WCC-Empa Report 24/3

System and performance audit of Surface Ozone, Carbon Monoxide, Methane and Carbon Dioxide at the Global GAW Station Bukit Kototabang, Indonesia, September/October 2024

Submitted to the World Meteorological Organization by

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GLOBAL ATMOSPHERE WATCH

Empa Materials Science and Technology

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1 Executive summary

The 9th WCC-Empa[1] system and performance audit at the Bukit Kototabang global GAW station (BKT) was conducted from 27 September to 4 October 2024 in accordance with the WMO/GAW quality assurance system (WMO, 2017). A list of all WCC-Empa audits and the corresponding audit reports are available on the GAW-Empa website. The following persons contributed to this audit:

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This report summarises the evaluation of the Bukit Kototabang GAW station in general and the measurements of surface ozone, methane, carbon dioxide, and carbon monoxide in particular.

The report will be distributed to the station manager of the Bukit Kototabang GAW station, the management of the Indonesian Agency for Meteorology Climatology and Geophysics (BMKG), the National focal point for GAW in Indonesia and to the World Meteorological Organization in Geneva. The report will be published as a WMO/GAW report and made available on the WCC-Empa website.

The recommendations found in this report are categorised as minor, important and critical, and are accompanied by a priority (*** indicates high, ** medium and * low priority) and a proposed completion date.

[1]WMO/GAW World Calibration Centre for Surface Ozone, Carbon Monoxide, Methane, Carbon Dioxide and Nitrous Oxide. WCC-Empa was assigned by WMO and is hosted by the Laboratory for Air Pollution and Environmental Technology of Empa, the Swiss Federal Laboratories for Materials Science and Technology. Its mandate is to conduct system and performance audits at Global GAW stations based on mutual agreement.

2 Site description and operation

2.1 Station management

The BKT GAW station is managed by the Climatology Division of BMKG Jakarta, which is responsible for station development and major investments. This is done in close cooperation with the local management of BKT, headed by the station manager. During weekdays, BKT is staffed by approximately 10-15 scientists, technical and administrative personnel. At weekends, one to three operators are present during working hours (07:30-16:00 local time). The operation and maintenance of the station and the measurements have improved considerably in recent years, and the cooperation between the BMKG headquarters and the various measurement sites is working well. Staff turnover is still high, but knowledge transfer has improved through the sharing of expertise within Indonesia. For example, station managers from all the Indonesian monitoring sites meet annually. The station staff's data analysis and interpretation skills have also improved, i.e. the staff is now fully independent of external partners. However, it remains important that staff with a scientific background are directly involved in the daily operation of the BKT station and that data are published in peer-reviewed literature. Given the critical role of atmospheric observations in this data-poor region, BMKG should prioritise the monitoring of greenhouse gases and air pollutants. This can be done by strengthening the monitoring programme not only at BKT but also at the other stations in the Indonesian monitoring network, by establishing collaborations with academia, by enhancing capacity building, by promoting data access and use, and by supporting research and development.

More information about the station management can be found on the BKT website (in Indonesian language only).

Recommendation 1 (, important, ongoing)**
Recognising the importance of atmospheric observations in this data-poor region, BMKG should prioritise the operation of BKT and other monitoring stations throughout Indonesia, as well as the scientific analysis of available data series.

Recommendation 2 (, important, ongoing)**
BMKG should explore all possibilities for training of station operators and scientists. Participation in GAWTEC and other training courses is highly recommended, and knowledge needs to be shared among BMKG staff.

Recommendation 3 (*, critical, ongoing)**
BKT data should be used scientifically. This should be done in collaboration between BKT, BMKG Jakarta and other partners.

2.2 Location and access

The Bukit Kototabang GAW station (0.20194°S, 100.31805°E, 864m above sea level) is in Sumatra, Indonesia, about 17 km north of the town of Bukittinggi. The station is located in the equatorial zone on the ridge of a high plateau, 40 km off the western coastline. The station is accessed via a small, paved road. This small access road has allowed farmers to develop the area, and agricultural activities have increased significantly in recent years. Research facilities and offices of the National Research and Innovation Agency (BRIN) are located about 200 m southeast of the GAW station. The GAW Station and BRIN share the same access road.

The site is suitable for the intended purpose, although local pollution is possible, mainly due to agricultural activities in the immediate vicinity of the station. Access to BKT by car is possible throughout the year. Further information is available from GAWSIS and the BKT website.

2.3 Station facilities

The BKT station has extensive laboratory and office space. Kitchen and sanitary facilities are available. The laboratories are air-conditioned and the temperature is set at 25°C to prevent condensation in the inlet systems. A stable high-speed internet connection is available. The power supply to the station is subject to frequent short-term outages, which are bridged by an uninterruptible power supply (UPS) and a large diesel generator located at the junction with the main road (approximately 2 km from the station). Frequent thunderstorms remain a major concern for the instrumentation at BKT, although the station's lighting protection has been improved. However, there is still an issue with the lightning protection of the new 100 m tower and measurements on the new platform cannot commence until this is resolved.

In conclusion, BKT is an ideal platform for both continuous atmospheric research and measurement campaigns. The following recommendation is made for the facilities:

> **Recommendation 4 (***, critical, 2025/26)**
> *The lightning protection issues of the 100 m tower need to be addressed.*

2.4 Measurement programme

BKT hosts a comprehensive measurement programme covering reactive and greenhouse gases, physical and optical properties of aerosols, and ancillary meteorological variables. Despite the extensive scope of the BKT aerosol programme, it has not yet undergone external evaluation. An overview of the measured species is available on the BKT website and on GAWSIS.

> **Recommendation 5 (***, critical, 2025/26)**
> *An external review of BKT aerosol programme by the World Calibration Centre for Aerosol Physics (WCCAP) is strongly recommended. This review is crucial for ensuring compliance with global standards and enhancing the quality and reliability of the measurements.*

In order to ensure ongoing and continuous time series, a budget must be available at BKT to deal with unforeseen repair costs with short response times.

> **Recommendation 6 (***, critical, ongoing)**
> *In the event of instrument failure, a budget must be available to resolve instrument problems in a timely manner.*

The information available on GAWSIS was reviewed during the audit. The last update was made by BMKG staff in April 2022 and the information found on GAWSIS was mostly up to date. However, some of the information (e.g. the list of station contacts) needs to be updated.

> **Recommendation 7 (**, important, ongoing)**
> *It is recommended that GAWSIS is updated annually or whenever there are major changes. Some of the information reviewed needs to be updated.*

2.5 Data management and data processing

Data from all analysers are transferred automatically to a central data acquisition computer on-site. There, data are processed and reviewed by on-site staff with custom built software.

2.6 Data submission

As of February 2025, the following BKT data within the scope of the audit were available at the World Data Centres:

BMKG, submitted to the World Data Centre for Reactive Gases (WDCRG):
O_3, three data sets:

1996-2007: https://doi.org/10.48597/DY93-KSCM
2007-2019: https://doi.org/10.48597/E9MC-P3HV
2021-2022: https://doi.org/10.48597/YKCC-8BFD

BMKG, submitted to the World Data Centre for Greenhouse Gases (WDCGG):
CO (2001-2023), CH_4 (2009-2023), CO_2 (2009-2023) (data gap for CH_4 and CO_2 from 2014-2018)

NOAA, submitted to the World Data Centre for Greenhouse Gases (WDCGG):
CO (2004-2023), CH_4 (2004-2023), CO_2 (2004-2023)

Data presented in this report were accessed on 22 November 2024.

Ozone data for 2019 and 2020 as and the most recent data since 2022 have not yet been submitted.

> **Recommendation 8 (**, important, 2025)**
> *Most data have been submitted with a delay of less than one year. However, some ozone data are not yet available from the WDCRG. It is recommended to submit O_3 data for the period from 2019/20 as soon as the final quality control has been completed.*
>
> **Recommendation 9 (*, minor, 2025)**
> *Ozone data for 1996 – 2007 are not accessible via the WDCRG. It is recommended to resubmit data for this period.*

2.7 Data review

As part of the system audit, data within the scope of WCC-Empa available at WDCRG was reviewed. Summary graphs and a brief description of the findings are provided in the Appendix.

The review of the ozone time series indicated that some of the data submitted appear to be invalid and require further quality control.

> **Recommendation 10 (***, critical, 2025)**
> *The ozone time series from 2021 onwards appear to contain invalid data. These datasets need further quality control and must be withdrawn in the meantime.*

The GHG and CO data available from the WDCGG appeared plausible, but the flagging of data (valid background and valid non-background data flags) was inconsistent over time. In addition, all CO_2 data submitted by BKMG to WDCGG are on the WMO-X2007 CO_2 scale according to the metadata.

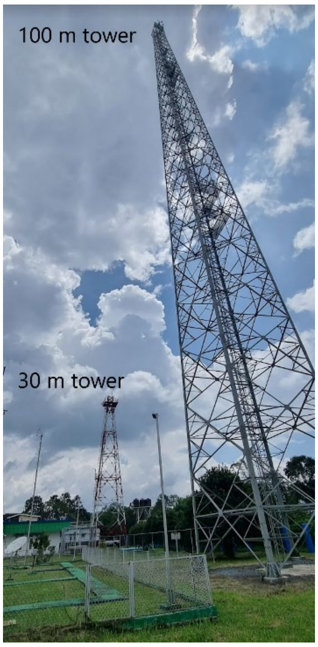
> **Recommendation 11 (**, important, 2025)**
> *It is recommended to resubmit the BMKG data for CO_2, CH_4 and CO with a consistent flagging for valid background and non-background data. In addition, the CO_2 data should be converted to the WMO-X2019 CO_2 scale when resubmitted.*

2.8 Documentation

Electronic logbooks are available for all instruments and the station itself. Instrument manuals are available at the site. The information was comprehensive and up to date, in contrast to the previous audit in 2019.

2.9 Air inlet system

GHGs and CO are currently sampled from the 30 m level of the old BKT tower. It is planned to move the inlet to the 100 m level of the new tower and to take additional measurements at the 30 m and 70 m levels (20 min each). However, this has not yet been implemented due to lightening protection issues. Currently, air is sampled from the 30 m level of the tower using approximately 40 m of ¼" Synflex 1300 tubing. This tubing is flushed using a membrane pump. The exact flow rate is not known but is several litres per minute. A stainless steel filter is mounted upstream of the Picarro 16 port manifold (model A0311) to prevent particles from entering the instrument. Downstream of the distribution manifold is a Perma Pure Nafion dryer (model PD-50T-24PP) operated in reflux mode using the Picarro vacuum pump. The current inlet system is suitable for GHG measurements.



Recommendation 12 (, important, 2025/26)**
It is recommended that measurements be concentrated on the new 100 m tower on the highest level and that the lower levels be used only occasionally. The highest level will be least affected by the surrounding vegetation.

A dedicated PFA line is used to the top of the laboratory building, approximately 3 m above the roof. The refrigeration system used to protect the instrument from water vapour condensation (see previous audit reports) has been replaced by two Erlenmeyer flasks connected by short pieces of silicone tubing, which may result in ozone loss. The current inlet system is adequate but it is recommended that it be checked for ozone loss.

Recommendation 13 (, important, 2025)**
The ozone inlet system, including the Erlenmeyer moisture traps, need to be checked for ozone loss.

3 Performance audit

3.1 Surface ozone measurements

Surface ozone measurements began at BKT in 1996, and continuous time series data are available since then.

Instrumentation. At the time of the audit, a Thermo Scientific ozone analyser (model 49iQ) was available. In addition, the ozone analyser of the Sorong measurement site was also available.

Standards. BKT is equipped with a Thermo Scientific ozone calibrator (model 49iQ-PS). The ozone calibrator of the Sorong station (same model) was also available during the audit.

Data acquisition. A custom-built system programmed in Delphi (Pascal) is used for ozone data acquisition. 1 minute time resolution is available for ozone and ancillary data.

Intercomparison (performance audit). The Thermo Scientific ozone analysers and calibrators of BKT and Sorong were compared to the WCC-Empa Travelling Standard (TS) with traceability to SRP#15. The internal ozone generator of the TS was used to generate a random sequence of ozone levels from 0 to 250 nmol mol^{-1}. The result of the comparisons is summarised below in relation to the WMO GAW Data Quality Objectives (DQOs) (WMO, 2013). The data were collected using the WCC-Empa data acquisition system (TS) and the internal data storage of the iQ instruments.

The calibration settings of the BKT Thermo Scientific 49iQ were adjusted during the audit and both the initial and final comparisons are shown below.

The following equations characterise the instrument bias and the remaining uncertainty after bias compensation. Uncertainties were calculated according to Klausen et al. (2003) and the WCC-Empa Standard Operating Procedure (SOP) (Empa, 2014). As the measurements refer to a conventionally agreed value of the ozone absorption cross section of 1.1476x10^{-17} cm^2 (Hearn, 1961), the uncertainties reported below do not include the uncertainty of the ozone absorption cross section.

Comparisons of the BKT and Sorong ozone analysers and calibrators showed significantly more noise and drift than usual. Similar behaviour has been observed in other Thermo iQ series instruments and Thermo should be contacted for corrective maintenance or repair.

Recommendation 14 (, important, 2025)**
Thermo needs to be contacted and questioned about the poor performance of the instrument, and the instrument should be returned to Thermo for corrective action.

BKT analyser Thermo Scientific 49iQ #1191412978 (BKG -1.8 nmol mol^{-1}, COEF 1.001), initial comparison:

Unbiased O_3 amount fraction X_{O3} (nmol mol^{-1}): X_{O3} = ([OA] – 1.69 nmol mol^{-1}) / 0.9855 (1)

Standard uncertainty u_{O3} (nmol mol^{-1}): u_{O3} = sqrt ((0.54 nmol mol^{-1})^2+ 2.10e-05 * X_{O3}^2) (2)

BKT analyser Thermo Scientific 49iQ #1191412978 (BKG +0.2 nmol mol^{-1}, COEF 1.027), final calibration settings:

Unbiased O_3 amount fraction X_{O3} (nmol mol^{-1}): X_{O3} = ([OA] + 0.26 nmol mol^{-1}) / 1.0030 (3)

Standard uncertainty u_{O3} (nmol mol^{-1}): u_{O3} = sqrt ((0.54 nmol mol^{-1})^2 + 2.10e-05 * X_{O3}^2) (4)

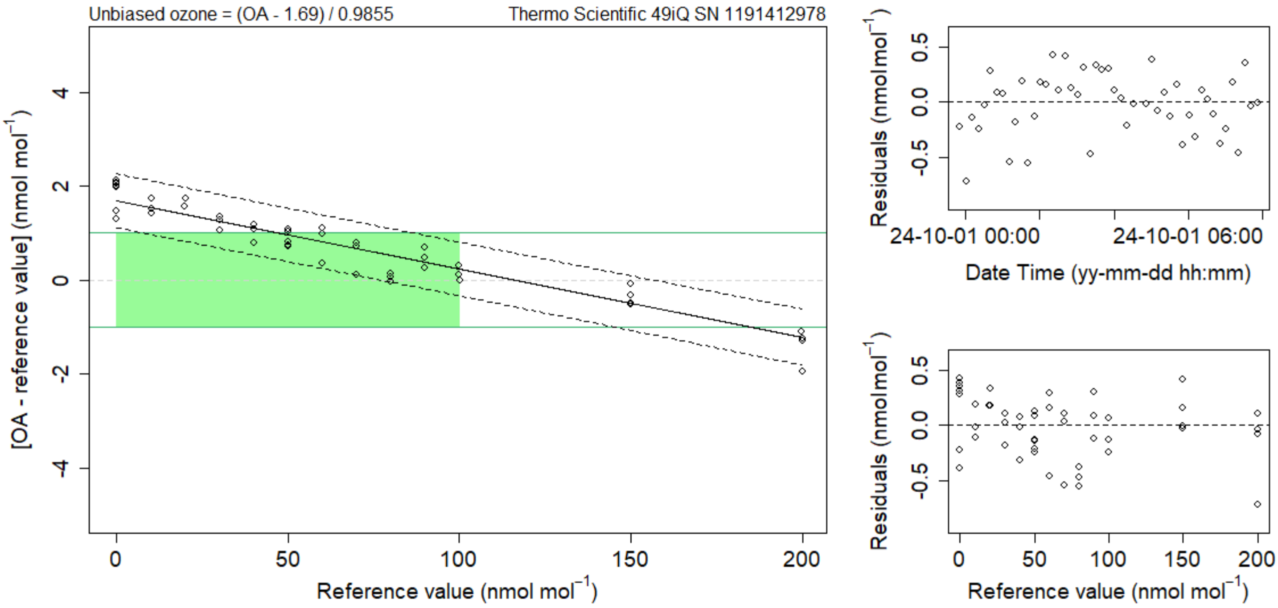


Figure 1. *Left: Bias of the BKT ozone analyser (Thermo Scientific 49iQ #1191412978, BKG -1.8 nmol mol^{-1}, COEF 1.001, initial comparison) with respect to the SRP as a function of the amount fraction. Each point represents the average of the last 5 one-minute values at a given level. The green area corresponds to the relevant amount fraction range, while the DQOs are indicated with green lines. The dashed lines around the regression lines are the Working-Hotelling 95% confidence bands. Right: Regression residuals of the ozone comparisons as a function of time (top) and amount fraction (bottom).*

After the initial comparison, the calibration settings were adjusted and the instrument was again compared to the TS. The results were as follows:

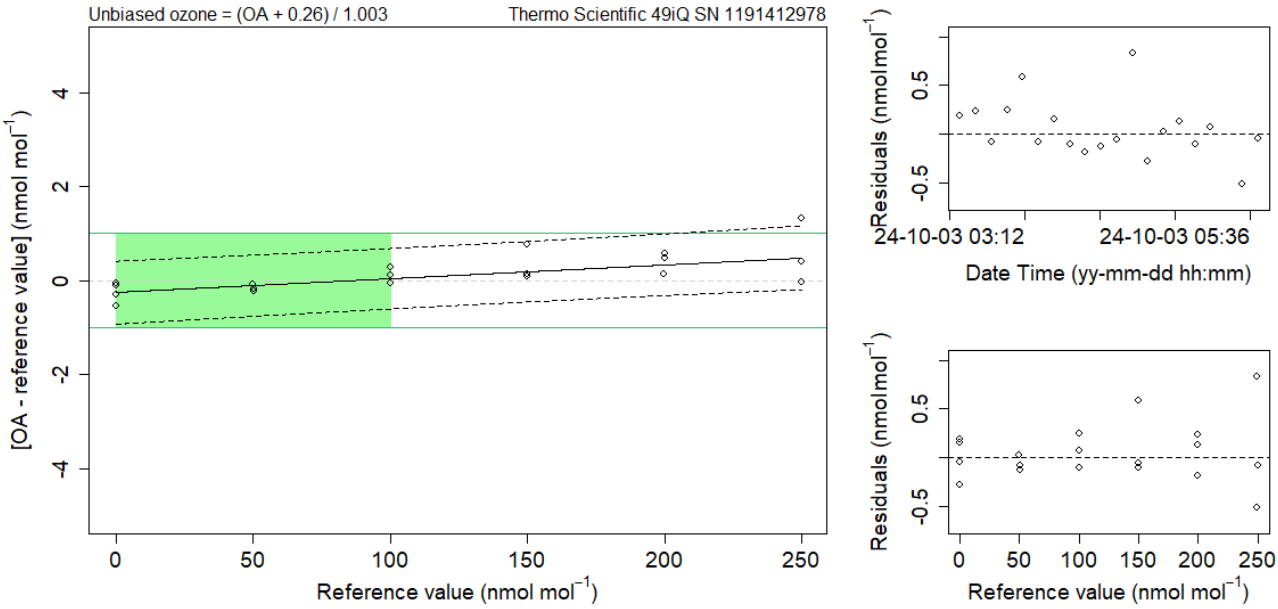


Figure 2. *Left: Bias of the BKT ozone analyser (Thermo Scientific 49iQ #1191412978, BKG +0.2 nmol mol^{-1}, COEF 1.027, final comparison) with respect to the SRP as a function of the amount fraction. Each point represents the average of the last 5 one-minute values at a given level. The green area corresponds to the relevant amount fraction range, while the DQOs are indicated with green lines. The dashed lines around the regression lines are the Working-Hotelling 95% confidence bands. Right: Regression residuals of the ozone comparisons as a function of time (top) and amount fraction (bottom).*

The results of the BKT ozone analyser comparisons can be summarised as follows:

The BKT Thermo Scientific 49iQ #1191412978 works correctly. However, the instrument noise is higher than other ozone instruments, especially the previous i-Series instruments.

