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Preliminary Global NO₂ Retrieval from EMI-II Onboard GF5B/DQ1 and Comparison to TROPOMI

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Abstract: The Environmental Trace Gases Monitoring Instrument (EMI-II) onboard the Chinese GaoFen-5B (GF5B) and DaQi-1 (DQ1) satellites is the successor of the previous EMI onboard the Chinese GaoFen-5 (GF5) satellite, and has a higher spatial resolution and a better signal-to-noise ratio. The GF5B and DQ1 were launched in September 2021 and April 2022, respectively. As part of China's ultraviolet-visible hyperspectral satellite instrument series, the EMI-II aims to conduct network observations of pollution gases globally in the morning and early afternoon. In this study, NO₂ data were retrieved from the EMI-II payloads on the GF5B and DQ1 satellites using the Differential Optical Absorption Spectroscopy (DOAS) algorithm. The two satellites were consistently compared, and the results showed strong consistency on various spatial and temporal scales ($R^2 > 0.8$). In four representative regions worldwide, NO₂ data from the EMI-II exhibited good spatial consistency with those from the TROPOMI. The correlation coefficient (R^2) of the total vertical column density (VCD) between the EMI-II and TROPOMI exceeded 0.85, and that of the tropospheric NO₂ VCD exceeded 0.57. Compared with single-satellite observations, the dual-satellite network of the GF5B and DQ1 can effectively increase the observation frequency. On a daily scale, dual-satellite observations can reduce the impact of cloud coverage by 6–8% compared to single-satellite observations, and there are two valid observations of nearly 50% of the world's regions. Additionally, the differences between the two satellites can reflect the NO₂ diurnal variations, which demonstrates the potential for studying pollutant gas diurnal variations.

Keywords: GaoFen-5B (GF5B); DaQi-1 (DQ1); Environmental Trace Gases Monitoring Instrument (EMI); DOAS; NO₂ retrieval; stratosphere and troposphere NO₂



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1. Introduction

Nitrogen oxides (NO_x = NO₂ + NO) are crucial species in the troposphere and stratosphere, and they enter the atmosphere through a combination of anthropogenic and natural processes. Tropospheric NO₂ directly affects human health and is an important precursor for the formation of ozone, which affects the OH concentration and shortens the lifetime of methane [1]. By participating in photochemical reactions with ozone, stratospheric NO₂

affects the ozone layer by acting as a catalyst for ozone destruction [2,3] or by suppressing ozone depletion [4]. Thus, it is essential to monitor these species on a global scale.

Since the mid-1990s, satellite observations of NO₂ have been used by atmospheric chemistry researchers to monitor the global daily NO₂ pollution, study the long-term and short-term changes in NO₂, locate the sources of NO_x emissions, and support the formulation of emission control policies and pollution prevention measures. Many space-based sensors onboard polar orbit satellites can provide NO₂ information via VIS band observations, e.g., the Global Ozone Monitoring Experiment (GOME) [5], Scanning Imaging Spectrometer for Atmospheric Cartography (SCIAMACHY) [6], Ozone Monitoring Instrument (OMI) [7], GOME-2 [8,9], and the Tropospheric Ozone Monitoring Instrument (TROPOMI) [10]. With the advantage of a finer spatial resolution and higher signal-to-noise ratio compared to other similar satellite missions, TROPOMI products have been widely used for detecting emission sources [11]. The EMI sensor onboard the GaoFen-5 satellite, which has a spatial resolution of $13 \times 48 \text{ km}^2$, has also demonstrated the capability for satellite-based global NO₂ monitoring [12,13]. In addition, Yang et al. (2014) investigated the feasibility of NO₂ retrieval based on the OMPS Nadir Mapper (NM) using the UV band of 345–390 nm [14], and the algorithm was implemented in the NOAA-20 OMPS-NM [15]. Alternatively, geostationary satellite missions like the GEMS (Geostationary Environment Monitoring Spectrometer) onboard the Geostationary Korea Multi-Purpose Satellite-2B (GK-2B), which was launched in February 2020, and the Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument, launched in April 2023, can provide measurements of NO₂ and other pollutants in the daytime on an hourly basis [16,17].

The Environmental Trace Gases Monitoring Instrument (EMI-II) aboard the Chinese GaoFen-5B (GF5B) and DaQi-1 (DQ1) satellites, which were launched in September 2021 and April 2022, respectively, is the successor of the EMI aboard the Chinese GaoFen-5 (GF5) satellite under the 13th Five-Year Plan for Space Infrastructure Development. Because the EMI data have worse signal-to-noise ratios, calibration accuracy, and spatial resolution than TROPOMI, several methods such as pre-calibration have been conducted to improve the spectral quality of EMI data before retrieval [18]. In addition, the earth radiance over the remote Pacific is used as a reference spectrum instead of solar irradiance in the EMI NO₂ retrieval setting, which is different from traditional DOAS retrieval, to eliminate the cross-track stripes in the retrieval as a result of imperfect irradiance measurements [12]. As a new data source for global NO₂ monitoring, EMI-II has a better calibration accuracy and spectral quality than EMI [19], and its detection performance and comparison with similar international instruments must be further evaluated.

Meanwhile, the combination of multiple instruments with different overpass times can improve the temporal resolution compared to a single polar orbiting satellite. This combination can also improve the daily coverage data and diminish the problem of missing data caused by cloud interference. In addition, the observed spectra at different overpass times contain information about the diurnal variation in the detection target. Combined OMI and GOME-2 observations have been used to investigate the diurnal variation in global formaldehyde [20], to more accurately measure the near-surface NO₂ [21], and to reconstruct spatially and temporally coherent tropospheric NO₂ [22]. The EMIs onboard GF5B and DQ1 with different overpass times have the advantages of networking observation and can avoid errors caused by differences in instrument design specifications and calibrations. This ability must be evaluated.

In summary, in this work, we focus on assessing the detection performance of the EMI-II for global NO₂ monitoring. In addition, combined GF5B and DQ1 observations were investigated and discussed. Section 2.1 briefly describes the EMI-II data and TROPOMI NO₂ data, which are used as a validation source. Section 2.2 discusses the DOAS-based retrieval method. Section 3 presents the derived NO₂ column results, an intercomparison between GF5B and DQ1, and the validation results with TROPOMI. Section 4 discusses the potential advantages of a dual-satellite network (e.g., increasing the frequency of

observations and facilitating the study of the diurnal variation in NO₂). Finally, Section 5 presents the conclusions.

2. Data and Methods

2.1. EMI-II

The EMI-II instruments onboard the GF5B and DQ1 satellites are similar to those onboard the GF5 satellite. Both are nadir-viewing push broom spectrometers flying in a sun-synchronous polar orbit and observe direct and atmospheric backscattered sunlight in the range of 240–710 nm through four channels. The instantaneous field of view (IFOV) and swath width are 114° and 2600 km, respectively. Table 1 lists the main differences in the technical parameters for the two payloads: (1) Spectral range of the four channels: the four channels of GF5 EMI and DQ1 EMI-II are UV1: 240–315 nm, UV2: 311–403 nm, VI1: 401–550 nm, and VI2: 545–470 nm; the four channels of GF5B EMI-II are UV1: 240–311 nm, UV2: 311–401 nm, VI1: 401–550 nm, and VIS2: 550–710 nm. (2) Spectral resolution: the spectral resolution of the GF5 EMI is 0.3–0.5 nm, and the spectral resolution of EMI-II is 0.3–0.6 nm. (3) Spatial resolution: the spatial resolution of GF5 EMI is 13 km × 48 km, and that of GF5B and DQ1 EMI-II is 13 km × 24 km. (4) Equator crossing time: the local overpass time of GF5 EMI and DQ1 EMI-II is 13:30, and that of GF5B EMI-II is 10:30.

