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

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Abstract
Nitrogen dioxide (NO₂) is a major air pollutant. Tropospheric NO₂ vertical column densities (VCDs) retrieved from sun-synchronous satellite instruments have provided abundant NO₂ data for environmental studies, but such data are limited by insufficient temporal sampling (e.g., once a day). The Geostationary Environment Monitoring Spectrometer (GEMS) launched in February 2020 monitors NO₂ at an unprecedented high temporal resolution. Here we present a research product for tropospheric NO₂...
VCDs, referred to as POMINO-GEMS. We develop a hybrid retrieval method combining GEMS and TROPOMI observations as well as GEOS-Chem simulations to generate hourly tropospheric NO$_2$ slant column densities (SCDs). We then derive tropospheric NO$_2$ air mass factors (AMFs) with explicit corrections for the anisotropy of surface reflectance and aerosol optical effects, through pixel-by-pixel radiative transfer calculations. Prerequisite cloud parameters are retrieved with the O$_2$-O$_2$ algorithm by using ancillary parameters consistent with those used in NO$_2$ AMF calculations. Initial retrieval of POMINO-GEMS tropospheric NO$_2$ VCDs for June–August 2021 reveals strong hotspot signals over megacities and distinctive diurnal variations over polluted and clean areas. POMINO-GEMS NO$_2$ VCDs agree well with our POMINO-TROPOMI v1.2.2 product ($R = 0.97$, and NMB = 3.6%) over Asia. Comparison with ground-based MAX-DOAS VCD data at nine sites shows a small bias of POMINO-GEMS (NMB = –15.7%); however, the correlation for diurnal variation varies from -0.66 to 0.90, suggesting location-dependent performance. Surface NO$_2$ concentrations estimated from POMINO-GEMS VCDs are consistent with measurements from the Ministry of Ecology and Environment of China at 855 sites (NMB = –24.1%, and $R = 0.95$ for diurnal correlation averaged over all sites). POMINO-GEMS data will be made freely available for users to study the spatiotemporal variations, sources and impacts of NO$_2$.

1. Introduction

Tropospheric nitrogen dioxide (NO$_2$) is an important air pollutant. It is a threat to human health, and also contributes to the formation of tropospheric ozone (O$_3$) and nitrate aerosol as an essential precursor (Crutzen, 1970; Shindell et al., 2009; Hoek et al., 2013; Chen et al., 2022). Satellite instruments provide observations of tropospheric NO$_2$ on a global scale, and they have been extensively used to estimate emissions of nitrogen oxides (NOx = NO + NO$_2$) (Lin and Mcelroy, 2011; Beirle et al., 2011; Gu et al., 2014; Kong et al., 2022a), surface NO$_2$ concentrations (Wei et al., 2022; Cooper et al., 2022), trends and variabilities (Richter et al., 2005; Cui et al., 2016; Krotkov et al., 2016; Van Der A et al., 2017), and impacts on human health and environment (Chen et al., 2021).

To date, most spaceborne instruments for NO$_2$ measurements, including the Ozone Monitoring Instrument (OMI), the Global Ozone Monitoring Experiment 2 (GOME-2) and the TROPospheric Monitoring Instrument (TROPOMI), are mounted on sun-synchronous low Earth orbit (LEO) satellites (Boersma et al., 2011; Richter et al., 2011; Van Geffen et al., 2020). These instruments passively measure
backscattered radiance from the Earth’s atmosphere, and measurements at each ground location are done 1–2 times a day. The Geostationary Environment Monitoring Spectrometer (GEMS) on board the Geostationary Korea Multi-Purpose Satellite-2B (GK-2B) was successfully launched in February 2020. The instrument provides measurements of NO$_2$ and other pollutants in the daytime on an hourly basis (Kim et al., 2020). It complements LEO satellite observations by providing a more comprehensive picture of the daytime evolution of NO$_2$.

There are three successive stages in the retrieval of tropospheric NO$_2$ vertical column densities (VCDs) in the UV-Vis range based on satellite observations. The first step is to retrieve total NO$_2$ slant column densities (SCDs) with the Differential Optical Absorption Spectroscopy (DOAS) technique, which provides the abundance of NO$_2$ along the effective light path from the sun through the atmosphere to the satellite instrument. Next, the contributions from stratospheric NO$_2$ to the total SCDs are removed in order to obtain tropospheric NO$_2$ SCDs. Finally, the tropospheric SCDs are converted to VCDs using calculated air mass factors (AMFs), which are highly sensitive to the observation geometry, cloud parameters, aerosols, surface conditions and the shape of the NO$_2$ vertical distribution. Over polluted areas, errors in the retrieved tropospheric NO$_2$ VCDs are dominated by the uncertainties in AMF calculations (Boersma et al., 2004; Lorente et al., 2016); errors are sensitive to assumptions on aerosol optical effects, surface reflectance, and a priori NO$_2$ vertical profiles (Zhou et al., 2010; Lin et al., 2014; Lin et al., 2015; Vasilkov et al., 2016; Lorente et al., 2018; Liu et al., 2019; Liu et al., 2020; Vasilkov et al., 2021).

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 the AMFs calculated based on the linearized pseudo-spherical scalar and vector discrete ordinate radiative transfer code (VLIDORT). 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, 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 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 variations of stratospheric VCDs from GEOS-Chem simulations. 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 product, ground-based 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 nested GEOS-Chem (v9-02) simulations. We then calculate tropospheric NO$_2$ AMFs to convert SCDs to VCDs. Details are described in the next sub-sections.

