



# Simultaneous measurements of near-surface CO<sub>2</sub> and NO<sub>2</sub> to monitor the fossil-fuel combustion-derived CO<sub>2</sub> in the Greater Tokyo Area

Hitoshi Irie<sup>1</sup>, Masataka Nomoto<sup>1,2</sup>, Yoshikazu Kamiya<sup>1,3</sup>, and Yukio Terao<sup>4</sup>

<sup>1</sup>Center for Environmental Remote Sensing, Chiba University, 1-33 Yayoicho, Inage-ku, Chiba 263-8522, Japan

<sup>2</sup>Ministry of Education, Culture, Sports, Science and Technology (MEXT), 3-2-2 Kasumigaseki, Chiyoda-ku, Tokyo 100-8959, Japan

<sup>3</sup>Chiba Prefectural Kisarazu High School, 4-1-1 Bunkyo, Kisarazu, Chiba 292-0804, Japan

<sup>4</sup>National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba, Ibaraki 305-8506, Japan

**Correspondence:** Hitoshi Irie (hitoshi.irie@chiba-u.jp)

Received: 29 December 2025 – Discussion started: 6 January 2026

Revised: 16 March 2026 – Accepted: 5 April 2026 – Published: 10 April 2026

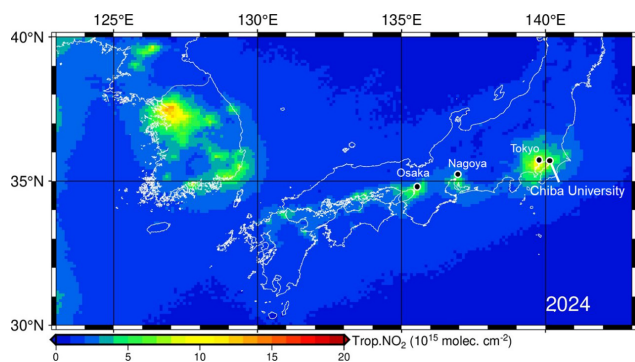
**Abstract.** Year-round continuous measurements of near-surface carbon dioxide (CO<sub>2</sub>) concentrations using in-situ trace gas analyzers were conducted simultaneously with nitrogen dioxide (NO<sub>2</sub>) measurements by International Air Quality and SKY Research Remote Sensing Network (A-SKY) Multi-Axis Differential Optical Absorption Spectroscopy (MAX-DOAS) at Chiba (35.625° N, 140.104° E, 60 m above sea level), located within the Greater Tokyo Area, Japan, during 2024. These simultaneous measurements revealed that CO<sub>2</sub> concentrations were low on days when near-surface NO<sub>2</sub> concentrations were markedly reduced. Furthermore, the CO<sub>2</sub> enhancement relative to the baseline concentration determined based on such low-NO<sub>2</sub>-concentration days ( $[\Delta\text{CO}_2]_{\text{N}}$ ) was positively correlated with NO<sub>2</sub> and black carbon concentrations. This finding indicates that  $[\Delta\text{CO}_2]_{\text{N}}$  is useful in observing the increase in fossil-fuel combustion-derived CO<sub>2</sub> within the Greater Tokyo Area. By employing this relatively simple method, CO<sub>2</sub> concentrations in megacities such as the Greater Tokyo Area can be monitored with high accuracy and precision, contributing to more effective emission mitigation strategies.

carbon dioxide (CO<sub>2</sub>), which remains the dominant anthropogenic driver of global warming (e.g., IPCC, 2021). Megacities – urban agglomerations with populations exceeding ten million – are disproportionately responsible for global CO<sub>2</sub> emissions due to concentrated energy consumption, transportation, and industrial activity. Establishing robust monitoring frameworks in megacities is thus essential to bridge local action with global climate goals, ensuring that mitigation strategies are evidence-based, transparent, and effective. Effective mitigation of fossil-fuel CO<sub>2</sub> emissions requires continuous monitoring of atmospheric CO<sub>2</sub> concentrations. However, globally, only a limited number of megacity sites conduct continuous measurements of CO<sub>2</sub> concentrations near the surface (e.g., Li et al., 2026).

The Greater Tokyo Area, which is sometimes conventionally referred to as the Tokyo megacity, is one of the world's largest metropolitan areas, with a population exceeding 37 million as of 2018 (UNPD, 2018). The Greater Tokyo Area comprises Tokyo and its surrounding major cities, including Yokohama, Kawasaki, Saitama, and Chiba, along with their connected suburban districts. The primary sources of anthropogenic CO<sub>2</sub> emissions in Tokyo are power generation, automobile transportation, and industry (Long and Yoshida, 2018). Large point sources, such as power plants and steelworks, are located along the Tokyo Bay Area. In residential areas, fossil fuel-related CO<sub>2</sub> emissions arise from household gas consumption and traffic exhaust (Hirano et al., 2015).

## 1 Introduction

The escalating climate crisis underscores the urgent need for precise monitoring of greenhouse gas emissions, particularly



**Figure 1.** Location of Chiba University. Observations were conducted at the Chiba University Atmospheric Environment Observation Supersite, located on the Nishi-Chiba campus of Chiba University. The colors show the annual mean tropospheric NO<sub>2</sub> column concentration for 2024, retrieved from the Tropospheric Ozone Monitoring Instrument (TROPOMI) aboard Sentinel-5 Precursor (S5P) satellite (Verhoelst et al., 2021).

Sugawara et al. (2021) investigated anthropogenic CO<sub>2</sub> emission changes in an urban area of Tokyo during the COVID-19 pandemic and found that the CO<sub>2</sub> emissions decreased by 20 % during the COVID-19 state of emergency compared to the same period during the past few years, mainly due to a decrease in car traffic. On the other hand, Shirai et al. (2012) analyzed aircraft CO<sub>2</sub> data over the Tokyo metropolitan region and found strong influences of fossil fuel CO<sub>2</sub> originating from the Asian continent. Therefore, it is necessary to account for the significant contribution from the Asian continent, to evaluate or estimate emissions from the Greater Tokyo Area.

To constrain anthropogenic emissions of CO<sub>2</sub> from the Tokyo Bay Area, Pisso et al. (2019) employed a Lagrangian inverse model together with data from in-situ aircraft CO<sub>2</sub> observations by the Comprehensive Observation Network for TRace gases by AirLiner (CONTRAIL), the Tsukuba tall tower of the Meteorological Research Institute (MRI) of the Japan Meteorological Agency, and surface sites from the World Data Center for Greenhouse Gases (WDCGG). As one of their conclusions, the challenges in estimating regional CO<sub>2</sub> fluxes from atmospheric observations were highlighted. Bisht et al. (2025) performed regional model simulations (WRF-GHG) with an improved resolution of 1 × 1 km<sup>2</sup> and found that point-source CO<sub>2</sub> emission and vertical distributions of CO<sub>2</sub> were better captured and represented. Yamada et al. (2025) conducted global high-resolution simulations of atmospheric CO<sub>2</sub> using flux data derived from global inverse analysis. Their simulations reproduced CO<sub>2</sub> variations at remote sites around Japan. Application of tagged tracers in the simulations revealed that variations in CO<sub>2</sub> concentrations at approximately 250 m above ground level from the Tokyo Skytree (35.71° N, 139.81° E) strongly depend on fluxes from the southwestern part of Tokyo, includ-

ing the western Tokyo Bay Area where large power plants are located. Based on the results, Yamada et al. (2025) argued the necessity of CO<sub>2</sub> observations that can capture emissions from the east coast of Tokyo Bay Area.