Table 1. Basic technical parameters of GF5 EMI and EMI-II onboard GF5B and DQ1.

Instrument Name		GF5 EMI	GF5B EMI-II	DQ1 EMI-II	TROPOMI
Spectral range	UV1 band	240 nm~315 nm	240 nm~311 nm	240 nm~315 nm	270 nm~300 nm
	UV2 band	311 nm~403 nm	311 nm~403 nm	311 nm~403 nm	300 nm~320 nm
	VIS1 band	401 nm~550 nm	403 nm~550 nm	401 nm~550 nm	310 nm~405 nm
	VIS2 band	545 nm~710 nm	550 nm~710 nm	545 nm~710 nm	405 nm~500 nm
Spectral resolution		0.3–0.5 nm	0.3–0.6 nm	0.3–0.6 nm	0.5–1 nm
Spatial resolution		48 km × 13 km	24 km × 13 km	24 km × 13 km	3.5 km × 5.5 km
Equator crossing time		Ascending node 13:30	Descending node 10:30	Ascending node 13:30	Ascending node 13:30

The EMI-II data have better calibration accuracy and spectral quality than those from GF5 EMI. Figure 1 shows the FWHM variation with the number of rows in the VIS band for DQ1 EMI-II, GF5B EMI-II, GF5 EMI, and TROPOMI. The variation standard deviations of DQ1, GF5B, GF5, and TROPOMI FWHM were 0.042 nm, 0.047 nm, 0.0545 nm, and 0.0041 nm, respectively. The FWHM variation in EMI-II strongly depends on the row number, especially for rows at the edge, but the stability of EMI-II has improved compared with that of GF5 EMI and is inferior to that of TROPOMI.

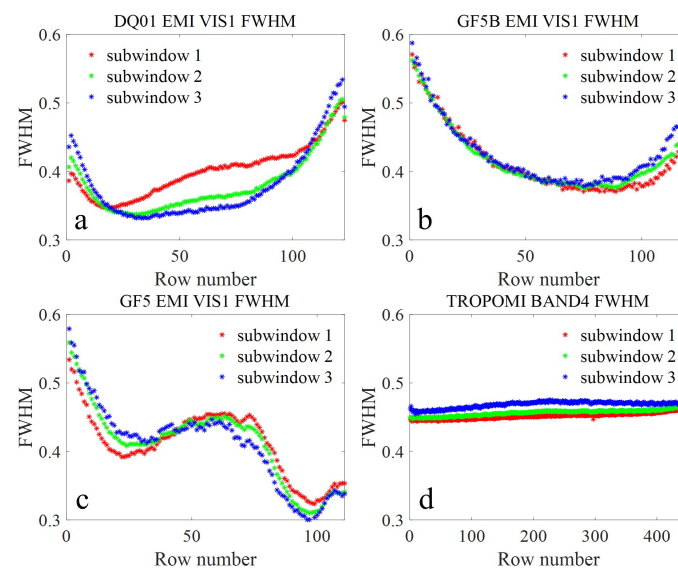


Figure 1. FWHM variation with the number of rows in the VIS band for (a) DQ1 EMI, (b) GF5B EMI, (c) GF5 EMI, and (d) TROPOMI.

2.2. TROPOMI NO₂

The TROPOMI NO₂ product has been updated and validated since its release [23]. In this paper, the V2.2 version product is used [24] to cross-validate with the EMI product. The fitting method for the TROPOMI NO₂ data follows that used in the study by Boersma et al. in 2011 [25] and the studies by Van Geffen et al. in 2020 [23] and 2022 [24], with a fitting error of approximately $0.5\text{--}0.6 \times 10^{15}$ molec./cm². The NO₂-v2.2 data showed a better performance when compared to that of the previous v1.x, especially over highly polluted areas. This improvement benefits from the improved calibration of TROPOMI version-2 level-1b (ir) radiance spectra and updated FRESCO cloud product, as well as the optimization of input parameters such as surface albedo, snow/ice information, and adjustment of the quality control scheme [24]. The ground-based validation results demonstrated the TROPOMI V2.2 NO₂ VCD has a 5% negative bias [24].

2.3. EMI-II NO₂ Retrieval Algorithm

The tropospheric NO₂ retrieval algorithm for GF5B and DQ1 EMI-II data is similar to that for GF5 EMI data [12] and involves three key steps.

(1) Spectral fitting to obtain the total NO₂ slant column density (SCD).

The NO₂ SCD was derived using the conventional differential optical absorption spectrometry (DOAS) method, which integrates the measurements along the effective optical path from the sun, through the atmosphere, to the instrument. In this study, Table 2 provides the parameters used for fitting the NO₂ spectrum. For GF5B and DQ1 EMI-II spectra, the reference spectra were obtained on 8 October 2021 and 23 May 2022, respectively. Within the fitting window of 405–465 nm, a fifth-order polynomial was applied. The fitting process incorporated the absorption cross-sections for NO₂ [220 K], O₃ [223 K], H₂O vapour, H₂O liquid, O₄, and the ring effect, all of which were convolved with the slit function to match the EMI-II's resolution. Additionally, a first-order intensity offset correction was applied. Prior to retrieving the SCD, a wavelength calibration was performed using solar Fraunhofer lines from a highly accurate reference solar atlas to minimize discrepancies between the radiance wavelength and the absorption cross-section [26].

Table 2. Spectral fitting parameter settings for GF5B EMI-II, DQ1 EMI-II, and TROPOMI.

Parameters		GF5B EMI-II	DQ1 EMI-II	TROPOMI
Fitting window		405–465 nm	405–465 nm	405–465 nm
Reference spectrum I_0		Irradiance measured on 8 October 2021	Irradiance measured on 23 May 2022	Annual mean (2005) solar reference
Polynomial		5th-order	5th-order	5th-order
Included cross-sections	O ₃	✓ (223 K)	✓ (223 K)	✓ (243 K)
	NO ₂	✓ (220 K)	✓ (220 K)	✓ (220 K)
	O ₄	✓ (293 K)	✓ (293 K)	✓ (293 K)
	H ₂ O vapour	✓ (280 K)	✓ (280 K)	✓ (280 K)
	H ₂ O (liquid)	✓ (295 K)	✓ (295 K)	✓ (295 K)
	Ring effect	✓	✓	✓
Offset correction		✓	✓	×

The initial SCD fitting results for EMI NO₂ display uneven stripes along the along-track direction. This phenomenon is attributed to the instability of the FWHM and calibration errors in the irradiance data. Such issues are common in payloads employing two-dimensional CCD push broom imaging, including similar instruments like OMI [25]. These biases need to be removed by spatial filtering before subsequent procedures.

We updated the de-stripe correction scheme based on the method in Cheng et al. (2019) [12]. Its main features are as follows: (1) pixels with SCDs exceeding 1.5σ are excluded when the mean SCD of each row is calculated; (2) after the preliminary correction, the mean VCD of each row is compared with the climatology value of a clean ocean area to obtain the revised SCD; (3) the revised SCD is used to correct the SCD correction value; (4) the revised SCD correction value is used to correct the initial SCD. The de-stripe scheme can preserve the variation characteristics of the SCD with the VZA in the cross-track direction, which is more realistic.

(2) Stratosphere-tropospheric separation (STS) was used to estimate the concentration of NO₂ in the stratosphere and remove it from the total SCD to obtain the tropospheric SCD.

