Assessment of Geostationary Environment Monitoring Spectrometer (GEMS) Tropospheric NO_2 Measurements Using Ground-Based Pandora Instrument in Quezon City

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Abstract: *This study evaluates the consistency between the Geostationary Environment Monitoring Spectrometer (GEMS) and Pandora NO_2 observations in the Philippines, marking the first Pandora-based assessment of satellite NO_2 in the country. The comparison focused on the month of April 2025 during which the air quality reached moderate to near-unhealthy levels (Air Quality Index=90) in the week of April 25–30. Retrievals from GEMS were filtered using cloud fraction (CF) thresholds (<0.3, <0.5, <0.7), while Pandora data were averaged ±10 minutes around each GEMS observation and corrected with a distance-weighted representativeness. For the full month of April, GEMS consistently underestimated Pandora measurements, with correlations not exceeding 0.535 and normalized mean bias (NMB) of about –65% to –68%. When the analysis was limited to April 25–30, the period of elevated pollution, GEMS still showed systematic underestimation but with stronger correlations reaching up to 0.752 while NMB values improved to –41% under low-cloud conditions. After applying the distance-weighted representativeness correction for both study periods, correlations and slopes increased slightly, but systematic underestimation persisted, indicating that retrieval biases stem from more than just spatial representativeness. Overall, both instruments showed potential for agreement, but systematic underestimation highlights the need for refinement and continued evaluation across broader conditions and timeframes. By expanding the temporal range, future assessments can capture both high and low NO_2 episodes as well as long-term patterns, providing a more comprehensive performance evaluation of GEMS and other satellite-based measurements against Pandora. Further refinement of the correction may also be needed to improve the comparisons. This will support its potential use in developing air quality forecasting and monitoring tools and predictive models for nationwide air quality assessment.*

Keywords: Air Quality, GEMS, Pandora, Remote Sensing, Tropospheric NO_2

Introduction

Air pollution remains one of the most pressing environmental and public health challenges worldwide. The State of Global Air Report (2024) estimated that exposure to polluted air contributed to 8.1 million premature deaths in 2021, making it the second leading risk factor for early mortality globally. Numerous studies have shown that air pollution is strongly linked to cardiopulmonary diseases, asthma, and lung cancer (WHO, 2013; U.S. EPA, 2024). Among the various pollutants, nitrogen dioxide (NO_2) is of particular concern due to its direct impacts on human health (Chen et al., 2012) and its central role in atmospheric chemistry as a precursor of aerosols, tropospheric ozone, and hydroxyl radicals (Crutzen, 1979; Seinfeld and Pandis, 1998; Boersma et al., 2009; Squizzato et al., 2013).

In the Philippines, air pollution poses a growing issue. In 2019, the Institute for Health Metrics and Evaluation reported 64,000 air pollution–related deaths in the country, a figure that rose to over 98,000 by 2021 (State of Global Air Report, 2024). Metro Manila, the country's most densely populated urban center, consistently records the highest pollution levels, particularly in its northern areas, where transport, industrial activity, and energy use are concentrated (Prudential PLC & Earth Observatory Singapore, 2023). NO_2, largely produced by these processes, is therefore a key trace gas for understanding and monitoring urban air pollution in the region.

Because NO_2 has a short lifetime of only a few hours, its distribution changes sharply near emission sources (Liu et al., 2016). This spatiotemporal variability underscores the need for continuous, high-resolution monitoring to assess air quality and characterize pollution dynamics. Satellite remote sensing has become a vital tool in this regard, complementing ground-based monitoring networks by providing broad spatial coverage. In Asia, the Geostationary Environment Monitoring Spectrometer (GEMS), onboard the Geostationary Korea Multipurpose Satellite-2B (GEO-KOMPSAT-2B), provides hourly observations of atmospheric composition, including NO_2 during daylight hours. However, satellite retrievals must be validated against reliable ground-based measurements to ensure accuracy, especially in regions with limited air quality monitoring networks like the Philippines.

To address this, the Philippine Space Agency (PhilSA) installed four Pandora spectrometers in Quezon City, Ilocos Norte, Palawan, and Cebu City under the Pan-Asia Partnership for Geospatial Air Pollution Information and the Pandora Asia Network (PAPGAPI-PAN) Philippines Project (PhilSA, 2024). These Pandora spectrometers provide high-quality ground-based measurements of atmospheric gases like NO_2 (NASA Pandora Project, n.d.), making them valuable references for validating satellite products such as those from GEM*S*.

