POMINO-GEMS : A Research Product for Tropospheric NO₂ Columns from Geostationary Environment Monitoring Spectrometer

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Abstract

Tropospheric vertical column densities (VCDs) of nitrogen dioxide (NO₂) retrieved from sun-synchronous satellite instruments have provided abundant NO₂ data for environmental studies, but such

39   data are limited by retrieval uncertainties and insufficient temporal sampling (e.g., once a day). The

40   Geostationary Environment Monitoring Spectrometer (GEMS) launched in February 2020 monitors NO_2

41   at an unprecedented hourly resolution during the daytime. Here we present a research product for

42   tropospheric NO_2 VCDs, referred to as POMINO-GEMS. We develop a hybrid retrieval method

43   combining GEMS, TROPOMI and GEOS-CF data to generate hourly tropospheric NO_2 slant column

44   densities (SCDs). We then derive tropospheric NO_2 air mass factors (AMFs) with explicit corrections for

45   surface reflectance anisotropy and aerosol optical effects, through parallelized pixel-by-pixel radiative

46   transfer calculations. Prerequisite cloud parameters are retrieved with the O_2-O_2 algorithm by using

47   ancillary parameters consistent with those used in NO_2 AMF calculations.

48   Initial retrieval of POMINO-GEMS tropospheric NO_2 VCDs for June–August 2021 exhibits strong

49   hotspot signals over megacities and distinctive diurnal variations over polluted and clean areas.

50   POMINO-GEMS NO_2 VCDs agree with the POMINO-TROPOMI v1.2.2 product ($R = 0.98$, and NMB

51     $= 4.9\%$) over East Asia, with slight differences associated with satellite viewing geometries and cloud

52   and aerosol properties affecting the NO_2 retrieval. POMINO-GEMS also shows good agreement with

53   OMNO2 v4 ($R = 0.87$, and NMB $= -16.8\%$) and GOME-2 GDP 4.8 ($R = 0.83$, and NMB $= -1.5\%$) NO_2

54   products. POMINO-GEMS shows small biases against ground-based MAX-DOAS NO_2 VCD data at

55   nine sites (NMB $= -11.1\%$) with modest or high correlation in diurnal variation at six urban and suburban

56   sites (R from 0.60 to 0.96). The spatiotemporal variation of POMINO-GEMS correlates well with

57   mobile-car MAX-DOAS measurements in the Three Rivers' Source region on the Tibetan Plateau ($R =$

58   0.81). Surface NO_2 concentrations estimated from POMINO-GEMS VCDs are consistent with

59   measurements from the Ministry of Ecology and Environment of China for spatiotemporal variation (R

60     $= 0.78$, and NMB $= -26.3\%$) as well as diurnal variation at all, urban, suburban and rural sites ($R \geq 0.96$).

61   POMINO-GEMS data will be made freely available for users to study the spatiotemporal variations,

62   sources and impacts of NO_2.

63   **1. Introduction**

64   Tropospheric nitrogen dioxide (NO_2) is an important air pollutant. It threatens human health, and

65   contributes to the formation of tropospheric ozone (O_3) and nitrate aerosols (Crutzen, 1970; Shindell et

66   al., 2009; Hoek et al., 2013; Chen et al., 2022). Satellite instruments provide observations of tropospheric

67   NO_2 on a global scale, and they have been extensively used to estimate emissions of nitrogen oxides

68   (NO_x = NO + NO_2) (Lin and Mcelroy, 2011; Beirle et al., 2011; Gu et al., 2014; Kong et al., 2022a),

69   surface NO_2 concentrations (Wei et al., 2022; Cooper et al., 2022), trends and variabilities (Richter et al.,

70   2005; Cui et al., 2016; Krotkov et al., 2016; Van Der A et al., 2017), and impacts on human health and

71   environment (Chen et al., 2021).

72   To date, most spaceborne instruments for NO_2 measurements, including the Global Ozone

73   Monitoring Instrument (GOME) (Burrows, 1999), the Ozone Monitoring Instrument (OMI) (Levelt et

74   al., 2006), the Global Ozone Monitoring Experiment 2 (GOME-2) (Callies et al., 2000) and the

75   TROPOspheric Monitoring Instrument (TROPOMI) (Veefkind et al., 2012), are mounted on sun-

76   synchronous low Earth orbit (LEO) satellites. These instruments passively measure backscattered

77   radiance from the Earth's atmosphere, and measurements at each ground location are done 1–2 times a

78   day. The Geostationary Environment Monitoring Spectrometer (GEMS) on board the Geostationary

79   Korea Multi-Purpose Satellite-2B (GK-2B) was successfully launched in February 2020. The instrument

80   provides measurements of NO_2 and other pollutants in the daytime on an hourly basis (Kim et al., 2020).

81   It complements LEO satellite observations by providing a more comprehensive picture of the daytime

82   evolution of NO_2.

83   There are three successive stages in the retrieval of tropospheric NO_2 vertical column densities

84   (VCDs) in the UV-Vis range based on satellite observations. The first step is to retrieve total NO_2 slant

85   column densities (SCDs) with spectral fitting techniques, such as the Differential Optical Absorption

86   Spectroscopy (DOAS). The SCD represents the abundance of NO_2 along the effective light path from

87   the sun through the atmosphere to the satellite instrument. Next, the contributions from stratospheric NO_2

88   to the total SCDs are removed in order to obtain tropospheric SCDs. Finally, the tropospheric SCDs are

89   converted to VCDs using calculated air mass factors (AMFs). The AMF calculations are highly sensitive

90   to the observation geometry, cloud parameters, aerosols, surface conditions and the shape of the NO_2

91   vertical distribution. Over polluted areas, errors in the retrieved tropospheric NO_2 VCDs are dominated

92   by the uncertainties in AMF calculations (Boersma et al., 2004; Lorente et al., 2016) associated with

93   aerosol optical effects, surface reflectance and a priori NO_2 vertical profiles (Zhou et al., 2010; Lin et al.,

94   2014; Lin et al., 2015; Vasilkov et al., 2016; Lorente et al., 2018; Liu et al., 2019; Liu et al., 2020;

95   Vasilkov et al., 2021).

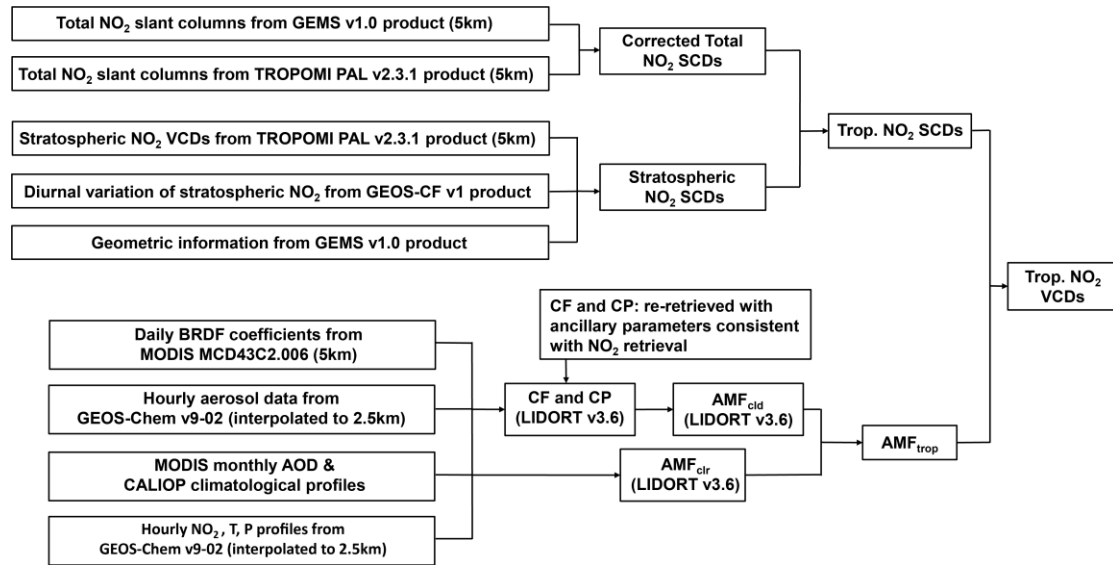
96   The official GEMS retrieval algorithm for tropospheric NO_2 VCDs is developed by Lee et al. (2020).

The total NO_2 SCDs are retrieved using the DOAS technique. They are then converted to total NO_2 VCDs by using a precomputed look-up table of box AMFs based on the linearized pseudo-spherical scalar and vector discrete ordinate radiative transfer code (VLIDORT) version 2.6. Finally, stratosphere-troposphere separation (STS) is performed to derive tropospheric NO_2. Validation results have shown the overall capability of the official GEMS NO_2 algorithm (Kim et al., 2023), but several problems are also reported, such as overestimation of total NO_2 SCDs and tropospheric NO_2 VCDs, and some degree of striping in NO_2 retrieval data.

In this study, we present a research product which we name as POMINO-GEMS. This product is built upon our Peking University OMI NO_2 (POMINO) algorithm which focuses on the tropospheric AMF calculations and has been applied to OMI and TROPOMI (Lin et al., 2014; Lin et al., 2015; Liu et al., 2019; Liu et al., 2020; Zhang et al., 2022). Here we extend the AMF calculation by constructing a hybrid method to estimate tropospheric SCDs for GEMS. The hybrid method makes use of the total SCDs from the official GEMS product, total SCDs and stratospheric VCDs from the official TROPOMI product, as well as hourly stratospheric VCD data from the NASA Global Earth Observing System Composition Forecast (GEOS-CF) v1 product. We validate our initial set of retrieval results for tropospheric NO_2 VCDs in June-July-August (JJA) 2021, by using independent data of tropospheric NO_2 from the POMINO-TROPOMI v1.2.2, OMNO2 v4 and GOME-2 GDP 4.8 products, ground-based and mobile-car MAX-DOAS measurements, and surface concentration observations from the Ministry of Ecology and Environment (MEE) of China. We provide a simplified estimate of retrieval errors in the end.

2. Method and data

2.1 Construction of POMINO-GEMS retrieval algorithm

Figure 1 shows the flow chart of POMINO-GEMS retrieval algorithm. There are two essential steps. The first is to calculate tropospheric NO_2 SCDs on an hourly basis, through fusion of total SCDs from the official GEMS v1.0 L2 NO_2 product, total SCDs and stratospheric VCDs from the TROPOMI PAL v2.3.1 L2 NO_2 product, and diurnal variations of stratospheric NO_2 from the GEOS-CF v1 product. We then calculate tropospheric NO_2 AMFs to convert SCDs to VCDs.

124

125 **Figure 1. Flow chart of POMINO-GEMS retrieval algorithm. The numbers in the boxes, such as 5 km, refer**

126 **to horizontal resolutions.**

127 **2.1.1 GEMS NO$_2$ and cloud data**

128   The GEMS instrument is on board the GK-2B satellite locating at 128.2°E over the equator (Kim

129 et al., 2020). The spectral wavelength range of GEMS is 300-500 nm, covering main absorption spectra

130 of aerosols and trace gases. The nominal spatial resolution is typically 7 km × 8 km for gases and 3.5 km

131 × 8 km for aerosols in the eastern and central scan domains; however, the north-south spatial resolution

132 can exceed 25 km in the western side. The whole field of view (FOV) covers about 20 Asian countries

133 within latitudes 5°S to 45°N and longitudes 80°E to 152°E. Given the variation of solar zenith angle

134 (SZA), there are four scan scenarios moving from east to west, including Half East (HE), Half Korea

135 (HK), Full Central (FC) and Full West (FW). It takes 30 minutes (for example, 00:45 – 01:15 UTC) for

136 GEMS to scan its full coverage during each scenario, and the next 30 minutes to transmit data to the

137 ground data center. The number of hourly GEMS observations per day varies from 6 in winter to 10 in

138 summer, corresponding to the annual movement of subsolar points relative to the Earth.

139   We take hourly total (stratospheric + tropospheric) NO$_2$ SCDs from the official GEMS v1.0 L2 NO$_2$

140 product, and convert them to 0.05° × 0.05 ° gridded data by means of an area-weighted oversampling

141 technique. The value of each grid cell is the mean value of pixel-based GEMS observations weighted by

142 the ratio of the overlap area of each pixel to the area of grid cell. We also use continuum reflectance data

143 (i.e., spectrally smooth reflectance from molecular and aerosol extinction as well as surface reflectance

144 effects) and O$_2$-O$_2$ SCDs from the official GEMS v1.0 L2 cloud product to re-calculate cloud parameters

145   as a prerequisite for tropospheric NO$_2$ AMF calculations. Details of the GEMS retrievals can be found

146   in the algorithm theoretical basis document (ATBD) (Lee et al., 2020).

2.1.2 TROPOMI, OMI and GOME-2 NO$_2$ data

148   Table S1 compares the basic information of GEMS with those of TROPOMI, OMI and GOME-2

149   instruments. In this study, TROPOMI data are used for derivation of POMINO-GEMS NO$_2$ VCDs, and

150   data from all of the three LEO instruments are used for comparison with POMINO-GEMS.