The STREAM STS method was used in this study to estimate the stratospheric VCD. This method is less dependent on external input data and directly uses satellite observations to calculate a series of weights for each pixel, based on which the stratospheric concentrations are obtained via weight convolution. Among them, the “pollution weight” is used to reduce the contribution of potential pollution areas, the “cloud weight” is used to increase the contribution of cloud observation pixels, and the “tropospheric residual weight” is used to adjust the total weight to avoid abnormal tropospheric residuals. The tropospheric residual is the difference between the total VCD and stratospheric VCD, which can be directly converted to tropospheric VCD as follows:

$$V_{trop} = R_{trop} \times \frac{A_{strat}}{A_{trop}} \quad (1)$$

where R_{trop} is the tropospheric residual; A_{strat} is a geometric air mass factor (AMF) (AMF_G) and is defined as $AMF_G = \sec \theta_s + \sec \theta_v$, which is a function of the solar zenith angle θ_s and satellite viewing angle θ_v in the absence of atmospheric scattering. A_{trop} is the tropospheric AMF.

(3) The tropospheric VCD is calculated using the ratio of the tropospheric SCD to the tropospheric AMF, with the method for calculating the tropospheric AMF following the approach of Boersma et al. (2004) [27]:

$$AMF = \frac{\sum_l m_l x_{a,l} \cdot c_l}{\sum_l x_{a,l}} \quad (2)$$

$$c_l = 1 - 0.003[T(p) - T_0] \quad (3)$$

where m_l represents the scattering weight AMF (box-AMF), which describes the vertical sensitivity of the retrieved parameters. $x_{a,l}$ denotes the NO₂ sub-column in layer l . c_l is the temperature correction factor used to adjust the absorption cross-section spectrum according to the effective temperature at the specific layer p . T_0 (220 K) refers to the temperature of the NO₂ absorption cross-section used in the DOAS fitting. The calculation of the AMF for partially cloudy scenes follows the methodology established by Boersma et al. (2011) [25], utilizing the Independent Pixel Approximation (IPA). This approach involves representing the scene as a linear combination of cloudy (M_{cl}) and clear (M_{cr}) components:

$$\text{AMF} = \omega \text{AMF}_{cl} + (1 - \omega) \text{AMF}_{cr} \quad (4)$$

where ω denotes the effective cloud fraction. In this paper, we use TROPOMI cloud products instead of EMI-II due to the lack of mature and public cloud products derived from EMI-II.

The calculation of box-AMF varies with three angles (solar zenith angle, viewing zenith angle, and relative azimuth angle) and three surface parameters (surface albedo, surface elevation, and surface pressure). In this study, the box-AMF lookup tables were computed using the SCIATRAN RTM [28], and AMF values were interpolated based on the actual conditions of these six parameters [12]. For the a priori NO₂ profiles and surface pressure parameters, we utilized data from the GEOS-cf CTM [29]. This CTM divides the atmosphere into 72 layers and provides outputs with a temporal resolution of one hour, a spatial resolution of $0.25^\circ \times 0.25^\circ$, and global coverage. The output information includes NO₂ profiles (in volume mixing ratio), temperature profiles (in K), hybrid pressure level profiles (in Pa), and the tropopause layer index (to differentiate between the stratosphere and troposphere). Surface albedo data and surface elevation data were obtained from the OMLER [30] and GMTED2010 products, respectively.

3. Results and Validation

3.1. SCD Uncertainty

To evaluate the uncertainty in the EMI-IIs' measured SCD, we employed a statistical analysis approach based on data from the EMI-II in the Pacific clean region (20°S – 20°N ; 160°E – 180°E), as outlined by [31]. Initially, we segmented the region into $2^\circ \times 2^\circ$ boxes. In theory, the AMF within each box should exhibit minimal variation, resulting in negligible VCD differences among pixels. Consequently, any changes in the total NO₂ columns within each box are assumed to stem from slant column measurement errors, primarily due to (random) instrument noise. Thus, variations in the total detected VCD are attributed to SCD errors. We then estimated the SCD uncertainty by analyzing the deviations of the SCD values for each valid pixel from the mean SCD of the respective box. Figure 2 displays histograms of the absolute differences for valid pixels from GF5B and DQ1 for June 2022. The SCD deviations follow a Gaussian distribution, suggesting that the observed variability within the boxes is predominantly due to random error. The Gaussian distribution widths were 0.42×10^{15} molec./cm² for GF5B and 0.37×10^{15} molec./cm² for DQ1 in June 2022, respectively, which are interpreted as the average slant column errors for the EMI-II measurements. The precision of the EMI-II NO₂ measurement is comparable to the capabilities of GOME-2, where the estimated average SCD uncertainty was 0.45×10^{15} molec./cm², as reported by [31], which is better than the OMI NO₂ measurements of 0.67×10^{15} , that were reported by [32] using the same method. GF-5B had a larger slant column error than DQ1, which can be partly attributed to the higher signal-to-noise ratio.

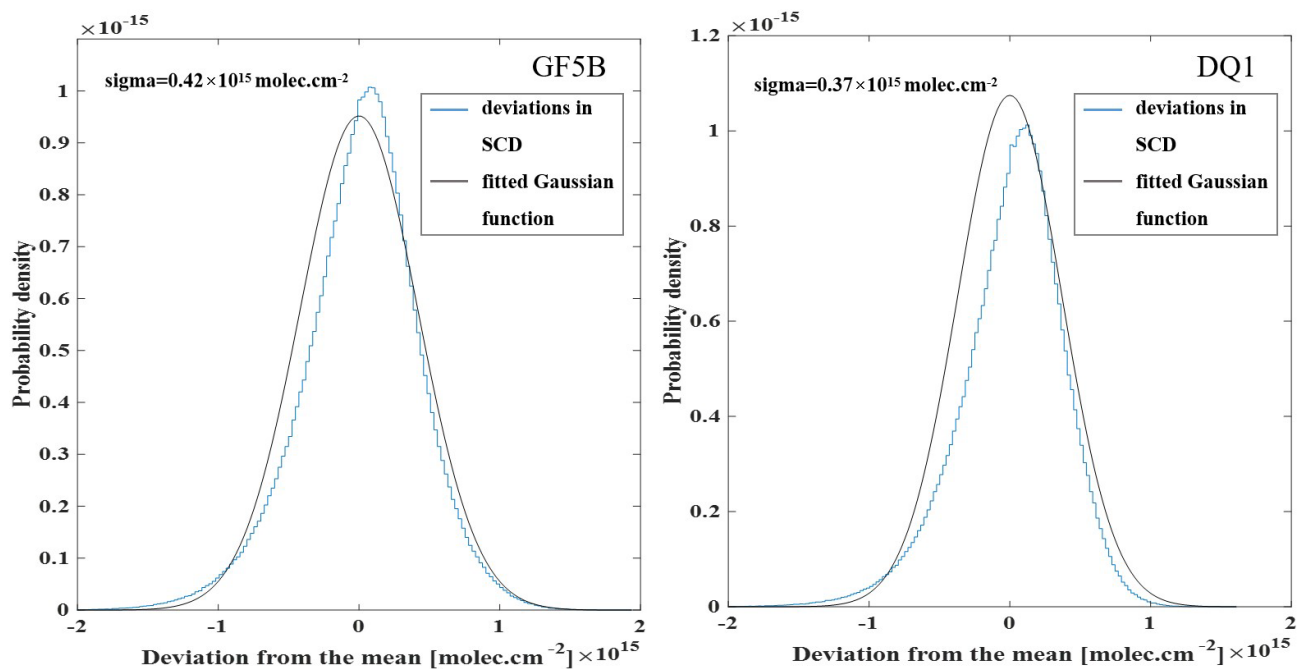


Figure 2. NO₂ SCD uncertainty from GF5B and DQ1. The blue line represents the distribution of deviations in SCD from the mean values of the box for all valid pixels. A Gaussian function, fitted to the histogram data, is illustrated by the black line.

