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Geostationary Satellites Total Ozone Observations: First Results on Ground-Based Networks Validation Efforts for TEMPO and GEMS

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Key Points:

- Tropospheric Emissions: Monitoring of Pollution (TEMPO) and Geostationary Environment Monitoring Spectrometer (GEMS) data demonstrate that these geostationary satellite instruments can measure rapid (intradiurnal) total ozone changes
- We report the first evaluation of the TEMPO and GEMS total ozone data products using observations from 100 ground-based stations
- Data quality was assessed for such as solar zenith angle and latitude dependencies, and to determine measurement precision

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract The Tropospheric Emissions: Monitoring of Pollution (TEMPO) instrument, launched in April 2023, is North America's first geostationary air pollution monitoring satellite mission. Together with Asia's Geostationary Environment Monitoring Spectrometer (GEMS) launched in 2020 and Europe's upcoming Sentinel-4, TEMPO contributes to nearly global coverage provided by geostationary satellite constellation. TEMPO and GEMS offer hourly, high-resolution data of ozone surpassing the once-daily observations of instruments like the TROPOspheric Monitoring Instrument (TROPOMI) in temporal resolution. This study presents TEMPO's total ozone data, demonstrating TEMPO's ability to observe sudden changes in ozone and UV index. Furthermore, TEMPO and GEMS measurements are validated using ground-based monitoring networks (Brewer, Dobson, and Pandora). Results show good agreement but also highlight latitude-dependent discrepancies between the satellite and ground-based data sets (−2% to 2% for TEMPO, −1% to −3% for GEMS). Findings are further validated using TROPOMI data and reanalysis models.

Plain Language Summary Data of total column ozone from two new geostationary satellite instruments are presented and have been compared with ground-based observations and low orbit satellite data. Overall, their data quality appears to be good, indicating the potential of these new satellite instruments for reliable ozone and UV index monitoring. While these instruments can observe ozone and sudden changes of ozone well, some issues affecting data quality were identified, especially when compared to the more established low orbit satellite instruments.

1. Introduction

The Tropospheric Emissions: Monitoring of Pollution (TEMPO) (Zoogman et al., 2017) and the Geostationary Environment Monitoring Spectrometer (GEMS) (Kim et al., 2020) are geostationary satellite instruments designed to enhance the monitoring of atmospheric composition. They were produced by the same manufacturer, BAE systems (https://www.baesystems.com/en-us/product/gems-tempo) and provide hourly data on air pollutants, but they differ in their spectral ranges, spatial resolutions, and coverage areas.

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TEMPO, a NASA mission, is the first instrument to observe air pollutants from a geostationary orbit over North America. Its field of regard (FoR) coverage area spans from approximately 18°N to 60°N and extends from 40°W to 150°W, including Mexico City in the south to the Canadian Oil Sands region in the north. GEMS, developed by the Korea Aerospace Research Institute, provides continuous monitoring of the same atmospheric constituents as TEMPO but across Asia. Its FoR is from approximately 5°S to 45°N and extends from 75°E to 145°E, covers the Korean Peninsula, China, Japan, and parts of Southeast Asia.

A detailed validation work for the GEMS total column ozone (TCO) data v2 product has been done by Baek et al. (2023) via comparison with the TROPOspheric Monitoring Instrument (TROPOMI) (Garane et al., 2019) and Ozone Mapping and Profiler Suite (Flynn et al., 2014) satellite data. As for ground-based measurements, in Baek et al., 2023, seven out of the eight sites were in South Korea or Japan, with only one site in Southeast Asia (Bangkok) thus covering a narrow range of observed latitudes. As a result, some verification work (e.g., latitude-dependent bias analyses) via ground-based observations was not possible.

In this work, TEMPO TCO v3 data and GEMS TCO v2 data have been compared with ground-based measurements from Brewer and Dobson spectrophotometers and Pandora spectrometers. To further validate the results, measurements from the TROPOMI and modeled data from the European Centre for Medium-Range Weather Forecasts' (ECMWF) Reanalysis 5th Generation (ERA5) and the Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2) were used.