Here, the present study focuses on the Chiba University Atmospheric Environment Observation Supersite (35.625° N, 140.104° E, 60 m above sea level) (Fig. 1), which is a key site in the international observation networks; International Air Quality and Sky Research Remote Sensing (A-SKY) network (e.g., Irie et al., 2021; Mizobuchi et al., 2025) and skyradiometer network (SKYNET) (e.g., Nakajima et al., 2020; Irie and Nakajima, 2022). Chiba is one of the key cities consisting of the Greater Tokyo Area, being located east of Tokyo, and lying downstream of major sources of air pollution (Fig. 1). From the satellite-retrieved tropospheric nitrogen dioxide (NO<sub>2</sub>) data in Fig. 1, it is also evident that the Greater Tokyo Area is isolated from other major urban areas such as Nagoya and Osaka. At this important site, we conducted year-round continuous measurements of near-surface CO<sub>2</sub> concentrations using in-situ trace gas analyzers and ground-based remote sensing using the A-SKY Multi-Axis Differential Optical Absorption Spectroscopy (A-SKY/MAX-DOAS). From these simultaneous measurements, an attempt was made to clarify the usefulness of simultaneous measurements of CO<sub>2</sub> and NO<sub>2</sub> measurement for simple and accurate monitoring of fossil-fuel combustion-derived CO<sub>2</sub> concentrations in the Greater Tokyo Area.

## 2 Observations

In the Chiba University Atmospheric Environment Observation Supersite, which is located east of Tokyo (Fig. 1), we conducted year-round continuous measurements of near-surface CO<sub>2</sub> concentrations using two different in-situ trace gas analyzer instruments in 2024. One is the LI-7810 trace gas analyzer (LI-COR, Inc.), which employs a high-precision single-frequency laser and uses Optical Feedback-Cavity Enhanced Absorption Spectroscopy (OF-CEAS) – a technique that combines Cavity-Enhanced Absorption Spectroscopy (CEAS) with Optical Feedback (OF) from a V-shaped optical cavity (Morville et al., 2014; Romanini et al., 2014). While the LI-7810 is optimized for precise methane (CH<sub>4</sub>) measurements, it also provides concurrent measurements of CO<sub>2</sub> and water vapor (H<sub>2</sub>O). Since the LI-7810 detects inherently weak CO<sub>2</sub> absorption signals that overlap with those of H<sub>2</sub>O, the occurrence of drift, including H<sub>2</sub>O-related interference, is anticipated. It should be noted that the LI-7810 outputs CO<sub>2</sub> concentration data for dry air. The other is the G4301 Cavity Ring-Down Spectrometer analyzer (Picarro, Inc.). On the rooftop of the same building, at 60 m above sea level, these two trace gas analyzers were operated simultaneously, each using its own inlet to conduct measurements independently. Measurements using the G4301 were calibrated reg-

ularly using three working standard gases that were further calibrated against the National Institute for Environmental Studies (NIES) CO<sub>2</sub> standard scale (Machida et al., 2011). Air samples for the G4301 were dehumidified by passing through a Nafion dryer. On the other hand, the observations using the LI-7810 were conducted without performing regular calibrations and without dehumidifying the sampled air. This approach was adopted to explore whether useful automated long-term measurements could be achieved with lower effort.

Simultaneously with the trace gas analyzers, we conducted measurements using the MAX-DOAS technique. Its principle is based on the DOAS method (e.g., Platt and Stutz, 2008), which derives trace gas concentrations using Lambert–Beer’s law by exploiting the characteristic absorption spectral structures of target species contained in hyperspectral measurements with high wavelength resolution. The measured hyperspectra include not only absorption features of trace gases but also influences from Rayleigh and Mie scattering. These lower-frequency (smooth wavelength-dependent) structures are approximated and removed using polynomials. This enables the identification of absorptions as weak as 0.1 % and allows highly precise retrieval of trace gas concentrations.

MAX-DOAS is a passive DOAS technique enhanced with multiple low-elevation angle measurements. Despite its relatively simple instrumentation, MAX-DOAS achieves precise retrievals by combining hyperspectral measurements at multiple elevation angles with high-accuracy wavelength calibration using Fraunhofer lines, radiative transfer modeling that accounts for atmospheric sphericity, and nonlinear inversion solved via the Levenberg–Marquardt method based on Bayes’ theorem (e.g., Irie et al., 2011). This enables simultaneous retrieval of vertical distribution information of aerosols and trace gases in the lower troposphere.

At Chiba, four A-SKY/MAX-DOAS systems were operated simultaneously, each directed toward a different azimuth angle: north (13° W), west (95° W), east (118° E), and south (175° E) (Irie et al., 2021; Mizobuchi et al., 2025). Each system consists mainly of a high-resolution ultraviolet–visible spectrometer (Maya2000Pro, Ocean Insight; 2048 detector channels, spectral resolution 0.2–0.4 nm), a telescope unit (manufactured by Prede Co., Ltd.), and optical fibers. Hyperspectral measurements obtained with this system are analyzed using our algorithm called the Japanese MAX-DOAS profile retrieval algorithm, version 2 (JM2) (Irie et al., 2008, 2011, 2015, 2019, 2021). JM2 simultaneously retrieves vertical profiles and tropospheric columns of eight components: NO<sub>2</sub>, H<sub>2</sub>O, formaldehyde, glyoxal, sulfur dioxide, ozone, and aerosol extinction coefficients at two wavelengths. Based on nearly two decades of experience with MAX-DOAS, we adopt elevation angles of 2, 3, 4, 6, 8, and 70° as standard. Instead of 90, 70° is used as the reference angle, which stabilizes the signal range across all elevation angles while maintaining constant spectrometer integration time. In the vertical

profile retrieval, the elevation angle settings were fully accounted in the radiative transfer calculations used to compute the differential air mass factors (e.g., Irie et al., 2011, 2015, 2019). Low elevation angles are set below 10°, which minimizes potential systematic errors from oxygen collision complexes (O<sub>4</sub>; O<sub>2</sub>–O<sub>2</sub>), reduces sensitivity to high-altitude retrievals (thus suppressing cloud interference), and enhances sensitivity to lower altitudes (Irie et al., 2015). Our unique MAX-DOAS observations are conducted within the framework of the international A-SKY ground-based remote sensing network (Irie et al., 2021) and are referred to as A-SKY/MAX-DOAS to distinguish them from other MAX-DOAS observations (e.g., Mizobuchi et al., 2025).

To enhance the spatial representativeness around Chiba, which is located in an urban area, the average of the observations from these four azimuth directions was used in the analysis described below. Indeed, the obtained aerosol optical properties and trace gas concentration data have high spatial representativeness, extending several kilometers or longer in the horizontal direction, as recent studies by Damiani et al. (2021, 2022) showed a clear positive correlation between fine-mode aerosol absorption optical depth in the 0–1 km altitude range derived from these observations and black carbon (BC) mass concentrations measured using a Black Carbon Monitor (BCM3130; Kanomax Japan). BCM3130 was developed initially as Continuous Soot Monitoring System (COSMOS) by Miyazaki et al. (2008) and Kondo et al. (2009). The correlation ensures the spatial representativeness of the measured BC mass concentrations. At this well-characterized observation site, we conducted continuous measurements of CO<sub>2</sub> concentrations using trace gas analyzers of LI-7810 and G4301 together with A-SKY/MAX-DOAS.

### 3 Results and Discussion

Figure 2a and b show the time series of CO<sub>2</sub> concentrations measured using LI-7810 and G4301 at the Chiba University Atmospheric Environment Supersite in 2024. Hourly averages are plotted. As mentioned above, while the G4301 was calibrated with standard gases, the LI-7810 data are uncalibrated raw data. Nevertheless, both datasets exhibit variations between 420 and 600 ppmv, and within this relatively wide concentration range, both instruments exhibited approximately the same temporal variations. However, when their difference was analyzed, it was found that the difference varied gradually on a seasonal timescale (Fig. 2c). Over the course of 2024, the mean difference ( $\pm$  standard deviation) was  $-4.2 \pm 4.2$  ppmv. In addition, the differences spanned a relatively wide range from  $-16.9$  to  $26.5$  ppmv. A pronounced difference of  $26.5$  ppmv occurred at 01:00 LT on 3 December (a day number of 338). At that time, the G4301 indicated  $448.5$  ppmv, whereas the LI-7810 measured  $470.0$  ppmv. The standard deviation of the 1 min values

within that hour was as high as 12.5 ppmv ( $\sim 2.8\%$ ). This may have resulted from measuring a high-CO<sub>2</sub>-concentration plume with relatively low spatial representativeness, particularly in urban atmospheres, due to imperfect coincidence of sampling location or timing. Thus, the complete removal of possible influence of an unexpected, highly localized emission source is challenging for monitoring of urban atmospheres.