3.2. Examples of the Total NO₂ VCD of GF-5B and DQ1

Figure 3 presents the global monthly distribution maps of the NO₂ VCD from GF5B (upper row) and DQ1 (middle row) in June 2022 (left panel) and December 2022 (right panel), which represent summer and winter, respectively. Both GF5B and DQ1 clearly exhibit classic seasonal patterns in the NO₂ distribution: during the summer, the average NO₂ concentration in the Northern Hemisphere exceeds that of the Southern Hemisphere, while in winter, the situation reverses, with the Southern Hemisphere displaying higher average NO₂ levels. This seasonal variation is clearly illustrated in the monthly average distribution maps of TROPOMI NO₂. Notably, stratospheric NO₂ is the primary contributor to this phenomenon, rather than NO₂ from anthropogenic sources.

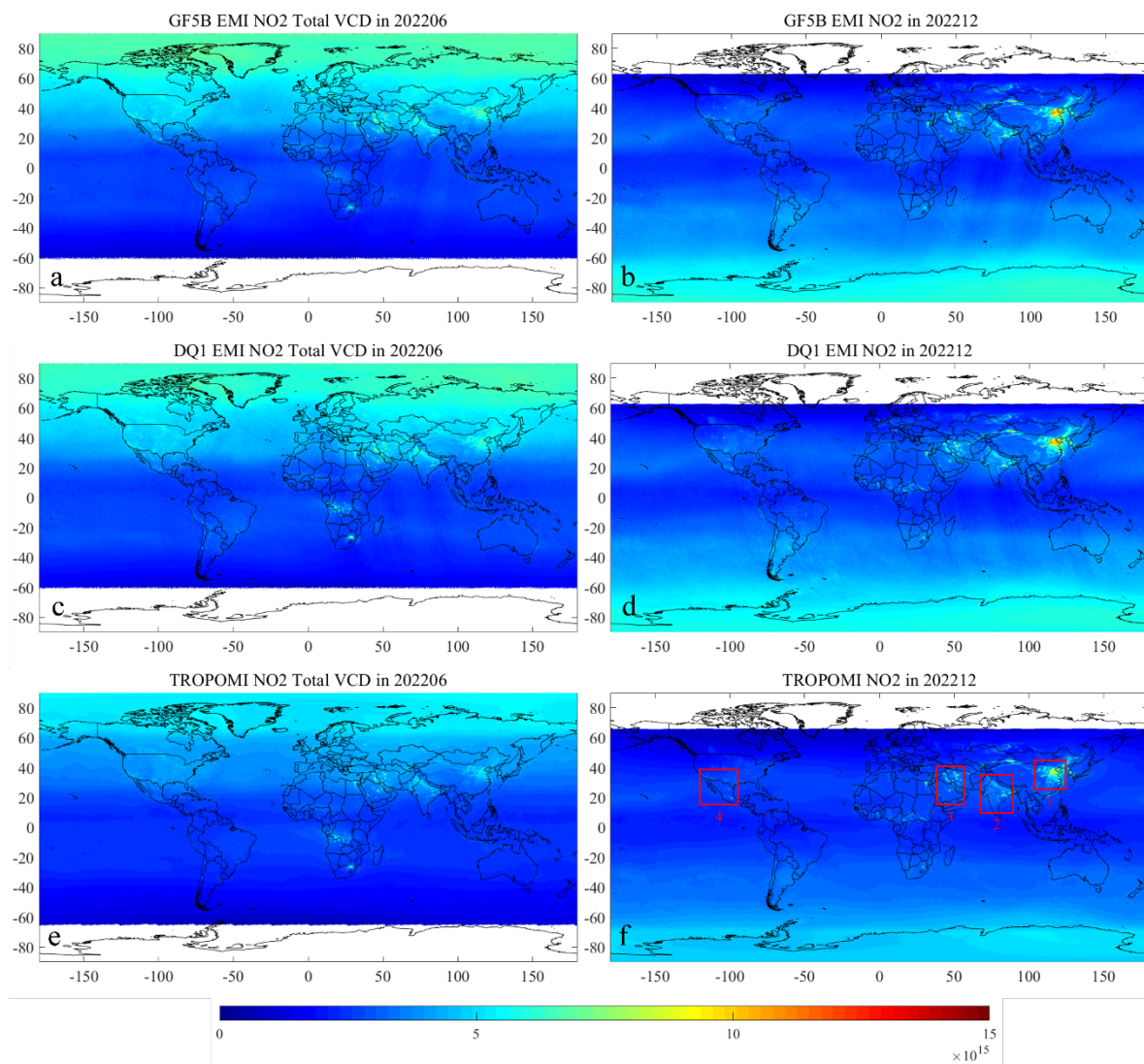


Figure 3. Monthly global NO₂ VCD distributions of GF5B (top), DQ1 (middle), and TROPOMI (bottom) products in July 2022 (left) and December 2022 (right). (a) GF5B EMI Monthly global NO₂ VCD in July 2022 (b) GF5B EMI Monthly global NO₂ VCD in December 2022 (c) DQ1 EMI Monthly global NO₂ VCD in July 2022 (d) DQ1 EMI Monthly global NO₂ VCD in December 2022 (e) TROPOMI Monthly global NO₂ VCD in July 2022 (f) TROPOMI Monthly global NO₂ VCD in December 2022. The four red square frame in subfigure (f) indicate the four typical study regions with notable NO₂ emissions, including eastern China (region 1), most parts of India (region 2), the Arabian Peninsula and Iran (region 3), and southern North America (region 4).

During the summer, NO₂ hotspots are prominent in regions such as South Dakota in the United States, eastern South Africa, Cairo in Egypt, Kuwait, Qatar, the United Arab Emirates, and Tehran in Iran. In the winter, NO₂ hotspots are notable in cities such as Riyadh in Saudi Arabia, Baghdad in Iraq, Tehran in Iran, the Jing-Jin-Ji region in China, and Seoul in South Korea. GF5B and DQ1 exhibited high levels of spatial consistency in both summer and winter. The global spatial distribution characteristics of NO₂ demonstrated by the EMI-II are consistent with earlier research results from similar instruments such as the GOME-2 [33], OMI [34], TROPOMI [35], and EMI [12], which indicates that the retrieval results from the EMI-II can characterize the spatial distribution features of NO₂.

3.3. Total VCD Satellite Intercomparison of GF5B and DQ1

Although the GF5B EMI-II and DQ1 EMI-II are two independent payloads, their technical statuses are identical. The spatial distribution consistency and temporal variation consistency of their NO₂ products may not reflect the accuracy of the retrieval results, and the intercomparison results of GF-5B and DQ1 include the inevitable variations of the diurnal cycle. However, they can indicate the ability of the payloads to characterize the spatial distribution and temporal variations in NO₂. The consistency comparison between the two sensors can serve as a cross-validation. Notable anomalies in their consistency may suggest a potential issue with one of the payloads. The variation in consistency can be used as a metric of temporal stability. Similar forms of satellite intercomparisons of the TROPOMI, GOME-2B, and OMI can be found in reference [36]. In addition, NO₂ products derived from multiple satellites with different local cross-times were combined to estimate the NO₂ emissions [37], and identifying the differences in input data to interpret the results is important. The difference in the NO₂ measurements between the GF5B and DQ1 is expected to depend on the source strength and factors that contribute to the diurnal variation.