2. Data Sets

2.1. Satellite Data

Launched in April 2023, TEMPO is an ultraviolet-visible (UV-VIS) imaging grating satellite instrument with a two-dimensional scanning capacity. TEMPO has high spatial (2×4.75 km at the center of its FoR) and temporal (hourly during daylight hours and more frequent scans in twilight conditions) resolution. The detailed description of the TEMPO instrument and measurements is described in Zoogman et al. (2017). In this work, we validated TEMPO's TCO data v3, which is adapted from the Total Ozone Mapping Spectrometer (TOMS) V8 algorithm (Bhartia & Wellemeyer, 2002). This algorithm uses two wavelength pairs, one (317.5 nm for ozone and 331.2 nm for the reflectivity) is for most conditions and the other (331.2 and 360 nm) is for high ozone and high solar zenith angle (SZA) conditions. When adapted for TEMPO, three parts of the algorithm were adjusted: (a) expanded viewing geometry to accommodate TEMPO's larger observing viewing zenith angle (VZA), (b) updated absorption coefficient from using BP (Bass & Paur, 1985) cross-section convolved to a triangular slit of 0.45 nm resolution (Full Width at Half Maximum) to using BDM (Brion et al., 1993; Daumont et al., 1992; Malicet et al., 1995) cross-section convolved to 0.60 nm resolution, and (c) the use of retrieved optical centroid cloud pressure from the TEMPO cloud product. More details of TEMPO TCO v3 data are provided in Park et al. (2024).

The GEMS, launched in February 2020, shares a similar design to TEMPO. It also provides total ozone data with hourly resolution and spatial resolution of 7×8 km at the center of FoR. GEMS TCO data product is also adapted from TOMS V8 algorithm, but includes an optimal estimation step (using seven wavelengths) to calculate the ozone profiles that were then used in its column values retrieval (Baek et al., 2023). As with TEMPO, GEMS' data product uses the BDM ozone cross-section. TEMPO v3 from August 2023 and GEMS v2 data from November 2020 both to September 2024 were included in this work. Given TOMS V8 algorithm has been verified in multiple satellite ozone retrievals (such as OMI's OMTO3 data (Balis et al., 2007)), it is expected that TEMPO and GEMS total ozone agreement with ground-based instruments should be within 1%–2%.

To help validate and compare the results from these two geostationary satellite instruments, TROPOMI offline TCO data was used. Unlike TEMPO and GEMS, TROPOMI's TCO data product uses the GODFIT v4 algorithm, which uses continuous measurements from 325 to 335 nm (Garane et al., 2019). The SDY (Serdyuchenko et al., 2014) ozone cross-section was used. Over low- and middle-latitudes, TROPOMI only measures once a day approximately around local solar noon (13:30). Detailed validation results for TROPOMI data can be found in Garane et al. (2019).

2.2. Ground-Based Measurements

Dobson spectrophotometers, developed in the 1920s, are among the earliest instruments for ozone monitoring (Dobson, 1931, 1968). They measure TCO by quantifying the differential absorption of solar UV radiation at four specific wavelengths between 305 and 340 nm. Brewer spectrophotometers, introduced in the 1980s, offer enhanced automated ozone monitoring (Kerr, 2010) using 5 wavelengths between 306 and 320 nm. Both Dobson and Brewer instruments are designated by the World Meteorological Organization (WMO) Global Atmosphere Watch for global and continuing monitoring of TCO variability and long-term changes (with an accuracy within ±1%). The agreement between Dobson and Brewer spectrophotometers is typically within ±1%, but could have seasonally varying differences due to Dobson having stronger effective temperature dependency (Voglmeier et al., 2024).

Pandora spectrometers measure TCO (Herman et al., 2015; Zhao et al., 2016) in the solar spectral range from 305 to 325 nm. The Pandonia Global Network (PGN, https://www.pandonia-global-network.org/) provides high-temporal-resolution total ozone data that have been used for validating satellite missions such as TROPOMI (e.g., Baek et al., 2024; Judd et al., 2020; Zhao et al., 2022). The original Pandora TCO data (processing version rout0) has precision better than 0.5% and accuracy better than 3%, but with a seasonal dependency when compared with Brewer data due to its sensitivity to stratospheric ozone temperature (Zhao et al., 2016). The most recent Pandora TCO data (rout2) shows comparable results with Brewer observations and has this temperature dependency issue largely resolved (with bias between Brewer and Pandora within ±1%). In this work, Pandora direct-sun measurements with air mass factor less than three are averaged into hourly data; technical details of ground-based data quality control can be found in Herman et al. (2015) and Zhao et al. (2016).