To characterize these features further, a histogram of the standard deviations of the 1 min values within each hour was examined for each of the LI-7810 and G4301 datasets (Fig. 3). The total numbers of hourly data points over the year were 8092 and 7036, respectively. Of these, nearly half had standard deviations of  $\leq 2$  ppmv. Conversely, the remaining half showed variations  $\geq 2$  ppmv, and in some cases exhibited very large fluctuations of up to  $\sim 30$  ppmv. Based on these results, data with hourly standard deviations  $\geq 2$  ppmv were excluded to remove short-term large fluctuations (Fig. 2d), while it is difficult to uniquely determine the threshold. As a result, over the year 2024, the mean difference ( $\pm$  standard deviation) became  $-3.0 \pm 3.6$  ppmv, smaller than the mean before exclusion. Consequently, the gradual seasonal-scale variation in the differences between the two instruments became more clearly evident (Fig. 2d).

To investigate the factors causing temporal variations on this seasonal scale, we examined the relationship with H<sub>2</sub>O concentration data simultaneously derived with CO<sub>2</sub> and CH<sub>4</sub> by the LI-7810. Figure 4 shows not only the difference in CO<sub>2</sub> concentration measured by the LI-7810 and G4301, but also the time series of H<sub>2</sub>O concentration derived concurrently with CO<sub>2</sub> by the LI-7810. As is immediately apparent, larger absolute differences in CO<sub>2</sub> concentration correspond to higher H<sub>2</sub>O concentrations, indicating a significant negative bias in the uncalibrated LI-7810 data due to the interference by H<sub>2</sub>O. It should be noted, however, that only data with a  $1\sigma$  standard deviation of the 1 min values within one hour less than 2 ppmv are plotted in Fig. 4. As the histogram (Fig. 3) shows, fluctuations exceeding 10 ppmv within an hour can occur regardless of H<sub>2</sub>O concentration. In such cases, the relative importance of interference due to H<sub>2</sub>O becomes smaller.

To quantitatively understand this relationship, their correlations were analyzed (Fig. 5). As expected, a clear anticorrelation was seen. From the slope of the regression line, we quantitatively estimated that a 1% increase in H<sub>2</sub>O concentration corresponds to a negative bias of 3.6 ppmv in the CO<sub>2</sub> concentration. This regression line may be useful for applying a single bias-correction equation over the one-year period of 2024 and for analyses conducted on an annual timescale. However, it remains uncertain whether the H<sub>2</sub>O interference introduces a bias in CO<sub>2</sub> concentration that consistently follows a linear relationship, and whether this works on seasonal timescales as well. In fact, although both the H<sub>2</sub>O concentrations in January and December 2024 indicate approximately 0.5%, the CO<sub>2</sub> concentration differ-

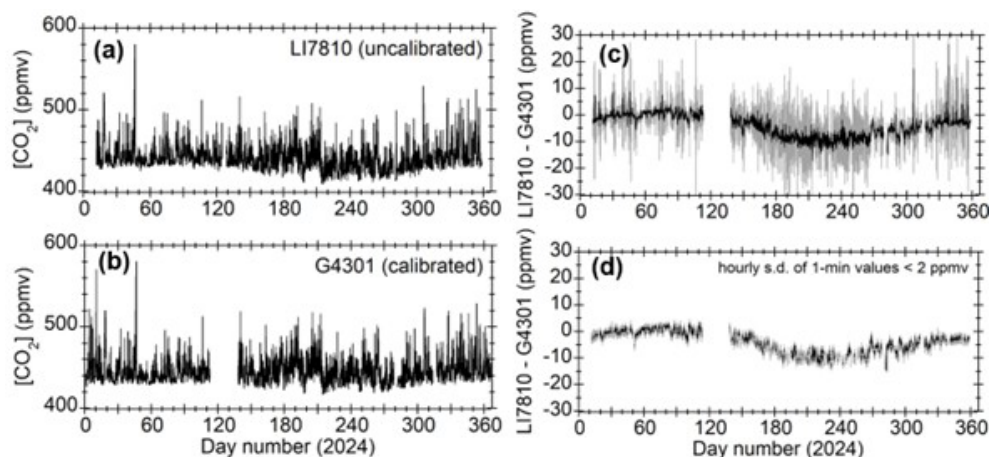
ences between the LI-7810 and G4301 differ by several ppmv (Fig. 4). We also found that the two groups appeared in different seasons: one corresponding to the period from April to August when H<sub>2</sub>O and temperature increase, and another corresponding to the period from September to December when they decrease. Comparing these groups, the slopes of the regression lines were similar, but the intercepts differed. The difference appears to be related to temperature and/or LI-7810 instrumental drift.

Given these difficulties, an attempt was made to derive a baseline concentration ( $[\text{CO}_2^*]_{\text{N}}$ ) by utilizing simultaneous A-SKY/MAX-DOAS observations of NO<sub>2</sub> concentration. Here, the brackets “[ ]” denote concentration. Figure 6a presents time series of NO<sub>2</sub> concentrations at 0–1 km altitude, retrieved from A-SKY/MAX-DOAS observations, together with CO<sub>2</sub> concentrations measured by LI-7810, covering the period from noon on 1 September to noon on 31 October 2024. This period corresponds to  $\pm 30$  d ( $N_{\text{day}} = 30$ ) from noon on 1 October 2024. To estimate the expected baseline CO<sub>2</sub> concentration  $[\text{CO}_2^*]_{\text{N}}$  at noon on 1 October 2024 when NO<sub>2</sub> concentrations are not elevated, the 5th percentile of NO<sub>2</sub> data within the  $\pm N_{\text{day}}$  period was calculated. Values below the 5th percentile are shown in red in Fig. 6a. The CO<sub>2</sub> concentration data measured at those identified times are shown in red in Fig. 6b and c. The average of these CO<sub>2</sub> data was used to estimate  $[\text{CO}_2^*]_{\text{N}}$  at noon on 1 October 2024.

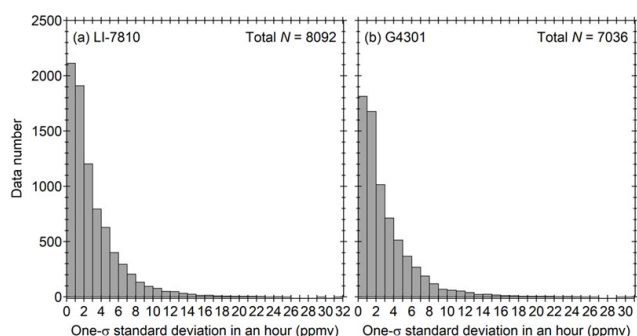
For the calibrated G4301, this  $[\text{CO}_2^*]_{\text{N}}$  is considered to represent the CO<sub>2</sub> concentration determined by factors other than local influences (primarily advection to the site), and is expected to exhibit gradual temporal variations on a seasonal timescale. In contrast, for the uncalibrated LI-7810, in addition to seasonal variations, instrumental drift is also expected to contribute. Regarding this drift, the primary timescale to be removed is the gradual seasonal-scale variation indicated by the difference between LI-7810 and G4301. Therefore, in this estimation,  $N_{\text{day}}$  was set to 45 d, corresponding to half of three months. However, additional variations on timescales shorter than seasonal are also anticipated. To investigate this,  $[\text{CO}_2^*]_{\text{N}}$  was also estimated with  $N_{\text{day}}$  set to 30 and 10 d.