The global spatial correlation coefficients (R^2) between GF5B and DQ1 in June and December 2022 were 0.985 and 0.973, respectively. Specific regions with notable NO₂ emissions were delineated, including eastern China (region 1), most parts of India (region 2), the Arabian Peninsula and Iran (region 3), and southern North America (region 4), as illustrated in Figure 3f. The spatial consistency between the GF5B and DQ1 was compared in these hotspot areas (Table 3). In regions 1, 2, and 3, the spatial consistency (R^2) between the GF5B and DQ1 exceeded 0.91, 0.84, and 0.8, respectively. However, significant variations were observed in region 4, where the R^2 values were 0.93 in June and 0.74 in December. A possible reason for this is that this region has lower NO₂ emissions in the winter and exhibits diurnal variations, which requires further investigation.

Table 3. Spatial consistency between GF5B and DQ1 in identified hotspot areas.

Region	202206		202212	
	R^2	RMSE	R^2	RMSE
Region 1	0.91	0.03	0.93	0.04
Region 2	0.92	0.03	0.86	0.03
Region 3	0.85	0.04	0.85	0.04
Region 4	0.94	0.02	0.75	0.02

Importantly, in June 2022, increased NO₂ values were observed in Central Africa in the spatial distribution maps of the DQ1 EMI-II and TROPOMI, but these high values were not detected in the GF5B EMI-II maps. In Central Africa, NO₂ is primarily emitted from biomass burning activities, such as straw burning and grassland fires, which typically take place during the daytime and require time to accumulate. The overpass time for the GF5B is 10:30 AM, while for the DQ1, it is 13:30 PM. Consequently, it is challenging to detect elevated NO₂ concentrations at 10:30 AM using GF5B data.

To compare the temporal consistency, typical city coordinates were selected in the highlighted regions in Figure 3f. The daily mean values within a 5 km radius around these latitudinal and longitudinal points were calculated over time. Figure 4 displays the daily variations in the mean NO₂ VCD and correlation between GF5B and DQ1 in the Beijing area from 1 September to 31 December 2022. The correlation coefficient (R^2) during this period was 0.84. In general, the NO₂ results of the two EMI-II payloads exhibited a relatively high consistency across different time and spatial scales. However, there are inevitable differences, which may primarily be attributed to uncertainties from the differences in the FWHM and SCD uncertainty.

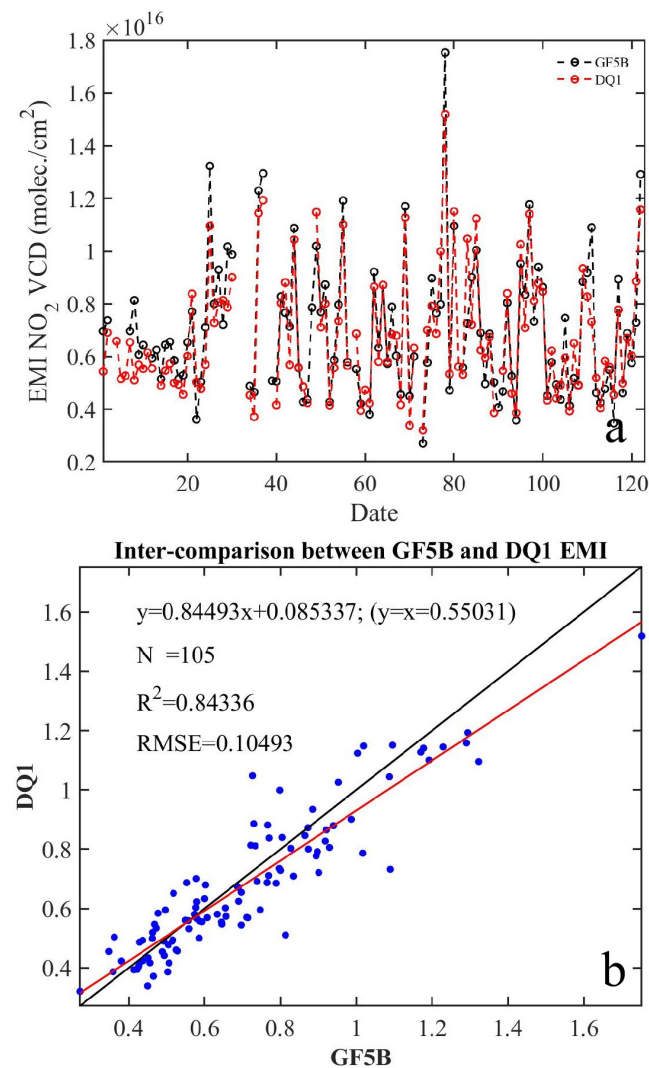


Figure 4. Intercomparison of the daily mean NO₂ VCD within 5 km of Beijing from GF5B and DQ1. (a) Daily variations in the mean NO₂ VCD (b) Correlation between GF5B and DQ1.

3.4. Total VCD Compared with TROPOMI

The TROPOMI has been in operation for six years. Its NO₂ products have undergone multiple iterations and optimizations, as validated by numerous ground-based MAX-DOAS measurements [38–41]. Cross-validation via TROPOMI products can indirectly reflect the accuracy of the trends in the EMI-II’s retrieval results. Due to the differences in the pixel spatial resolution between the EMI and TROPOMI, as well as the variations in the central latitude and longitude of the pixels, this study divides the research area into multiple 0.25° grids for comparative analysis. The NO₂ value for each grid is calculated by determining the mean of the pixels whose central coordinates fall within the grid. Subsequently, the grid values from the EMI are compared with those from the TROPOMI.

In both summer and winter, the global hotspot regions identified by the EMI-II on single days are entirely consistent with those captured by the TROPOMI. The global correlation coefficient (R^2) between the GF5B and TROPOMI was 0.93 on 5 July 2022 and 0.88 on 20 December 2022. For the DQ1, the corresponding values were 0.92 and 0.89 on the same dates. Compared with the TROPOMI (Figure 5), the GF5B and DQ1 EMI-II clearly exhibited entirely consistent global hotspot regions on a monthly timescale. In June 2022, the global correlation coefficient between the GF5B (DQ1) EMI-II and TROPOMI was 0.99 (0.98). In December 2022, the correlations between the GF5B and DQ1 EMI-II were 0.98 and 0.97, respectively, compared to those of the TROPOMI. The total VCD of the EMI-II

was 12% higher than that of the TROPOMI. The main reason for this may be the different correction methods used in the de-stripe correction process.