![Flow chart of POMINO-GEMS retrieval algorithm](https://doi.org/10.5194/amt-2023-46)

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

2.1.1 GEMS NO$_2$ and cloud data

The GEMS instrument is on board the GK-2B satellite locating at 128.2°E over the equator (Kim
The spectral wavelength range of GEMS is 300-500 nm, covering main absorption spectra of aerosols and trace gases. The nominal spatial resolution is typically 7 km × 8 km for gases and 3.5 km × 8 km for aerosols in the eastern and central scan domain; however, the north-south spatial resolution can exceed 25 km in the western side. The whole field of view (FOV) covers about 20 Asian countries within latitudes 5°S to 45°N and longitudes 80°E to 152°E. Given the variation of solar zenith angle (SZA), there are four scan scenarios, including Half East (HE), Half Korea (HK), Full Central (FC) and Full West (FW), moving from east to west. It takes 30 minutes (for example, 00:45–01:15 UTC) for GEMS to scan its full coverage during each measurement, and the next 30 minutes to transmit data to the ground data center. The number of hourly GEMS observations per day varies from 6 in winter to 10 in summer, corresponding to the annual movement of subsolar points relative to the Earth.

We take hourly total NO$_2$ SCDs from the official GEMS v1.0 L2 NO$_2$ product, and convert them to 0.05° × 0.05° gridded data by means of an area-weighted oversampling technique. We also use continuum reflectances and O$_3$-O$_2$ SCDs from the official GEMS v1.0 L2 cloud product to re-calculate cloud parameters as a prerequisite for tropospheric NO$_2$ AMF calculations. Details of the GEMS retrievals can be found in the algorithm theoretical basis document (ATBD) (Lee et al., 2020).

### 2.1.2 TROPOMI NO$_2$ data

The TROPOMI instrument is on board the sun-synchronous satellite Sentinel-5 Precursor, with an Equator overpass time of about 13:30 local solar time (LST) (Van Geffen et al., 2020). It provides measurements for various trace gases, aerosols and cloud properties with a wide spectral range from UV to shortwave infrared. TROPOMI achieves daily global coverage with a full swath width of about 2600 km. The horizontal resolution is 3.5 km × 7 km (3.5 km × 5.5 km since 6 August 2019) at nadir, with a maximum width of about 14 km for pixels near the edge of the swath.

We use total NO$_2$ SCDs and stratospheric NO$_2$ VCDs from the official TROPOMI PAL v2.3.1 L2 NO$_2$ product, and convert them to 0.05° × 0.05° gridded data, again using an area-weighted oversampling technique. Details of TROPOMI total SCD retrievals and stratospheric VCD calculations are given in the TROPOMI ATBD (Van Geffen et al., 2022a). This intermediate product is reprocessed with TROPOMI NO$_2$ data processor v2.3.1 for the period from 1 May 2018 to 14 November 2021; it will be replaced by the full mission reprocessing with NO$_2$ processor v2.4.0 in the future (Eskes et al., 2021).

The most important improvement in this product over the previous OFFL v1.3 is the replacement of the
FRESCO-S algorithm with the FRESCO-wide cloud retrieval algorithm, which leads to more reasonable cloud pressure (CP) estimates and substantial increases in tropospheric NO$_2$ VCDs (by 20%–50%) over polluted regions like Eastern China in winter (Eskes et al., 2021; Van Geffen et al., 2022b).

In addition, we use the POMINO-TROPOMI v1.2.2 tropospheric NO$_2$ VCD product to compare with POMINO-GEMS results. The previous POMINO-TROPOMI v1 data show better data in polluted situations and improved consistency with MAX-DOAS measurements when compared with the official TM5-MP-DOMINO (OFFLINE) product (Liu et al., 2020). POMINO-TROPOMI v1.2.2 improves upon v1 by (1) using tropospheric NO$_2$ SCD and CP data from the updated TROPOMI PAL v2.3.1 NO$_2$ product, (2) interpolating the daily NO$_2$ pressure, temperature and aerosol vertical profiles into a horizontal grid of 2.5 km x 2.5 km for subsequent tropospheric AMF calculations, and (3) including several minor bug fixes.

### 2.1.3 Calculation of total NO$_2$ SCDs

We use TROPOMI data to correct GEMS total NO$_2$ SCDs, taking into account potential issues in GEMS data. Figures 2a and b show the spatial distribution of monthly mean total NO$_2$ geometric column densities (GCDs, calculated as SCDs divided by geometric AMFs) in June 2021 from TROPOMI PAL v2.3.1 and GEMS v1.0, respectively. The horizontal resolution is 0.05° × 0.05°. The GCDs are used to compare the two products after removing the effect of measurement geometry. Matching for each day between hourly GEMS observations and the TROPOMI data at the closest observation time is done to ensure temporal compatibility. The figures show that the spatial pattern of GEMS GCDs agrees well with that from TROPOMI, with high values over the North China Plain (NCP) and Northwestern India, as well as major metropolitan clusters such as Seoul and the Yangtze River Delta (YRD). However, there are two systematic problems in GEMS GCDs. Firstly, the GEMS GCD values are abnormally high over the northern and northwestern part of GEMS FOV, especially over Mongolia, Qinghai, Inner Mongolia, Xinjiang and Tibet of China. Secondly, the west-east stripes exist over the whole domain, similar to the spurious across-track variability issue for OMI. This stripe issue is likely associated with the specific scan modes of GEMS, as well as periodically occurring bad pixels as one of remaining calibration issues (Boersma et al., 2011; Lee et al., 2023).
Figure 2. Spatial distribution of monthly mean total NO$_2$ GCDs on a 0.05° × 0.05° grid in June 2021. (a) TROPOMI PAL v2.3.1 product, (b) official GEMS v1.0 product, (c) corrected POMINO-GEMS product that spatiotemporally match with TROPOMI, and (d) corrected POMINO-GEMS product at all observation hours.