The present study extended the GEMS-Pandora comparison to the Philippines by providing an initial comparison of tropospheric NO_2 column data from GEMS and from the Pandora installed at the Manila Observatory, Quezon City during April 2025 when a moderate to near-unhealthy air quality index was reported by Flores (2025). By assessing the consistency between these two instruments, this work provides initial insights into the performance of

GEMS over Quezon City and contributes to efforts in strengthening satellite-based air quality monitoring in the Philippines.

Literature Review

Several studies have demonstrated the value of Pandora spectrometers in validating NO_2 retrievals from GEMS. Kim et al. (2023) conducted one of the first comprehensive GEMS–Pandora comparisons over South Korea, reporting that GEMS generally underestimated Pandora observations. Correlation coefficient (R) ranged from 0.62 to 0.78, while mean bias errors were consistently negative. After correcting for horizontal representativeness, correlations improved to 0.69 to 0.81. Notably, the correlation improved under less cloudy conditions (cloud fraction<0.3), highlighting GEMS stronger sensitivity to NO_2 variability during clear-sky conditions.

Another study by Lange et al. (2024) evaluated GEMS operational v2.0 tropospheric NO_2 vertical column densities (VCDs) during the GEMS Map of Air Pollution (GMAP) and Satellite Integrated Joint monitoring of Air Quality (SIJAQ) campaigns. In contrast to the earlier underestimation, GEMS showed systematic overestimation, with a median relative bias of +64% and an R of 0.75. Bae et al. (2025) expanded the validation across all Korean Pandora sites seeing the same positive bias. GEMS NO_2 total column density (TCD) was on average 41% higher than Pandora and an R of 0.87; overestimation was more pronounced in urban regions compared to non-metropolitan areas. Seasonal and diurnal effects were also observed. Biases were larger in winter and weekday diurnal cycles in Busan revealed that GEMS produced a midday peak, whereas Pandora remained nearly constant until 14 local standard time (LST) before rising.

Pandora has also played a central role in the validation of the Tropospheric Monitoring Instrument (TROPOMI) NO_2 retrievals. Studies like Judd et al. (2020) compared TROPOMI tropospheric vertical columns with Pandora in New York City. It exhibited a persistent low bias, with a median percent difference of –30%. Retrievals improved when higher-resolution model profiles from NAM-CMAQ were applied to TROPOMI reducing the bias from –33% to –19%. Kim et al. (2023) also compared TROPOMI NO_2 total column with Pandora and found that the two instruments correlated moderately with R ranging from 0.58 to 0.74 but underestimated by -0.64×10^{16} to $–0.19 \times 10^{16}$ molecules/cm^2.

Despite these advances, validation remains geographically imbalanced as most studies focus on South Korean and East Asian sites. However, little is known about GEMS performance in tropical Southeast Asia. Expanding validation efforts to such regions, including the

Philippines, is critical to building a more comprehensive understanding of GEMS performance under diverse conditions.

Methodology

a. Study Area and Period

Manila Observatory (14.6350°N, 121.0780°E), Quezon City, Philippines, shown in Figure 1, hosts the Pandora spectrometer used in this study. The instrument has been operating at this site since July 2024, providing continuous ground-based measurements of trace gases.

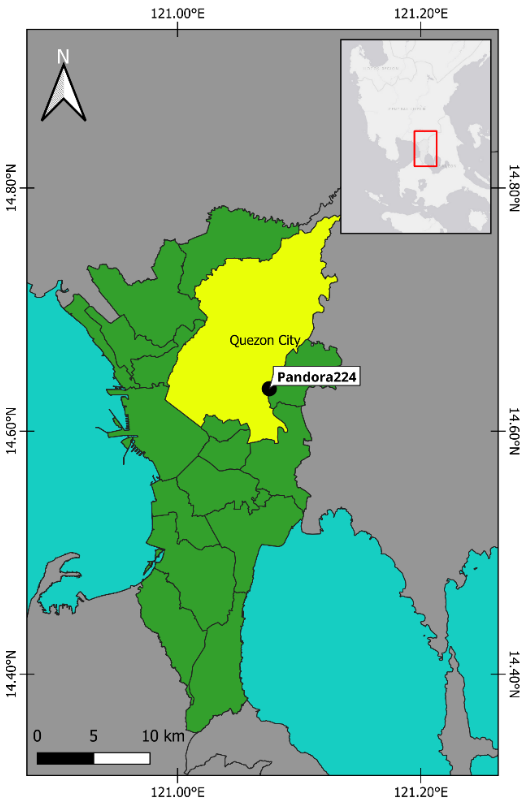


Figure 1: Map of Metro Manila highlighting Quezon City in yellow and other areas of Metro Manila in green. The black dot marks the location of the Pandora spectrometer at the Manila Observatory (Pandora 224). The inset shows the position of Metro Manila within the Philippines (red box).