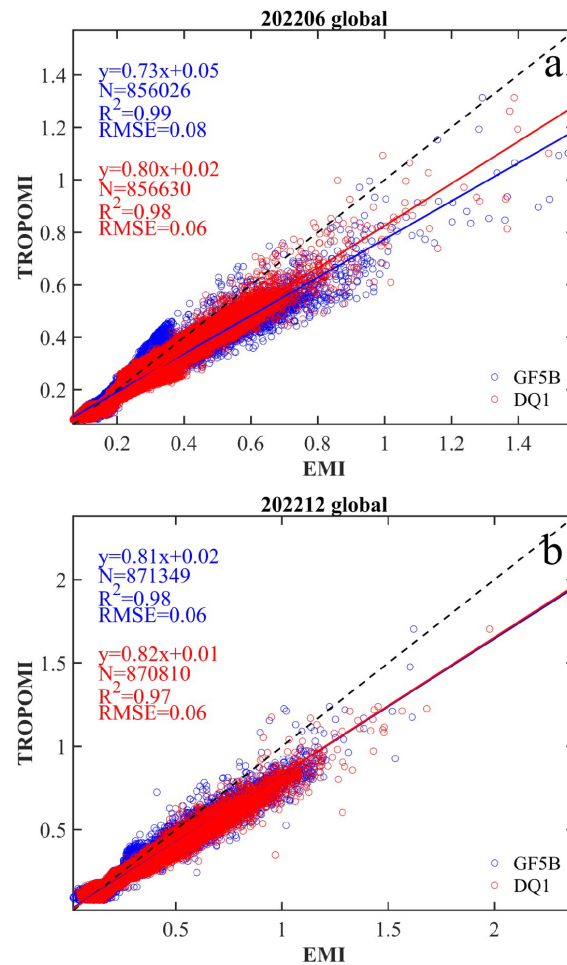


Figure 5. Global NO₂ VCD correlation between GF5B and DQ1 EMI-II with TROPOMI in June (a) and December (b) 2022.

In the highlighted regions in Figure 3f, the EMI-II observational results were compared with the TROPOMI results on a seasonal scale. Figure 6 depicts the seasonal averages of the GF5B and DQ1 EMI-II in regions 1 (first row), 2 (second row), 3 (third row), and 4 (fourth row), which correspond to the TROPOMI data in the spring (first column), summer (second column), autumn (third column), and winter (fourth column). In all the regions during the different seasons, the seasonal mean correlation (R^2) between the EMI-II and TROPOMI exceeds 0.9 except for in spring in region 4 (0.82). The primary reason for this is that region 4 has the lowest average NO₂ concentration among the four regions, and the spring season results in the lowest NO₂ concentration throughout the year in this region.

The uncertainty in the NO₂ total VCD comprises two main components: (a) uncertainty from the SCD retrieval and (b) uncertainty introduced by strip correction. The uncertainty associated with the SCD retrieval is primarily influenced by the DOAS fitting process, with the contributing factors ranked as follows: the instrument signal-to-noise ratio, accuracy of data radiative correction and wavelength calibration, cloud effects, and precision of the least squares algorithm. Nonetheless, the predominant source of uncertainty in the NO₂ total VCD is attributed to strip correction, which cannot be quantitatively assessed. As noted in R10, the strip phenomenon in the SCD retrieval results is so significant that subsequent retrievals cannot proceed without strip correction. Consequently, this study attributes the primarily uncertainty in the NO₂ total VCD to de-stripe correction.

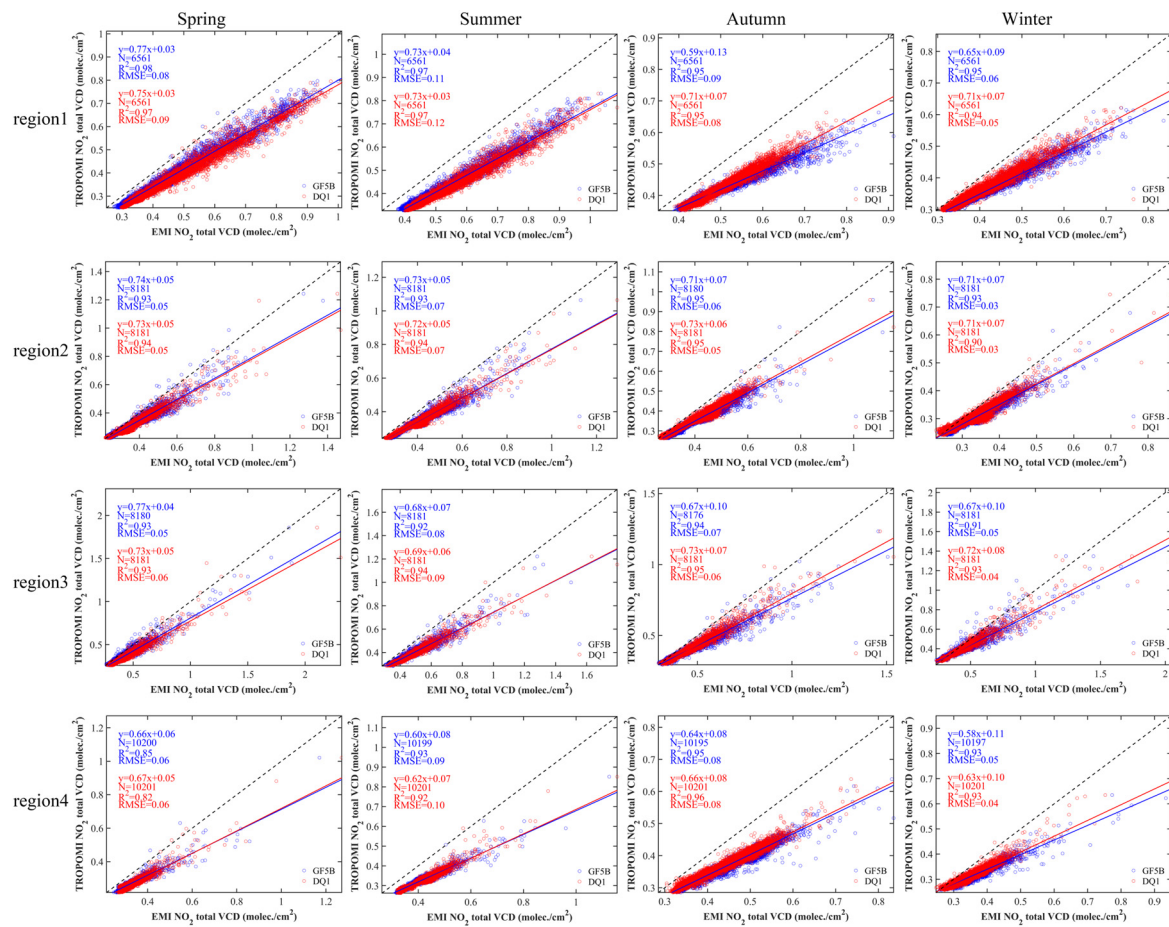


Figure 6. Seasonal averages of the GF5B and DQ1 EMI-II NO₂ VCDs in four regions with TROPOMI.

3.5. Tropospheric VCD

Figure 7 presents the tropospheric NO₂ VCD over region 3 on 6 July 2022 (top), the weekly average of 16–22 July 2022 (middle), and the monthly average of 27 June–27 July 2022 (bottom). The first, second, and third columns show the spatial distributions from the GF5B and DQ1 EMI-II and TROPOMI. The fourth column illustrates the fit between the EMI-II and TROPOMI data. On the daily time scales, the correlation coefficient (R^2) between the EMI-II and TROPOMI spatial distributions exceeds 0.57. On a weekly average time scale, the R^2 is greater than 0.72. On a monthly average time scale, the R^2 is greater than 0.78. The high correlation between the EMI-II and TROPOMI in both the spatial distribution and temporal variation indicates that the EMI-II has similar capabilities to those of the TROPOMI in characterizing the spatial and temporal features of tropospheric NO₂.

The tropospheric NO₂ results are slightly higher than those of the TROPOMI. The uncertainties associated with the retrieval of tropospheric NO₂ primarily arise from three factors: (a) the uncertainty in the total VCD, (b) the uncertainty in stratosphere–troposphere separation, and (c) the uncertainty in calculating the tropospheric AMF. While the uncertainty of the total VCD has been analyzed in Section 3.4, this section will concentrate on the analysis of the latter two aspects.