151   We use total NO$_2$ SCDs and stratospheric NO$_2$ VCDs from the official TROPOMI PAL v2.3.1 L2

152   NO$_2$ product, and convert them to 0.05° × 0.05 °gridded data, again using an area-weighted oversampling

153   technique. Details of TROPOMI total SCD retrievals and stratospheric VCD calculations are given in

154   the TROPOMI ATBD (Van Geffen et al., 2022a). The TROPOMI PAL product is reprocessed with

155   TROPOMI NO$_2$ data processor v2.3.1 for the period from 1 May 2018 to 14 November 2021; it will be

156   replaced by the full mission reprocessing with NO$_2$ processor v2.4.0 in the future (Eskes et al., 2021).

157   The most important improvement in this PAL product upon the previous OFFL v1.3 is the replacement

158   of the FRESCO-S algorithm with the FRESCO-wide cloud retrieval algorithm, which leads to higher,

159   more reasonable cloud pressure (CP) estimates and substantial increases in tropospheric NO$_2$ VCDs (by

160   20% – 50%) over polluted regions like Eastern China in winter (Eskes et al., 2021; Van Geffen et al.,

161   2022b).

162   We use the POMINO-TROPOMI v1.2.2, OMNO2 v4 (Lamsal et al., 2021) and GOME-2 GDP 4.8

163   (Valks et al., 2019) tropospheric NO$_2$ VCD products to compare with POMINO-GEMS results. The

164   previous POMINO-TROPOMI v1 data show higher accuracy in polluted situations and improved

165   consistency with MAX-DOAS measurements when compared with the official TM5-MP-DOMINO

166   (OFFLINE) product (Liu et al., 2020). POMINO-TROPOMI v1.2.2 improves upon v1 by (1) using

167   tropospheric NO$_2$ SCD and CP data from the updated TROPOMI PAL v2.3.1 NO$_2$ product, (2)

168   interpolating the daily NO$_2$, pressure, temperature and aerosol vertical profiles from nested GEOS-Chem

169   (v9-02) simulations into a horizontal grid of 2.5 km x 2.5 km for subsequent tropospheric AMF

170   calculations, and (3) including several minor bug fixes.

171   We select valid satellite pixels following common practice. For the daily POMINO-TROPOMI

172   v1.2.2 L2 NO$_2$ product, we exclude pixels with SZA or viewing zenith angle (VZA) greater than 80°,

173   high albedos caused by ice or snow on the ground, quality flag values (from the TROPOMI PAL v2.3.1

174 product) less than 0.5 or cloud radiance fraction (CRF) greater than 50%, and then map the valid data to

175 a $0.05° \times 0.05°$ grid. For the daily OMNO2 v4 L2 NO_2 product, we exclude pixels with SZA or VZA

176 greater than 80°, with scene Lambert-equivalent reflectivity (LER) greater than 0.3, affected by row

177 anomaly (XTrackQualityFlags is not zero), marked without quality assurance (vcdQualityFlag is not an

178 even integer) or with CRF greater than 50%, and then map the valid data to a $0.25° \times 0.25°$ grid. For the

179 daily GOME-2 GDP 4.8 L2 NO_2 product, we exclude pixels with latitude greater than 70°, SZA greater

180 than 80°, failed retrieval (NO2Tropo_Flag is set to 1 or 2) or with CRF greater than 50%, and then map

181 the valid data to a $0.5° \times 0.5°$ grid.

182 **2.1.3 GEOS-CF stratospheric NO_2 data**

183 The NASA GEOS-CF system combines the Global Earth Observing System (GEOS) weather

184 analysis and forecasting system with GEOS-Chem v12.0.1 chemistry module (http://geoschem.org) to

185 provide near real-time estimates of atmospheric compositions with daily 5-day forecasts. Detailed

186 information of the model, including chemistry, emissions and deposition, and evaluation of the GEOS-

187 CF tropospheric simulation and forecast skill are presented in Keller et al. (2021). In particular, the

188 GEOS-Chem v12.0.1 chemistry scheme includes online stratospheric chemistry that is fully coupled with

189 tropospheric chemistry through the Unified tropospheric-stratospheric Chemistry eXtension (UCX)

190 mechanism (Eastham et al., 2014). The GEOS-CF stratospheric results are consistent with satellite

191 observations, albeit with notable underestimation of NO_x and HNO_3 in the polar regions (Knowland et

192 al., 2022b).

193 The GEOS-CF outputs have a horizontal resolution of $0.25° \times 0.25°$ and a temporal resolution of 1

194 hour for NO_2 and other ancillary data used here (Knowland et al., 2022a). We convert instantaneous

195 stratospheric NO_2 volume mixing ratio in dry air at each hour (e.g., 00:00 UTC) into $0.05° \times 0.05°$

196 gridded vertical column densities based on estimated tropopause information in GEOS-CF v1. In Section

197 2.1.5, we first evaluate GEOS-CF v1 stratospheric NO_2 VCDs with those of TROPOMI PAL v2.3.1

198 product, and then calculate hourly stratospheric NO_2 VCDs by combining GEOS-CF v1 data for each

199 hour and TROPOMI PAL v2.3.1 stratospheric NO_2 VCD data in the early afternoon.

200 **2.1.4 Calculation of total NO_2 SCDs**

201 We use TROPOMI data to correct GEMS total NO_2 SCDs, given known issues in GEMS data.

202 Specifics for the NO_2 SCD retrieval of TROPOMI PAL v2.3.1 and GEMS v1.0 operational products are

203   provided in Table S2.

204   Figure 2a and b show the spatial distribution of monthly mean total NO$_2$ geometric column densities

205   (GCDs, calculated as SCDs divided by geometric AMFs) in June 2021 from TROPOMI PAL v2.3.1 and

206   GEMS v1.0, respectively. The horizontal resolution is 0.05° × 0.05 °. The GCDs are used to compare the

207   two products after removing the effect of measurement geometry. Matching for each day between hourly

208   GEMS observations and the TROPOMI data at the closest observation time is done to ensure temporal

209   compatibility. The figures show that the spatial pattern of GEMS GCDs agrees well with that of

210   TROPOMI, with high values over the North China Plain (NCP) and Northwestern India, as well as major

211   metropolitan clusters such as Seoul and the Yangtze River Delta (YRD). However, there are two

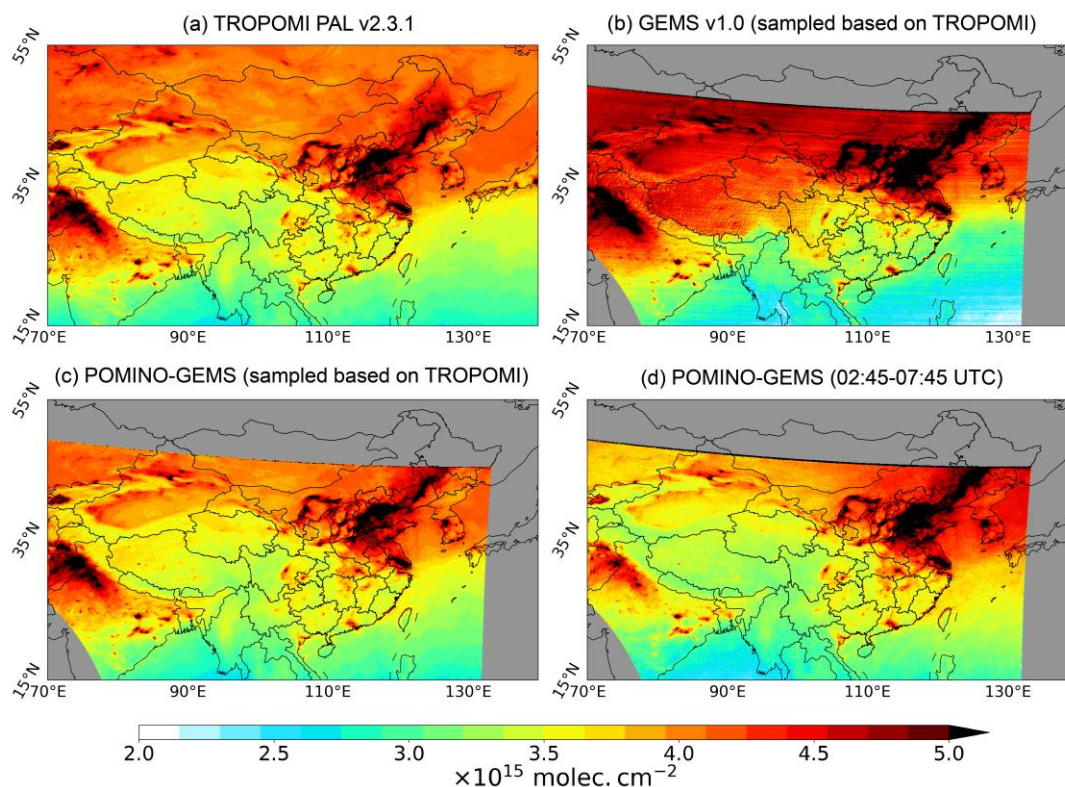
212   systematic problems in GEMS GCDs. First, the GEMS GCD values are abnormally high over the

213   northern and northwestern parts of GEMS FOV, especially over Mongolia, Qinghai, Inner Mongolia,

214   Xinjiang and Tibet of China. Second, west-east stripes exist over the whole domain, similar to the

215   spurious across-track variability issue for OMI. This stripe issue exists at all hours (Figure S1). It is likely

216   associated with the specific scan modes of GEMS, as well as periodically occurring bad pixels as one of

217   remaining calibration issues (Boersma et al., 2011; Lee et al., 2023).

218
219   **Figure 2. Spatial distribution of monthly mean total NO$_2$ GCDs on a 0.05° × 0.05 °grid in June 2021. (a) The**
220   **TROPOMI PAL v2.3.1 product, (b) the official GEMS v1.0 product that spatiotemporally matches with**
221   **TROPOMI, (c) the corrected POMINO-GEMS product that spatiotemporally matches with TROPOMI,**

222 **and (d) the corrected POMINO-GEMS product averaged over 02:45 – 07:45 UTC. Note the range of the**

223 **color bar is 2.0 – 5.0 × 10^{15} molec. cm^{-2}. The regions in grey mean there are no valid observations.**

224 To correct the two issues in the GEMS official total NO_2 SCD product, we combine GEMS and

225 TROPOMI observations to obtain hourly $0.05° \times 0.05°$ corrected total NO_2 SCDs for each day using Eqs.

226 (1) and (2):

$$\Delta GCD = \frac{1}{n} \sum_{i=1}^{n} (GCD_{total,h_i}^{TROPOMI} - GCD_{total,h_i}^{GEMS}) \tag{1}$$

$$SCD_{total,h}^{corrected} = SCD_{total,h}^{GEMS} + \Delta GCD \times AMFgeo_h^{GEMS} \tag{2}$$

229 In Eqs. (1) and (2), index h represents the hour of GEMS observations on each day; h_i the hour

230 when both GEMS and TROPOMI have valid observations for the same grid cell; and n the number of h_i.

231 The value of n is 1 or 2 depending on the overpass times of TROPOMI. There are two steps in the

232 correction process. First, we calculate a geometry-independent correction map for each day using total

233 NO_2 GCDs from GEMS and TROPOMI that match spatially and temporally (Eq. (1)). We use the

234 absolute difference instead of a scaling factor as a simple correction. We then apply the correction to the

235 original GEMS total NO_2 SCDs at each hour on the same day, with the diurnal variation in AMF

236 associated with measurement geometry accounted for (Eq. (2)).

237 In Eq. (2), we implement a simple geometric correction (concerning SZAs and VZAs) for AMFs

238 instead of using the actual AMFs; the latter could account for the differences in relative azimuth angles

239 and other factors. Specific derivation of this assumption is given in Section 1 of the Supplement

240 Information (SI). The correction is assumed to be acceptable with an extra uncertainty introduced to the

241 total NO_2 SCDs, as will be further discussed in Section 3.5.

242 Figure 2c shows the monthly mean corrected POMINO-GEMS total NO_2 GCDs in June 2021 after

243 spatial and temporal matching with TROPOMI. The corrected GCD values in the northern GEMS FOV

244 are much reduced compared with those in the original GEMS data. Moreover, most stripe-like patterns

245 are removed in the corrected GCDs. Figure 2d is similar to Fig. 2c but for GCDs averaged over 02:45 –

246 07:45 UTC in June 2021. Figure S3 further compares the original GEMS and POMINO-GEMS total

247 NO_2 GCDs at each hour in JJA 2021, showing similar improvements as well. The differences between

248 Figure 2c and d indicate the influence of different sampling hours combined with the daily correction

249 map. Specifically, the correction value of each grid cell is calculated at the specific hour when both

250 GEMS and TROPOMI have valid observations, but this value is applied to original GEMS SCDs at all

251 hours.

252   Our correction method is done for each grid cell. We tested other correction methods by applying

253 the same correction value to grid cells within a $20° \times 20°$ domain, at the same latitude, or at the same

254 longitude. These alternative methods can reduce the high bias over the northern and northwestern GEMS

255 FOV to various extents, but cannot remove the stripes (not shown). We also note that our simple

256 correction is a temporary solution before the aforementioned systematic problems in the official GEMS

257 SCD retrieval are solved by improving spectral fitting. In Sections 3.3 and 3.4, we compare the diurnal

258 variations of tropospheric NO_2 VCDs based on corrected and uncorrected GEMS SCDs.

259 **2.1.5 Calculation of stratospheric and tropospheric NO_2 SCDs**

260   We construct a dataset of hourly stratospheric NO_2 SCDs at $0.05° \times 0.05°$ by using TROPOMI PAL

261 v2.3.1 stratospheric NO_2 VCDs, diurnal variation of stratospheric NO_2 VCDs provided by GEOS-CF v1

262 product, and GEMS geometric AMFs.

