SYSTEM AND PERFORMANCE AUDIT OF SURFACE OZONE, CARBON MONOXIDE, METHANE, CARBON DIOXIDE AND NITROUS OXIDE AT THE

GLOBAL GAW STATION JUNGFRAUJOCH SWITZERLAND MARCH 2015

Submitted to the World Meteorological Organization by

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CONTENTS

EXECUTIVE SUMMARY AND RECOMMENDATIONS

The third system and performance audit by WCC-Empa[1] at the Global GAW station Jungfraujoch was conducted from 17 - 19 March 2015 in agreement with the WMO/GAW quality assurance system (WMO, 2007b). The measurements of gaseous GAW parameters within the scope of the current audit at the Jungfraujoch (JFJ) GAW station are mainly made by Empa (Swiss Federal Laboratories for Materials Science and Technology) as a joint project with the Federal Office for the Environment (FOEN) and the University of Bern (CO_2 only). Other contributors to the GAW programme include the Paul Scherrer Institute (comprehensive aerosol programme), MeteoSwiss (meteorological parameters) as well as various other institutions contributing to additional continuous and campaign-type observations. A summary is published on a yearly basis in the activity report of the International Foundation High Altitude Research Stations Jungfraujoch and Gornergrat, available at http://www.ifjungo.ch.

Previous audits at Jungfraujoch GAW station were conducted in January 1999 (Herzog et al., 1999) and July 2006 (Zellweger et al., 2006), the latter jointly with the World Calibration Centre for N_2O (Scheel, 2008). A few weeks before the current audit, a system and performance audit was carried out by the Integrated Carbon Observation System (ICOS) Atmospheric Thematic Center (ATC) Mobile Laboratory (MobileLab) operated by the Finnish Meteorological Institute (FMI).

The following people contributed to the audit:

Dr. Christoph Zellweger	Empa Dübendorf, WCC-Empa
Dr. Martin Steinbacher	Empa Dübendorf, National Air Pollution Monitoring Network
Mr. Simon A. Wyss	Empa Dübendorf, National Air Pollution Monitoring Network
Dr. Michael Schibig	Climate and Environmental Physics Institute, University of Bern

This report summarises the assessment of the Jungfraujoch GAW station in general, as well as the surface ozone, carbon monoxide, methane, carbon dioxide and nitrous oxide measurements in particular.

The report is distributed to the involved institutes of the JFJ station and the World Meteorological Organization in Geneva. The report will be posted on the internet.

The recommendations found in this report are graded as minor, important and critical and are complemented with a priority (*** indicating highest priority) and a suggested completion date.

Station Management

The JFJ research facility is managed by The International Foundation High Altitude Research Stations Jungfraujoch and Gornergrat. As an international organization, the Foundation is dedicated to providing the infrastructure and support for scientific research of international significance. The parameters of the audit scope are measured by Empa as part of the National Air Pollution Monitoring Network (NABEL) as a joint project with the Federal Office for the Environment (FOEN), and the University of Bern. Details of the organisation are available from the corresponding websites and links therein.

Empa:	http://www.empa.ch/web/s503/nabel
FOEN:	http://www.bafu.admin.ch/luft/index.html?lang=en
University of Bern:	http://www.climate.unibe.ch/?L1=research&L2=atm_gases

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

Station Location and Access

The high alpine research station Jungfraujoch (3580 m, 46.547°N 7.985°E) is situated on a mountain saddle between the two mountains Jungfrau and Mönch. The station is located in the centre of Europe and is surrounded by highly industrialized regions at much lower altitudes. This special geographical situation offers the possibility to study unpolluted air masses as well as to investigate the transport and source regions of anthropogenic pollutants. The site is all year round accessible by train.

Further information about the JFJ station is available from the GAW Station Information System (GAWSIS) (gawsis.meteoswiss.ch/GAWSIS//index.html#/search/station/stationReportDetails/451).

Station Facilities

The Jungfraujoch GAW station comprises several laboratories. The measurements of the audit scope are made in the Sphynx building. It was recognized during the last WCC-Empa audit in 2006 that the air conditioning was insufficient. In the meantime, the situation improved significantly, but laboratory temperature variations might still be critical for temperature sensitive measurements. Most of the available space is occupied by permanent measurements, but some additional space may be used for campaign based experiments. Due to its location it is an ideal platform for atmospheric research.

> **Recommendation 1 (**, important, 2016)**
> *Laboratory temperature variations are still high, and part of the instrumentation is installed in areas without air conditioning. It is recommended that all parts of the laboratory are air conditioned. Laboratory temperature variation should not exceed ±5°C.*

Operation and Maintenance

The station is visited by NABEL staff in irregular intervals but at least once per month. All instruments are closely monitored remotely. In case of instrument problems or failure, response time is usually within a few days. Furthermore, custodians live permanently at JFJ. They can be contacted for technical assistance if needed.

Measurement Programme

The JFJ station comprises a very comprehensive measurement programme that covers all focal areas of the GAW programme. It is further part of national and international research programmes such as EMEP (European Monitoring and Evaluation Programme) or AGAGE (Advanced Global Atmospheric Gases Experiment). An overview on measured species is available from GAWSIS.

> **Recommendation 2 (**, minor, 2016)**
> *GAWSIS needs to be updated to reflect the recent change in the carbon monoxide and nitrous oxide instrumentation.*

Air Inlet System

The sample inlet is located on the top of the Sphinx building at a height of 5 m above the roof. The inlet is made of stainless steel which is heated to 10°C to avoid icing if the inlet and condensation of water vapour. The total length is approximately 3 m, with an inner diameter of 9 cm and a flow rate of 870 l/min. From there, a manifold flushed with 100 l/min serves as sampling ports for the most analysers, whereas the GHG instruments are directly connected to the main stainless steel inlet by ⅛″ SS tubing. The pressure and temperature in the main inlet are recorded in Empa's central data acquisition system. Inlet filters are replaced in regular intervals, and the changes are noted in the log book.

The air inlet system is state of the art and adequate for its intended purpose. However, a possible concern is the close proximity of the inlet system to the tourist platform, where smoking is still allowed. It is possible that the measurements are influenced by these activities on calm days. Investigations that study the potential contamination by local pollution sources already started with additional measurements at the East Ridge Station, which is located approximately 500 m to the west at 150 m higher altitude.

Surface Ozone Measurements

The surface ozone measurements at Jungfraujoch were established in 1986 and continuous time series are available since then.

Instrumentation. The station is equipped with two ozone analysers (TEI 49i and TEI 49C). The instrumentation is adequate for its intended purpose. Normally, only the data of the TEI 49i instrument is used. The other instrument is used as part of the nitrogen oxides measurement system, and serves as backup ozone measurements in case of data gaps of the main instrument. The main ozone analyser is replaced at least in two year intervals and is sent to the Swiss representative of the manufacturer for cleaning, service and the replacement of wear parts.

Standards. Ozone transfer standards (TEI 49C-PS) are available at Empa. The transfer standards have full traceability to the WMO/GAW reference (Standard Reference Photometer SRP#15) maintained at Empa within the framework of the NABEL and WCC-Empa programmes. Calibrations of the transfer standards (TS) against the SRP are made at least twice per year, and on-site calibration using the TS are made two to three times per year.

Intercomparison (Performance Audit). The ozone analysers at JFJ were compared against the WCC-Empa travelling standard (TS) with traceability to a Standard Reference Photometer (SRP). The result of the comparisons is summarised below with respect to the WMO GAW Data Quality Objectives (DQOs) (WMO, 2013). The data was acquired by the WCC-Empa data acquisition system, and no further corrections were applied. The following equations characterise the bias of the instruments:

Main station analyser:

TEI 49i #CM08320009 (BKG +0.0 ppb, COEF 1.008):

Unbiased O_3 mixing ratio (ppb): X_{O3} (ppb) = ([OA] – 0.32 ppb) / 0.9960 (1a)

Standard uncertainty (ppb): u_{O3} (ppb) = sqrt (0.37 ppb^2 + 2.87e-05 * X_{O3}^2) (1b)

Backup station analyser:

TEI 49C #429508925 (BKG +0.5 ppb, COEF 1.026):

Unbiased O_3 mixing ratio (ppb): X_{O3} (ppb) = ([OA] - 0.31 ppb) / 1.0081 (1c)

Standard uncertainty (ppb): u_{O3} (ppb) = sqrt (0.34 ppb^2 + 2.74-05 * X_{O3}^2) (1d)

The result of the comparison is further illustrated in the figures below.

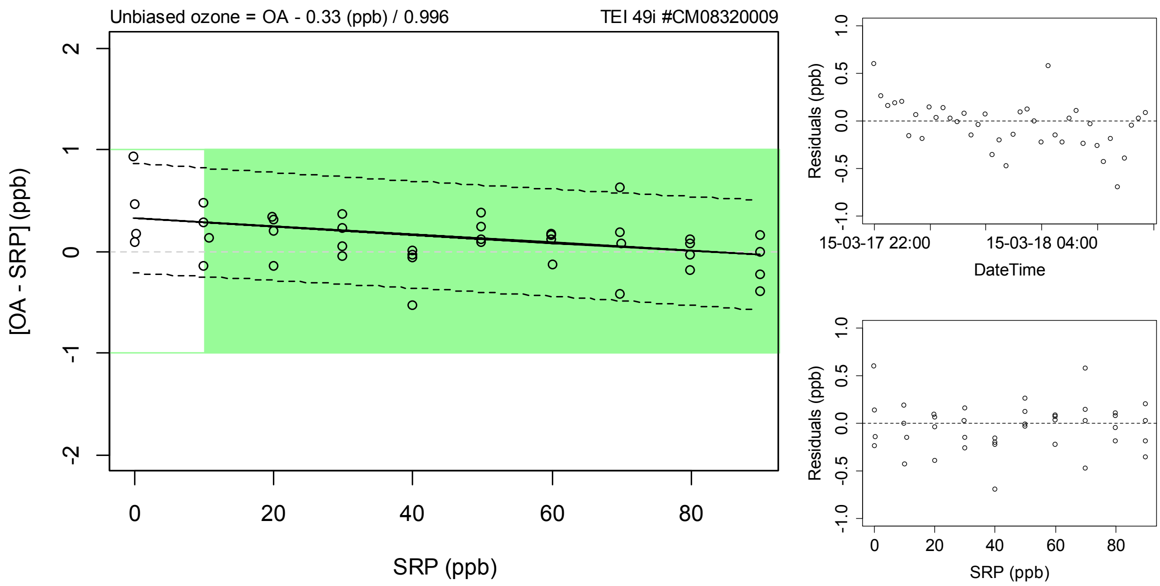

Figure 1. *Left: Bias of the JFJ ozone analyser (TEI 49i #CM08320009) with respect to the SRP as a function of mole fraction. Each point represents the average of the last 10 one-minute values at a given level. The green lines correspond to the DQOs and the green area to the mole fraction range relevant for JFJ. The dashed lines about the regression lines are the Working-Hotelling 95% confidence bands. Right: Regression residuals of the ozone comparisons as a function of time (top) and mole fraction (bottom).*