To correct the two issues in the GEMS official total NO$_2$ SCD product, we combine GEMS and TROPOMI observations to obtain hourly 0.05° × 0.05° corrected total NO$_2$ SCDs for each day using Eqs. (1) and (2):

\[
\Delta \text{GCD} = \frac{1}{n} \sum_{i=1}^{n} (\text{GCD}_{\text{total},h_i}^{\text{TROPOMI}} - \text{GCD}_{\text{total},h_i}^{\text{GEMS}})
\]

(1)

\[
\text{SCD}_{\text{corrected}}^{\text{total},h} = \text{SCD}_{\text{GEMS}}^{\text{total},h} + \Delta \text{GCD} \times \text{AMF}_{\text{geo, GEMS}}^{h}
\]

(2)

In Eqs. (1) and (2), index $h$ represents the hour of GEMS observations on each day; $h_i$ the hour when both GEMS and TROPOMI have valid observations for the same grid cell; and $n$ the number of $h_i$. The value of $n$ is 1 or 2 depending on the overpass times of TROPOMI. There are two steps in the correction process. Firstly, we calculate a geometry-independent correction map for each day using total NO$_2$ GCDs from GEMS and TROPOMI that match spatially and temporally (Eq. (1)). We use the absolute difference instead of a scaling factor as a simple correction. We then apply the correction to the original GEMS total NO$_2$ SCDs at each hour on the same day, by accounting for the diurnal variation in AMF associated with measurement geometry (Eq. (2)).
Figure 2c shows monthly mean corrected POMINO-GEMS total NO$_2$ GCDs in June 2021 after spatial and temporal matching with TROPOMI. The corrected GCD values in northern GEMS FOV are much reduced compared with those in the original GEMS data. Moreover, most stripe-like patterns are removed in the corrected GCDs.

Figure 2d is similar to Fig. 2c but for GCDs averaged at all observation hours in June 2021. The differences between Figures 2c and 2d indicate the influence of different sampling times as well as the limitation of daily correction map. Specifically, the correction value of each grid cell is calculated at the specific hour when both GEMS and TROPOMI have valid observations, but this value is applied to original GEMS SCDs at all hours.

2.1.4 Calculation of stratospheric and tropospheric NO$_2$ SCDs

We construct a dataset of hourly stratospheric NO$_2$ SCDs at 0.05° × 0.05° by using TROPOMI stratospheric NO$_2$ VCDs, diurnal variation of stratospheric NO$_2$ VCDs provided by GEOS-Chem simulations, and GEMS geometric AMFs. Nested GEOS-Chem v9-02 simulations for Asia at 0.25° lat. × 0.3125° long. with 47 vertical layers are driven with daily GEOS-FP meteorological fields; see details in our previous studies (Lin et al., 2014; Lin et al., 2015). We add the simulated NO$_2$ sub-columns within layers 37 to 43 (roughly above 17 km) to represent NO$_2$ VCDs in the stratosphere.

First, we calculate stratospheric NO$_2$ VCDs at a reference hour for each day using Eqs. (3) and (4):

\[
\text{ratio}_{h_0}^h = \frac{\text{VCD}_{\text{strat},h}}{\text{VCD}_{\text{strat},h_0}} \tag{3}
\]

\[
\text{VCD}_{\text{strat},h} = \frac{1}{n} \sum_{i=1}^{n} \text{VCD}_{\text{TROPOMI},\text{strat},h_i} \times \text{ratio}_{h_0}^h \tag{4}
\]

Here, Eq. (3) defines the ratio of GEOS-Chem simulated stratospheric NO$_2$ at hour $h$ to that at the reference hour $h_0$, which is chosen to be 00:00 UTC (Figure S1). In Eq. (4), $h_i$ represents the observation time of every TROPOMI orbit that overlaps with GEMS FOV, and $n$ the number of $h_i$ for each grid cell.

Second, we use the ratio from a given time $h$ to $h_0$ and stratospheric NO$_2$ VCDs at $h_0$ to derive stratospheric NO$_2$ VCDs at $h$ for each day (Eq. (5)).

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

Figure 3 shows the derived monthly mean stratospheric NO$_2$ VCDs at each hour in June 2021 on a 0.05° × 0.05° grid. The spatial patterns are very similar at different times, indicating weak simulated diurnal variation of stratospheric NO$_2$ in summer. There is a strong meridional gradient of stratospheric NO$_2$.
with the higher values in the north associated with longer lifetimes.