The study period covers the entire month of April 2025, including the 25th to 30th, when Metro Manila experienced moderate to near-unhealthy air quality levels. This period allowed an initial evaluation of GEMS's performance against Pandora in the Philippines, focusing on correlation between the two instruments during moderate to high pollution events.

b. Data Sources

i. GEMS Satellite Data

Onboard the GEO-KOMPSAT-2B satellite, launched in February 2020, GEMS provides hourly daytime measurements (eight measurements per day between 00:45 and 06:45 UTC) of trace gases including NO_2, sulfur dioxide (SO_2), ozone (O_3), formaldehyde (HCHO), and aerosols over East and Southeast Asia (5°S–45°N and 75–145°E, NIER). It is a hyperspectral UV–visible spectrometer covering 300–500 nm with a spectral resolution of ~0.6 nm and a spatial resolution of approximately 3.5 × 8 km^2.

This study used the tropospheric NO_2 vertical column density (VCD) from the operational GEMS Level 2 version 3.0 product. Following the recommendation of the GEMS User Guide (https://nesc.nier.go.kr/en/html/satellite/guide/guide.do, last accessed: 20 August 2025), only data with a final algorithm flag of 0, which indicates values suitable for use, were retained for analysis.

ii. Pandora Spectrometer

Pandora spectrometer is a ground-based instrument that measures direct sunlight across a wavelength range of 280-525 nm, with spectral resolution of about 0.6 nm (Herman et al., 2018) and temporal resolution of about 2 min. (Tzortziou et al., 2012; Yun et al., 2013). Aside from direct sun measurements, the instrument also provides tropospheric column observations when operated in multi-axis. It was developed by National Aeronautics and Space Administration (NASA) to fill the lack of ground-based observations that retrieves column amounts of several trace gases such as NO_2, HCHO, and O_3.

This study utilized the level-2 tropospheric NO_2 VCD product obtained from the Pandora instrument installed at the Manila Observatory (Pandora 224). Only data points flagged as high or medium quality (quality flags 0, 1, 10, and 11) were retained for analysis. Both assured and unassured categories within these quality levels were included to maximize data coverage, following the approach of Oak et al. (2024).

Although both instruments provide valuable NO_2 measurements, their measurement geometries differ. GEMS captures atmospheric columns that are averaged over an area equal to its spatial resolution, while Pandora measures the atmospheric column directly above the station. In particular, Pandora NO_2 columns are retrieved along a direct solar light path that may pass through more than one GEMS pixel, depending on the Sun's position during the day (Figure 2). This mismatch in spatial coverage introduces horizontal representativeness errors between the two instruments (Kim et al., 2023).

c. Methods

The analysis was focused on two periods: (1) full month of April 2025, and (2) April 25-30, 2025, which corresponds to a week of moderate to near-unhealthy air quality. Pandora observations were time-matched with the GEMS overpasses by only considering measurements within ±10 minutes of each satellite retrieval. The mean Pandora NO_2 VCD within this window was assigned as the representative ground-based value for comparison. To account for potential geolocation offsets, GEMS NO_2 retrievals were extracted from a neighborhood window spanning ±0.1° in latitude and longitude around the station, following Fu et al. (2024).

As another layer of analysis, GEMS cloud fraction (CF) was used to evaluate the influence of clouds on NO_2 retrievals. Comparisons were carried out using CF thresholds of 0.3, 0.5, and 0.7 to examine how varying levels of cloud interference affect the agreement between GEMS and Pandora observations.

To account for the differences in measurement geometry of GEMS and Pandora, this study followed the approach of Kim et al. (2023), in which two GEMS pixels were selected: (1) the pixel closest to the Pandora site, and (2) the pixel closest to the line of sight of Pandora measurements. The weighted mean NO_2 VCD accounting for horizontal representativeness was calculated as:

$$VCD_{hr} = \frac{d_2 VCD_1 + d_1 VCD_2}{d_1 + d_2} \quad (1)$$

where VCD_{hr} is the NO_2 VCD corrected for horizontal representativeness, d_1 and d_2 are distances from Pandora to the center of the two GEMS pixels, VCD_1 and VCD_2 are the GEMS NO_2 VCD values of the two pixels.

For the two study periods, comparisons were performed with and without distance-weighted horizontal representativeness correction (hereafter correction). This approach enabled a systematic evaluation of both cloud interference and differences in measurement geometry, providing a clearer understanding of their influence on the consistency between GEMS and Pandora observations.

