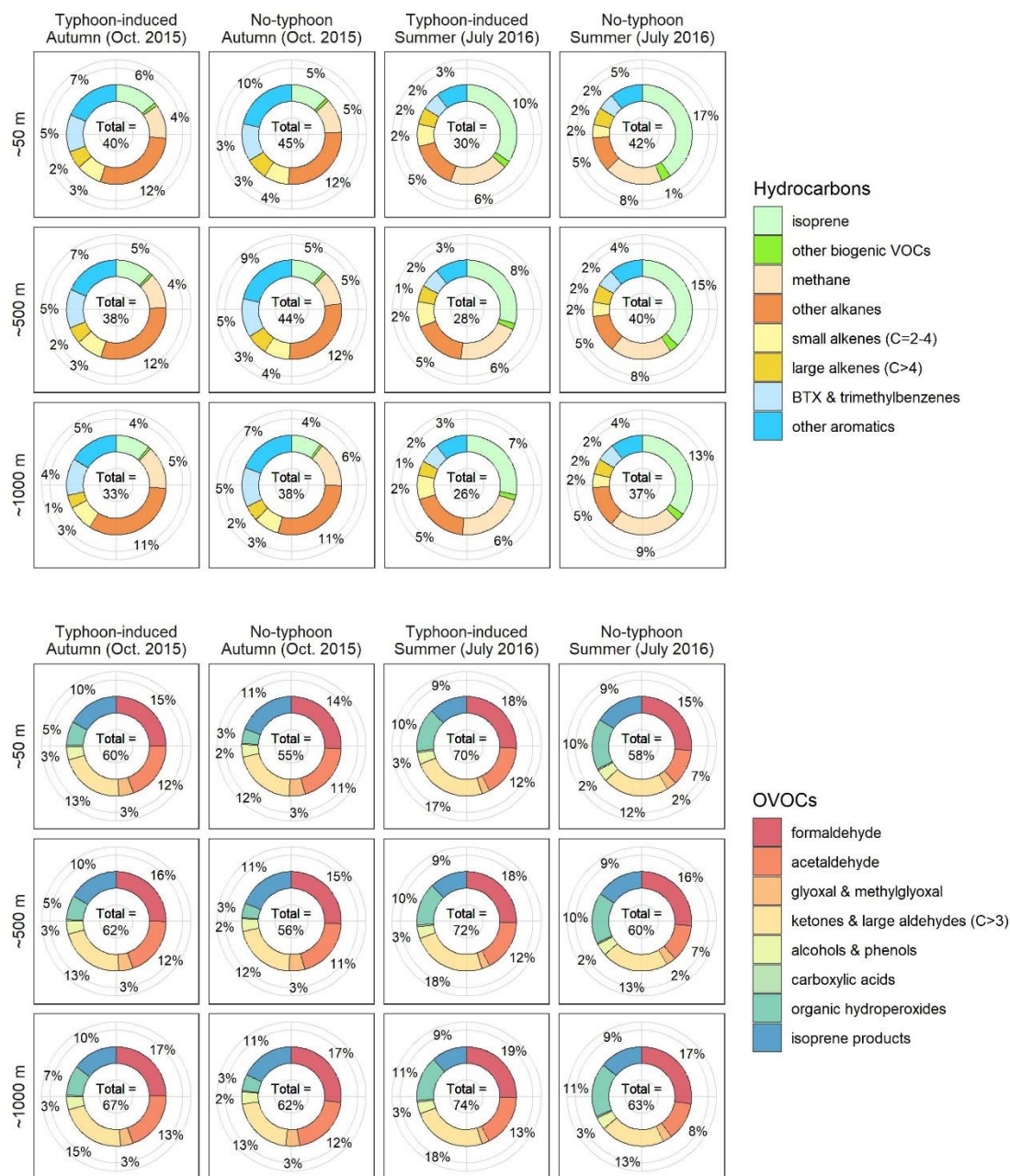


Figure S10. Proportional contributions of hydrocarbons and OVOC species or subcategories to daytime-mean (9:00–17:00 LT) k_{OH} (or $OH+VOCs$ reaction rates) at the Heshan site, shown at the height of ~50 m, ~500 m and ~1000 m on the typhoon-induced and no-typhoon O_3 pollution days of two seasons. Detailed SAPRC07 species corresponding to the above species or subcategories are listed in Table S4.