2.3. Reanalysis Data

ERA5 (Hersbach et al., 2020) and MERRA-2 (Gelaro et al., 2017) incorporate observational records from satellite measurements and other sources, using data assimilation systems to produce consistent, spatiotemporally complete atmospheric reanalysis data sets.

ERA5, developed by ECMWF, spans from 1940 to the present and has total ozone data set with an hourly temporal resolution and a $0.25° \times 0.25°$ spatial resolution. MERRA-2, produced by NASA's Global Modeling and Assimilation Office (GMAO), provides data from 1980 to the present with a spatial resolution of $0.5° \times 0.625°$ also on an hourly basis. Both ERA5 and MERRA-2 include an assimilation of ozone data from satellite instruments such as the Ozone Monitoring Instrument and the Microwave Limb Sounder. These modeled ozone data sets have been used as an independent reference in studies of long-term ozone trends, stratospheric dynamics, impact of climate variability on ozone distribution, and ground-based measurement verification (e.g., Wang et al., 2023; Zhao et al., 2023; Ziemke et al., 2019).

3. Advantages of Geostationary Observation

One significant advantage of geostationary satellite instruments is their ability to monitor hourly atmospheric changes. This temporal resolution is particularly important for tracking diurnal variations in anthropogenic air pollutants, such as NO_2, which are challenging to resolve using polar-orbiting satellite instruments (e.g., Griffin et al., 2019). Monitoring substantial intra-diurnal variations in TCO has less desirability due to its slow changing rates (e.g., typically less than 2 Dobson Units (DU)/hr in midlatitude regions) (Zhao et al., 2023). However, these variations, driven by photochemical processes and atmospheric dynamics (e.g., Sakazaki et al., 2013), can have a significant impact on the UV Index. For example, a 1% change in TCO typically results in a 1.2% change in surface UV radiation (WMO, 2011).

Figure 1 illustrates examples of such rapid ozone changes observed by the TEMPO and GEMS satellite instruments. On 14 June 2024, southern Ontario experienced an increase in TCO of up to 80 DU within a single day —equivalent to a 27% increase relative to a baseline of 300 DU. While this increase does not pose a health risk, contrasting cases, such as 7 April 2022, in South Korea, highlight the potential for adverse effects. On this date, a sudden 50 DU decrease in TCO within two hours caused the UV Index to escalate from the “high” range (6–7) to the “very high” range (8–10), highlighting the importance of continuous, high-resolution ozone monitoring for public health.

4. Validation of TEMPO and GEMS Total Ozone

In this section, we identify two major dependencies that affect TEMPO and GEMS data. Additional validation results are given in Supporting Information S1. Figure 2 shows the maps for the ground-based monitoring sites in