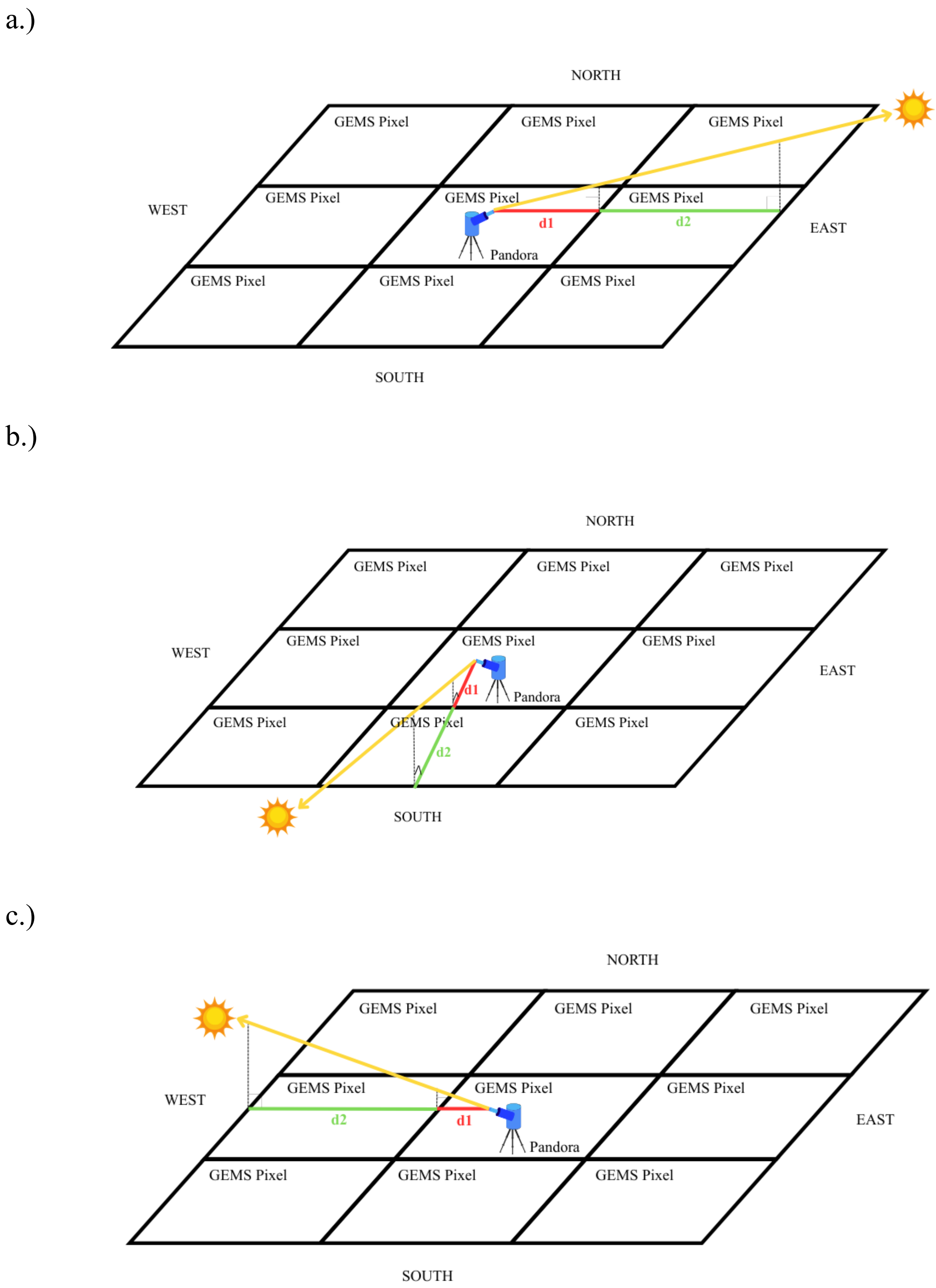


Figure 2: Light path changes according to Pandora direct-sun measurement geometry. Panels (a), (b) and (c) represent morning, noon, and afternoon hours, respectively. Adapted from Figure 12 in Kim et. al. (2023).

Results and Discussion

a. Whole Month of April 2025

Figure 3 shows scatterplots of GEMS versus Pandora NO_2 measurements under different CF thresholds. Panels (a–c) and panels (d-f) present the results without and with correction, respectively.

The comparison between GEMS and Pandora NO_2 measurements was evaluated using regression slope, R, root mean square error (RMSE), mean bias error (MBE), and normalized mean bias (NMB). The slope and R parameters capture the agreement and strength of the comparison while the RMSE, MBE, and NMB capture the magnitude and direction of the differences (under or over-estimates), which allows easier interpretation of underestimation severity.