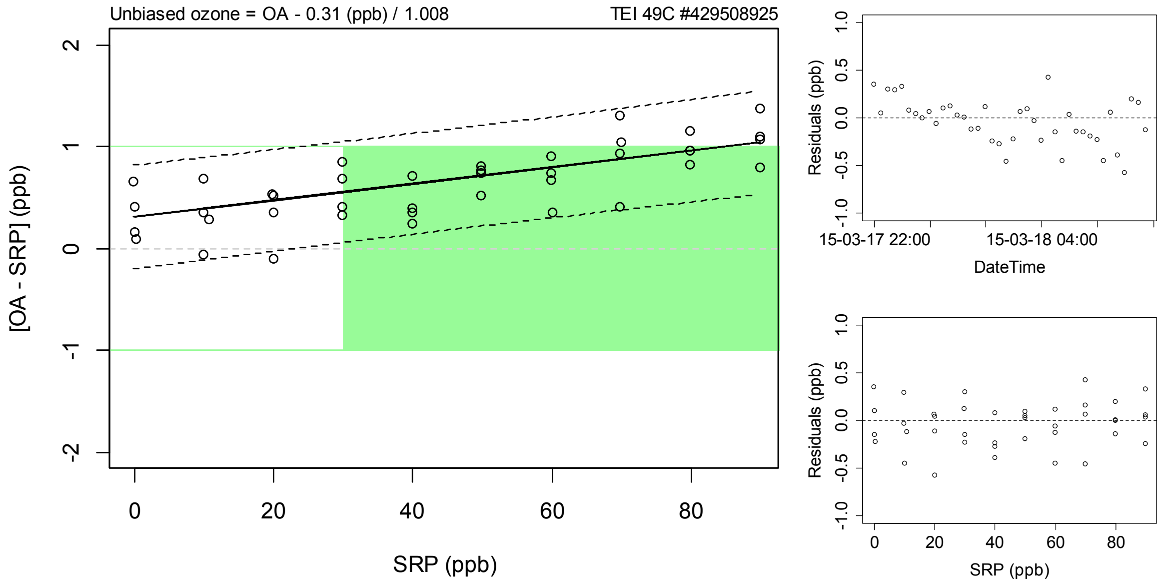

Figure 2. *Same as above for the backup ozone analyser TEI 49C #429508925.*

The results of the comparison can be summarised as follows:

The TEI 49i #CM08320009 ozone analyser is in good calibration and the bias is within the WMO/GAW DQOs for the relevant mole fraction range. The backup analyser has a slightly larger bias with respect to the ozone reference; however, data of this instrument is normally not used for data submission. The instrumentation at JFJ is adequate for ozone measurements.

Carbon Monoxide Measurements

Carbon monoxide measurements at Jungfraujoch were established in 1996, and continuous time series are available since then.

Instrumentation. Jungfraujoch is equipped with different CO instruments. The main analyser is based on Cavity Ring Down Spectroscopy (CRDS) (Picarro G2401). In addition, CO is also measured using cavity enhanced off-axis Integrated Cavity Output Spectroscopy (OA-ICOS) technology (LGR-23r). Despite the superior precision of the OA-ICOS technology to the CRDS instrument, the latter is still selected as master instrument due to the long experience of the operators with this type of analysers and the robustness and the long-term stability of the instrument. Previously, CO was also measured by Non-dispersive Infrared (NDIR) absorption technique (Horiba APMA 360 and APMA 370) and gas chromatography with Flame Ionisation Detector (FID). The current instrumentation is state of the art for CO measurement.

Standards. Picarro G2401, # CFKADS2133: Three calibration standards with traceability to the WMO/GAW reference scale and a unit to generate CO-free air are available at JFJ for calibration. Calibrations are performed every 61 hours. Additionally, a target tank for quality control is measured every 15 hours.

LGR-23r #12-0066: Three calibration standards with traceability to the WMO/GAW reference scale are available at JFJ and are measured every 33 hours. In addition, a working standard, which is measured every three hours to account for short-term fluctuations of the instrument's sensitivity, and a target tank for quality control (measured every 16 hours) are available. A list of the available standards is given in the Appendix. At the time of the audit, the WMO-X2014 CO calibration scale was used. This scale was revised in December 2015 with the release of the WMO-X2014A CO calibration scale.

Recommendation 3 (, important, before next data submission)**
It is recommended to change to the WMO-X2014A calibration scale. Previously acquired data should also be re-evaluated accordingly.

Intercomparison (Performance Audit). The comparison involved repeated challenges of the JFJ instruments with randomised carbon monoxide levels using WCC-Empa travelling standards. The following equations characterise the instrument bias, and the results are further illustrated in Figure 3 and 4 with respect to the WMO GAW DQOs (WMO, 2014):

Picarro G2401, # CFKADS2133:

Unbiased CO mixing ratio: X_{CO} (ppb) = (CO + 3.9) / 1.0078 (2a)

Remaining standard uncertainty: u_{CO} (ppb) = sqrt (9.7 ppb^2 + 1.01e-04 * X_{CO}^2) (2b)

LGR-23r #12-0066:

Unbiased CO mixing ratio: X_{CO} (ppb) = (CO + 1.4) / 1.0083 (2c)

Remaining standard uncertainty: u_{CO} (ppb) = sqrt (0.3 ppb^2 + 1.01e-04 * X_{CO}^2) (2d)

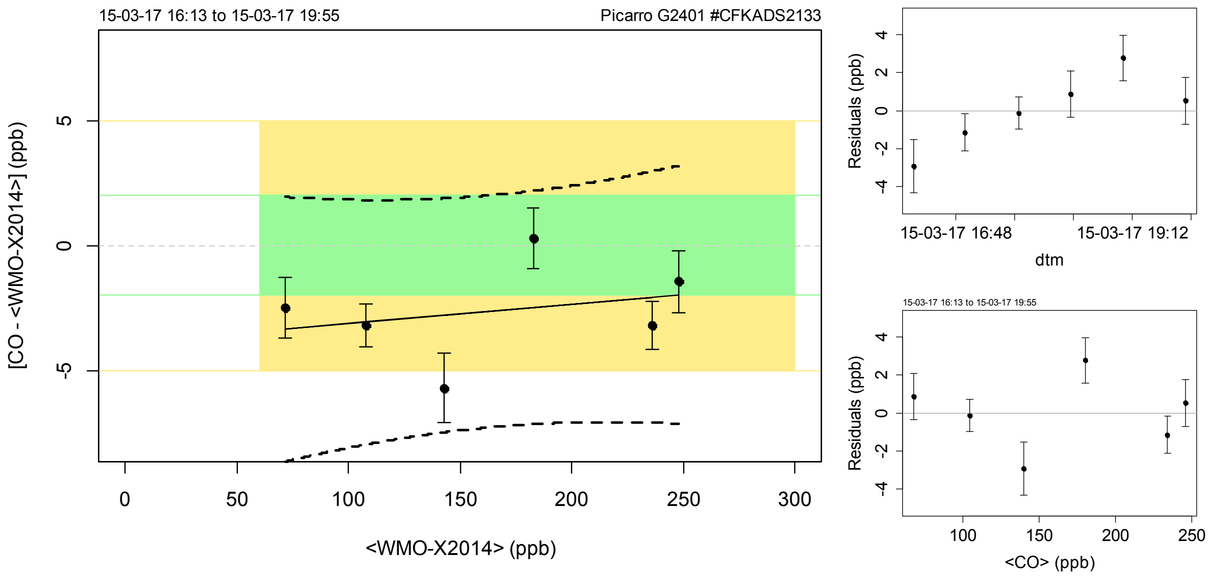

Figure 3. *Left: Bias of the JFJ Picarro G2401, # CFKADS2133 carbon monoxide instrument with respect to the WMO-X2014 reference scale as a function of mole fraction. Each point represents the average of data at a given level from a specific run. The error bars show the standard deviation of individual measurement points. The green and yellow lines correspond to the WMO compatibility and extended compatibility goals, and the green and yellow areas to the mole fraction range relevant for JFJ. The dashed lines around the regression lines are the Working-Hotelling 95% confidence bands. Right: Regression residuals (time dependence and mole fraction dependence).*

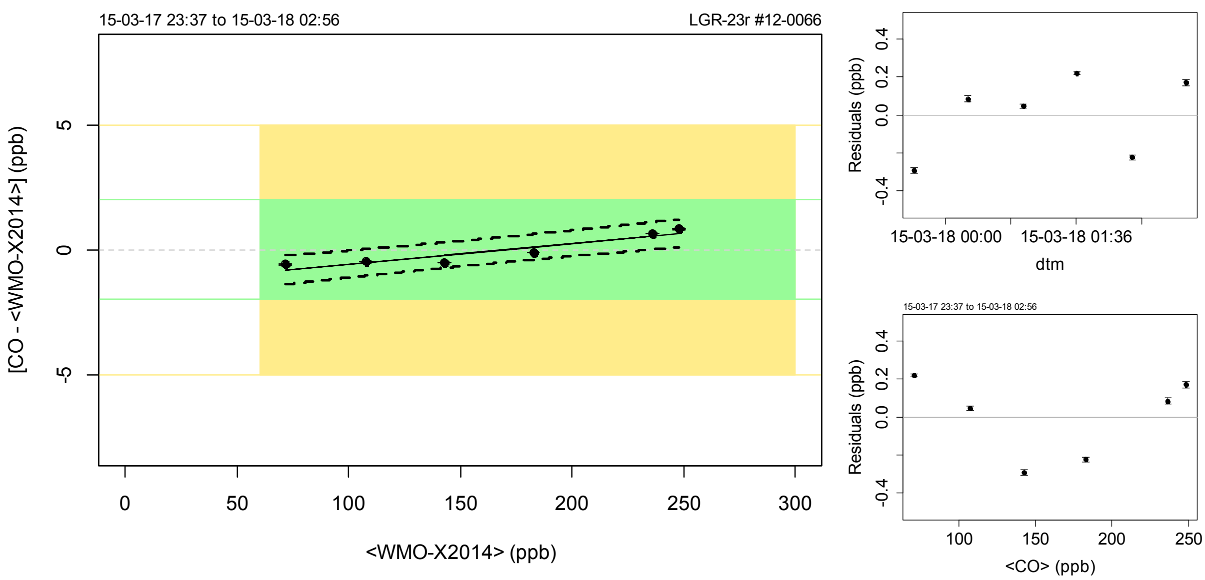

Figure 4. *Same as above, LGR-23r for the.*

The results of the comparisons can be summarised as follows:

Agreement only within the extended WMO/GAW compatibility goals of ±5 ppb was found for the CRDS instrument. Considerably smaller deviations also associated with smaller uncertainties were found for the OA-ICOS analyser LGR 23-r with an agreement well within the WMO/GAW compatibility goals of ±2 ppb over the entire relevant mole fraction range. The instrumentation is adequate, and no further action is required.

Methane Measurements

Measurements of methane at JFJ commenced in 2005, and continuous data series are available since then. Initially, these measurements were made using a GC/FID system (Agilent 6890). In 2009, a Picarro G1301 CRDS instrument was installed, and since then, data of the CRDS instrument is considered for submission to the WMO/GAW data centre. The G1301 was replaced by a Picarro G2401 instrument in 2010, which again was replaced by another Picarro G2401 in June 2014.

Instrumentation. Picarro G2401, including a Nafion© drying system and a custom made calibration unit. Ambient air is sampled from the top of the Sphinx building, 5 m above the roof. Calibrations using three standards are made every 61 h, while a target tank is measured every 15 h.

Standards. Three calibration standards with traceability to the WMO/GAW reference scale are available at JFJ. In addition, a target tank is available. A list of the available standards is given in the Appendix.

Intercomparison (Performance Audit). The comparison involved repeated challenges of the JFJ instrument with randomised CH_4 levels from travelling standards. The results of the comparison measurements for the individual measurement parameters are summarised and illustrated below.