BKT calibrator Thermo Scientific 49iQ-PS #1191412979 (BKG 0.0 nmol mol^{-1}, COEF 1.000):

Unbiased O_3 amount fraction X_{O3} (nmol mol^{-1}): X_{O3} = ([OC] + 6.12 nmol mol^{-1}) / 0.9717 (5)

Standard uncertainty u_{O3} (nmol mol^{-1}): u_{O3} = sqrt ((0.54 nmol mol^{-1})^2 + 2.06e-05 * X_{O3}^2) (6)

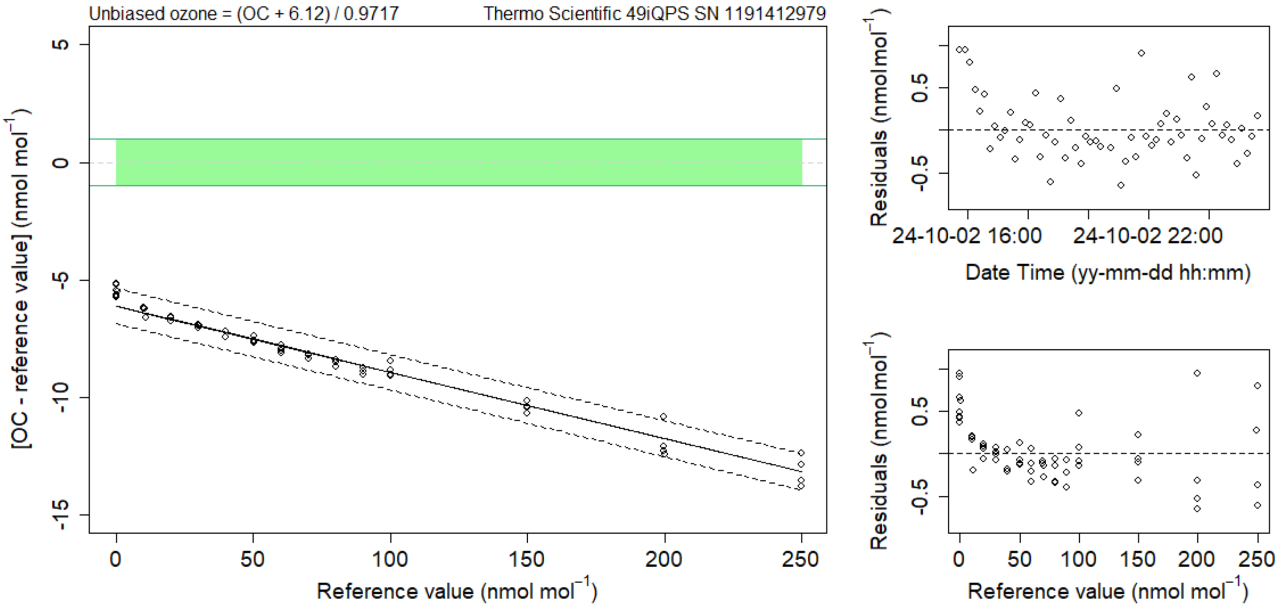


Figure 3. *Left: Bias of the BKT ozone calibrator (Thermo Scientific 49iQ-PS #1191412979, BKG 0.0 nmol mol^{-1}, COEF 1.000) with respect to the SRP as a function of the amount fraction. Each point represents the average of the last 5 one-minute values at a given level. The green area corresponds to the relevant amount fraction range, while the DQOs are indicated with green lines. The dashed lines around the regression lines are the Working-Hotelling 95% confidence bands. Right: Regression residuals of the ozone comparisons as a function of time (top) and amount fraction (bottom).*

The results of the BKT ozone calibrator comparison can be summarised as follows:

The BKT Thermo Scientific 49iQ-PS # 1191412979 ozone calibrator measured low compared to the WCC-Empa reference instrument. A slight non-linearity was also found. The plumbing of this calibrator does not support a straightforward connection to an external ozone reference. In conclusion, the performance of the 49iQ-PS ozone calibrator is significantly inferior to the 49i-PS instrument previously available at BKT.

Recommendation 15 (*, minor, 2025/26)

The Thermo Scientific 49iQ-series ozone analysers and calibrators are inferior to the older 49i-series. The 49i-series is currently still available. For purchases in the near future, 49i series instruments are preferred. If possible, the BKT 49iQ analyser and calibrator should be exchanged for 49i series instruments from stations with less stringent data quality requirements.

Comparisons were also made with the Sorong ozone analyser and calibrator, and the results are summarised below.

Sorong Thermo Scientific 49iQ #12215317647 (BKG +1.1 nmol mol^{-1}, COEF 1.014):

Unbiased O_3 amount fraction X_{O3} (nmol mol^{-1}): X_{O3} = ([OA] + 1.63 nmol mol^{-1}) / 1.0125 (7)

Standard uncertainty u_{O3} (nmol mol^{-1}): u_{O3} = sqrt ((0.54 nmol mol^{-1})^2 + 2.06e-05 * X_{O3}^2) (8)

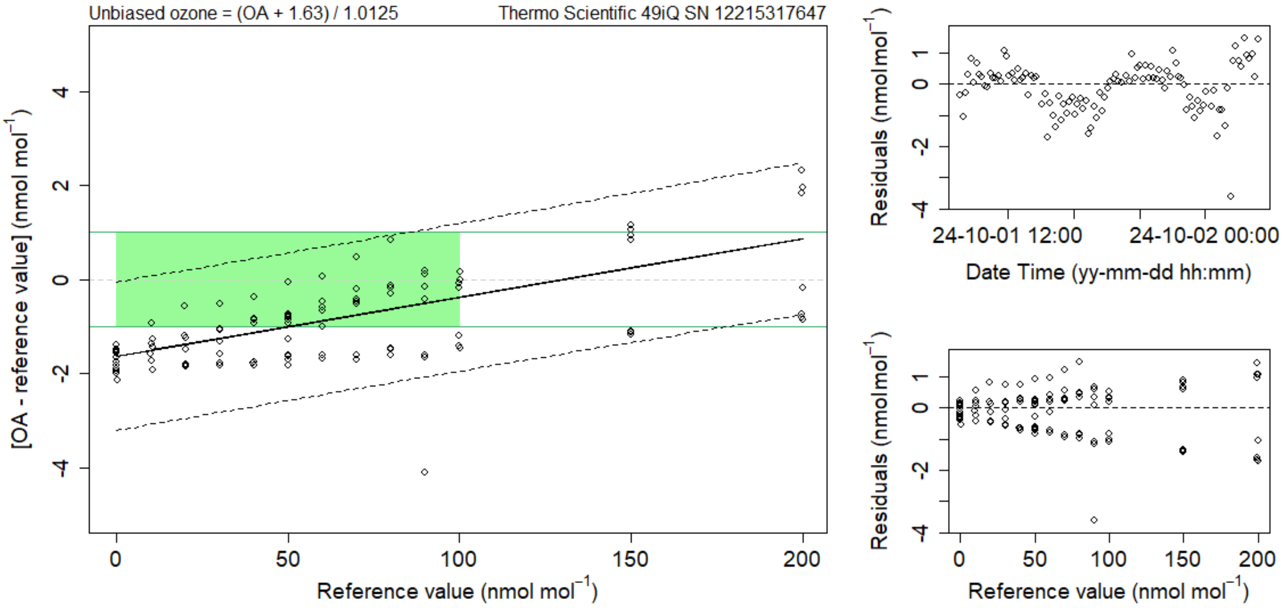


Figure 4. *Left: Bias of the Sorong ozone analyser (Thermo Scientific 49iQ #12215317647, BKG +1.1 nmol mol^{-1}, COEF 1.014) with respect to the SRP as a function of the amount fraction. Each point represents the average of the last 5 one-minute values at a given level. The green area corresponds to the relevant amount fraction range, while the DQOs are indicated with green lines. The dashed lines around the regression lines are the Working-Hotelling 95% confidence bands. Right: Regression residuals of the ozone comparisons as a function of time (top) and amount fraction (bottom).*

The results of the comparisons of the Sorong ozone analyser can be summarised as follows:

The stability of this instrument was poor compared to other analysers. It showed significant drift over time. Similar results were found for other 49iQ analysers. The observed problems are most likely instrument related. The above recommendations for the iQ series apply also to this instrument.

Sorong calibrator Thermo Scientific 49iQ-PS #12215317648 (BKG 0.0 nmol mol^{-1}, COEF 1.000):

Unbiased O_3 amount fraction X_{O3} (nmol mol^{-1}): X_{O3} = ([OC] + 0.18 nmol mol^{-1}) / 0.9915 (9)

Standard uncertainty u_{O3} (nmol mol^{-1}): u_{O3} = sqrt ((0.54 nmol mol^{-1})^2 + 2.06e-05 * X_{O3}^2) (10)

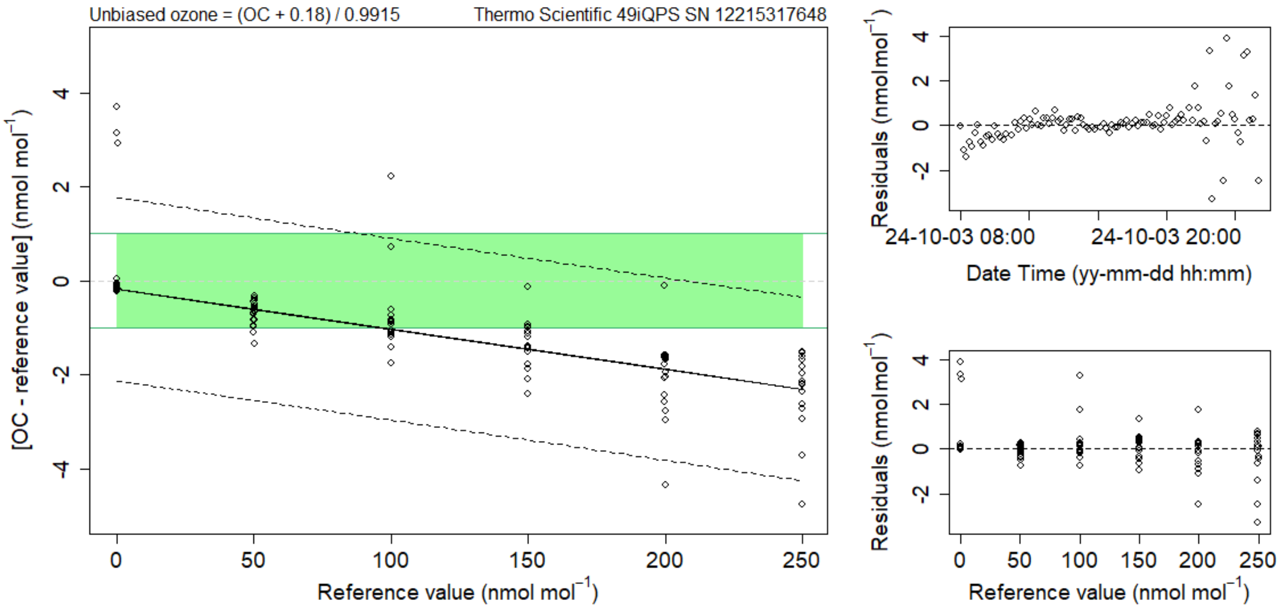


Figure 5. *Left: Bias of the Sorong ozone calibrator (Thermo Scientific 49iQ-PS #12215317648, BKG 0.0 nmol mol^{-1}, COEF 1.000) with respect to the SRP as a function of the amount fraction. Each point represents the average of the last 5 one-minute values at a given level. The green area corresponds to the relevant amount fraction range, while the DQOs are indicated with green lines. The dashed lines around the regression lines are the Working-Hotelling 95% confidence bands. Right: Regression residuals of the ozone comparisons as a function of time (top) and amount fraction (bottom).*

The results of the BKT ozone calibrator comparison can be summarised as follows:

The instrument showed periods of drift and poor stability but was in relatively good agreement with the SRP on average. The COEF setting of the instrument should be increased to 1.008 for better agreement with the WCC-Empa reference. The above comments and recommendation for the 49iQ-series also apply to this calibrator. The instrument has significant stability problems.

3.2 Carbon monoxide measurements

Continuous measurements of CO at BKT started in 2001 and continuous data are available since then.

Instrumentation. BKT is equipped with a Picarro G2401 CRDS analyser and a Picarro 16-Port Distribution Manifold (model A0311) for the calibration of the instrument. The sample air is dried using a Nafion dryer (Perma Pure PD-50T-24MPP).

Standards. Three reference standards from the GAW Central Calibration Laboratory (CCL) are available at BKT. A working standard and a target cylinder are also available. An overview of available standard gases is given in Table 11 in the Appendix.

Calibration. A sequence of ambient air (2880 min) followed by measurement of the target and working standard (15 min each) is repeated 5 times. The three NOAA CCL standards are then measured for 15 min each. Calibrations are performed using the CCL standards and the WS is used to compensate for instrument drift by a Loess fit.

Data acquisition. The internal data acquisition of the CRDS analyser is used and the highest resolution (1-2 s resolution) raw data files are stored. The data is also acquired using a custom-build data acquisition system programmed in Delphi.

Intercomparison (performance audit). The comparison consisted of repeated challenges of the BKT instruments with randomly selected levels of carbon monoxide amount fractions using the WCC-Empa travelling standards.

The following equations characterise the instrument bias and the results are further illustrated in Figure 6 with respect to the WMO/GAW compatibility goals and the extended compatibility goals (WMO, 2024):

Picarro G2401 #3035-CFKADS2294:

Unbiased CO mixing ratio: X_{CO} (nmol mol^{-1}) = (CO + 2.40 nmol mol^{-1}) / 0.9993 (11)

Remaining standard uncertainty: u_{CO} (nmol mol^{-1}) = sqrt ((2.8 nmol mol^{-1})^2 + 1.01e-04 * X_{CO}^2) (12)

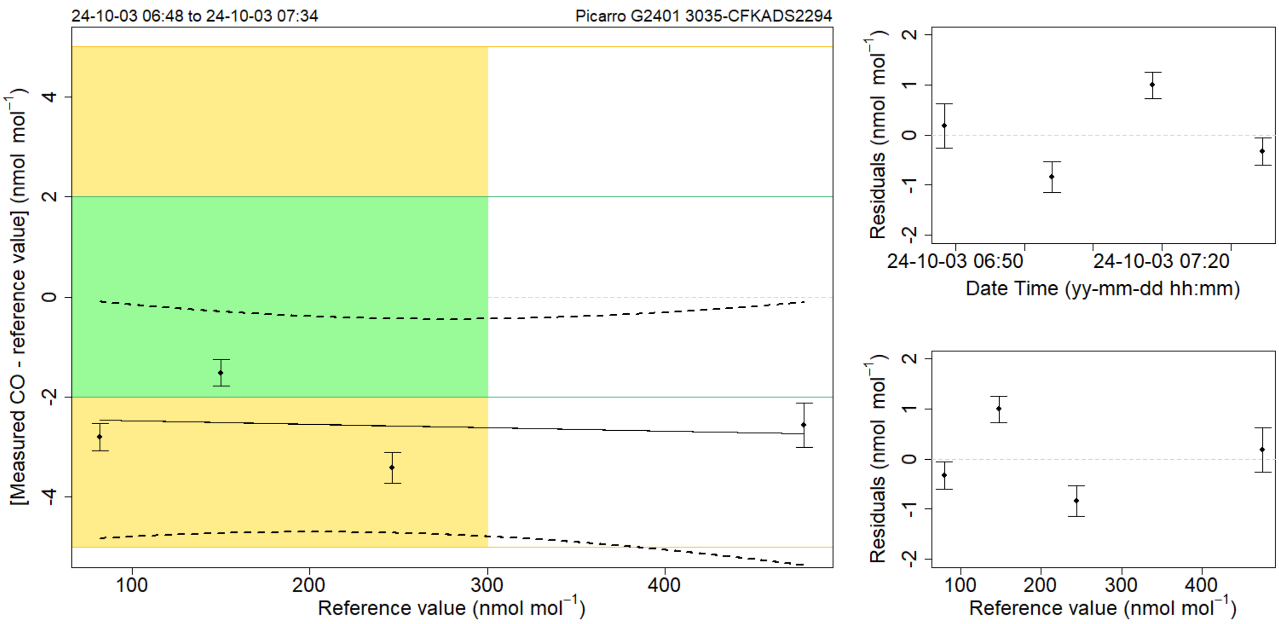


Figure 6. *Left: Bias of the PICARRO G2401 #3035-CFKADS2294 carbon monoxide instrument with respect to the WMO-X2014A reference scale as a function of the amount fraction. Each point represents the average of data at a given level from a specific run. The uncertainty bars show the standard deviation of each measurement point. The green and yellow lines correspond to the WMO compatibility and extended compatibility goals, and the green and yellow areas correspond to the amount fraction range relevant for BKT. The dashed lines around the regression lines are the Working-Hotelling 95% confidence bands. Right: Regression residuals (time dependence and amount fraction dependence).*

The result of the comparison can be summarised as follows:

BKT measurements were about 2.4 nmol mol^{-1} lower compared to WCC-Empa. The difference is most likely to be caused by a small upward drift of the BKT CO calibration standards. CO drift is a known problem with CO standards. Regular re-calibrations at the CCL and the application of a drift correction are therefore necessary to compensate for the drift.

Recommendation 16 (, important, 2025/26)**
It is recommended that the BKT laboratory standards are returned to the CCL for a recalibration. Alternatively, the purchase of additional standards from the CCL at regular intervals (e.g. one standard gas per year) should be considered.

3.3 Methane measurements

Continuous measurements of CH_4 at BKT started in 2009 with a Picarro G1301 CH_4/CO_2 analyser. This instrument broke down in 2014 and was replaced by a Picarro G2401 in October 2018. Continuous CH_4 data are available from 2009 to 2014 and since January 2019.

Instrumentation, standards, calibration and data acquisition. See CO.

Intercomparison (performance audit). The comparison consisted of repeated challenges of the BKT instrument with randomly selected CH_4 levels from travelling standards.

The following equation characterises bias of the instrument. The results are further illustrated in Figure 7 with respect to the relevant amount fraction range and the WMO/GAW compatibility goals and the extended compatibility goals (WMO, 2024).

Picarro G2401 #3035-CFKADS2294:

Unbiased CH_4 mixing ratio: X_{CH4} (nmol mol^{-1}) = (CH_4 – 1.84 nmol mol^{-1}) / 0.9992 (13)

Remaining standard uncertainty: u_{CH4} (nmol mol^{-1}) = sqrt ((0.36 nmol mol^{-1})^2+ 1.30e-07 * X_{CH4}^2) (14)

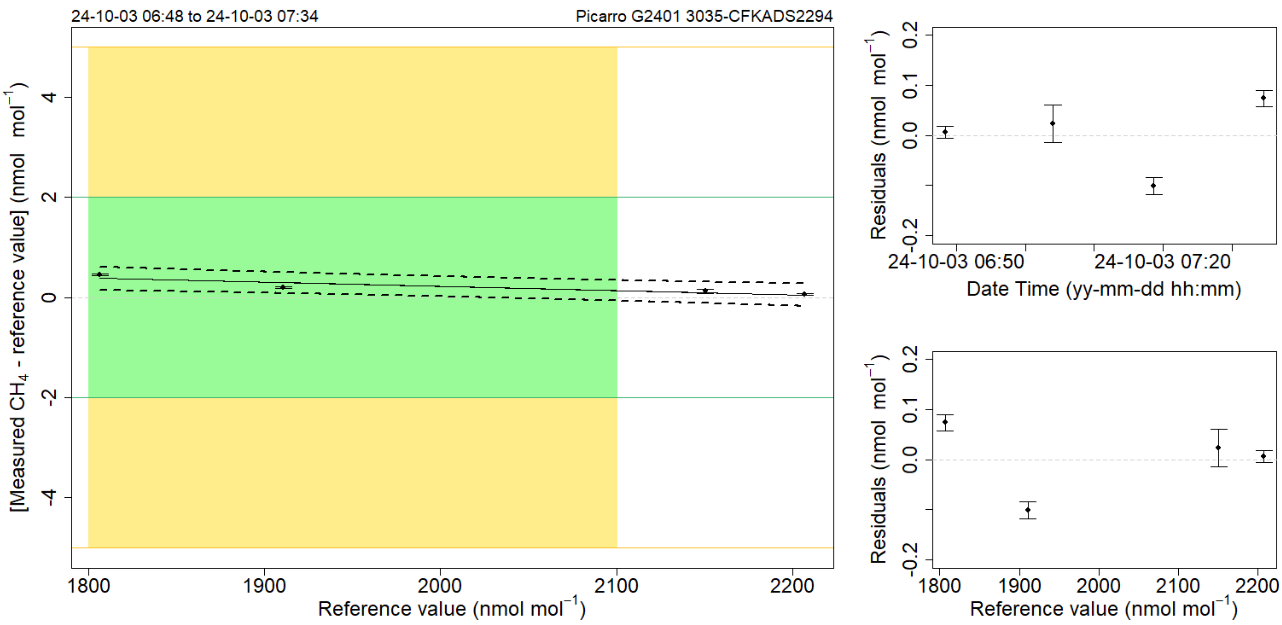


Figure 7. *Left: Bias of the Picarro G2401 #3035-CFKADS2294 instrument with respect to the WMO-X2004A CH_4 reference scale as a function of the amount fraction. Each point represents the average of data at a given level from a specific run. The uncertainty bars show the standard deviation of individual measurement points. The green and yellow lines correspond to the WMO compatibility and extended compatibility goals, and the green and yellow areas correspond to the amount fraction range relevant for BKT. The dashed lines around the regression lines are the Working-Hotelling 95% confidence bands. Right: Regression residuals (time dependence and amount fraction dependence).*

The result of the comparison can be summarised as follows:

Excellent agreement, well within the WMO/GAW network compatibility goal, was found in the relevant range of amount fractions. The good results indicate that the whole system, including calibration procedures and standard gases, is fully adequate and no further action is required at this time.