In the STREAM STS algorithm, three critical weighting factors influence the uncertainty of the results. First, the calculation of “pollution weight” relies on the EMI total VCD results and the multi-year monthly averaged climatological tropospheric NO₂ dataset from the TROPOMI. Utilizing the climatological dataset from the EMI can improve the accuracy of the “pollution weight”. Second, the calculation of “cloud weight” employs the TROPOMI cloud fraction and cloud pressure data. Due to differences in the spatial resolution, a single EMI pixel may encompass multiple TROPOMI pixels. The development of dedicated EMI

cloud products is expected to improve the accuracy of “cloud weight” calculations. Finally, the calculation of the “tropospheric residual weight” requires a “latitudinally corrected” initial stratospheric concentration, which may introduce unquantifiable uncertainties.

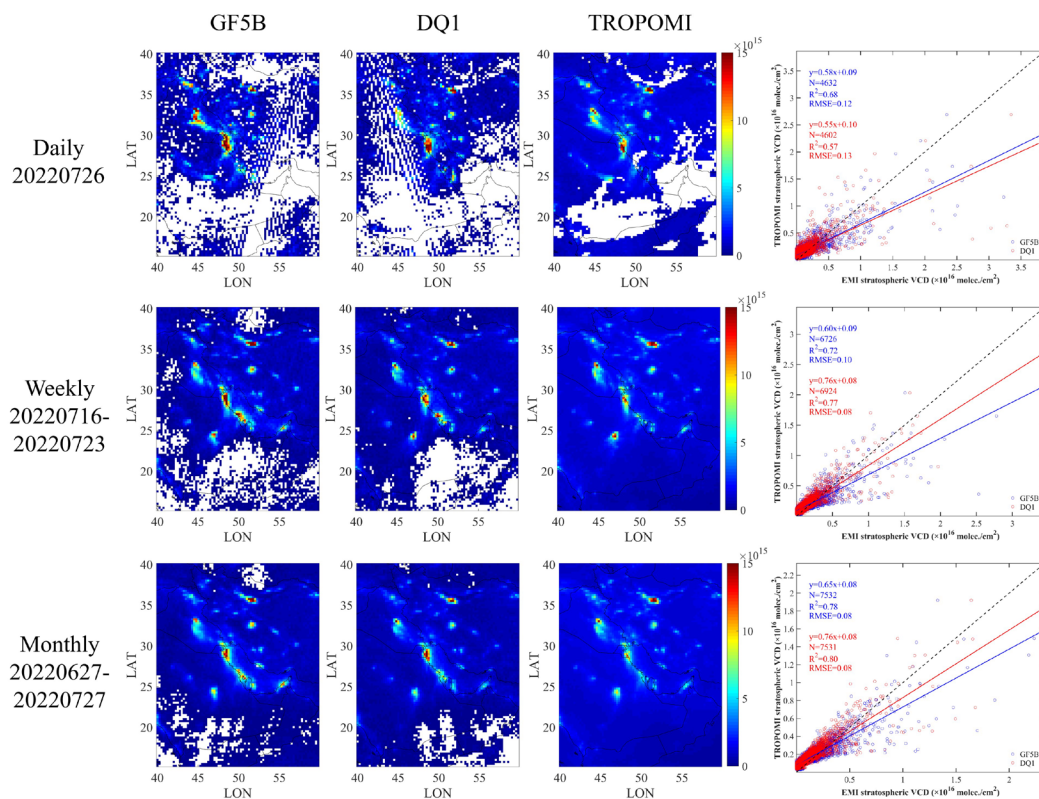


Figure 7. Spatial distributions of tropospheric NO₂ VCD over the Arabian Peninsula and Iran region on 6 July 2022 (**top**), weekly average of 16–22 July 2022 (**middle**), and monthly average of 27 June–27 July 2022 (**bottom**) of GF5B and DQ1 EMI-II and of TROPOMI.

The parameters utilized in the calculation of the tropospheric AMF include geometric parameters, surface parameters, NO₂ profiles, and aerosol and cloud parameters. The measurement geometry is well defined and, thus, does not significantly contribute to AMF errors. Surface parameters and NO₂ profiles are sourced from the GEOS-CF CTM; therefore, the error introduced is negligible. Consequently, the tropospheric AMF primarily depends on aerosol characteristics and cloud cover.

The radiative transfer simulations conducted by Boersma et al. (2004) [27] demonstrated that cloud parameter retrievals are highly sensitive to aerosol presence. Compared to a purely molecular scattering atmosphere, higher cloud radiative fractions and lower cloud pressures are observed when aerosols are present [27]. They also highlighted a strong agreement between explicit aerosol corrections and corrections made through cloud parameters.

Aerosol events with high concentrations are rare on the global scale. In China, the spatiotemporal distribution of aerosols has been extensively studied. High levels of aerosol pollution are concentrated in the North China Plain, Weihe Plain, Chengdu-Chongqing region, and southern Xinjiang, primarily driven by urban activities and dust transport. As a study on the retrieval algorithm widely used for global NO₂ monitoring, this paper does not directly use aerosol parameters when calculating the tropospheric AMF, but instead indirectly considers the impact of aerosols through cloud parameters. This method has been theoretically proven to be feasible and is widely applied in operational retrieval algorithms [24,34,42].

Additionally, an empirical aerosol optical thickness value of 0.06 was adopted during the computation of the box-AMF LUT, which is consistent with the method used by Yang et al. (2019) [43]. We further calculated the box-AMF both with and without the presence

of aerosols and assessed the effects of aerosols on the box-AMF. When the aerosol optical depth is set to 0.1, the absolute difference between the two calculations does not exceed 0.01. In extreme scenarios, the influence of aerosols on the box-AMF is limited to a maximum of 7%. Under typical conditions (surface pressure = 1013 hPa, albedo = 0.05, SZA = 0°, VZA = 0°, and RAA = 45°), the impact of aerosols on the box-AMF is approximately 0.39%.

4. Discussion

The use of the GF5B and DQ1 dual-satellite constellations for atmospheric composition observations can significantly increase the frequency of measurements and partially compensate for the impact of clouds on the effective observation coverage of single satellites. To evaluate the ability of the dual-satellite network to improve the observation frequency, we applied a grid to the EMI-II NO₂ data with a resolution of 0.25 degrees for the statistical analysis. Because there are currently no officially released cloud products for EMI-II, the criteria for cloud identification in EMI-II were set here with radiance at a wavelength of 480 nm exceeding 20 $\mu\text{W}\cdot\text{cm}^{-2}\cdot\text{nm}^{-1}$.

As depicted in Figure 8a,b show the cloud coverage distributions from single-satellite observations of the GF5B and DQ1 on July 5, 2022. The grid percentages with cloud coverage for the GF5B and DQ1 were 17.08% and 17.68%, respectively. The grid percentages with clear-sky coverage accounted for 60.45% and 60.83% for the GF5B and DQ1, respectively, whereas the grid percentages with no observations accounted for 22.47% and 21.49%. Figure 8c displays the coverage types from the dual-satellite observations of the GF5B and DQ1 on the same day. Compared with single satellites, the grid percentage with cloud coverage from both satellites was 10.22%, i.e., decreases of 6.86% for the GF5B and 7.46% for the DQ1. Additionally, 49.95% of the global regions was observed twice by the dual satellites, which effectively increased the number of observations. Figure 8d shows the distribution of effective observation counts for the GF5B and DQ1 for the entire month of July in 2022. The dual-satellite network significantly enhances the number of observations in regions including northern and southern Africa, the Middle East, western Australia, and western North America during this month.