The following equation characterises the instrument bias. The result is further illustrated in Figure 5 with respect to the relevant mole fraction range and the WMO/GAW compatibility goals and extended compatibility goals (WMO, 2014).

Picarro G2401, #CFKADS2133:

Unbiased CH_4 mixing ratio: X_{CH4} (ppb) = (CH_4 – 1.9 ppb) / 0.99919 (3a)

Remaining standard uncertainty: u_{CH4} (ppb) = sqrt (0.1 ppb^2 + 1.30e-07 * X_{CH4}^2) (3b)

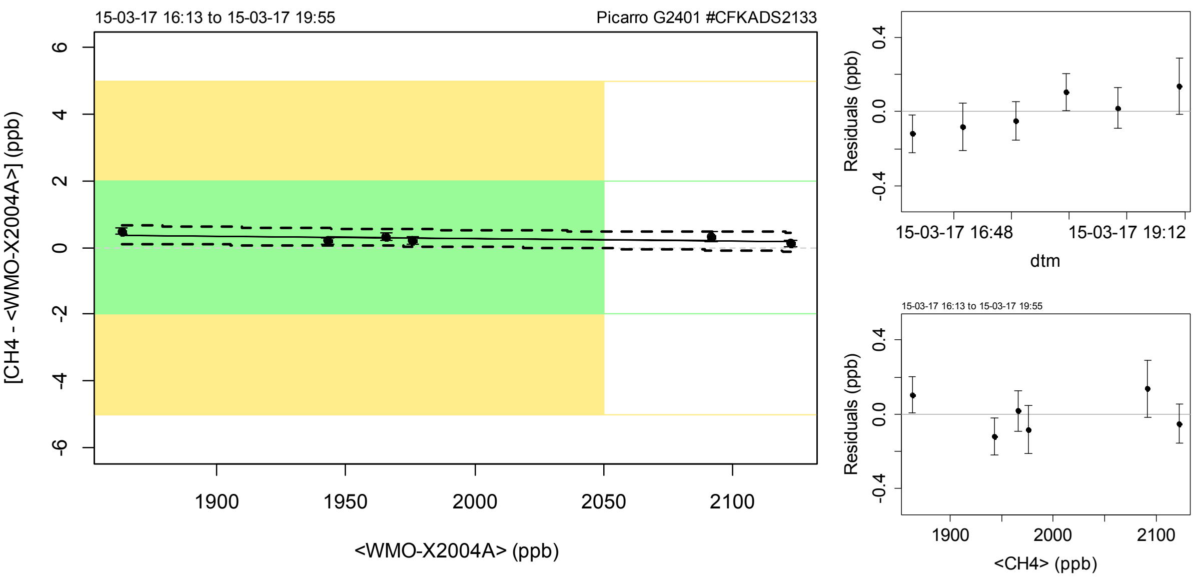

Figure 5. *Left: Bias of the PICARRO G2401 #CFKADS2133 methane instrument with respect to the WMO-X2004 CH_4 reference scale as a function of mole fraction. Each point represents the average of data at a given level from a specific run. The error bars show the standard deviation of individual measurement points. The green and yellow lines correspond to the WMO compatibility and extended compatibility goals, and the green and yellow areas to the mole fraction range relevant for JFJ. The dashed lines around the regression lines are the Working-Hotelling 95% confidence bands. Right: Regression residuals (time dependence and mole fraction dependence).*

The result of the comparison can be summarised as follows:

Agreement well within the WMO/GAW compatibility goals of ±2 ppb was found in the entire mole fraction range tested during the audit. These results show that the instrumentation is fully adequate and no further action is required.

Carbon Dioxide Measurements

Measurements of carbon dioxide at JFJ commenced in 2004, made by the division of Climate and Environmental Physics at the University of Bern (KUP) using a nondispersive infrared gas analyser (NDIR) in combination with a paramagnetic O_2 analyser, and continuous data series are available since then. Additionally, a CRDS CO_2 analyser was installed by Empa as part of the National Air Pollution Monitoring Network (NABEL) in 2009 (details see CH_4 measurements).

Instrumentation. Empa: Picarro G2401, details see CH_4 above. University of Bern: Sick Maihak S710 NDIR spectrometer, air is cryogenically dried to a dew point of -90°C (FC-100D21, FTS systems, USA). Details of the calibration scheme are given in Schibig et al. (2015).

Standards. Empa: Picarro G2401, details see CH_4 above. University of Bern: see Schibig et al. (2015).

Intercomparison (Performance Audit). The comparison involved repeated challenges of the JFJ instrument with randomised CO_2 levels from travelling standards. The results of the comparison measurements for the individual measurement parameters are summarised and illustrated below.

The following equation characterises the instrument bias. The result is further illustrated in Figure 6 with respect to the relevant mole fraction range and the WMO/GAW compatibility goals and extended compatibility goals (WMO, 2014).

Empa: Picarro G2401, #CFKADS2133:

Unbiased CO_2 mixing ratio: X_{CO2} (ppm) = (CO_2 – 0.10 ppm) / 0.99975 (4a)

Remaining standard uncertainty: u_{CO2} (ppm) = sqrt (0.011 ppm^2 + 3.28e-08 * X_{CO2}^2) (4b)

University of Bern: Sick Maihak S710:

Unbiased CO_2 mixing ratio: X_{CO2} (ppm) = (CO_2 + 3.62 ppm) / 1.00907 (4c)

Remaining standard uncertainty: u_{CO2} (ppm) = sqrt (0.060 ppm^2 + 3.28e-08 * X_{CO2}^2) (4d)

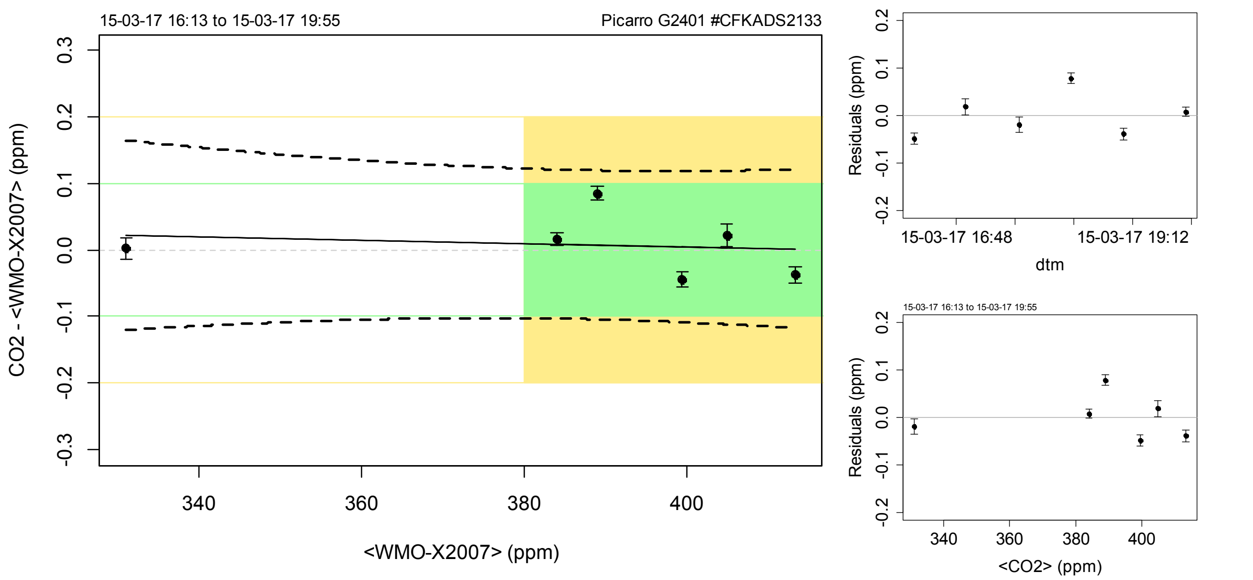

Figure 6. *Left: Bias of the PICARRO G2401 #CFKADS2133 CO_2 instrument with respect to the WMO-X2007 reference scale as a function of mole fraction. Each point represents the average of data at a given level from a specific run. The error bars show the standard deviation of individual measurement points. The green and yellow lines correspond to the WMO compatibility and extended compatibility goals, and the green and yellow areas to the mole fraction range relevant for JFJ. The dashed lines around the regression lines are the Working-Hotelling 95% confidence bands. Right: Regression residuals (time dependence and mole fraction dependence).*

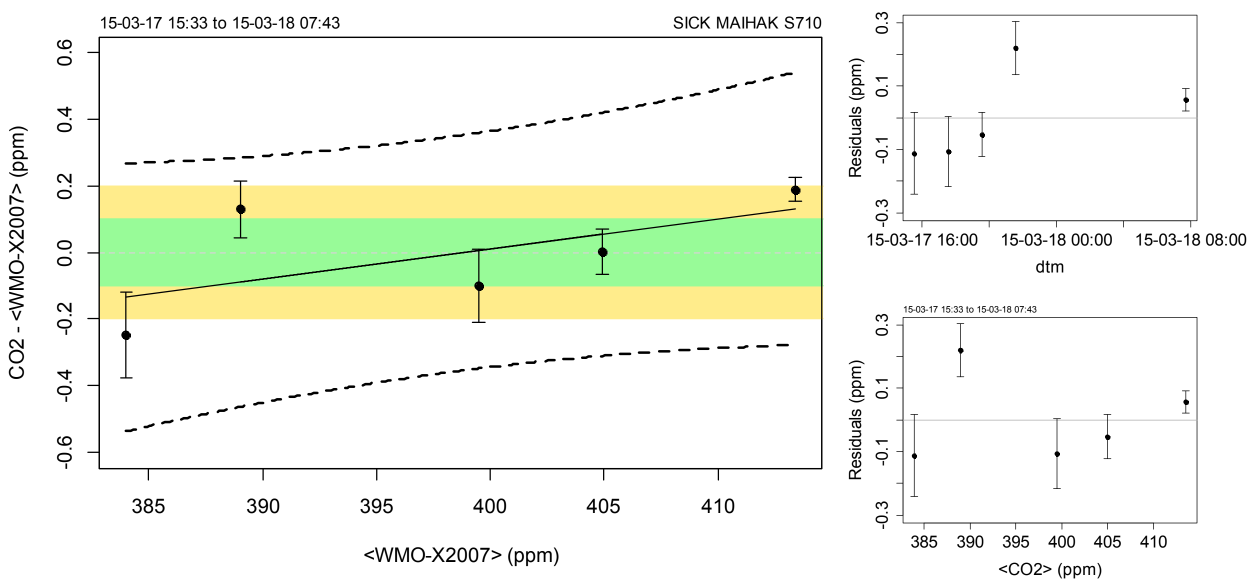

Figure 7. *Same as above for the Sick Maihak S710 instrument. The low CO_2 standard was not measured since it was outside the calibrated range of this instrument.*

The result of the comparison can be summarised as follows:

Agreement within the WMO/GAW compatibility goals of ±0.1 ppm was found in the entire mole fraction range tested during the audit for the CRDS instrument. A slightly higher bias with associated larger uncertainties was found for the NDIR instrument, which is expected due to the more difficult calibration procedure of this technique. The results of both instruments show that the instrumentation is adequate and no further action is required.

Nitrous Oxide Measurements

Nitrous oxide measurements at Jungfraujoch were established in 2005, and continuous time series are available since then.