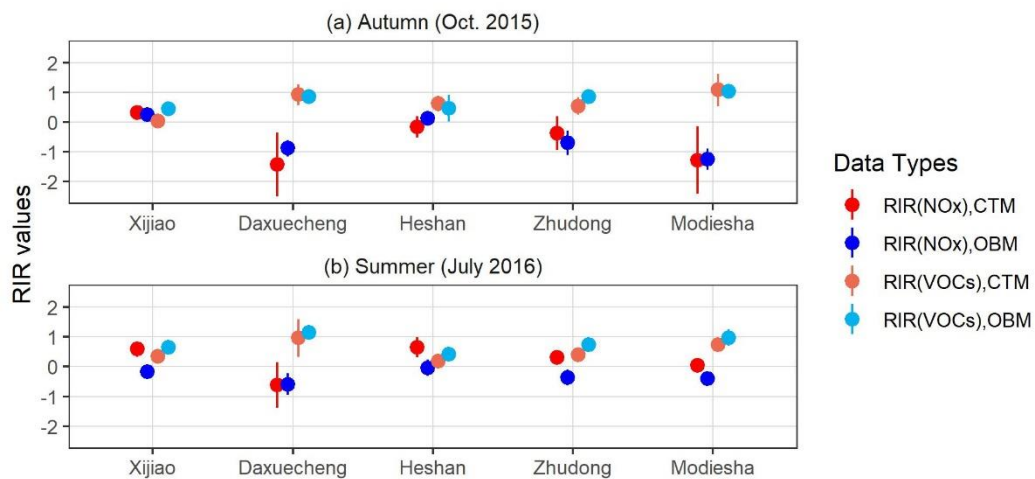


Figure S11. RIR values at five sites within the PRD on the O₃ pollution days of (a) autumn 2015 and (b) summer 2016, calculated using chemical transport models (CTM; this study) and observation-based method (OBM; Jiang, 2018).

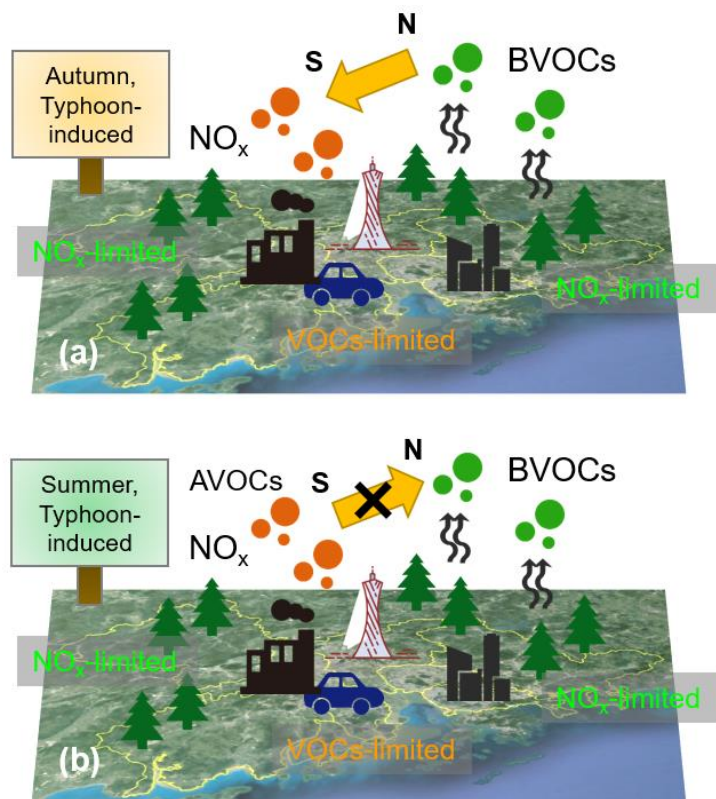


Figure S12. Illustration of typhoon influence on the mixing of O_3 precursors within the PRD in (a) autumn and (b) summer. AVOCs and BVOCs denote VOCs emitted from anthropogenic and biogenic sources, respectively.