In Figure 3 (a-c), higher correlations were observed at stricter CF thresholds, with CF < 0.3 producing the strongest relationship (R = 0.481, slope = 0.13). However, all CF thresholds have consistently low (0.12–0.13) slopes, confirming that GEMS underestimates Pandora. It was also found that by increasing the CF threshold, MBE values remained strongly negative (–0.67 × 10^{16} molecules/cm²) corresponding to NMBs of –68% to –70% while the RMSE values remained consistent near 0.99 × 10^{16} molecules/cm. Across all CF thresholds (0.3–0.7), the p-values remained extremely small (10^{-13} to 10^{-12}), confirming that the observed correlations are highly significant**.** These results emphasize that cloudier conditions reduce agreement between GEMS and Pandora. The summary of the results is shown in Table 1.

Meanwhile in Figure 3 (d-f), the same conclusion can be drawn with varying CF, i.e. performance is best under clear-sky conditions. Compared with the non-corrected version, R, slope, and RMSE improved to 0.535, 0.22, and 0.948 × 10^{16} molecules/cm², respectively. While the biases were slightly reduced (MBE improved to –0.651 × 10^{16} molecules/cm²; NMB improved to -64.6%). These indicate that weighted correction partially alleviated the bias and scatter, though systematic underestimation remained. All correlations were statistically significant, with p-values ranging from 1.664 × 10^{-15} to 6.951 × 10^{-12} across the CF thresholds. Table 2 summarizes the results.

However, looking at CF < 0.5 and CF < 0.7, weighted correction lowered RMSE and NMB, and correlations weakened slightly (R = 0.469–0.486). This suggests that representativeness correction is most effective under clear-sky conditions, while under cloudier conditions, retrieval uncertainty dominates as seen in Kim et al. (2023).

