First observation of tropospheric nitrogen dioxide from the Environmental Trace Gases Monitoring Instrument onboard the GaoFen-5 satellite

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Abstract

The Environmental Trace Gases Monitoring Instrument (EMI) is the first Chinese satellite-borne UV–Vis spectrometer aiming to measure the distribution of atmospheric trace gases on a global scale. The EMI instrument onboard the GaoFen-5 satellite was launched on 9 May 2018. In this paper, we present the tropospheric nitrogen dioxide (NO2) vertical column density (VCD) retrieval algorithm dedicated to EMI measurement. We report the first successful retrieval of tropospheric NO2 VCD from the EMI instrument. Our retrieval improved the original EMI NO2 prototype algorithm by modifying the settings of the spectral fit and air mass factor calculations to account for the on-orbit instrumental performance changes. The retrieved EMI NO2 VCDs generally show good spatiotemporal agreement with the satellite-borne Ozone Monitoring Instrument and TROPOspheric Monitoring Instrument (correlation coefficient $R$ of $\sim$0.9, bias < 50%). A comparison with ground-based MAX-DOAS (Multi-Axis Differential Optical Absorption Spectroscopy) observations also shows good correlation with an $R$ of 0.82. The results indicate that the EMI NO2 retrieval algorithm derives reliable and precise results, and this algorithm can feasibly produce stable operational products that can contribute to global air pollution monitoring.

Introduction

The Environmental Trace Gases Monitoring Instrument (EMI)1 is the first Chinese satellite-borne spectrometer with the aim to measure atmospheric pollutants from space. The EMI payload onboard the GaoFen-5 satellite was successfully launched on 9 May 2018. The GaoFen-5 satellite has a polar orbit at an altitude of 706 km. The Chinese EMI instrument is expected to contribute to the understanding of global air quality and atmospheric chemistry, similar to predecessor European and American satellite missions, e.g., the Ozone Monitoring Instrument (OMI)2 and TROPOspheric Monitoring Instrument (TROPOMI)3. EMI has instrumental characteristics that are similar to OMI and TROPOMI, e.g., the local overpass time at $\sim$13:30, spectral coverage, push-broom imaging technique, and daily global coverage. Both EMI and TROPOMI (launched in 2017) are new-generation satellite-borne air pollutant sensors compared to the OMI that was launched in 2004. TROPOMI follows the heritage of OMI in both instrument design and trace gas retrievals, but with higher spatial resolution and signal-to-noise ratio. A prototype EMI nitrogen dioxide (NO2) retrieval algorithm was developed before launch based on the OMI NO2 retrieval. However, optimization of the NO2 retrieval algorithm was necessary to adapt the unexpected issues of EMI after launch, especially spectral calibration.

Nitrogen oxides (NOx), defined as the sum of nitrogen oxide and NO2, are the major pollutants contributing to ozone and secondary aerosol formation in the
troposphere through photochemical reactions. Sources of 
NOx include fossil fuel combustion, vehicle emissions, 
biomass burning, and lightning. Due to rapid industrial-
ization and urbanization in the past few decades, 
China has become one of the largest NOx emitters in the 
world. As a result, China is experiencing a series of severe 
air pollution problems. In addition to measuring NO2 
distribution directly from space, applications of satellite 
remote sensing may include estimations of pollutant 
emissions, air quality trend detection, model validation, 
and assimilation of satellite data.

Figure 1a illustrates the optical design of the EMI 
satellite instrument. The EMI instrument covers the 
ultraviolet (UV) and visible (Vis) spectral ranges from 240 
to 710 nm with a spectral resolution of 0.3–0.5 nm. Light 
received by the telescope is depolarized by a scrambler 
and subsequently split into four spectral channels, the 
UV1 (240–315 nm), UV2 (311–403 nm), VIS1 (401–550 nm), and VIS2 (545–710 nm) channels. Each 
spectrometer is equipped with a two-dimensional charge-
coupled device (CCD) detector, with one dimension used 
for spectral coverage and the other dimension used for 
spatial coverage. The EMI instrument scans in the nadir 
direction toward the earth’s surface with an opening angle 
of 114° corresponding to a swath width of 2600 km, 
enabling daily global coverage with a nadir resolution of 
12 × 13 km² and a local overpass time of 13:30 (Fig. 1b).