Table S1. Summary of causes of typhoon-induced O₃ pollution in East Asia reported in previous studies. PRD, Pearl River Delta; YRD, Yangtze River Delta; NCP, North China Plain; BVOC, biogenic volatile organic compounds. Studies focusing on the PRD are listed first, followed by those in other regions; within each region, shorter-term studies are presented before long-term analyses. Full references are provided in the main manuscript.

Reference	Region	Period	Causes of typhoon-induced O ₃ pollution				
			Enhanced photochemistry	Stagnation / O ₃ accumulation	Transport of upwind air pollutants	Transport of stratospheric O ₃	Others
Wang et al., 1998	Hong Kong (PRD)	July, Sep. & Oct. 1994	√	√			Recirculation of urban plumes
Wang et al., 2001	Hong Kong (PRD)	Sep.-Oct. 1996	√		√		Recirculation of urban plumes
So & Wang, 2003	Hong Kong (PRD)	Aug. 1999	√	√	√		
Lam et al., 2005	Hong Kong (PRD)	Aug. 1999	√	√	√		
Huang et al., 2005	Hong Kong (PRD)	Sep. 1999	√		√		
Wang & Kwok, 2003	Hong Kong (PRD)	Sep. 2001	√	√	√		
Jiang et al., 2008	Hong Kong (PRD)	Sep. 2001	√	√	√		
Wei et al., 2007	PRD	Sep. 2004	√	√			Increase in BVOC emission
Wang et al., 2010	PRD	Oct. 2004	√		√		
Wei et al., 2016	Hong Kong (PRD)	July 2005	√	√	√		
Yang et al., 2012	Hong Kong (PRD)	Aug. 2008			√		Boundary-layer expansion
Wang et al., 2015	Hong Kong (PRD)	Oct.-Nov. 2010	√	√	√		
Zhang et al., 2014	PRD	Aug. 2012		√	√		
Yao et al., 2016	Guangzhou (PRD)	Aug. 2012		√			
Chen et al., 2018	Hong Kong (PRD)	Aug. 2012	√		√	√	
Li et al., 2018	Huizhou (PRD)	July 2013	√	√	√		
Wang et al., 2023	PRD	Aug. 2015	√	√			Increase in BVOC emission
Li et al., 2022	PRD	July 2016	√	√			

Table S1. (continued)

Reference	Region	Period	Causes of typhoon-induced O ₃ pollution				
			Enhanced photochemistry	Stagnation / O ₃ accumulation	Transport of upwind air pollutants	Transport of stratospheric O ₃	Others
Yue et al., 2018	Guangzhou (PRD)	July-Aug. 2016	√	√		√	
Chow et al., 2019	Hong Kong (PRD)	Aug. 2017	√	√	√		
Huang et al., 2021	Hong Kong (PRD)	July 2017	√		√		
Yang et al., 2026	PRD	Aug. 2019		√	√		
Ouyang et al., 2022	PRD	Sep.-Oct. 2019	√	√	√		Recirculation driven by sea breezes
Chen et al., 2026	Guangdong Province	Aug.-Sep. 2020	√		√	√	
Liu et al., 2023	Zhuhai (PRD)	Sep. 2022	√	√	√		
Wang et al., 2024a	PRD	Sep. 2022	√		√	√	Increase in BVOC emission
Zhu et al., 2025	Hong Kong (PRD)	May 2023	√	√	√		
He et al., 2026	PRD	July 2023		√	√		
Wang et al., 2025a	PRD	Sep. 2024		√	√	√	Transport channel through interactions with South Asia High
Yang et al., 2011	Hong Kong (PRD)	1998-2008		√	√		
Ling et al., 2013	Hong Kong (PRD)	2005-2010	√		√		
Ding et al., 2023	PRD	2009-2018	√	√			
Deng et al., 2019	Panyu (PRD)	2012-2013	√	√	√		Effects of scattered aerosol on radiation
Wang et al., 2022	PRD	2013-2018	√		√		Increase in BVOC emission
Qu et al., 2021	PRD	2014-2018	√ (autumn)	√ (summer)	√	√ (autumn)	
Zhao et al., 2022	PRD	2015-2020	√				Downwards transport
Hu et al., 2023	PRD	2015-2020	√	√			

