



A dataset of ground-based VCDs (O_3 , NO_2 , HCHO , HONO , SO_2) and AOD observations from the hyperspectral vertical remote sensing network in China (2020–2025)

Yikai Li¹, Chengzhi Xing^{1,*}, Peiyuan Jiao², Cheng Liu^{2,3,4,*}

¹ Key Lab of Environmental Optics & Technology, Anhui Institute of Optics and Fine Mechanics, Hefei Institutes of Physical Science, Chinese Academy of Sciences, Hefei, 230031, China

² Department of Precision Machinery and Precision Instrumentation, University of Science and Technology of China, Hefei, 230026, China

³ State Key Laboratory of Advanced Environmental Technology, Guangzhou 510640, China.

⁴ Anhui Key Laboratory of Polar Environment and Emerging Pollutants, School of Earth and Space Sciences. University of Science and Technology of China, Hefei 230026, China

*Corresponding to: Chengzhi Xing (xingcz@aiofm.ac.cn), Cheng Liu (chliu81@ustc.edu.cn).

Abstract. With the rapid development of satellite observations of atmospheric composition and aerosols, long-term, independent, and standardized ground-based column measurements have become increasingly important for satellite product validation, retrieval error diagnosis, and multi-source data fusion. However, long-term ground-based column datasets covering multiple atmospheric constituents and processed using a unified framework remain limited in China. This study presents a ground-based dataset of multi-component vertical column densities (VCDs) and aerosol optical depth (AOD) from the Chinese Hyperspectral Vertical Remote Sensing Network for 2020–2025. The dataset includes VCDs of O_3 , NO_2 , HCHO , HONO , and SO_2 , together with AOD. It is based on observations from 53 MAX-DOAS sites across China, covering approximately 22.5–44.1° N and 80.1–122.7° E. The sites represent urban agglomerations, suburban transition zones, industrial areas, coastal and island environments, inland basins, arid and semi-arid regions, and the Tibetan Plateau. All observations were processed using a unified retrieval and quality-control framework to ensure consistency among sites and species. AOD has the broadest coverage, with 53 valid sites and 1073 valid site-months. NO_2 and HCHO each cover 52 sites and more than 1000 valid site-months. SO_2 and HONO cover 45 and 44 sites, respectively. O_3 covers 29 sites and 588 valid site-months. For valid months, the median monthly completeness is 83.9% for O_3 , NO_2 , HCHO , and SO_2 , and 86.7% for HONO and AOD. Comparisons with independent observations show correlation coefficients of 0.899, 0.734, and 0.551 for MAX-DOAS NO_2 , HCHO , and O_3 VCDs against satellite products, respectively. The correlation between AOD and AERONET is 0.879. Correlations of NO_2 , SO_2 , and O_3 VCDs with CNEMC surface observations are 0.720, 0.624, and 0.678, respectively. This dataset provides a long-term, independent, and standardized ground-based reference for validating satellite VCD and AOD products, diagnosing retrieval biases, supporting satellite–AI integration and bias correction, and evaluating chemical transport models. The dataset is freely available at Zenodo (<https://doi.org/10.5281/zenodo.22691855>, Xing et al., 2026).



1 Introduction

China has experienced rapid urbanization and continued industrial restructuring. Air pollution control has also become more stringent. Accordingly, air-quality management has gradually shifted from single-pollutant reduction toward coordinated control of multiple pollutants and more refined management (He et al., 2024; Shao et al., 2025; Zhang et al., 2026a). O₃, aerosols, NO₂, HCHO, HONO, and SO₂ are key atmospheric components that affect air quality, human health, and atmospheric oxidation capacity. Surface O₃ is a strong oxidant. It can damage the respiratory system, reduce crop yields, and affect regional climate. It is mainly produced through sunlight-driven photochemical reactions involving NO_x and VOCs and is removed through dry deposition and chemical reactions (Li et al., 2025a, 2024; Ma et al., 2025). Aerosols reduce visibility and affect cardiopulmonary health. They also influence climate and photochemistry by scattering and absorbing solar radiation. Their sources include primary particle emissions and secondary formation from precursors such as SO₂, NO_x, and VOCs. Removal occurs mainly through wet deposition, dry deposition, and atmospheric transport (Jiao et al., 2025; Song et al., 2023; Zhu et al., 2025). NO₂ is a respiratory irritant and an important precursor of O₃ and nitrate aerosol. Its major sources include traffic, industrial combustion, and power generation. It is removed through photolysis, oxidation, and deposition (Lin et al., 2023; Xing et al., 2026; Zou et al., 2025). HCHO is harmful to human health and is an important intermediate in VOC oxidation. It is emitted directly and is also produced from the oxidation of anthropogenic and biogenic VOCs. It is further removed by photolysis and oxidation (Mo et al., 2023; Wu et al., 2023; Yuping Chen et al., 2023). HONO usually occurs at low concentrations, but its photolysis can rapidly produce OH radicals in the early morning. It therefore affects atmospheric oxidation capacity and secondary pollution formation. HONO originates from direct emissions and heterogeneous conversion of NO_x on ground and aerosol surfaces. Photolysis is its major daytime sink (Li et al., 2025b; Xing et al., 2023, 2024). SO₂ can irritate the respiratory system and contribute to acid deposition. It can also be oxidized to form sulfate aerosol. Major sources include coal combustion, industrial processes, and ship emissions. Its main removal pathways are oxidation, wet deposition, and dry deposition (Li et al., 2026; Peng et al., 2026; Xing et al., 2025). The emissions, transformation, and removal of these components are closely coupled. Together, they shape regional air pollution and its evolution.

Satellite instruments such as OMI, TROPOMI, GEMS, and MODIS provide VCD products for several trace gases and AOD products. These observations are widely used for emission detection, pollution transport analysis, and air-quality assessment (Ji et al., 2026; Whitburn et al., 2026; Zhang et al., 2026b). China has strong emissions, diverse pollution types, and pronounced contrasts in topography and climate. Satellite observations therefore provide important and systematic spatial information for regional atmospheric studies and environmental management.

However, satellite retrievals are affected by cloud screening, surface albedo, aerosols, air mass factors, a priori profiles, pixel representativeness, and overpass time (Bae et al., 2025; Li et al., 2023b; Ryan et al., 2020). These uncertainties can be larger in complex environments such as coastal regions, basins, mountains, and plateaus. Regional biases may therefore occur. Long-term, independent, and standardized ground-based observations are needed to validate and constrain satellite products. Several ground-based remote-sensing networks are available internationally, including PGN,



NDACC/FRM4DOAS, and the Asian MAX-DOAS network. However, their publicly available coverage in China remains limited, with sites mainly in Beijing and Hefei (De Mazière et al., 2018; Kanaya et al., 2014; Zhang et al., 2025). These sites cannot fully represent the diverse urban agglomerations, coastal regions, basins, arid and semi-arid areas, and plateau environments across China. The national air-quality monitoring network operated by the China National Environmental Monitoring Center (CNEMC) provides extensive near-surface in situ measurements. These observations represent surface pollution well, but they differ from satellite VCD and AOD products in sampling volume, vertical representativeness, and measured quantity (Kong et al., 2021). Ground-based hyperspectral VCD and AOD observations are more directly comparable with satellite products because both represent atmospheric column-integrated quantities (Peng et al., 2024). A long-term, multi-component, and quality-controlled ground-based VCD and AOD network across representative regions of China is therefore valuable. It can support satellite validation, diagnose retrieval errors, improve retrieval algorithms, and broaden the use of satellite products.

Ground-based VCD and AOD datasets can also support the integration of satellite remote sensing and artificial intelligence. Machine-learning and deep-learning methods have been widely used for filling satellite data gaps, correcting satellite biases, estimating surface pollution, and predicting air quality (Li et al., 2023a; Wei et al., 2021, 2023). The performance of these models depends strongly on high-quality, long-term, and independent training and validation data. Ground-based VCD and AOD observations are closer to satellite observations in both physical quantity and sampling scale than conventional surface measurements. They can therefore provide more direct constraints for satellite–AI retrieval, data fusion, and prediction. They are also suitable for supervised learning, bias correction, and evaluation of model generalization.

In this study, we develop and release a ground-based dataset of O₃, NO₂, HCHO, HONO, and SO₂ VCDs and AOD from the Chinese Hyperspectral Vertical Remote Sensing Network for 2020–2025. The dataset includes 53 sites across China. These sites cover major urban agglomerations, coastal regions, inland basins, arid and semi-arid regions, and the Tibetan Plateau. A unified processing and quality-control framework is applied to all sites. The main objectives are to (1) provide long-term and spatially extensive multi-component column observations for characterizing atmospheric variability across representative regions of China; (2) provide an independent ground-based reference with physically comparable quantities for validating multi-source satellite VCD and AOD products and diagnosing retrieval errors; (3) provide standardized training and validation data for satellite–AI retrieval, bias correction, data fusion, and air-quality prediction; and (4) provide observational constraints for studies of regional atmospheric oxidation, pollution evolution, and related climate effects.

2 Experimental setup

2.1 Description of the monitoring sites

The Chinese Hyperspectral Vertical Remote Sensing Network covers approximately 22.5–44.1° N and 80.1–122.7° E. It extends across North, East, South, Southwest, Northwest, Northeast, and Central China. The sites include densely populated



urban agglomerations, suburban transition zones, industrial areas, coastal and island environments, inland basins, mountain–
 plain transition zones, arid and semi-arid regions, and high-altitude areas of the Tibetan Plateau. This broad coverage captures
 atmospheric column characteristics under diverse geographic, climatic, and emission conditions. Geographic coordinates and
 altitudes of all sites are listed in Table 1.

Sites in North China are mainly distributed across Beijing, Hebei, Shanxi, and Inner Mongolia. They include CAMS, CAMS2,
 NC, UCAS, IAP, WD, XH, SJZ_LC, DZ, IMNU, and SXU. CAMS and CAMS2 were co-located but operated as independent
 instruments/data records. Sites in and around Beijing represent the core of the Beijing–Tianjin–Hebei urban agglomeration
 and include megacity and suburban environments. SJZ_LC, SXU, and IMNU extend the network to the Taihang Mountains
 and the Inner Mongolia Plateau. These sites provide observations across contrasting mountainous and plain environments. East
 China has the densest site coverage. Sites include SH_XH, SH_BS, SAES, NUIST, AHU, HFU, HF_HD, AMB, SI, FX, CF,
 HNU, QD_SU, TS, TA, NB, LA, DY, HZ, 3CLEAR, ZJ_JH, and HNI. They cover the Yangtze River Delta, the East China
 coast, the Shandong hills, inland mountains, and offshore islands. This region is highly urbanized and has strong industrial and
 traffic emissions. Land–sea interactions are also important. South China sites are mainly located in the Pearl River Delta and
 along the Fujian coast. They include SUST, GIG, GZ_LK, GZ_PZ, GZ_TM, GZ_LW, GZ_PY, and XM. These sites represent
 subtropical environments with high temperature, high humidity, strong solar radiation, and pronounced monsoon influence.
 Southwest China includes CQ, CD, YN, LS, and AL. These sites represent the Sichuan Basin, the southeastern margin of the
 Tibetan Plateau, and high-altitude plateau environments. LS and AL provide particularly valuable observations for assessing
 satellite performance under high-albedo, high-altitude, and low-pollution conditions. Northwest China includes LZ, XA,
 XJ_HJZ, and XJ_GQB. They cover Lanzhou, Xi'an, the northern slope of the Tianshan Mountains, and the southern margin
 of the Junggar Basin. These sites represent arid and semi-arid conditions and are influenced by dust transport. JHI represents
 Northeast China and is located near Liaodong Bay and the Bohai coast. It is influenced by industry, port activities, and land–
 sea interactions. Central China is represented by LY and HN. These sites are located in the central plains and the transition
 zone between Central and North China and provide observations of pollution accumulation and regional transport.