263   Figure S4 shows the comparison results between GEOS-CF v1 and TROPOMI PAL v2.3.1

264 stratospheric NO_2 VCDs in June 2021. Consistent spatial and temporal sampling is done. N is the total

265 number of matched $0.05° \times 0.05°$ grid cells. The stratospheric VCDs from both products vary in the range

266 of $2 - 5 \times 10^{15}$ molec. cm^{-2}, with spatiotemporal correlation of 0.99, linear regression slope of 0.99 and

267 normalized mean bias (NMB) of 0.02%. This consistency provides confidence on the overall reliability

268 of GEOS-CF stratospheric NO_2 data.

269   First, we calculate stratospheric NO_2 VCDs at a reference hour for each day using Eqs. (3) and (4):

270
$$\text{ratio}_{h_0}^h = \frac{\text{VCD}_{\text{strat},h}^{\text{GEOS-CF}}}{\text{VCD}_{\text{strat},h_0}^{\text{GEOS-CF}}} \tag{3}$$

271
$$\text{VCD}_{\text{strat},h_0} = \frac{1}{n} \sum_{i=1}^{n} \frac{\text{VCD}_{\text{strat},h_i}^{\text{TROPOMI}}}{\text{ratio}_{h_0}^{h_i}} \tag{4}$$

272   Here, Eq. (3) defines the ratio of GEOS-CF stratospheric NO_2 at hour h to that at the reference hour

273 h_0, which is chosen to be 01:00 UTC (Figure S5). In Eq. (4), h_i represents the observation time of every

274 TROPOMI orbit that overlaps with GEMS FOV, and n the number of h_i for each grid cell.

275   Second, we use the ratio from a given time h to h_0 and stratospheric NO_2 VCDs at h_0 to derive

276 stratospheric NO_2 VCDs at h for each day (Eq. (5)).

277
$$\text{VCD}_{\text{strat},h} = \text{VCD}_{\text{strat},h_0} \times \text{ratio}_{h_0}^h \tag{5}$$

278   Figure 3 shows the derived monthly mean stratospheric NO_2 VCDs at each hour in June 2021 on a

279 0.05° × 0.05 °grid. The abrupt decease of stratospheric NO_2 VCDs after sunrise is caused by resumed

280 photochemical conversion of NO_2 to NO (Li et al., 2021b). There is a strong meridional gradient of

281 stratospheric NO_2 in the daytime, with the higher values in the north associated with longer lifetimes.

282 The stratospheric NO_2 increase quasi-linearly during the daytime; linear regression to the mean

283 stratospheric NO_2 VCDs over the whole domain from 01:45 to 07:45 UTC results in an increasing rate

284 of $(1.12\pm0.03) \times 10^{14}$ molec. cm^{-2} h^{-1}. This result is consistent with previous work showing quasi-linear

285 growth in the daytime at rates of $0.5 - 2 \times 10^{14}$ molec. cm^{-2} h^{-1} depending on latitude and season (Li et

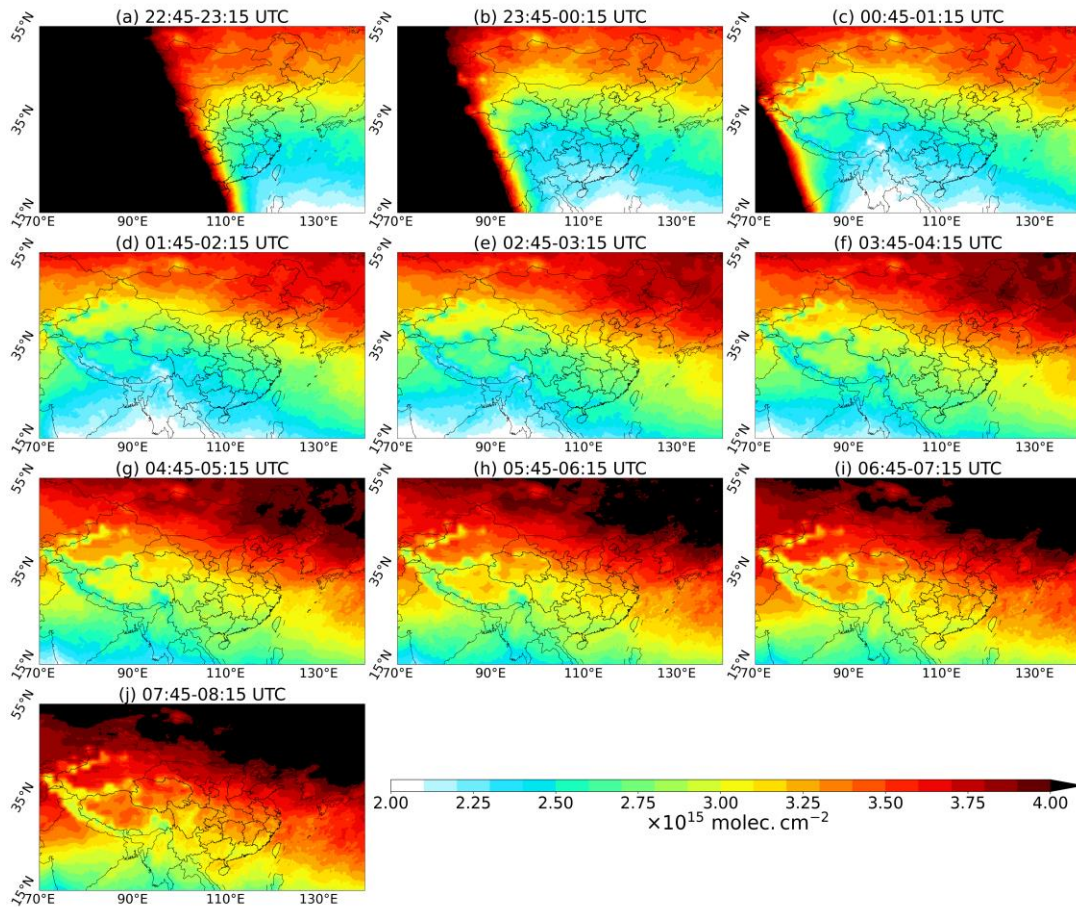
286 al., 2021b; Dirksen et al., 2011).

287 Finally, we use GEMS geometric AMFs to convert the stratospheric NO_2 VCDs to SCDs at each

288 hour, and then subtract them from the total SCDs to obtain tropospheric SCDs (Eqs. (6) and (7)). In the

289 stratosphere, the geometric AMFs are essentially the same as the actual AMFs

290
$$SCD_{strat,h} = VCD_{strat,h} \times AMFgeo_h^{GEMS} \tag{6}$$

291
$$SCD_{trop,h}^{GEMS*} = SCD_{total,h}^{corrected} - SCD_{strat,h} \tag{7}$$

292

293 **Figure 3. Spatial distribution of POMINO-GEMS derived monthly mean stratospheric NO_2 VCDs at each**

294 **hour on a 0.05° × 0.05 °grid in June 2021. Note the range of the color bar is $2.0 - 4.0 \times 10^{15}$ molec. cm^{-2}.**

2.1.6 Calculation of tropospheric AMFs

Tropospheric NO_2 AMF is dependent on three factors as defined in Palmer et al. (2001): the viewing geometry, the scattering weights describing the sensitivity of the backscattered spectrum to the abundance of the absorber, and a priori NO_2 vertical profile (Eq. (8)).

$$\text{AMF} = \text{AMF}_\text{G} \int_0^{z_\text{T}} w(z)S(z)\mathrm{d}z \tag{8}$$

In Eq. (8), AMF_G is the geometric AMF and a function of SZA and VZA, $w(z)$ the scattering weight at altitude z, $S(z)$ the normalized vertical profile of NO_2 number density, and z_T the tropopause. Following Yang et al. (2023), we refer to $\int_0^{z_\text{T}} w(z)S(z)\mathrm{d}z$ as the scattering correction factor for discussion in Section 3.2. For tropospheric AMF calculations (Figure 1), we use a parallelized AMFv6 package driven by LIDORT version 3.6; this is similar to the one used in our previous POMINO products (Lin et al., 2014; Lin et al., 2015; Liu et al., 2019) but with modifications to adapt to the geostationary observing characteristics and high spatiotemporal resolution of GEMS. We take daily BRDF coefficients with a horizontal resolution of 5 km from the MODIS MCD43C2.006 dataset (Lucht et al., 2000) to account for the anisotropy of surface reflectance over land and coastal ocean regions , and OMLER v3 albedo over open ocean (Zhou et al., 2010; Lin et al., 2014; Liu et al., 2020). Hourly-varying aerosol parameters, a priori NO_2 profiles, temperature profiles and pressure profiles are interpolated from nested GEOS-Chem (v9-02) results to a horizontal resolution of 2.5 km, using the Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) method. Furthermore, we deploy AOD observations from the MODIS/Aqua Collection 6.1 MYD04_L2 dataset to constrain model-simulated AOD on a monthly basis (Lin et al., 2014; Lin et al., 2015; Liu et al., 2019; Liu et al., 2020); and we use a self-constructed monthly climatological dataset of aerosol extinction profiles based on CALIOP L2 data over 2007-2015 to constrain modeled aerosol vertical profiles on a monthly climatology basis (Liu et al., 2019). We re-retrieve cloud parameters based on O_2-O_2 SCDs and continuum reflectances from the official GEMS v1.0 cloud product, using ancillary parameters consistent with those used in NO_2 AMF calculations. Instead of relying on a look-up table (LUT), we conduct pixel-by-pixel radiative transfer calculations with the parallelized AMFv6 package. The independent pixel approximation (IPA) is assumed for cloud-contaminated pixels as in other algorithms. Finally, we use the AMF data to convert tropospheric NO_2 SCDs to VCDs.

Invalid pixels in the POMINO-GEMS product are filtered based on the following criteria. We

324 exclude pixels with SZA or VZA greater than 80°, or with the ground covered by ice or snow. To

325 minimize cloud contamination, we exclude pixels with CRF greater than 50%.

2.2 Estimation of surface NO₂ concentrations

327 In order to validate satellite NO₂ products with surface concentration measurements from MEE, we

328 convert tropospheric NO₂ VCDs from satellite products on a 0.05° × 0.05 ° grid to surface NO₂ mass

329 concentrations using GEOS-Chem simulated NO₂ vertical profiles and the box heights of the lowest

330 model layer (Eq. (9)).

$$C_{\text{surf}} = \text{VCD}_{\text{trop}}^{\text{SAT}} \times R^{\text{GC}} \times \frac{M}{N \times H^{\text{GC}}} \times 2 \tag{9}$$

332 In Eq. (9), C_{surf} represents the estimated surface NO₂ mass concentration in µg m⁻³, $\text{VCD}_{\text{trop}}^{\text{SAT}}$ the

333 satellite tropospheric VCD in molecules. m⁻², R^{GC} the GEOS-Chem simulated hourly ratio of NO₂ sub-

334 column in the lowest layer to the total tropospheric column, M the NO₂ molar mass in µg mol⁻¹, N the

335 Avogadro constant, and H^{GC} the box height of the lowest layer in m. The thickness of the lowest layer

336 of GEOS-Chem (about 130 m) is too large for the layer average NO₂ mass concentration to represent

337 that near the ground (Liu et al., 2018a); thus the derived concentration is multiplied by a factor of 2 to

338 roughly account for the vertical gradient from the height of ground instrument to the center of the model

339 layer. However, the constant correction factor of 2 neglects the diurnal variation of NO₂ vertical gradient,

340 which is related to the diurnal variation of planetary boundary layer (PBL) heights. This issue is discussed

341 in detail in Section 3.4.

2.3 Ground-based MAX-DOAS measurements

343 We use ground-based MAX-DOAS NO₂ measurements, together with POMINO-TROPOMI v1.2.2,

344 OMNO2 v4 and GOME-2 GDP 4.8 NO₂ products, to validate the POMINO-GEMS retrieval results. The

345 types, geolocations and observation times of MAX-DOAS stations are summarized in Table S3, and the

346 location of each site is shown in Figure S6. Details of each site are described in Section 2 of the SI.

347 Kanaya et al. (2014) and Hendrick et al. (2014) have discussed the error in MAX-DOAS NO₂ retrieval:

348 uncertainties from a priori aerosol and NO₂ profiles are the largest source by 10% – 14%, and the total

349 retrieval uncertainty is typically 12% – 17%.

350 To ensure sampling consistency in time, we average all valid MAX-DOAS measurements within

351 each observation period of GEMS (i.e., 30 minutes) for hourly comparison, and within ± 1.5 h of

TROPOMI, OMI and GOME-2 overpass time for daily comparison. Following the procedures in previous studies (Lin et al., 2014; Liu et al., 2020), we exclude all matched MAX-DOAS data for which the standard deviation exceeds 20% of the mean value to minimize the influence of local events. To ensure sampling consistency in space, we select valid satellite pixels within 5 km of MAX-DOAS sites for POMINO-GEMS and POMINO-TROPOMI v1.2.2, 25 km for OMNO2 v4 and 50 km for GOME-2 GDP 4.8, and conduct spatial averaging. The Grubbs statistical test, which is used to detect outliers in a univariate data set assumed to exhibit normal distribution (Grubbs, 1950), is performed to exclude outliers in both MAX-DOAS and satellite data before comparison. Only one data pair from Fudan University site is identified as an outlier and removed (Figure S7), and we get 1348 matched hourly data pairs in total.