When  $N_{\text{day}} = 10$  was used,  $[\text{CO}_2^*]_{\text{N}}$  exhibited short-term fluctuations as well, likely due to insufficient number of data used for accurate estimations (Fig. 7). This suggested that an  $N_{\text{day}}$  longer than 10 d is more appropriate. On the other hand, comparison of  $[\text{CO}_2^*]_{\text{N}}$  time variations with  $N_{\text{day}}$  set to 30 and 45 d showed that both produced similar gradual seasonal-scale changes. Thus, setting  $N_{\text{day}}$  to 30 d was found to be sufficient. This does not preclude the use of 45 d, but since shorter timescales can also be captured, a smaller  $N_{\text{day}}$  is preferable.

Similarly to  $[\text{CO}_2^*]_{\text{N}}$ , we also estimated  $[\text{CO}_2^*]_{\text{B}}$ , the expected CO<sub>2</sub> concentration during periods when BC concentrations measured simultaneously by COSMOS were notably low (Fig. 7). As shown,  $[\text{CO}_2^*]_{\text{B}}$  also exhibited gradual seasonal-scale variations, supporting the  $[\text{CO}_2^*]_{\text{N}}$  estimation. However, detailed analysis revealed that  $[\text{CO}_2^*]_{\text{B}}$  was approx-



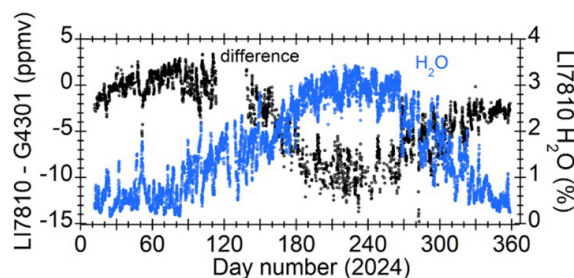
**Figure 2.** Time series plots of CO<sub>2</sub> concentrations measured using (a) G4301 and (b) LI-7810 at the Chiba University Atmospheric Environment Observation Supersite in 2024. Hourly averages are shown. Note that the G4301 was calibrated with standard gases and dehumidified, whereas the LI-7810 data are uncalibrated raw values. (c) Differences between LI-7810 and G4301 CO<sub>2</sub> concentrations. The gray shading indicates the  $1\sigma$  standard deviation of the 1 min values within each hour for LI-7810. (d) Differences between LI-7810 and G4301 CO<sub>2</sub> concentrations plotted only for hours in which the standard deviation was  $\leq 2$  ppmv.



**Figure 3.** Histograms of the  $1\sigma$  standard deviations of 1 min CO<sub>2</sub> concentration data within each hour, measured by (a) LI-7810 and (b) G4301 at the Chiba University Atmospheric Environment Supersite in 2024. The total numbers of hourly data points of LI-7810 and G4301 for the year were 8092 and 7036, respectively.

imately 5 ppmv higher than  $[\text{CO}_2^*]_{\text{N}}$ . This indicates that CO<sub>2</sub> concentration increases can occur even when BC concentrations are very low. Such differences between  $[\text{CO}_2^*]_{\text{B}}$  and  $[\text{CO}_2^*]_{\text{N}}$  are interpreted, at least partly, by regulated BC emissions as a result of transitions such as from diesel to gasoline vehicles, or from coal-fired to natural gas-fired power generation.

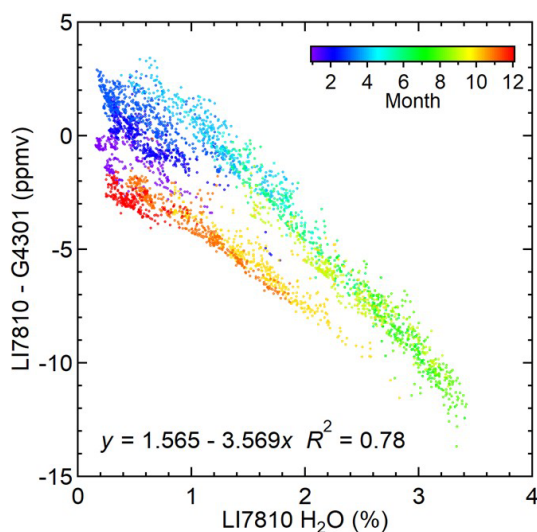
Figure 8 shows a time series of the increase in CO<sub>2</sub> concentration  $[\Delta\text{CO}_2]_{\text{N}}$ , defined as  $[\text{CO}_2]$  minus  $[\text{CO}_2^*]_{\text{N}}$ . The  $[\Delta\text{CO}_2]_{\text{N}}$  values were obtained by combining LI-7810 and A-SKY/MAX-DOAS measurements. The estimated increase  $[\Delta\text{CO}_2]_{\text{N}}$  reached  $147 \pm 2$  ppmv at 09:00 on 15 February (Day 46). At this time, the A-SKY/MAX-DOAS NO<sub>2</sub> data reached  $14 \pm 4$  ppbv, and the BC concentration also reached  $1.9 \pm 0.1 \mu\text{g m}^{-3}$ . As this example illustrates, the Figs. 8 and



**Figure 4.** Time series of the difference in CO<sub>2</sub> concentration measured using the uncalibrated LI-7810 and the calibrated G4301 at the Chiba University Atmospheric Environment Supersite in 2024. Hourly averages are shown. Only differences for which the 1 h standard deviation of the 1 min data is  $\leq 2$  ppmv are plotted. The blue line indicates the time series of H<sub>2</sub>O concentration simultaneously derived with CO<sub>2</sub> by the LI-7810.

9 clearly show that when  $[\Delta\text{CO}_2]_{\text{N}}$  is high, NO<sub>2</sub> and BC concentrations also tend to be elevated. The same features were also seen in the  $[\Delta\text{CO}_2]_{\text{N}}$  values obtained by combining G4301 and A-SKY/MAX-DOAS (not shown to avoid redundancy).

To confirm the tendency, the correlation between  $[\Delta\text{CO}_2]_{\text{N}}$  and  $[\text{NO}_2]$  and the correlation between  $[\Delta\text{CO}_2]_{\text{N}}$  and  $[\text{BC}]$  were analyzed (Fig. 10). Both exhibit clear positive correlations, indicating that the primary factors driving the increase in  $[\Delta\text{CO}_2]_{\text{N}}$  are common with those responsible for increases in  $[\text{NO}_2]$  and  $[\text{BC}]$ . In particular, the tight positive correlation with NO<sub>2</sub> ( $R^2 = 0.97$  for LI-7810 and  $R^2 = 0.94$  for G4301), which has a relatively short photochemical lifetime, suggests that the increase in  $[\Delta\text{CO}_2]_{\text{N}}$  is mainly attributable to fossil-fuel combustion sources in the