3.4 Carbon dioxide measurements

Continuous measurements of CO_2 at BKT started in 2009 with a Picarro G1301 CH_4/CO_2 analyser. This instrument broke down in 2014 and was replaced by a Picarro G2401 in October 2018. Continuous CO_2 data are available from 2009 to 2014 and since January 2019.

Instrumentation, standards, calibration and data acquisition. See CO.

Intercomparison (performance audit). The comparison consisted of repeated challenges of the BKT instrument with randomly selected CO_2 levels from travelling standards.

The following equations characterise the instrument bias. The result is further illustrated in Figure 8 with respect to the relevant amount fraction range and the WMO/GAW compatibility goals and the extended compatibility goals (WMO, 2024).

Picarro G2401 #3035-CFKADS2294:

Unbiased CO_2 mixing ratio: X_{CO2} (µmol mol^{-1}) = (CO_2 – 1.47 µmol mol^{-1}) / 0.9971 (15)

Remaining standard uncertainty: u_{CO2} (µmol mol^{-1}) = sqrt ((0.11 µmol mol^{-1})^2 + 3.28e-8 * $X_{CO2}{}^2$) (16)

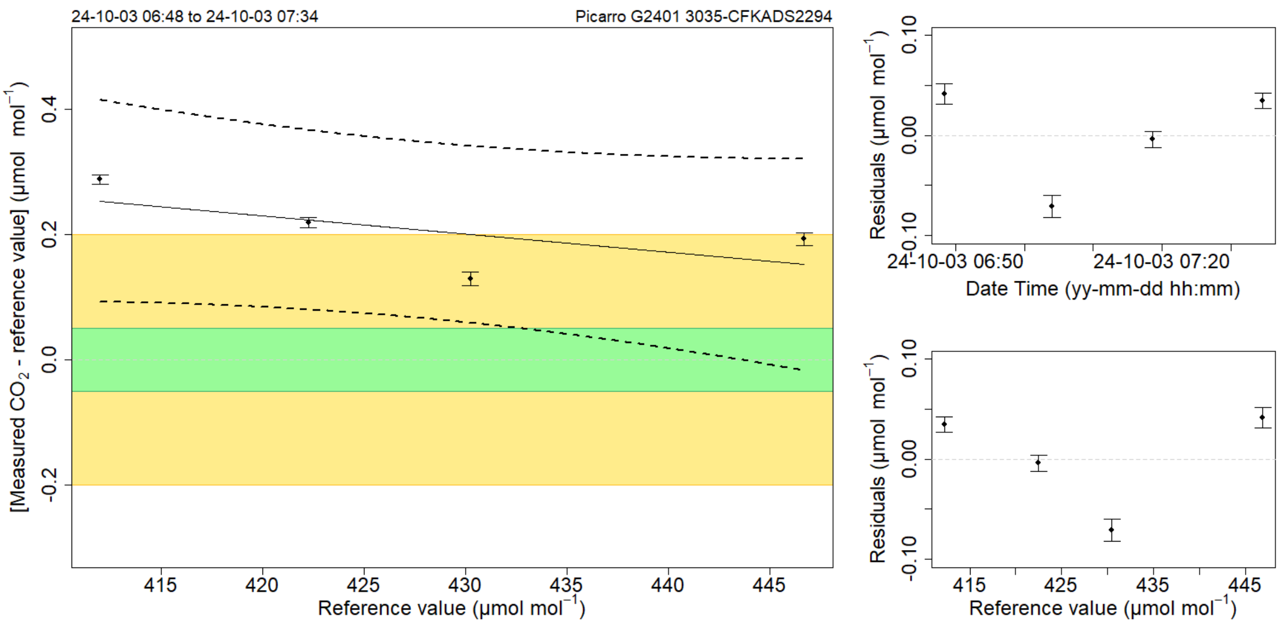


Figure 8. *Left: Bias of the Picarro G2401 #3035-CFKADS2294 CO_2 instrument with respect to the WMO-X2019 reference scale as a function of the amount fraction. Each point represents the average of data at a given level from a specific run. The uncertainty bars show the standard deviation of each measurement point. The green and yellow lines correspond to the WMO compatibility and extended compatibility goals, and the green and yellow areas correspond to the amount fraction range relevant for BKT. The dashed lines around the regression lines are the Working-Hotelling 95% confidence bands. Right: Regression residuals (time dependence and amount fraction dependence).*

The result of the comparison can be summarised as follows:

The result of the BKT CO_2 comparison was slightly exceeding the WMO GAW network compatibility goals. This could be due to the remaining bias in the amount fraction assignments of the CCL standards. The standards were originally calibrated to the WMO-X2007 CO_2 scale in 2018. For the current audit, the values from the CCL website were used. These values are slightly higher than the average correction based on the scale conversion function provided by NOAA (Hall et al., 2021), which explains about 0.05 µmol mol^{-1} of the observed difference. Therefore, a recalibration of the BKT laboratory standards should be considered as recommended above.

4 Comparison of BKT performance audit results with other stations

This section compares the results of the BKT performance audit with other station audits conducted by WCC-Empa. The method used to relate the results to other audits was developed and described by Zellweger et al. (2016) for CO_2 and CH_4, and Zellweger et al. (2019) for CO, but is also applicable to other compounds. Essentially, the bias in the middle of the relevant amount fraction range is plotted against the slope of the linear regression analysis of the performance audit. The relevant amount fraction ranges are taken from the recommendation of the GGMT-2019 meeting (WMO, 2024) for CO_2, CH_4, and CO and refer to conditions commonly found in unpolluted air masses. For surface ozone, the amount fraction range of 0--100 nmol mol^{-1} was chosen as this covers most of the natural ozone abundance in the troposphere. This results in well-defined bias/slope combinations that are acceptable for meeting the WMO/GAW compatibility network goals in a given amount fraction range. Figure 9 shows the bias vs. slope of the WCC-Empa performance audits for O_3, CO, CH_4 and CO_2. The grey dots show all comparisons made during the WCC-Empa audits for the main station analysers but exclude cases with known instrumental problems. Where an adjustment was made during an audit, only the final comparison is shown. The results of the current BKT audit are shown as coloured dots in Figure 9.

For the BKT surface ozone analyser, the result was within the DQOs after adjustment of the calibration settings. The BKT ozone calibrator read significantly lower than the WCC-Empa reference instrument.

The Southern Hemisphere (SH) WMO/GAW network compatibility goals were met for CH_4. CO was within the extended network compatibility goal. The CO_2. comparisons slightly exceeded the extended WMO/GAW network compatibility goals.

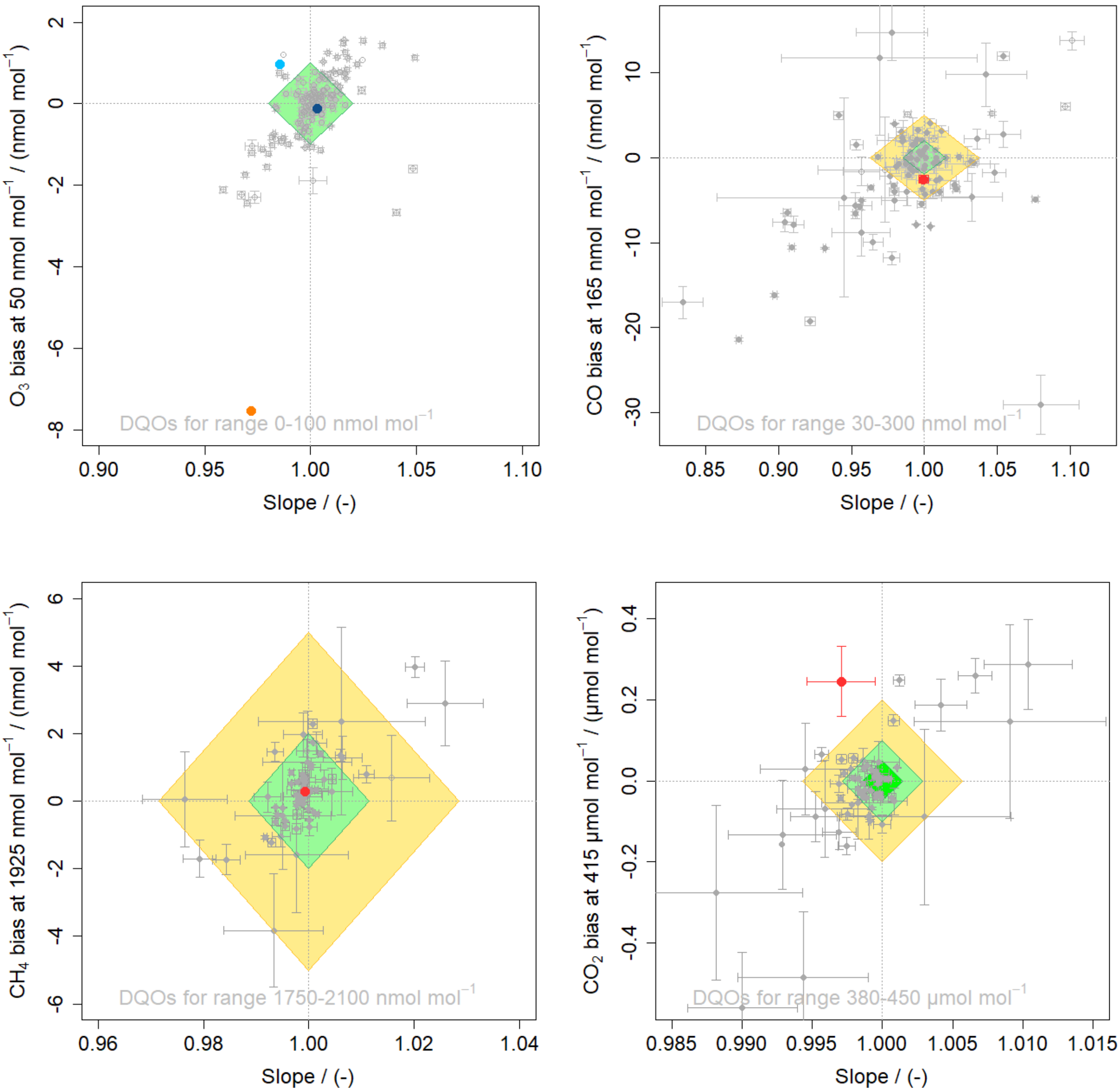


Figure 9. *O_3 (top left), CO (top right), CH_4 (bottom left) and CO_2 (bottom right) bias in the middle of the relevant amount fraction range compared to the slope of the WCC-Empa performance audits. The grey dots correspond to previous performance audits by WCC-Empa at different stations, while the coloured dots show BKT results (light blue: BKT Thermo 49iQ, initial settings, dark blue: BKT Thermo 49i, final settings, orange: BKT Thermo 49iQ-PS, red: Picarro G2401). Filled symbols refer to a comparison with the same calibration scale at the station and at the WCC, while open symbols indicate a scale difference. The uncertainty bars refer to the standard uncertainty. The coloured areas correspond to the WMO/GAW compatibility goals (green, shades for southern and northern hemisphere for CO_2) and the extended compatibility goals (yellow).*

5 Parallel measurements of ambient air

The audit included parallel measurements of CO_2, CH_4 and CO using the Sorong Picarro G2401 #617-CFKADS2001 as the travelling instrument (TI). The Sorong instrument was used because the WCC-Empa travelling instrument failed during the audit. The BKT CRDS instrument was compared with the TI between 4 and 22 October 2024. The TI was connected to an independent inlet line leading to the same inlet location as the BKT analyser. The TI sampled air in the following sequence: 3210 min of ambient air from the independent inlet, followed by 75 min measurement of three standard gases, each for 25 min. The sample air was dried using a Nafion dryer (Perma Pure model PD-50T-12MPS) in reflux mode with the Picarro pump for the vacuum in the purge air stream. To account for the residual effect of water vapour, the internal Picarro correction function (Rella et al., 2013; Zellweger et al., 2012) was used for the CO_2 and CH_4 data of the TI. Details of the TI calibration are given in the Appendix. The results of the ambient air comparison are presented below. The BKT data were processed by BMKG.

Figures 10 to 12 show the comparison of hourly CO, CH_4 and CO_2 measurements between the TI and the BKT instruments. The hourly averages were calculated on the basis of 1 minute data with simultaneous data availability from the BKT station analyser and the TI.

The results of the ambient air comparison can be summarised as follows:

5.1 Carbon monoxide

BKT ambient air measurements were approximately 4.4 nmol mol^{-1} lower than the TI. This is slightly more than for the TS comparison. For further improvement, a drift correction based on the recalibration of BKT laboratory standards or an alternative calibration approach using zero air and a standard with a high CO amount fraction (> 1 µmol mol^{-1}) should be implemented.

5.2 Methane

Good agreement within the WMO/GAW network compatibility goals was found between the TI and the BKT instrument, confirming the results of the travelling standard comparisons. Temporal variability was well captured by both instruments.

5.3 Carbon dioxide

The agreement between the TI and BKT instrument was within the extended WMO/GAW network compatibility goal (median -0.14 µmol mol^{-1}). This result differs from the TS comparison, where the BKT reading was slightly higher. However, the differences are small and could be caused by slightly different air intake locations of the two inlet systems.

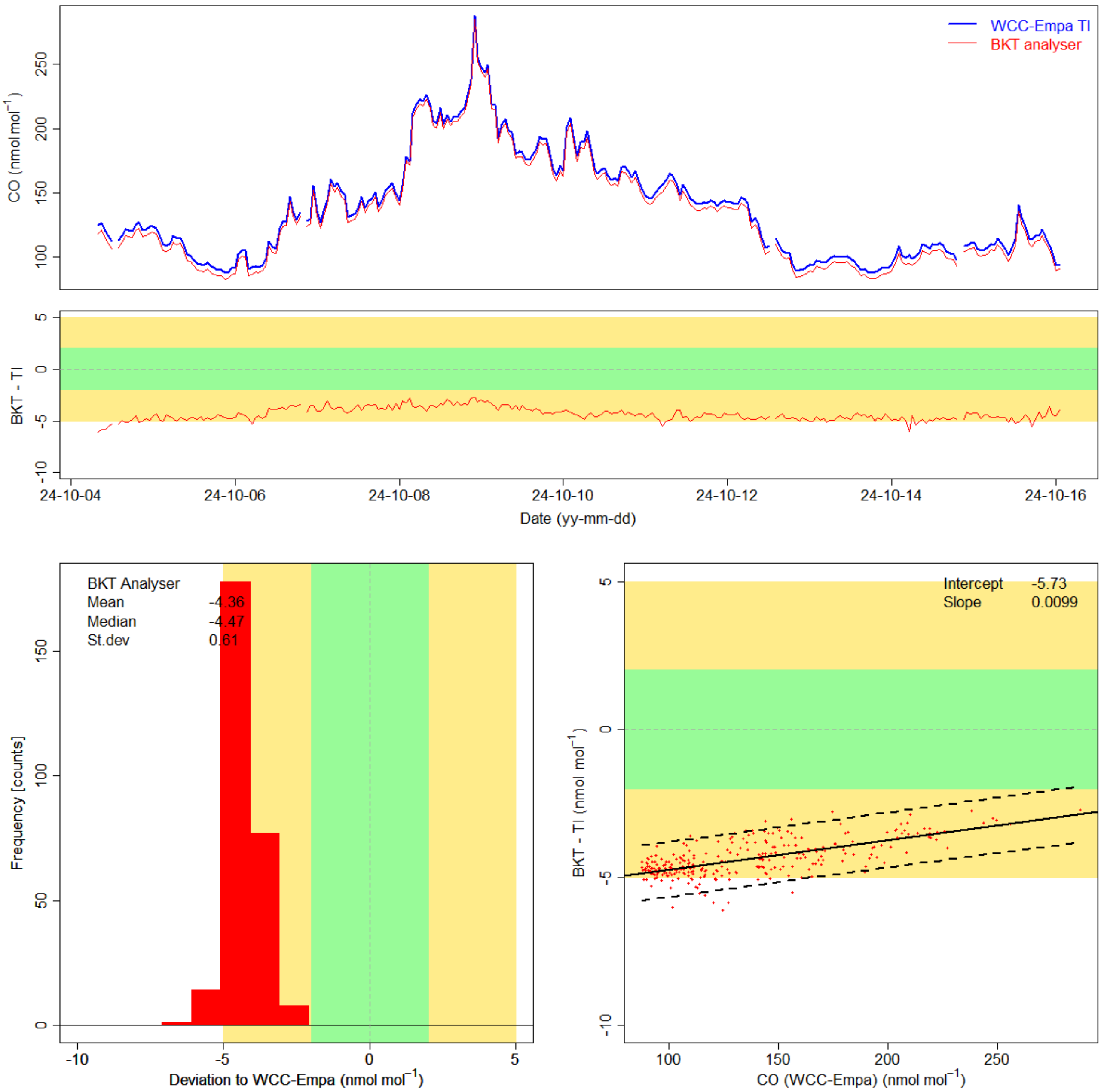


Figure 10. *Top: Comparison of the Picarro G2401 #3035-CFKADS2294 with the travelling instrument for CO. Time series based on hourly data and the difference between the station instrument and the TI are shown. Bottom left: CO deviation histograms for the Picarro G2401 #3035-CFKADS2294 analyser compared to the WCC-Empa TI. Bottom right: BKT instrument bias as a function of the CO amount fraction. The coloured areas correspond to the WMO/GAW compatibility (green) and extended compatibility (yellow) goals.*

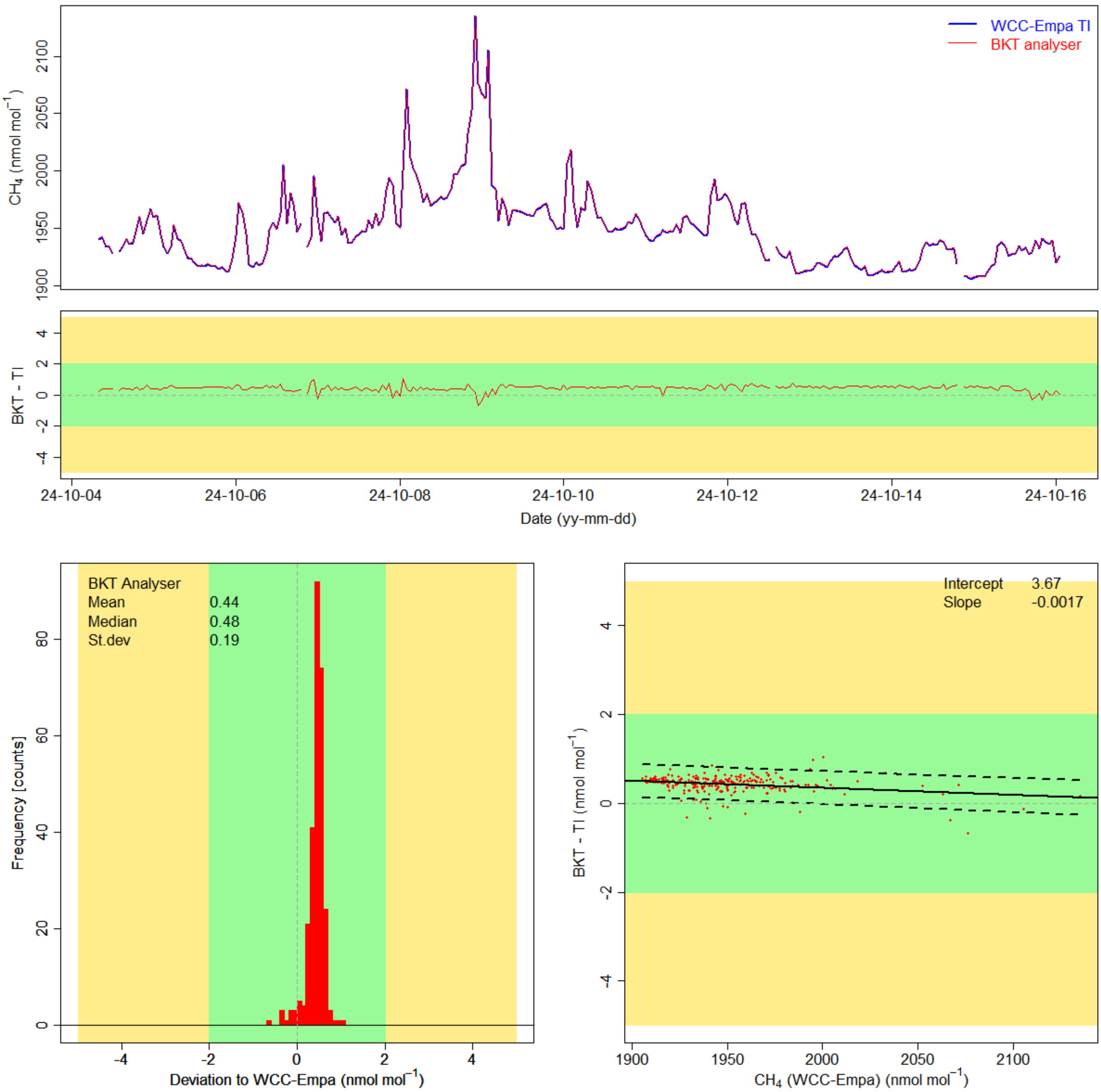


Figure 11. *Top: Comparison of the G2401 #3035-CFKADS2294 analyser (main instrument) with the WCC-Empa travelling instrument for CH_4. Time series based on hourly data and the difference between the station instrument and the TI are shown. Bottom left: CH_4 deviation histograms for the G2401 #3035-CFKADS2294 analyser compared to the WCC-Empa TI. Bottom right: BKT instrument bias as a function of the CH_4 amount fraction. The coloured areas correspond to the WMO/GAW compatibility (green) and extended compatibility (yellow) goals.*