Instrumentation. Jungfraujoch was initially equipped with a GC/ECD system (Agilent 6890). Details are available from a previous audit report of the WCC-N_2O (Scheel, 2008). This system is still operational but the main analyser is now based on cavity enhanced off-axis Integrated Cavity Output Spectroscopy (OA-ICOS) technology (LGR-23r). The current instrumentation is state of the art for N_2O measurement.

Standards. Three calibration standards with traceability to the WMO/GAW reference scale are available at JFJ and are measured every 33 hours. In addition, a working standard, which is measured every three hours to account for short-term fluctuations of the instrument's sensitivity, and a target tank for quality control (measured every 16 hours) are available. A list of the available standards is given in the Appendix.

Intercomparison (Performance Audit). The comparison involved repeated challenges of the JFJ instruments with randomised nitrous oxide levels using WCC-Empa travelling standards. The following equations characterise the instrument bias, and the results are further illustrated in Figure 3 and 4 with respect to the WMO GAW DQOs (WMO, 2014):

LGR-23r #12-0066:

Unbiased N_2O mixing ratio: X_{N2O} (ppb) = (N_2O – 0.87) / 0.99654 (5a)

Remaining standard uncertainty: u_{N2O} (ppb) = sqrt (0.022 ppb^2 + 1.01e-07 * X_{N2O}^2) (5b)

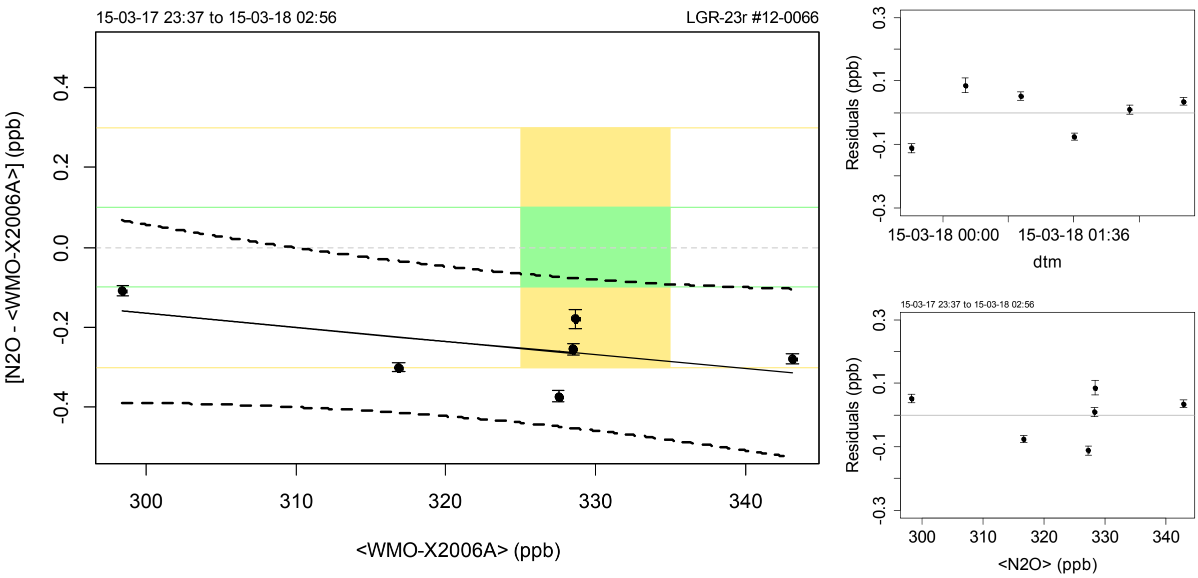

Figure 8. *Left: Bias of the JFJ LGR-23r nitrous oxide instrument with respect to the WMO-X2006A reference scale as a function of mole fraction. Each point represents the average of data at a given level from a specific run. The error bars show the standard deviation of individual measurement points. The green and yellow lines correspond to the WMO compatibility and extended compatibility goals, and the green and yellow areas to the mole fraction range relevant for JFJ. The dashed lines around the regression lines are the Working-Hotelling 95% confidence bands. Right: Regression residuals (time dependence and mole fraction dependence).*

The result of the comparison can be summarised as follows:

The agreement of the OA-ICOS analyser LGR 23-r did not comply with the WMO/GAW compatibility goals but the average bias was within the extended compatibility goal of 0.3 ppb. It should therefore be explored if the current analytical system can further be optimised. However, it should also be noted that this result is still good compared to the majority of N_2O comparisons which often exceed the extended compatibility goal.

Recommendation 4 (, minor, 2016)**
It should be explored if the current analytical system can be optimised with respect to N_2O measurements. To identify potential sources for the bias, a full uncertainty budget is needed.

Parallel Measurements of Ambient Air

The audit included parallel measurements of CO_2, CH_4 and CO with a WCC-Empa travelling instrument (TI) (Picarro G2401 SN # 1497-CFKADS2098). The TI was running from 19 March 2015 through 29 May 2015. The TI was using a completely separate inlet line leading to the same air intake location as the JFJ station inlet. In addition, air was also sampled from the inlet for halocarbon observations, which is located below the tourist platform. The TI was sampling using the following sequence: 1435 min ambient air from the independent WCC inlet, 300 min ambient air from the halocarbon inlet followed by 30 min measurement of three standard gases (10 min each). To account for the effect of water vapour a correction function (Rella et al., 2013; Zellweger et al., 2012) was applied to the WCC-Empa CRDS data. Details of the calibration of the TI are given in the Appendix. The following figures show the results of the ambient air comparisons.

Carbon dioxide:

Figure 9 shows the CO_2 comparison of the Picarro G2401 analyser with the WCC-Empa TI (1 min data). It can be seen that the temporal variation was well captured by both instruments, and the bias was on average within the WMO/GAW compatibility goal of 0.1 ppm. The TI sampled air from two different independent inlets; for most of the time, an independent inlet located at the same location as the station inlet was used. During the periods indicated by vertical grey bars in Figure 9, a second inlet located below the tourist platform was used. Figure 10 shows deviation histograms (1 min data) of the bias for all data, for the period when the TI sampled from the same inlet location as the station analyser, and for the period when the TI sampled from inlet below the tourist platform. The best agreement with an average bias of 0.00±0.08 ppm is observed for the case where both instruments sampled from the same location. This confirms that the JFJ inlet system is fully adequate, and no leaks are present. However, a higher bias of 0.18±0.62 ppm was observed when the two inlet locations were compared. Further, the distribution of the observed bias is asymmetrical, with more cases where the station instrument measured higher values compared to the TI. Most likely this was caused by the influence of the touristic activities on the Sphynx platform located approximately 12 m below the station inlet and 5 m above the second inlet. An example of a day with potential influence through tourist activities is shown in Figure 11. This particular day was characterized by relatively calm conditions with daytime wind speed ranging from 0 to 7.5 m/s. During this day, significantly higher CO_2 levels were observed from the inlet above the platform, which is a clear indication that the air intake location of the JFJ station is subject to local influence under such conditions. Individual 1 min values of CO_2 were up to 6 ppm higher at the JFJ inlet, and up to approximately 1 ppm higher for hourly averages.

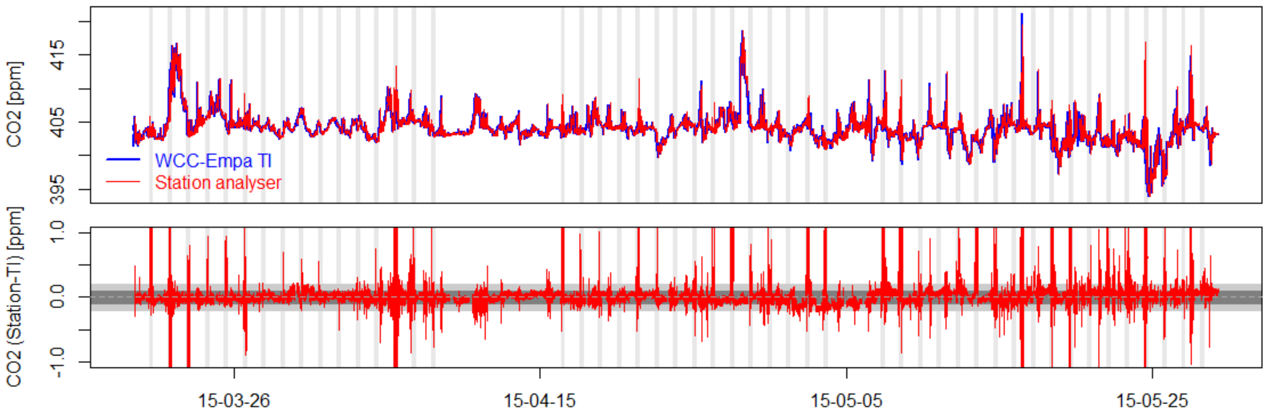

Figure 9. CO_2 comparison at JFJ between the WCC-Empa travelling instrument and the JFJ Picarro G2401. Upper panel: CO_2 time series (1 min data). Lower panel: CO_2 bias of the station analyser vs time. The horizontal grey areas correspond to the WMO/GAW compatibility (dark grey) and extended compatibility (light grey) goals; vertical grey bars (left diagrams) illustrate when different inlets were used (see text for details).

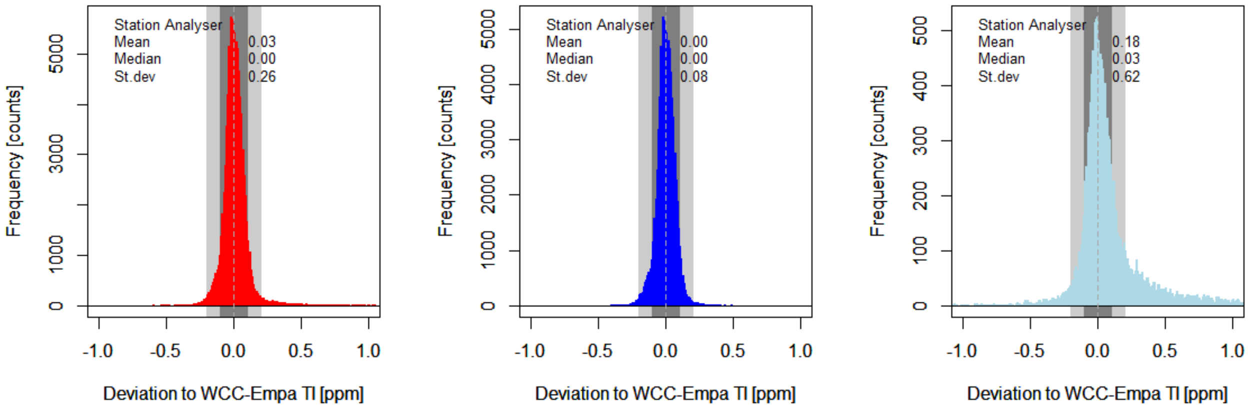

Figure 10. Deviation histograms (Station analyser – TI) for all data (left), for the period when the TI sampled from the same inlet location as the station analyser (middle) and for the period when the TI sampled from inlet below the tourist platform (right).