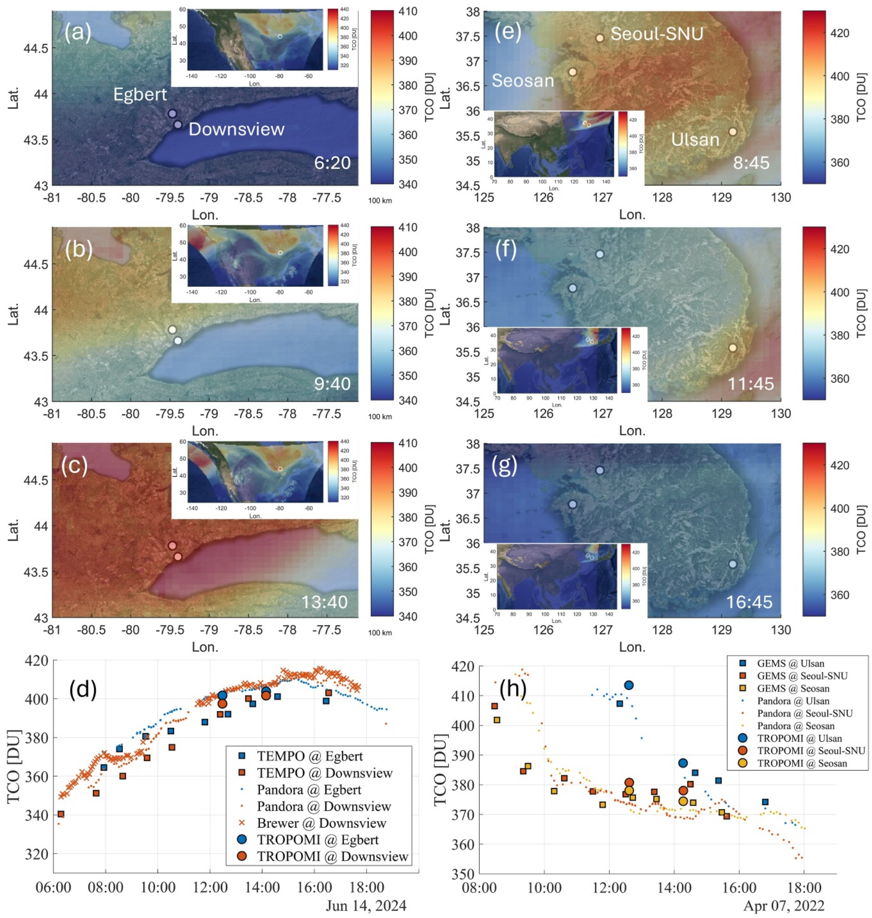

Figure 1. Examples of hourly observation from geostationary instruments with panels (a–d) for 14 June 2024 and (e–h) for 7 April 2022. Panels (a–c) and (e–g) show Tropospheric Emissions: Monitoring of Pollution (TEMPO) and Geostationary Environment Monitoring Spectrometer (GEMS) total column ozone fields, respectively. Panels (d, h) show time series of the TEMPO and GEMS observations, respectively.

this study. High-quality hourly average ground-based observations are used to coincide with overpass satellite observations (closest pixel, with maximum distance <15 km). For the TEMPO analysis, total ozone measurements from two Dobson sites, four Brewer sites, and 58 Pandora sites were included (see Figure 2a). For the GEMS analysis, measurements were from two Dobson, eight Brewer, and 26 Pandora sites. TEMPO data were filtered using the following parameters: cloud fraction <0.2, ozone below clouds <30 DU, and effective surface reflectivity at 331 nm <70%. GEMS data selection was based on the same filters except using reflectivity from 340 nm. These filters removed 35% and 52% of coincident measurements from TEMPO and GEMS, respectively. The percentage difference (ΔTCO = (SA − GB)/GB; SA = satellite observations and GB = ground-based observations) reveals TEMPO's strong latitude dependence, ranging from 2% to −2% from low to high latitudes (Figure 2b). GEMS shows a smaller latitude dependence compared to TEMPO (−1% to −3%, Figure 1e). Results for both geostationary satellite instruments show small opposite slopes than those for TROPOMI (within ±1%; see Figures 2c and 2f). Note that Garane et al. (2019) reported no significant latitude dependency from TROPOMI when compared with Brewer and Dobson measurements available from the World Ozone and Ultraviolet Radiation Data Centre (WOUDC).

For PGN, the current official Pandora total ozone data (rout2) uses information from climatology (McPeters et al., 2007) to estimate the ozone's effective temperature (see Text S2 in Supporting Information S1). It is worth noting that a small shift of this temperature relative to the climatology would result in a weak latitude dependence compared to TROPOMI. In the future, more Brewer and Dobson observations from the U.S. and Asia could be included for further examination of this issue.