Table 1. Geographic information of the stations in the Chinese Hyperspectral Ground Based Vertical Remote Sensing Network.

No.	Region	Site	Longitude	Latitude	Altitude
1	North China	Chinese Academy of Meteorological Sciences (CAMS)	116.3206	39.9472	100
2		Chinese Academy of Meteorological Sciences (CAMS2)	116.3206	39.9472	100
3		Nancheng (NC)	116.127	39.781	60
4		University of Chinese Academy of Sciences (UCAS)	116.675	40.408	120
5		The Institute of Atmospheric Physics (IAP)	116.3761	39.975	40
6		Wangdu (WD)	115.15	38.17	35
7		Xianghe (XH)	116.976	39.761	10
8		Shijiazhuang_Luancheng (SJZ_LC)	114.6097	37.9072	70
9		Dezhou (DZ)	116.3717	37.4322	23
10		Shanxi University (SXU)	112.5805	37.6319	780
11		Inner Mongolia Normal University (IMNU)	111.6869	40.801	138
12	East China	Shanghai_Xuhui (SH_XH)	121.4333	31.1705	3



13		Shanghai_Baoshan (SH_BS)	121.445	31.39	10
14		Shanghai Academy of Environmental Sciences (SAES)	121.2532	31.1018	3
15		Nanjing University of Information Science and Technology (NUIST)	118.7167	32.2075	73
16		Anhui University (AHU)	117.1808	31.775	30
17		Hefei University (HFU)	117.2142	31.7497	30
18		Hefei_Hengda (HF_HD)	117.295	31.8758	30
19		Anhui Meteorological Bureau (AMB)	117.2469	31.8632	40
20		Science Island (SI)	117.1708	31.9056	24
21		Feixi (FX)	117.08	31.69	40
22		Changfeng (CF)	117.182	32.21	30
23		Huaibei Normal University (HNU)	116.806	33.983	35
24		Qingdao_Shandong University (QD_SU)	120.67	36.348	10
25		Taishan (TS)	117.1056	36.255	1500
26		Tai'an (TA)	117.0608	36.2028	170
27		Dongying (DY)	118.98	37.76	3
28		Ningbo (NB)	121.895	29.7513	10
29		Lin'an (LA)	119.7516	30.2972	140
30		Hangzhou (HZ)	120.169	30.225	24
31		Zhejiang_Jinhua (ZJ_JH)	119.51	28.58	849
32		Huaniao Island (HNI)	122.6728	30.8611	60
33		Zhongke Sanqing Technology Co., Ltd. (3CLEAR)	120.251	31.995	23
34		Southern University of Science and Technology (SUST)	113.9964	22.6094	40
35		Guangzhou Institute of Geochemistry (GIG)	113.3586	23.15	30
36		Guangzhou_Liangkou (GZ_LK)	113.58	23.54	205
37	South China	Guangzhou_Puzhou (GZ_PZ)	113.6	22.75	15
38		Guangzhou_Timian (GZ_TM)	113.29	23.55	164
39		Guangzhou_Liwan (GZ_LW)	113.259	23.132	15
40		Guangzhou_Panyu (GZ_PY)	113.392	23.047	33
41		Xiamen_Institute of Urban Environment (XM)	118.0583	24.6111	0
42		Chongqing (CQ)	106.5061	29.6036	332
43	Southwest China	Chengdu (CD)	104.04	30.66	505
44		Yunnan (YN)	99.7256	28.0078	3700
45		Lhasa (LS)	91.18	29.65	3663
46		Ali (AL)	80.12	32.5	4287
47		Lanzhou University (LZ)	103.8536	36.0419	1600
48	Northwest China	Xi'an (XA)	108.9889	34.2542	425
49		Xinjiang_Huanjingzhan (XJ_HJZ)	87.5605	43.9307	604
50		Xinjiang_Ganquanbao (XJ_GQB)	87.4318	44.1028	484
51	Northeast China	Juehua Island (JHI)	120.7764	40.475	18
52	Central China	Luoyang (LY)	112.4597	34.673	100
53		Henan (HN)	111.669	33.64	1239



2.2 MAX-DOAS measurements

The MAX-DOAS instruments at the 53 sites operated during different periods from 2020 to 2025. Each instrument consisted of two AvaSpec-ULS2048L-USB2 spectrometers, a telescope, and two stepper motors. The spectrometers covered 296–408 nm in the ultraviolet and 420–565 nm in the visible range. The telescope had an angular precision better than 0.1° and a field of view below 0.3° . The stepper motors controlled the elevation and azimuth angles. The elevation sequence was 1° , 2° , 3° , 4° , 5° , 6° , 8° , 10° , 15° , 30° , and 90° . One full scan required approximately 12 min, depending slightly on scattered sunlight intensity. Dark current and electronic offsets were recorded at night and corrected during spectral analysis. Measurements with solar zenith angles (SZAs) greater than 75° were excluded to reduce stratospheric interference.

Differential slant column densities (dSCDs) of O_4 , NO_2 , HCHO , HONO , O_3 , and SO_2 were retrieved using QDOAS developed by BIRA-IASB. The retrieval settings are listed in Table S1. Spectra measured at 90° elevation were used as reference spectra. Differential absorption between each low-elevation spectrum and the reference spectrum was used to derive dSCDs. Representative DOAS fits for the six components are shown in Figure S1. Strict quality control was applied. Retrievals with root-mean-square fitting residuals greater than 5×10^{-4} were excluded. Cloud contamination was identified using the color index (CI). A fifth-order polynomial was fitted to the CI, and measurements with CI values more than 10% below the fitted value were removed.

The retrieved dSCDs were converted to VCDs using air mass factors (AMFs). The AMF depends on atmospheric radiative transfer and is affected by trace-gas concentrations, pressure, temperature, aerosol and cloud vertical distributions, and surface albedo. Aerosol vertical profiles and AOD at 361 nm were first retrieved from O_4 dSCDs using the optimal estimation method (OEM), with VLIDORT as the forward radiative-transfer model. These aerosol products were then used as a priori inputs for the AMF calculation. SCIATRAN was used to simulate the AMFs. The resulting AMFs were finally used to convert the trace-gas dSCDs to VCDs.

2.3 Ancillary Data

To evaluate the accuracy of the MAX-DOAS dataset, we compared it with several widely used independent datasets. These include TROPOMI satellite products, CNEMC surface observations, and AERONET ground-based remote-sensing products. Official TROPOMI products were used. The nearest satellite pixel with latitude and longitude differences below 0.025° from each ground site was selected. Pixels with $\text{cloud_fraction} \geq 0.3$ or $\text{qa_value} \leq 0.75$ were excluded. For CNEMC, the nearest station within 5 km of each hyperspectral site was selected. AERONET has fewer collocated sites and observations. The spatial matching threshold was therefore extended to 10 km. The selected CNEMC and AERONET sites are listed in Tables S2 and S3.



3 Ground-based column observations of atmospheric composition and aerosols

The dataset contains ground-based VCDs of O₃, NO₂, HONO, HCHO, and SO₂, together with AOD, for 2020–2025. Figure 1 summarizes monthly data completeness at each site. The color indicates the percentage of valid observations relative to the theoretically available observations in each month. A completeness of 100% indicates nearly continuous valid observations during the available daytime measurement period. The observation periods differ among sites because the sites were established at different times and because retrieval availability varies among species.

AOD has the broadest coverage, with 53 valid sites and 1073 valid site-months. A site-month was defined as valid when monthly data completeness exceeded 10%. NO₂ and HCHO each have 52 valid sites and more than 1000 valid site-months. SO₂ and HONO are available at 45 and 44 sites, respectively. O₃ has the smallest spatial coverage, with 29 valid sites and 588 valid site-months. For valid months, mean monthly completeness is 72.7% for O₃ and 75.1% for HONO, and 73%–74% for the other components. Median monthly completeness is 83.9% for O₃, NO₂, HCHO, and SO₂, and 86.7% for HONO and AOD. Most valid months therefore contain a high fraction of usable observations.





165

Figure 1: Monthly data integrity of O₃, aerosol, NO₂, HCHO, HONO, and SO₂ observations at each site during 2020–2025.

Figure 2 summarizes the relative retrieval errors of each component across the network. Clear differences are found among components. O₃ and aerosol retrievals are relatively stable. Mean relative errors of O₃ at individual sites are mainly 2%–9%, with a network mean of approximately 4.6%. Aerosol retrievals also show relatively low errors. The mean relative error is approximately 6.8%, and most sites are below 10%. This indicates good stability of the O₄-based aerosol retrieval. NO₂ and HCHO show moderate relative errors. The mean relative error of NO₂ is approximately 10.7%, although values exceed 20% at some high-altitude or short-term sites. The mean relative error of HCHO is approximately 11.6%, with most sites between 7% and 15%. These uncertainties are suitable for long-term statistical analysis. HONO and SO₂ have larger relative errors. Their network means are approximately 25.1% and 26.1%, respectively. HONO concentrations are generally low and its spectral absorption is weak. The retrieval is therefore more sensitive to noise, spectral fitting, and observing conditions. SO₂ is strongly affected by local and intermittent emissions. Its signal-to-noise ratio can be low under clean conditions or far from emission sources, which increases the relative retrieval error.

175

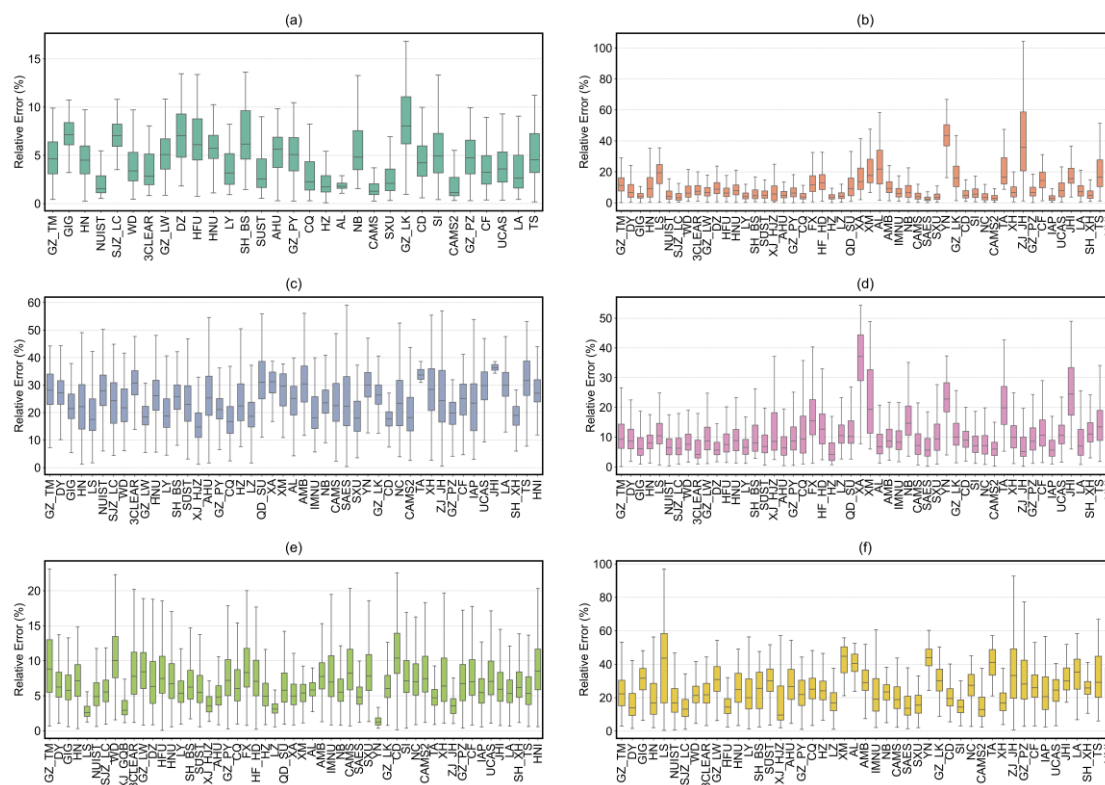


Figure 2. Distribution of relative retrieval errors for VCDs (O₃, NO₂, HCHO, HONO, SO₂) and AOD at each site. The box plots show the median, interquartile range, and spread among sites.