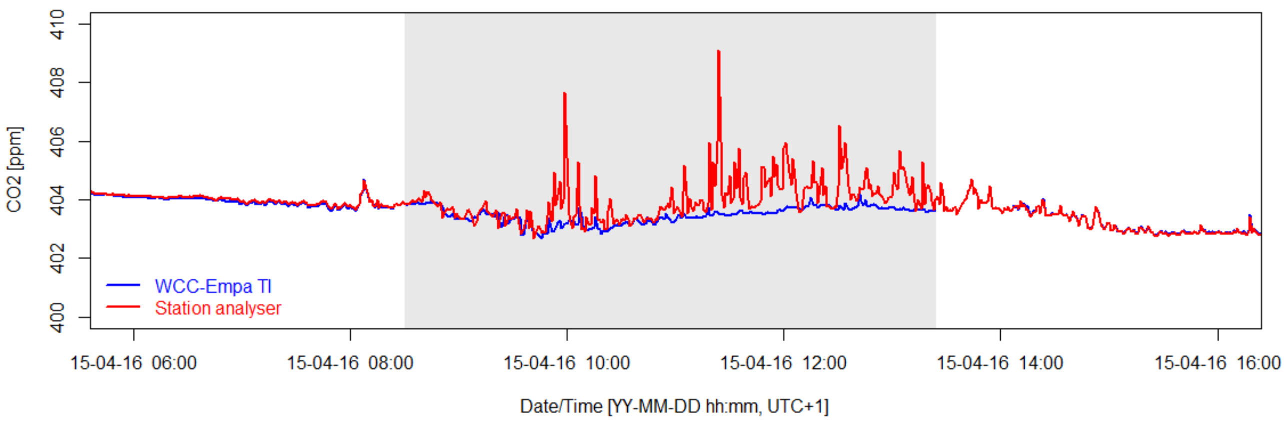

Figure 11. CO_2 comparison at JFJ between the WCC-Empa TI and the JFJ Picarro G2401 during a calm day in April 2015 (1 min data). White area: both instruments sampled air from the same air intake location above the tourist platform. Grey area: TI sampled air from the inlet below the tourist platform.

Methane:

Figure 12 shows the CH_4 comparison of the Picarro G2401 analyser with the WCC-Empa TI. As for CO_2, the temporal variation was well captured by both instruments, and the bias was on average within the WMO/GAW compatibility goal of 2 ppb. Figure 13 shows deviation histograms (1 min data) of the bias for all data, for the period when the TI sampled from the same inlet location as the station analyser and for the period when the TI sampled from inlet below the tourist platform. We observed a difference in the bias when both instruments sampled from the same location (1.25±1.26 ppb) and the inlet below the tourist platform (1.77±1.73 ppb). The reason for this might be similar as for CO_2; it could be that local emissions from tourist activities are observed during days with low wind speed and thermally induced upward transport. Alternatively, the same meteorological conditions also favour upward transport of air that originates from inside the Sphynx building. CH_4 indoor mole fraction are significantly higher compared to ambient due to the use of CH_4 in Argon as a carrier gas of the GC/ECD system. The ambient air comparison for the same day as above is shown in Figure 10. During this day, significantly higher CH_4 levels were observed from the inlet above the platform. Individual 1 min values of CH_4 were up to 25 ppb higher at the JFJ inlet, and up to approximately 5 ppb higher for hourly averages. However, most of the other days do not reveal such a large effect.

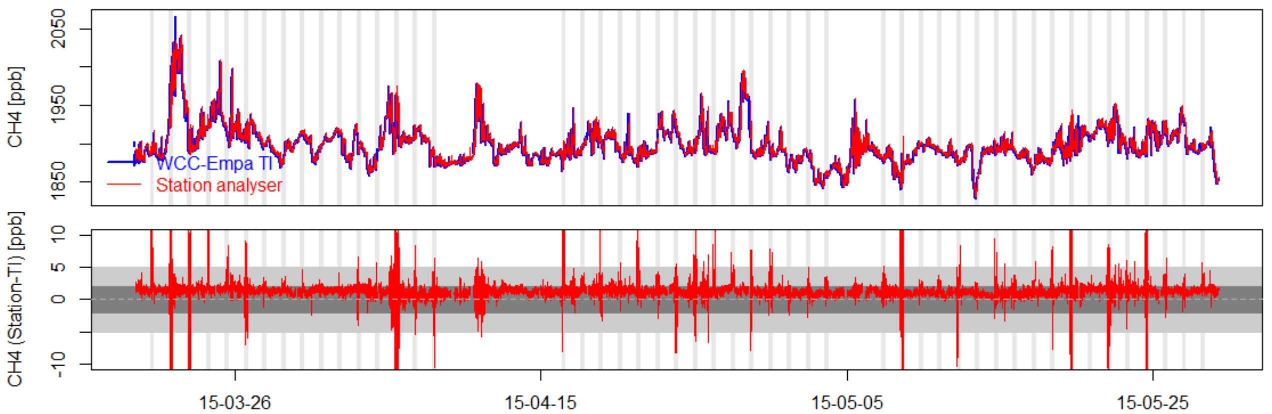

Figure 12. CH_4 comparison at JFJ between the WCC-Empa travelling instrument and the JFJ Picarro G2401. Upper panel: CH_4 time series (1 min data). Lower panel: CH_4 bias of the station analyser vs time. The horizontal grey areas correspond to the WMO/GAW compatibility (dark grey) and extended compatibility (light grey) goals; vertical grey bars (left diagrams) illustrate when different inlets were used (see text for details).

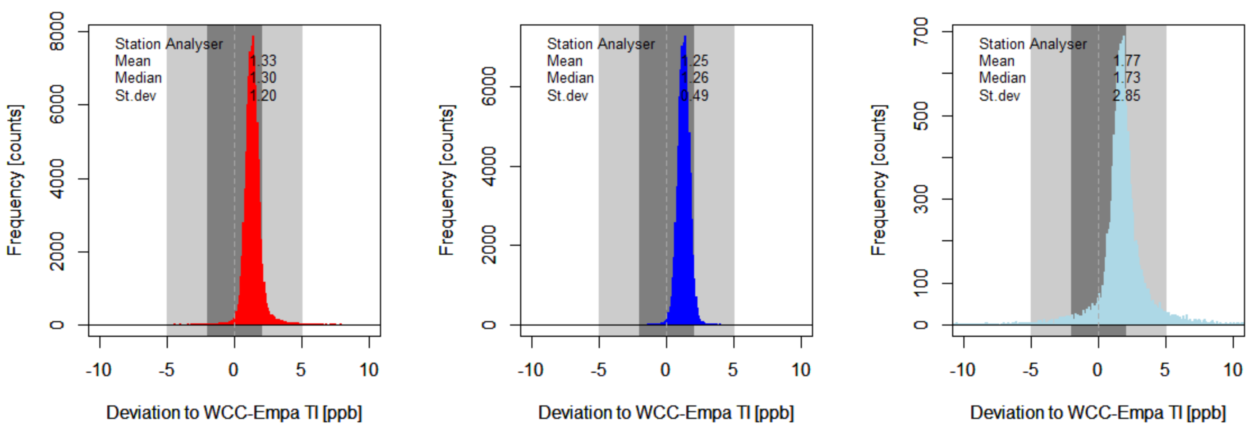

Figure 13. Deviation histograms (Station analyser – TI) for all data (left), for the period when the TI sampled from the same inlet location as the station analyser (middle) and for the period when the TI sampled from inlet below the tourist platform (right).

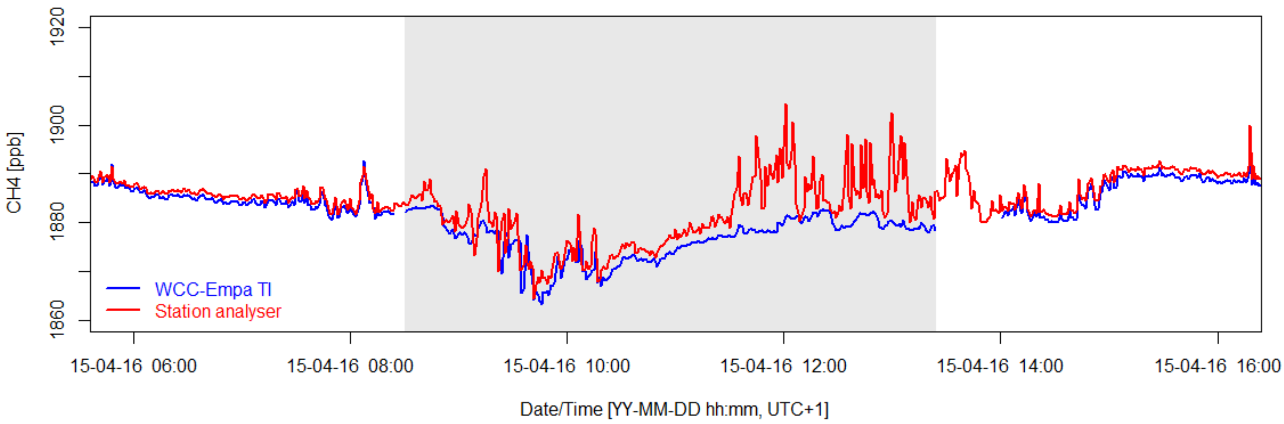

Figure 14. CH_4 comparison at JFJ between the WCC-Empa TI and the JFJ Picarro G2401 during a calm day in April 2015 (1 min data). White area: both instruments sampled air from the same air intake location above the tourist platform. Grey area: TI sampled air from the inlet below the tourist platform.

Carbon Monoxide:

Due to the larger noise in the CO signals of the TI and the station analysers, 1h averages were used for the CO comparison. Results of the CO comparison (1h data) between the WCC-Empa TI and the JFJ Picarro G2401 analyser are shown in Figures 15 and 16, and for the JFJ LGR-23r analyser in Figures 17 and 18. The temporal variation was well captured by all instruments. The average deviation was within the WMO/GAW compatibility goal for both instruments, and the results confirm the findings of the performance audit with travelling standards. However, as for CH_4 and CO_2, a significant difference was found between the two inlet locations. This is further illustrated in the histogram plots in Figures 16 and 18 and as a time series plot during the same day as for the other species in Figure 19. The difference between the two inlet locations was for both instruments approximately 1.5 ppb. The ambient air comparison for the same day as above is shown in Figure 19 for the LGR-23r instrument. Again, similar results were observed as for the other species. During this day, individual 1 min values of CO were up to 40 ppb higher at the JFJ inlet, and up to approximately 15 ppb higher for hourly averages.

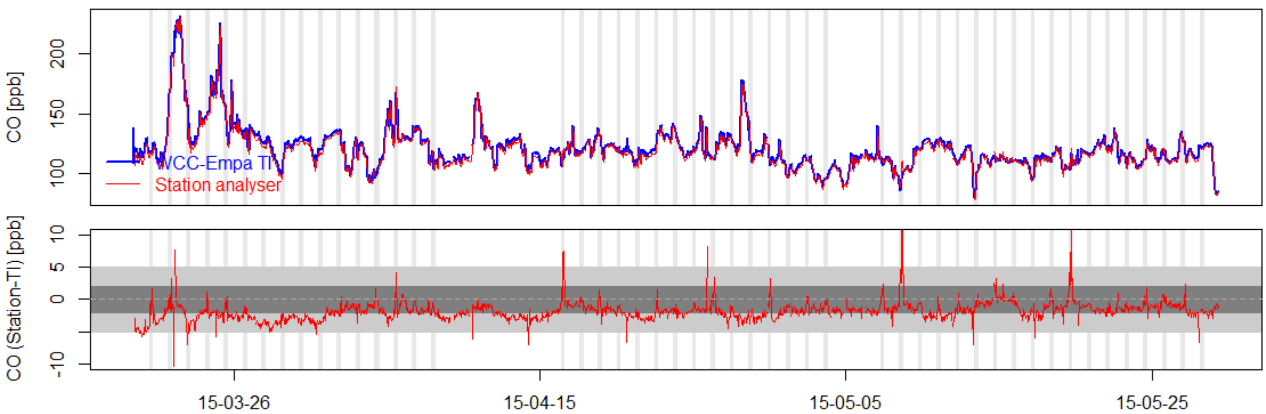

Figure 15. CO comparison at JFJ between the WCC-Empa travelling instrument and the JFJ Picarro G2401 analyser. Upper panel: CO time series (1 h data). Lower panel: CO bias of the station analyser vs time. The horizontal grey areas correspond to the WMO/GAW compatibility (dark grey) and extended compatibility (light grey) goals; vertical grey bars (left diagrams) illustrate when different inlets were used (see text for details).