Finally, we use GEMS geometric AMFs to convert the stratospheric NO$_2$ VCDs to SCDs at each hour, and then subtract them from the total SCDs to obtain tropospheric SCDs (Eqs. (6) and (7)). In the stratosphere, the geometric AMFs are essentially the same as the actual AMFs

$$SCD_{\text{strat},h} = VCD_{\text{strat},h} \times \text{AMF}_{\text{geo}}^{\text{GEMS}}$$  \hspace{1cm} (6)$$

$$SCD_{\text{trop},h}^{\text{GEMS}} = SCD_{\text{corrected}}^{\text{total},h} - SCD_{\text{strat},h}$$  \hspace{1cm} (7)$$

Figure 3. Spatial distribution of POMINO-GEMS derived monthly mean stratospheric NO$_2$ VCDs at each hour on a 0.05° × 0.05° grid in June 2021. Note the range of the color bar is 2.0 – 4.0 × 10$^{15}$ molec. cm$^{-2}$.

2.1.5 Calculation of tropospheric AMFs

For tropospheric AMF calculations (Figure 1), we use a parallelized LIDORT-driven AMFv6 package; 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; Lin et al., 2014; Lin et al., 2015;
Liu et al., 2020) to account for the anisotropy of surface reflectance (Zhou et al., 2010). Hourly-varying aerosol parameters, a priori NO\textsubscript{2} profiles as well as temperature 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 MYD04\_L2 dataset (Lin et al., 2014; Lin et al., 2015; Liu et al., 2019; Liu et al., 2020) to constrain model-simulated AOD on a monthly basis, 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 retrieve cloud parameters based on O\textsubscript{2}-O\textsubscript{2} SCDs and continuum reflectances from the official GEMS v1.0 cloud product, using ancillary parameters consistent with those used in NO\textsubscript{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\textsubscript{2} SCDs to VCDs.

Invalid pixels are filtered based on the following criteria. We exclude pixels with solar zenith angle (SZA) or viewing zenith angle (VZA) greater than 80°, or with the ground covered by ice or snow. To minimize cloud contamination, we exclude pixels with cloud radiance fractions (CRF) greater than 50% in the POMINO-GEMS product.

### 2.2 Estimation of surface NO\textsubscript{2} concentrations

In order to validate satellite NO\textsubscript{2} products with surface concentration measurements from MEE, we convert tropospheric NO\textsubscript{2} VCDs on a 0.05° × 0.05° grid to surface NO\textsubscript{2} mass concentrations using GEOS-Chem simulated NO\textsubscript{2} vertical profiles and the box heights of the lowest model layer (Eq. (8)).

\[
C_{\text{surf}} = VCD_{\text{trop}}^{\text{SAT}} \times R_G^\text{GC} \times \frac{M}{N \times H_G^\text{GC}} \times 2
\]

In Eq. (8), \(C_{\text{surf}}\) represents the estimated surface NO\textsubscript{2} mass concentration in μg m\textsuperscript{-3}, \(VCD_{\text{trop}}^{\text{SAT}}\) the satellite tropospheric VCD in molec. m\textsuperscript{2}, \(R_G^\text{GC}\) the GEOS-Chem simulated ratio of NO\textsubscript{2} sub-column in the lowest layer to the total column, \(M\) the NO\textsubscript{2} molar mass in μg mol\textsuperscript{-1}, \(N\) the Avogadro constant, and \(H_G^\text{GC}\) the box height of the lowest layer in m. The thickness of the lowest layer of GEOS-Chem (about 130 m) is too large for the layer average NO\textsubscript{2} mass concentration to represent that near the ground (Liu...
et al., 2018); thus the derived concentration is multiplied by a factor of 2 to roughly account for the vertical gradient from the height of ground instrument to the center of the model layer.

### 2.3 Ground-based MAX-DOAS measurements

We use ground-based MAX-DOAS measurements to validate the POMINO-GEMS and POMINO-TROPOMI v1.2.2 NO$_2$ products (Figure S2). The types, geolocations and observation times of MAX-DOAS stations are summarized in Table 1. Details of each site are described in supplement information (SI).

<table>
<thead>
<tr>
<th>Site name</th>
<th>Type</th>
<th>Geolocation</th>
<th>Measurement time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fudan University</td>
<td>Urban</td>
<td>121.52°E, 31.34°N</td>
<td>1 June – 31 August</td>
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<td>2021</td>
</tr>
<tr>
<td>Xuzhou</td>
<td>Suburban</td>
<td>117.14°E, 34.22°N</td>
<td>1 June – 31 August</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>2021</td>
</tr>
<tr>
<td>Hefei</td>
<td>Suburban</td>
<td>117.16°E, 31.91°N</td>
<td>1 June – 30 June</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2021</td>
</tr>
<tr>
<td>Nanhui</td>
<td>Suburban</td>
<td>121.80°E, 31.06°N</td>
<td>1 June – 31 August</td>
</tr>
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<td></td>
<td></td>
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<td>2021</td>
</tr>
<tr>
<td>Chongming</td>
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<td>121.82°E, 31.50°N</td>
<td>1 June – 31 August</td>
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<td></td>
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<td>2021</td>
</tr>
<tr>
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</tr>
<tr>
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<td>Suburban</td>
<td>116.96°E, 39.75°N</td>
<td>1 June – 31 August</td>
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<td>2021</td>
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<tr>
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<td>1 June – 31 August</td>
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<td></td>
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<td>2021</td>
</tr>
<tr>
<td>Cape Hedo</td>
<td>Remote</td>
<td>128.25°E, 26.87°N</td>
<td>1 June – 31 August</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>2021</td>
</tr>
</tbody>
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To ensure sampling consistency in time, we average all valid MAX-DOAS measurements within
each observation period of GEMS (i.e., 30 minutes) for hourly comparison, and within ±1.5 h of TROPOMI overpass time for daily comparison. Following the procedure 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 and conduct spatial averaging. The Grubbs statistical test is performed to exclude outliers in both MAX-DOAS and satellite data before comparison.