Table S1. (continued)

Reference	Region	Period	Causes of typhoon-induced O ₃ pollution				
			Enhanced photochemistry	Stagnation / O ₃ accumulation	Transport of upwind air pollutants	Transport of stratospheric O ₃	Others
Fu et al., 2022	Hainan	Sep.-Nov. 2019	√		√		
Fu et al., 2023b	Hainan	Oct. 2020	√	√	√		
Li et al., 2025	Hainan	July 2024			√		BVOC transport
Fu et al., 2023a	Hainan	2015-2020	√		√		
Jiang et al., 2015	Xiamen & Quanzhou (Fujian)	June 2014				√	
Li et al., 2023	Putian, Xiamen & Quanzhou (Fujian)	Sep. 2021	√	√			
Wang et al., 2025b	Fujian	Sep. 2022	√		√		
Yan et al., 2023	Fuzhou (Fujian)	2014-2019	√	√			High shipping emission contributions
Ge et al., 2022	Fujian	2015-2020			√		
Cheng et al., 2014	Central Taiwan	Sep. 2005	√	√	√		Leeward effects
Hung & Lo, 2015	Southwest Taiwan	Aug. 2011 Sep. 2013	√	√			Leeward effects
Lo & Hung, 2015	South Taiwan	June-July 2013		√			Leeward effects
Lo et al., 2024	South Taiwan	July & Sep. 2013, Aug.-Oct., 2023	√	√			Leeward effects
Lin et al., 2021	West Taiwan	July 2018		√	√		Leeward effects
Chauhan & Liou, 2022	Taiwan	Aug. 2020			√	√	
Chen et al., 2021	South China	2014-2018				√	
Shu et al., 2016	YRD	Aug. 2013	√	√	√		
Yan et al., 2018	Hangzhou (YRD)	July 2014		√	√		

Table S1. (continued)

Reference	Region	Period	Causes of typhoon-induced O ₃ pollution				
			Enhanced photochemistry	Stagnation / O ₃ accumulation	Transport of upwind air pollutants	Transport of stratospheric O ₃	Others
Hu et al., 2024	YRD	June 2018			√		Recirculation of O ₃ -rich air above sea
Zhan & Xie, 2022	YRD	July 2018	√	√			
Zhan et al., 2024	Suzhou (YRD)	July 2018	√	√	√		Influence of multiple thermal circulations
Zhan et al., 2020	YRD	Summer 2018	√	√	√	√	
Xu et al., 2023	YRD	July 2021	√	√	√		Increase in BVOC emission
Wan et al., 2025	Jiaxing (YRD)	Sep. 2022	√	√	√		
Wang et al., 2022	YRD	2013-2018	√		√		Increase in BVOC emission
Liu et al., 2026	Nanjing (YRD)	2014-2023	√	√	√		
Xi et al., 2025a	YRD	2018-2021	√	√	√		
Xi et al., 2025b	YRD	2018-2022	√	√			
Zheng et al., 2021	South east China (YRD & Fujian)	Aug.-Sep. 2017			√		
Du et al., 2025	Southeast China	2013-2019	√	√			
Qi et al., 2024	Southeast China	2014-2019	√ (YRD)		√ (PRD)		Co-effects from heatwaves
Ouyang et al., 2025	Southeast China	2014-2024	√		√		Increase in BVOC emission
Shan et al., 2009	Jinan (NCP)	June 2003	√		√		
Yin et al., 2009	Jinan (NCP)	June 2005	√		√		
Meng et al., 2022	NCP	July 2018	√			√	
Chen et al., 2022	NCP	July 2021				√	
Xu et al., 2024	NCP	Sep. 2021		√			

Table S1. (continued)

Reference	Region	Period	Causes of typhoon-induced O ₃ pollution				
			Enhanced photochemistry	Stagnation / O ₃ accumulation	Transport of upwind air pollutants	Transport of stratospheric O ₃	Others
Wang et al., 2024b	East China (NCP/YRD)	Aug.-Sep. 2020	√	√	√		
Shao et al., 2022	China	2014-2020	√	√	√		Interactions with other weather systems, more fuel evaporation
Shin & Song, 2017	Korea	Aug.-Sep. 2011		√	√		
Itahashi, 2023	Japan	Sep. 2020			√		

Table S2. Information on O₃ pollution days during the simulation periods. “Distance” refers to distance between the typhoon center and the Pearl River Delta region.