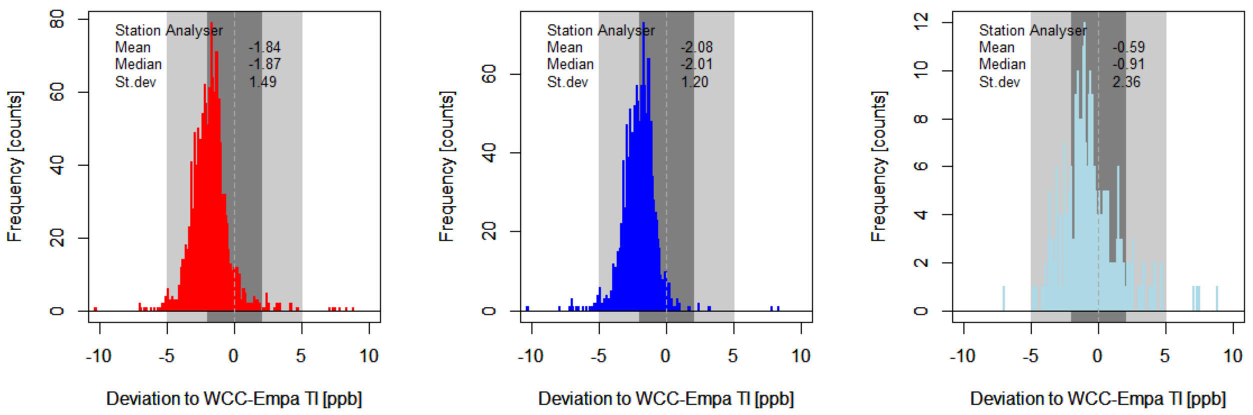

Figure 16. Deviation histograms for CO (Station analyser Picarro G2401– TI) for all data (left), for the period when the TI sampled from the same inlet location as the station analyser (middle) and for the period when the TI sampled from inlet below the tourist platform (right).

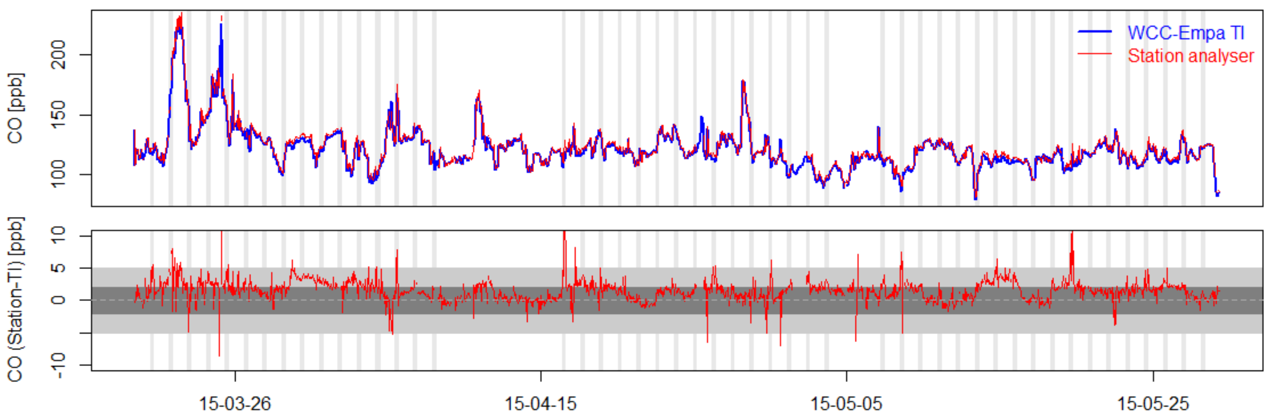

Figure 17. CO comparison at JFJ between the WCC-Empa travelling instrument and the JFJ LGR-23r analyser. Upper panel: CO time series (1 h data). Lower panel: CO bias of the station analyser vs time. The horizontal grey areas correspond to the WMO/GAW compatibility (dark grey) and extended compatibility (light grey) goals; vertical grey bars (left diagrams) illustrate when different inlets were used (see text for details).

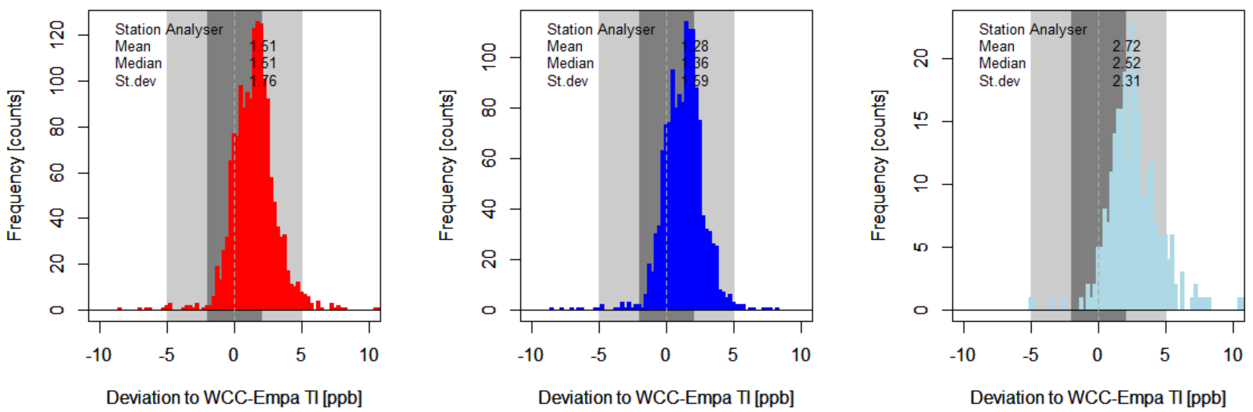

Figure 18. Deviation histograms for CO (Station analyser LGR-23r – TI) for all data (left), for the period when the TI sampled from the same inlet location as the station analyser (middle) and for the period when the TI sampled from inlet below the tourist platform (right).

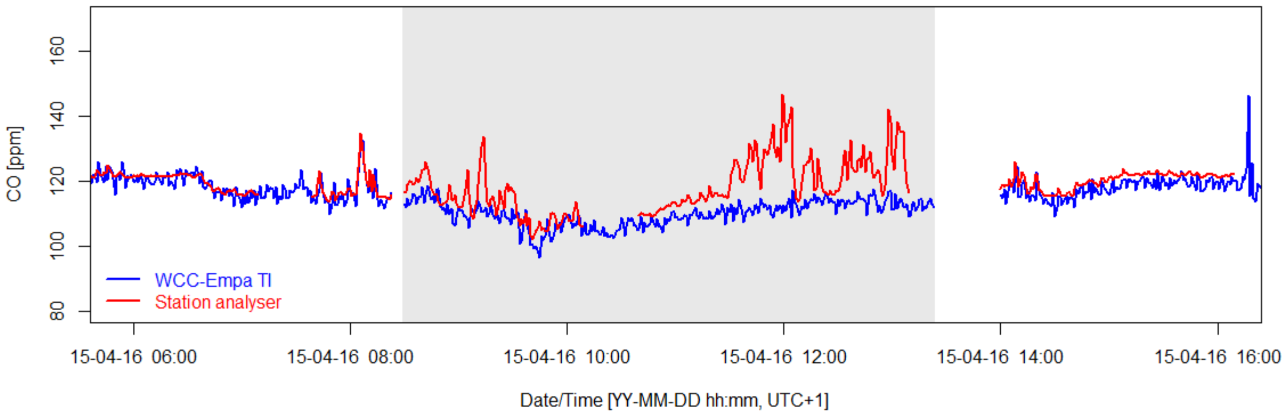

Figure 19. CO comparison at JFJ between the WCC-Empa TI and the JFJ LGR-23r during a calm day in April 2015 (1 min data). White area: both instruments sampled air from the same air intake location above the tourist platform. Grey area: TI sampled air from the inlet below the tourist platform.

Discussion of the ambient air comparison results

The comparison of the two inlet locations clearly indicates an influence of the tourist activities on the measurements. The location on top of the Sphynx building measures considerably higher CO, CO_2 and CH_4 mole fractions compared to the location below the tourist platform during calm days. The potential issue was also recognised by the involved institutes, and parallel measurements at the old telecom building on the east ridge of Jungfraujoch, approximately 125 m higher and 1 km southwest of the Sphynx, are currently carried out to further asses the suitability of the JFJ location. WCC-Empa supports this initiative but also recommends exploring solutions within the existing infrastructure.

Recommendation 5 (, important, 2017)**
It should be explored if a more suitable inlet location is possible using the current JFJ infrastructure.
Recommendation 6 (, important, 2017)**
Activities causing high levels of local pollution (e.g. smoking) should not be allowed on the tourist platform and be minimised at the entire surrounding of the JFJ station.

Data Acquisition and Management

The data acquisition system at JFJ is based on a commercial solution from Breitfuss GmbH (Easy-Comp, Anacomp and Anavis). The whole system including backup policy, data transfer and evaluation is fully adequate.

Documentation

All information is entered in electronic log books. An electronic tool (UWEDAT - Maintenance Tool) is available to document all instrument and station relevant information. The instrument manuals are available at the site. The reviewed information was comprehensive and up to date.

Data Submission

Surface O_3 (1986-2014), CO (1996-2014), CH_4 (2005-2015), CO_2 (2004-2015, University of Bern; 2010-2015, Empa) and N_2O (2005-2014) data have been submitted to the World Data Centre for Greenhouse Gases (WDCGG). Empa usually submits data in yearly intervals.

Conclusions

The Global GAW station Jungfraujoch is situated at an important location for the GAW programme, which makes the available data a very significant contribution to GAW. It has one of the most comprehensive measurement programmes within the GAW network.

All assessed parameters were of high data quality and met on average the WMO/GAW compatibility goals with the exception of N_2O, where only the extended goal was reached.

The continuation of the Jungfraujoch measurement series is highly recommended and important for GAW. The large number of measured atmospheric constituents in combination with the high data quality enables state of the art research projects.

Summary Ranking of the Jungfraujoch GAW Station

System Audit Aspect	Adequacy[#]	Comment
Measurement programme	(5)	Very comprehensive programme.
Access	(5)	Year round access by train.
Facilities		
Laboratory and office space	(4)	Adequate but limited space for additional research campaigns.
Internet access	(5)	Sufficient bandwidth
Air Conditioning	(4)	Available but still temperature variations
Power supply	(5)	Reliable with very few power cuts
General Management and Operation		
Organisation	(5)	Well-coordinated between different partners
Competence of staff	(5)	Highly skilled staff
Air Inlet System	(3)	Potential influence from tourist activities, episodes with water condensation in CO/N_2O system
Instrumentation		
Ozone	(5)	Adequate instrumentation
CO/N2O (LGR-23-r)	(5)	Adequate instrumentation
$CO_2/CH_4/CO$ (Picarro G2401)	(5)	Adequate instrumentation
CO_2 (Sick Maihak S710)	(4)	Adequate but significantly nosier compared to Picarro
Standards		
Ozone	(5)	TEI 49i-PS available at Empa
CO, CO_2, CH_4, N_2O	(5)	NOAA standards / working standards available
Data Management		
Data acquisition	(5)	Fully adequate system
Data processing	(5)	Highly experienced staff
Data submission (Empa)	(5)	Yearly submissions

[#]0: inadequate thru 5: adequate.