2.4 Ground-based MEE NO$_2$ measurements

We use hourly surface NO$_2$ mass concentration measurements from the MEE air quality monitoring network (https://quotsoft.net/air/). By 2021, more than 2000 MEE stations across China have been established, providing hourly observations for NO$_2$ and five other air pollutants. Most stations are in urban or suburban areas. We filter the MEE sites for comparison with satellite data using mean surface-to-total ratios of NO$_2$ ($R^{GC}$) in June-July-August 2021 defined in section 2.2. The spatial distribution of $R^{GC}$ is shown in Figure S3a. Only MEE sites at the grid cells where the surface-to-total ratio is larger than the 95th percentile across all grid cells within the GEMS domain (i.e., 0.12) are included; this results in 855 valid MEE sites, as shown in Figure S3b.

To compare with satellite-derived surface NO$_2$ concentration data, we average over all valid MEE sites in each 0.05° × 0.05° grid cell to generate gridded MEE NO$_2$ data for each hour. To ensure sampling consistency for each day, we average MEE observations for two consecutive hours to match GEMS hourly observations – for example, we match the mean value of MEE NO$_2$ concentrations in 13:00–14:00 and 14:00–15:00 LST with the GEMS NO$_2$ in 13:45–14:15 LST. We also match MEE observations over the period 13:00–14:00 LST with TROPOMI-derived surface NO$_2$.

3. Results and discussion

3.1 POMINO-GEMS tropospheric NO$_2$ VCDs

Figure 4 shows mean POMINO-GEMS tropospheric NO$_2$ VCDs at each hour on a 0.05° × 0.05° grid in JJA 2021. High values of tropospheric NO$_2$ columns (>10 × 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 NOx 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\textsubscript{2} VCDs are much lower (\(< 1 \times 10^{15} \text{ molec. cm}^{-2}\)) over most of western China and the open ocean, due to low anthropogenic and natural emissions.

Figure 4. Spatial distribution of POMINO-GEMS tropospheric NO\textsubscript{2} VCDs at each hour on a 0.05° × 0.05° grid in JJA 2021.

Figures 5 presents NO\textsubscript{2} VCDs in the morning, noon and afternoon in JJA 2021 for eastern China. Data are averaged from 22:45–01:45 UTC (06:45–09:45 Beijing Time, BJT), 02:45–04:45 UTC (10:45–12:45 BJT) and 05:45–07:45 UTC (13:45–15:45 BJT) to represent the morning, noon and afternoon, respectively. In the morning (Figure 5a), there are clear city signals with high NO\textsubscript{2} values, reflecting abundant NOx emissions from traffic. The spatial gradients of NO\textsubscript{2} from urban centers to outskirts are very strong. However, these spatial gradients are greatly reduced in the noon and afternoon (Figure 5b and c). For example, the differences of tropospheric NO\textsubscript{2} VCDs between the urban center of Xi’an (108.93°N, 34.27°E) and its surrounding areas (within 50 km) are reduced from about \(8 \times 10^{15}\) molec.
cm² in the morning to about $4 \times 10^{15}$ molec. cm² at noon, and then to below $2 \times 10^{15}$ molec. cm² in the afternoon. This is likely due to chemical loss of traffic-associated NO₂, increased emissions from other sectors (e.g., industry), and/or enhanced horizontal transport smearing the gradient.

Figure 5. Spatial distribution of three-hour-mean POMINO-GEMS tropospheric NO₂ VCDs on a 0.05° × 0.05° grid over eastern China in the (a) morning, (b) noon and (c) afternoon in JJA 2021.

Over western China with low tropospheric NO₂ VCDs (Figure 6), there is a roughly monotonic increase of tropospheric NO₂ by about $1 \times 10^{15}$ molec. cm² within daily GEMS observations. This increase is likely dominated by biogenic NOx emissions that are sensitive to sunshine intensity and surface temperature (Kong et al., 2022b; Weng et al., 2020). Future studies are needed to understand the exact causes.

Figure 6. Spatial distribution of three-hour-mean POMINO-GEMS tropospheric NO₂ VCDs on a 0.05° × 0.05° grid over western China in JJA 2021. The local solar time in this region is 1-3 hours earlier than Beijing Time.

3.2 Comparison with POMINO-TROPOMI v1.2.2 NO₂ product

Figures 7a and b show the POMINO-GEMS and POMINO-TROPOMI v1.2.2 tropospheric NO₂ VCDs, respectively, on a 0.05° × 0.05° grid averaged over JJA 2021. Cloud screening is implemented based on the CRFs from each product. To ensure temporal compatibility, matching between hourly
GEMS observations and the TROPOMI data at the closest observation time is done for each day. Overall, POMINO-GEMS agrees well with POMINO-TROPOMI with a spatial correlation coefficient of 0.97, a linear regression slope of 1.15 and a small positive normalized mean bias (NMB) of 3.6% (Figure 7c).