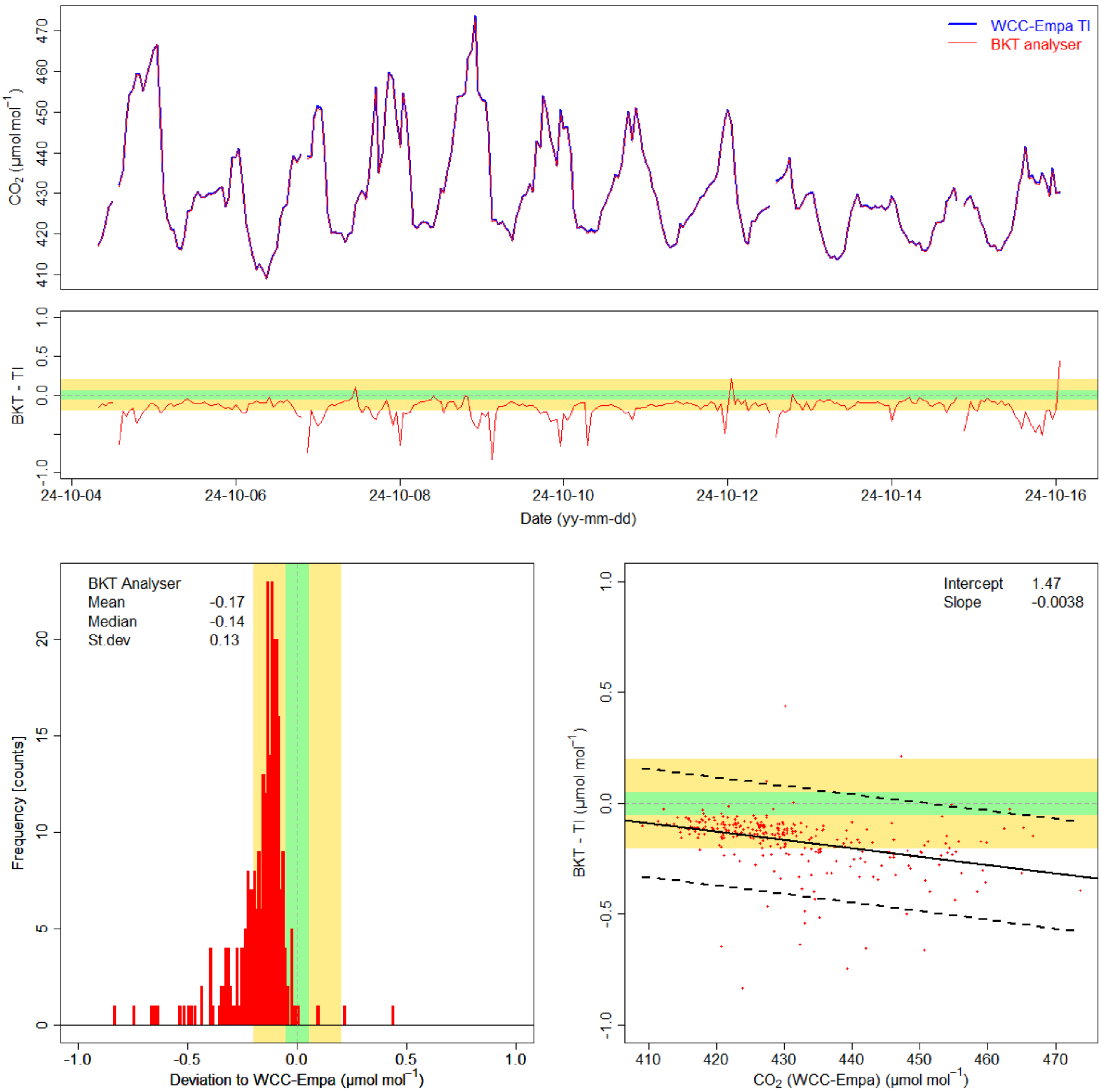


Figure 12. *Top: Comparison of the G2401 #3035-CFKADS2294 analyser (main instrument) with the WCC-Empa travelling instrument for CO_2. Time series based on hourly data and the difference between the station instrument and the TI are shown. Bottom left: CO_2 deviation histograms for the Picarro G2401 #3035-CFKADS2294 analyser compared to the WCC-Empa TI. Bottom right: BKT instrument bias as a function of the CH_4 amount fraction. The coloured areas correspond to the WMO/GAW compatibility (green) and extended compatibility (yellow) goals.*

6 Conclusions

The Bukit Kototabang GAW global station provides an excellent infrastructure for long-term continuous observations in all WMO/GAW focus areas, as well as for research projects. BKT contributes significantly to the GAW programme by providing observations in a data-poor region of the world. Given the unique and long-term nature of the measurements, continued technical and financial support from BMKG headquarters is essential for the sustainable operation of the station. The financial support should allow for short response times in case of technical problems. In addition, the skills of the station staff need to be strengthened, both technically and scientifically. Collaboration with external partners, both national and international, should be continued and intensified.

The continuation of the Bukit Kototabang measurement series is of great importance to GAW. The large number of atmospheric constituents measured in this data-poor region enables research projects and services. Therefore, BMKG should treat GHG and air quality measurements as a top priority, also at its other monitoring sites.

The GHG measurements evaluated were of sufficiently high data quality and mostly met the extended WMO/GAW network compatibility goals in the relevant amount fraction range. The observed bias of CO_2 measurements was slightly larger than the extended WMO/GAW network compatibility goal.

Compared to the last audit by WCC-Empa in 2019, the quality of ozone measurements has decreased due to the poorer performance of the new ozone instruments (both analyser and calibrator). It is recommended to reinstall the previous instruments if they are still available.

Table 1 summarises the results of the performance audit with travelling standards and the ambient air comparison in relation to the WMO/GAW compatibility goals.

Table 1. *Summary of the results of the performance audit and parallel measurement in Bukit Kototabang. A tick mark in the table indicates that the compatibility goal (green) or the extended compatibility goal (orange) was met on average, and ✗ indicates results exceeding the compatibility goals.*

Compound / Instrument	**Range**	**Unit**	**BKT within DQO/eDQO**
O_3 (Thermo Scientific 49iQ #1191412978), BKT, initial settings	0 -100	nmol mol^{-1}	✗
O_3 (Thermo Scientific 49iQ #1191412978), BKT, final settings	0 -100	nmol mol^{-1}	✓
CO (Picarro G2401 #3035-CFKADS2294)	30 - 300	nmol mol^{-1}	✓
CO (Picarro G2401 #3035-CFKADS2294), parallel measurements	NA	nmol mol^{-1}	✓
CH_4 (Picarro G2401 #3035-CFKADS2294)	1750 - 2100	nmol mol^{-1}	✓
CH_4 (Picarro G2401 #3035-CFKADS2294), parallel measurements	NA	nmol mol^{-1}	✓
CO_2 (Picarro G2401 #3035-CFKADS2294)	380 - 450	µmol mol^{-1}	✗
CO_2 (Picarro G2401 #3035-CFKADS2294), parallel measurements	NA	µmol mol^{-1}	✓

7 Summary ranking of the Bukit Kototabang GAW station

System Audit Aspect	Adequacy[#]	Comment
Measurement programme	(4)	Comprehensive programme
Access	(5)	Year-round access
Facilities		
Laboratory and office space	(5)	Adequate, with space for additional research campaigns
Internet access	(5)	High speed connection
Air Conditioning	(5)	Fully adequate system
Power supply	(4)	Mostly reliable and stable, backup UPS, 100 m tower lightning protection required
General Management and Operation		
Organisation	(4)	Well-coordinated and managed, but operates under budgetary constraints
Competence of staff	(4)	Skilled and motivated staff, further training needed
Air Inlet System	(4)	Adequate air inlet systems
Instrumentation		
Ozone (Themo Scientific 49iQ)	(3)	Thermo iQ series has stability issues
CH_4/CO_2/CO Picarro G2401	(5)	State of the art instrumentation
Standards		
O_3 (Themo Scientific 49iQ-PS)	(3)	Thermo iQ series has stability issues
CO, CO_2, CH_4	(5)	CCL standards
Data Management		
Data acquisition	(5)	Fully adequate systems
Data processing	(4)	Qualified staff, appropriate procedures
Data submission to WDCRG	(3)	Timely submission, some data gaps and questionable data
Data submission to WDCGG	(4)	Timely submission, some data flagging issues

[#]0: inadequate thru 5: adequate.

Appendix

A1. List of recommendations

The recommendations made in this report are summarised below, with an indication of their priority, significance and proposed completion date.

#	Recommendation	Priority	Significance	Date
1	Recognising the importance of atmospheric observations in this data-poor region, BMKG should prioritise the operation of BKT and other monitoring stations throughout Indonesia, as well as the scientific analysis of available data series.	Medium	Important	Ongoing
2	BMKG should explore all possibilities for training of station operators and scientists. Participation in GAWTEC and other training courses is highly recommended, and knowledge needs to be shared among BMKG staff.	Medium	Important	Ongoing
3	*BKT data should be used scientifically. This should be done in collaboration between BKT, BMKG Jakarta and other partners.*	High	Critical	Ongoing
4	The lightning protection issues of the 100 m tower need to be addressed.	High	Critical	2025/26
5	An external review of BKT aerosol programme by the World Calibration Centre for Aerosol Physics (WCCAP) is strongly recommended. This review is crucial for ensuring compliance with global standards and enhancing the quality and reliability of our measurements.	High	Critical	2025/26
6	In the event of instrument failure, a budget must be available to resolve instrument problems in a timely manner.	High	Critical	Ongoing
7	It is recommended that GAWSIS is updated annually or whenever there are major changes. Some of the information reviewed needs to be updated.	Medium	Important	Ongoing
8	Most data have been submitted with a delay of less than one year. However, some ozone data are not yet available from the WDCRG. It is recommended to submit O3 data for the period from 2019/20 as soon as the final quality control has been completed.	Medium	Important	2025
9	Ozone data for 1996 – 2007 are not accessible via the WDCRG. It is recommended to resubmit data for this period.	Low	Minor	2025
10	The ozone time series from 2021 onwards appear to contain invalid data. These datasets need further quality control and must be withdrawn in the meantime.	High	Critical	2025
11	It is recommended to resubmit the BMKG data for CO_2, CH_4 and CO with a consistent flagging for valid background and non-background data. In addition, the CO2 data should be converted to the WMO-X2019 CO_2 scale when resubmitted.	Medium	Important	2025
12	It is recommended that measurements be concentrated on the new 100 m tower on the highest level and that the lower levels be used only occasionally. The highest level will be least affected by the surrounding vegetation.	Medium	Important	2025/26
13	The ozone inlet system, including the Erlenmeyer moisture traps, need to be checked for ozone loss.	Medium	Important	2025

#	Recommendation	Priority	Significance	Date
14	Thermo needs to be contacted and questioned about the poor performance of the instrument, and the instrument should be returned to Thermo for corrective action.	Medium	Important	2025
15	The Thermo Scientific 49iQ-series ozone analysers and calibrators are inferior to the older 49i-series. The 49i-series is currently still available. For purchases in the near future, 49i series instruments are preferred. If possible, the BKT 49iQ analyser and calibrator should be exchanged for 49i series instruments from stations with less stringent data quality requirements.	Low	Minor	2025/26
16	It is recommended that the BKT laboratory standards are returned to the CCL for a recalibration. Alternatively, the purchase of additional standards from the CCL at regular intervals (e.g. one standard gas per year) should be considered.	Medium	Important	2025/26

A2. Data review

The following figures show summary plots of BKT data obtained from WDCRG and WDCGG on 22 November 2024. The plots show time series of hourly data, frequency distribution and diurnal and seasonal variations.

Surface ozone submitted by BMKG:

Three BKT O_3 datasets were available from WDCRG, which are shown in the figures below.

- The first dataset covering the period from 2007 to 2019 looks good at first glance in terms of amount fraction, trend, seasonal and diurnal variation. The data of this set is only available in µg/m^3.
- The second dataset covering the period from 2007 to 2019 looks good at first glance in terms of amount fraction, trend, seasonal and diurnal variation.
- The third dataset covering 2021 and part of 2022 shows three distinctly different periods. While the average ozone level looks good, the variation and amount fraction are different for the three periods.

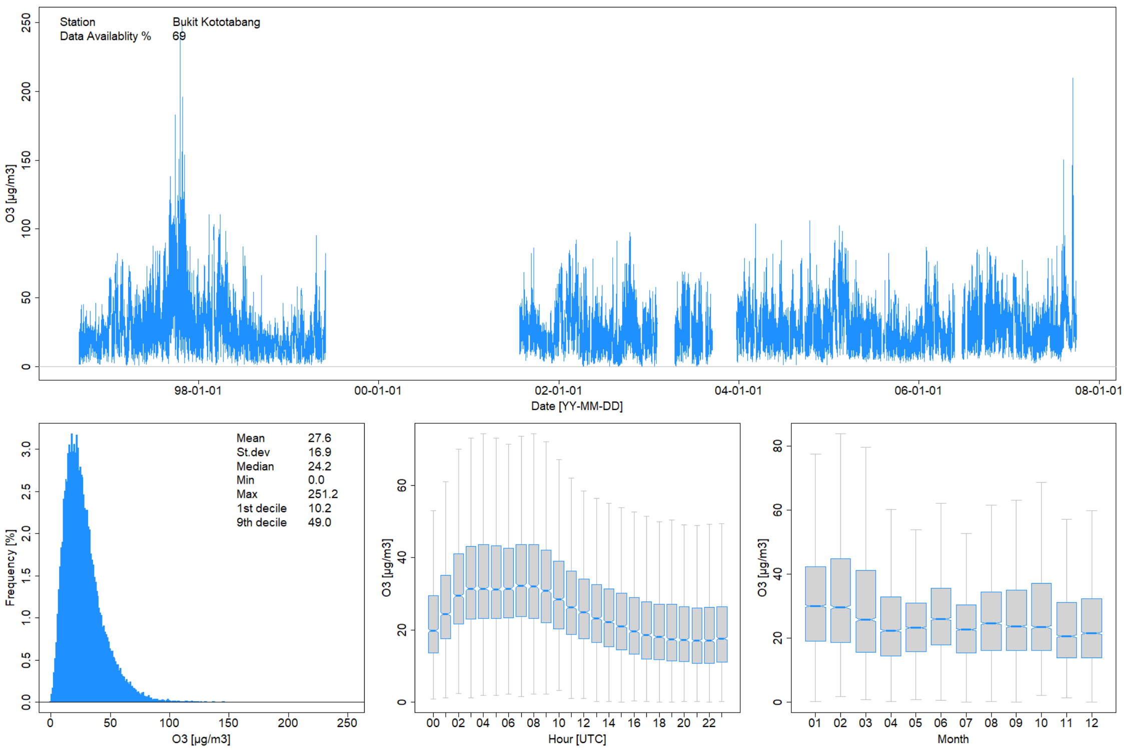


Figure 13. *WDCRG O_3 data for the period 1996 to 2007. Top: Time series, hourly averages. Bottom: Left: frequency distribution, middle: diurnal variation, right: seasonal variation; the horizontal blue line indicates the median and the blue boxes the interquartile range.*

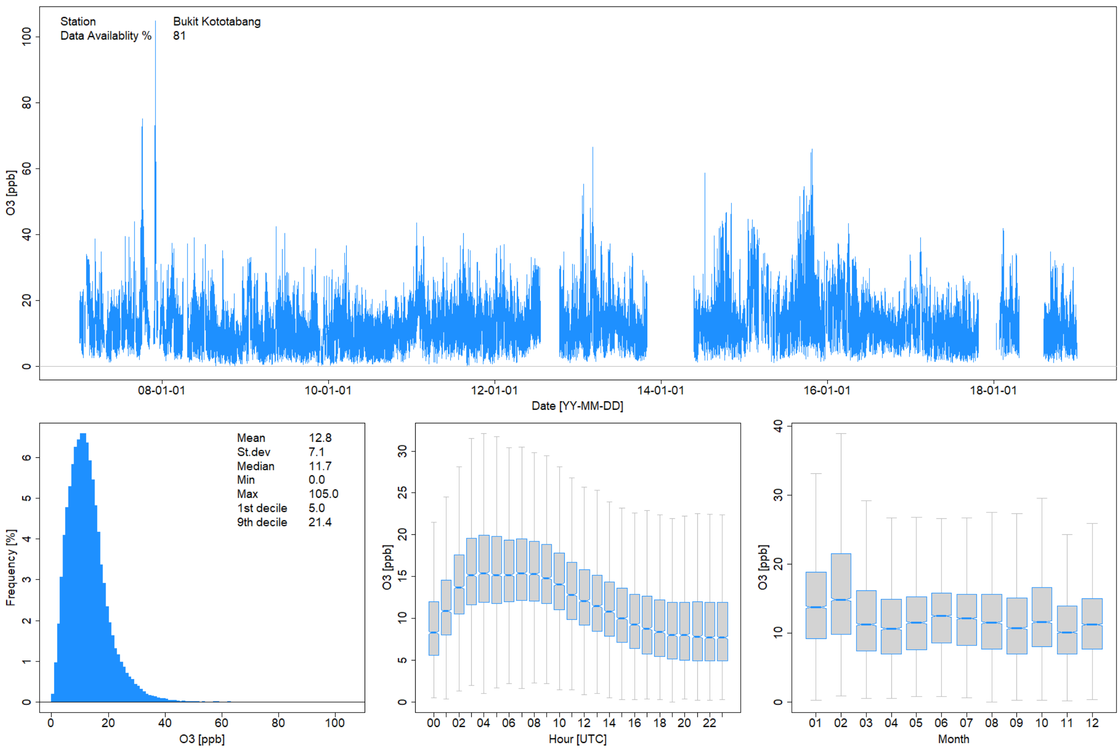


Figure 14. *WDCRG O_3 data for the period 2007 to 2019. Top: Time series, hourly averages. Bottom: Left: frequency distribution, middle: diurnal variation, right: seasonal variation; the horizontal blue line indicates the median and the blue boxes the interquartile range.*

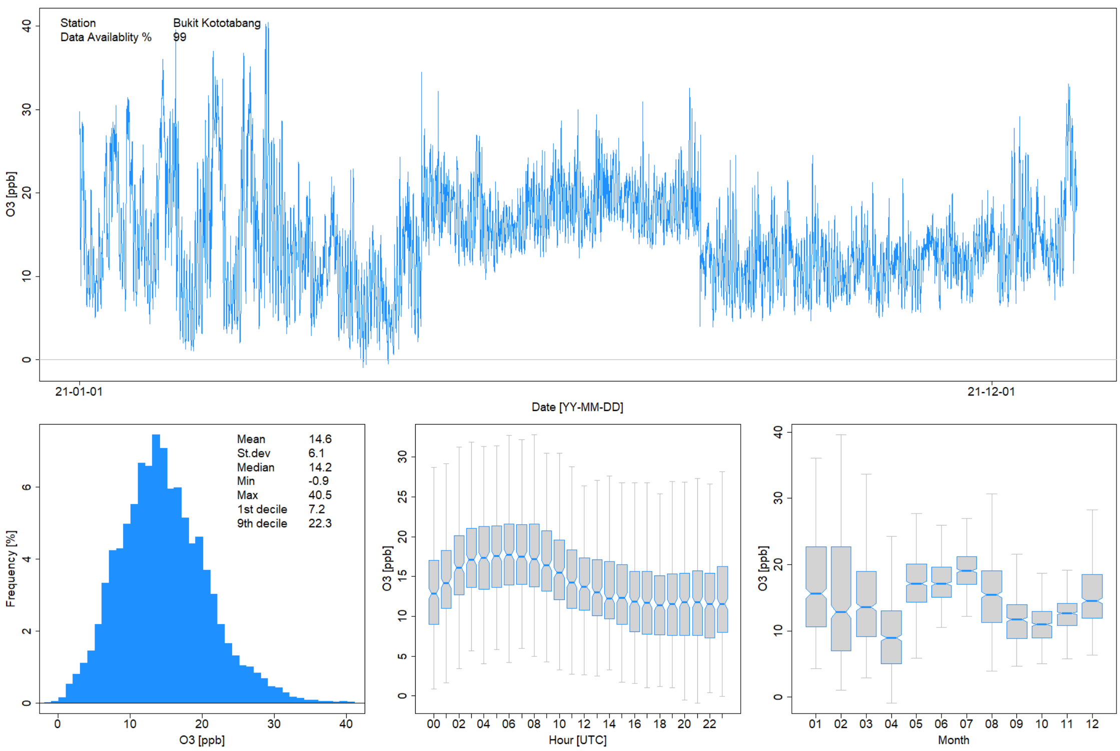


Figure 15. *WDCRG O_3 data set for the period 2021 to 2022. Top: Time series, hourly averages. Bottom: Left: frequency distribution, middle: diurnal variation, right: seasonal variation; the horizontal blue line indicates the median and the blue boxes the interquartile range.*