2.4 Mobile-car MAX-DOAS measurements

We use tropospheric NO_2 VCDs from mobile-car MAX-DOAS measurements performed by the Chinese Academy of Meteorological Sciences (CAMS) in the Three Rivers' Source region in July 2021 (Cheng et al., 2023). The Three Rivers' Source region is on the northeastern Tibetan Plateau in western China, which is isolated from massive anthropogenic activities, and hence a good place for observations of atmospheric compositions in the background atmosphere. The field campaign lasted from 18th to 30th July 2021 and included four closed-loop journeys, beginning from the meteorological bureau of the city of Xining (the Capital of Qinghai Province) to the meteorological bureau of Dari County of the Guoluo Tibetan Autonomous Prefecture, to the meteorological bureau of Yushu Tibetan Autonomous Prefecture, and then back to Xining City (Figure S6). The spectral analysis of the measurement spectra in the fitting window of 400-434 nm was implemented with the DOAS method. Sequential Fraunhofer reference spectrum (FRS) is used to derive NO_2 differential slant column densities (DSCDs), which are then converted to VCDs by adopting the geometric approximation method. The errors are estimated to be less than 20% at high altitudes. More detailed descriptions of instrumentation, field campaign and data retrieval are in Cheng et al. (2023).

We average all valid mobile-car MAX-DOAS measurements within each observation period of GEMS in each 0.05° × 0.05 °grid cell, to ensure spatiotemporal consistency. Over relatively clean areas with little human influence and biomass burning such as the Three Rivers' Source region, a large portion of NO_2 is located in the middle and upper troposphere, which is not accounted for in the mobile-car data

381   via such a DSCD-based retrieval method. Indeed, Cheng et al. (2023) showed that the official TROPOMI

382   NO_2 VCDs are higher than mobile-car data by about 40%. Considering that the diurnal variation of

383   middle and upper tropospheric NO_2 is much smaller than that in the lower troposphere, we focus on the

384   correlation of NO_2 diurnal variation between POMINO-GEMS and mobile car MAX-DOAS data.

385   **2.5 Ground-based MEE NO_2 measurements**

386   We use hourly surface NO_2 mass concentration measurements from the MEE air quality monitoring

387   network. By 2021, more than 2000 MEE stations across China have been established, providing hourly

388   observations for NO_2 and five other air pollutants. Most stations are in urban or suburban areas.

389   The spatial distribution of all MEE sites in the GEMS FOV is shown in Figure S8a, and that of MEE

390   sites over urban, suburban and rural regions are shown in Figure S8b–d, respectively. The classification

391   of sites is based on Tencent user location data with a horizontal resolution of $0.05° \times 0.05°$ for every 0.5

392   second from 31 August to 30 September 2021 (Figure S8e), adopted from previous work (Kong et al.,

393   2022a). Here, urban MEE sites are defined as where the mean location request times is larger than 50

394   times per second, suburban sites refer to 5-50 times per second, and rural sites refer to less than 5 times

395   per second. The number of sites for urban, suburban and rural sites are 808, 554 and 71, respectively.

396   At MEE sites, molybdenum catalyzed conversion from NO_2 to NO and subsequent

397   chemiluminescence measurement of NO is done to estimate NO_2 concentrations. The heated

398   molybdenum catalyst has low chemical selectivity, leading to strong interference from other oxidized

399   nitrogen species such as nitric acid (HNO_3) and peroxyacetyl nitrate (PAN). Therefore, MEE data tend

400   to overestimate the actual NO_2 concentrations, with the extent of overestimation about 10% – 50%

401   (Boersma et al., 2009; Liu et al., 2018a). The overestimation is dependent on the oxidation level of NO_x,

402   but is currently unclear for each site and hour.

403   To compare with satellite-derived surface NO_2 concentration data, we average over all valid MEE

404   sites in each $0.05° \times 0.05°$ grid cell to generate gridded MEE NO_2 data for each hour. To ensure sampling

405   consistency for each day, we average MEE observations at two consecutive hours to match GEMS hourly

406   observations – for example, we match the mean value of MEE NO_2 concentrations in 13:00 – 14:00 and

407   14:00 – 15:00 local solar time (LST) with the GEMS NO_2 in 13:45 – 14:15 LST. We also match MEE

408   observations over the period 13:00 – 14:00 LST with TROPOMI-derived and OMI-derived surface NO_2,

409   and 9:00 – 10:00 LST with GOME-2-derived surface NO_2.

3. Results and discussion

3.1 POMINO-GEMS tropospheric NO₂ VCDs

Figure 4 shows mean POMINO-GEMS tropospheric NO_2 VCDs at each hour on a $0.05° \times 0.05°$ grid in JJA 2021. High values of tropospheric NO_2 columns ($> 10 \times 10^{15}$ molec. cm^{-2}) are evident over populous regions such as South Korea, central and eastern China, and northern India. Clear hotspot signals reveal intense NO_x emissions over city clusters such as Beijing-Tianjin-Hebei (BTH), Yangtze River Delta (YRD), Pearl River Delta (PRD) and Seoul Metropolitan Area (SMA), as well as isolated megacities such as Osaka and Nagoya in Japan, Chengdu and Urumqi in China, and New Delhi in India. Tropospheric NO_2 VCDs are much lower ($< 1 \times 10^{15}$ molec. cm^{-2}) over most of western China and the open ocean, due to low anthropogenic and natural emissions.

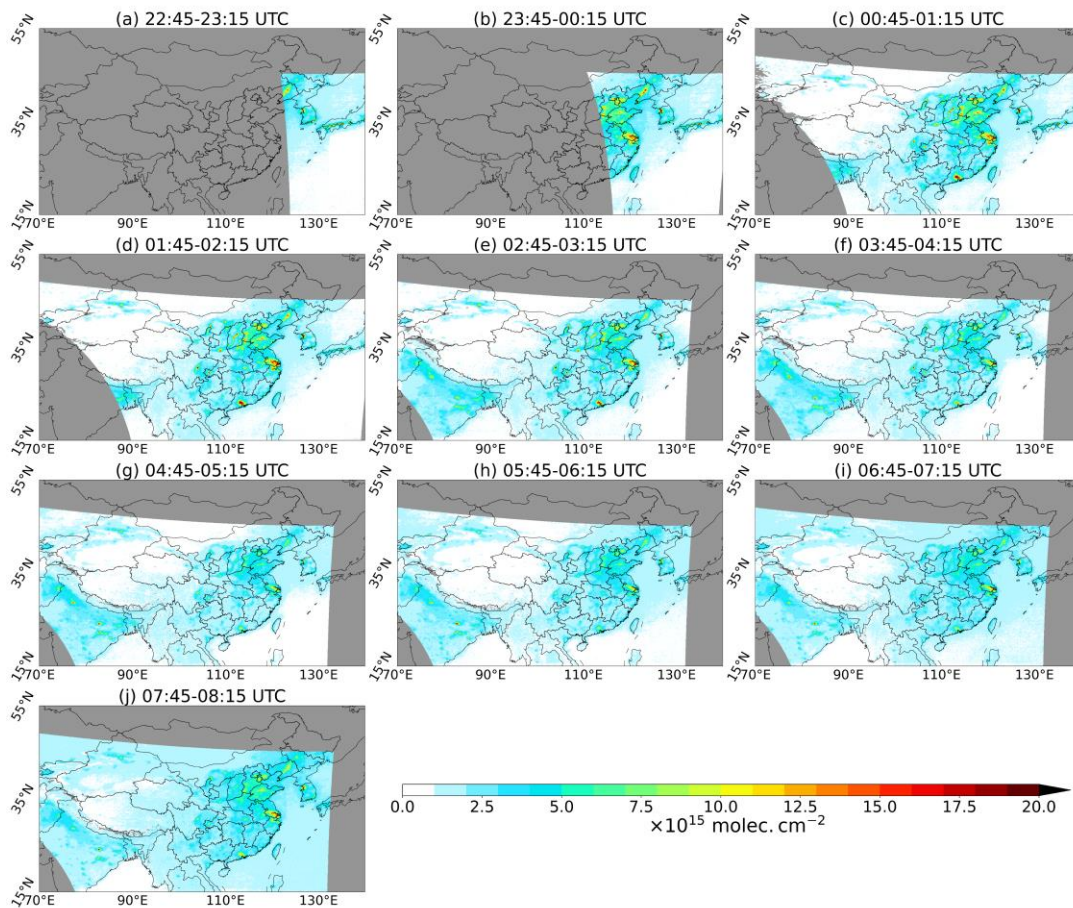



Figure 4. Spatial distribution of POMINO-GEMS tropospheric NO₂ VCDs at each hour on a 0.05° × 0.05° grid in JJA 2021. The regions in grey mean there are no valid observations.

Figure 5a-c present NO_2 VCDs in the morning, noon and afternoon in JJA 2021 for eastern China. Data are averaged in 22:45 – 01:45 UTC (06:45 – 09:45 Beijing Time, BJT), 02:45 – 04:45 UTC (10:45

425 – 12:45 BJT) and 05:45 – 07:45 UTC (13:45 – 15:45 BJT) to represent the morning, noon and afternoon,

426 respectively. In the morning (Figure 5a), there are clear city signals with high NO_2 values, reflecting

427 abundant NO_x emissions from traffic. The spatial gradients of NO_2 from urban centers to outskirts are

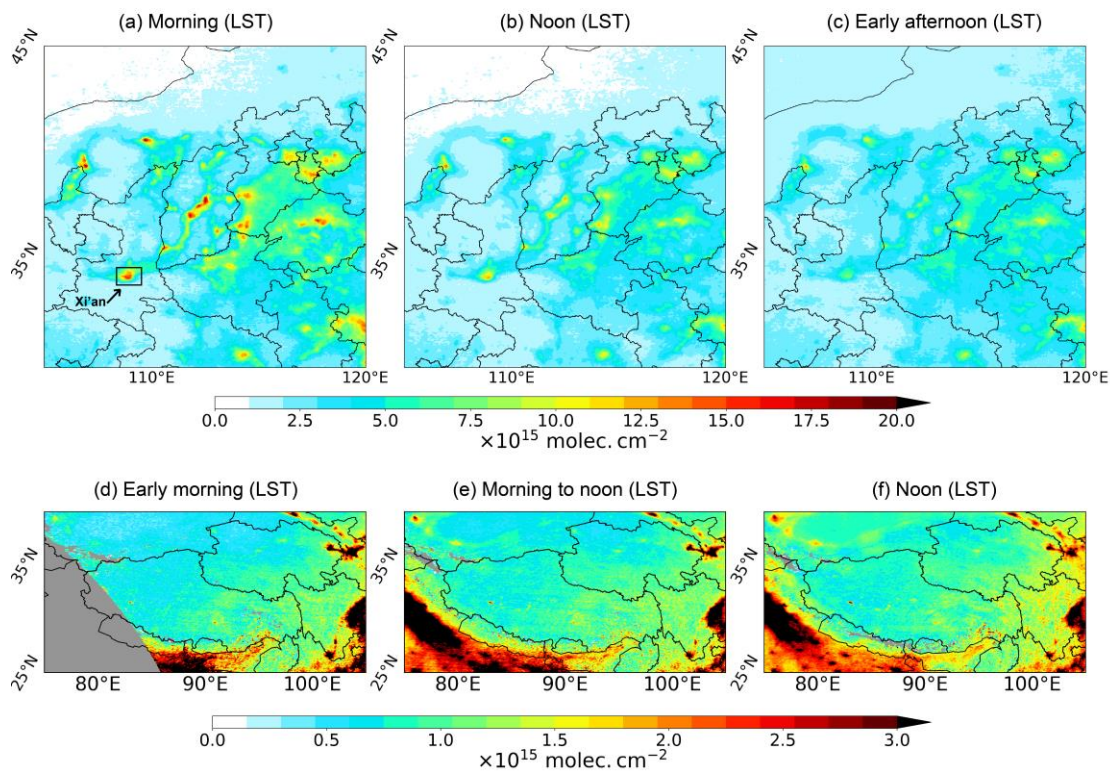
428 very strong. However, these spatial gradients are greatly reduced in the noon and afternoon (Figure 5b

429 and c). For example, the differences of tropospheric NO_2 VCDs between the urban center of Xi'an

430 (108.93°N, 34.27°E) and its surrounding areas (within 50 km) are reduced from about 8×10^{15} molec.

431 cm^{-2} in the morning to about 4×10^{15} molec. cm^{-2} at noon, and then to below 2×10^{15} molec. cm^{-2} in the

432 afternoon. This is likely due to chemical loss of traffic-associated NO_2, increased emissions from other

433 sectors (e.g., industry), and/or enhanced horizontal transport smearing the spatial gradient.

434
435 **Figure 5. Spatial distribution of three-hour-mean POMINO-GEMS tropospheric NO_2 VCDs in JJA 2021 on**
436 **a 0.05° × 0.05 °grid. The first row is for eastern China in the (a) morning (22:45 – 01:45 UTC), (b) noon**
437 **(02:45 – 04:45 UTC) and (c) afternoon (05:45 – 07:45 UTC). The second row is for western China in the (d)**
438 **early morning (00:45 – 01:45 UTC), (e) morning to noon (02:45 – 04:45 UTC) and (f) noon (05:45 – 07:45**
439 **UTC). The regions in grey mean there are no valid observations.**

440 Over western China with low tropospheric NO_2 VCDs (Figure 5d-f), there is a gradual increase of

441 tropospheric NO_2 by about 1×10^{15} molec. cm^{-2} from the early morning to noon. This increase is likely

442 dominated by biogenic NO_x emissions that are sensitive to sunshine intensity and surface temperature

443 (Kong et al., 2022b; Weng et al., 2020; Kong et al., 2023). Future studies are needed to understand the

444   exact causes.