Date	Number of days	Classification	Weather systems
October 14-16, 2015	3	Autumn, typhoon-induced	Typhoons Koppu & Champi
October 21, 2015	1	Autumn, typhoon-induced	Typhoon Champi
October 28, 2015	1	Autumn, no-typhoon	Subtropical high
November 3-5, 2015	3	Autumn, no-typhoon	Transformed high pressure
October 17-19, 2015	3	Not included in comparisons (distance < 20%)	Typhoons Koppu & Champi
October 13, 2015	1	Not included in comparisons (distance > 80%)	Typhoons Koppu & Champi
October 22-25, 2015	4	Not included in comparisons (distance > 80%)	Typhoon Champi
July 7-8, 2016	2	Summer, typhoon-induced	Typhoon Nepartak
July 30-31, 2016	2	Summer, typhoon-induced	Typhoon Nida
July 22-26, 2016	5	Summer, no-typhoon	Subtropical high
July 29, 2016	1	Summer, no-typhoon	Subtropical high
July 9, 2016	1	Not included in comparisons (distance < 20%)	Typhoon Nepartak

Table S3. Setup of WRF simulations

Physics option / Data	Selection
Microphysics	Lin et al. scheme
Longwave radiation	CCTM scheme
Shortwave radiation	Dudhia scheme
Land surface	Noah Land Surface Model
Planetary boundary layer	ACM2 PBL
Cumulus Parameterization	Kain-Fritsch scheme
Initial conditions	NCEP FNL reanalysis (1°×1°)
Assimilation data source	NCEP ADP Global Upper Air (DS 351.0) and Surface (DS 461.0) Observational Weather Data

Table S4. List of SAPRC07 species corresponding to different hydrocarbon (HC) and oxidized volatile organic compound (OVOC) groups.

Groups	Subcategories	SAPRC07 species
HCs	Biogenic VOCs	Isoprene Other BVOCs
		ISOPRENE APIN, TERP, SESQ
	Alkanes	Methane Other alkanes
		CH4 ALK1, ALK2, ALK3, ALK4, ALK5
	Alkenes	Small alkenes (C=2-4) Large alkenes (C>4)
		ETHENE, PROPENE, BUTADIENE13 OLE1, OLE2
	Aromatics	BTX & trimethylbenzenes Other aromatics
		BENZENE, TOLUENE, MXYL, OXYL, PXYL, TRIMETH_BENZ124 ARO1, ARO2
	OVOCs	Formaldehyde
		HCHO
		Acetaldehyde
		CCHO
		Glyoxal & methylglyoxal
		GLY, MGLY
		Ketones and large aldehydes (C>3)
		RCHO, PRD2, MEK, BALD, ACETONE, MACR, ACROLEIN, MVK, HOCCHO
		Alcohols & phenols
		MEOH, ETOH, CRES, NPHE
		Carboxylic acids
		HCOOH, CCOOH, RCOOH
		Organic hydroperoxides
		COOH, ROOH, R6OOH, RAOOH, CCOOOH, RCOOOH
		Isoprene products
		AFG1, AFG2, AFG3, RNO3, IPRD

Table S5. Comparisons between simulated daytime chemical indicators of O₃ production (P(O₃), L_{OH}, OPE) in this study with previous publications for the PRD. CTM, chemical transport model; OBM, observation-based model.