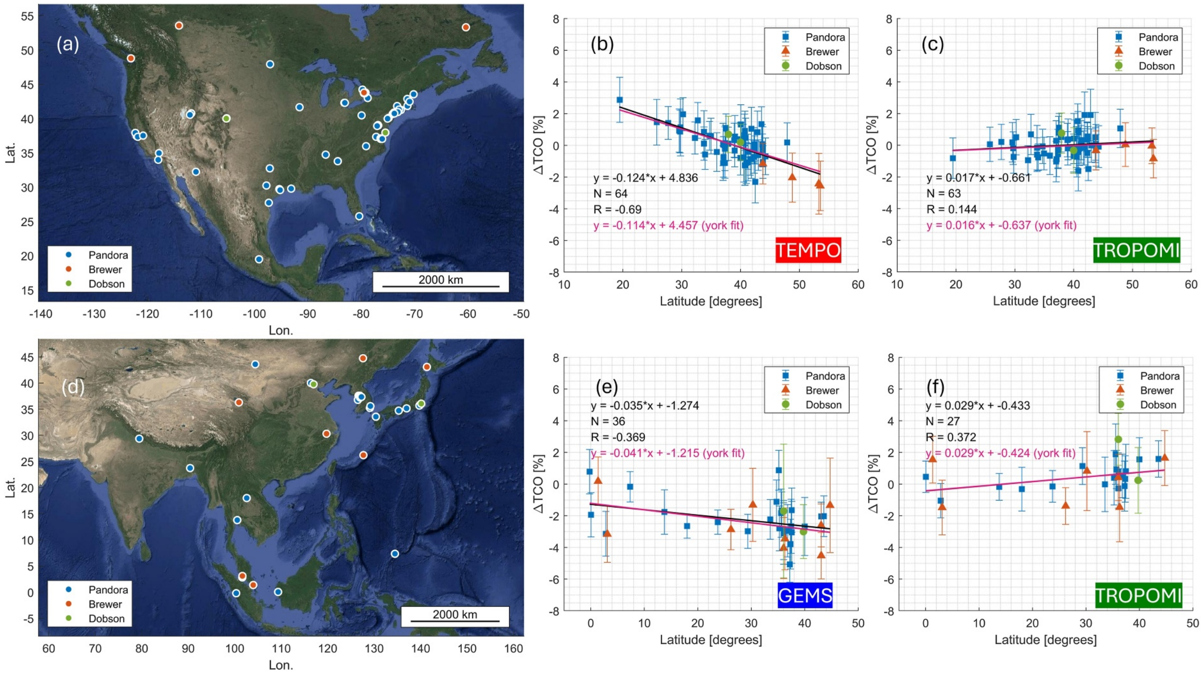

Figure 2. Site maps of Brewer, Dobson, and Pandora observations to perform validation for (a) Tropospheric Emissions: Monitoring of Pollution (64 sites) and (d) Geostationary Environment Monitoring Spectrometer (GEMS) (36 sites) total ozone data products. (b, e) Are percentage differences between TEMPO(GEMS) and ground-based observations (ΔTCO) versus latitudes of the sites, respectively. (c, f) Are the same as (b, e) but using TROPOspheric Monitoring Instrument total ozone observations. Error bars represent 1 standard deviation of ΔTCO. The black line represents a simple linear fit, while the red line represents a linear fit accounting for measurement uncertainty (York et al., 2004).

4.1. SZA Dependency

When compared to ground-based measurements (with slant column ozone <1,000 DU to assure high quality), TEMPO and GEMS TCO data both show an SZA dependency (see Figures 3a and 3c). Simple empirical corrections (Equations 1 and 2) were made to correct this SZA dependency (for SZA ≤ 80°). The correction parameters were determined using ground-based network observations. The corrected results are shown in Figures 3b and 3d. Fundamentally, such an SZA dependency issue could be due to the non-linear response from the satellite instruments to the measurand, that is, the slant column ozone (likely from systematic radiometric bias in the ratio of the two wavelengths used in the total ozone retrieval based on preliminary sensitivity studies).

$$\mathrm{TCO}_{\mathrm{tempo\_corrected}} = \mathrm{TCO}_{\mathrm{tempo}} \times \left(5.29e^{-4}\mathrm{SZA} + 0.97\right) \tag{1}$$

$$\mathrm{TCO}_{\mathrm{gems\_corrected}} = \mathrm{TCO}_{\mathrm{gems}} \times \left(3.92e^{-4}\mathrm{SZA} + 1.01\right) \tag{2}$$

4.2. Latitude Dependency

As SZA depends on latitude, the SZA dependency would yield a dependency on latitude. To separate these two effects, a SZA empirical correction was applied to TEMPO and GEMS data prior to comparisons with ground-based and reanalysis-modeled data sets. Figure 4 confirms that the SZA and latitude dependency issues are independent. TEMPO shows consistent latitude dependencies for both warm and cold seasons (on a range from −0.16 to −0.11% per latitude degree). Thus, latitude dependency can be further rectified by doing an empirical correction with VZA (a similar method used in Section 4.1; see Text S5 in Supporting Information S1).