In this paper, we present a new tropospheric NO2 ver-
tical column density (VCD, i.e., the vertical integral of 
NO2 concentration from the earth’s surface to the top of 
the atmosphere) retrieval algorithm dedicated to the EMI 
instrument. Details of the spectral retrieval, stratospheric–tropospheric separation of the NO2 column 
and slant to vertical column conversion are presented. 
The first EMI retrieval of tropospheric NO2 columns is 
compared to datasets from modern state-of-the-art Euro-
pean and American satellite sensors.

Results
NO2 retrieval overview
The retrieval of tropospheric NO2 VCDs from satellite 
UV–Vis observations typically follows a state-of-the-art 
three-step approach. First, the total NO2 slant column 
density (SCD) are retrieved from nadir radiance spectra nor-
malized by the solar irradiance, using the differential optical 
absorption spectroscopy (DOAS) technique. Subsequently, 
the stratospheric NO2 columns are separated from the total 
NO2 SCDs by assuming longitudinal homogeneity of stra-
tospheric NO2, while neglecting the minor contribution of 
tropospheric NO2 (usually on the order of 10¹⁴ molecules 
cm⁻²) over remote clean regions. Last, tropospheric NO2 
SCDs are converted to VCDs using air mass factors 
(AMFs). The AMF is defined as the ratio between SCD and 
VCD. It is a measure of the effective optical path length from 
the top of the atmosphere to the earth’s surface and reflected 
to the satellite through the atmosphere:

\[ M = \frac{S}{V} \]  

where \( M \) is the AMF, \( S \) denotes the SCD, and \( V \) represents 
the VCD. The AMF can be calculated with a radiative
transfer model (RTM). The final tropospheric NO$_2$ VCD can be derived after subtracting the stratospheric contribution and AMF conversion:

$$V_{\text{tropo}} = \frac{S - V_{\text{strat}} \times M_{\text{strat}}}{M_{\text{tropo}}} = \left( \frac{S}{M_{\text{strat}}} - V_{\text{strat}} \right) \times \frac{M_{\text{strat}}}{M_{\text{tropo}}}$$

(2)

where $V_{\text{tropo}}$ and $V_{\text{strat}}$ denote tropospheric and stratospheric $V$, respectively. $M_{\text{tropo}}$ and $M_{\text{strat}}$ represent tropospheric and stratospheric $M$, respectively. Details of the stratospheric estimation and AMF calculation are provided in the “Materials and methods” section.

Figure 2 shows an example of EMI NO$_2$ retrieval of $S$, $V_{\text{strat}}$, and $V_{\text{tropo}}$ on 1 January 2019. Enhanced NO$_2$ levels are observed in Eastern China, India, and the Middle East.

Algorithm improvements

A prototype EMI NO$_2$ retrieval is developed before launch. The prototype algorithm is very similar to the
However, due to unexpected issues, i.e., low signal-to-noise ratio at the edges of the spectral channels, bad irradiance measurement due to a diffuser calibration issue, and spectral saturation issue, the NO2 retrieval setting must be further optimized to address these issues. A series of sensitivity tests, including cloud correction, fitting wavelength range, reference selection, and spectral precalibration, have been performed to optimize the settings for tropospheric NO2 VCD retrieval. Table 1 lists the updated retrieval settings of the EMI NO2 retrieval. Parameters used in the OMI QA4ECV NO2 retrieval\(^{17}\) are also listed for reference.

The EMI NO2 fitting range is shifted slightly from 405–465 nm (OMI operational NO2 setting\(^{17}\)) to 420–470 nm to avoid the lower signal-to-noise ratio region at the edges of the VIS1 channel. Figure 3 illustrates an example of the retrieval of NO2 SCD, i.e., the NO2 amount integrated along the optical path in the atmosphere, by applying the DOAS fit to the EMI-measured spectrum.