CO data submitted by BMKG and NOAA:

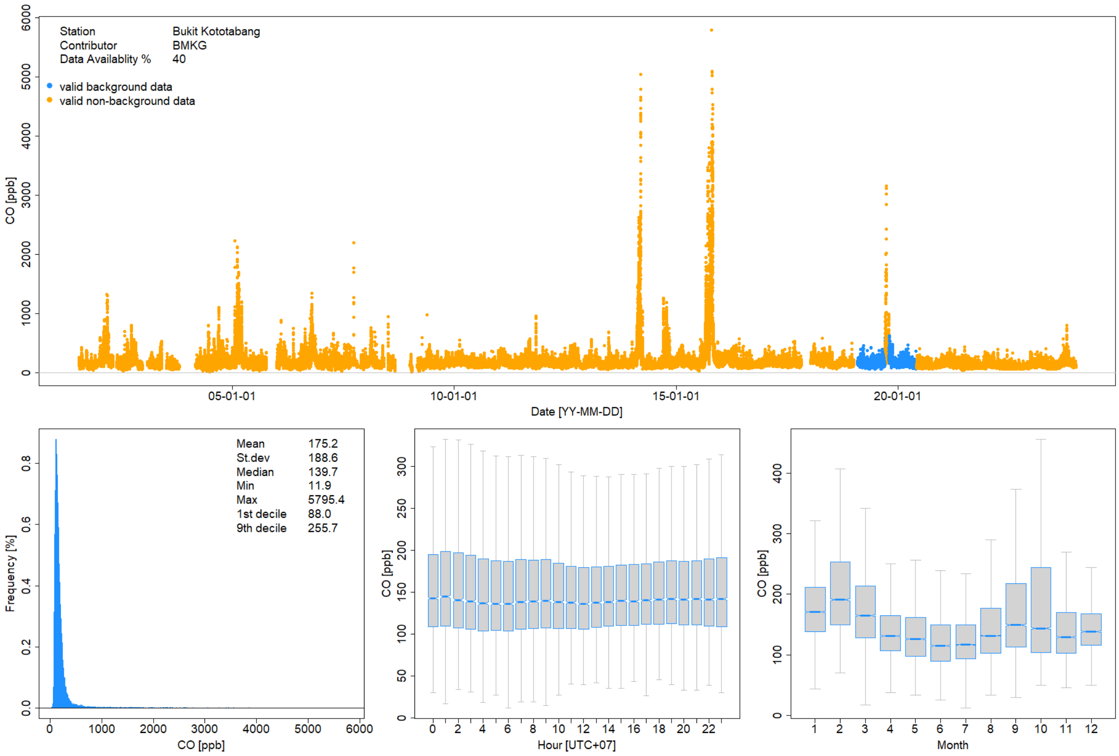


Figure 16. *BKT in-situ CO data accessed from WDCGG. Top: Time series, hourly average. Bottom: Left: frequency distribution. Middle: seasonal variation, right: diurnal variation; the horizontal blue line denotes to the median and the blue boxes the inter-quartile range.*

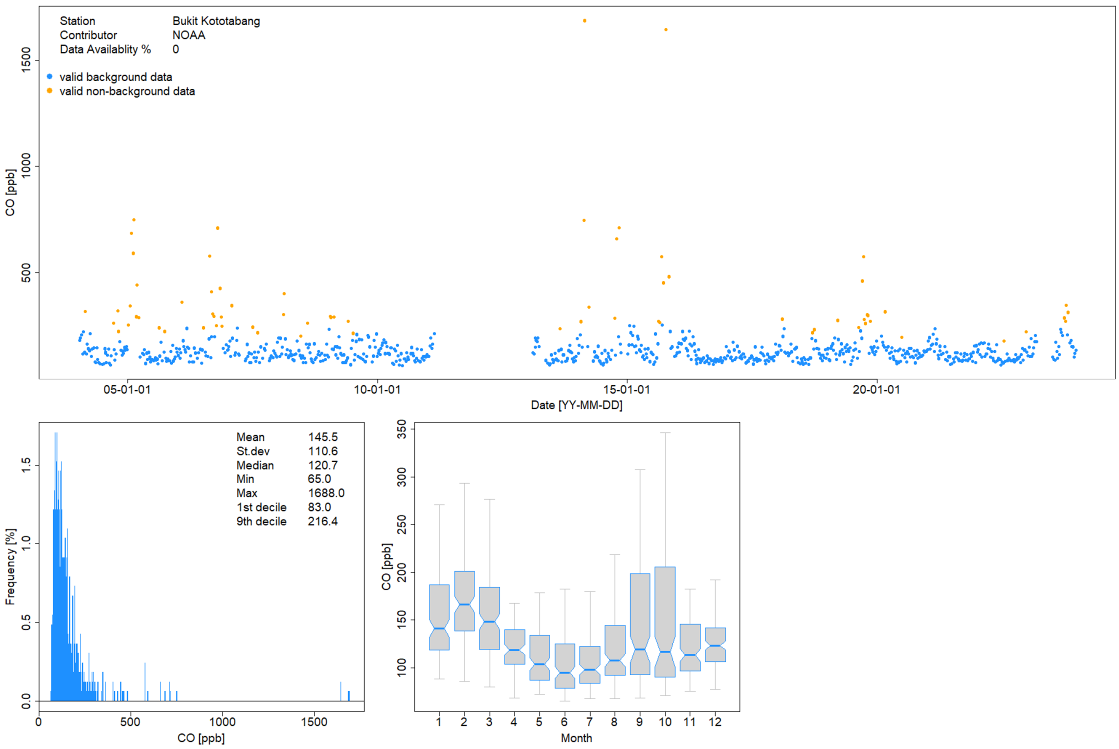


Figure 17. *BKT CO flask data (2004-2023) submitted to WDCGG by NOAA. Top: Time series, hourly averages. Bottom: Left: frequency distribution, right: seasonal variation; the horizontal blue line indicates the median and the blue boxes the interquartile range.*

CH_4 data submitted by BMKG and NOAA:

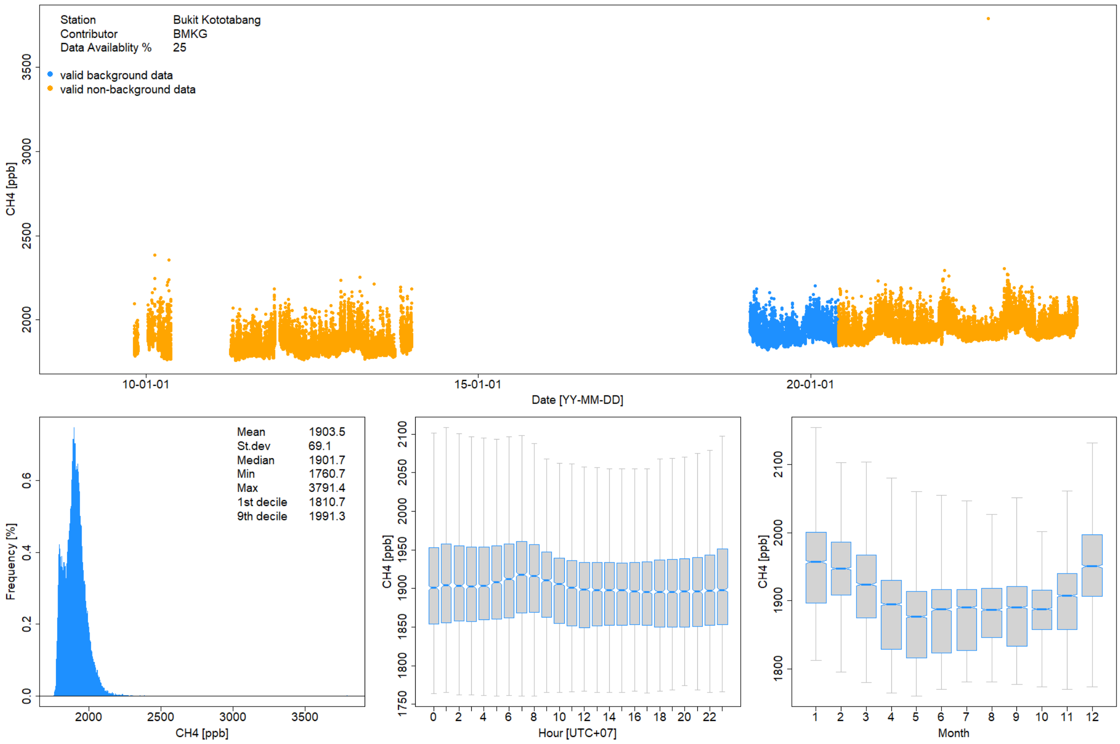


Figure 18. *BKT in-situ CH_4 data accessed from WDCGG. Top: Time series, hourly average. Bottom: Left: frequency distribution. Middle: seasonal variation, right: diurnal variation; the horizontal blue line denotes to the median and the blue boxes the inter-quartile range.*

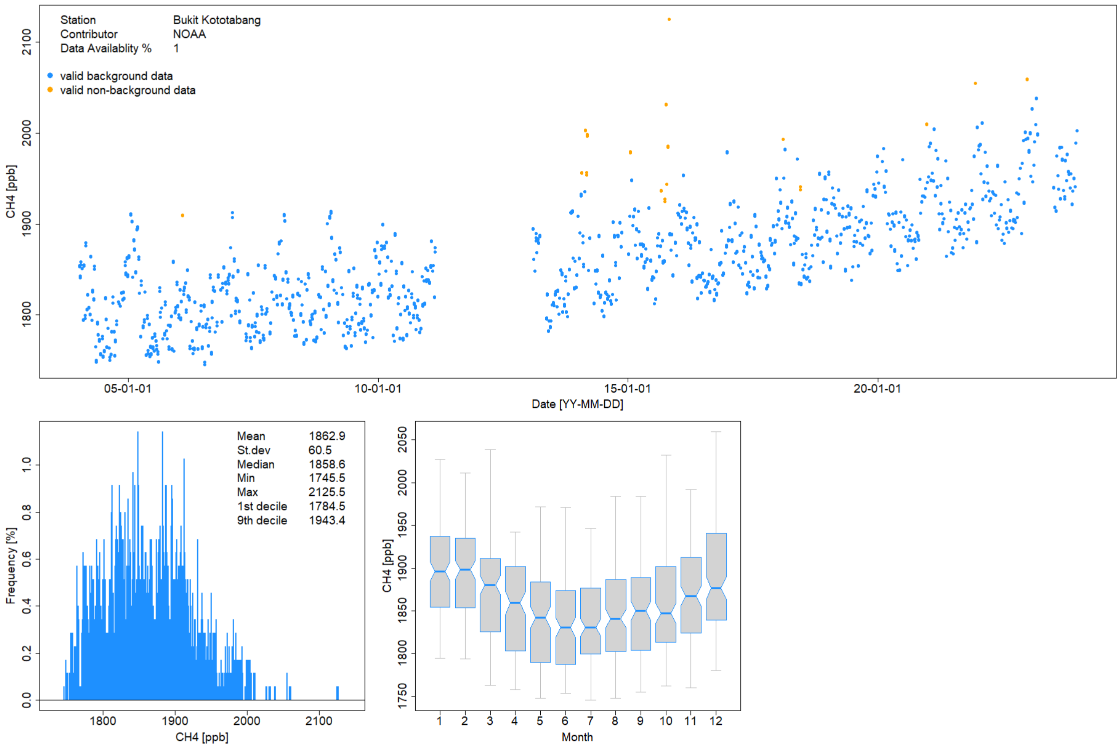


Figure 19. *BKT CH_4 flask data (2004-2023) submitted to WDCGG by NOAA. Top: Time series, hourly averages. Bottom: Left: frequency distribution, right: seasonal variation; the horizontal blue line indicates the median and the blue boxes the interquartile range.*

CO_2 data submitted by BMKG and NOAA:

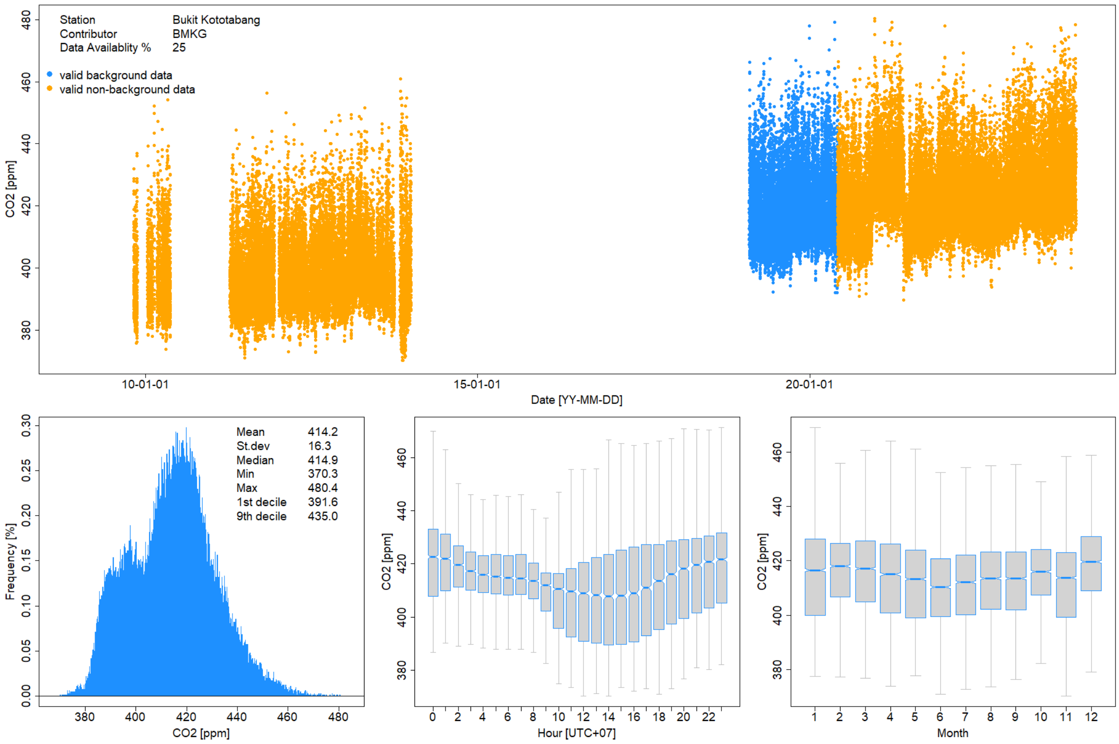


Figure 20. *BKT in-situ CO_2 data accessed from WDCGG. Top: Time series, hourly average. Bottom: Left: frequency distribution. Middle: seasonal variation, right: diurnal variation; the horizontal blue line denotes to the median and the blue boxes the inter-quartile range.*

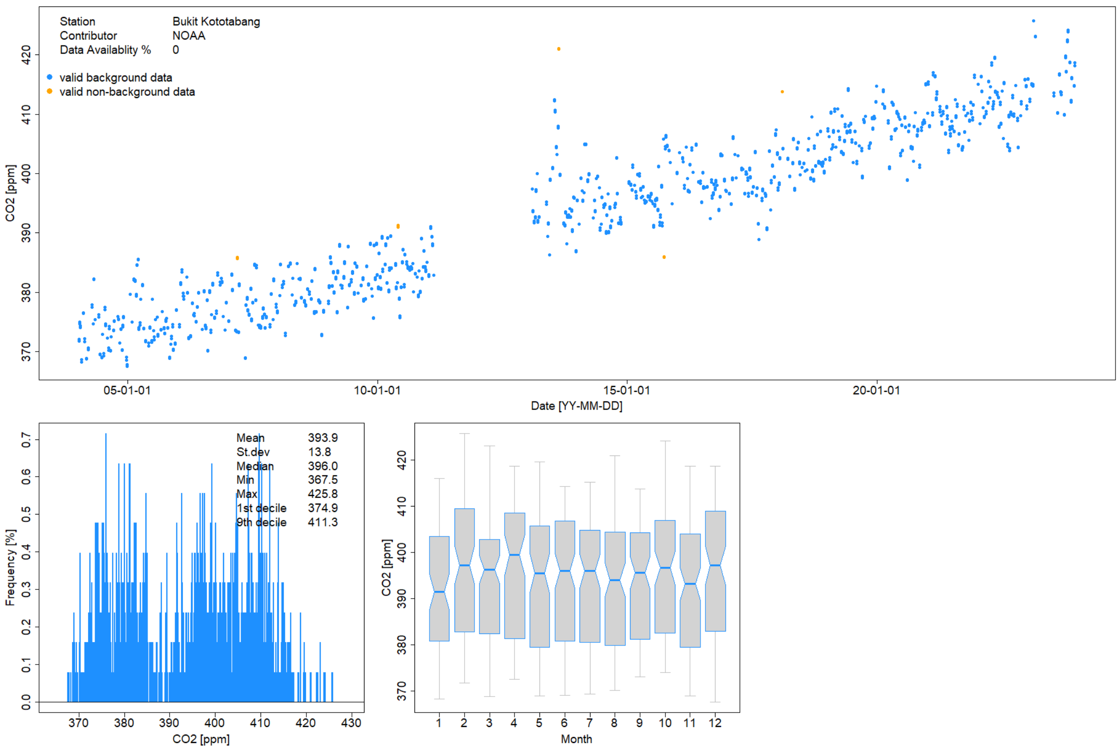


Figure 21. *BKT CO_2 flask data (2004-2023) submitted to WDCGG by NOAA. Top: Time series, hourly averages. Bottom: Left: frequency distribution, right: seasonal variation; the horizontal blue line indicates the median and the blue boxes the interquartile range.*

BMKG GHG and CO data:

- Data set looks mostly sound in terms of mole fraction, trend, seasonal and diurnal variation.
- Flagging has been inconsistent over the years. Valid background data flags were assigned only in 2019 and 2020, all other years have been flagged as valid non-background data.
- BMKG is encouraged to compare the in-situ data with the NOAA flask data.

NOAA GHG and CO flask data:

- The data set looks mostly sound in terms of mole fraction, trend, seasonal and diurnal variations.
- Variability is high compared to other stations in the NOAA flask network due to frequent occurrence of pollution episodes and CO_2 uptake by vegetation at BKT.

A3. Surface ozone comparisons

All procedures were carried out according to the standard operating procedure (WCC-Empa SOP) and included comparisons of the travelling standard with the standard reference photometer at Empa before and after the analyser comparison. The internal ozone generator of the WCC-Empa transfer standard was used to generate a random sequence of ozone levels ranging from 0 to 250 nmol mol^{-1}. Zero air was generated using a custom-built zero air generator (Nafion dryer, Purafil, activated charcoal). The TS was connected to the station analysers and calibrators using approximately 1.5 m of PFA tubing. Table 2 details the experimental setup for the comparisons between the travelling standard and the station instruments. The data used for evaluation were recorded by the WCC-Empa and BKT data acquisition systems.

Table 2. *Experimental details of the ozone comparison.*

Travelling standard (TS)	
Model, S/N	Thermo Scientific 49i-PS #1171430027 (WCC-Empa)
Settings	BKG +0.0, COEF 0.991
Pressure readings (hPa)	Initial: Ambient 919.1; TS 919.5 No adjustments were made
BKT ozone analyser (OA)	
Model, S/N	Thermo Scientific 49iQ #1191412978
Principle	UV absorption
Settings	Initial: BKG -1.8 nmol mol^{-1}, COEF 1.001 Final: BKG 0.2 nmol mol^{-1}, COEF 1.027
Pressure readings (hPa)	Initial: Ambient 915.5; OA 916.1 No adjustments were made
BKT ozone calibrator (OC)	
Model, S/N	Thermo Scientific 49iQ-PS #1191412979
Principle	UV absorption
Settings	BKG +0.0 nmol mol^{-1}, COEF 1.000
Pressure readings (hPa)	Initial: Ambient 915.0; OC 922.1 No adjustments were made
Sorong ozone analyser (OA)	
Model, S/N	Thermo Scientific 49iQ #12215317647
Principle	UV absorption
Settings	BKG +1.1 nmol mol^{-1}, COEF 1.014
Pressure readings (hPa)	Initial: Ambient 915.1; OA 776.1 The pressure sensor was calibrated before the comparisons. Final: Ambient 915.1; OA 915.1
Sorong ozone calibrator (OC)	
Model, S/N	Thermo Scientific 49iQ-PS #12215317648
Principle	UV absorption
Settings	BKG +0.0 nmol mol^{-1}, COEF 1.000
Pressure readings (hPa)	Initial: Ambient 915.7; OC 916.1 No adjustments were made

Results

Each ozone level was measured for ten minutes, and the last five 1-minute averages were aggregated. These aggregates were used to evaluate the comparison. All results are valid for the calibration factors given in Table 2 above. The travelling standard (TS) readings were compensated for bias with respect to the standard reference photometer (SRP) before the evaluation of the ozone analyser values. The same treatment was applied as for the ambient air analysis.