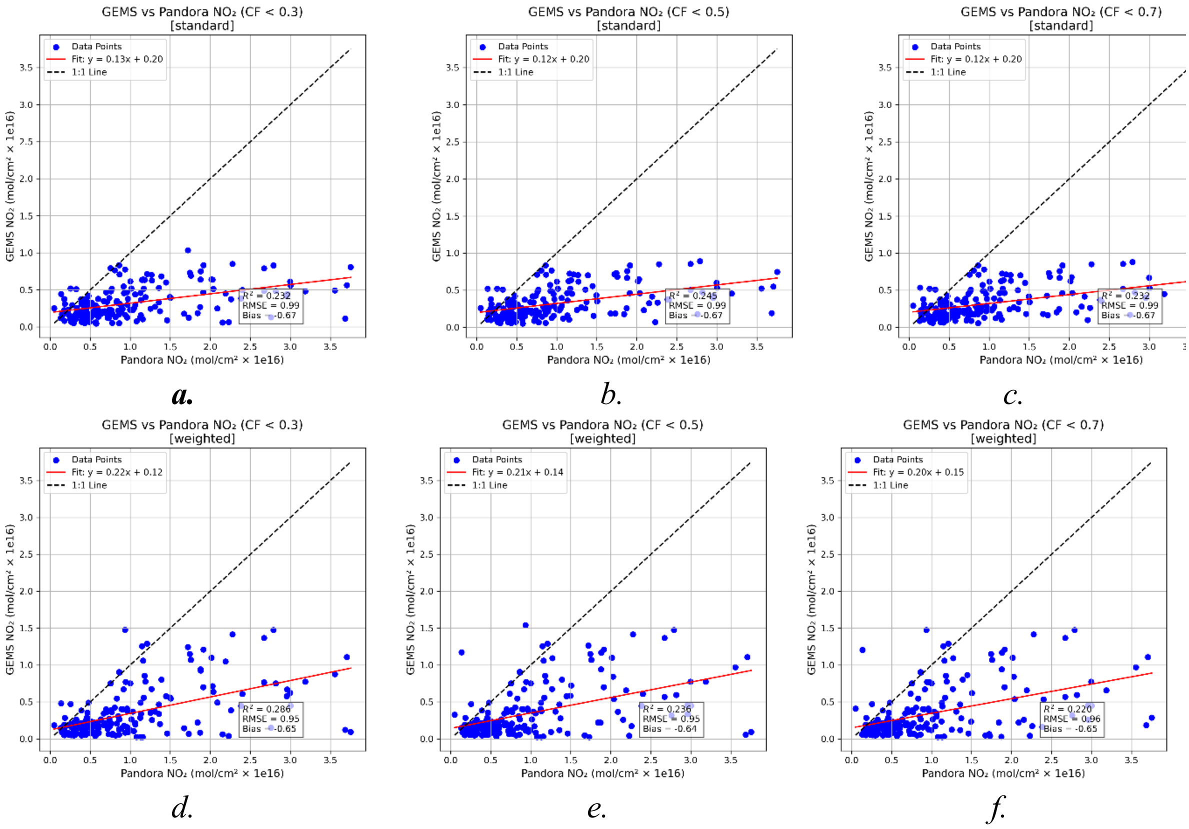


Figure 3: Scatterplots of NO_2 vertical column density (VCD) comparing Pandora and GEMS for the whole month of April 2025, under different cloud fraction (CF) thresholds. Panels a–c show data before correction: (a) CF < 0.3, (b) CF < 0.5, and (c) CF < 0.7. Panels d–f show data after applying correction: (d) CF < 0.3, (e) CF < 0.5, and (f) CF < 0.7. The dashed black line represents the 1:1 relationship, and the solid red line indicates the linear regression fit.

Table 1: Statistical evaluation of NO_2 VCD comparisons between Pandora and GEMS for the whole month of April 2025 before distance-weighted correction. Reported metrics include the correlation coefficient (R), root mean square error (RMSE), mean bias error (MBE), and normalized mean bias (NMB)

CF Threshold	R	RMSE	MBE	NMB	p-value
CF < 0.3	0.481	0.993	-0.673	-68.5%	1.782×10^{-12}
CF < 0.5	0.495	0.989	-0.669	-69.5%	3.071×10^{-13}
CF < 0.7	0.482	0.992	-0.669	-69.9%	1.484×10^{-12}

Table 2: Statistical evaluation of NO_2 VCD comparisons between Pandora and GEMS for the whole month of April 2025 after applying correction. Reported metrics include the correlation coefficient (R), root mean square error (RMSE), mean bias error (MBE), and normalized mean bias (NMB)

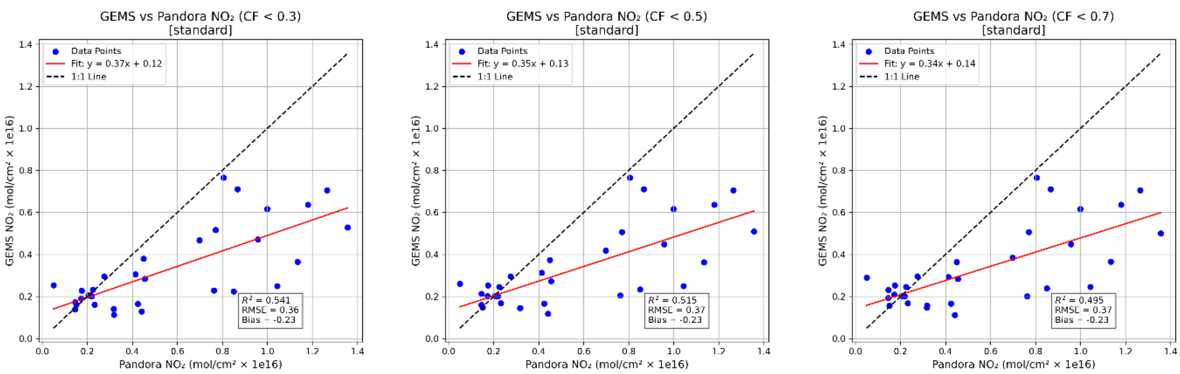
CF Threshold	R	RMSE	MBE	NMB	p-value
CF < 0.3	0.535	0.948	-0.651	-64.6%	1.664×10^{-15}
CF < 0.5	0.486	0.954	-0.641	-64.8%	8.912×10^{-13}
CF < 0.7	0.469	0.963	-0.645	-65.9%	6.951×10^{-12}