The spectral saturation issue (i.e., the analogue photon signal reaches the maximum digital value of the CCD detector) is critical for EMI observations over bright clouds due to its high surface reflectance. Supplementary Figure 1 shows the global spatial pattern of the root mean square (RMS) of the spectral fitting residual, cloud radiance fraction from TROPOMI observations, and the true color image from the MODIS-Aqua instrument on 1 January 2019. The spatial pattern of the fitting residual RMS is correlated to the cloud pattern. Therefore, we filtered pixels with relatively large spectral fitting residuals, i.e., the RMS values >0.004.

The key calibration data measured during the on-ground calibration\(^{12}\) seem unsuitable for EMI on-orbit measurements due to the degradation and stability of the instrument in the complex space environment (e.g., cosmic radiation exposure\(^{18}\) and possible instrument changes since launch\(^{19}\)). Therefore, we recalibrated the EMI earth radiance measurements by comparing the EMI radiance to TROPOMI measurements and RTM simulations. An advantage of DOAS is that it does not rely on precisely calibrated radiance and is less sensitive to the variability in radiometric calibration than other methods based on discrete radiance (e.g., SBUV and TOMS ozone retrieval algorithms\(^{20}\)).

Figure 4 shows the comparisons of NO2 SCDs for one orbit on 4 January 2019 retrieved using these spectral fitting scenarios: (a) current settings of the EMI NO2 retrieval listed in Table 1; (b) using the measured irradiance spectrum as a reference; and (c) same as in (a) but without spectral precalibration. Irradiance spectra measured by EMI are currently accounting for some calibration issues, and these issues are probably related to the interference of the space environment on the hemispheric reflectance of solar diffusers\(^{18}\). NO2 SCDs retrieved with irradiance as a reference show large biases and errors, particularly the central part of the measurement swath (Fig. 4b). Therefore, it is not optimal to use the direct sun irradiance spectra as a reference. To avoid the influence of abnormal irradiance spectra, we use cloud-free earth radiance measurements over the Pacific Ocean as a reference\(^{21}\). Compared to using solar irradiance as a reference, using earth radiance as a reference greatly reduced the spectral noise in the fit residual (Fig. 4a, b).

| Configurations and parameters | OMI NO2 product (Boersma et al.\(^{17}\)) | EMI NO2 product (in this study) |
|------------------------------|------------------------------------------|---------------------------------|
| NO2 SCDs fitting             |                                          |                                 |
| Wavelength range             | 405–465 nm                               | 420–470 nm                      |
| Radiometric calibration      | Using calibrated (ir)radiance\(^{30}\)   | Recalibrated the earth radiance measurements |
| Reference spectrum           | Solar irradiance averaged between 2005–2009 (ref. \(^{36}\)) | Daily earth radiance over the remote Pacific |
| Instrument slit function     | Preflight measured\(^{31}\)              | Calibrated online by using solar atlas\(^{22}\), Gaussian shape assumed. |
| NO2 AMF calculations         |                                          |                                 |
| Radiative transfer model (RTM) | Doubling-Adding KNMI (DAK) model\(^{17}\) | Vector Linearized Discrete Ordinate Radiative Transfer (VLIDORT) model\(^{14}\) |
| Calculation method           | Lookup table interpolation               | Lookup table interpolation      |
| A priori NO2 profile         | The global chemistry Transport Model version 5 (TMS)\(^{35}\) simulations at 1 × 1° | The GEOS-Chem v10-01 at 2 × 2.5° for the global domain\(^{33}\), and WRF-Chem v3.7 at ~20 km for the China domain\(^{34}\) |
| Stratospheric–tropospheric separation | Data assimilation\(^{17}\) | Reference sector method\(^{14}\) |
which is likely related to the differences between spectra measured with the solar and earth-viewing modes. The mean RMS of fitting residual by using earth radiance as a reference over cloud-free regions is 30% smaller than that with irradiance as a reference, as shown in Fig. 4a, b.