Figure 7. Comparison between POMINO-GEMS and POMINO-TROPOMI tropospheric NO\textsubscript{2} VCDs. Spatial distributions of (a) POMINO-GEMS and (b) POMINO-TROPOMI v1.2.2 tropospheric NO\textsubscript{2} VCDs on a 0.05° × 0.05° grid in JJA 2021. (c) Scatterplot for tropospheric NO\textsubscript{2} VCDs between these two products. Colors represent the data density. Panels (d) and (e) are absolute and relative differences between POMINO-GEMS and POMINO-TROPOMI v1.2.2, respectively.

POMINO-GEMS VCDs are higher than those from POMINO-TROPOMI over eastern China and smaller over the oceans (Figures 7d and e). These differences are mainly because POMINO-GEMS AMFs are lower (higher) than POMINO-TROPOMI AMFs over polluted regions (ocean). POMINO-GEMS explicitly employs CALIOP-corrected aerosol vertical profiles and re-calculates cloud fraction and cloud pressure based on continuum reflectances and O\textsubscript{2}–O\textsubscript{2} SCDs from GEMS observations. By comparison, POMINO-TROPOMI v1.2.2 does not use CALIOP observations to constrain aerosol vertical profiles; and it takes the FRESCO-wide cloud pressure data from TROPOMI PAL v2.3.1 NO\textsubscript{2} product and re-calculates cloud fraction at 440 nm. Constraint by CALIOP observations results in higher aerosol-concentrated layer heights (Liu et al., 2019), which enhances the “screening” effect on the absorption by NO\textsubscript{2} over polluted regions and leads to lower AMFs. Over remote areas where lightning produced NO\textsubscript{2} is presented at altitudes higher than the aerosol-concentrated layer, higher aerosols tend to enhance the “albedo” effect and lead to higher AMFs (Lin et al., 2015).
3.3 Validation with MAX-DOAS NO\textsubscript{2} VCD measurements

The scatterplot in Figure 8a compares POMINO-GEMS tropospheric NO\textsubscript{2} VCDs in JJA 2021 at all GEMS observation hours with matched MAX-DOAS measurements at nine sites. POMINO-GEMS correlates with MAX-DOAS ($R = 0.62$) with a small negative bias (NMB = −15.7%). The linear regression shows a slope of 0.47 and intercept of $3.37 \times 10^{15}$ molec. cm\textsuperscript{-2}, reflecting underestimation of POMINO-GEMS tropospheric NO\textsubscript{2} VCDs on high-NO\textsubscript{2} days.

Figure 8. Evaluation of satellite NO\textsubscript{2} VCD data using MAX-DOAS measurements. (a) Scatterplot for tropospheric NO\textsubscript{2} VCDs ($\times 10^{15}$ molec. cm\textsuperscript{-2}) between MAX-DOAS and POMINO-GEMS at all GEMS observation hours in JJA 2021. Each data pair denotes an hour. (b-c) Scatterplots for tropospheric NO\textsubscript{2} VCDs ($\times 10^{15}$ molec. cm\textsuperscript{-2}) in JJA 2021 (b) between MAX-DOAS and POMINO-GEMS at 13:45–14:15 LST and (c) between MAX-DOAS and POMINO-TROPOMI v1.2.2. Each data pair denotes a day. Each MAX-DOAS stations are color-coded as indicated.

Figures 8b-c further use MAX-DOAS measurements to evaluate POMINO-GEMS and POMINO-TROPOMI v1.2.2 tropospheric NO\textsubscript{2} VCDs at the overpass time of TROPOMI. In Figure 8b, POMINO-GEMS data at 13:45–14:15 LST are used to match the overpass time of TROPOMI. POMINO-TROPOMI product is evaluated in the context of understanding the relative performance of POMINO-GEMS. Each data point represents a day. Figures 8b-c shows that the day-to-day variability of MAX-DOAS measurements is well captured by POMINO-TROPOMI v1.2.2 ($R = 0.83$), but less so by POMINO-GEMS ($R = 0.64$). Linear regression results show an underestimate of tropospheric NO\textsubscript{2} VCDs in POMINO-TROPOMI v1.2.2 product (NMB = −18.1%), as also found in previous studies (Liu et al., 2020). POMINO-GEMS exhibits a small bias (NMB = −3.2%), but station-dependent performance is apparent in the scatterplot of Figure 8b. At the two remote sites of Fukue and Cape Hedo with low NO\textsubscript{2}, POMINO-GEMS tends to overestimate MAX-DOAS measurements. At the seven urban/suburban sites, the data pairs are more scattered and located both above and below the 1:1 line, resulting in a small NMB. Furthermore, the normalized mean error (NME) of POMINO-GEMS relative to MAX-DOAS measurements (46.3% at all observation hours and 48.9% at 13:45–14:45 LST) is higher than that of
POMINO-TROPOMI (34.3%), indicating that the uncertainty in POMINO-GEMS NO\textsubscript{2} is larger than POMINO-TROPOMI. Figure 9 also compares the diurnal variation of tropospheric NO\textsubscript{2} VCDs between POMINO-GEMS and MAX-DOAS at eight MAX-DOAS stations. At each site, NO\textsubscript{2} values are averaged in JJA 2021 at each hour for comparison, and the number of valid days at each hour is shown in Figure S4. The Cape Hedo site is not included because there are few valid MAX-DOAS data points at each hour. Figures 9a-g show that at the urban and suburban sites, MAX-DOAS NO\textsubscript{2} peaks in the mid-to-late morning, declines towards the minimum values at noon, and then gradually increases in the afternoon. Strong correlation of NO\textsubscript{2} diurnal variation between POMINO-GEMS and MAX-DOAS is found at Xuzhou ($R = 0.90$) and Hefei ($R = 0.72$), although the correlation is much weaker at Fudan University ($R = 0.23$) and Nanhui ($R = 0.12$). At Chongming, Xianghe and Dianshan Lake sites, POMINO-GEMS exhibits a maximum in the late afternoon and a second maximum in the mid-morning (Figures 9e-g), a pattern which is poorly correlated with MAX-DOAS ($R = -0.02$, -0.23 and -0.66, respectively). At Fukue, MAX-DOAS NO\textsubscript{2} shows a peak in the morning and then declines to low values around $1 \times 10^{15}$ molec. cm$^{-2}$, but this diurnal pattern is not captured by POMINO-GEMS. Overall, the mixed performance at these eight sites suggests that more work is warranted to further improve the POMINO-GEMS retrieval algorithm.
Figure 9. Diurnal variation of hourly tropospheric NO$_2$ VCDs ($\times 10^{15}$ molec. cm$^{-2}$) from MAX-DOAS and POMINO-GEMS at eight sites in JJA 2021. The error bars denote the standard deviation of MAX-DOAS and POMINO-GEMS NO$_2$ at each hour in JJA 2021, respectively. The temporal correlation coefficients are also shown. In each panel, the blue square with an error bar represents the mean value and standard deviation of POMINO-TROPOMI v1.2.2 NO$_2$ in JJA 2021.