The results of the assessment are shown in the following table (individual measurement points) and are also presented in the Executive Summary.

Table 3. *Comparison of the BKT ozone analyser (OA) Thermo Scientific 49iQ #1191412978 (BKG -1.8 nmol mol^{-1}, COEF 1.001, initial comparison) with the bias corrected WCC-Empa travelling standard (TS).*

Date – Time	TS (nmol mol^{-1})	sdTS (nmol mol^{-1})	OA (nmol mol^{-1})	sdOA (nmol mol^{-1})	OA-TS (nmol mol^{-1})	OA-TS (%)
2024-09-30 23:51	0.19	0.13	1.65	0.50	1.46	NA
2024-10-01 00:01	199.83	0.04	197.89	0.53	-1.94	-0.97
2024-10-01 00:11	50.11	0.07	50.92	0.37	0.81	1.62
2024-10-01 00:21	100.05	0.06	100.03	0.50	-0.02	-0.02
2024-10-01 00:31	149.91	0.10	149.38	0.30	-0.53	-0.35
2024-10-01 00:41	0.05	0.12	2.02	0.22	1.97	3940.00
2024-10-01 00:51	90.00	0.05	90.47	0.59	0.47	NA
2024-10-01 01:01	40.13	0.03	41.32	0.24	1.19	2.97
2024-10-01 01:11	70.07	0.05	70.19	0.28	0.12	0.17
2024-10-01 01:21	30.09	0.04	31.16	0.55	1.07	3.56
2024-10-01 01:31	10.50	0.35	12.23	0.38	1.73	16.48
2024-10-01 01:41	80.05	0.10	80.02	0.53	-0.03	-0.04
2024-10-01 01:51	50.07	0.06	50.89	0.40	0.82	1.64
2024-10-01 02:01	20.08	0.15	21.65	0.44	1.57	7.82
2024-10-01 02:11	60.07	0.07	61.05	0.29	0.98	1.63
2024-10-01 02:21	0.15	0.09	2.26	0.20	2.11	NA
2024-10-01 02:31	199.80	0.08	198.69	0.19	-1.11	-0.56
2024-10-01 02:41	149.93	0.08	149.86	0.11	-0.07	-0.05
2024-10-01 02:51	50.07	0.06	51.16	0.38	1.09	2.18
2024-10-01 03:01	100.02	0.10	100.32	0.23	0.30	0.30
2024-10-01 03:11	0.11	0.17	2.10	0.14	1.99	NA
2024-10-01 03:21	80.02	0.06	80.07	0.58	0.05	0.06
2024-10-01 03:31	20.16	0.08	21.89	0.76	1.73	8.58
2024-10-01 03:41	60.06	0.03	61.17	0.45	1.11	1.85
2024-10-01 03:51	90.01	0.04	90.70	0.36	0.69	0.77
2024-10-01 04:01	30.14	0.10	31.49	0.47	1.35	4.48
2024-10-01 04:11	70.08	0.10	70.79	0.41	0.71	1.01
2024-10-01 04:21	50.09	0.12	50.83	0.31	0.74	1.48
2024-10-01 04:31	10.21	0.16	11.74	0.44	1.53	14.99
2024-10-01 04:51	40.11	0.04	41.20	0.35	1.09	2.72
2024-10-01 05:01	0.12	0.10	2.20	0.42	2.08	NA
2024-10-01 05:11	199.83	0.13	198.53	0.18	-1.30	-0.65
2024-10-01 05:21	50.06	0.09	51.10	0.55	1.04	2.08
2024-10-01 05:31	100.03	0.07	100.13	0.31	0.10	0.10
2024-10-01 05:41	149.88	0.08	149.55	0.48	-0.33	-0.22
2024-10-01 05:51	0.09	0.05	1.39	0.27	1.30	NA
2024-10-01 06:01	90.01	0.05	90.26	0.27	0.25	0.28

Date – Time	TS (nmol mol⁻¹)	sdTS (nmol mol⁻¹)	OA (nmol mol⁻¹)	sdOA (nmol mol⁻¹)	OA-TS (nmol mol⁻¹)	OA-TS (%)
2024-10-01 06:11	40.09	0.13	40.87	0.34	0.78	1.95
2024-10-01 06:21	70.10	0.08	70.88	0.51	0.78	1.11
2024-10-01 06:31	30.13	0.09	31.40	0.30	1.27	4.22
2024-10-01 06:41	10.51	0.35	11.94	0.24	1.43	13.61
2024-10-01 06:51	80.10	0.06	80.24	0.13	0.14	0.17
2024-10-01 07:01	50.10	0.08	50.82	0.41	0.72	1.44
2024-10-01 07:11	20.12	0.06	21.69	0.37	1.57	7.80
2024-10-01 07:21	60.08	0.07	60.43	0.23	0.35	0.58
2024-10-01 07:31	0.18	0.16	2.22	0.45	2.04	NA
2024-10-01 07:41	199.82	0.14	198.57	0.20	-1.25	-0.63
2024-10-01 07:51	149.92	0.03	149.41	0.46	-0.51	-0.34

Table 4. *Comparison of the BKT ozone analyser (OA) Thermo Scientific 49iQ #1191412978 (BKG 0.2 nmol mol^{-1}, COEF 1.027, final comparison) with the bias corrected WCC-Empa travelling standard (TS).*

Date – Time	TS (nmol mol⁻¹)	sdTS (nmol mol⁻¹)	OA (nmol mol⁻¹)	sdOA (nmol mol⁻¹)	OA-TS (nmol mol⁻¹)	OA-TS (%)
2024-10-03 03:19	0.18	0.13	0.11	0.34	-0.07	NA
2024-10-03 03:29	199.84	0.05	200.41	0.77	0.57	0.29
2024-10-03 03:39	249.84	0.06	250.24	0.46	0.40	0.16
2024-10-03 03:49	99.99	0.07	100.28	0.50	0.29	0.29
2024-10-03 03:59	149.92	0.09	150.69	0.22	0.77	0.51
2024-10-03 04:09	50.10	0.05	49.92	0.30	-0.18	-0.36
2024-10-03 04:19	0.16	0.11	0.06	0.27	-0.10	NA
2024-10-03 04:29	99.97	0.07	99.91	0.28	-0.06	-0.06
2024-10-03 04:39	199.79	0.07	199.94	0.19	0.15	0.08
2024-10-03 04:49	50.16	0.07	49.92	0.29	-0.24	-0.48
2024-10-03 04:59	149.97	0.06	150.10	0.45	0.13	0.09
2024-10-03 05:09	249.72	0.10	251.04	0.61	1.32	0.53
2024-10-03 05:19	0.21	0.09	-0.32	0.37	-0.53	NA
2024-10-03 05:29	50.07	0.12	49.98	0.11	-0.09	-0.18
2024-10-03 05:39	199.87	0.04	200.34	0.57	0.47	0.24
2024-10-03 05:49	149.88	0.07	149.96	0.46	0.08	0.05
2024-10-03 05:59	99.97	0.08	100.08	0.31	0.11	0.11
2024-10-03 06:19	249.78	0.04	249.75	0.34	-0.03	-0.01
2024-10-03 06:29	0.19	0.05	-0.12	0.10	-0.31	NA

Table 5. *Comparison of the BKT ozone calibrator (OC) Thermo Scientific 49iQ-PS #1191412979 (BKG +0.0 nmol mol^{-1}, COEF 1.000) with the bias corrected WCC-Empa travelling standard (TS).*

Date – Time	TS (nmol mol^{-1})	sdTS (nmol mol^{-1})	OC (nmol mol^{-1})	sdOC (nmol mol^{-1})	OC-TS (nmol mol^{-1})	OC-TS (%)
2024-10-02 15:45	0.13	0.11	-5.04	0.55	-5.17	NA
2024-10-02 15:55	199.81	0.09	188.99	0.77	-10.82	-5.42
2024-10-02 16:05	249.77	0.11	237.38	0.14	-12.39	-4.96
2024-10-02 16:15	100.03	0.04	91.56	0.17	-8.47	-8.47
2024-10-02 16:25	149.89	0.04	139.75	0.06	-10.14	-6.76
2024-10-02 16:35	0.15	0.16	-5.55	0.13	-5.70	NA
2024-10-02 16:45	90.00	0.05	81.11	0.21	-8.89	-9.88
2024-10-02 16:55	40.09	0.13	32.89	0.11	-7.20	-17.96
2024-10-02 17:05	70.05	0.09	61.86	0.19	-8.19	-11.69
2024-10-02 17:15	30.06	0.14	23.08	0.20	-6.98	-23.22
2024-10-02 17:25	10.25	0.11	4.05	0.13	-6.20	-60.49
2024-10-02 17:35	80.01	0.05	71.29	0.16	-8.72	-10.90
2024-10-02 17:45	50.13	0.07	42.48	0.21	-7.65	-15.26
2024-10-02 17:55	20.12	0.13	13.52	0.12	-6.60	-32.80
2024-10-02 18:05	60.09	0.08	52.32	0.25	-7.77	-12.93
2024-10-02 18:15	0.18	0.05	-5.52	0.24	-5.70	NA
2024-10-02 18:25	199.80	0.07	187.71	0.21	-12.09	-6.05
2024-10-02 18:35	149.93	0.04	139.51	0.47	-10.42	-6.95
2024-10-02 18:45	249.73	0.06	235.94	0.75	-13.79	-5.52
2024-10-02 18:55	99.99	0.06	90.90	0.07	-9.09	-9.09
2024-10-02 19:05	0.26	0.04	-5.49	0.16	-5.75	NA
2024-10-02 19:15	80.08	0.09	71.37	0.12	-8.71	-10.88
2024-10-02 19:25	20.12	0.09	13.54	0.13	-6.58	-32.70
2024-10-02 19:35	60.08	0.06	52.05	0.20	-8.03	-13.37
2024-10-02 19:45	90.01	0.05	80.95	0.33	-9.06	-10.07
2024-10-02 19:55	30.15	0.14	23.11	0.15	-7.04	-23.35
2024-10-02 20:05	70.06	0.10	61.82	0.14	-8.24	-11.76
2024-10-02 20:15	50.10	0.10	42.43	0.16	-7.67	-15.31
2024-10-02 20:25	10.83	0.53	4.21	0.38	-6.62	-61.13
2024-10-02 20:45	40.11	0.04	32.65	0.17	-7.46	-18.60
2024-10-02 20:55	0.07	0.05	-5.57	0.13	-5.64	NA
2024-10-02 21:05	199.88	0.12	187.46	0.29	-12.42	-6.21
2024-10-02 21:15	249.73	0.14	236.17	0.29	-13.56	-5.43
2024-10-02 21:25	99.98	0.14	90.95	0.54	-9.03	-9.03
2024-10-02 21:35	149.94	0.09	139.26	0.74	-10.68	-7.12
2024-10-02 21:45	0.11	0.09	-5.11	0.97	-5.22	NA
2024-10-02 21:55	90.02	0.03	81.29	0.15	-8.73	-9.70
2024-10-02 22:05	40.12	0.10	32.68	0.18	-7.44	-18.54
2024-10-02 22:15	70.03	0.08	61.81	0.13	-8.22	-11.74
2024-10-02 22:25	30.13	0.10	23.24	0.15	-6.89	-22.87
2024-10-02 22:35	10.54	0.39	4.32	0.35	-6.22	-59.01
2024-10-02 22:45	80.01	0.05	71.49	0.25	-8.52	-10.65
2024-10-02 22:55	50.09	0.04	42.68	0.08	-7.41	-14.79
2024-10-02 23:05	20.15	0.11	13.40	0.17	-6.75	-33.50
2024-10-02 23:15	60.09	0.09	51.94	0.03	-8.15	-13.56
2024-10-02 23:25	0.31	0.06	-5.19	1.18	-5.50	NA

Date – Time	TS (nmol mol^{-1})	sdTS (nmol mol^{-1})	OC (nmol mol^{-1})	sdOC (nmol mol^{-1})	OC-TS (nmol mol^{-1})	OC-TS (%)
2024-10-02 23:35	199.80	0.05	187.49	0.31	-12.31	-6.16
2024-10-02 23:45	149.93	0.05	139.47	0.18	-10.46	-6.98
2024-10-02 23:55	249.70	0.04	236.80	0.13	-12.90	-5.17
2024-10-03 00:05	99.95	0.06	91.07	0.23	-8.88	-8.88
2024-10-03 00:15	0.11	0.20	-5.34	0.18	-5.45	NA
2024-10-03 00:25	80.04	0.05	71.61	0.37	-8.43	-10.53
2024-10-03 00:35	20.20	0.13	13.57	0.10	-6.63	-32.82
2024-10-03 00:45	60.07	0.04	52.14	0.21	-7.93	-13.20
2024-10-03 00:55	90.03	0.07	80.98	0.12	-9.05	-10.05
2024-10-03 01:05	30.18	0.11	23.23	0.08	-6.95	-23.03
2024-10-03 01:15	70.08	0.05	61.71	0.09	-8.37	-11.94
2024-10-03 01:25	50.10	0.07	42.49	0.17	-7.61	-15.19
2024-10-03 01:35	10.16	0.09	3.92	0.15	-6.24	-61.42

Table 6. *Comparison of the Sorong ozone analyser (OA) Thermo Scientific 49iQ #12215317647 (BKG +1.1 nmol mol^{-1}, COEF 1.014) with the bias corrected WCC-Empa travelling standard (TS).*

Date – Time	TS (nmol mol^{-1})	sdTS (nmol mol^{-1})	OA (nmol mol^{-1})	sdOA (nmol mol^{-1})	OA-TS (nmol mol^{-1})	OA-TS (%)
2024-10-01 09:04	0.12	0.11	-1.87	0.17	-1.99	NA
2024-10-01 09:14	199.87	0.09	199.70	0.25	-0.17	-0.09
2024-10-01 09:24	50.10	0.09	48.83	0.27	-1.27	-2.53
2024-10-01 09:34	99.97	0.06	99.88	0.25	-0.09	-0.09
2024-10-01 09:44	149.95	0.07	151.02	0.19	1.07	0.71
2024-10-01 09:54	0.13	0.08	-1.43	0.12	-1.56	NA
2024-10-01 10:04	90.07	0.08	90.26	0.27	0.19	0.21
2024-10-01 10:14	40.07	0.04	39.25	0.19	-0.82	-2.05
2024-10-01 10:24	70.09	0.07	69.58	0.12	-0.51	-0.73
2024-10-01 10:34	30.14	0.08	28.82	0.16	-1.32	-4.38
2024-10-01 10:44	10.15	0.09	8.57	0.18	-1.58	-15.57
2024-10-01 10:54	80.01	0.02	79.71	0.19	-0.30	-0.37
2024-10-01 11:04	50.13	0.07	49.34	0.21	-0.79	-1.58
2024-10-01 11:14	20.12	0.09	18.92	0.08	-1.20	-5.96
2024-10-01 11:24	60.04	0.10	59.45	0.18	-0.59	-0.98
2024-10-01 11:34	0.05	0.16	-1.49	0.11	-1.54	NA
2024-10-01 11:44	199.87	0.08	201.82	0.13	1.95	0.98
2024-10-01 11:54	149.96	0.02	151.11	0.06	1.15	0.77
2024-10-01 12:04	50.05	0.11	49.31	0.20	-0.74	-1.48
2024-10-01 12:14	100.04	0.05	100.02	0.20	-0.02	-0.02
2024-10-01 12:24	0.09	0.10	-1.43	0.13	-1.52	NA
2024-10-01 12:34	80.01	0.11	79.88	0.20	-0.13	-0.16
2024-10-01 12:44	20.18	0.08	18.93	0.17	-1.25	-6.19
2024-10-01 12:54	60.08	0.09	59.41	0.15	-0.67	-1.12
2024-10-01 13:04	90.03	0.12	89.86	0.12	-0.17	-0.19
2024-10-01 13:14	30.10	0.05	28.50	0.26	-1.60	-5.32
2024-10-01 13:24	70.09	0.08	69.61	0.16	-0.48	-0.68
2024-10-01 13:34	50.09	0.07	49.27	0.11	-0.82	-1.64
2024-10-01 13:44	10.79	0.57	9.51	0.53	-1.28	-11.86

Date – Time	TS (nmol mol^{-1})	sdTS (nmol mol^{-1})	OA (nmol mol^{-1})	sdOA (nmol mol^{-1})	OA-TS (nmol mol^{-1})	OA-TS (%)
2024-10-01 14:04	40.10	0.07	38.33	0.13	-1.77	-4.41
2024-10-01 14:14	0.10	0.13	-1.84	0.08	-1.94	NA
2024-10-01 14:24	199.85	0.12	198.99	0.19	-0.86	-0.43
2024-10-01 14:34	50.08	0.11	48.46	0.17	-1.62	-3.23
2024-10-01 14:44	99.97	0.02	98.57	0.15	-1.40	-1.40
2024-10-01 14:54	149.95	0.07	148.82	0.05	-1.13	-0.75
2024-10-01 15:04	0.19	0.08	-1.82	0.15	-2.01	NA
2024-10-01 15:14	90.00	0.12	88.36	0.24	-1.64	-1.82
2024-10-01 15:24	39.99	0.09	38.21	0.30	-1.78	-4.45
2024-10-01 15:34	70.01	0.04	68.32	0.10	-1.69	-2.41
2024-10-01 15:44	30.14	0.09	28.31	0.12	-1.83	-6.07
2024-10-01 15:54	10.56	0.38	8.62	0.48	-1.94	-18.37
2024-10-01 16:04	80.01	0.04	78.39	0.07	-1.62	-2.02
2024-10-01 16:14	50.02	0.08	48.38	0.14	-1.64	-3.28
2024-10-01 16:24	20.16	0.11	18.30	0.20	-1.86	-9.23
2024-10-01 16:34	60.07	0.06	58.39	0.18	-1.68	-2.80
2024-10-01 16:44	0.36	0.10	-1.80	0.11	-2.16	NA
2024-10-01 16:54	199.77	0.07	199.02	0.24	-0.75	-0.38
2024-10-01 17:04	149.93	0.04	148.75	0.10	-1.18	-0.79
2024-10-01 17:14	50.09	0.10	48.38	0.26	-1.71	-3.41
2024-10-01 17:24	100.03	0.05	98.57	0.27	-1.46	-1.46
2024-10-01 17:34	0.13	0.15	-1.77	0.10	-1.90	NA
2024-10-01 17:44	79.97	0.09	78.48	0.15	-1.49	-1.86
2024-10-01 17:54	20.13	0.10	18.32	0.44	-1.81	-8.99
2024-10-01 18:04	60.07	0.03	59.06	0.41	-1.01	-1.68
2024-10-01 18:14	90.06	0.07	89.64	0.17	-0.42	-0.47
2024-10-01 18:24	30.13	0.05	29.05	0.17	-1.08	-3.58
2024-10-01 18:34	70.07	0.05	69.65	0.11	-0.42	-0.60
2024-10-01 18:44	50.11	0.05	49.19	0.21	-0.92	-1.84
2024-10-01 18:54	10.81	0.33	9.38	0.34	-1.43	-13.23
2024-10-01 19:14	40.06	0.05	39.21	0.09	-0.85	-2.12
2024-10-01 19:24	0.19	0.16	-1.34	0.22	-1.53	NA
2024-10-01 19:34	199.81	0.11	201.64	0.17	1.83	0.92
2024-10-01 19:44	50.11	0.08	49.32	0.26	-0.79	-1.58
2024-10-01 19:54	100.08	0.08	100.23	0.16	0.15	0.15
2024-10-01 20:04	149.94	0.06	150.78	0.19	0.84	0.56
2024-10-01 20:14	0.14	0.09	-1.34	0.04	-1.48	NA
2024-10-01 20:24	90.03	0.09	90.13	0.20	0.10	0.11
2024-10-01 20:34	40.06	0.14	39.14	0.29	-0.92	-2.30
2024-10-01 20:44	70.04	0.04	69.84	0.18	-0.20	-0.29
2024-10-01 20:54	30.15	0.08	29.10	0.22	-1.05	-3.48
2024-10-01 21:04	10.21	0.10	8.85	0.18	-1.36	-13.32
2024-10-01 21:14	80.05	0.06	79.86	0.18	-0.19	-0.24
2024-10-01 21:24	50.08	0.11	49.21	0.07	-0.87	-1.74
2024-10-01 21:34	20.19	0.07	18.69	0.07	-1.50	-7.43
2024-10-01 21:44	60.08	0.09	59.62	0.23	-0.46	-0.77
2024-10-01 21:54	0.13	0.02	-1.26	0.20	-1.39	NA
2024-10-01 22:04	199.83	0.08	201.78	0.13	1.95	0.98