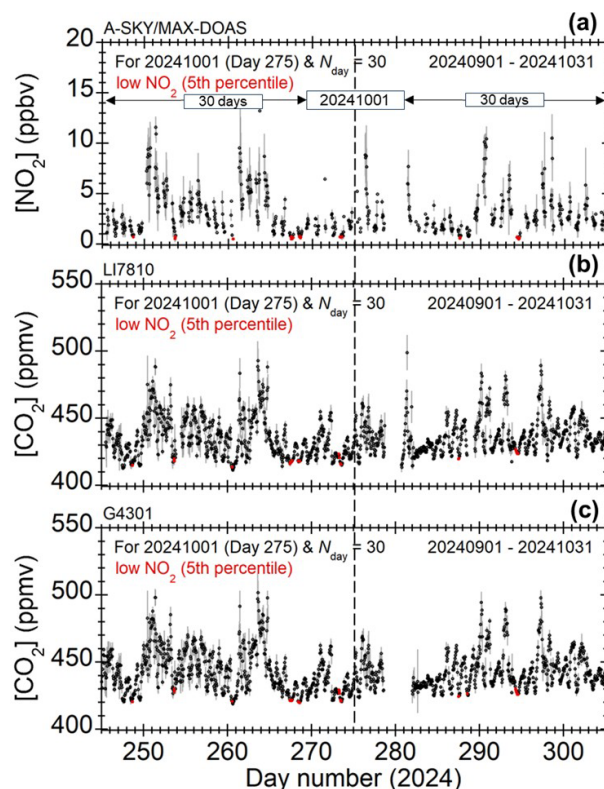


**Figure 5.** Correlations of the difference in CO<sub>2</sub> concentration measured using the uncalibrated LI-7810 and the calibrated G4301 with LI-7810 H<sub>2</sub>O concentration data. Month is indicated by color. The regression line and its equation are also shown.

vicinity of the observation site. Thus,  $[\Delta\text{CO}_2]_{\text{N}}$  observed in Chiba is considered to be closely linked to fossil-fuel CO<sub>2</sub> emissions in the urban atmosphere around Chiba, making it highly promising for monitoring purposes.

It should be noted that, in the present study, CO<sub>2</sub> enhancements were estimated by defining the baseline using NO<sub>2</sub>, not by using the  $[\Delta\text{CO}_2]_{\text{N}} - [\text{NO}_2]$  or  $[\Delta\text{CO}_2]_{\text{N}} - [\text{BC}]$  correlations. The slope of these correlations or the ratios (i.e.,  $[\Delta\text{CO}_2]_{\text{N}} / [\text{NO}_2]$  and  $[\Delta\text{CO}_2]_{\text{N}} / [\text{BC}]$ ) may reflect differences in emission sources, meteorological conditions, photochemical processes, and the influence of vegetation. For example, air masses with a high  $[\Delta\text{CO}_2]_{\text{N}} / [\text{NO}_2]$  ratio are likely associated with emissions from thermal power plants, whereas those with a low ratio are indicative of emissions from automobiles. Such detailed analyses, however, are beyond the scope of this study and will be investigated elsewhere. The regression line for the  $[\Delta\text{CO}_2]_{\text{N}} - [\text{NO}_2]$  correlation shows an intercept close to zero (Fig. 10a), supporting the validity of the background concentration subtraction. Positive intercepts of the regression lines for the  $[\Delta\text{CO}_2]_{\text{N}} - [\text{BC}]$  correlations as seen in Fig. 10b are considered to have caused by regulated BC emissions as a result of transitions such as from diesel to gasoline vehicles, or from coal-fired to natural gas-fired power generation, as mentioned earlier. The data point with the highest BC concentration may have influenced the intercept of the regression line. To assess this effect, we excluded the highest-BC data point and found that the intercept remained positive, although it decreased from  $\sim 5$  to  $\sim 2$  ppmv.

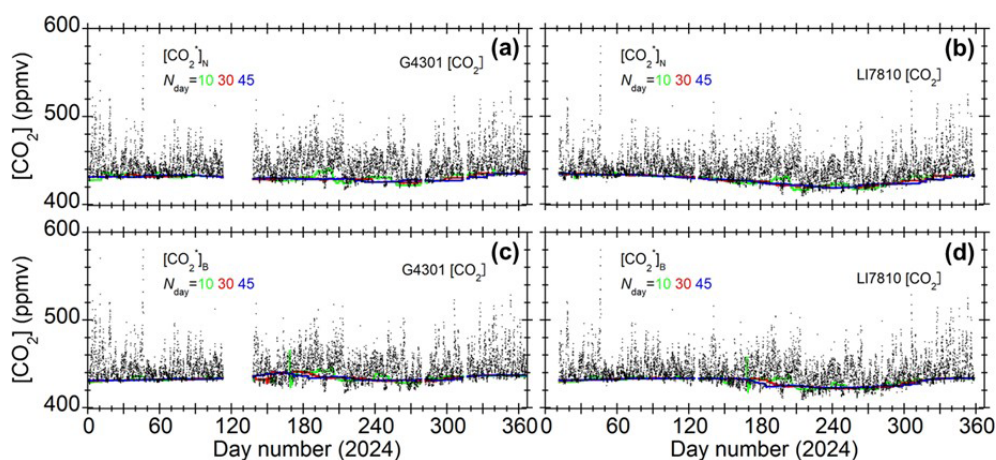
To evaluate the accuracy and precision of the  $[\Delta\text{CO}_2]_{\text{N}}$  estimate, we examined the correlation of  $[\Delta\text{CO}_2]_{\text{N}}$  values derived from CO<sub>2</sub> measurements with LI-7810 and G4301



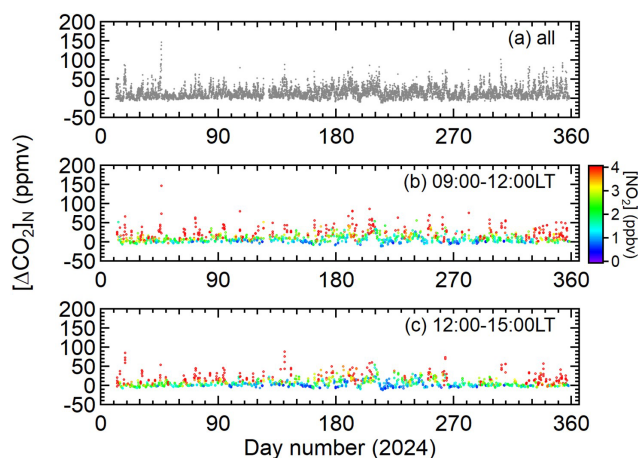
**Figure 6.** Time series of (a) NO<sub>2</sub> concentrations at 0–1 km altitude observed with A-SKY/MAX-DOAS and (b) LI-7810- and (c) G4301-measured CO<sub>2</sub> concentrations at the Chiba University Atmospheric Environment Monitoring Supersite from noon on 1 September to noon on 31 October 2024. Hourly averages are plotted. This period corresponds to  $\pm 30$  d ( $N_{\text{day}} = 30$ ) from noon on 1 October 2024. To estimate the expected CO<sub>2</sub> concentration  $[\text{CO}_2^*]_{\text{N}}$  at noon on 1 October 2024 when NO<sub>2</sub> concentrations are not elevated, the 5th percentile of NO<sub>2</sub> data within the  $\pm N$  day period was calculated. Values below the 5th percentile are shown in red in the panel (a). The CO<sub>2</sub> concentration data measured at those identified times are shown in red in the panels b and c. For each of LI-7810 and G4301, the average of these CO<sub>2</sub> data was used to estimate  $[\text{CO}_2^*]_{\text{N}}$  at noon on 1 October 2024.

(Fig. 11). As shown in the figure, the regression line of this correlation exhibited a very high coefficient of determination ( $R^2 = 0.98$ ), a slope close to unity (0.97), and an intercept nearly equal to zero ( $-0.90$  ppmv). It should be noted that the LI-7810 observations were conducted without performing regular calibrations and without dehumidifying the sampled air. Nevertheless, the  $[\Delta\text{CO}_2]_{\text{N}}$  values obtained from both instruments agreed remarkably well. This indicates that simultaneous measurements of CO<sub>2</sub> with A-SKY/MAX-DOAS NO<sub>2</sub> enable highly accurate and precise estimation of  $[\Delta\text{CO}_2]_{\text{N}}$ .