445   Figure 6 shows the diurnal variation of POMINO-GEMS tropospheric NO_2 VCDs over six different

446   region groups in the GEMS FOV. The six groups are defined based on the levels of mean POMINO-

447   GEMS tropospheric NO_2 VCDs at 12:00 LST in JJA 2021 ($VCD_{12:00\ LST}$), and their spatial distributions

448   are also shown in each panel. We convert the observation time from UTC to LST for each time zone in

449   this domain (+5 time zone: 70°E – 82.5° E; +6 time zone: 82.5°E – 97.5°E; +7 time zone: 97.5°E –

450   112.5°E; +8 time zone: 112.5°E – 127.5°E; +9 time zone: 127.5°E – 140°E), and show the NO_2 diurnal

451   variations in each time zone with different colors. For low NO_2 situations ($VCD_{12:00\ LST} \leq 2 \times 10^{15}$ molec.

452   cm^{-2}), NO_2 grow in the morning time in +5 and +6 time zones but not in other time zones. Over high

453   NO_2 situations ($VCD_{12:00\ LST} > 8 \times 10^{15}$ molec. cm^{-2}, in cities and suburban areas), NO_2 in all time zones

454   exhibit a minimum around noontime and a morning peak at 09:00 – 10:00 LST, consistent with previous

455   findings for specific polluted locations (Boersma et al., 2008; Boersma et al., 2009; Li et al., 2021a;

456   Ghude et al., 2020; Herman et al., 2019; Biswas and Mahajan, 2021). In all groups and time zones,

457   tropospheric NO_2 VCDs grow from noon to the afternoon.

458   The NO_2 diurnal variations are related to multiple driving factors. Different sources with distinctive

459   diurnal patterns dominate the NO_x emissions over different regions. Lightning and biogenic activities are

460   the major emission sources over low NO_2 land areas, and they tend to intensify with temperature and

461   radiation in the daytime. Anthropogenic emissions are dominant over polluted cities and suburban areas,

462   where the traffic emissions tend to peak in the mid-morning and late afternoon (Jing et al., 2016; Liu et

463   al., 2018b; Naiudomthum et al., 2022). In addition, the photochemistry plays an important role. NO_2 is

464   in chemical balance with NO, and the ratio of NO_2 and NO depends on radiation, ozone and peroxyl

465   radicals. NO_x is oxidized to nitric acid and organic nitrates by radicals in the daytime, the level of which

466   depends on radiation, ozone and volatile organic compounds. Thus the lifetime of NO_2 reaches the

467   minimum value around noon, i.e., a few hours in summer. Furthermore, atmospheric transport also affects

468   the diurnal variation of NO_2 at high-value places (e.g., cities) and their surroundings. Further studies are

469   needed to determine the exact causes of NO_2 diurnal variations at individual places.

470

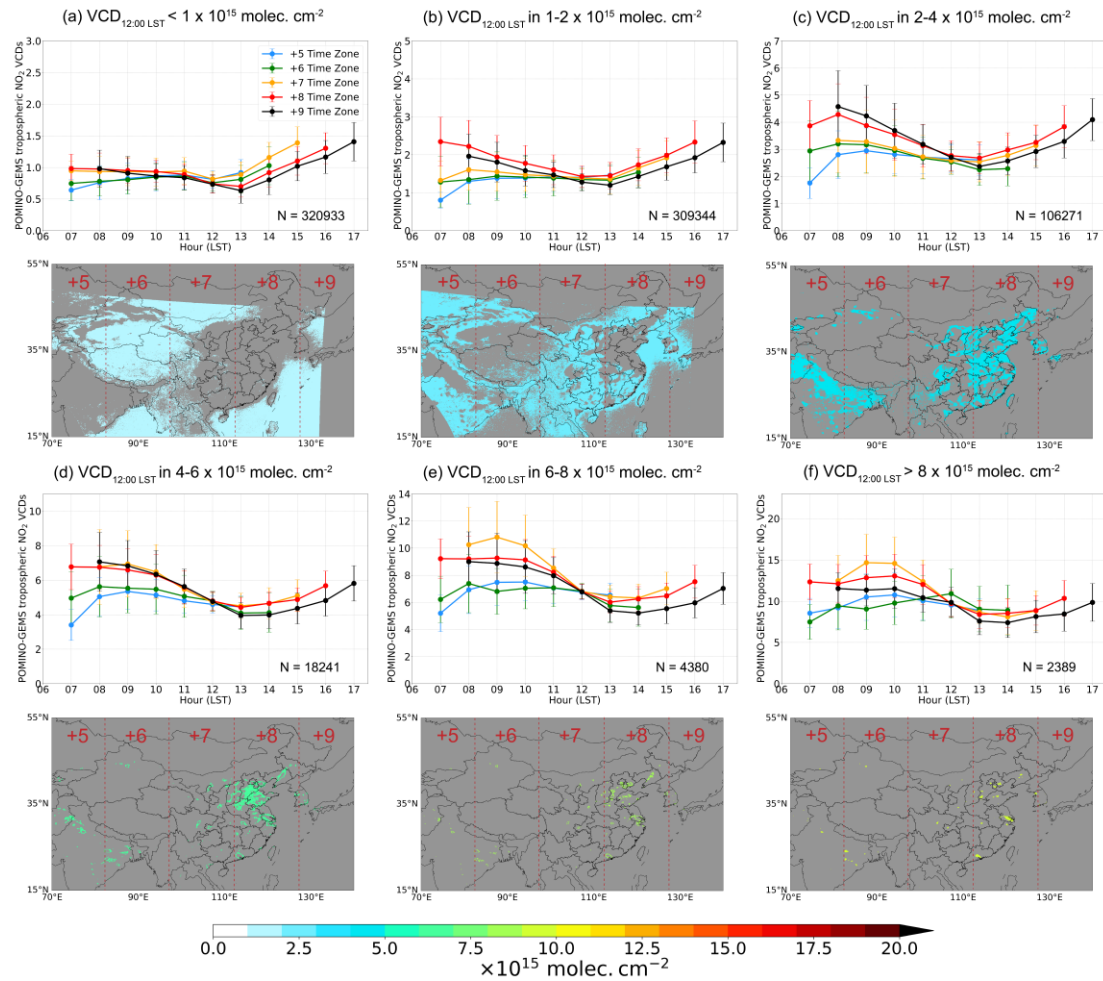



Figure 6. POMINO-GEMS NO₂ diurnal variations for six region groups classified based on mean

472   **POMINO-GEMS tropospheric NO₂ VCDs at 12:00 LST in JJA 2021 (VCD$_{12:00\ LST}$). (a) VCD$_{12:00\ LST}$ less than**

473   **1×10^{15} molec. cm⁻²; (b) VCD$_{12:00\ LST}$ in $1 - 2 \times 10^{15}$ molec. cm⁻²; (c) VCD$_{12:00\ LST}$ in $2 - 4 \times 10^{15}$ molec. cm⁻²;**

474   **(d) VCD$_{12:00\ LST}$ in $4 - 6 \times 10^{15}$ molec. cm⁻²; (e) VCD$_{12:00\ LST}$ in $6 - 8 \times 10^{15}$ molec. cm⁻² and (f) VCD$_{12:00\ LST}$**

475   **larger than 8×10^{15} molec. cm⁻². In each panel, different colors denote the NO₂ diurnal variation in different**

476   **time zones. N denotes the total number of valid 0.05° × 0.05° grid cells in each region. The error bars denote**

477   **the standard deviation of tropospheric NO₂ VCDs at each hour in each time zone.**

478   **3.2 Comparison with POMINO-TROPOMI v1.2.2, OMNO2 v4 and GOME-2 GDP 4.8 NO₂ VCD**

479   **products**

480   Figure 7a and b show the POMINO-GEMS and POMINO-TROPOMI v1.2.2 tropospheric NO₂

481   VCDs, respectively, on a 0.05° × 0.05 ° grid averaged over JJA 2021. Cloud screening is implemented

482   based on the CRFs from each product. To ensure temporal compatibility, matching between hourly

483   GEMS observations and the TROPOMI data at the closest observation time is done for each day. Overall,

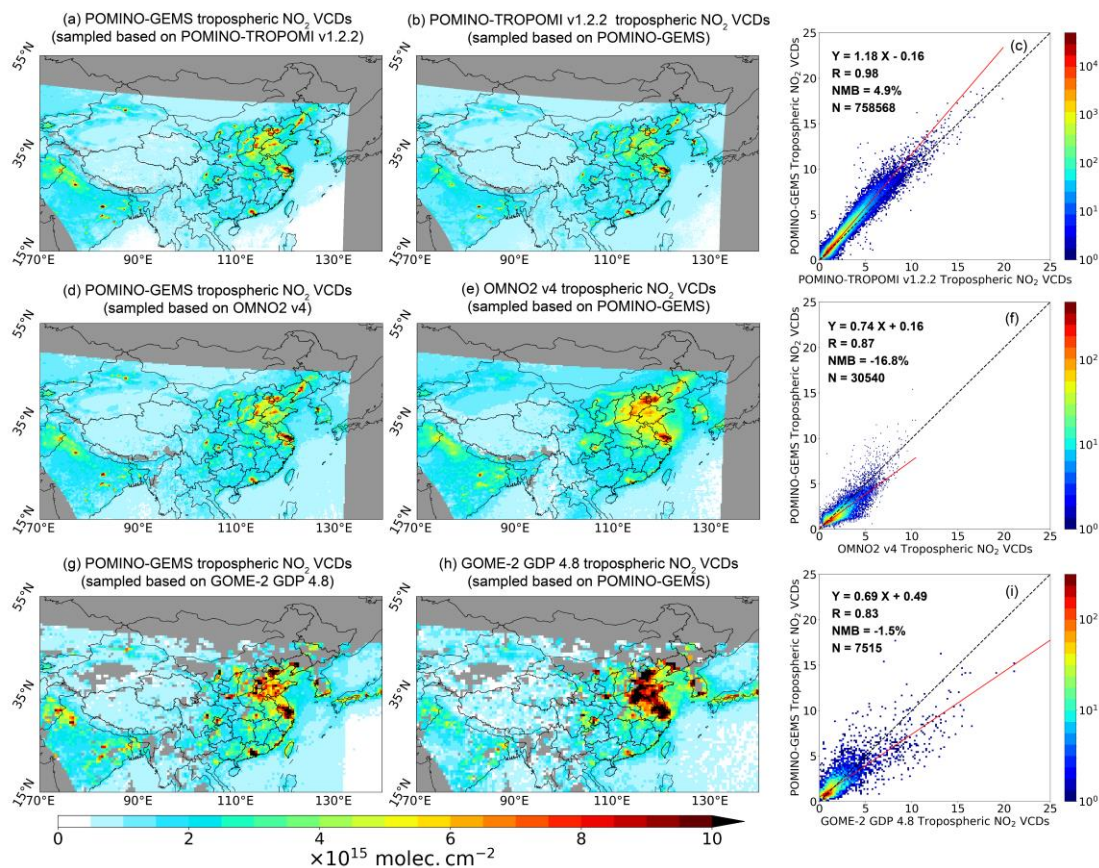
484   POMINO-GEMS agrees well with POMINO-TROPOMI with a spatial correlation coefficient of 0.98, a

485   linear regression slope of 1.18 and a small positive NMB of 4.9% (Figure 7c). Regionally, POMINO-

486 GEMS VCDs are higher than those of POMINO-TROPOMI v1.2.2 over eastern China, most India and

487 northwestern GEMS FOV, but smaller over western China and the oceans (Figure 7a, b; see Figure S9c

488 and d for differences plots). These differences are related to tropospheric NO₂ AMFs and SCDs. Detailed

489 discussion is given in Section 3 of the SI.

490

491 **Figure 7. Comparison between POMINO-GEMS and other products for tropospheric NO₂ VCDs in JJA**

492 **2021. (a-b) Between POMINO-GEMS and POMINO-TROPOMI v1.2.2 on a 0.05° × 0.05 °grid, (d-e)**

493 **between POMINO-GEMS and OMNO2 v4 on a 0.25° × 0.25 °grid, and (g-h) between POMINO-GEMS and**

494 **GOME-2 GDP 4.8 on a 0.5° × 0.5 °grid. (c), (f) and (i) are respective scatterplots, in which the colors**

495 **represent data density. The regions in grey mean there are no valid observations.**

496 Figure 7d-f and g-i show the comparison results of POMINO-GEMS tropospheric NO₂ VCDs with

497 OMNO2 v4 on a 0.25° × 0.25° grid and GOME-2 GDP 4.8 on a 0.5° × 0.5 °grid averaged over JJA 2021,

498 respectively. POMINO-GEMS NO₂ VCDs exhibit good spatial consistency with the two independent

499 products (*R* = 0.87 and 0.83), although with slightly lower values than OMNO2 v4 (by 16.8%) and

500 GOME-2 GDP 4.8 (by 1.5%). These VCD differences are expected, considering the differences in the

501 retrieval algorithm. For example, the POMINO-GEMS algorithm implements explicit aerosol

502 corrections in the radiative transfer calculation, while OMNO2 v4 and GOME-2 GDP 4.8 treat aerosols

503 as "effective clouds". POMINO-GEMS accounts for the anisotropy of surface reflectance by adopting

504 MODIS BRDF coefficients, whereas OMNO2 v4 and GOME-2 GDP 4.8 use geometry-dependent and

505 regular LER, respectively. The horizontal resolution of a priori NO_2 profiles in POMINO-GEMS is 25

506 km (and interpolated to 2.5 km), $1° \times 1.25°$ in OMNO2 v4 and $1.875° \times 1.875°$ in GOME-2 GDP 4.8

507 (Valks, 2019; Lamsal et al., 2021).