3.4 Validation with surface NO$_2$ concentration measurements from MEE

The scatterplot in Figure 10a further compares surface NO$_2$ concentrations derived from POMINO-GEMS with MEE measurements at all hours. Here, each data pair represents a site and hour averaged over
all days in JJA 2021. POMINO-GEMS derived surface NO$_2$ concentrations show good agreement with MEE measurements in terms of spatiotemporal correlation ($R = 0.76$) and bias (NMB = −24.1%). Despite the overall underestimate, POMINO-GEMS derived surface NO$_2$ concentrations show overestimation at some high-value situations, which mainly occur over the YRD region (Figure S5). These differences reflect errors in POMINO-GEMS NO$_2$ VCDs, in the conversion from tropospheric VCDs to surface concentrations, and/or in MEE measurements. In particular, the MEE measurements are contaminated by oxidation products of NO$_2$ (e.g., HNO$_3$ and PANs) and tend to overestimate the actual concentrations of NO$_2$ (Liu et al., 2018), with the extent of contamination more severe for more aged air.

Figure 10. Evaluation of satellite derived surface NO$_2$ concentrations using MEE measurements. (a) Scatterplot for surface NO$_2$ concentrations (μg m$^{-3}$) between MEE and POMINO-GEMS at all GEMS observation hours averaged over JJA 2021. (b-c) Scatterplot for surface NO$_2$ concentrations in JJA 2021 between MEE and POMINO-GEMS at 13:45 – 14:15 LST, and (c) between MEE and POMINO-TROPOMI v1.2.2. The color bar represents the data density.

Figures 10b-c show validation results for satellite-derived surface NO$_2$ concentrations with MEE measurements at 855 sites 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, with correlation coefficients of 0.55 and 0.57, respectively. POMINO-GEMS exhibits higher linear regression slope (0.44) with smaller NMB (−37.2%) and NME (40.6%). The values of satellite data are lower than those from MEE measurements, in part because of the aforementioned contamination issues in MEE data.

Figure 11 further examines the diurnal variation of surface NO$_2$ concentrations averaged over JJA 2021 and 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 MAX-DOAS VCD data (Figure 9), due to the difference in sampling size between MEE and...
MAX-DOAS, as well as the vertical distribution of NO\textsubscript{2} that affects the relationship between surface and columnar NO\textsubscript{2}. POMINO-GEMS derived surface NO\textsubscript{2} concentrations show similar diurnal variations to those from MEE ($R = 0.95$), although with a peak at 10:00 LST and a gradual increase beginning at 14:00 LST.

Figure 11. Diurnal variation of hourly surface NO\textsubscript{2} concentrations (μg m\textsuperscript{-3}) for MEE and POMINO-GEMS in JJA 2021. The error bars denote the standard deviation of MEE and POMINO-GEMS derived surface NO\textsubscript{2} concentrations at each hour in JJA 2021, respectively. The blue square with an error bar represents the mean value and standard deviation of POMINO-TROPOMI v1.2.2 derived surface NO\textsubscript{2} concentrations.

3.5 Error estimates for POMINO-GEMS tropospheric NO\textsubscript{2} VCDs

Total retrieval errors for POMINO-GEMS tropospheric NO\textsubscript{2} VCDs are compounded from the calculations of total SCDs, stratospheric SCDs, and tropospheric AMFs. Spatial and temporal averaging across GEMS pixels can greatly reduce the random errors but will not affect the systematic errors. Here, we provide a preliminary estimate of retrieval errors.