Indicator	Season	Method	Region / Site	Period	Values	References
P(O ₃)	Autumn	CTM	Central PRD	Oct. 2015	5-15 ppb h ⁻¹	This study
		OBM	Tai Mo Shan, Hong Kong	Sep.-Nov. 2010	daily mean = 2.9 ppb h ⁻¹ peak = 8-10 ppb h ⁻¹	Ling et al., 2014
		OBM	Tsuen Wan, Hong Kong	Sep.-Nov. 2010	daily mean = 8.1 ppb h ⁻¹ peak = 18-22 ppb h ⁻¹	Ling et al., 2014
		OBM	Heshan, Jiangmen	Oct.-Nov. 2014	14 ppb h ⁻¹	Tan et al., 2018
		CTM	GDEMC, Guangzhou	Oct. 2004	12 ppb h ⁻¹	Wang et al., 2010
		CTM	Xinken, Guangzhou	Oct. 2004	9 ppb h ⁻¹	Wang et al., 2010
		CTM	Donghu, Jiangmen	Oct. 2004	14 ppb h ⁻¹	Wang et al., 2010
	Summer	CTM	Central PRD	July 2016	10-25 ppb h ⁻¹	This study
		OBM	Guangzhou	July 2006	39 ppb h ⁻¹ at noon	Lu et al., 2010
		OBM	Backgarden	July 2006	26 ppb h ⁻¹ at noon	Lu et al., 2010
L _{OH}	Autumn	CTM	Central PRD	Oct. 2015	4-6	This study
		OBM	Tai Mo Shan, Hong Kong	Sep.-Nov. 2010	4-65	Ling et al., 2014
		OBM	Tsuen Wan, Hong Kong	Sep.-Nov. 2010	2-25	Ling et al., 2014
		CTM	Guangzhou	Oct. 2008	1.5-2	Liu et al., 2010
	Summer	CTM	Central PRD	July 2016	2-4	This study
		OBM	Guangzhou	July 2006	2.7	Lu et al., 2010
		OBM	Backgarden	July 2006	2.9	Lu et al., 2010
		CTM	Guangzhou	July 2008	2.5-3	Liu et al., 2010
OPE	Autumn	CTM	PRD (regional mean)	Oct. 2015	7.0	This study
		CTM	GDEMC, Guangzhou	Oct. 2004	2.9-4.0	Wang et al., 2010
		CTM	Xinken, Guangzhou	Oct. 2004	4.2-5.9	Wang et al., 2010
		CTM	Donghu, Jiangmen	Oct. 2004	3.3-7.3	Wang et al., 2010
	Summer	CTM	PRD (regional mean)	July 2016	9.4	This study
		OBM	Guangzhou	July 2006	2.1	Lu et al., 2010
		OBM	Backgarden	July 2006	7.8	Lu et al., 2010

Table S6. Summary of main findings from this study.

Contents	General characteristics	Typhoon influences in autumn	Typhoon influences in summer
Transport pathways	Vertical exchange > horizontal transport	Vertical exchange and horizontal transport ↑ (upwind and background O ₃ transport ↑)	Vertical exchange and horizontal transport ↑ (upwind O ₃ transport ↑)
Precursor transport	~30% of direct O ₃ transport contributions; APNs dominate in autumn; NO _x dominate in summer	Contribution ↑; NO _x and APNs transport ↑; HCs and OVOCs transport ↓	Contribution ↑; NO _x and APN transport ↑ (wind reversal)
O ₃ production rate	Higher P(O ₃) in central PRD and in summer	P(O ₃) ↑ (cloud ↓; solar radiation ↑)	P(O ₃) ↓ (cloud ↑; solar radiation ↓)
O ₃ production efficiency	Higher L _{OH} in central PRD and in autumn; higher OPE in surrounding areas	L _{OH} ↓; OPE ↑ (aged air masses)	L _{OH} ↓; OPE ↑ (aged air masses)
OH reactivity	OVOCs dominate VOC contributions to k _{OH}	Minor changes; BVOC contributions in upwind areas ↑ (BVOC emissions ↑)	Spatial redistribution (wind reversal)
O ₃ sensitivity	VOC-limited in urban areas and NO _x -limited in surrounding areas; more NO _x -limited aloft and in summer	More NO _x -limited (enhanced precursor mixing)	More NO _x -limited (wind reversal; redistributed precursor transport)