Dübendorf, December 2016

Dr. C. Zellweger
WCC-Empa

Dr. B. Buchmann
Head of Department

APPENDIX

Ozone Measurements

Comparison of the Ozone Analyser and Ozone Calibrator

All procedures were conducted 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 comparison of the analyser.

Setup and Connections

The internal ozone generator of the WCC-Empa transfer standard was used for generation of a randomised sequence of ozone levels ranging from 0 to 90 ppb. Zero air was generated using a custom built zero air generator (Silicagel, activated charcoal, Purafil). The TS was connected to the station analyser using approx. 1.5 m of PFA tubing. Table 1 details the experimental setup during the comparisons of the travelling standard with the station analysers. The data used for the evaluation was recorded by the WCC-Empa data acquisition system.

Table 1. Experimental details of the ozone comparison.

Travelling standard (TS)	
Model, S/N	TEI 49i-PS #0810-153 (WCC-Empa)
Settings	BKG -01, COEF 1.008
Main station analyser (OA)	
Model, S/N	TEI 49i #CM08320009
Principle	UV absorption
Range	0-1 ppm
Settings	BKG +0.0 ppb, COEF 1.008
Pressure readings (hPa)	Ambient 658.7; OA 659.7
Backup station analyser (OA)	
Model, S/N	TEI 49C #429508925
Principle	UV absorption
Range	0-1 ppm
Settings	BKG -0.5 ppb, COEF 1.026
Pressure readings (mmHg)	Ambient 658.7; OA 657.2

Results

Each ozone level was applied for 15 minutes, and the last 5 one-minute averages were aggregated. These aggregates were used in the assessment of the comparison. All results are valid for the calibration factors as given in Table 1 above. The readings of the travelling standard (TS) were compensated for bias with respect to the Standard Reference Photometer (SRP) prior to the evaluation of the ozone analyser (OA) and calibrator (OC) values.

The results of the assessment is shown in the following Tables (individual measurement points) and further presented in the Executive Summary (Figure and Equations).

Table 2. Ten-minute aggregates computed from the last 10 of a total of 15 one-minute values for the comparison of the JFJ ozone analyser (OA) TEI 49i #CM08320009 with the WCC-Empa travelling standard (TS).

Date - Time (UTC)	Run #	Level (ppb)	TS (ppb)	OA (ppb)	sdTS (ppb)	sdOA (ppb)	OA-TS (ppb)	OA-TS (%)
2015-03-17 21:58	1	0	-0.12	0.72	0.14	0.19	0.84	NA
2015-03-17 22:13	1	50	50.02	50.24	0.16	0.40	0.22	0.4
2015-03-17 22:28	1	30	30.02	30.25	0.18	0.28	0.23	0.8
2015-03-17 22:43	1	10	10.00	10.37	0.21	0.25	0.37	3.7
2015-03-17 22:58	1	90	89.99	89.94	0.11	0.10	-0.05	-0.1
2015-03-17 23:13	1	40	40.02	39.88	0.20	0.35	-0.14	-0.3
2015-03-17 23:28	1	20	20.03	20.22	0.17	0.16	0.19	0.9
2015-03-17 23:43	1	80	80.01	79.63	0.08	0.35	-0.38	-0.5
2015-03-17 23:58	1	70	69.96	69.96	0.21	0.38	0.00	0.0
2015-03-18 00:13	1	60	60.03	59.97	0.15	0.22	-0.06	-0.1
2015-03-18 00:28	2	0	0.08	0.46	0.28	0.29	0.38	NA
2015-03-18 00:43	2	30	29.96	30.06	0.09	0.16	0.10	0.3
2015-03-18 00:58	2	50	50.01	49.96	0.30	0.39	-0.05	-0.1
2015-03-18 01:13	2	80	80.01	79.89	0.12	0.33	-0.12	-0.1
2015-03-18 01:28	2	10	10.76	10.80	0.44	0.49	0.04	0.4
2015-03-18 01:43	2	20	20.03	20.12	0.20	0.18	0.09	0.4
2015-03-18 01:58	2	60	59.96	59.94	0.17	0.39	-0.02	0.0
2015-03-18 02:13	2	90	90.00	89.39	0.14	0.28	-0.61	-0.7
2015-03-18 02:28	2	40	39.99	39.80	0.08	0.37	-0.19	-0.5
2015-03-18 02:43	2	70	69.95	69.34	0.21	0.38	-0.61	-0.9
2015-03-18 02:58	3	0	0.32	0.42	0.35	0.09	0.10	NA
2015-03-18 03:13	3	20	19.94	20.16	0.21	0.31	0.22	1.1
2015-03-18 03:28	3	50	49.98	50.07	0.11	0.36	0.09	0.2
2015-03-18 03:43	3	10	9.95	10.13	0.35	0.20	0.18	1.8
2015-03-18 03:58	3	40	39.97	39.77	0.26	0.37	-0.20	-0.5
2015-03-18 04:13	3	70	69.93	70.37	0.11	0.49	0.44	0.6
2015-03-18 04:28	3	30	30.04	29.96	0.22	0.37	-0.08	-0.3
2015-03-18 04:43	3	60	60.13	59.82	0.26	0.28	-0.31	-0.5
2015-03-18 04:58	3	90	90.03	89.80	0.12	0.59	-0.23	-0.3
2015-03-18 05:13	3	80	80.05	79.96	0.21	0.59	-0.09	-0.1
2015-03-18 05:28	4	0	0.12	0.12	0.37	0.18	0.00	NA
2015-03-18 05:43	4	50	49.95	49.89	0.22	0.44	-0.06	-0.1
2015-03-18 05:58	4	30	30.06	29.88	0.32	0.35	-0.18	-0.6
2015-03-18 06:13	4	10	10.10	9.85	0.35	0.14	-0.25	-2.5
2015-03-18 06:28	4	90	90.02	89.58	0.11	0.50	-0.44	-0.5
2015-03-18 06:43	4	40	39.98	39.30	0.12	0.24	-0.68	-1.7
2015-03-18 06:58	4	20	20.13	19.87	0.17	0.30	-0.26	-1.3
2015-03-18 07:13	4	80	80.00	79.75	0.06	0.46	-0.25	-0.3
2015-03-18 07:28	4	70	70.03	69.92	0.07	0.33	-0.11	-0.2
2015-03-18 07:43	4	60	60.04	60.04	0.10	0.23	0.00	0.0

Table 3. Ten-minute aggregates computed from the last 10 of a total of 15 one-minute values for the comparison of the backup ozone analyser (OA) TEI 49C #429508925 with the WCC-Empa travelling standard (TS).

Date - Time (UTC)	Run #	Level (ppb)	TS (ppb)	OA (ppb)	sdTS (ppb)	sdOA (ppb)	OA-TS (ppb)	OA-TS (%)
2015-03-17 21:58	1	0	-0.12	0.44	0.14	0.09	0.56	NA
2015-03-17 22:13	1	50	50.02	50.62	0.16	0.43	0.60	1.2
2015-03-17 22:28	1	30	30.02	30.74	0.18	0.34	0.72	2.4
2015-03-17 22:43	1	10	10.00	10.58	0.21	0.13	0.58	5.8
2015-03-17 22:58	1	90	89.99	91.14	0.11	0.22	1.15	1.3
2015-03-17 23:13	1	40	40.02	40.58	0.20	0.24	0.56	1.4
2015-03-17 23:28	1	20	20.03	20.43	0.17	0.11	0.40	2.0
2015-03-17 23:43	1	80	80.01	80.77	0.08	0.18	0.76	0.9
2015-03-17 23:58	1	70	69.96	70.71	0.21	0.29	0.75	1.1
2015-03-18 00:13	1	60	60.03	60.60	0.15	0.32	0.57	0.9
2015-03-18 00:28	2	0	0.08	0.40	0.28	0.07	0.32	NA
2015-03-18 00:43	2	30	29.96	30.51	0.09	0.27	0.55	1.8
2015-03-18 00:58	2	50	50.01	50.59	0.30	0.56	0.58	1.2
2015-03-18 01:13	2	80	80.01	80.77	0.12	0.22	0.76	0.9
2015-03-18 01:28	2	10	10.76	10.94	0.44	0.48	0.18	1.7
2015-03-18 01:43	2	20	20.03	20.27	0.20	0.23	0.24	1.2
2015-03-18 01:58	2	60	59.96	60.70	0.17	0.40	0.74	1.2
2015-03-18 02:13	2	90	90.00	90.58	0.14	0.26	0.58	0.6
2015-03-18 02:28	2	40	39.99	40.20	0.08	0.32	0.21	0.5
2015-03-18 02:43	2	70	69.95	70.18	0.21	0.43	0.23	0.3
2015-03-18 02:58	3	0	0.32	0.33	0.35	0.06	0.01	NA
2015-03-18 03:13	3	20	19.94	20.35	0.21	0.13	0.41	2.1
2015-03-18 03:28	3	50	49.98	50.63	0.11	0.39	0.65	1.3
2015-03-18 03:43	3	10	9.95	10.21	0.35	0.32	0.26	2.6
2015-03-18 03:58	3	40	39.97	40.22	0.26	0.39	0.25	0.6
2015-03-18 04:13	3	70	69.93	71.05	0.11	0.47	1.12	1.6
2015-03-18 04:28	3	30	30.04	30.31	0.22	0.42	0.27	0.9
2015-03-18 04:43	3	60	60.13	60.30	0.26	0.42	0.17	0.3
2015-03-18 04:58	3	90	90.03	90.88	0.12	0.29	0.85	0.9
2015-03-18 05:13	3	80	80.05	80.66	0.21	0.64	0.61	0.8
2015-03-18 05:28	4	0	0.12	0.20	0.37	0.09	0.08	NA
2015-03-18 05:43	4	50	49.95	50.31	0.22	0.42	0.36	0.7
2015-03-18 05:58	4	30	30.06	30.26	0.32	0.32	0.20	0.7
2015-03-18 06:13	4	10	10.10	9.93	0.35	0.22	-0.17	-1.7
2015-03-18 06:28	4	90	90.02	90.90	0.11	0.51	0.88	1.0
2015-03-18 06:43	4	40	39.98	40.08	0.12	0.15	0.10	0.3
2015-03-18 06:58	4	20	20.13	19.91	0.17	0.19	-0.22	-1.1
2015-03-18 07:13	4	80	80.00	80.95	0.06	0.18	0.95	1.2
2015-03-18 07:28	4	70	70.03	70.88	0.07	0.28	0.85	1.2
2015-03-18 07:43	4	60	60.04	60.53	0.10	0.20	0.49	0.8

GHG and CO Measurements

Monitoring Set-up and Procedures

Standards

For the LGR-23r instrument, a sequence of working and target tanks as well as 3 calibration standards is run using a valve sequencer unit. The Picarro is also calibrated using a custom made calibration unit, and 4 calibration standards (including CO free air) and a target gas are regularly measured. The following standards are used for the calibration of the LGR-23r instrument:

LGR-23r:

port; internal Empa filling number; cylinder number; regulator; comment; N2O [ppb]; CO [ppb]

port2; E-085; Luxfer Europe D991124; Scott Specialty S/N 1412151; cal gas, 313.82, 216.09

port3; E-088; Luxfer Europe D986926; Scott Specialty S/N 1415788; cal gas, 328.97, 353.19

port4; E-087; Luxfer Europe D860411; Scott Specialty S/N 1412132; cal gas, 343.78, 190.59

port6; E-128; Luxfer Europe D780050; TESCOM; working gas, 327.51, 184.94

Regulators:

Scott Specialty regulators: model 51318Brass, Tescom regulators: model 64-3440KA412

Calibration scales: WMO CO_2 X2007, WMO CH_4 X2004, WMO CO X2004 (for Picarro), WMO CO X2014 (for LGR), and WMO N_2O X2006A

Calibration sequence: The following table shows the calibration sequence of the LGR-23-r instrument:

Table 4. Calibration sequence of the LGR-23-r.