As described in Section 2, we calculate hourly total SCDs based on the original GEMS SCD data and daily TROPOMI-guided corrections. We tentatively estimate the error in our corrected total SCD data to be 10%, which is the same as the TROPOMI total SCD error (Van Geffen et al., 2022a), considering that we essentially adjust GEMS total SCDs to match TROPOMI values. In constructing the stratospheric NO\textsubscript{2} SCDs, the stratospheric VCDs are taken from TROPOMI PAL v2.3.1, scaled based on GEOS-Chem simulations to account for diurnal variation, and then applied with geometric AMFs. We
assign an error of $0.2 \times 10^{15}$ molec. cm$^{-2}$ (5%–10%) to our hourly stratospheric SCDs, the same as the value for TROPOMI (Van Geffen et al., 2022a). As such, we assume no error contributions from the GEOS-Chem-based scaling and geometric AMFs. As most of the errors in total SCDs are absorbed in the calculation of stratospheric SCDs (Van Geffen et al., 2015), the errors in tropospheric SCDs should be $0.2 \times 10^{15}$ molec. cm$^{-2}$ (5%–40%) at most.

Tropospheric AMF calculations are the dominant error source for retrieved tropospheric NO$_2$ VCDs over polluted regions. According to Liu et al. (2020), the AMF errors caused by uncertainties in surface reflectance and a priori NO$_2$ profiles are about 10% each, 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 overall AMF errors for POMINO-GEMS are estimated to be 20%–30%, as determined by adding these errors in quadrature.

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 pixels over remote regions with low tropospheric NO$_2$ abundances, the overall retrieval uncertainty is dominated by errors in tropospheric SCDs and can reach $0.2 \times 10^{15}$ molec. cm$^{-2}$ (or 30%–50%). For pixels with abundant tropospheric NO$_2$, the uncertainty of retrieved tropospheric VCDs is dominated by the AMF errors and is estimated to be about 25%–35%. The error magnitude is supported by the NMB and NME values shown in the validation results against MAX-DOAS and MEE data (Figure 8a, b and Figure 10a, b).

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 GEMS v1.0 L2 NO$_2$ product, total and stratospheric NO$_2$ columns from TROPOMI PAL v2.3.1 L2 NO$_2$ product, and stratospheric NO$_2$ diurnal variations from GEOS-Chem simulations. 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 to VCDs. A preliminary estimate of retrieval errors is also given.
Our initial POMINO-GEMS data for JJA 2021 shows high values of tropospheric NO$_2$ VCDs with clear hotspots (> $10 \times 10^{15}$ molec. cm$^{-2}$) over regions where anthropogenic emissions of NOx are abundant. The spatial gradients of tropospheric NO$_2$ VCDs from urban centers to surrounding areas are substantial in the morning due to traffic emissions, and gradients are much reduced at noon and in the afternoon. By comparison, a roughly monotonic increase of tropospheric NO$_2$ VCDs from the morning to the afternoon is observed over clean regions of western China, likely as a result of enhanced biogenic emissions.

POMINO-GEMS tropospheric NO$_2$ VCDs agree with POMINO-TROPOMI v1.2.2 in terms of spatial correlation (0.97) and NMB (3.6%). POMINO-GEMS is also comparable with ground-based MAX-DOAS measurements at nine rural/suburban/urban sites with a small NMB ($-15.7\%$), although the correlations are modest ($R = 0.62$). Both the bias and correlation values are smaller than POMINO-TROPOMI v1.2.2 (NMB = $-18.1\%$, $R = 0.83$). POMINO-GEMS captures the diurnal variation of MAX-DOAS NO$_2$ VCDs at the Xuzhou ($R = 0.90$) and Hefei ($R = 0.72$) sites but not at others, for reasons that are not clear at present.

We also compare surface NO$_2$ concentrations derived from VCDs from POMINO-GEMS and POMINO-TROPOMI v1.2.2 products against MEE measurements, taking advantage of the large number of MEE sites. For 855 selected sites at all GEMS observation hours, POMINO-GEMS derived surface NO$_2$ concentration data exhibit a small NMB ($-24.1\%$). For these sites at TROPOMI overpass times, POMINO-GEMS derived surface NO$_2$ concentrations show a smaller magnitude of NMB ($-37.2\%$) than POMINO-TROPOMI v1.2.2 ($-47.0\%$). Excellent agreement in diurnal variation between POMINO-GEMS derived and MEE NO$_2$ averaged over all sites is exhibited ($R = 0.95$).

Overall, our comprehensive validation process highlights the good performance of POMINO-GEMS tropospheric NO$_2$ VCD product, both in magnitude and spatiotemporal variation. 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 the necessary inputs for our research product.

Data availability. The POMINO-GEMS NO$_2$ data are available 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. MEE surface NO₂ measurements can be downloaded from https://quotsoft.net/air/. MAX-DOAS measurements can be provided upon requests to the corresponding owners.

**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. MV, QH, KQ, YC, YK, JX and PX provided the MAX-DOAS measurements. HK helped process MEE measurements. LC and ML helped analyze the validation results. All authors commented on the paper.

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

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**References**


van der A, R. J., Mijling, B., Ding, J., Koukouli, M. E., Liu, F., Li, Q., Mao, H., and Theys, N.: Cleaning up the air: effectiveness of air quality policy for SO2 and NOx emissions in China, Atmos.


Weng, H., Lin, J., Martin, R., Millet, D. B., Jaegle, L., Ridley, D., Keller, C., Li, C., Du, M., and