Another noteworthy aspect concerns the error analysis. Figure 11 also shows error bars representing the uncertainty of  $[\Delta\text{CO}_2]_{\text{N}}$ . The uncertainty is considered to originate from

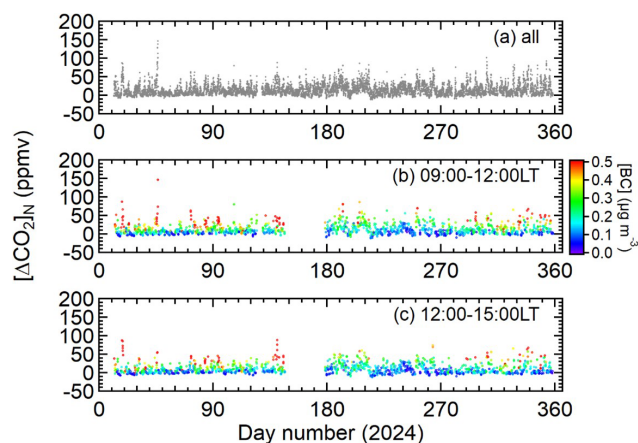


**Figure 7.** Time series of CO<sub>2</sub> concentrations ([CO<sub>2</sub>]) measured using (a, c) G4301 and (b, d) LI-7810. One-hour averages are plotted. As described in the text, the G4301 data are calibrated with standard gases and dehumidified, whereas the LI-7810 data are uncorrected raw data. In panels a and b, the expected CO<sub>2</sub> concentration ([CO<sub>2</sub>\*]<sub>N</sub>) when NO<sub>2</sub> concentrations are not elevated is also shown, derived from simultaneous observations with A-SKY/MAX-DOAS. The green, red, and blue lines represent [CO<sub>2</sub>\*]<sub>N</sub> estimated with  $N_{\text{day}}$  set to 10, 30, and 45, respectively. Panels c and d are similar, but show the expected CO<sub>2</sub> concentration when BC concentrations are not elevated ([CO<sub>2</sub>\*]<sub>B</sub>), based on simultaneous observations with COSMOS.



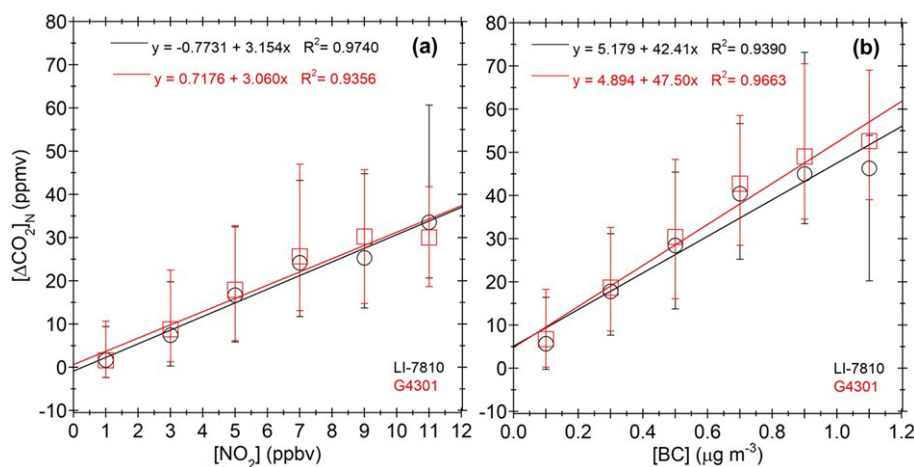
**Figure 8.** Time series of the CO<sub>2</sub> concentration increase ([ $\Delta\text{CO}_2$ ]<sub>N</sub>) obtained by combining LI-7810 and A-SKY/MAX-DOAS measurements. (a) All hourly values are plotted. To improve clarity by minimizing the influence of the diurnal variation pattern of NO<sub>2</sub>, (b) the time series of [ $\Delta\text{CO}_2$ ]<sub>N</sub> for local times of 09:00–12:00 and (c) for 12:00–15:00 are shown separately. The simultaneously measured NO<sub>2</sub> concentrations are indicated by color.

(1) hourly fluctuations in CO<sub>2</sub> concentration, (2) the magnitude of variability in CO<sub>2</sub> values measured when the NO<sub>2</sub> concentration was below its 5th percentile, and (3) drift on time scales shorter than  $N_{\text{day}}$  (including interference effects of water vapor). Despite these characteristics, [ $\Delta\text{CO}_2$ ]<sub>N</sub> values derived from LI-7810 and G4301 both exhibited nearly the same magnitude of error (Fig. 11). Although the error in LI-7810 [ $\Delta\text{CO}_2$ ]<sub>N</sub> due to the drift was evidently larger than that of G4301, the overall error magnitude was nearly identi-

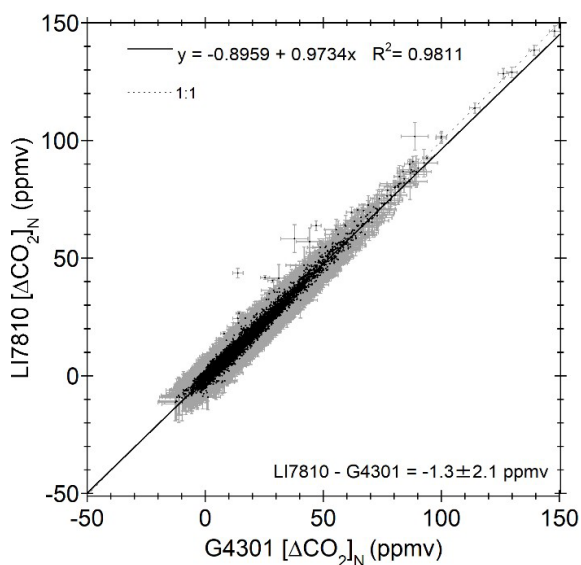


**Figure 9.** Same as Fig. 8 but BC concentrations are indicated by color.

cal, suggesting that the contribution of the drift was relatively small, and that the other factors 1 and 2 were the dominant sources of uncertainty. This is also supported by the fact that the mean difference ( $\pm 1\sigma$  standard deviation) between LI-7810 [ $\Delta\text{CO}_2$ ]<sub>N</sub> and G4301 [ $\Delta\text{CO}_2$ ]<sub>N</sub> was  $-1.3 \pm 2.1$  ppmv, which is very small, and the mean error was within the range of the  $1\sigma$  standard deviation. Thus, even when CO<sub>2</sub> measurements from an uncalibrated gas analyzer were used, we found that simultaneous measurements with NO<sub>2</sub> provide a simple and accurate means of monitoring fossil-fuel combustion-derived CO<sub>2</sub> concentrations in the Greater Tokyo Area.



**Figure 10.** (a) Correlation between  $[\Delta\text{CO}_2]_{\text{N}}$  and A-SKY/MAX-DOAS NO<sub>2</sub> data. (b) Correlation between  $[\Delta\text{CO}_2]_{\text{N}}$  and COSMOS BC data. In each plot, the median values are shown for bins of 2 ppbv (for NO<sub>2</sub>) and 0.2 μg m<sup>−3</sup> (for BC). LI-7810 and G4301 data are shown in black and red, respectively. Error bars represent the range encompassing 67 % of the data points.



**Figure 11.** Correlation between  $[\Delta\text{CO}_2]_{\text{N}}$  values estimated from LI-7810 and G4301 CO<sub>2</sub> data using simultaneous A-SKY/MAX-DOAS NO<sub>2</sub> observations. Hourly values are plotted. Gray error bars indicate the uncertainty in  $[\Delta\text{CO}_2]_{\text{N}}$ . The uncertainty is considered to include (1) hourly fluctuations in CO<sub>2</sub> concentration, (2) the uncertainty in estimating  $[\text{CO}_2^*]_{\text{N}}$ , and (3) drift on time scales shorter than  $N_{\text{day}}$  (including interference effects of water vapor). The 1 : 1 relationship is shown by the dotted line.