Although using radiance as a reference improved the spectral retrieval, the radiance reference also contains a NO$_2$ absorption signal. Therefore, we must calculate the SCD offset to compensate for the residual NO$_2$ signal in the reference spectrum. The SCD offset is calculated using the NO$_2$ AMF multiplied by the a priori NO$_2$ profile taken from the GEOS-Chem model simulations (Supplementary Fig. 2). The NO$_2$ simulation over clean remote regions is generally consistent with independent satellite observations, with a monthly mean bias of $<0.26 \times 10^{15}$ molecules cm$^{-2}$ (Supplementary Fig. 3). Then, the SCD offset is added back to the NO$_2$ SCDs.

To account for the small variation in the spectral alignment due to the thermal variation in space, we calibrated the additional spectral shift or squeeze and instrument slit function through cross-correlation with a high-resolution solar spectrum atlas prior to the NO$_2$ DOAS fitting. The precalibrated measurement spectra lead to an ~30% smaller SCD fitting uncertainty than using initial calibration parameters (Fig. 4c), as well as a fit residual, and the SCD is nearly unchanged (within ~3.3%).

**Discussion**

The tropospheric NO$_2$ VCDs retrieved from EMI spectra are first validated against the OMI QA4ECV NO$_2$ products and the operational TROPOMI NO$_2$ products. EMI measurements are compared to the OMI and TROPOMI products due to their similar instrument characteristics, i.e., the push-broom design, spectral bands, and near-noon overpass time at ~13:30. Note that the TROPOMI NO$_2$ product generally followed the OMI QA4ECV NO$_2$ retrieval algorithm, but TROPOMI has a higher signal-to-noise ratio and spatial resolution. Figure 5 shows the monthly averaged NO$_2$ VCDs measured by EMI, OMI, and TROPOMI in January 2019. EMI NO$_2$ VCDs generally show similar spatial patterns and
The EMI dataset overestimates NO2 VCDs by up to 50% the satellite instrument with a higher spatial resolution. EMI NO2 and TROPOMI NO2 were also evaluated. For observations. The spatiotemporal correlations between NCP and India (Fig. 5d) compared to the TROPOMI over polluted regions, such as the North China Plain (NCP) is 0.92 (Fig. 6). The remaining discrepancies between EMI and TROPOMI are mainly due to the NO2 vertical profile used in the tropospheric AMF calculation, while the spectral fitting method (<3%) and stratospheric estimation method (<10%) only show a minor contribution (Supplementary Fig. 5).

The EMI tropospheric NO2 VCDs are also compared to the ground-based NO2 measurements from the Multi-AXis Differential Optical Absorption Spectroscopy (MAX-DOAS) instruments over northern China. A good agreement with a Pearson correlation coefficient (R) of 0.82 is found between the two datasets during January–August 2019 (Fig. 7, Supplementary Fig. 6). However, EMI generally underestimates tropospheric NO2 VCDs by 30% compared to MAX-DOAS. The biases can be explained by the difference in spatial coverage between the ground-based and satellite observations24,25. In general, both satellite and ground-based validations of EMI NO2 measurements show good agreement with correlation coefficients (R) of 0.8–0.9, indicating that a
new EMI tropospheric NO₂ retrieval provides reliable results for the investigation of air pollution distribution.

**Materials and methods**

**The stratosphere–troposphere separation**

The stratospheric contribution of NO₂ must be subtracted from the total NO₂ column to derive the tropospheric NO₂ column. In the EMI NO₂ retrieval, we used the STRatospheric Estimation Algorithm from Mainz to estimate the stratospheric contribution, which is based on the assumption that there is negligible contribution of tropospheric NO₂ columns over the remote Pacific and cloudy pixels in the middle latitudes. The weighting factors based on cloud and polluted regions,
which determines their impacts on the stratospheric estimate, are assigned to each satellite pixel. Subsequently, spatial smoothing based on weighted convolution is used to estimate the global stratospheric column.