508   Based on comparisons with POMINO-TROPOMI v1.2.2, OMNO2 v4 and GOME-2 GDP 4.8 NO_2

509 VCDs, we conclude that POMINO-GEMS NO_2 columns show good agreement with LEO satellite data,

510 with lower values by 20% at most.

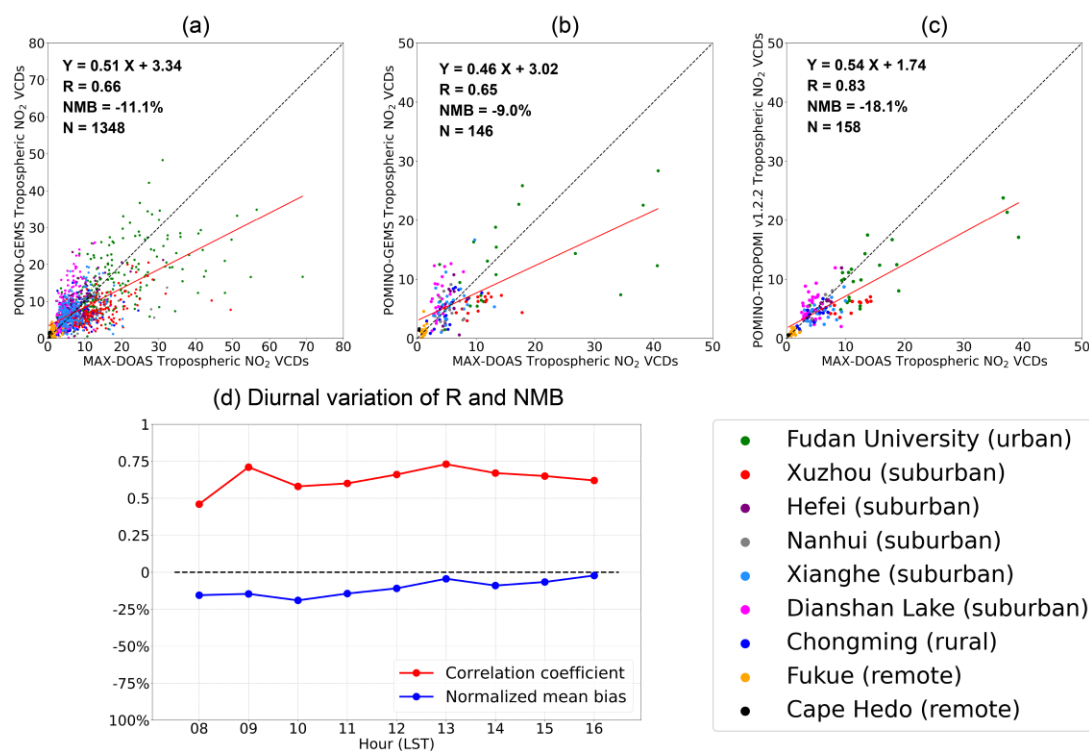
511 **3.3 Validation with MAX-DOAS NO_2 VCD measurements**

512   The scatterplot in Figure 8a compares POMINO-GEMS tropospheric NO_2 VCDs in JJA 2021 at all

513 GEMS observation hours with matched ground based MAX-DOAS measurements at nine sites.

514 POMINO-GEMS correlates with MAX-DOAS ($R = 0.66$) with a small negative bias (NMB = −11.1%).

515 The linear regression shows a slope of 0.51 and intercept of 3.34×10^{15} molec. cm^{-2}, reflecting

516 underestimation of POMINO-GEMS tropospheric NO_2 VCDs on high-NO_2 days.

517
518 **Figure 8. Evaluation of satellite NO_2 VCD data using ground-based MAX-DOAS measurements. (a)**

519 **Scatterplot for tropospheric NO_2 VCDs ($\times 10^{15}$ molec. cm^{-2}) between MAX-DOAS and POMINO-GEMS at**

520 **all GEMS observation hours in JJA 2021. Each data pair denotes an hour. (b-c) Scatterplots for**

521 **tropospheric NO_2 VCDs ($\times 10^{15}$ molec. cm^{-2}) in JJA 2021 (b) between MAX-DOAS and POMINO-GEMS at**

522 **13:45 – 14:15 LST and (c) between MAX-DOAS and POMINO-TROPOMI v1.2.2. Each data pair denotes a**

523 **day. Each MAX-DOAS station is color-coded. (d) Diurnal variations of spatiotemporal correlation**

 coefficients and NMBs of POMINO-GEMS tropospheric NO$_2$ VCDs relative to ground-based MAX-DOAS

 data.

526   Figure 8b-c further use MAX-DOAS measurements to evaluate POMINO-GEMS and POMINO-

527 TROPOMI v1.2.2 tropospheric NO$_2$ VCDs at the overpass time of TROPOMI. In Figure 8b, POMINO-

528 GEMS data at 13:45 – 14:15 LST are used to match the overpass time of TROPOMI. The POMINO-

529 TROPOMI product is evaluated in the context of understanding the relative performance of POMINO-

530 GEMS. Each data point represents a day. Figure 8b-c show that the day-to-day variability of MAX-

531 DOAS measurements is well captured by POMINO-TROPOMI v1.2.2 ($R = 0.83$), but less so by

532 POMINO-GEMS ($R = 0.65$). Linear regression results show an underestimate of tropospheric NO$_2$ VCDs

533 in POMINO-TROPOMI v1.2.2 (NMB = −18.1%), as also found in previous studies (Liu et al., 2020).

534 POMINO-GEMS exhibits a small bias (NMB = −9.0%), but station-dependent performance is apparent.

535 At the two remote sites of Fukue and Cape Hedo with low NO$_2$, POMINO-GEMS NO$_2$ columns are

536 higher than those of MAX-DOAS measurements. At the other sites, the data pairs are more scattered and

537 located both above and below the 1:1 line, resulting in a small NMB.

538   Figure 8d shows the NMBs and correlation coefficients of POMINO-GEMS NO$_2$ VCDs relative to

539 ground-based MAX-DOAS data at each hour. The negative NMBs reach a maximum of about 20% at

540 10:00 BJT, and decrease to less than 10% in the afternoon. The correlation coefficients are modest or

541 high (0.45 – 0.73) at all hours.

542   Figure 9 compares the diurnal variation of tropospheric NO$_2$ VCDs between POMINO-GEMS and

543 MAX-DOAS at eight stations. At each site, NO$_2$ values are averaged in JJA 2021 at each hour for

544 comparison, and the number of valid days for each hour is also shown. The Cape Hedo site is not included

545 because there are few valid MAX-DOAS data points at each hour. Figure 10a-f show that at the urban

546 and suburban sites, MAX-DOAS NO$_2$ (black lines) peaks in the mid-to-late morning, declines towards

547 the minimum values at noon around 13:00 LST, and then gradually increases in the afternoon. Strong

548 correlation of NO$_2$ diurnal variation between POMINO-GEMS (red solid lines) and MAX-DOAS is

549 found at Xuzhou ($R = 0.82$), Hefei ($R = 0.96$), Fudan University ($R = 0.84$), Nanhui ($R = 0.79$) and

550 Xianghe ($R = 0.94$). At the Dianshan Lake site, POMINO-GEMS NO$_2$ columns increase but MAX-

551 DOAS data decrease from 08:00 to 09:00 LST, resulting in a lower correlation coefficient ($R = 0.60$). At

552 Chongming and Fukue sites, MAX-DOAS NO$_2$ shows a peak in the morning without evident increase in

553 the early afternoon, but this diurnal pattern is not fully captured by POMINO-GEMS. At Fukue,

554   POMINO-GEMS NO$_2$ exhibit abrupt changes at 12:00 and 13:00 LST due to few valid data.

555   In addition, comparison of POMINO-GEMS diurnal variation with NO$_2$ data from GOME-2 in the

556   morning and OMI and TROPOMI in the early afternoon shows good agreement at Hefei, Nanhui,

557   Dianshan Lake, Chongming and Fukue sites. The differences between POMINO-GEMS to MAX-DOAS

558   NO$_2$ VCDs are comparable or smaller than those between LEO satellite and MAX-DOAS NO$_2$ VCDs.

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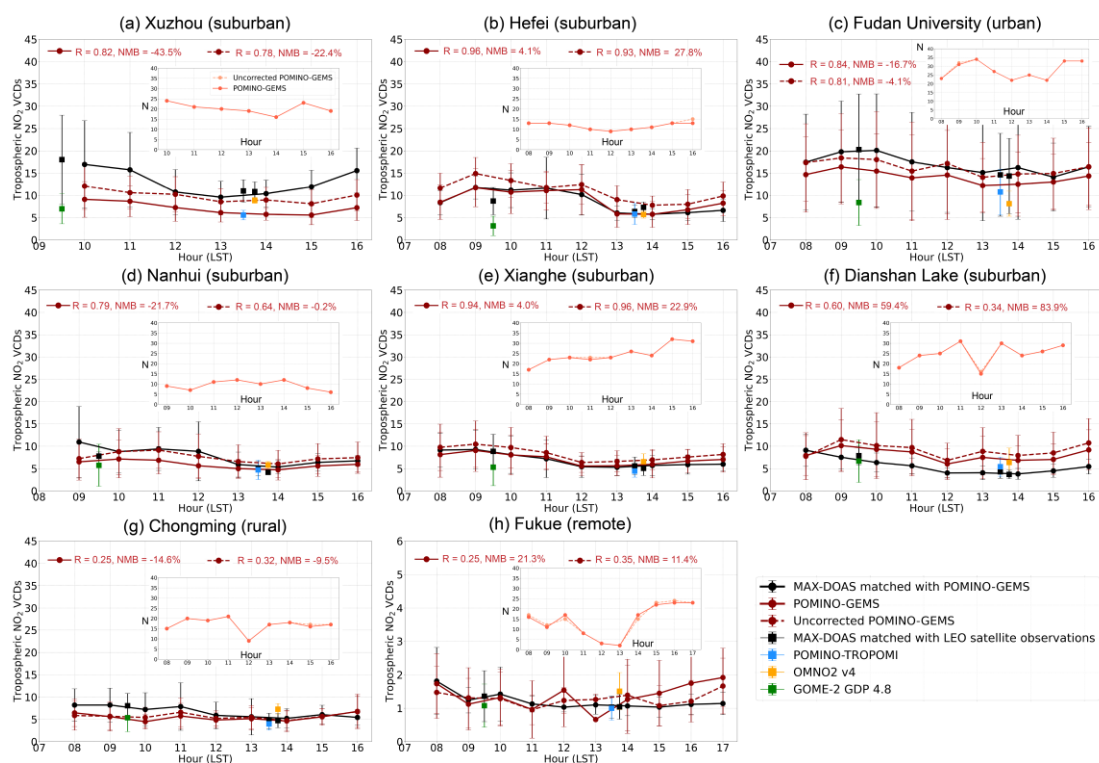


Figure 9. Diurnal variation of hourly tropospheric NO$_2$ VCDs ($\times 10^{15}$ molec. cm^{-2}) of MAX-DOAS (black lines), and POMINO-GEMS with TROPOMI correction (red solid lines). and re-calculated POMINO-GEMS without TROPOMI correction (red dashed lines) at eight sites in JJA 2021. The error bars denote the standard deviation of MAX-DOAS and POMINO-GEMS NO$_2$ at each hour, respectively. Diurnal correlation and all-hour-mean NMB of POMINO-GEMS against MAX-DOAS data are shown. The number of valid days for each hour is also presented. The black squares with an error bar represent the mean value and standard deviation of MAX-DOAS tropospheric NO$_2$ VCDs matched with POMINO-TROPOMI v1.2.2 (blue squares), OMNO2 v4 (orange squares) and GOME-2 GDP 4.8 (green squares), respectively.