#### 4 Conclusions

To clarify the usefulness of simultaneous near-surface CO<sub>2</sub> and NO<sub>2</sub> measurements for simple and accurate monitoring of fossil-fuel combustion-derived CO<sub>2</sub> in the Greater Tokyo Area, year-round continuous measurements of near-surface CO<sub>2</sub> concentrations using LI-7810 and G4301 trace gas

analyzers were conducted simultaneously with NO<sub>2</sub> measurements by A-SKY/MAX-DOAS at Chiba, located within the Greater Tokyo Area, during 2024. These simultaneous measurements revealed that CO<sub>2</sub> concentrations were low on days when near-surface NO<sub>2</sub> concentrations were also low. Furthermore, the  $[\Delta\text{CO}_2]_{\text{N}}$  values estimated based on such low-NO<sub>2</sub>-concentration days was positively correlated with NO<sub>2</sub> and BC concentrations. This finding indicates that  $[\Delta\text{CO}_2]_{\text{N}}$  captures the increase in fossil-fuel combustion-derived CO<sub>2</sub> within the Greater Tokyo Area. Interestingly, the correlation of  $[\Delta\text{CO}_2]_{\text{N}}$  values derived from LI-7810 and G4301 showed a very high coefficient of determination ( $R^2 = 0.98$ ), a slope close to unity (0.97), and an intercept nearly equal to zero (−0.90 ppmv), although the LI-7810 observations were conducted without performing regular calibrations and without dehumidifying the sampled air. By employing this relatively simple method, fossil-fuel combustion-derived CO<sub>2</sub> concentrations in megacities such as the Greater Tokyo Area can be monitored with high accuracy and precision, contributing to more effective emission mitigation strategies.

*Code and data availability.* The LI-7810 and MAX-DOAS data are available upon request to the corresponding author (hitoshi.irie@chiba-u.jp). The G4301 data are available upon request to Yukio Terao (yterao@nies.go.jp).

*Author contributions.* HI, MN, and YK designed the present study, performed observation and analysis, and wrote the paper, with support from all the authors. YT performed the G4301 measurement and participated in the discussion of results. All authors have read and agreed to the published version of the manuscript.

*Competing interests.* The contact author has declared that none of the authors has any competing interests.

*Disclaimer.* Publisher's note: Copernicus Publications remains neutral with regard to jurisdictional claims made in the text, published maps, institutional affiliations, or any other geographical representation in this paper. The authors bear the ultimate responsibility for providing appropriate place names. Views expressed in the text are those of the authors and do not necessarily reflect the views of the publisher.

*Special issue statement.* This article is part of the special issue "SKYNET – the international network for aerosol, clouds, and solar radiation studies and their applications (AMT/ACP inter-journal SI)". It does not belong to a conference.

*Acknowledgements.* We thank Ms. Miho Ohama and Ms. Megumi Uehara for their technical assistance in the continuous operation of the instruments. The measurements using G4301 were supported by Dr. Toshinobu Machida and Dr. Motoki Sasakawa for the NIES09 CO<sub>2</sub> scale. We acknowledge the free use of TROPOMI tropospheric NO<sub>2</sub> column data from <https://www.temis.nl/> (last access: 1 December 2025).

*Financial support.* This research was supported by JSPS KAKENHI (grant nos. 20H04320 and 22H05004), the JAXA 4th research announcement on the Earth Observations, and the Virtual Laboratory (VL) project by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan. The measurements using G4301 were supported by the Environment Research and Technology Development Fund (grant nos. JP-MEERF21S20810 and JPMEERF24S12202) of the Environmental Restoration and Conservation Agency, provided by the Ministry of the Environment of Japan.

*Review statement.* This paper was edited by Teruyuki Nakajima and reviewed by two anonymous referees.

## References

- Bisht, J. S. H., Patra, P. K., Takigawa, M., Kanaya, Y., Yamaguchi, M., Machida, T., and Tanimoto, H.: High-resolution simulation of CO<sub>2</sub> using WRF-GHG over the Kanto region in Japan, *J. Geophys. Res.-Atmos.*, 130, e2025JD043589, <https://doi.org/10.1029/2025JD043589>, 2025.
- Damiani, A., Irie, H., Yamaguchi, K., Hoque, H. M. S., Nakayama, T., Matsumi, Y., Kondo, T., and Da Silva, A.: Variabilities in PM<sub>2.5</sub> and black carbon surface concentrations reproduced by aerosol optical properties estimated by sky radiometer and MAX-DOAS instruments, *Remote Sens.*, 13, 3163, <https://doi.org/10.3390/rs13163163>, 2021.
- Damiani, A., Irie, H., Belikov, D. A., Kaizuka, S., Hoque, H. M. S., and Cordero, R. R.: Peculiar COVID-19 effects in the Greater Tokyo Area revealed by spatiotemporal variabilities of tropospheric gases and light-absorbing aerosols, *Atmos. Chem. Phys.*, 22, 12705–12726, <https://doi.org/10.5194/acp-22-12705-2022>, 2022.
- Hirano, T., Sugawara, H., Murayama, S., and Kondo, H.: Diurnal variation of CO<sub>2</sub> flux in an urban area of Tokyo, *SOLA*, 11, 100–103, <https://doi.org/10.2151/sola.2015-024>, 2015.
- IPCC (Intergovernmental Panel on Climate Change): *Climate Change 2021: The Physical Science Basis*, Cambridge University Press, Cambridge, <https://doi.org/10.1017/9781009157896>, 2021.
- Irie, H.: International air quality and sky research remote sensing network (A-SKY), Its development and satellite atmosphere product validation, *J. Remote Sens. Soc. JPN*, 41, 575–581, <https://doi.org/10.11440/rssj.41.575>, 2021.
- Irie, H. and Nakajima, T.: SKYNET, in: *Handbook of Air Quality and Climate Change*, edited by: Akimoto, H. and Tanimoto, H., Springer Nature, Singapore, [https://doi.org/10.1007/978-981-15-2527-8\\_52-1](https://doi.org/10.1007/978-981-15-2527-8_52-1), 2022.
- Irie, H., Kanaya, Y., Akimoto, H., Iwabuchi, H., Shimizu, A., and Aoki, K.: First retrieval of tropospheric aerosol profiles using MAX-DOAS and comparison with lidar and sky radiometer measurements, *Atmos. Chem. Phys.*, 8, 341–350, <https://doi.org/10.5194/acp-8-341-2008>, 2008.
- Irie, H., Takashima, H., Kanaya, Y., Boersma, K. F., Gast, L., Wittrock, F., Brunner, D., Zhou, Y., and Van Roozendael, M.: Eight-component retrievals from ground-based MAX-DOAS observations, *Atmos. Meas. Tech.*, 4, 1027–1044, <https://doi.org/10.5194/amt-4-1027-2011>, 2011.
- Irie, H., Nakayama, T., Shimizu, A., Yamazaki, A., Nagai, T., Uchiyama, A., Zaizen, Y., Kagamitani, S., and Matsumi, Y.: Evaluation of MAX-DOAS aerosol retrievals by coincident observations using CRDS, lidar, and sky radiometer in Tsukuba, Japan, *Atmos. Meas. Tech.*, 8, 2775–2788, <https://doi.org/10.5194/amt-8-2775-2015>, 2015.
- Irie, H., Hoque, H. M. S., Damiani, A., Okamoto, H., Fatmi, A. M., Khatri, P., Takamura, T., and Jarupongsakul, T.: Simultaneous observations by sky radiometer and MAX-DOAS for characterization of biomass burning plumes in central Thailand in January–April 2016, *Atmos. Meas. Tech.*, 12, 599–606, <https://doi.org/10.5194/amt-12-599-2019>, 2019.
- Irie, H., Yonekawa, D., Damiani, A., Hoque, H. M. S., Sudo, K., and Itahashi, S.: Continuous multi-component MAX-DOAS observations for the planetary boundary layer ozone variation analysis at Chiba and Tsukuba, Japan from 2013 to 2019, *Prog. Earth Planet. Sci.*, 8, 31, <https://doi.org/10.1186/s40645-021-00424-9>, 2021.
- Kondo, Y., Sahu, L., Kuwata, M., Miyazaki, Y., Takegawa, N., Moteki, N., Imaru, J., Han, S., Nakayama, T., Kim Oanh, N. T., Hu, M., Kim, Y. J., and Kita, K.: Stabilization of the mass absorption cross section of black carbon for filter-based absorption photometry by the use of a heated inlet, *Aerosol Sci. Technol.*, 43, 741–756, <https://doi.org/10.1080/02786820902889879>, 2009.
- Li, J., Li, P., Han, P., Cheng, Z., Li, J., Zhang, T., Chen, D., Zheng, Y., Zeng, N., and Zhang, G.: Advances in the design of urban CO<sub>2</sub> emission monitoring networks: a review, *Carbon Res.*, 5, 3, <https://doi.org/10.1007/s44246-025-00239-z>, 2026.