GEMS data shows a smaller latitude dependency but this dependence varies across the seasons (Figure 4b). For example, in warm seasons, GEMS's latitude dependency is only from −0.03% to 0.01% per latitude degree, while the value in cold seasons ranges from −0.08% to −0.07% per latitude degree. A similar feature was reported by Baek et al. (2024) when GEMS data were compared with TROPOMI observations (where up to −4% bias between GEMS and TROPOMI was found in December at 40°N). The GEMS team is working on an updated

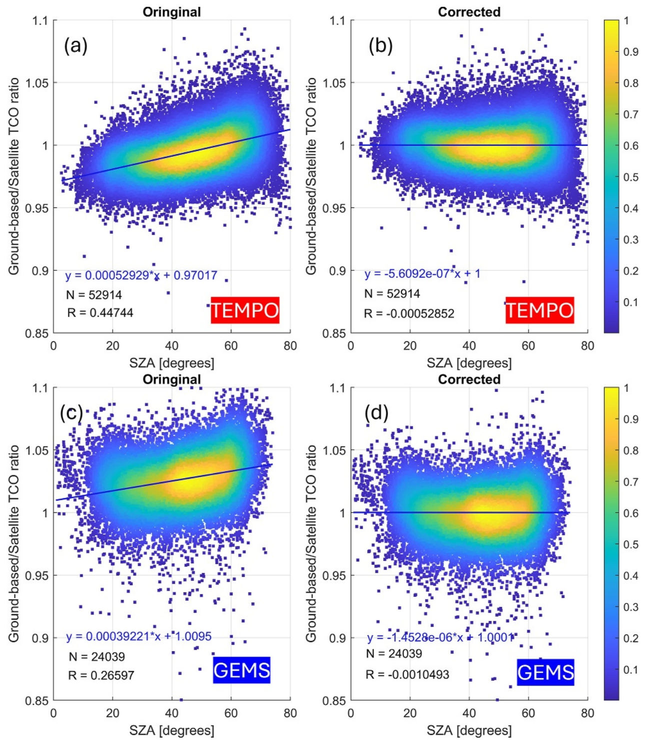

Figure 3. The ratio of ground-based and satellite total ozone observations versus solar zenith angle (SZA). The plots are color-coded by data density. Panels (a, c) show the Tropospheric Emissions: Monitoring of Pollution (TEMPO) and Geostationary Environment Monitoring Spectrometer (GEMS) results without any SZA correction, respectively; panels (b, d) show the TEMPO and GEMS results with the empirical SZA corrections, respectively.

version of total ozone product (v2.1) that will address the seasonal bias issue. The comparison against the reanalysis-modeled ozone data sets identified similar seasonal bias for both TEMPO v3 and GEMS v2 ozone products. This confirms that latitudinal dependency is related to problems with TEMPO and GEMS data and not with the ground-based data.

4.3. Daily Variation

One major advantage of TEMPO and GEMS observations is their hourly coverage. Figure 5 shows their percentage deviations from ground-based measurements binned by local hours. As both TEMPO and GEMS show SZA dependency, which is correlated to local time, the analysis here must use the corrected data sets. In general, no obvious diurnal biases have been observed, indicating consistently good quality of TEMPO and GEMS data across the day (except for the identified SZA dependency issue). On average, TEMPO and GEMS only show 0.02% ± 1.56% (mean ± 1 std) and 0.04% ± 2.03% offsets compared to ground-based measurements, while the 25th and 75th percentiles for the differences are within the −1.5%–2% range throughout the day.

4.4. Precision

We can further examine the precision of satellite ozone measurements by examining the statistics of ΔTCO. The results in Figure 6 suggest that TEMPO data has a comparable precision as TROPOMI data. The standard deviation of ΔTCO for TEMPO and TROPOMI (observations within TEMPO's FoR) are 1.45% and 1.34%, respectively, indicating both data sets have less than 1.5% uncertainty on 1 sigma level when compared with ground-based measurements. In addition, the median values ($\tilde{x}$) of $\sigma(\Delta TCO_{daily})$ are 1.28% (Figure 6e) and 1.19% (Figure 6f) for TEMPO and TROPOMI (in the TEMPO region) with 95th percentile values as 2.04% and 1.92%, respectively. This result indicates that on a daily basis, the majority of the coincident observations from different ground-based sites agree within 1.5%, and 95% of the coincident observations agree within 2%.