Date – Time	TS (nmol mol^{-1})	sdTS (nmol mol^{-1})	OA (nmol mol^{-1})	sdOA (nmol mol^{-1})	OA-TS (nmol mol^{-1})	OA-TS (%)
2024-10-01 22:14	149.88	0.08	150.81	0.21	0.93	0.62
2024-10-01 22:24	50.06	0.06	49.30	0.18	-0.76	-1.52
2024-10-01 22:34	100.00	0.09	99.83	0.22	-0.17	-0.17
2024-10-01 22:44	0.16	0.09	-1.49	0.11	-1.65	NA
2024-10-01 22:54	80.03	0.04	78.57	0.18	-1.46	-1.82
2024-10-01 23:04	20.18	0.06	18.37	0.28	-1.81	-8.97
2024-10-01 23:14	60.06	0.05	58.46	0.19	-1.60	-2.66
2024-10-01 23:24	90.01	0.10	88.41	0.16	-1.60	-1.78
2024-10-01 23:34	30.16	0.13	28.38	0.14	-1.78	-5.90
2024-10-01 23:44	70.05	0.14	68.42	0.04	-1.63	-2.33
2024-10-01 23:54	50.05	0.12	48.35	0.24	-1.70	-3.40
2024-10-02 00:04	10.21	0.08	8.47	0.08	-1.74	-17.04
2024-10-02 00:24	40.17	0.05	38.34	0.17	-1.83	-4.56
2024-10-02 00:34	0.15	0.08	-1.69	0.10	-1.84	NA
2024-10-02 00:44	199.81	0.10	199.01	0.19	-0.80	-0.40
2024-10-02 00:54	50.11	0.06	48.29	0.11	-1.82	-3.63
2024-10-02 01:04	100.02	0.09	98.82	0.13	-1.20	-1.20
2024-10-02 01:14	149.90	0.13	148.80	0.08	-1.10	-0.73
2024-10-02 01:24	0.07	0.08	-1.69	0.07	-1.76	NA
2024-10-02 01:34	90.00	0.10	85.89	11.23	-4.11	-4.57
2024-10-02 01:44	40.09	0.14	39.73	0.20	-0.36	-0.90
2024-10-02 01:54	70.03	0.06	70.52	0.26	0.49	0.70
2024-10-02 02:04	30.12	0.03	29.60	0.04	-0.52	-1.73
2024-10-02 02:14	10.45	0.37	9.52	0.48	-0.93	-8.90
2024-10-02 02:24	80.03	0.11	80.87	0.27	0.84	1.05
2024-10-02 02:34	50.10	0.06	50.03	0.30	-0.07	-0.14
2024-10-02 02:44	20.11	0.12	19.56	0.12	-0.55	-2.73
2024-10-02 02:54	60.08	0.07	60.16	0.11	0.08	0.13
2024-10-02 03:04	0.23	0.12	-1.17	0.16	-1.40	NA
2024-10-02 03:14	199.77	0.00	202.08	0.12	2.31	1.16

Table 7. *Comparison of the Sorong ozone calibrator (OC) Thermo Scientific 49iQ-PS #12215317648 (BKG +0.0 nmol mol^{-1}, COEF 1.000) with the bias corrected WCC-Empa travelling standard (TS).*

Date – Time	TS (nmol mol^{-1})	sdTS (nmol mol^{-1})	OC (nmol mol^{-1})	sdOC (nmol mol^{-1})	OC-TS (nmol mol^{-1})	OC-TS (%)
2024-10-03 08:01	0.22	0.18	-0.01	0.11	-0.23	NA
2024-10-03 08:11	199.86	0.06	196.89	0.30	-2.97	-1.49
2024-10-03 08:21	249.75	0.08	246.02	0.15	-3.73	-1.49
2024-10-03 08:31	100.03	0.03	98.28	0.18	-1.75	-1.75
2024-10-03 08:41	149.91	0.04	147.49	0.18	-2.42	-1.61
2024-10-03 08:51	50.05	0.03	49.09	0.11	-0.96	-1.92
2024-10-03 09:01	0.14	0.09	-0.01	0.26	-0.15	NA
2024-10-03 09:11	99.97	0.05	98.22	0.23	-1.75	-1.75
2024-10-03 09:21	199.84	0.05	197.06	0.55	-2.78	-1.39
2024-10-03 09:31	50.07	0.07	48.97	0.18	-1.10	-2.20
2024-10-03 09:41	149.88	0.12	148.00	0.19	-1.88	-1.25
2024-10-03 09:51	249.74	0.06	246.81	0.32	-2.93	-1.17

Date – Time	TS (nmol mol^{-1})	sdTS (nmol mol^{-1})	OC (nmol mol^{-1})	sdOC (nmol mol^{-1})	OC-TS (nmol mol^{-1})	OC-TS (%)
2024-10-03 10:01	0.18	0.06	-0.01	0.20	-0.19	NA
2024-10-03 10:11	50.05	0.07	49.08	0.31	-0.97	-1.94
2024-10-03 10:21	199.82	0.07	197.40	0.19	-2.42	-1.21
2024-10-03 10:31	149.91	0.05	147.82	0.23	-2.09	-1.39
2024-10-03 10:41	100.01	0.04	98.60	0.30	-1.41	-1.41
2024-10-03 11:01	249.78	0.04	247.05	0.16	-2.73	-1.09
2024-10-03 11:11	0.12	0.06	0.06	0.08	-0.06	NA
2024-10-03 11:21	99.95	0.04	98.76	0.21	-1.19	-1.19
2024-10-03 11:31	249.69	0.04	247.54	0.35	-2.15	-0.86
2024-10-03 11:41	149.92	0.08	148.80	0.44	-1.12	-0.75
2024-10-03 11:51	50.07	0.07	49.35	0.26	-0.72	-1.44
2024-10-03 12:01	199.83	0.07	198.23	0.17	-1.60	-0.80
2024-10-03 12:11	0.21	0.10	0.04	0.05	-0.17	NA
2024-10-03 12:21	249.73	0.04	248.04	0.30	-1.69	-0.68
2024-10-03 12:31	50.08	0.05	49.49	0.40	-0.59	-1.18
2024-10-03 12:41	100.00	0.08	98.94	0.24	-1.06	-1.06
2024-10-03 12:51	149.95	0.04	148.83	0.20	-1.12	-0.75
2024-10-03 13:01	199.83	0.08	198.24	0.17	-1.59	-0.80
2024-10-03 13:11	0.17	0.13	0.03	0.15	-0.14	NA
2024-10-03 13:21	199.83	0.08	198.25	0.32	-1.58	-0.79
2024-10-03 13:31	249.75	0.08	248.14	0.17	-1.61	-0.64
2024-10-03 13:41	100.05	0.10	99.19	0.25	-0.86	-0.86
2024-10-03 13:51	149.90	0.06	148.71	0.22	-1.19	-0.79
2024-10-03 14:01	50.09	0.06	49.27	0.24	-0.82	-1.64
2024-10-03 14:11	0.20	0.12	0.05	0.15	-0.15	NA
2024-10-03 14:21	99.91	0.04	99.16	0.29	-0.75	-0.75
2024-10-03 14:31	199.87	0.03	198.25	0.25	-1.62	-0.81
2024-10-03 14:41	50.07	0.11	49.24	0.26	-0.83	-1.66
2024-10-03 14:51	149.90	0.04	148.82	0.23	-1.08	-0.72
2024-10-03 15:01	249.75	0.06	247.78	0.54	-1.97	-0.79
2024-10-03 15:11	0.30	0.05	0.12	0.07	-0.18	NA
2024-10-03 15:21	50.10	0.04	49.43	0.22	-0.67	-1.34
2024-10-03 15:31	199.80	0.08	197.72	0.27	-2.08	-1.04
2024-10-03 15:41	149.91	0.06	148.39	0.36	-1.52	-1.01
2024-10-03 15:51	100.07	0.06	98.86	0.24	-1.21	-1.21
2024-10-03 16:11	249.72	0.06	247.35	0.21	-2.37	-0.95
2024-10-03 16:21	0.20	0.08	0.09	0.14	-0.11	NA
2024-10-03 16:31	99.96	0.03	98.82	0.15	-1.14	-1.14
2024-10-03 16:41	249.82	0.08	247.20	0.58	-2.62	-1.05
2024-10-03 16:51	149.95	0.10	148.50	0.18	-1.45	-0.97
2024-10-03 17:01	50.05	0.03	49.35	0.16	-0.70	-1.40
2024-10-03 17:11	199.86	0.09	197.90	0.43	-1.96	-0.98
2024-10-03 17:21	0.16	0.10	0.09	0.13	-0.07	NA
2024-10-03 17:31	249.68	0.06	247.46	0.14	-2.22	-0.89
2024-10-03 17:41	50.11	0.03	49.74	0.25	-0.37	-0.74
2024-10-03 17:51	99.98	0.05	98.89	0.12	-1.09	-1.09
2024-10-03 18:01	149.90	0.08	148.49	0.38	-1.41	-0.94
2024-10-03 18:11	199.83	0.06	198.16	0.20	-1.67	-0.84

Date – Time	TS (nmol mol^{-1})	sdTS (nmol mol^{-1})	OC (nmol mol^{-1})	sdOC (nmol mol^{-1})	OC-TS (nmol mol^{-1})	OC-TS (%)
2024-10-03 18:21	0.20	0.13	-0.04	0.14	-0.24	NA
2024-10-03 18:31	199.78	0.05	198.00	0.27	-1.78	-0.89
2024-10-03 18:41	249.80	0.07	247.60	0.55	-2.20	-0.88
2024-10-03 18:51	99.99	0.04	99.06	0.29	-0.93	-0.93
2024-10-03 19:01	149.93	0.04	148.96	0.14	-0.97	-0.65
2024-10-03 19:11	50.13	0.11	49.49	0.18	-0.64	-1.28
2024-10-03 19:21	0.28	0.08	0.11	0.22	-0.17	NA
2024-10-03 19:31	99.99	0.08	99.38	0.20	-0.61	-0.61
2024-10-03 19:41	199.86	0.10	197.81	2.00	-2.05	-1.03
2024-10-03 19:51	50.12	0.07	49.61	0.22	-0.51	-1.02
2024-10-03 20:01	149.92	0.05	148.91	0.27	-1.01	-0.67
2024-10-03 20:11	249.77	0.08	248.25	0.26	-1.52	-0.61
2024-10-03 20:21	0.10	0.11	-0.07	0.19	-0.17	NA
2024-10-03 20:31	50.02	0.06	49.58	0.05	-0.44	-0.88
2024-10-03 20:41	199.82	0.02	198.19	0.75	-1.63	-0.82
2024-10-03 20:51	149.92	0.09	148.93	0.22	-0.99	-0.66
2024-10-03 21:01	100.01	0.04	99.18	0.23	-0.83	-0.83
2024-10-03 21:21	249.73	0.09	248.22	0.29	-1.51	-0.60
2024-10-03 21:31	0.19	0.16	0.22	0.26	0.03	15.79
2024-10-03 21:41	99.99	0.05	100.71	3.12	0.72	0.72
2024-10-03 21:51	249.70	0.04	248.16	0.21	-1.54	-0.62
2024-10-03 22:01	149.93	0.05	148.53	0.22	-1.40	-0.93
2024-10-03 22:11	50.09	0.08	49.68	0.18	-0.41	-0.82
2024-10-03 22:21	199.81	0.10	197.23	2.00	-2.58	-1.29
2024-10-03 22:31	0.24	0.19	3.37	7.35	3.13	NA
2024-10-03 22:41	249.68	0.10	244.08	7.80	-5.60	-2.24
2024-10-03 22:51	50.14	0.08	49.60	0.28	-0.54	-1.08
2024-10-03 23:01	99.95	0.02	99.07	0.14	-0.88	-0.88
2024-10-03 23:11	149.96	0.10	149.03	0.72	-0.93	-0.62
2024-10-03 23:21	199.85	0.09	195.49	6.04	-4.36	-2.18
2024-10-03 23:31	0.14	0.14	3.84	7.74	3.70	NA
2024-10-03 23:41	199.81	0.10	199.70	3.59	-0.11	-0.06
2024-10-03 23:51	249.74	0.14	247.91	0.24	-1.83	-0.73
2024-10-04 00:01	100.03	0.06	99.29	0.32	-0.74	-0.74
2024-10-04 00:11	149.90	0.06	148.12	1.27	-1.78	-1.19
2024-10-04 00:21	50.09	0.08	48.75	1.48	-1.34	-2.68
2024-10-04 00:31	0.33	0.09	3.25	6.90	2.92	NA
2024-10-04 00:41	99.97	0.10	102.19	6.96	2.22	2.22
2024-10-04 00:51	199.86	0.08	198.18	0.14	-1.68	-0.84
2024-10-04 01:01	50.08	0.07	49.76	0.23	-0.32	-0.64
2024-10-04 01:11	149.87	0.07	149.74	2.02	-0.13	-0.09
2024-10-04 01:21	249.77	0.07	245.01	7.24	-4.76	-1.91

A4. Carbon monoxide comparisons

All procedures were carried out in accordance with the Standard Operating Procedure (WMO, 2007) and included comparisons of the travelling standards at Empa before and after the audit. The WCC-Empa travelling standards are 30 l aluminium cylinders containing a mixture of natural and synthetic air. Details of the traceability of the travelling standards to the WMO/GAW reference standard at NOAA and the assigned values and standard uncertainties are given below.

Results

The results of the evaluations are presented in the Executive Summary, and the individual measurements of the TS are shown in the following tables.

Table 8. *CO aggregates calculated from individual analyses (mean and standard deviation of the mean) for each level during the comparison of the Picarro G2401 #3035-CFKADS2294 instrument (AL) with the WCC-Empa TS (WMO-X2014A CO scale).*

Date / Time	TS Cylinder	TS (nmol mol^{-1})	sdTS (nmol mol^{-1})	AL (nmol mol^{-1})	sdAL (nmol mol^{-1})	N	AL-TS (nmol mol^{-1})	AL-TS (%)
(24-10-03 07:04:00)	210406_CA02859	246.5	2.2	243.1	0.3	3	-3.4	-1.4
(24-10-03 07:34:40)	210407_CC311707	82.0	2.8	79.2	0.3	3	-2.8	-3.4
(24-10-03 06:48:20)	220811_CC749997	478.3	3.1	475.7	0.4	3	-2.6	-0.5
(24-10-03 07:18:40)	240314_CB08963	150.0	1.0	148.5	0.3	3	-1.5	-1.0

A5. Methane comparisons

All procedures were carried out in accordance with the Standard Operating Procedure (WMO, 2007) and included comparisons of the travelling standards at Empa before and after the audit. The WCC-Empa travelling standards are 30 l aluminium cylinders containing a mixture of natural and synthetic air. Details of the traceability of the travelling standards to the WMO/GAW reference standard at NOAA and the assigned values and standard uncertainties are given below.

Results

The result of the assessment is presented in the Executive Summary, and the individual measurements of the TS are presented in the following table.

Table 9. *CH_4 aggregates calculated from individual analyses (mean and standard deviation of the mean) for each level during the comparison of the Picarro G2401 #3035-CFKADS2294 instrument (AL) with the WCC-Empa TS (WMO-X2004A CH_4 scale).*

Date / Time	TS Cylinder	TS (nmol mol^{-1})	sdTS (nmol mol^{-1})	AL (nmol mol^{-1})	sdAL (nmol mol^{-1})	N	AL-TS (nmol mol^{-1})	AL-TS (%)
(24-10-03 07:04:00)	210406_CA02859	2150.55	0.08	2150.67	0.04	3	0.12	0.01
(24-10-03 07:34:40)	210407_CC311707	1806.36	0.09	1806.81	0.02	3	0.45	0.02
(24-10-03 06:48:20)	220811_CC749997	2207.18	0.09	2207.24	0.01	3	0.06	0.00
(24-10-03 07:18:40)	240314_CB08963	1910.58	0.18	1910.77	0.02	3	0.19	0.01

A6. Carbon dioxide comparisons

All procedures were carried out in accordance with the Standard Operating Procedure (WMO, 2007) and included comparisons of the travelling standards at Empa before and after the audit. The WCC-Empa travelling standards are 30 l aluminium cylinders containing a mixture of natural and synthetic air. Details of the traceability of the travelling standards to the WMO/GAW reference standard at NOAA and the assigned values and standard uncertainties are given below.

Results

The results of the assessment are presented in the Executive Summary, and the individual measurements of the TS are presented in the following table.

Table 10. *CO_2 aggregates calculated from individual analyses (mean and standard deviation of the mean) for each level during the comparison of the Picarro G2401 #3035-CFKADS2294 instrument (AL) with the WCC-Empa TS (WMO-X2019 CO_2 scale).*

Date / Time	TS Cylinder	TS (µmol mol^{-1})	sdTS (µmol mol^{-1})	AL (µmol mol^{-1})	sdAL (µmol mol^{-1})	N	AL-TS (µmol mol^{-1})	AL-TS (%)
(24-10-03 07:04:00)	210406_CA02859	430.24	0.04	430.37	0.01	3	0.13	0.03
(24-10-03 07:34:40)	210407_CC311707	411.99	0.05	412.28	0.01	3	0.29	0.07
(24-10-03 06:48:20)	220811_CC749997	446.69	0.02	446.88	0.01	3	0.19	0.04
(24-10-03 07:18:40)	240314_CB08963	422.26	0.01	422.48	0.01	3	0.22	0.05

A7. Calibration Standards for CO, CH_4 and CO_2

Table 11 provides an overview the standard gases available for calibration of the CO, CH_4 and CO_2 instruments.

Table 11 *BKT calibration standards as of October 2024.*

Cylinder ID	CO (X2014A) (nmol mol^{-1})	CH_4 (X2004A) (nmol mol^{-1})	CO_2 (X2019) (µmol mol^{-1})	Usage
CC498769	73.55	1836.32	349.69	Laboratory standard (CCL)
CC499026	126.24	1864.11	395.30	Laboratory standard (CCL)
CC499101	270.82	2190.30	426.73	Laboratory standard (CCL)
130822_CB10280	226.79	1860.60	332.35	Target / working standard
181129_CB11549	88.60	1895.80	37.64	Target / working standard
210406_CA02859	246.51	2150.55	430.24	Spare tank, provided by WCC-Empa in 2024
210407_CC311707	82.02	1806.36	411.99	Spare tank, provided by WCC-Empa in 2024
220811_CC749997	478.3	2207.18	446.69	Spare tank, provided by WCC-Empa in 2024
240314_CB08963	150.02	1910.58	422.26	Spare tank, provided by WCC-Empa in 2024

A8. WCC-Empa ozone traveling standard

The WCC-Empa Travelling Standard (TS) was compared with the standard reference photometer before and after the audit. The instruments used were

WCC-Empa Ozone Reference: NIST Standard Reference Photometer SRP #15 (Master)

WCC-Empa TS: Thermo Scientific 49i-PS #1171430027, BKG 0.0, COEF 0.991

Zero air source: Compressed air - Dryer - Breitfuss zero air generator – Purafil – Charcoal –Filter

The results of the TS calibration before and after the audit are shown in Table 12. The TS passed the pre-audit evaluation criteria defined for maximum acceptable bias (Klausen et al., 2003) (see 17). The data were pooled and evaluated by linear regression analysis, taking into account the uncertainties of both instruments. From this, the unbiased ozone mixing ratio produced (and measured) by the TS can be calculated (equation 17). The uncertainty of the TS (equation 18) was previously estimated (see equation 19 in (Klausen et al., 2003)).

$$X_{TS} \text{ (nmol mol}^{-1}\text{)} = ([TS] + 0.18 \text{ nmol mol}^{-1}) / 1.0018 \quad (17)$$

$$u_{TS} \text{ (nmol mol}^{-1}\text{)} = \text{sqrt} ((0.43 \text{ nmol mol}^{-1})^2 + (0.0034 * X)^2) \quad (18)$$

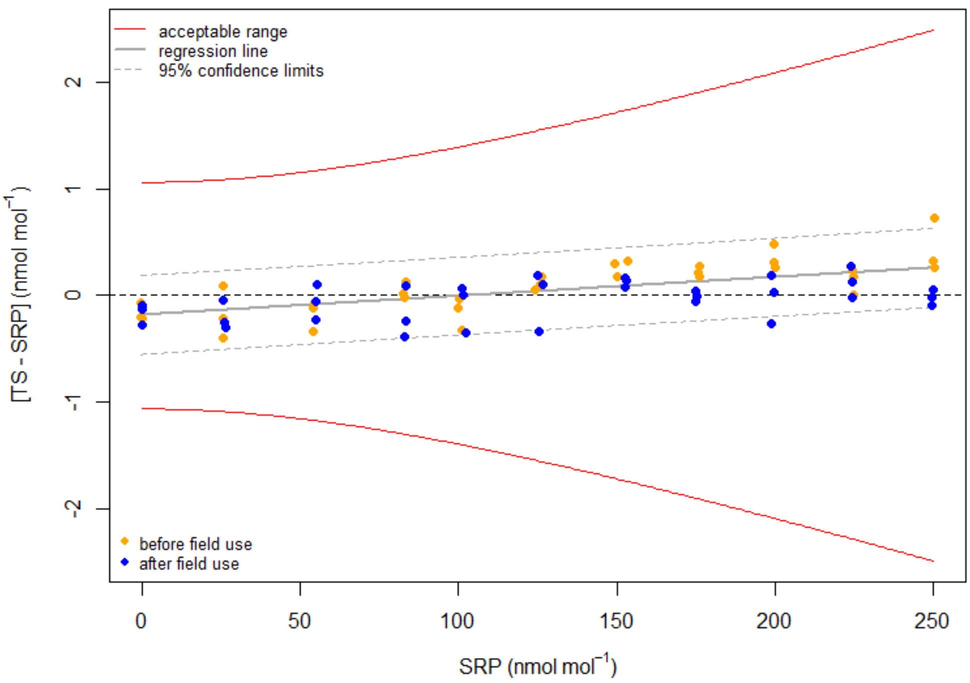


Figure 22. *Deviations between Traveling Standard (TS) and Standard Reference Photometer (SRP) before and after use of the TS in the field.*