- Long, Y. and Yoshida, Y.: Quantifying city-scale emission responsibility based on input-output analysis – insight from Tokyo, Japan, *Appl. Energy*, 218, 349–360, 2018.
- Machida, T., Tohjima, Y., Katsumata, K., and Mukai, H.: A new CO<sub>2</sub> calibration scale based on gravimetric one-step dilution cylinders in National Institute for Environmental Studies – NIES 09 CO<sub>2</sub> Scale, in: Report of the 15th WMO/IAEA Meeting of Experts on Carbon Dioxide, Other Greenhouse Gases and Related Tracers Measurement Techniques, edited by: Brand, W. A., Jena, Germany, 7–10 September 2009, WMO/GAW Report No. 194, 165–169, 2011.
- Miyazaki, Y., Kondo, Y., Sahu, L. K., Imaru, J., Fukushima, N., and Kano, M.: Performance of a newly designed continuous soot monitoring system (COSMOS), *J. Environ. Monit.*, 10, 1109–1240, <https://doi.org/10.1039/B806957C>, 2008.
- Mizobuchi, S., Irie, H., and Shimizu, S.: Long-term continuous observations of horizontal inhomogeneity in water vapor concentration in the lower atmosphere using A-SKY/MAX-DOAS, *Prog. Earth Planet. Sci.*, 12, 52, <https://doi.org/10.1186/s40645-025-00724-4>, 2025.
- Morville, J., Romanini, D., and Kerstel, E.: Cavity Enhanced Absorption Spectroscopy with Optical Feedback, in: Cavity-Enhanced Spectroscopy and Sensing, Vol. 179, edited by: Gagliardi, G. and Loock, H.-P., Springer Berlin Heidelberg, Berlin, Heidelberg, 163–209, [https://doi.org/10.1007/978-3-642-40003-2\\_5](https://doi.org/10.1007/978-3-642-40003-2_5), 2014.
- Nakajima, T., Campanelli, M., Che, H., Estellés, V., Irie, H., Kim, S.-W., Kim, J., Liu, D., Nishizawa, T., Pandithurai, G., Soni, V. K., Thana, B., Tugjurn, N.-U., Aoki, K., Go, S., Hashimoto, M., Higurashi, A., Kazadzis, S., Khatri, P., Kouremeti, N., Kudo, R., Marengo, F., Momoi, M., Ningombam, S. S., Ryder, C. L., Uchiyama, A., and Yamazaki, A.: An overview of and issues with sky radiometer technology and SKYNET, *Atmos. Meas. Tech.*, 13, 4195–4218, <https://doi.org/10.5194/amt-13-4195-2020>, 2020.
- Pisso, I., Patra, P., Takigawa, M., Machida, T., Matsueda, H., and Sawa, Y.: Assessing Lagrangian inverse modelling of urban anthropogenic CO<sub>2</sub> fluxes using in situ aircraft and ground-based measurements in the Tokyo area, *Carbon Balance Manage.*, 14, 6, <https://doi.org/10.1186/s13021-019-0118-8>, 2019.
- Platt, U. and Stutz, J.: Differential Optical Absorption spectroscopy, Principles and Applications, XV, 597 pp., 272 illus., 29 in color, Physics of Earth and Space Environments, Springer, Berlin, Germany, ISBN 978-3-540-21193-8, 2008.
- Romanini, D., Ventrillard, I., Méjean, G., Morville, J., and Kerstel, E.: Introduction to Cavity Enhanced Absorption Spectroscopy, in: Cavity-Enhanced Spectroscopy and Sensing, Vol. 179, edited by: Gagliardi, G. and Loock, H.-P., Springer Berlin Heidelberg, Berlin, Heidelberg, 1–60, [https://doi.org/10.1007/978-3-642-40003-2\\_1](https://doi.org/10.1007/978-3-642-40003-2_1), 2014.
- Shirai, T., Machida, T., Matsueda, H., Sawa, Y., Niwa, Y., Maksyutov, S., and Higuchi, K.: Relative contribution of transport/surface flux to the seasonal vertical synoptic CO<sub>2</sub> variability in the troposphere over Narita, *Tellus B*, 64, 19138, <https://doi.org/10.3402/tellusb.v64i0.19138>, 2012.
- Sugawara, H., Ishidoya, S., Terao, Y., Takane, Y., Kikegawa, Y., and Nakajima, K.: Anthropogenic CO<sub>2</sub> emissions changes in an urban area of Tokyo, Japan, due to the COVID-19 pandemic: A case study during the state of emergency in April–May 2020, *Geophys. Res. Lett.*, 48, e2021GL092600, <https://doi.org/10.1029/2021GL092600>, 2021.
- UNDP (United Nations Population Division): The World's cities in 2018: data booklet, The 2018 Revision Rep., United Nations, <https://doi.org/10.18356/c93f4dc6-en>, 2018.
- Verhoelst, T., Compernelle, S., Pinardi, G., Lambert, J.-C., Eskes, H. J., Eichmann, K.-U., Fjæraa, A. M., Granville, J., Niemeijer, S., Cede, A., Tiefengraber, M., Hendrick, F., Pazmiño, A., Bais, A., Bazureau, A., Boersma, K. F., Bogner, K., Dehn, A., Donner, S., Elokhov, A., Gebetsberger, M., Goutail, F., Grutter de la Mora, M., Gruzdev, A., Gratsea, M., Hansen, G. H., Irie, H., Jepsen, N., Kanaya, Y., Karagkiozidis, D., Kivi, R., Kreher, K., Levelt, P. F., Liu, C., Müller, M., Navarro Comas, M., Piters, A. J. M., Pommereau, J.-P., Portafaix, T., Prados-Roman, C., Puentedura, O., Querel, R., Remmers, J., Richter, A., Rimmer, J., Rivera Cárdenas, C., Saavedra de Miguel, L., Sinyakov, V. P., Stremme, W., Strong, K., Van Roozendaal, M., Veeffkind, J. P., Wagner, T., Wittrock, F., Yela González, M., and Zehner, C.: Ground-based validation of the Copernicus Sentinel-5P TROPOMI NO<sub>2</sub> measurements with the NDACC ZSL-DOAS, MAX-DOAS and Pandora global networks, *Atmos. Meas. Tech.*, 14, 481–510, <https://doi.org/10.5194/amt-14-481-2021>, 2021.
- Yamada, K., Niwa, Y., Terao, Y., Tohjima, Y., Tsuboi, K., Ishijima, K., and Murayama, S.: Estimation of CO<sub>2</sub> fluxes from Tokyo using a global model and tower observation, *J. Meteor. Soc. JPN*, 103, 67–85, <https://doi.org/10.2151/jmsj.2025-004>, 2025.