568   As we use TROPOMI total NO$_2$ SCDs to correct those of GEMS, this may influence the NO$_2$ diurnal

569   variation of original GEMS observations. Thus we also compare MAX-DOAS data with re-calculated

570   POMINO-GEMS tropospheric NO$_2$ VCDs without correction in total SCDs (red dashed lines in Figure

571   9). Compared to our default POMINO-GEMS data (with correction), excluding the correction leads to

572   lower diurnal correlation coefficients at Xuzhou, Hefei, Fudan University, Nanhui and Dianshan Lake,

573   but higher correlation coefficients at Xianghe, Chongming and Fukue. Excluding the correction increases

574 the NMB at three sites but decreases the NMB at five sites. We conclude that at these eight sites (in the

575 eastern areas), no significant influence on the diurnal variation of POMINO-GEMS tropospheric NO_2

576 VCDs is brought in through TROPOMI-based correction for total NO_2 SCDs.

577   Figure 10 compares the diurnal variations between POMINO-GEMS and mobile-car MAX-DOAS

578 tropospheric NO_2 VCD data in the Three Rivers' Source region on the Tibetan Plateau. Results of

579 POMINO-GEMS with and without total SCD correction are shown in the red solid and dashed lines,

580 respectively. Mobile-car MAX-DOAS data show an evident decrease of tropospheric NO_2 VCDs from

581 the morning to noon with little change thereafter. Such NO_2 diurnal patterns reflect the spatial and

582 temporal variations of tropospheric NO_2 along the driving route. The high NO_2 values with large standard

583 deviation at 09:00 BJT is due to enhanced pollution and variability in the morning when the car is in or

584 near the Xining city. The NO_2 diurnal variations of POMINO-GEMS with correction correlate well with

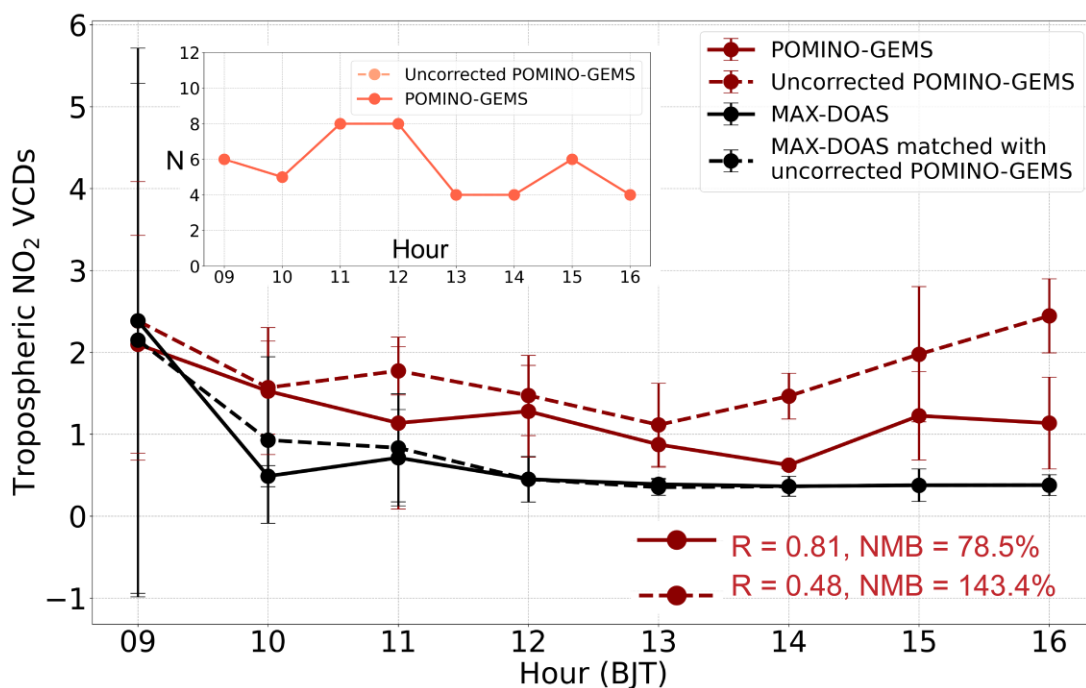
585 those of mobile-car MAX-DOAS data (R = 0.81). In contrast, POMINO-GEMS without total SCD

586 correction exhibits much poorer correlation with mobile-car MAX-DOAS data, due to the erroneous

587 increase in the afternoon.

588   Overall, the validation results with independent ground-based and mobile-car MAX-DOAS

589 measurements provide confidence on the general characteristics of POMINO-GEMS NO_2 diurnal

590 variations.

591

592 **Figure 10. Diurnal variation of hourly mean tropospheric NO_2 VCDs ($\times 10^{15}$ molec. cm^{-2}) of mobile-car**

593 **MAX-DOAS and POMINO-GEMS in the Three Rivers' Source region. The black solid lines denote MAX-**

DOAS data that spatiotemporally match with POMINO-GEMS with total SCD correction (red solid lines). The black dashed lines denote MAX-DOAS data that spatiotemporally match with POMINO-GEMS without correction (red dashed lines). The error bars denote the standard deviation of MAX-DOAS and POMINO-GEMS NO_2 at each hour during the field campaign, respectively. Values for diurnal correlation and mean NMB of POMINO-GEMS relative to MAX-DOAS are shown. The number of days with valid data for each hour is also presented.

3.4 Validation with surface NO_2 concentration measurements from MEE

The scatterplot in Figure 11a compares surface NO_2 concentrations derived from POMINO-GEMS with MEE measurements at all hours. POMINO-GEMS derived surface NO_2 concentrations show good agreement with MEE measurements in terms of spatiotemporal correlation ($R = 0.78$) and bias (NMB = -26.3%), but are higher than those of MEE at some high-value situations, which mainly occur over the YRD region (Figure S14). These differences reflect errors in POMINO-GEMS NO_2 VCDs, in the conversion from tropospheric VCDs to surface concentrations, and in MEE data (due to potential contamination by nitric acid and organic nitrates (Liu et al., 2018a)).

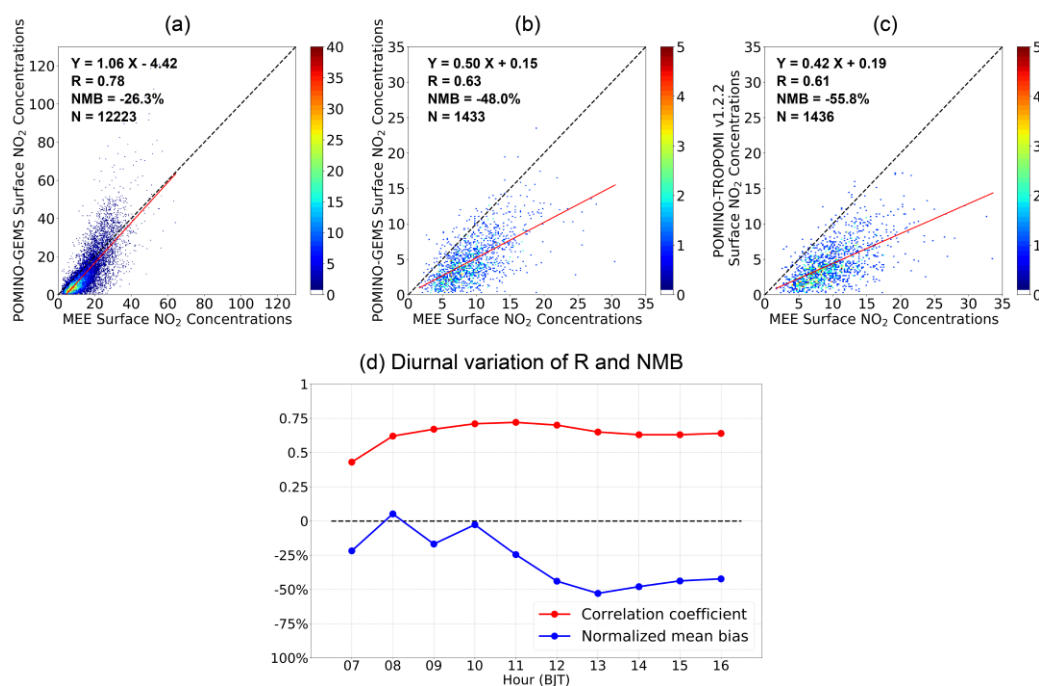



Figure 11. Evaluation of satellite-derived surface NO_2 concentrations (µg m^{-3}) using MEE measurements in JJA 2021. (a) Scatterplot for MEE and POMINO-GEMS at all GEMS observation hours averaged over all days in JJA 2021. (b) Scatterplot for MEE and POMINO-GEMS at 13:45 – 14:15 LST. (c) Scatterplot for MEE and POMINO-TROPOMI v1.2.2. The color bar represents the data density. (d) Diurnal variations of spatiotemporal correlation coefficients and NMBs of POMINO-GEMS derived surface NO_2 concentrations relative to MEE measurements.

Figure 11b-c show validation results for satellite-derived surface NO_2 concentrations with MEE

measurements at the overpass time of TROPOMI (i.e., early afternoon). Here, each data pair denotes a MEE site. POMINO-GEMS results at 13:45 – 14:15 LST are used to match the overpass time of TROPOMI data. Overall, both satellite-based datasets show good spatial correlation with MEE measurements ($R = 0.63$ and 0.61). POMINO-GEMS exhibits higher linear regression slope (0.50) with smaller NMB (−48.0%). The values of satellite data are lower than those from MEE, especially in the afternoon (Figure 11d). This is in part because of the aforementioned contamination issues in MEE data, which becomes severer in the afternoon as the air gets more aged throughout the daytime.

Figure 12a examines the diurnal variation of surface NO_2 concentrations averaged over JJA 2021 at all sites. The MEE data show a smooth and monotonic decline from the early morning to the early afternoon, with a slight increase beginning at 15:00 LST. This diurnal pattern differs from those seen in ground-based MAX-DOAS VCD data (Figure 9), due to the difference in sampling size between MEE and MAX-DOAS, the diurnal variation of NO_2 vertical distribution that affects the relationship between surface and columnar NO_2, as well as the insensitivity of NO_2 columns to changes in PBL heights. POMINO-GEMS derived surface NO_2 concentrations show similar diurnal variations to those of MEE ($R = 0.97$), although with a peak at 10:00 LST and a gradual increase beginning at 14:00 LST. The discrepancies between POMINO-GEMS and MEE surface NO_2 concentrations at different hours are likely caused by the assumed constant correction factor of 2 to account for the vertical gradient of NO_2 from the height of ground instrument to the center of the first model layer (Section 2.2). In the morning when the PBL is low, most NO_2 molecules are near the ground and the vertical gradient of NO_2 over polluted regions is the largest in the daytime, so the factor of 2 may lead to underestimation of derived surface NO_2 concentrations. In contrast, in the afternoon, the PBL mixing is much stronger and the vertical gradient of NO_2 is much smaller, thus the factor of 2 may lead to overestimated surface NO_2 concentrations. Note that the consistency between POMINO-GEMS and MEE data does not depend on the total SCD correction (Table S4).

To quantify the influences of the diurnal variation of hourly column-to-surface ratio from GEOS-Chem simulations, we compare the MEE measurements with POMINO-GEMS derived surface NO_2 concentrations using daily column-to-surface ratio (Figure S15). As expected, POMINO-GEMS derived NO_2 concentrations show a similar diurnal variation as the tropospheric NO_2 VCDs do, with two peaks in the mid-morning and afternoon, and a minimum at noon. The temporal correlation coefficient with

645 MEE is only about 0.23. Thus it is more reasonable to use hourly ratio for comparison with MEE

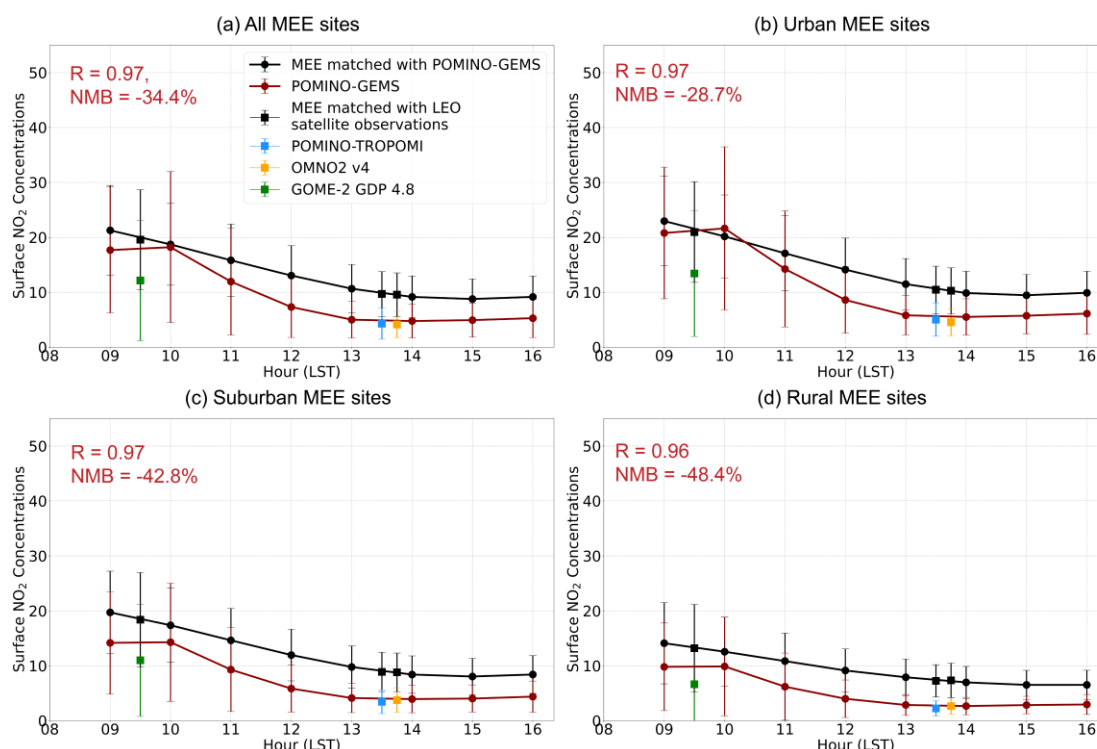
646 measurements, as done in our study.