180



3.1 AOD

Figure 3 shows the mean diurnal variations in AOD across different stations from 2020 to 2025. The seasonal diurnal variations are shown in Fig. S2. Overall, AOD increases during the morning and decreases in the afternoon. The network mean rises from 0.78 at 08:00 local time to approximately 1.09 at 12:00–13:00. It then decreases to 0.75 at 17:00. The midday value is nearly 40% higher than the morning value.

AOD levels and diurnal amplitudes differ substantially among regions. Several sites in Northwest China and on the Tibetan Plateau show high AOD. Mean AOD values at XJ_GQB and XJ_HJZ are 2.53 and 1.67, with peaks of 4.12 and 2.52, respectively. Both sites are located near the northern slope of the Tianshan Mountains and the southern margin of the Junggar Basin. Arid and semi-arid conditions, exposed surfaces, dust activity, and mountain-front circulation may contribute to the high aerosol loading (Xia et al., 2008). The mean AOD at LS is 2.05 and reaches 3.35 at 14:00. Its observation period is relatively short and is concentrated mainly in summer. The high values may therefore reflect local summer dust, strong convective boundary-layer development, or short-term transport over the plateau. In contrast, the mean AOD at AL is only 0.08, indicating low aerosol loading at this high-altitude background site (Pokharel et al., 2019). Large differences are also found among North China sites. DZ has a mean AOD of 1.47. It reaches 2.38 at 10:00 and decreases to 0.63 at 17:00. This large diurnal range may reflect the combined effects of aerosol formation and removal, hygroscopic growth, horizontal transport, and boundary-layer evolution. Mean AOD values at CAMS and WD are 0.59 and 0.62, with peaks of 0.67 and 0.68 around 13:00. IMNU has a lower mean AOD of 0.31. AOD in South China is generally moderate. Most sites show an increase from morning to midday followed by an afternoon decrease. Mean AOD values at GIG, GZ_LW, GZ_PZ, and GZ_TM are 0.81, 0.87, 0.76, and 0.74, respectively. GIG reaches 1.04 at 11:00, GZ_LW reaches 1.02 at 13:00, and GZ_PZ reaches 0.94 at 10:00. The Pearl River Delta is characterized by high temperature and humidity, strong solar radiation, and active urban, industrial, traffic, and biogenic emissions. These conditions favor secondary aerosol formation and hygroscopic growth. High humidity can further enhance aerosol extinction (Kong et al., 2020). Several sites in East China also show high AOD and pronounced diurnal variation. Mean AOD values at HZ, AHU, NUIST, and HF_HD are 1.16, 1.06, 1.02, and 1.05, with peaks of 1.49, 1.33, 1.35, and 1.62, respectively. These sites are located in and around the Yangtze River Delta, where population density and industrial and traffic emissions are high. Abundant aerosol precursors and enhanced daytime photochemistry can increase AOD (Yu et al., 2019). Among coastal and island sites, HNI has a mean AOD of 0.50. This value is lower than those at most inland urban sites, likely because local anthropogenic emissions are weaker over the island environment (Wang et al., 2016).

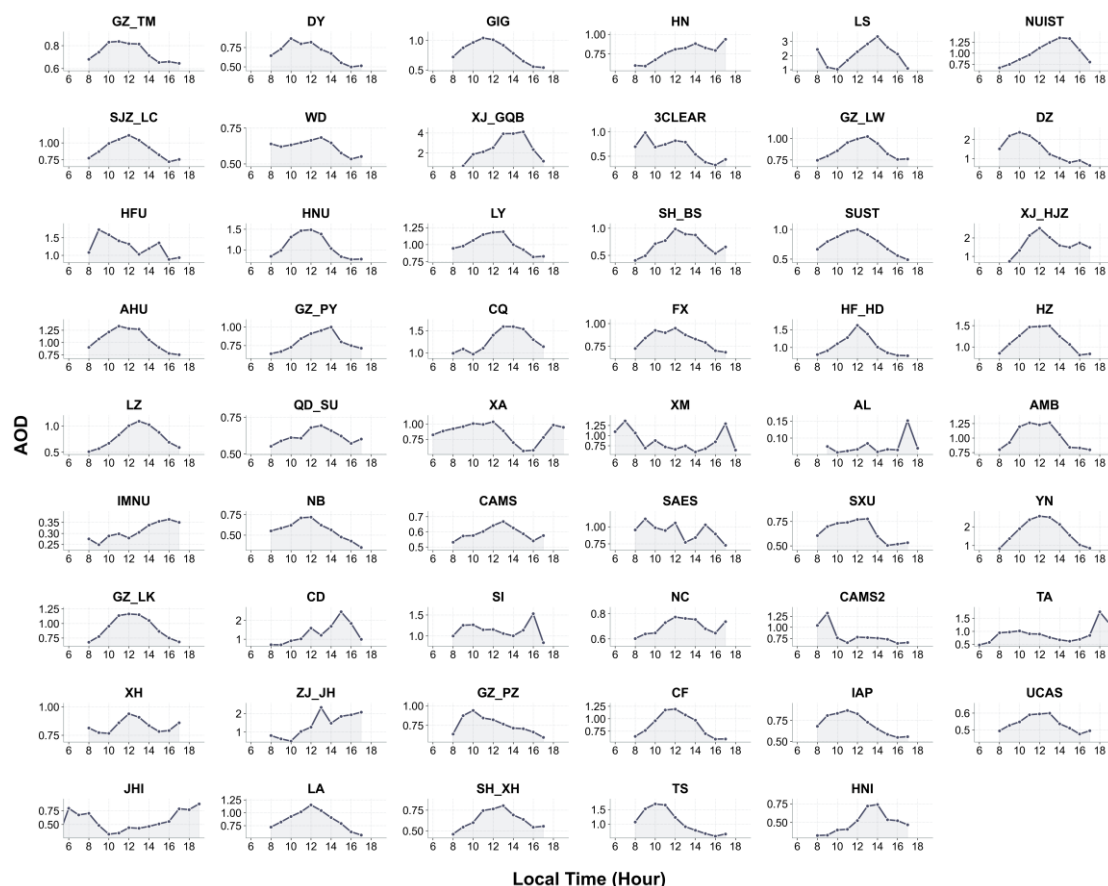


Figure 3: Mean diurnal variations of AOD at each site during 2020–2025.

3.2 O₃ VCD

O₃ is a typical secondary pollutant formed through nonlinear photochemical reactions of NO_x and VOCs under solar radiation. It is also an important indicator of atmospheric oxidation capacity and photochemical pollution. Figure 4 shows the mean diurnal variation of O₃ VCD at each site during 2020–2025. The seasonal diurnal variations are shown in Fig. S3. Overall, O₃ VCD shows clear daytime accumulation. The network mean is 0.64×10^{18} molecules cm⁻² at 08:00 and decreases to 0.59×10^{18} molecules cm⁻² at 10:00. It then increases steadily and reaches 1.50×10^{18} molecules cm⁻² at 17:00. The afternoon maximum is more than 150% higher than the late-morning minimum.

Sites in the Pearl River Delta show a consistent afternoon enhancement of O₃. Mean O₃ VCDs at GIG, GZ_TM, GZ_PZ, and GZ_PY are 0.72 , 0.77 , 0.64 , and 0.62×10^{18} molecules cm⁻², respectively. At GIG, O₃ VCD increases from 0.56×10^{18} molecules cm⁻² at 08:00 to 0.88×10^{18} molecules cm⁻² at 16:00. GZ_TM reaches 1.57×10^{18} molecules cm⁻² at 16:00. The Pearl River Delta is a subtropical urban agglomeration with high temperature and humidity, strong solar radiation, and active VOC emissions. These conditions favor photochemical reactions. The afternoon increase in O₃ VCD therefore mainly reflects regional photochemical production and accumulation of O₃ (Jiang et al., 2010). Several sites in East and Central China also



show strong afternoon increases in O₃ VCD. Mean O₃ VCDs at SI and TS are 1.61×10^{18} and 1.56×10^{18} molecules cm⁻², respectively. Their 17:00 peaks reach 4.78×10^{18} and 4.27×10^{18} molecules cm⁻². SI is influenced by the Yangtze River Delta urban agglomeration and is affected by regional photochemical production and transport (Li et al., 2012). TS is located at high altitude on Mount Tai. Local emissions are relatively weak, but the site is more sensitive to regional transport, mountain circulation, and residual-layer O₃. The valid observation period at TS is relatively limited. Its high values may therefore partly reflect specific seasons or high-O₃ episodes. The mean O₃ VCD at HN is 1.11×10^{18} molecules cm⁻² and reaches 2.95×10^{18} molecules cm⁻² at 17:00. This may reflect strong regional photochemical production and transport in the transition zone between Central and North China (Su et al., 2023). The diurnal variation of O₃ VCD is more complex in North China. CAMS has a mean O₃ VCD of 0.91×10^{18} molecules cm⁻². It reaches 1.33×10^{18} molecules cm⁻² at 09:00 and then decreases around noon. WD has a mean value of 0.76×10^{18} molecules cm⁻² and reaches 0.98×10^{18} molecules cm⁻² at 16:00. Morning O₃ at urban and suburban North China sites can be suppressed by NO titration (Li et al., 2021). As solar radiation increases, NO₂ photolysis and VOC oxidation accelerate, and O₃ is produced and accumulated. Boundary-layer growth can also mix O₃-rich residual-layer air downward and further increase the column amount (Zhu et al., 2020).

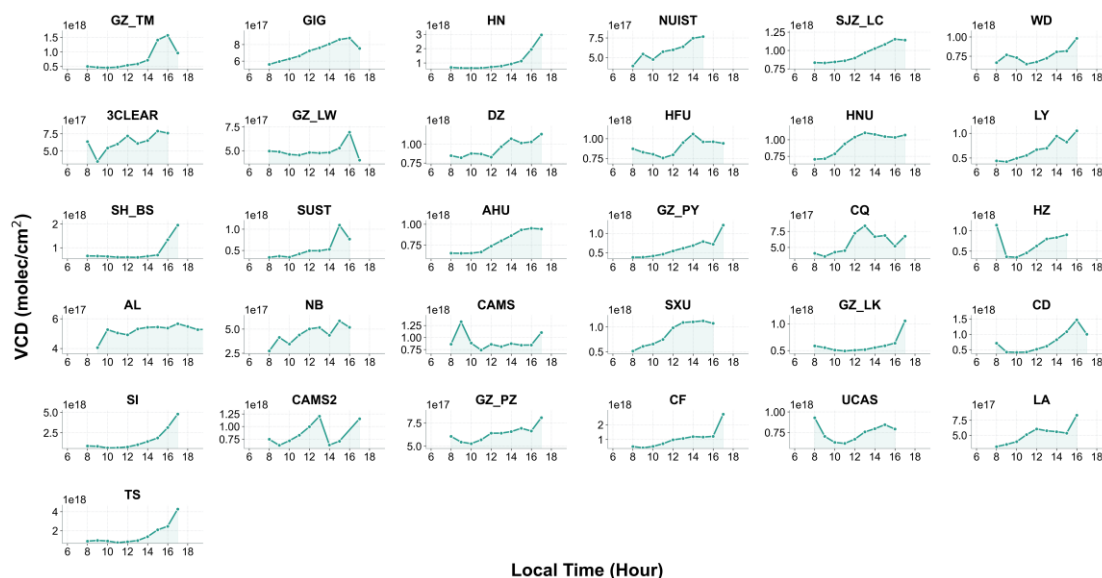


Figure 4: Mean diurnal variations of O₃ VCD at each site during 2020–2025.