**NO$_2$ AMF calculations**

The EMI NO$_2$ AMFs of each atmospheric layer (i.e., Box-AMFs) are calculated at 445 nm by the linearized pseudospherical vector model VLIDORT$^{26}$ version 2.7. In addition to the solar and satellite-viewing geometries provided in the level 1 data, additional atmospheric and surface information are needed in the AMF calculations. Surface albedo at 442 nm is taken from the OMI minimum earth’s surface Lambertian equivalent reflectance$^{27}$ and interpolated to the EMI footprints. Considering the same local overpass time between EMI and TROPOMI, cloud top pressure and cloud fraction from TROPOMI$^{28}$ are used for the calculations of EMI NO$_2$ AMFs. A priori NO$_2$ profiles are taken from the high-resolution (~20 km) WRF-Chem simulations for the China domain and from GEOS-Chem simulations at the resolution of 2 × 2.5° for the global domain (Supplementary Fig. 7). The spatial resolution of the NO$_2$ a priori profile is reportedly one of the dominant uncertainty sources during the NO$_2$ AMF calculations$^{29}$. To expedite the calculation, these box-AMFs are precalculated and stored in the six-dimensional lookup table. Then, the box-AMF for each EMI observation can be derived by interpolating within the lookup table.

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**Author contributions**

C.Z. performed the data analysis and wrote the manuscript. C.L. supervised this research and conceived the idea. K.L.C. contributed to the data interpretation and manuscript revisions. H.L., B.L., C.X., and W.T. processed the MAX-DOAS data. H.Z., F.S., and J.L. built the EMI instrument. C.Z. prepared the paper with inputs from all co-authors.
Data availability
The EMI level 1 and NO$_2$ datasets are available from Cheng Liu (chliu81@usc.edu.cn) upon reasonable request. The OMI QA4ECV NO$_2$ and TROPOMI NO$_2$ datasets are available from http://www.temis.nl/airpollution/no2.html.

Conflict of interest
The authors declare that they have no conflict of interest.