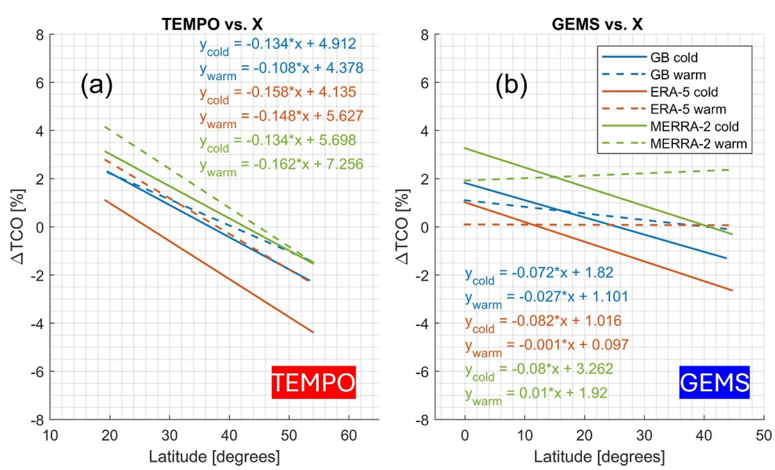

Figure 4. (a) Tropospheric Emissions: Monitoring of Pollution (TEMPO) and (b) Geostationary Environment Monitoring Spectrometer (GEMS) seasonal latitude dependencies, verified by using ground-based (GB) observations and reanalysis models. Warm seasons are from April to September, cold seasons are from October to March. TEMPO and GEMS data have been corrected for their solar zenith angle dependencies.

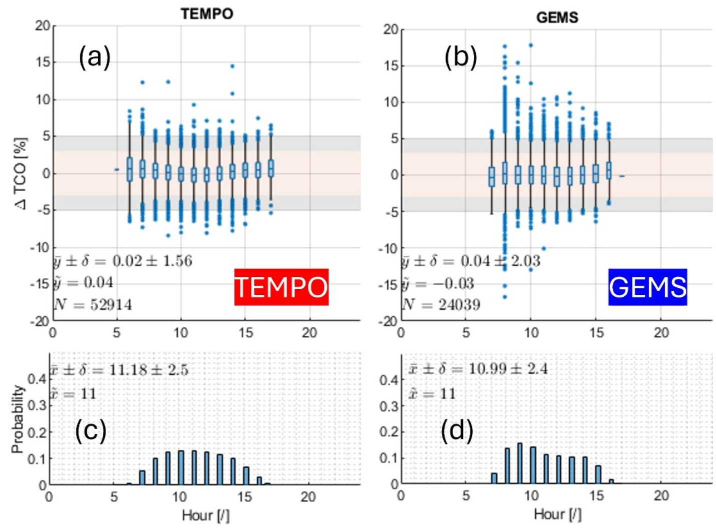

Figure 5. (a) Whisker plots of Tropospheric Emissions: Monitoring of Pollution (TEMPO) and (b) Geostationary Environment Monitoring Spectrometer (GEMS) hourly deviations from ground-based measurements. Each box shows the median (central mark), 25th and 75th percentiles (box edges), whiskers (non-outlier extremes), and outliers (dot markers). (c, d) Show the probability histograms of coincident measurements between satellite and ground-based measurements. TEMPO and GEMS data have been corrected for their solar zenith angle dependency.

A similar analysis for GEMS and TROPOMI (observations within GEMS's FoR) confirmed GEMS also has a comparable precision as TROPOMI does (for this region). The standard deviation of ΔTCO for GEMS and TROPOMI are 1.82% and 1.84%, respectively, which are only slightly higher than the numbers found for TEMPO (and TROPOMI observations in the TEMPO's region). However, the 95th percentile values of $\sigma(\Delta TCO_{daily})$ for GEMS and TROPOMI (in the GEMS region) are 3.07% and 3.44%, respectively, which are about 1% higher than the values for TEMPO and TROPOMI (in the TEMPO region). This result reflects the fact that the ground-based sites and observations in GEMS' FoR are sparser than those in TEMPO's FoR. It is important to point out that such precision analysis is only as accurate as the information provided by the ground-based network (due to limited sampling over time and space), thus more reliable ground-based observations (more observations and more