3.3 NO₂ VCD

NO₂ is an important indicator of NO_x emissions. Figure 5 shows the mean diurnal variation of NO₂ VCD at each site during 2020–2025. The seasonal diurnal variations are shown in Fig. S4. Overall, NO₂ VCD shows a diurnal pattern opposite to that of O₃ VCD. The network mean is 1.25×10^{16} molecules cm⁻² at 08:00 and increases slightly to 1.30×10^{16} molecules cm⁻² at 09:00. It then decreases to 1.05×10^{16} molecules cm⁻² at 13:00 and increases again in the afternoon.



Large spatial differences are observed in NO₂ VCD. CQ, XA, SXU, CD, and SH_XH have relatively high mean values of 2.25, 2.16, 2.06, 1.87, and 1.75×10^{16} molecules cm⁻², respectively. CQ and CD are located in the Sichuan Basin. Basin topography and local meteorological conditions restrict pollutant dispersion. Strong emissions and urban activities can therefore lead to high NO₂ levels (Ning et al., 2018). XA and SXU are located in the Guanzhong Basin and near Taiyuan, respectively. Both are strongly affected by traffic, industrial combustion, and energy-related emissions, which maintain high NO₂ VCDs (Zhang et al., 2023). XJ_HJZ also shows a relatively high mean NO₂ VCD. However, its observation period is short. The result may therefore be more strongly influenced by local emissions and dispersion conditions during the sampled period. Sites in the Pearl River Delta show a typical high-morning, low-midday, and high-evening pattern in NO₂ VCD. Mean values at GIG, GZ_PZ, and GZ_TM are 1.57, 1.27, and 0.76×10^{16} molecules cm⁻², respectively. At GIG, NO₂ VCD is 1.70×10^{16} molecules cm⁻² at 08:00, decreases to 1.16×10^{16} molecules cm⁻² at 13:00, and rises to 1.95×10^{16} molecules cm⁻² at 17:00. At GZ_PZ, it decreases from 1.60×10^{16} molecules cm⁻² at 08:00 to 1.04×10^{16} molecules cm⁻² at 14:00. Traffic, industrial, and residential emissions are dense in the Pearl River Delta. High morning NO₂ can reflect nighttime accumulation and rush-hour emissions. The midday decrease is associated with stronger photolysis, O₃ production, and boundary-layer dilution. In the evening, weaker photolysis and continued rush-hour emissions lead to a renewed increase in NO₂ (Li et al., 2023b). NO₂ VCD in North China also shows a strong anthropogenic influence. CAMS has a mean NO₂ VCD of 1.58×10^{16} molecules cm⁻². It reaches 1.90×10^{16} molecules cm⁻² at 08:00 and decreases to 1.19×10^{16} molecules cm⁻² at 17:00. WD has a mean value of 1.25×10^{16} molecules cm⁻². It reaches 1.49×10^{16} molecules cm⁻² at 09:00 and decreases to 0.69×10^{16} molecules cm⁻² at 17:00. Under the high-emission conditions of the North China Plain, stable nighttime stratification and morning traffic emissions favor NO₂ accumulation. During the day, boundary-layer growth and stronger NO₂ photolysis reduce NO₂ VCD (Ma et al., 2013). The lowest NO₂ VCDs occur at AL, YN, and TS, with mean values of 0.14, 0.19, and 0.35×10^{16} molecules cm⁻², respectively. AL and YN represent high-altitude background environments on the Tibetan Plateau and in northwestern Yunnan. Local anthropogenic NO_x emissions are weak, and NO₂ VCDs are therefore much lower than those at urban sites (Ma et al., 2020). TS is located in Shandong but at high altitude. The mountain environment reduces the influence of local near-surface emissions, and its NO₂ VCD is closer to the regional background.

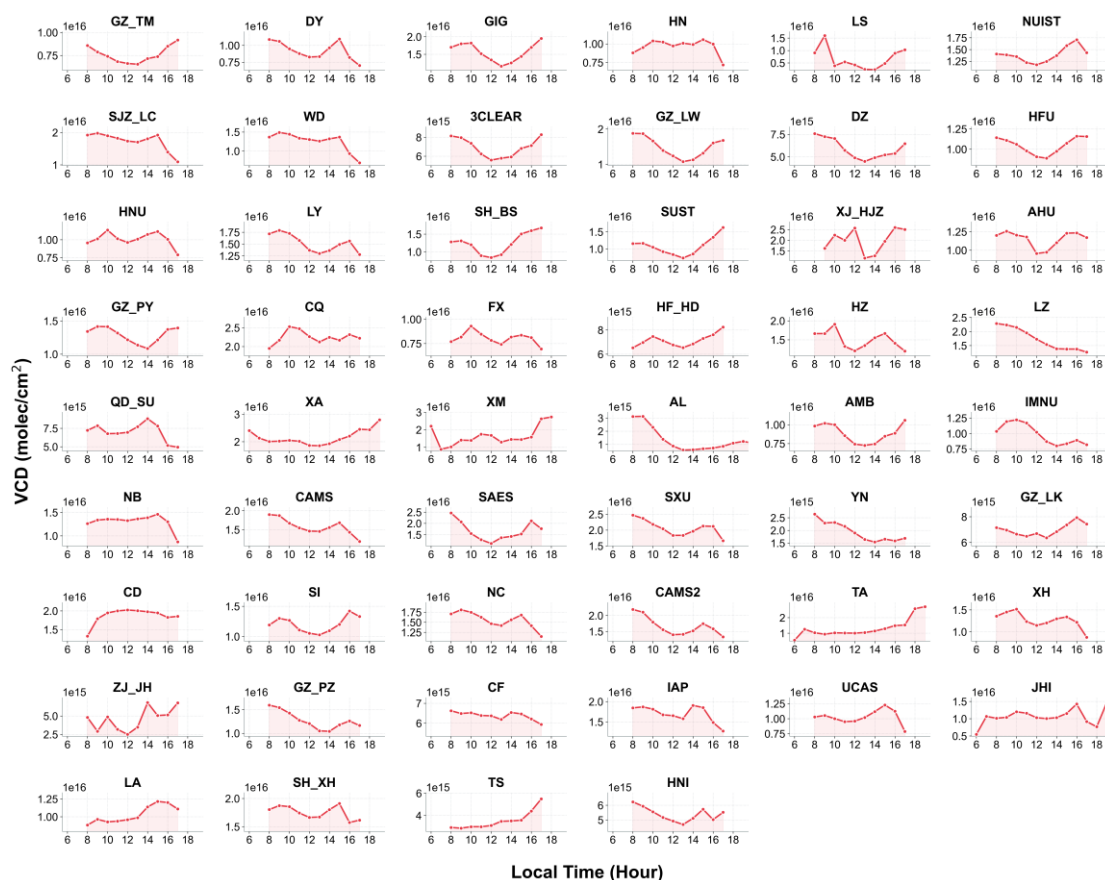


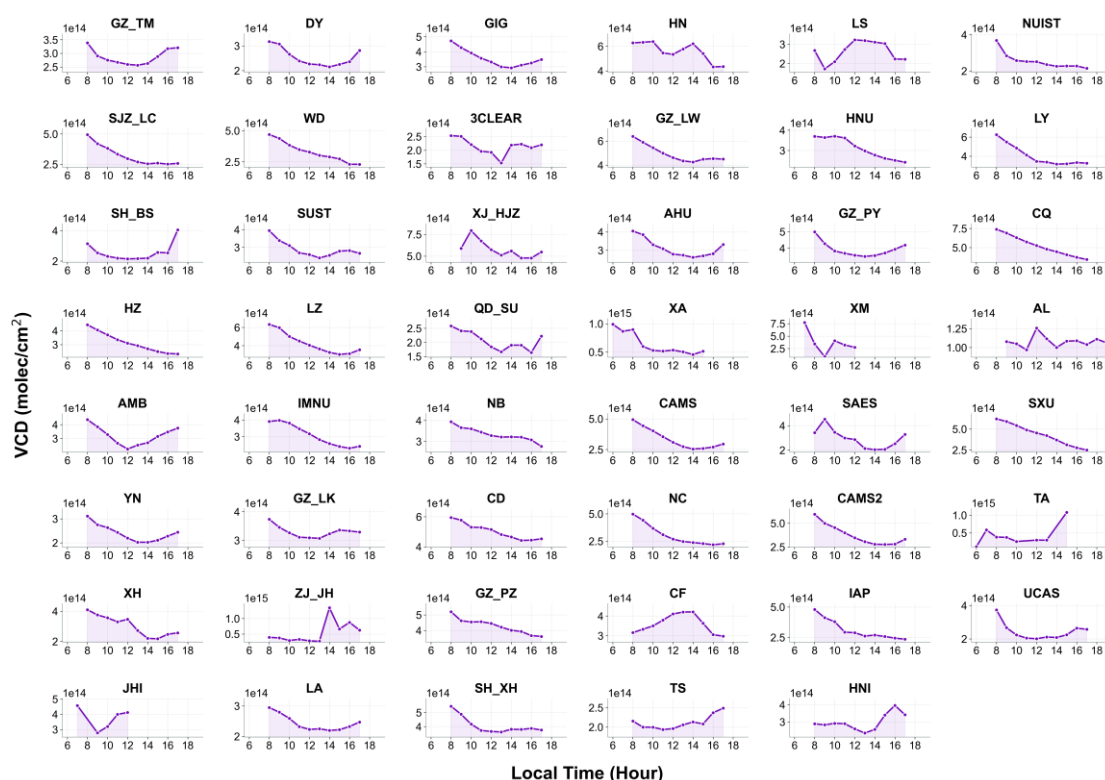
Figure 5: Mean diurnal variations of NO₂ VCD at each site during 2020–2025.

275 3.4 HONO VCD

HONO is an important early-morning source of OH radicals and contributes to the onset of daytime atmospheric oxidation and O₃ photochemistry. Figure 6 shows the mean diurnal variation of HONO VCD at each site during 2020–2025. The seasonal diurnal variations are shown in Fig. S5. Overall, HONO VCD is highest in the morning and decreases during the day. The network mean reaches 0.67×10^{15} molecules cm⁻² at 07:00 and is 0.44×10^{15} molecules cm⁻² at 08:00. It then decreases to 0.30
 280 $\times 10^{15}$ molecules cm⁻² at 13:00. The midday value is more than 50% lower than the morning maximum. High HONO VCDs are found at XA, HN, ZJ_JH, CQ, and CD, with mean values of 0.64 , 0.56 , 0.54 , 0.52 , and 0.50×10^{15} molecules cm⁻², respectively. XA reaches 0.99×10^{15} molecules cm⁻² at 06:00 and decreases to 0.46×10^{15} molecules cm⁻² at 14:00. This pattern shows strong morning accumulation followed by daytime photolysis. XA, CQ, and CD are located in the Guanzhong and Sichuan basins. Their relatively enclosed topography favors nighttime accumulation of NO_x and HONO under
 285 stable stratification. Urban traffic and combustion emissions also provide precursors for heterogeneous HONO formation (Li et al., 2022). XJ_HJZ has a relatively high mean HONO VCD as well. Its observations are concentrated in a short winter



period, so the values may mainly reflect low-temperature stable conditions and short-term local accumulation. The morning HONO enhancement is also consistent across Pearl River Delta sites. Mean HONO VCDs at GIG, GZ_PZ, and GZ_TM are 0.36, 0.43, and 0.29×10^{15} molecules cm^{-2} , respectively. At GIG, HONO VCD decreases from 0.47×10^{15} molecules cm^{-2} at 08:00 to 0.29×10^{15} molecules cm^{-2} at 14:00. At GZ_PZ, it decreases from 0.52×10^{15} molecules cm^{-2} at 08:00 to 0.36×10^{15} molecules cm^{-2} at 17:00. The Pearl River Delta has high humidity, strong NO_x emissions, and complex urban surfaces. These conditions favor heterogeneous HONO formation on the ground, building surfaces, and aerosols at night. After sunrise, HONO is rapidly photolyzed to produce OH radicals. This process can provide an important radical source for initiating morning photochemistry in the region (Yu et al., 2022). Mean HONO VCDs at CAMS and WD in North China are 0.34 and 0.33×10^{15} molecules cm^{-2} , respectively. CAMS reaches 0.49×10^{15} molecules cm^{-2} at 08:00 and decreases to 0.25×10^{15} molecules cm^{-2} at 14:00. At WD, HONO VCD decreases from 0.47×10^{15} molecules cm^{-2} at 08:00 to 0.23×10^{15} molecules cm^{-2} at 17:00. These patterns indicate nighttime and early-morning accumulation of HONO over the North China Plain, where NO_x emissions are strong and the nocturnal boundary layer is stable. Rapid photolysis and boundary-layer development then reduce the column during the day (Wang et al., 2019b). HONO VCDs are much lower at plateau and background sites. Mean HONO VCD is only 0.11×10^{15} molecules cm^{-2} at AL and 0.26×10^{15} molecules cm^{-2} at LS. These low values mainly reflect weak NO_x emissions and limited heterogeneous production at high altitude (Xing et al., 2021). Overall, HONO VCD is characterized by a morning maximum followed by a daytime decrease. HONO photolysis may therefore be an important process that initiates morning atmospheric oxidation in Chinese urban regions.