b. April 25 -30, 2025

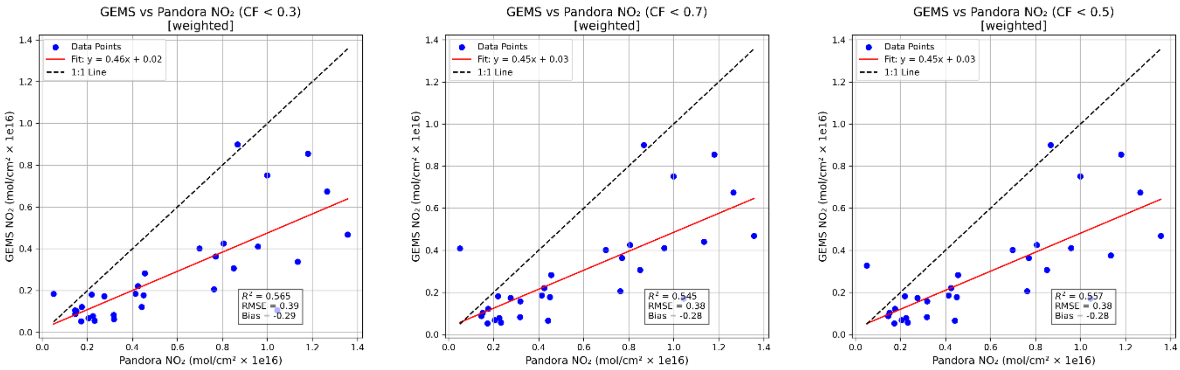
The analysis was repeated for April 25–30, 2025 (Figure 4; Table 3). Results followed the same general trends as the full month, with stronger correlations with stricter CF thresholds and persistent underestimation by GEMS.

For the standard comparison, correlation was highest at CF < 0.3 (R = 0.736, slope = 0.37) while it was lower with looser thresholds (R = 0.704, slope = 0.34 at CF < 0.7). The same pattern is apparent in RMSE values, while MBE and NMB remained stable at about –0.23 × 10^{16} molecules/cm² and –41%, respectively. These patterns confirm that clear-sky conditions yield the strongest correlation and lowest error. However, compared to the full-month results, correlations during this episode were notably higher, indicating better consistency between GEMS and Pandora during moderate to high pollution events. The associated p-values for all thresholds were consistently very small, ranging from 2.43 × 10^{-6} to 1.00 × 10^{-5}, confirming that the correlations are statistically significant. Results are summarized in Table 3.

After applying correction, performance improved at CF < 0.3 (R = 0.752, slope = 0.46) but RMSE increased slightly (0.388 × 10^{16} molecules/cm²), suggesting that the correction captured variability more effectively but introduced larger deviations. At higher CF thresholds (CF < 0.5 and CF < 0.7), the improvements were less pronounced, with only small changes in correlation and slope. The p-values for these weighted results also remained in the same narrow range, from 1.08 × 10^{-6} to 2.11 × 10^{-6}, further confirming the significance of the relationships. Table 4 shows the summary of the results.



a *b* *c*



d *e* *f*

Figure 4: Scatterplots of NO_2 vertical column density (VCD) comparing Pandora and GEMS for April 25–30, 2025, under different cloud fraction (CF) thresholds. Panels a–c show data before correction: (a) CF < 0.3, (b) CF < 0.5, and (c) CF < 0.7. Panels d–f show data after applying correction: (d) CF < 0.3, (e) CF < 0.5, and (f) CF < 0.7. The dashed black line represents the 1:1 relationship, and the solid red line indicates the linear regression fit.

Table 3: Statistical evaluation of NO_2 VCD comparisons between Pandora and GEMS for April 25-30, 2025, before applying correction. Reported metrics include the correlation coefficient (R), root mean square error (RMSE), mean bias error (MBE), and normalized mean bias (NMB)

CF Threshold	R	RMSE	MBE	NMB	p-value
CF < 0.3	0.736	0.362	-0.234	- 41.5%	2.431×10^{-6}
CF < 0.5	0.717	0.367	-0.234	- 41.5%	6.7×10^{-5}
CF < 0.7	0.704	0.369	-0.233	- 41.3%	2.4×10^{-4}

Table 4: Statistical evaluation of NO_2 VCD comparisons between Pandora and GEMS for April 25-30, 2025, after applying correction. Reported metrics include the correlation coefficient (R), root mean square error (RMSE), mean bias error (MBE), and normalized mean bias (NMB)

CF Threshold	R	RMSE	MBE	NMB	p-value
CF < 0.3	0.752	0.388	-0.289	- 51.1%	1.081×10^{-6}
CF < 0.5	0.747	0.383	-0.280	- 49.6%	1.412×10^{-6}
CF < 0.7	0.738	0.381	-0.275	- 48.8%	2.107×10^{-6}

Both periods show the same fundamental features: (1) systematic underestimation, (2) cloud contamination reduces correlation, and (3) correction modestly improves agreement.