647   To further test the reliability of our VCD-to-surface-concentration conversion method (Eq. (9)), we

648 apply the same method to MAX-DOAS NO_2 VCDs and compare the resulting surface NO_2

649 concentrations with MEE data. As shown in Figure S16, the diurnal variation of MAX-DOAS derived

650 surface NO_2 concentrations correlates well with that of MEE measurements ($R = 0.96$), in support of our

651 conversion method.

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653 **Figure 12. Diurnal variation of hourly surface NO_2 concentrations (µg m^{-3}) of MEE (back lines) and**

654 **POMINO-GEMS (red lines) in JJA 2021. (a) At all MEE sites, (b) at urban sites, (c) at suburban sites and**

655 **(d) at rural sites. The error bars denote the standard deviation of MEE and POMINO-GEMS derived**

656 **surface NO_2 concentrations at each hour in JJA 2021, respectively. Diurnal correlation and mean NMB of**

657 **POMINO-GEMS relative to MEE are also listed. The black squares with an error bar represent the mean**

658 **value and standard deviation of MEE data matched with POMINO-TROPOMI v1.2.2 (blue squares),**

659 **OMNO2 v4 (orange squares) and GOME-2 GDP 4.8 (green squares), respectively.**

660   Figure 12b-d show the comparison of NO_2 diurnal variations for different groups of MEE sites. The

661 diurnal variations of POMINO-GEMS derived surface NO_2 concentrations show similar characteristics

662 over urban, suburban and rural regions, and all correlate well with those of MEE data. Meanwhile,

663 surface NO_2 concentrations derived from LEO satellite observations also agree well with those of

664 POMINO-GEMS, except that POMINO-GEMS derived surface NO_2 concentrations are higher than

665 those of GOME-2 GDP 4.8 by about 40% – 60%. We conclude that validation with extensive MEE

666 measurements presents promising performance of POMINO-GEMS retrievals, especially the great

667 agreement of POMINO-GEMS NO_2 diurnal variation with MEE data over urban, suburban and rural

668 regions.

669 **3.5 Error estimates for POMINO-GEMS tropospheric NO_2 VCDs**

670 Total retrieval errors for POMINO-GEMS tropospheric NO_2 VCDs are derived from the

671 calculations of total SCDs, stratospheric SCDs, and tropospheric AMFs. Spatial and temporal averaging

672 across GEMS pixels can greatly reduce the random errors, but will not affect the systematic errors. Here,

673 we provide a preliminary estimate of POMINO-GEMS errors for the summertime retrieval discussed

674 above.

675 As described in Section 2, we calculate hourly total SCDs based on the original GEMS SCD data

676 and daily TROPOMI-guided corrections. According to the GEMS ATBD of NO_2 retrieval algorithm, the

677 SCD errors from the DOAS method are < 5.65% at high-NO_2 conditions (NO_2 VCD > 1×10^{15} molec.

678 cm^{-2}) (Lee et al., 2020). The NO_2 SCD errors of TROPOMI are reported to be $0.5 – 0.6 \times 10^{15}$ molec.

679 cm^{-2} (10% in a relative sense) (Van Geffen et al., 2022a). Given the assumption we made in adjusting

680 GEMS total SCDs to match TROPOMI values, we tentatively estimate the error in our corrected total

681 SCD data to be $0.5 – 0.7 \times 10^{15}$ molec. cm^{-2} (10% in a relative sense) for most regions and 0.9×10^{15}

682 molec. cm^{-2} (20% – 30%) at the edge of the northwestern GEMS FOV.

683 In constructing the stratospheric NO_2 SCDs, the stratospheric VCDs are taken from TROPOMI PAL

684 v2.3.1, scaled based on GEOS-CF v1 stratospheric NO_2 to account for diurnal variation, and then applied

685 with geometric AMFs. We assign a constant error of 0.2×10^{15} molec. cm^{-2} (5% – 10%) to our hourly

686 stratospheric SCDs, the same as the value for TROPOMI (Van Geffen et al., 2022a). Few studies have

687 assessed the accuracy of stratospheric NO_2 and its diurnal variation from GEOS-CF data (Knowland et

688 al., 2022b), but our comparison between GEOS-CF and TROPOMI shows great consistency (Section

689 2.1.5). As most of the errors in total SCDs are absorbed in the stratosphere-troposphere separation step

690 (Van Geffen et al., 2015), the errors in tropospheric SCDs should be 10% – 30% depending on different

691 cases, with higher relative biases in cleaner situations.

692 Tropospheric AMF calculations are the dominant error source for retrieved tropospheric NO_2 VCDs

693 over polluted regions. According to Liu et al. (2020), the AMF errors caused by uncertainty in surface

reflectance are about 10%, and errors induced by uncertainties in aerosol parameters are about 10% in clean regions and 20% for heavily polluted situations. We further assume that the O_2-O_2 cloud retrieval algorithm introduces another error at the 10% level to the NO_2 AMFs. The uncertainty in a priori NO_2 vertical profiles is estimated to cause an AMF error by 10% (Liu et al., 2020). Yang et al. (2023) suggested that the NO_2 profiles from GEOS-Chem (version 13.3.4) might contain incorrect timing of PBL mixing growth in the morning and thus introduce a relative root-mean-square error of 7.6% and NMB of 2.7% in AMF; however, this error could be greatly dampened by averaging over a long time period. The free tropospheric NO_2 bias in GEOS-Chem NO_2 profiles might also contribute to the retrieval errors especially over remote regions. Adding these errors in quadrature leads to the overall AMF errors for POMINO-GEMS at 20% – 40%.

The overall uncertainty in POMINO-GEMS tropospheric NO_2 VCDs is estimated by adding in quadrature the errors in tropospheric NO_2 SCDs and AMFs, when these errors are expressed in the relative sense. For remote regions with low tropospheric NO_2 abundances, the overall retrieval uncertainties can reach 30% – 50% and are dominated by errors in tropospheric SCDs. For regions with abundant tropospheric NO_2, the uncertainties of retrieved tropospheric VCDs are dominated by the AMF errors and are estimated to be about 20% – 30%.

As shown in Figure 8d and Figure 11d, the maximum negative NMB of POMINO-GEMS tropospheric NO_2 VCDs relative to ground-based MAX-DOAS data is about 20% in the mid-morning, and the NMB of POMINO-GEMS derived surface NO_2 concentrations to MEE measurements is −30% on average. Thus our estimated error magnitude is supported by the independent ground-based MAX-DOAS and MEE data.

4. Conclusions

The GEMS instrument provides an unprecedented opportunity for air quality monitoring at a high spatiotemporal resolution. Our POMINO-GEMS algorithm retrieves tropospheric NO_2 VCDs as a research product. The algorithm first calculates hourly tropospheric NO_2 SCDs through fusion of total NO_2 SCDs from the GEMS v1.0 L2 NO_2 product, total and stratospheric NO_2 columns from the TROPOMI PAL v2.3.1 L2 NO_2 product, and stratospheric NO_2 diurnal variations from the GEOS-CF v1 dataset. The fusion approach reduces the high bias in total SCDs and removes the stripe-like patterns in the official GEMS v1.0 product. Our algorithm then calculates tropospheric NO_2 AMFs to convert SCDs

723   to VCDs. A preliminary estimate of retrieval errors is also given.

724   Our initial POMINO-GEMS data for JJA 2021 shows high values of tropospheric NO_2 VCDs with

725   clear hotspots ($> 10 \times 10^{15}$ molec. cm^{-2}) over regions where anthropogenic emissions of NO_x are abundant.

726   The spatial gradients of tropospheric NO_2 VCDs from urban centers to surrounding areas are substantial

727   in the morning due to traffic emissions, but the gradients are much reduced at noon and in the afternoon.

728   A gradual increase of tropospheric NO_2 VCDs from the morning to noon is observed over clean regions

729   of western China, likely as a result of enhanced biogenic emissions. Over high NO_2 regions where

730   anthropogenic activities dominate the NO_x emissions, NO_2 columns increase until a peak at $09:00 - 10:00$

731   LST, decrease to the minimum at noon and then increase in the afternoon again. Such characteristics of

732   NO_2 diurnal variations are associated with the changes in natural and anthropogenic NO_x emissions,

733   photochemistry and atmospheric transport.

734   POMINO-GEMS tropospheric NO_2 VCDs agree well with POMINO-TROPOMI v1.2.2 in terms of

735   spatial correlation (0.98) and NMB (4.9%). POMINO-GEMS data are also consistent with the OMNO2

736   v4 tropospheric NO_2 VCD product in the early afternoon and GOME-2 GDP 4.8 tropospheric NO_2 VCD

737   product in the morning, with R of 0.87 and 0.83, and NMB of -16.8% and -1.5%, respectively.

738   POMINO-GEMS tropospheric NO_2 VCDs are comparable with ground-based MAX-DOAS

739   measurements at nine ground-based sites with a small NMB (-11.1%), although the correlation is modest

740   ($R = 0.66$). Both the bias and correlation values are smaller than POMINO-TROPOMI v1.2.2 (NMB =

741   -18.1%, $R = 0.83$). More importantly, POMINO-GEMS well captures the diurnal variation of MAX-

742   DOAS NO_2 VCDs at Xuzhou ($R = 0.82$), Hefei ($R = 0.96$), Fudan University ($R = 0.84$), Nanhui ($R =$

743   0.79), Xianghe ($R = 0.94$) and Dianshan Lake ($R = 0.60$) sites, although the correlations are relatively

744   poor at Chongming and Fukue sites. Comparison with mobile-car MAX-DOAS measurements in the

745   Three Rivers' Source region on the Tibetan Plateau also shows good correlation in NO_2 diurnal variation

746   ($R = 0.81$).

747   We also compare surface NO_2 concentrations derived from tropospheric NO_2 VCDs in POMINO-

748   GEMS and POMINO-TROPOMI v1.2.2 against MEE data, taking advantage of the large number of

749   MEE sites. POMINO-GEMS derived surface NO_2 concentration data exhibit a small NMB (-26.3%).

750   For these sites at TROPOMI overpass times, POMINO-GEMS derived surface NO_2 concentrations show

751   a smaller magnitude of NMB (-48.0%) than POMINO-TROPOMI v1.2.2 (-55.8%). Excellent

agreement in diurnal variation between POMINO-GEMS derived and MEE NO_2 is exhibited over all (R = 0.97), urban (R = 0.97), suburban (R = 0.97) and rural (R = 0.96) sites.

Overall, our comprehensive validation process highlights the good performance of POMINO-GEMS tropospheric NO_2 VCD product, both in magnitude and spatiotemporal variation. However, there are still several limitations in our study. To address the systematic overestimation and stripes problems in the original GEMS data, we correct GEMS total NO_2 SCDs by using TROPOMI data as a temporary solution. For example, we implement a simple geometric correction to combine GEMS and TROPOMI total NO_2 SCDs, but their differences in scattering geometry are only partly accounted for. Thus this correction works well in most regions, but may introduce SCD uncertainties up to 0.9×10^{15} molec. cm^{-2} (20% – 30%) at the edge of the northwestern GEMS FOV. Currently, the Environmental Satellite Center of South Korea is updating the NO_2 SCD data to v2.0. We will update our POMINO-GEMS algorithm accordingly, once the updated official NO_2 product becomes available to provide necessary inputs for our research product. In addition, in the conversion from NO_2 VCDs to surface concentrations, we use a constant correction factor of 2 to account for the strong NO_2 vertical gradient near the surface. This simple treatment does not account for the diurnal variation of the correction factor, and thus may introduce errors in the derived surface NO_2 concentrations. Nevertheless, the current POMINO-GEMS data serve as our initial attempt to derive the diurnal variations of tropospheric NO_2 at a high spatiotemporal resolution from GEMS, and they are expected to offer a useful source of information for various applications such as air quality analysis and emission constraint.

Data availability. The POMINO-GEMS NO_2 data will be freely available soon at the ACM group product website (http://www.pku-atmos-acm.org/acmProduct.php/). The TROPOMI PAL v2.3.1 L2 product can be downloaded from https://data-portal.s5p-pal.com. The OMNO2 v4 L2 product can be downloaded from https://aura.gesdisc.eosdis.nasa.gov/data/Aura_OMI_Level2/OMNO2.003/. The GOME-2 GDP 4.8 L2 product can be downloaded from http://acsaf.org/ after registration. The GEOS-CF v1.0 dataset can be downloaded from https://gmao.gsfc.nasa.gov/weather_prediction/GEOS-CF/data_access/. The MEE surface NO_2 measurements can be downloaded from https://quotsoft.net/air/. The ground-based and mobile-car MAX-DOAS measurements can be provided upon requests to the corresponding owners.

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Author contributions. JL conceived this research. YZ and JL designed the algorithm and validation process. YZ performed all calculations with additional code support from HK. YZ and JL wrote the paper. RS provided LIDORT. JK, HL, JP and HH provided GEMS data. MVR, FH, TiW, PW, QH, KQ, YC, YK, JX, PX, XT, SZ and SW provided the ground-based MAX-DOAS measurements. SC, XC, JM and ThW provided the mobile-car MAX-DOAS measurements. HK helped process MEE measurements. LC and ML helped analyze the validation results. All authors commented on the paper.

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

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