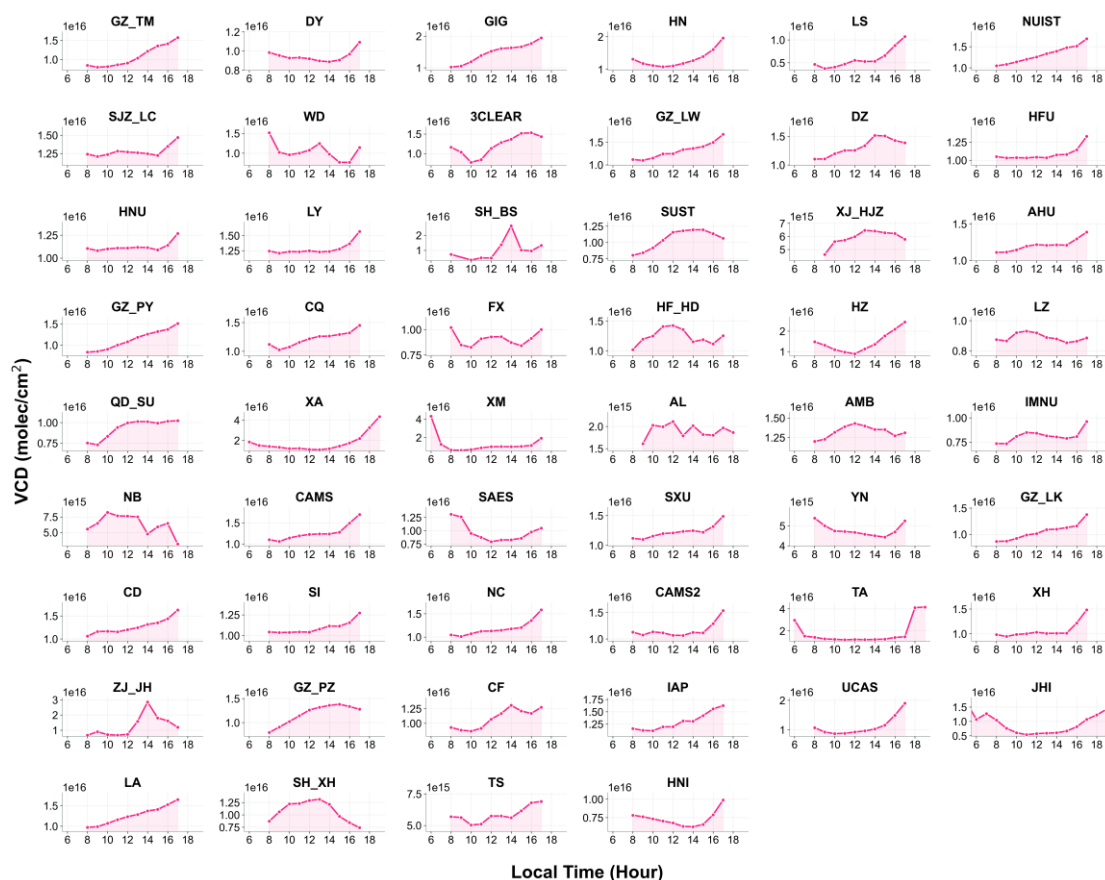


305 **Figure 6: Mean diurnal variations of HONO VCD at each site during 2020–2025.**

3.5 HCHO VCD

HCHO is an important oxygenated volatile organic compound in the atmosphere. It can be directly emitted from vehicle exhaust, industrial sources, biomass burning, and solvent use. It is also produced by oxidation of anthropogenic and biogenic VOCs (Li et al., 2024). Figure 7 shows the mean diurnal variation of HCHO VCD at each site during 2020–2025. The seasonal diurnal variations are shown in Fig. S6. The network mean is 0.95×10^{16} molecules cm^{-2} at 10:00 and increases gradually to 1.33×10^{16} molecules cm^{-2} at 17:00. This corresponds to an increase of approximately 40%.

High HCHO VCDs are found at TA, XA, GIG, HZ, AMB, and HN, with mean values of 1.83, 1.78, 1.48, 1.45, 1.33, and 1.32×10^{16} molecules cm^{-2} , respectively. GIG and HZ are located in the Pearl River Delta and Yangtze River Delta, where anthropogenic VOC emissions are strong and photochemical activity is high. HCHO VCD therefore remains relatively high at these sites. TA and XA show high HCHO peaks, but their observation periods are shorter. The extremes may therefore be influenced by specific seasons or pollution episodes. The daytime increase in HCHO VCD is most pronounced in the Pearl River Delta. GIG has a mean HCHO VCD of 1.48×10^{16} molecules cm^{-2} . It increases from 1.02×10^{16} molecules cm^{-2} at 08:00 to 1.95×10^{16} molecules cm^{-2} at 17:00, an increase of approximately 90%. GZ_TM has a mean value of 1.08×10^{16} molecules cm^{-2} . It increases from 0.80×10^{16} molecules cm^{-2} at 09:00 to 1.57×10^{16} molecules cm^{-2} at 17:00. GZ_PZ has a mean value of 1.18×10^{16} molecules cm^{-2} and reaches 1.38×10^{16} molecules cm^{-2} at 15:00. The region has high temperature and humidity, strong solar radiation, and active VOC emissions. Oxidation of both anthropogenic and biogenic VOCs can therefore enhance HCHO production (He et al., 2019). HCHO VCD also increases strongly during the day at many East China sites. HZ has a mean HCHO VCD of 1.45×10^{16} molecules cm^{-2} and reaches 2.44×10^{16} molecules cm^{-2} at 17:00. AHU, HFU, NUIST, LA, SH_XH, and SH_BS also generally show lower values in the morning and higher values in the afternoon. Similar to the Pearl River Delta, the Yangtze River Delta has strong industrial, traffic, solvent-use, and residential emissions. Vegetation and regional transport also contribute. Oxidation of anthropogenic and biogenic VOCs may therefore be an important driver of the daytime HCHO increase (Su et al., 2019). Coastal sites can also be affected by land–sea breeze circulation, which modulates the timing of HCHO transport and accumulation. Diurnal patterns of HCHO VCD differ among North China sites such as CAMS, WD, SJZ_LC, DZ, SXU, and IMNU. However, most sites still show an overall daytime increase. CAMS has a mean HCHO VCD of 1.27×10^{16} molecules cm^{-2} and reaches 1.70×10^{16} molecules cm^{-2} at 17:00. WD has a mean value of 1.05×10^{16} molecules cm^{-2} , but it is already 1.51×10^{16} molecules cm^{-2} at 08:00. It then decreases and remains relatively low during the afternoon. HCHO VCD is generally low at plateau and background sites. Mean values at AL, YN, TS, and LS are 0.19, 0.48, 0.58, and 0.59×10^{16} molecules cm^{-2} , respectively.



335 **Figure 7: Mean diurnal variations of HCHO VCD at each site during 2020–2025.**

3.6 SO₂ VCD

Compared with secondary pollutants such as O₃ and HCHO, SO₂ is more directly affected by local emission sources, intermittent point-source emissions, regional transport, and dispersion conditions (Wang et al., 2019b). Figure 8 shows the mean diurnal variation of SO₂ VCD at each site during 2020–2025. The seasonal diurnal variations are shown in Fig. S7.

340 Overall, the network mean is 0.72×10^{16} molecules cm⁻² at 08:00. It decreases to 0.56×10^{16} molecules cm⁻² at 13:00 and then increases again to 0.72×10^{16} molecules cm⁻² at 17:00.

The highest SO₂ VCDs occur at JHI, SJZ_LC, XH, SXU, LZ, and WD. Their mean values are 1.38, 1.03, 1.01, 0.97, 0.93, and 0.89×10^{16} molecules cm⁻², respectively. JHI is located near Liaodong Bay and the Bohai coast. It has the highest mean SO₂ VCD and reaches 1.97×10^{16} molecules cm⁻² at 18:00. Coastal industry, port activities, and ship emissions may all contribute

345 to these high values (Chen et al., 2018). SO₂ VCD is generally high in North China. WD has a mean value of 0.89×10^{16} molecules cm⁻². It decreases to 0.67×10^{16} molecules cm⁻² at 12:00 and increases to 1.81×10^{16} molecules cm⁻² at 17:00. CAMS has a mean SO₂ VCD of 0.69×10^{16} molecules cm⁻². It decreases to 0.59×10^{16} molecules cm⁻² at 13:00 and rises to 0.86×10^{16} molecules cm⁻² at 17:00. The relatively high SO₂ levels in North China may reflect the combined influence of coal



combustion, industrial emissions, and regional transport (Tan et al., 2020). SO₂ VCD in South China is generally lower than
 350 at the high-value sites in North China. This may be related to substantial SO₂ emission reductions in the Pearl River Delta and
 lower regional intensities of sulfur-containing fuel combustion and industrial emissions (Wang et al., 2019a). Mean SO₂ VCDs
 at GIG, GZ_PZ, and GZ_TM are 0.40 , 0.39 , and 0.49×10^{16} molecules cm⁻², respectively. At GIG, SO₂ VCD decreases from
 0.47×10^{16} molecules cm⁻² at 08:00 to 0.36×10^{16} molecules cm⁻² at 13:00. At GZ_PZ, it decreases from 0.55×10^{16} molecules
 cm⁻² at 08:00 to 0.31×10^{16} molecules cm⁻² at 13:00. GZ_TM reaches 0.64×10^{16} molecules cm⁻² at 17:00. SO₂ shows strong
 355 site-to-site differences in East China and coastal regions. SI has a mean SO₂ VCD of 0.65×10^{16} molecules cm⁻² and reaches
 0.86×10^{16} molecules cm⁻² at 17:00. TA has a mean value of 0.87×10^{16} molecules cm⁻² and reaches 1.09×10^{16} molecules
 cm⁻² at 14:00. Coastal sites such as XM, HNI, NB, and SH_XH may be influenced by ship emissions, port activities, and land–
 sea breeze circulation. These processes can enhance SO₂ VCD during specific periods of the day. SO₂ VCD is generally low
 at plateau and background sites. The mean value is only 0.03×10^{16} molecules cm⁻² at AL, 0.30×10^{16} molecules cm⁻² at YN,
 360 and 0.45×10^{16} molecules cm⁻² at TS. These values indicate weak local sulfur emissions. Overall, SO₂ VCD shows stronger
 spatial heterogeneity and source dependence than O₃ and HCHO. Its diurnal variation is controlled not only by boundary-layer
 dilution and oxidation but also by industrial emissions, coal combustion, port and ship emissions, and regional transport.