Table 12. *Mean values calculated over at least five minutes for the comparison of the WCC-Empa Traveling Standard (TS) with the Standard Reference Photometer (SRP).*

Date	Run	Level#	SRP (nmol mol^{-1})	sdSRP (nmol mol^{-1})	TS (nmol mol^{-1})	sdTS (nmol mol^{-1})
2024-08-27	1	250	249.93	0.25	250.25	0.23
2024-08-27	1	25	25.70	0.32	25.31	0.12
2024-08-27	1	100	99.99	0.33	99.87	0.14
2024-08-27	1	175	176.04	0.32	176.22	0.20
2024-08-27	1	125	125.91	0.21	126.02	0.20
2024-08-27	1	55	54.49	0.35	54.42	0.12
2024-08-27	1	85	83.07	0.25	83.05	0.20
2024-08-27	1	225	224.26	0.18	224.50	0.27
2024-08-27	1	155	153.41	0.24	153.74	0.18
2024-08-27	1	200	199.39	0.31	199.87	0.09
2024-08-27	1	0	-0.10	0.34	-0.29	0.13
2024-08-27	2	85	83.24	0.29	83.37	0.23
2024-08-27	2	150	149.43	0.16	149.73	0.22
2024-08-27	2	25	25.57	0.26	25.35	0.08
2024-08-27	2	100	100.14	0.16	100.11	0.16
2024-08-27	2	0	0.04	0.28	-0.17	0.16
2024-08-27	2	125	124.27	0.24	124.33	0.13
2024-08-27	2	250	250.23	0.44	250.49	0.20
2024-08-27	2	55	54.33	0.21	53.99	0.21
2024-08-27	2	200	199.78	0.39	200.05	0.32
2024-08-27	2	175	175.77	0.23	175.99	0.21
2024-08-27	2	225	224.68	0.27	224.69	0.20
2024-08-27	3	250	250.28	0.37	251.00	0.19
2024-08-27	3	225	224.59	0.32	224.77	0.24
2024-08-27	3	55	54.30	0.23	54.19	0.32
2024-08-27	3	150	150.06	0.20	150.24	0.17
2024-08-27	3	175	176.21	0.25	176.48	0.12
2024-08-27	3	125	126.22	0.40	126.39	0.13
2024-08-27	3	100	101.03	0.43	100.71	0.14
2024-08-27	3	200	199.49	0.23	199.80	0.15
2024-08-27	3	85	82.73	0.38	82.75	0.23
2024-08-27	3	0	-0.06	0.28	-0.13	0.08
2024-08-27	3	25	25.65	0.22	25.74	0.11
2025-01-10	4	55	55.43	0.36	55.53	0.13
2025-01-10	4	85	83.58	0.29	83.68	0.16
2025-01-10	4	125	124.87	0.36	125.06	0.13
2025-01-10	4	0	-0.01	0.31	-0.09	0.09
2025-01-10	4	200	199.46	0.38	199.49	0.32
2025-01-10	4	225	223.68	0.31	223.96	0.20
2025-01-10	4	155	152.93	0.49	153.07	0.25
2025-01-10	4	25	25.79	0.31	25.74	0.12
2025-01-10	4	250	249.94	0.53	250.00	0.21
2025-01-10	4	175	175.06	0.38	175.00	0.23
2025-01-10	4	100	101.33	0.29	101.34	0.12
2025-01-10	5	55	55.13	0.30	55.08	0.15

Date	Run	Level#	SRP (nmol mol⁻¹)	sdSRP (nmol mol⁻¹)	TS (nmol mol⁻¹)	sdTS (nmol mol⁻¹)
2025-01-10	5	200	198.86	0.53	199.05	0.33
2025-01-10	5	155	152.69	0.44	152.86	0.23
2025-01-10	5	85	83.28	0.46	83.05	0.20
2025-01-10	5	125	125.39	0.34	125.05	0.16
2025-01-10	5	175	175.31	0.41	175.31	0.29
2025-01-10	5	250	249.42	0.28	249.33	0.25
2025-01-10	5	105	102.50	0.27	102.15	0.14
2025-01-10	5	0	0.10	0.40	-0.18	0.18
2025-01-10	5	25	26.50	0.29	26.20	0.10
2025-01-10	5	225	224.15	0.24	224.13	0.18
2025-01-10	6	250	249.56	0.51	249.54	0.16
2025-01-10	6	200	198.86	0.28	198.60	0.30
2025-01-10	6	175	175.03	0.44	175.07	0.23
2025-01-10	6	155	152.78	0.33	152.85	0.20
2025-01-10	6	125	126.58	0.24	126.68	0.15
2025-01-10	6	55	55.05	0.40	54.83	0.19
2025-01-10	6	225	224.22	0.41	224.34	0.29
2025-01-10	6	85	83.04	0.76	82.66	0.36
2025-01-10	6	100	101.00	0.28	101.07	0.14
2025-01-10	6	25	26.18	0.36	25.93	0.10
2025-01-10	6	0	-0.02	0.50	-0.15	0.11

#The level is only indicative.

A9. WCC-Empa GHG and CO traveling standards

WCC-Empa refers to the primary reference standards maintained by the Central Calibration Laboratory (CCL) of the WMO/GAW programme for carbon monoxide, carbon dioxide and methane. NOAA has been designated by WMO as the CCL for the above parameters. WCC-Empa maintains a set of laboratory standards obtained from the CCL, which are regularly compared with the CCL through travelling standards and the addition of new laboratory standards from the CCL. The following calibration scales have been used to assign the amount fractions to the TS:

CO: WMO-X2014A scale (https://gml.noaa.gov/ccl/co_scale.html)
CO_2: WMO-X2019 scale (Hall et al., 2021)
CH_4: WMO-X2004A scale (Dlugokencky et al., 2005)
N_2O: WMO-X2006A scale (https://gml.noaa.gov/ccl/n2o_scale.html)

More information about the NOAA calibration scales can be found on the NOAA website. The scales were propagated to the TS using the following instruments:

CO, CO_2 and CH_4: Picarro G2401 (Cavity Ring-Down Spectroscopy).
CO and N_2O: Los Gatos 23-r (Mid-IR Spectroscopy).

For CO, only data from the Picarro G2401 instrument have been used. This instrument is calibrated using a high working standard (3244 nmol mol^{-1}) and CO-free air. The use of a high CO standard reduces the potential bias due to standard drift, which is a common problem with CO in air mixtures.

Table 13 gives an overview of the WCC-Empa laboratory standards used to calibrate the WCC-Empa TS on the CCL scales. The results including the standard deviations of the WCC-Empa TS are given in Table 14 and Figure 22 shows the analysis of the TS over time.

Table 13. *CCL laboratory standards and working standards at WCC-Empa.*

Cylinder	CO (nmol mol^{-1})	CH_4 (nmol mol^{-1})	N_2O (nmol mol^{-1})	CO_2 (µmol mol^{-1})
CC339478[#]	463.76	2485.25	357.19	484.63
CB11499[#]	141.03	1933.77	329.15	407.53
CB11485[#]	110.88	1844.78	328.46	394.49
CA02789*	448.67	2097.48	342.18	496.15
190618_CC703041[§]	3244.00	2258.07	NA	419.82

[#] used for calibrations of CO_2, CH_4 and N_2O
* used for calibrations of CO
[§] used for calibrations of CO (Picarro G2401)

Table 14. *Calibration summary of the WCC-Empa travelling standards for CH_4, CO_2, N_2O and CO. The letters in parenthesis refer to the instrument used for the analysis: (P) Picarro, (L) Los Gatos.*

TS	Pressure (psi)	CH_4 (P) (nmol mol^{-1})	sd	CO_2 (P) (µmol mol^{-1})	sd	N_2O (L) (nmol mol^{-1})	sd	CO (P) (nmol mol^{-1})	sd
210406_CA02859	1900	2150.55	0.08	430.24	0.04	373.23	0.44	246.51	2.23
210407_CC311707	1900	1806.36	0.09	411.99	0.05	332.99	0.05	82.02	2.78
220811_CC749997	2000	2207.18	0.09	446.69	0.02	391.17	0.33	478.30	3.14
240314_CB08963	1940	1910.58	0.18	422.26	0.01	343.62	0.03	150.02	1.00

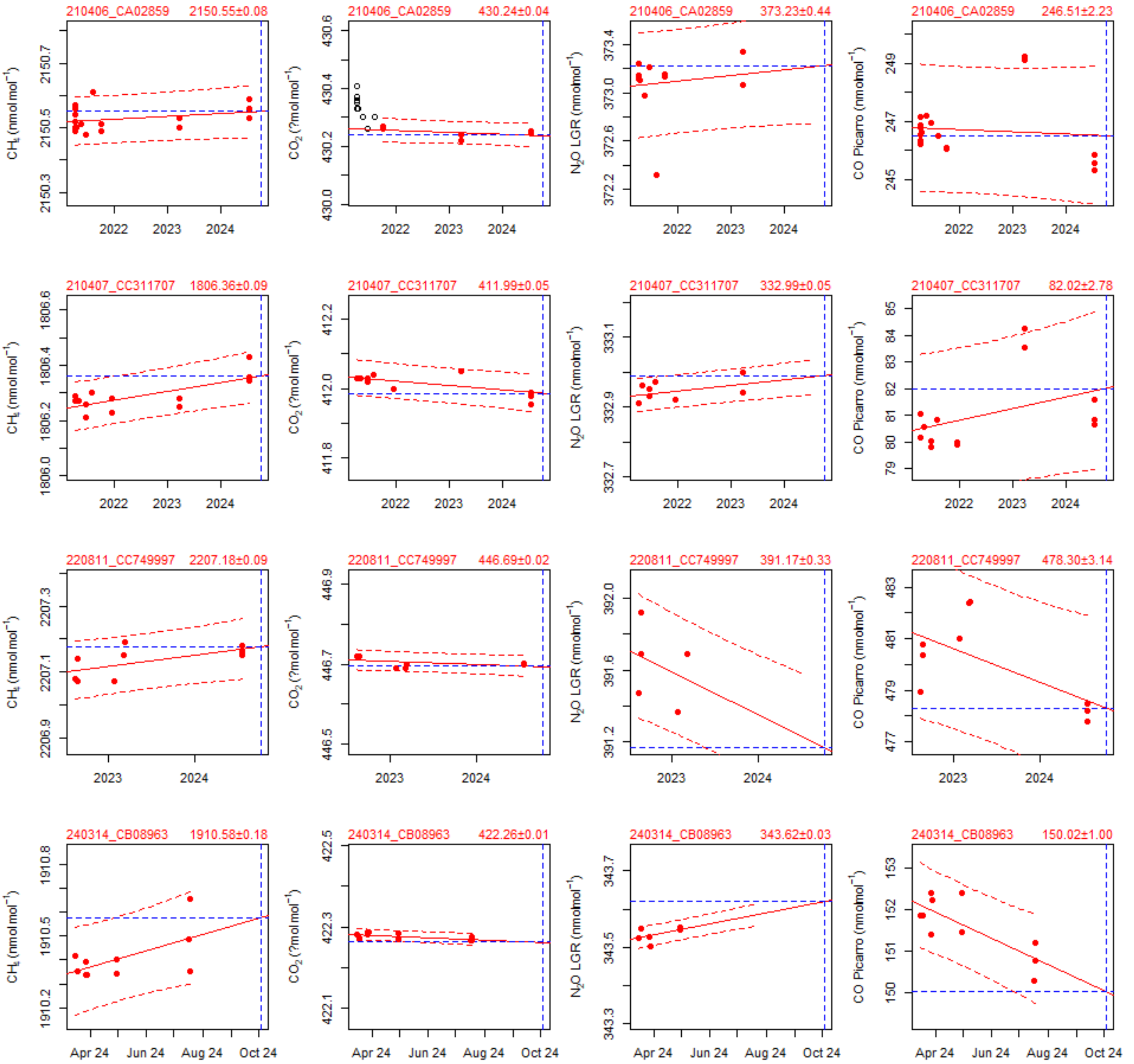


Figure 23. *Results of the WCC-Empa TS calibrations for CH_4, CO_2, N_2O and CO. Only the values of the red solid circles were considered for averaging. The red solid line is the average of the points that were considered for the assignment of the values; the red dotted line corresponds to the standard deviation of the measurement. The blue vertical line refers to the audit date.*

A10. Calibration of the travelling instrument

The calibration of the WCC-Empa travelling instrument is shown in the following figures. For CH_4 and CO_2, the Picarro G2401 #617-CFKADS2001 was calibrated every 3210 minutes using one WCC-Empa TS as the working standard and two TS as target tanks. Based on the working standard measurements, a Loess fit drift correction was applied to the data as shown in the figure below. The maximum drift between two WS measurements was approximately 0.5 nmol mol^{-1} for CH_4 and 0.05 µmol mol^{-1} for CO_2. All target cylinder measurements were within half of the WMO GAW compatibility goals.

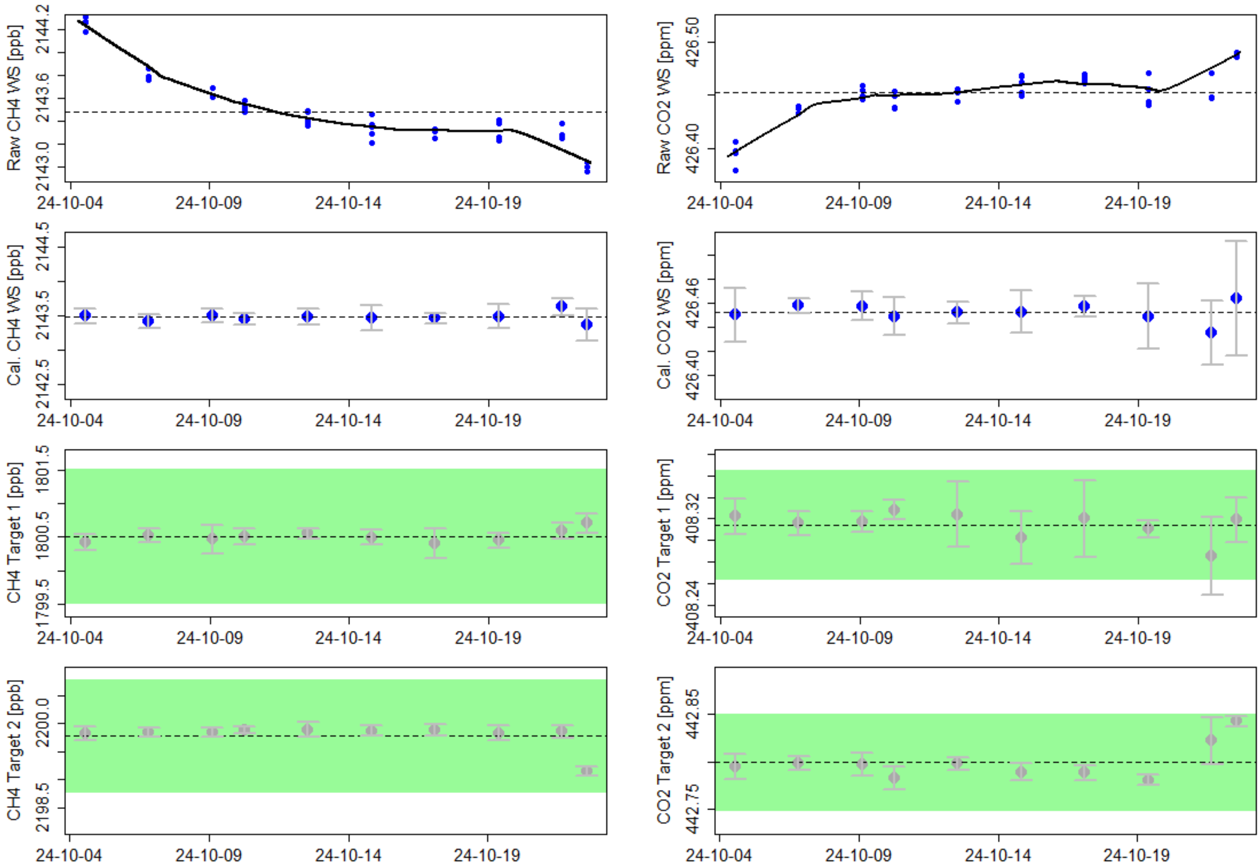


Figure 24. *CH_4 (left panel) and CO_2 (right panel) calibrations of the TI. The top panel shows the raw 1 min values of the working standard and the Loess fit (black line) used to account for drift. The second panel shows the variation of the WS after applying the drift correction. The bottom panel shows the results from the two target cylinders. Individual points in the three lower panels are 5-minute averages and the uncertainty bars represent the standard deviation. The green area represents half of the WMO/GAW compatibility goals.*

For CO, the Picarro G2401 was calibrated every 3210 minutes using three WCC-Empa TS as working standards. Based on the working standard measurements, a Loess fit drift correction was first applied to the data, as shown in the figure below.

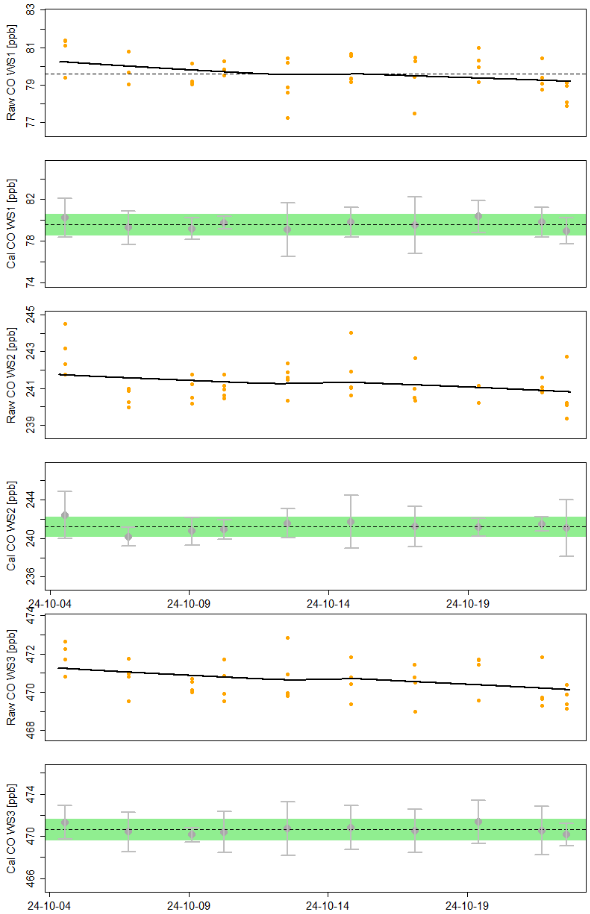


Figure 25. *CO calibrations of the TI. The panels with the orange dots show the raw 1 min values of the working standards and the Loess fit (black line) used to account for the drift. The other panels show the variation of the WS after application of the drift correction. Individual points in these panels are 5 min averages and the uncertainty bars represent the standard deviation. The green area represents half of the WMO/GAW compatibility goals.*

A linear function of the drift-corrected working standard data of then was then used to calculate calibrated CO data, which is shown in the figure below.

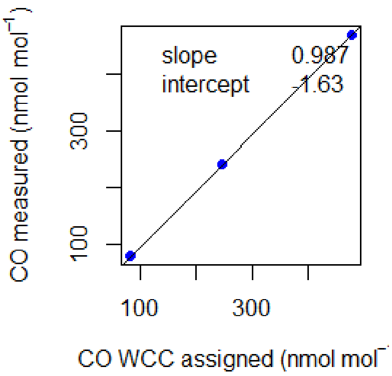


Figure 26. *CO calibration function based on the average values of the drift corrected working standard measurements.*

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List of abbreviations

BKG	Background
BKT	Bukit Kototabang GAW Station
BRIN	National Research and Innovation Agency
CCL	Central Calibration Laboratory
COEF	Coefficient
CRDS	Cavity Ring-Down Spectroscopy
DQO	Data Quality Objective
ECD	Electron Capture Detection
eDQO	Extended Data Quality Objective
FID	Flame Ionisation Detection
GAW	Global Atmosphere Watch
GAWSIS	GAW Station Information System
GHG	Greenhouse Gases
IR	Infrared
LGR	Los Gatos Research
LS	Laboratory Standard
NA	Not Applicable
NDIR	Non-Dispersive Infrared
NOAA	National Oceanic and Atmospheric Administration
QA/SAC	Quality Assurance/Science Activity Centre
RCC	Regional Calibration Centre
SH	Southern Hemisphere
SOP	Standard Operating Procedure
SN	Serial Number
SRP	Standard Reference Photometer
TI	Travelling Instrument
TROPOS	Leibnitz Institute for Tropospheric research
TS	Traveling Standard
WCCAP	World Calibration Centre for Aerosol Physics
WCC-Empa	World Calibration Centre Empa
WDCGG	World Data Centre for Greenhouse Gases
WDCRG	World Data Centre for Reactive Gases
WMO	World Meteorological Organization
WS	Working Standard