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References
1. Zhang, C. X. et al. Preflight evaluation of the performance of the chinese environmental trace gas monitoring instrument (EMI) by spectral analyses of nitrogen dioxide. IEEE Trans. Geosci. Remote Sens. 56, 3323–3332 (2018).
2. Levelt, P. F. et al. The ozone monitoring instrument. IEEE Trans. Geosci. Remote Sens. 44, 1093–1101 (2006).
3. Veefkind, J. P. et al. TROPOMI on the ESA Sentinel-5 Precursor: a GMES mission for global observations of the atmospheric composition for climate, air quality and ozone layer applications. Remote Sens. Environ. 120, 70–85 (2012).
4. Atkinson, R. Atmospheric chemistry of VOCs and NO$_x$. Atmos. Environ. 34, 2063–2101 (2000).
5. Crippa, M. et al. Gridded emissions of air pollutants for the period 1970-2012 within EDGAR v4.3.2. Earth Syst. Sci. Data 10, 1987–2013 (2018).
6. An, Z. S. et al. Severe haze in northern China: a synergy of anthropogenic emissions and atmospheric processes. Proc. Natl Acad. Sci. USA 116, 8657–8666 (2019).
7. Gao, M. et al. Estimates of health impacts and radiative forcing in winter haze in eastern china through constraints of surface PM$_{2.5}$ predictions. Environ. Sci. Technol. 51, 2178–2185 (2017).
8. Liu, F. et al. NO$_2$ emission trends over Chinese cities estimated from OMI observations during 2005 to 2015. Atmos. Chem. Phys. 17, 9261–9275 (2017).
9. Zhang, C. X. et al. Satellite UV-Vis spectroscopy: implications for air quality trends and their driving forces in China during 2005-2015. Light. Sci. Appl. 8, 100 (2019).
10. Liu, X. L. et al. Assimilation of satellite NO$_2$ observations at high spatial resolution using OSSEs. Atmos. Chem. Phys. 17, 7067–7081 (2017).
11. Zhao, M. J. et al. Preflight calibration of the Chinese Environmental trace gas monitoring instrument (EMI). Atmos. Meas. Tech. 11, 5403–5419 (2018).
12. Platt, U. & Stutz, J. Differential Optical Absorption Spectroscopy, pp 135–174 (Springer, Berlin, Heidelberg, 2008).
13. Beirle, S. et al. The STRatospheric Estimation Algorithm from Manz (STREAM): estimating stratospheric NO$_2$ from nadir-viewing satellites by weighted convolution. Atmos. Meas. Tech. 9, 2753–2779 (2016).
14. Valks, P. et al. Operational total and tropospheric NO$_2$ column retrieval for GOME-2. Atmos. Meas. Tech. 4, 1491–1514 (2011).
15. Palmer, P. I. et al. Air mass factor formulation for spectroscopic measurements from satellites: application to formaldehyde retrievals from the global ozone monitoring experiment. J. Geophys. Res. 106, 14539–14550 (2001).
16. Boersma, K. F. et al. Improving algorithms and uncertainty estimates for satellite NO$_2$ retrievals: results from the quality assurance for the essential climate variables (QA4ECV) project. Atmos. Meas. Tech. 11, 6651–6678 (2018).
17. Zhao, M. J. et al. Effect of AO/LV/RO exposure on spaceborne diffusers: a comparative experiment. Appl. Opt. 54, 9157–9166 (2015).
18. Schenkeveld, V. M. E. et al. In-flight performance of the ozone monitoring instrument. Atmos. Meas. Tech. 10, 1957–1966 (2017).
19. Heath, D. F. et al. The solar backscatter ultraviolet and total ozone mapping spectrometer (SBUV/OMI) for Nimbus G. Optical Eng. 14, 144323 (1975).
20. Anand, J. S., Monks, P. S. & Leigh, R. J. An improved retrieval of tropospheric nitrogen dioxide. Earth Syst. Sci. Data 10, 7067–7081 (2018).
21. Chance, K. & Kurucz, R. L. An improved high-resolution solar reference spectrum for earth’s atmosphere measurements in the ultraviolet, visible, and near infrared. J. Quant. Spectrosc. Radiat. Transf. 111, 1289–1295 (2010).
22. Griffin, D. et al. High-resolution mapping of nitrogen dioxide with TROPOMI: first results and validation over the canadian oil sands. Geophys. Res. Lett. 46, 1049–1060 (2019).
23. Chan, K. L. et al. Observations of tropospheric aerosols and NO$_2$ in Hong Kong over 5 years using ground based MAX-DOAS. Sci. Total Environ. 619–620, 1545–1556 (2018).
24. Chan, K. L. et al. MAX-DOAS measurements of tropospheric NO$_2$ and HCHO in Nanjing and a comparison to ozone monitoring instrument observations. Atmos. Chem. Phys. 19, 10051–10071 (2019).
25. Spur, R. J. D. VIUDORT: a linearized pseudo-spherical vector discrete ordinate radiative transfer code for forward model and retrieval studies in multilayer multiple scattering media. J. Quant. Spectrosc. Radiat. Transf. 102, 316–342 (2006).
26. Kleipool, Q. L. et al. Earth surface reflectance climatology from 3 years of OMI data. J. Geophys. Res. 113, D18308 (2008).
27. Loyola, D. G. et al. The operational cloud retrieval algorithms from TROPOMI on board Sentinel-5 Precursor. Atmos. Meas. Tech. 11, 409–427 (2018).
28. Kuhlmann, G. et al. Development of a custom OMI NO$_2$ data product for evaluating biases in a regional chemistry transport model. Atmos. Chem. Phys. 15, 5627–5644 (2015).
29. van den Oord, G. H. J. et al. OMI level 0 to 1b processing and operational aspects. IEEE Trans. Geosci. Remote Sens. 44, 1380–1397 (2006).
30. Dirkxen, R. et al. Prelaunch characterization of the Ozone Monitoring Instrument transfer function in the spectral domain. Appl. Opt. 45, 3972–3981 (2006).
31. Williams, J. E. et al. The high-resolution version of TmS-MP for optimized satellite retrievals: description and validation. Geosci. Model Dev. 10, 721–750 (2017).
32. Wang, S. W. et al. Growth in NO$_2$ emissions from power plants in China: bottom-up estimates and satellite observations. Atmos. Chem. Phys. 12, 4439–4447 (2012).
33. Su, W. J. et al. Characterization of ozone in the lower troposphere during the 2016 G20 conference in Hangzhou. Sci. Rep. 7, 17368 (2017).