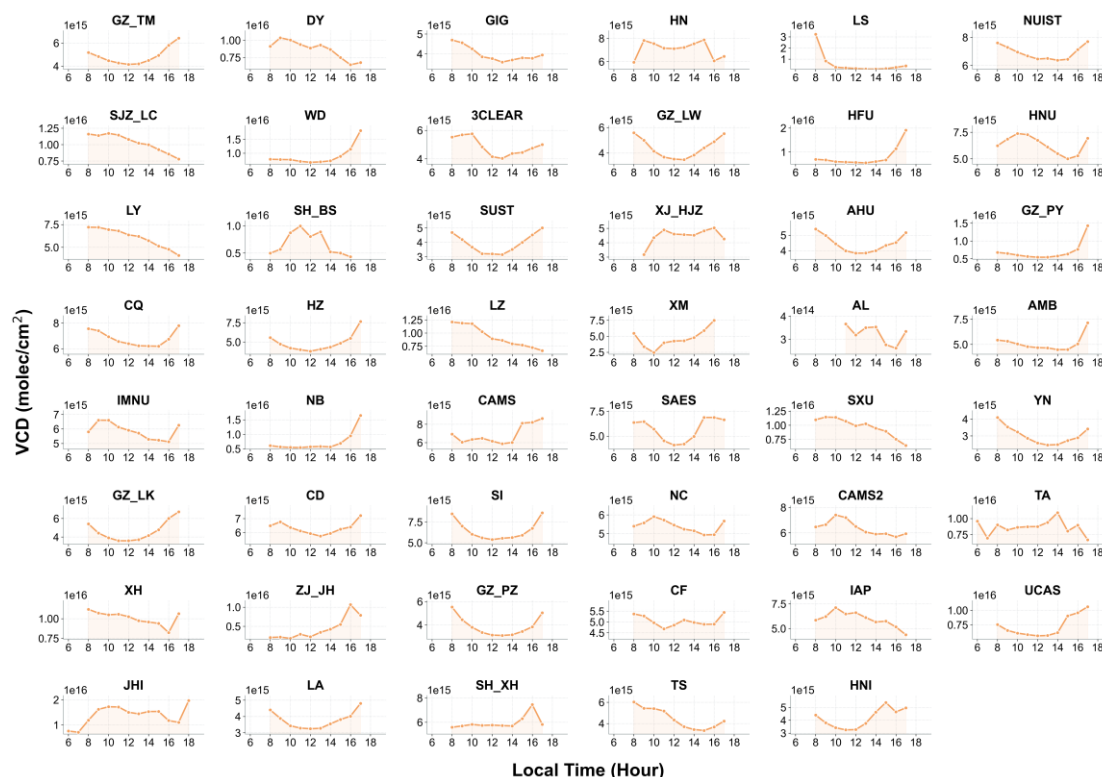


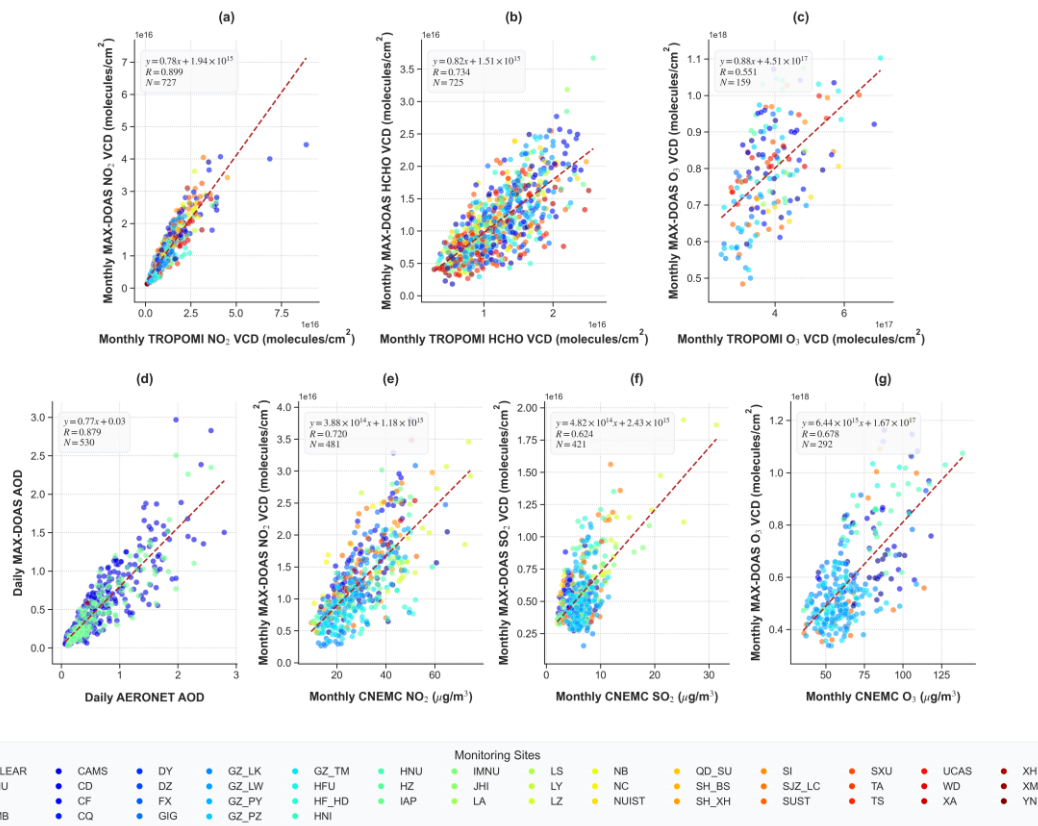
Figure 8: Mean diurnal variations of SO₂ VCD at each site during 2020–2025.



365 3.7 Validation

To evaluate the reliability of the MAX-DOAS dataset, we compared the VCD and AOD products with TROPOMI, CNEMC, and AERONET observations. Monthly means were used for TROPOMI and CNEMC, while daily means were used for AERONET. The results are shown in Fig. 9. NO₂ VCD shows the best agreement with the satellite product, with a correlation coefficient of 0.899. HCHO VCD also shows a strong positive correlation, with a coefficient of 0.734 and a slope of 0.82. The correlation coefficient for O₃ VCD is 0.551, and the slope is 0.88. The slope is close to unity, indicating that the two datasets capture similar amplitudes of monthly O₃ variation. The lower correlation of O₃ than of NO₂ and HCHO may reflect its more complex vertical distribution and the influence of the residual layer, regional background, and vertical mixing.

AOD is strongly correlated with AERONET, with a correlation coefficient of 0.879. Differences may arise because MAX-DOAS uses scattered sunlight, whereas AERONET primarily uses direct-sun observations. The two retrieval systems also differ in observation geometry and sampling characteristics. MAX-DOAS column measurements and CNEMC surface observations represent different atmospheric quantities. Their correlations nevertheless provide an additional assessment of the temporal consistency of the dataset. NO₂ shows the highest correlation, with a coefficient of 0.720. This indicates a close relationship between NO₂ VCD and surface NO₂ concentration. NO₂ is generally concentrated within the boundary layer and is strongly controlled by traffic, industrial, and combustion emissions. SO₂ shows a moderate correlation with CNEMC surface concentrations, with a coefficient of 0.624. O₃ VCD has a correlation coefficient of 0.678 with surface O₃. This indicates that the O₃ column captures the major month-to-month changes in surface O₃. However, the relationship is more complex than for NO₂ because O₃ VCD also includes contributions from the upper boundary layer, residual layer, and regional background.



385 **Figure 9: Comparisons of MAX-DOAS VCD and AOD observations with TROPOMI, AERONET and CNEMC observations.**

4 Summary

This study develops and releases a ground-based dataset of O₃, NO₂, HCHO, HONO, and SO₂ VCDs and AOD from the Chinese Hyperspectral Vertical Remote Sensing Network for 2020–2025. The dataset integrates observations from 53 MAX-DOAS sites across China. It covers North, East, South, Southwest, Northwest, Northeast, and Central China, together with the Tibetan Plateau. The sites include major urban agglomerations, industrial areas, coastal and island environments, inland basins, arid and semi-arid regions, and high-altitude background areas. The large contrasts in emissions, topography, climate, and surface conditions provide long-term and spatially representative ground-based observations of key atmospheric column components across China.

A unified processing and quality-control framework was applied to all sites and components. AOD, NO₂, and HCHO have the broadest spatial and temporal coverage. HONO, SO₂, and O₃ have smaller coverage but still provide valuable multi-year records at many sites. Retrieval uncertainties differ among components. O₃ and AOD retrievals are relatively stable. NO₂ and HCHO show moderate uncertainties that are suitable for long-term statistical analysis. HONO and SO₂ have larger relative errors because of weaker absorption signals, lower concentrations, and stronger effects of intermittent local emissions.



The dataset shows clear and physically consistent diurnal variations among atmospheric components. AOD generally increases from morning to around noon and then decreases in the afternoon. This pattern reflects the combined effects of aerosol formation, hygroscopic growth, boundary-layer evolution, and regional transport. O₃ and HCHO generally increase in the afternoon because of photochemical production and VOC oxidation. NO₂ and HONO show stronger morning signals and decrease during the day because of photolysis, dilution, and boundary-layer development. SO₂ shows stronger spatial heterogeneity and source dependence, with clear enhancements at several industrial, inland, and coastal sites. These multi-component column observations provide a useful basis for studies of regional photochemistry, atmospheric oxidation capacity, emission impacts, and aerosol–gas interactions.

Independent comparisons further demonstrate the reliability and application value of the dataset. MAX-DOAS NO₂ VCD agrees well with satellite NO₂ products. HCHO, O₃, and AOD also show stable positive correlations with satellite or AERONET observations. Comparisons with CNEMC surface measurements show that the column data capture major monthly variations in near-surface pollution. The relationship differs among components because VCDs also include contributions from the boundary layer, residual layer, and regional background. Overall, this dataset provides an independent, long-term, and physically comparable ground-based reference for satellite VCD and AOD products over China. It can also support satellite bias correction, satellite–AI retrieval and data fusion, air-quality prediction, chemical transport model evaluation, and studies of multi-pollutant atmospheric processes.

415 **Code and data availability**

The VCDs of atmospheric composition and AOD over the major regions of China presented here are available at Zenodo (<https://doi.org/10.5281/zenodo.22691855>, Xing et al., 2026).

Author contributions

All authors contributed to the generation of the dataset described in this paper. YL, CX, and CL wrote the manuscript, while all other authors participated in its revision.

Competing interests

The contact author has declared that neither they nor their co-authors have any competing interests.

Disclaimer

Publisher’s note: Copernicus Publications remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Financial support

This research is supported by grants from the National Natural Science Foundation of China (42622510).