The systematic underestimation observed in both cases is consistent with earlier validation studies. Kim et al. (2023) and Ghahremanloo et al. (2024) reported that GEMS tends to underestimate Pandora observations, Seasonal influences may have contributed to the bias in this study, as April falls within the Philippine dry season, when higher temperatures and stronger solar radiation accelerate photochemical reactions that shorten the lifetime of NO_2. This can create localized variability in surface NO_2 that satellites cannot fully capture, reducing consistency with satellite column retrievals (Boersma et al., 2009). This seasonal pattern aligns with broader GEMS observations across East Asia, which show higher NO_2 levels in winter and lower values in summer (Choi et al., 2021; Jang et al., 2017). Representativeness differences also play a role. Pandora observes localized plumes while GEMS averages over a broader footprint, leading to systematically lower values. Bae et al. (2025) highlighted that such hotspots below satellite resolution can drive retrieval discrepancies, with additional uncertainties at larger solar zenith angles due to errors in air mass factor calculations. Together, these factors explain why GEMS consistently underestimates Pandora measurements across both periods.

As for the decreasing correlation with increasing CF, Kim et al. (2023) also observed this trend, showing that high correlations and low RMSE were achieved only under low-CF conditions, where GEMS and Pandora captured consistent diurnal NO_2 variations. As CF increased, the correlation weakened and RMSE rose, indicating that increased cloud cover reduces the sensitivity of GEMS to NO_2 below or within cloud layers.

Representativeness correction provided only slight improvements, consistent with Kim et al. (2023). Although correlation increased modestly, substantial biases persisted despite spatial adjustments, underscoring the limited ability of this correction to eliminate systematic measurement errors.

Despite these common patterns, the strength of agreement differed between periods. From April 25-30, correlations were stronger ($R \leq 0.75$), and underestimation was less severe (NMB ~ –41% to –51%). In contrast, the full-month analysis showed weaker agreement ($R \leq 0.535$) and larger underestimation (NMB ~ –65% to –68%). The stronger agreement during April 25-30, may be due to higher NO_2 levels and more spatially uniform pollution, which enhanced the satellite signal and reduced point-to-pixel mismatch. In contrast, the full-month analysis may have included a lower concentration of NO_2 and cloudier days, conditions that increase retrieval uncertainty and amplify the systematic underestimation.

Overall, both short- and long-term comparisons show that while correlations are moderate and improved slightly after correction, GEMS continues to systematically underestimate Pandora, revealing the persistence of systematic biases. Nevertheless, the agreement across both periods confirms that the underestimation is robust and not simply an artifact of limited sampling, as all correlations were statistically significant ($p < 0.01$–0.05 across CF thresholds).

Conclusion and Recommendation

This study presents the first validation of GEMS tropospheric NO_2 retrievals against Pandora observations in the Philippines, focusing on Quezon City during April 2025. Results show that GEMS consistently underestimated Pandora throughout the study period. Agreement was strongly influenced by cloud fraction, with the highest correlations observed under CF < 0.3. Applying a horizontal representativeness correction modestly improved slopes and reduced scatter but was insufficient to eliminate the systematic underestimation. These results suggest that clear-sky conditions provide the most reliable comparisons and that biases arise from factors beyond spatial representativeness. The findings are robust across both short- and long-term comparisons, as underestimation, cloud dependence, and the limited impact of correction were consistently observed, with all correlations remaining statistically significant. Overall, this assessment highlights limitations in the current GEMS retrieval algorithm suggesting users should consider cloud conditions and potential biases when interpreting GEMS NO_2 data, particularly for quantitative analyses in urban environments.

To enhance satellite–ground agreement, future work should apply strict cloud filtering (CF < 0.3) and refine correction approaches. Bias correction methods, whether statistical or machine learning-based—including deep learning models—may help reduce systematic discrepancies. As this is the first Pandora-based NO_2 validation in the Philippines, extending the study to cover multiple months or seasons would be beneficial. A longer dataset would enable assessment of seasonal variability in NO_2 and its impact on satellite–ground agreement. Incorporating measurements from the three other Pandora spectrometers installed across the country, along with meteorological factors such as wind, temperature, and boundary layer height, could further clarify the role of local atmospheric conditions in shaping correlations with GEMS.

Continuous ground-based validation remains essential for monitoring satellite retrieval accuracy. Combining high-quality ground-based observations with algorithmic or data-driven corrections will strengthen the reliability of GEMS tropospheric NO_2 measurements. Such efforts provide a stronger foundation for air quality management in the Philippines and support evidence-based policy decisions to protect public health in rapidly urbanizing regions.

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Data Availability

GEMS Level 2 NO_2 data can be accessed at https://nesc.nier.go.kr/en/html/datasvc/index.do# (NIER, 2025). Data from Pandora instruments are freely available through the Pandonia Global Network (PGN) data archive at https://data.pandonia-global-network.org/Cologne/ (Pandonia Global Network, 2024).

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