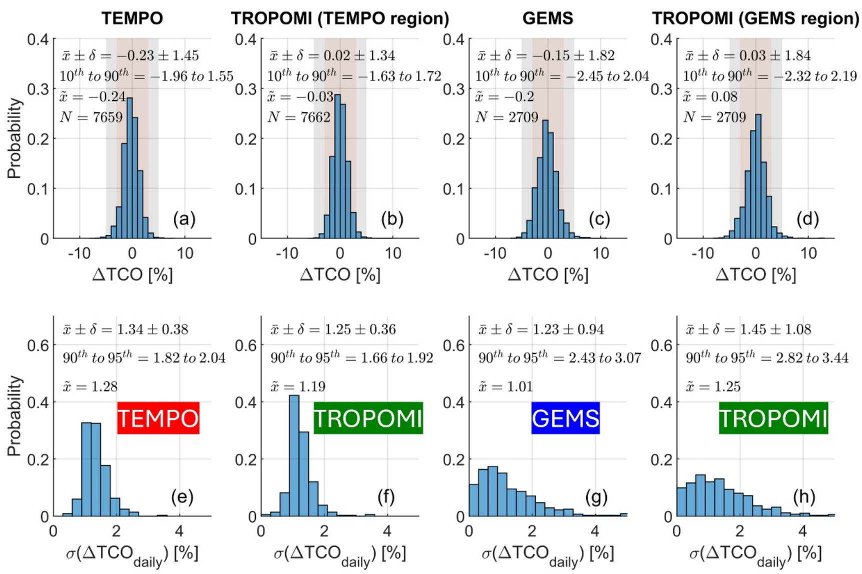

Figure 6. Histograms of ΔTCO and daily sigma values for Tropospheric Emissions: Monitoring of Pollution (TEMPO) data and TROPOspheric Monitoring Instrument (TROPOMI) observations within TEMPO's field of regard (FoR). Similarly, histograms of ΔTCO and daily sigma values for Geostationary Environment Monitoring Spectrometer (GEMS) data and TROPOMI observations within GEMS's FoR.

spatial coverage) are needed to support the validation work for modern satellite data with high spatial resolution coverage.

5. Conclusions

TEMPO and GEMS demonstrated their ability to observe rapid total ozone changes. TEMPO v3 and GEMS v2 TCO data demonstrate good precision (better than 2%) and accuracy (ranging from −2% to 2% for TEMPO and −1% to −3% for GEMS) when compared to data from ground-based networks, other satellite observations and reanalysis models. However, to fully utilize these geostationary satellite observations for research applications, certain issues must be addressed. Specifically, this study highlights SZA and latitude dependency issues. Both TEMPO and GEMS data require SZA corrections, though these corrections differ in magnitude. After applying SZA corrections, both instruments show good agreement with ground-based measurements in capturing intra-diurnal variations. Both TEMPO and GEMS demonstrated latitudinal dependency. For TEMPO it is constant throughout the year, while GEMS data exhibits latitude dependency with a seasonal component, necessitating more advanced correction methods in future work. This work highlights new geostationary satellite instruments' potential to improve the monitoring of TCO with high spatial and temporal resolution.

Data Availability Statement

The Brewer, Dobson, and Pandora observations can be found on WOUDC (https://woudc.org/data/explore.php?lang=en), EUBrewnet (https://eubrewnet.aemet.es/eubrewnet), and PGN (https://data.ovh.pandonia-global-network.org/) (last access: 1 December 2024). TEMPO and TROPOMI observations are available from Earthdata (https://search.earthdata.nasa.gov/search, last access: 19 November 2024). GEMS data can be downloaded from https://nesc.nier.go.kr/ (last access: 28 November 2024). TEMPO, TROPOMI, and GEMS overpass files over station data are available from: https://hpfx.collab.science.gc.ca/~deg001/tempo_ovp/, https://hpfx.collab.science.gc.ca/~deg001/tropomi_ovp/, and https://hpfx.collab.science.gc.ca/~deg001/gems_ovp/, respectively. ERA5 data are downloaded from Copernicus Climate Change Service, Climate Data Store, (2023) (last access: 1 December 2024). MERRA-2 data are downloaded from Global Modeling and Assimilation Office (GMAO) (2015) (last access: 1 December 2024).

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