References

- Bae, K., Song, C.-K., Van Roozendaal, M., Richter, A., Wagner, T., Merlaud, A., Pinardi, G., Friedrich, M. M., Fayt, C., Dimitropoulou, E., Lange, K., Bösch, T., Zilker, B., Latsch, M., Behrens, L. K., Ziegler, S., Ripperger-Lukosiunaite, S., Kuhn, L., Lauster, B., Reischmann, L., Uhlmannsiek, K., Cede, A., Tiefengraber, M., Gebetsberger, M., Park, R. J., Lee, H., Hong, H., Chang, L.-S., and Jeon, K.: Validation of GEMS operational v2.0 total column NO₂ and HCHO during the GMAP/SIJAQ campaign, *Science of The Total Environment*, 974, 179190, <https://doi.org/10.1016/j.scitotenv.2025.179190>, 2025.
- Chen, D., Zhao, N., Lang, J., Zhou, Y., Wang, X., Li, Y., Zhao, Y., and Guo, X.: Contribution of ship emissions to the concentration of PM_{2.5}: A comprehensive study using AIS data and WRF/Chem model in Bohai Rim Region, China, *Science of The Total Environment*, 610–611, 1476–1486, <https://doi.org/10.1016/j.scitotenv.2017.07.255>, 2018.
- De Mazière, M., Thompson, A. M., Kurylo, M. J., Wild, J. D., Bernhard, G., Blumenstock, T., Braathen, G. O., Hannigan, J. W., Lambert, J.-C., Leblanc, T., McGee, T. J., Nedoluha, G., Petropavlovskikh, I., Seckmeyer, G., Simon, P. C., Steinbrecht, W., and Strahan, S. E.: The Network for the Detection of Atmospheric Composition Change (NDACC): history, status and perspectives, *Atmospheric Chemistry and Physics*, 18, 4935–4964, <https://doi.org/10.5194/acp-18-4935-2018>, 2018.
- He, C., Liu, J., Zhou, Y., Zhou, J., Zhang, L., Wang, Y., Liu, L., and Peng, S.: Synergistic PM_{2.5} and O₃ control to address the emerging global PM_{2.5}-O₃ compound pollution challenges, *Eco-Environment & Health*, 3, 325–337, <https://doi.org/10.1016/j.eehl.2024.04.004>, 2024.
- He, Z., Wang, X., Ling, Z., Zhao, J., Guo, H., Shao, M., and Wang, Z.: Contributions of different anthropogenic volatile organic compound sources to ozone formation at a receptor site in the Pearl River Delta region and its policy implications, *Atmospheric Chemistry and Physics*, 19, 8801–8816, <https://doi.org/10.5194/acp-19-8801-2019>, 2019.
- Ji, Y., Wu, H., Liu, X., Zhou, W., Wang, L., and Cui, L.: Satellite estimation of global air sea CO₂ flux from 2000 to 2020, *Sci Rep*, <https://doi.org/10.1038/s41598-026-51215-5>, 2026.
- Jiang, F., Guo, H., Wang, T. J., Cheng, H. R., Wang, X. M., Simpson, I. J., Ding, A. J., Saunders, S. M., Lam, S. H. M., and Blake, D. R.: An ozone episode in the Pearl River Delta: Field observation and model simulation, *J. Geophys. Res.*, 115, 2009JD013583, <https://doi.org/10.1029/2009JD013583>, 2010.
- Jiao, P., Xing, C., Li, Y., Ji, X., Tan, W., Li, Q., Liu, H., and Liu, C.: A dataset of ground-based vertical profile observations of aerosol, NO₂, and HCHO from the hyperspectral vertical remote sensing network in China (2019–2023), *Earth System Science Data*, 17, 3167–3187, <https://doi.org/10.5194/essd-17-3167-2025>, 2025.
- Kanaya, Y., Irie, H., Takashima, H., Iwabuchi, H., Akimoto, H., Sudo, K., Gu, M., Chong, J., Kim, Y. J., Lee, H., Li, A., Si, F., Xu, J., Xie, P.-H., Liu, W.-Q., Dzholia, A., Postlyakov, O., Ivanov, V., Grechko, E., Terpugova, S., and Panchenko, M.: Long-term MAX-DOAS network observations of NO₂ in Russia and Asia (MADRAS) during the period 2007–2012: instrumentation, elucidation of climatology, and comparisons with OMI satellite observations and global model simulations, *Atmospheric Chemistry and Physics*, 14, 7909–7927, <https://doi.org/10.5194/acp-14-7909-2014>, 2014.



- 460 Kong, L., Hu, M., Tan, Q., Feng, M., Qu, Y., An, J., Zhang, Y., Liu, X., and Cheng, N.: Aerosol optical properties under different pollution levels in the Pearl River Delta (PRD) region of China, *Journal of Environmental Sciences*, 87, 49–59, <https://doi.org/10.1016/j.jes.2019.02.019>, 2020.
- Kong, L., Tang, X., Zhu, J., Wang, Z., Li, J., Wu, H., Wu, Q., Chen, H., Zhu, L., Wang, W., Liu, B., Wang, Q., Chen, D., Pan, Y., Song, T., Li, F., Zheng, H., Jia, G., Lu, M., Wu, L., and Carmichael, G. R.: A 6-year-long (2013–2018) high-resolution air quality reanalysis dataset in China based on the assimilation of surface observations from CNEMC, *Earth System Science Data*, 13, 529–570, <https://doi.org/10.5194/essd-13-529-2021>, 2021.
- 465 Li, B., Hu, Q., Gao, M., Liu, T., Zhang, C., and Liu, C.: Physical informed neural network improving the WRF-CHEM results of air pollution using satellite-based remote sensing data, *ATMOSPHERIC ENVIRONMENT*, 311, <https://doi.org/10.1016/j.atmosenv.2023.120031>, 2023a.
- 470 Li, C., Gao, J., Xie, F., Li, M., Zhu, R., Li, B., Zhang, Y., Luo, Q., and Zhang, Y.: UV-DOAS combined with waveband self-competitive spectral reconstruction method: a novel system for 5-decade dynamic range sulfur dioxide detection, *Measurement*, 265, 120345, <https://doi.org/10.1016/j.measurement.2026.120345>, 2026.
- Li, K., Jacob, D. J., Liao, H., Qiu, Y., Shen, L., Zhai, S., Bates, K. H., Sulprizio, M. P., Song, S., Lu, X., Zhang, Q., Zheng, B., Zhang, Y., Zhang, J., Lee, H. C., and Kuk, S. K.: Ozone pollution in the North China Plain spreading into the late-winter haze season, *Proceedings of the National Academy of Sciences*, 118, e2015797118, <https://doi.org/10.1073/pnas.2015797118>, 2021.
- 475 Li, L., Chen, C. H., Huang, C., Huang, H. Y., Zhang, G. F., Wang, Y. J., Wang, H. L., Lou, S. R., Qiao, L. P., Zhou, M., Chen, M. H., Chen, Y. R., Streets, D. G., Fu, J. S., and Jang, C. J.: Process analysis of regional ozone formation over the Yangtze River Delta, China using the Community Multi-scale Air Quality modeling system, *Atmospheric Chemistry and Physics*, 12, 10971–10987, <https://doi.org/10.5194/acp-12-10971-2012>, 2012.
- 480 Li, T., Wu, J., Wang, Y., and Su, Y.: Improved seamless mapping of surface O₃ concentrations using an integrated deep learning framework, *npj Clim Atmos Sci*, 8, 124, <https://doi.org/10.1038/s41612-025-01007-x>, 2025a.
- Li, X., Bei, N., Wu, J., Wang, R., Liu, S., Liu, L., Jiang, Q., Tie, X., Molina, L. T., and Li, G.: Heterogeneous HONO formation deteriorates the wintertime particulate pollution in the Guanzhong Basin, China, *Environmental Pollution*, 303, 119157, <https://doi.org/10.1016/j.envpol.2022.119157>, 2022.
- 485 Li, Y., Xing, C., Peng, H., Song, Y., Zhang, C., Xue, J., Niu, X., and Liu, C.: Long-term observations of NO₂ using GEMS in China: Validations and regional transport, *Science of The Total Environment*, 904, 166762, <https://doi.org/10.1016/j.scitotenv.2023.166762>, 2023b.
- Li, Y., Xing, C., Hong, Q., Jiao, P., Peng, H., Tang, Z., and Liu, C.: Ozone Formation Sensitivity at Various Altitudes: Seeking the Optimal Method for Sensitivity Threshold Determination, *Environ. Sci. Technol. Lett.*, 11, 1334–1339, <https://doi.org/10.1021/acs.estlett.4c00777>, 2024.
- 490 Li, Y., Xing, C., Peng, H., Jiao, P., Zhang, Q., Liu, C., Sun, Z., Tan, W., and Liu, C.: Vertical Differences in NO₂ -to-HONO Heterogeneous Conversion and HONO-Driven OH Production over Inland, Coastal, and Island Regions, *Environ. Sci. Technol.*, *acs.est.5c10318*, <https://doi.org/10.1021/acs.est.5c10318>, 2025b.
- 495 Lin, J., Xing, C., Liu, C., Tan, W., Wang, W., Wu, P., Lu, C., Li, Q., and Liu, T.: Hyperspectral imaging technique supports dynamic emission inventory of coal-fired power plants in China, *Science Bulletin*, 68, 1248–1251, <https://doi.org/10.1016/j.scib.2023.05.020>, 2023.



- Ma, J., Dörner, S., Donner, S., Jin, J., Cheng, S., Guo, J., Zhang, Z., Wang, J., Liu, P., Zhang, G., Pukite, J., Lampel, J., and Wagner, T.: MAX-DOAS measurements of NO₂, SO₂, HCHO, and BrO at the Mt. Waliguan WMO GAW global baseline station in the Tibetan Plateau, *Atmospheric Chemistry and Physics*, 20, 6973–6990, <https://doi.org/10.5194/acp-20-6973-2020>, 2020.
- Ma, J. Z., Beirle, S., Jin, J. L., Shaiganfar, R., Yan, P., and Wagner, T.: Tropospheric NO₂ vertical column densities over Beijing: results of the first three years of ground-based MAX-DOAS measurements (2008–2011) and satellite validation, *Atmos. Chem. Phys.*, 13, 1547–1567, <https://doi.org/10.5194/acp-13-1547-2013>, 2013.
- Ma, W., Xing, C., Wang, W., Zhang, Q., Wang, Z., Yang, Y., and Liu, C.: Ozone pollution monitoring using a full-time hyperspectral tomography system for multiple air pollutants, *Nat Commun*, 17, 245, <https://doi.org/10.1038/s41467-025-66944-w>, 2025.
- Mo, X., Gong, D., Liu, Y., Li, J., Zhao, Y., Zhao, W., Shen, J., Liao, T., Wang, H., and Wang, B.: Ground-based formaldehyde across the Pearl River Delta: A snapshot and meta-analysis study, *Atmospheric Environment*, 309, 119935, <https://doi.org/10.1016/j.atmosenv.2023.119935>, 2023.
- Ning, G., Wang, S., Ma, M., Ni, C., Shang, Z., Wang, J., and Li, J.: Characteristics of air pollution in different zones of Sichuan Basin, China, *Science of The Total Environment*, 612, 975–984, <https://doi.org/10.1016/j.scitotenv.2017.08.205>, 2018.
- Peng, B., Liu, H., Li, S., Liao, N., and Zhu, M.: A cross-instrument concentration detection method based on domain adaptation: For mixed gas of NO and SO₂, *Sensors and Actuators B: Chemical*, 458, 139844, <https://doi.org/10.1016/j.snb.2026.139844>, 2026.
- Peng, H., Xing, C., Li, Y., Zhang, C., Lin, J., Xue, J., Wang, X., Song, Y., Niu, X., and Liu, C.: Studies on regional ozone formation sensitivities and transport with higher spatiotemporal resolutions in a stereoscopic dimension: GEMS and vertical observations, *Atmospheric Research*, 302, 107314, <https://doi.org/10.1016/j.atmosres.2024.107314>, 2024.
- Pokharel, M., Guang, J., Liu, B., Kang, S., Ma, Y., Holben, B. N., Xia, X., Xin, J., Ram, K., Rupakheti, D., Wan, X., Wu, G., Bhattarai, H., Zhao, C., and Cong, Z.: Aerosol Properties Over Tibetan Plateau From a Decade of AERONET Measurements: Baseline, Types, and Influencing Factors, *Journal of Geophysical Research: Atmospheres*, 124, 13357–13374, <https://doi.org/10.1029/2019JD031293>, 2019.
- Ryan, R. G., Silver, J. D., Querel, R., Smale, D., Rhodes, S., Tully, M., Jones, N., and Schofield, R.: Comparison of formaldehyde tropospheric columns in Australia and New Zealand using MAX-DOAS, FTIR and TROPOMI, *Atmos Meas Tech*, 13, 6501–6519, <https://doi.org/10.5194/amt-13-6501-2020>, 2020.
- Shao, M., Xu, C., Lv, S., Jin, X., Mu, Q., and Zhu, J.: Mechanisms of O₃ and PM_{2.5} evolution along the cold wave passage in Eastern China, *npj Clim Atmos Sci*, 8, 199, <https://doi.org/10.1038/s41612-025-01088-8>, 2025.
- Song, Y., Xing, C., Liu, C., Lin, J., Wu, H., Liu, T., Lin, H., Zhang, C., Tan, W., Ji, X., Liu, H., and Li, Q.: Evaluation of transport processes over North China Plain and Yangtze River Delta using MAX-DOAS observations, *Atmos. Chem. Phys.*, 23, 1803–1824, <https://doi.org/10.5194/acp-23-1803-2023>, 2023.
- Su, F., Xu, Q., Yin, S., Wang, K., Liu, G., Wang, P., Kang, M., Zhang, R., and Ying, Q.: Contributions of local emissions and regional background to summertime ozone in central China, *Journal of Environmental Management*, 338, 117778, <https://doi.org/10.1016/j.jenvman.2023.117778>, 2023.