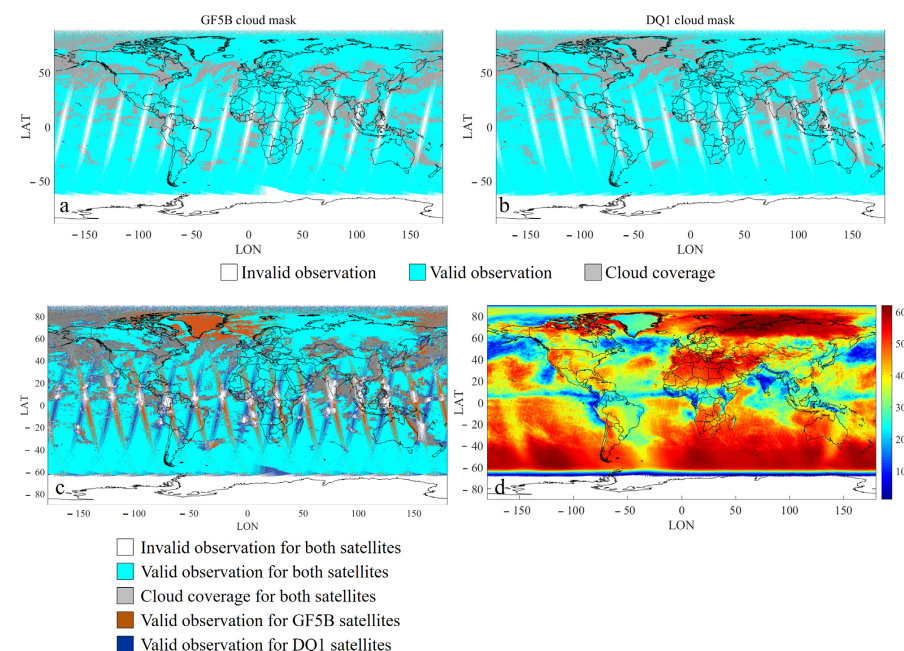


Figure 8. Statistical analysis of the cloud coverage. Cloud coverage distributions from the single-satellite observations of GF5B (a) and DQ1 (b) on July 5, 2022. (c) Coverage types from the dual-satellite observations of GF5B and DQ1 on the same day. (d) Distribution of effective observation counts for GF5B and DQ1 for the entire month of July in 2022.

Because the GF5B and DQ1 uses identical retrieval algorithms, input parameters, and auxiliary data in the EMI-II retrievals, we assumed little variation in the stratospheric NO₂ levels. Then, the differences in the retrieved VCDs between the two instruments can be attributed to NO₂ signal discrepancies. In other words, the disparity between the DQ1 and GF5B can represent the NO₂ diurnal variation information. Figure 9a,b illustrate the spatial distribution of the daily (5 July 2022) and monthly (July 2022) average differences between the DQ1 and GF5B. At the daily scale, significant instances of the DQ1 measurements that are higher than those of the GF5B are at the border between Congo and Angola, which may indicate that NO₂ emissions from this source predominantly occur in the morning. On the monthly scale, many emission sources in the Middle East, Iran, and China present higher values for the GF5B than the DQ1. This result may shed some light on the timing of NO₂ emissions from these sources.

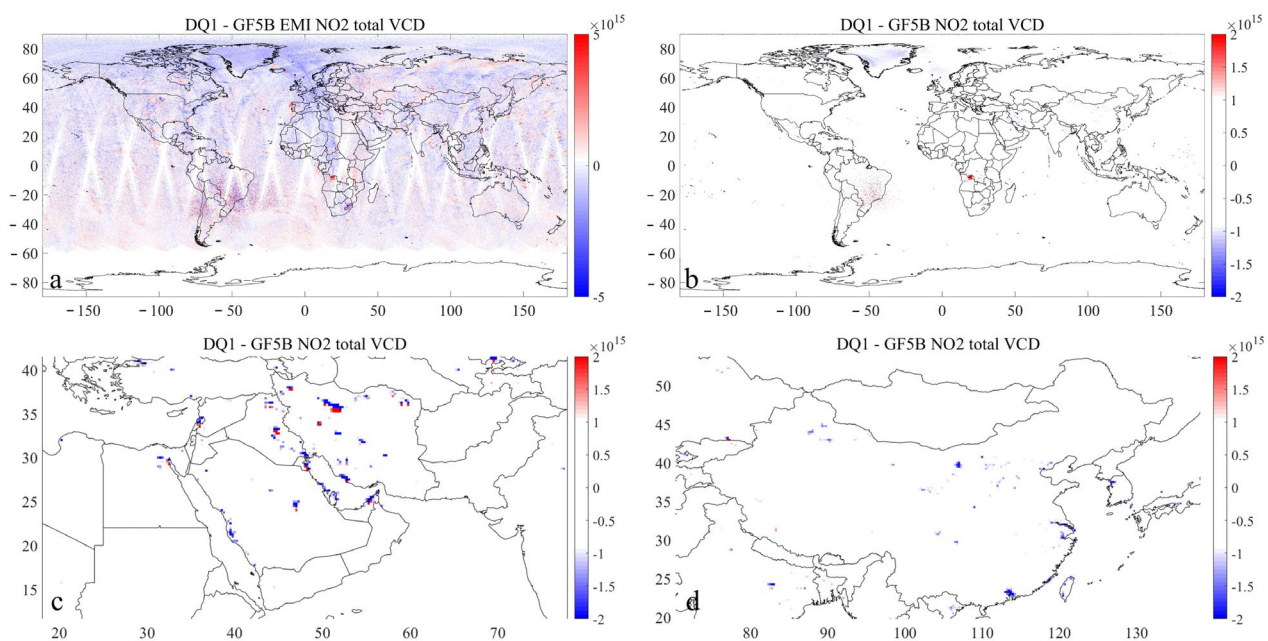


Figure 9. Spatial distribution of average differences between DQ1 and GF5B on 5 July 2022 (a) and July 2022 (b–d).

5. Conclusions

This paper presents the retrieval of the total and tropospheric NO₂ VCD based on the EMI-II payloads onboard the GF5B and DQ1 satellites. The spectral fitting methods for the SCD retrieval followed the approach used for the GF5 EMI. During the de-stripe correction, the SCD correction values were modified by the climatology values of the clean ocean areas, so the SCD values were closer to reality with an uncertainty of 0.42×10^{15} molec./cm². The STREAM method was used for the STS step, and NO₂ profiles from the GEOS-cf CTM outputs were used for the tropospheric AMF calculations. The GF5B and DQ1 retrieval results were comprehensively compared considering different spatial scales (globally, regionally, and city) and temporal scales (daily and monthly). The results showed excellent consistency between the GF5B and DQ1 retrievals ($R^2 > 0.8$), except for a few specific emission sources that exhibited clear diurnal variations. Additionally, the EMI-II retrieval results were validated against TROPOMI products in four typical regions. Overall, the EMI-II retrieval results exhibited good spatial consistency with the TROPOMI results, where the correlation coefficients (R^2) exceeded 0.85 and 0.57 for the total VCD and tropospheric VCD. The dual-satellite network of the GF5B and DQ1 enhanced the frequency of the atmospheric composition observations and reduced the impact of cloud coverage on the valid observation areas. The differences between the two satellites partially explain the diurnal variations in the NO₂ concentrations.

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Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

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Conflicts of Interest: Author Liangxiao Cheng is employed by China Siwei Surveying and Mapping Technology Co., Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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