- 535 Su, W., Liu, C., Hu, Q., Zhao, S., Sun, Y., Wang, W., Zhu, Y., Liu, J., and Kim, J.: Primary and secondary sources of ambient formaldehyde in the Yangtze River Delta based on Ozone Mapping and Profiler Suite (OMPS) observations, *Atmospheric Chemistry and Physics*, 19, 6717–6736, <https://doi.org/10.5194/acp-19-6717-2019>, 2019.
- Tan, W., Liu, C., Wang, S., Liu, H., Zhu, Y., Su, W., Hu, Q., and Liu, J.: Long-distance mobile MAX-DOAS observations of NO₂ and SO₂ over the North China Plain and identification of regional transport and power plant emissions, *Atmospheric Research*, 245, 105037, <https://doi.org/10.1016/j.atmosres.2020.105037>, 2020.
- 540 Wang, F., Chen, Y., Meng, X., Fu, J., and Wang, B.: The contribution of anthropogenic sources to the aerosols over East China Sea, *Atmospheric Environment*, 127, 22–33, <https://doi.org/10.1016/j.atmosenv.2015.12.002>, 2016.
- Wang, G., Deng, X.-J., Wang, C.-L., Zhang, X.-Y., Yan, H.-H., Chen, D.-H., and Guo, T.: A New and Detailed Assessment of the Spatiotemporal Characteristics of the SO₂ Distribution in the Pearl River Delta Region of China and the Effect of SO₂ Emission Reduction, *Aerosol Air Qual. Res.*, 19, 1900–1910, <https://doi.org/10.4209/aaqr.2019.03.0135>, 2019a.
- 545 Wang, Y., Dörner, S., Donner, S., Böhnke, S., De Smedt, I., Dickerson, R. R., Dong, Z., He, H., Li, Z., Li, Z., Li, D., Liu, D., Ren, X., Theys, N., Wang, Y., Wang, Y., Wang, Z., Xu, H., Xu, J., and Wagner, T.: Vertical profiles of NO₂, SO₂, HONO, HCHO, CHOCHO and aerosols derived from MAX-DOAS measurements at a rural site in the central western North China Plain and their relation to emission sources and effects of regional transport, *Atmospheric Chemistry and Physics*, 19, 5417–5449, <https://doi.org/10.5194/acp-19-5417-2019>, 2019b.
- 550 Wei, J., Li, Z., Pinker, R. T., Wang, J., Sun, L., Xue, W., Li, R., and Cribb, M.: Himawari-8-derived diurnal variations in ground-level PM_{2.5} pollution across China using the fast space-time Light Gradient Boosting Machine (LightGBM), *Atmospheric Chemistry and Physics*, 21, 7863–7880, <https://doi.org/10.5194/acp-21-7863-2021>, 2021.
- Wei, J., Li, Z., Wang, J., Li, C., Gupta, P., and Cribb, M.: Ground-level gaseous pollutants (NO₂, SO₂, and CO) in China: daily seamless mapping and spatiotemporal variations, *Atmospheric Chemistry and Physics*, 23, 1511–1532, <https://doi.org/10.5194/acp-23-1511-2023>, 2023.
- Whitburn, S., Clarisse, L., De Longueville, H., Shine, K. P., Coheur, P. F., Clerbaux, C., and Delcloo, A. W.: Satellite-based estimates of radiative forcing of long-lived halogenated gases from spectral observations, *Commun Earth Environ*, <https://doi.org/10.1038/s43247-026-03691-w>, 2026.
- 560 Wu, Y., Huo, J., Yang, G., Wang, Y., Wang, L., Wu, S., Yao, L., Fu, Q., and Wang, L.: Measurement report: Production and loss of atmospheric formaldehyde at a suburban site of Shanghai in summertime, *Atmospheric Chemistry and Physics*, 23, 2997–3014, <https://doi.org/10.5194/acp-23-2997-2023>, 2023.
- Xia, X., Wang, P., Wang, Y., Li, Z., Xin, J., Liu, J., and Chen, H.: Aerosol optical depth over the Tibetan Plateau and its relation to aerosols over the Taklimakan Desert, *Geophysical Research Letters*, 35, <https://doi.org/10.1029/2008GL034981>, 2008.
- 565 Xing, C., Liu, C., Wu, H., Lin, J., Wang, F., Wang, S., and Gao, M.: Ground-based vertical profile observations of atmospheric composition on the Tibetan Plateau (2017–2019), *Earth Syst. Sci. Data*, 13, 4897–4912, <https://doi.org/10.5194/essd-13-4897-2021>, 2021.
- 570 Xing, C., Xu, S., Song, Y., Liu, C., Liu, Y., Lu, K., Tan, W., Zhang, C., Hu, Q., Wang, S., Wu, H., and Lin, H.: A new insight into the vertical differences in NO₂ heterogeneous reaction to produce HONO over inland and marginal seas, *Atmospheric Chemistry and Physics*, 23, 5815–5834, <https://doi.org/10.5194/acp-23-5815-2023>, 2023.



- Xing, C., Liu, C., Ye, C., Xue, J., Wu, H., Ji, X., Ou, J., and Hu, Q.: Observations of the vertical distributions of summertime atmospheric pollutants in Nam Co: OH production and source analysis, *Atmos. Chem. Phys.*, 24, 10093–10112, <https://doi.org/10.5194/acp-24-10093-2024>, 2024.
- 575 Xing, C., Wei, S., Li, Y., Jiao, P., Liu, C., Chen, J., Wang, W., Peng, H., Song, Y., and Liu, C.: Fast-hyperspectral imaging remote sensing: Emission quantification of NO₂ and SO₂ from marine vessels, *Light Sci Appl*, 14, 308, <https://doi.org/10.1038/s41377-025-01922-x>, 2025.
- Xing, C., Peng, H., Zou, T., Song, Y., and Liu, C.: UAV-Based Hyperspectral Imaging Bridges the Spatial Gap in Pollution Source Identification, *Anal. Chem.*, 98, 5381–5393, <https://doi.org/10.1021/acs.analchem.5c06398>, 2026.
- 580 Xing, C., Li, Y., and Liu, C.: A dataset of ground-based VCDs (O₃, NO₂, HCHO, HONO, SO₂) and AOD observations from the hyperspectral vertical remote sensing network in China (2020–2025), <https://doi.org/10.5281/zenodo.22691855>, 2026.
- Yu, X., Shen, L., Xiao, S., Ma, J., Lü, R., Zhu, B., Hu, J., Chen, K., and Zhu, J.: Chemical and Optical Properties of Atmospheric Aerosols during the Polluted Periods in a Megacity in the Yangtze River Delta, China, *Aerosol Air Qual. Res.*, 19, 103–117, <https://doi.org/10.4209/aaqr.2017.12.0572>, 2019.
- 585 Yu, Y., Cheng, P., Li, H., Yang, W., Han, B., Song, W., Hu, W., Wang, X., Yuan, B., Shao, M., Huang, Z., Li, Z., Zheng, J., Wang, H., and Yu, X.: Budget of nitrous acid (HONO) at an urban site in the fall season of Guangzhou, China, *Atmospheric Chemistry and Physics*, 22, 8951–8971, <https://doi.org/10.5194/acp-22-8951-2022>, 2022.
- Yuping Chen, Wang, M., Yao, Y., Zeng, C., Zhang, W., Yan, H., Gao, P., Fan, L., and Ye, D.: Research on the ozone formation sensitivity indicator of four urban agglomerations of China using Ozone Monitoring Instrument (OMI) satellite data and ground-based measurements, *Science of The Total Environment*, 869, 161679, <https://doi.org/10.1016/j.scitotenv.2023.161679>, 2023.
- 590 Zhang, Y., Tian, J., Wang, Q., Qi, L., Manousakas, M. I., Han, Y., Ran, W., Sun, Y., Liu, H., Zhang, R., Wu, Y., Cui, T., Daellenbach, K. R., Slowik, J. G., Prévôt, A. S. H., and Cao, J.: High-time-resolution chemical composition and source apportionment of PM_{2.5} in northern Chinese cities: implications for policy, *Atmos. Chem. Phys.*, 23, 9455–9471, <https://doi.org/10.5194/acp-23-9455-2023>, 2023.
- 595 Zhang, Y., Wei, Y., de Leeuw, G., Liu, O., Chen, Y., Lv, Y., Zhang, Y., and Li, Z.: Relation between total vertical column density and near-surface NO₂ based on in situ and Pandora ground-based remote sensing observations, *Atmospheric Chemistry and Physics*, 25, 10643–10660, <https://doi.org/10.5194/acp-25-10643-2025>, 2025.
- 600 Zhang, Y., Xu, R., Wu, Y., Huang, W., Yang, Z., Wen, B., Liu, Y., Xu, Z., Li, Z., Yu, W., Chen, G., Zhou, S., Ye, T., Lavigne, E., Coelho, M. S. Z. S., Saldiva, P. H. N., Matus, P., Tantrakarnapa, K., Song, J., Guo, Y., and Li, S.: Compound effects of extreme heat and wildfire-PM_{2.5} air pollution on child hospitalizations in multiple countries, *Nat. Health*, <https://doi.org/10.1038/s44360-026-00133-x>, 2026a.
- Zhang, Y., Heinrich, V. H. A., Bourgoïn, C., Wang, X., Li, X., Du, Y., and Atkinson, P. M.: Natural forest expansion is a larger carbon sink than secondary forests in moist tropics, *Nat. Geosci.*, <https://doi.org/10.1038/s41561-026-01984-5>, 2026b.
- 605 Zhu, J., Penner, J. E., Hong, C., Liu, H., Zhao, X., Deng, J., Liu, C.-Q., Zhang, Q., and Fu, P.: Cropland expansion reduces biogenic secondary organic aerosol and associated radiative cooling, *Nat. Geosci.*, 18, 624–630, <https://doi.org/10.1038/s41561-025-01718-z>, 2025.



Zhu, X., Ma, Z., Qiu, Y., Liu, H., Liu, Q., and Yin, X.: An evaluation of the interaction of morning residual layer ozone and mixing layer ozone in rural areas of the North China Plain, *Atmospheric Research*, 236, 104788, <https://doi.org/10.1016/j.atmosres.2019.104788>, 2020.

- 610 Zou, T., Xing, C., Tan, W., Wu, Z., and Liu, C.: Meter-Scale UAV Hyperspectral Remote Sensing for Pollution Source Attribution: Dynamic Reference Spectrum Optimization and Surface Albedo Correction, *Environ. Sci. Technol.*, acs.est.5c08110, <https://doi.org/10.1021/acs.est.5c08110>, 2025.