Time (min)	Sample / Gas
160	Ambient air
20	Working Std
160	Ambient air
20	Working Std
160	Ambient air
20	Working Std
160	Ambient air
20	Working Std
160	Ambient air
20	Working Std
80	Ambient air
25	Target gas
160	Ambient air
20	Working Std
160	Ambient air
20	Working Std
160	Ambient air
20	Working Std
160	Ambient air
20	Working Std
160	Ambient air

Time (min)	Sample / Gas
20	Working Std
80	Ambient air
25	Target gas
25	Cal gas port 2
25	Cal gas port 3
25	Cal gas port 4
80	Ambient air
25	Cal gas port 2
25	Cal gas port 3
25	Cal gas port 4
25	Target gas

Picarro G2401:

port; internal Empa filling number; cylinder no; regulator; comment; CO_2 [ppm]; CH_4 [ppb]; CO [ppb]

port1; E-062; Luxfer Europe D621867; Veriflo V-134107; cal gas; 394.11; 1834.79; 374.99

port5; E-086; Luxfer Europe D991125; Veriflo V-134108; cal gas; 418.03; 1964.84; 212.33

port7; CO zero air; -; -; generated on-site; -; -; 0

port9; E-080; Luxfer Europe D780049; Scott Specialty S/N 1415789; cal gas; 431.27; 1981.81; 272.10

CO zero air: produced on-site with ambient air treated with a heated CO to CO_2 catalytic converter and a Sofnocat cartridge; remaining air is free from CO but contains variable amounts of CO_2 and CH_4; thus, zero air measurement is only used for CO calibration.

Regulators:

Veriflo regulators; type 959100 S 4P V1 30 4 (Series 959S, 316L SS, 4 ports, all 1/4" NPT, outlet gauge 0-100 psig, inlet gauge 0-3000 psig, both manometers 2").

Scott Specialty regulators: model 51318Brass

Table 5. Calibration sequence of the Picarro G2401.

Time (min)	Sample / Gas
450	Ambient air
30	Target gas
900	Ambient air
30	Cal gas port 1
30	Cal gas port 5
30	Cal gas port 9
30	Cal gas port 7
900	Ambient air
30	Target gas
900	Ambient air
30	Target gas
450	Ambient air

Sick Maihak S710:

Sick Maihak S710 NDIR spectrometer, air is cryogenically dried to a dew point of -90°C (FC-100D21, FTS systems, USA). Details of the calibration scheme are given in Schibig et al. (2015).

Comparison of the Carbon Monoxide Analyser

All procedures were conducted according to the Standard Operating Procedure (WMO, 2007a) and included comparisons of the travelling standards at Empa before the comparison of the analysers. Details of the traceability of the travelling standards to the WMO/GAW Reference Standard at NOAA/ESRL are given in the appendix.

Setup and Connections

Table 6 shows details of the experimental setup during the comparison of the transfer standard and the station analysers. The data used for the evaluation was recorded by the JFJ data acquisition system.

Table 6. Experimental details of GHG and CO comparisons.

Travelling standard (TS)	
WCC-Empa Travelling standards (6 l aluminium cylinder containing a mixture of natural and synthetic air), assigned values and standard uncertainties see Table 15.	
LGR-23r (CO and N_2O), Empa	
Model, S/N	LGR-23r #12-0066
Principle	Cavity enhanced off-axis Integrated Cavity Output Spectroscopy (OA-ICOS)
Drying system	PERMAPURE Nafion drier
Picarro G2401 (CO, CO_2 and CH_4), Empa	
Model, S/N	Picarro G2401, S/N CFKADS2133
Principle	Cavity Ring Down Spectroscopy (CRDS)
Drying system	PERMAPURE Nafion drier
Sick Maihak S710	
Model, S/N	Sick Maihak S710 NDIR spectrometer
Principle	Non-Dispersive Infrared (NDIR) Absorption Spectroscopy
Drying system	Cryogenic (dew point of -90°C), FC-100D21, FTS systems, USA
Comparison procedures	
Connection	The TS were connected to spare calibration gas ports

Results

The results of the assessment are shown in the Executive Summary (figures and equations), and the individual measurements of the TS are presented in the following Tables.

Table 7. CO aggregates computed from single analysis (mean and standard deviation of mean) for each level during the comparison of the LGR-23r #12-0066 instrument (AL) with the WCC-Empa TS (WMO-X2014 CO scale).

Date / Time	TS Cylinder	TS (ppb)	sdTS (ppb)	AL (ppb)	sdAL (ppb)	N	AL-TS (ppb)	AL-TS (%)
(15-03-17 23:37:00)	130819_FB03853	142.8	0.6	142.3	0.0	21.0	-0.5	-0.4
(15-03-18 00:16:30)	140514_FB03930	236.1	0.1	236.7	0.0	22.0	0.6	0.3
(15-03-18 00:57:00)	100212_FF31496	107.8	0.1	107.3	0.0	21.0	-0.5	-0.4
(15-03-18 01:36:30)	130905_FB03358	71.4	0.4	70.8	0.0	22.0	-0.6	-0.8
(15-03-18 02:17:00)	140515_FB03350	182.7	0.1	182.6	0.0	21.0	-0.1	-0.1
(15-03-18 02:56:30)	130423_FF30491	247.8	0.1	248.6	0.0	22.0	0.8	0.3

Table 8. CO aggregates computed from single analysis (mean and standard deviation of mean) for each level during the comparison of the Picarro G2401 #CFKADS2133 instrument (AL) with the WCC-Empa TS (WMO-X2014 CO scale).

Date / Time	TS Cylinder	TS (ppb)	sdTS (ppb)	AL (ppb)	sdAL (ppb)	N	AL-TS (ppb)	AL-TS (%)
(15-03-17 16:13:30)	130819_FB03853	142.8	0.6	137.1	1.4	24.0	-5.7	-4.0
(15-03-17 16:55:30)	140514_FB03930	236.1	0.1	232.9	1.0	24.0	-3.2	-1.4
(15-03-17 17:39:30)	100212_FF31496	107.8	0.1	104.6	0.9	24.0	-3.2	-3.0
(15-03-17 18:21:30)	130905_FB03358	71.4	0.4	68.9	1.2	24.0	-2.5	-3.5
(15-03-17 19:04:30)	140515_FB03350	182.7	0.1	183.0	1.2	24.0	0.3	0.2
(15-03-17 19:55:30)	130423_FF30491	247.8	0.1	246.3	1.2	24.0	-1.5	-0.6

Table 9. CH_4 aggregates computed from single analysis (1-min mean and standard deviation) for each level during the comparison of the Picarro G2401 #CFKADS2133 (OA) with the WCC-Empa TS.

Date / Time	TS Cylinder	TS (ppb)	sdTS (ppb)	OA (ppb)	sd OA (ppb)	N	OA-TS (ppb)	OA-TS (%)
(15-03-17 16:13:30)	130819_FB03853	1943.01	0.13	1943.21	0.10	24	0.20	0.01
(15-03-17 16:55:30)	140514_FB03930	1975.95	0.09	1976.16	0.13	24	0.21	0.01
(15-03-17 17:39:30)	100212_FF31496	2122.57	0.06	2122.69	0.10	24	0.12	0.01
(15-03-17 18:21:30)	130905_FB03358	1862.94	0.13	1863.43	0.10	24	0.49	0.03
(15-03-17 19:04:30)	140515_FB03350	1965.65	0.07	1965.97	0.11	24	0.32	0.02
(15-03-17 19:55:30)	130423_FF30491	2091.81	0.08	2092.15	0.15	24	0.34	0.02

Table 10. CO_2 aggregates computed from single analysis (1-min mean and standard deviation) for each level during the comparison of the Picarro G2401 #CFKADS2133 (OA) with the WCC-Empa TS.

Date / Time	TS Cylinder	TS (ppm)	sdTS (ppm)	OA (ppm)	sd OA (ppm)	N	OA-TS (ppm)	OA-TS (%)
(15-03-17 16:13:30)	130819_FB03853	399.48	0.04	399.44	0.01	24	-0.04	-0.01
(15-03-17 16:55:30)	140514_FB03930	404.93	0.02	404.95	0.02	24	0.02	0.00
(15-03-17 17:39:30)	100212_FF31496	331.04	0.02	331.04	0.02	24	0.00	0.00
(15-03-17 18:21:30)	130905_FB03358	389.01	0.02	389.10	0.01	24	0.09	0.02
(15-03-17 19:04:30)	140515_FB03350	413.40	0.03	413.36	0.01	24	-0.04	-0.01
(15-03-17 19:55:30)	130423_FF30491	384.01	0.03	384.03	0.01	24	0.02	0.01

Table 11. CO_2 aggregates computed from single analysis (1-min mean and standard deviation) for each level during the comparison of the Picarro G2401 #CFKADS2133 (OA) with the WCC-Empa TS.

Date / Time	TS Cylinder	TS (ppm)	sdTS (ppm)	OA (ppm)	sd OA (ppm)	N	OA-TS (ppm)	OA-TS (%)
(15-03-17 15:33:00)	130423_FF30491	384.01	0.03	383.76	0.13	6	-0.25	-0.07
(15-03-17 17:35:00)	130819_FB03853	399.48	0.04	399.38	0.11	6	-0.10	-0.03
(15-03-17 19:35:00)	140514_FB03930	404.93	0.02	404.93	0.07	6	0.00	0.00
(15-03-17 21:36:00)	130905_FB03358	389.01	0.02	389.14	0.08	6	0.13	0.03
(15-03-18 07:43:00)	140515_FB03350	413.40	0.03	413.59	0.04	6	0.19	0.05

Table 12. N_2O aggregates computed from single analysis (mean and standard deviation of mean) for each level during the comparison of the LGR-23r #12-0066 instrument (AL) with the WCC-Empa TS (WMO-X2006A N_2O scale).

Date / Time	TS Cylinder	TS (ppb)	sdTS (ppb)	AL (ppb)	sdAL (ppb)	N	AL-TS (ppb)	AL-TS (%)
(15-03-17 23:37:00)	130819_FB03853	327.52	0.02	327.15	0.01	21	-0.37	-0.11
(15-03-18 00:16:30)	140514_FB03930	328.65	0.01	328.47	0.02	22	-0.18	-0.05
(15-03-18 00:57:00)	100212_FF31496	298.42	0.02	298.31	0.01	21	-0.11	-0.04
(15-03-18 01:36:30)	130905_FB03358	316.86	0.03	316.56	0.01	22	-0.30	-0.09
(15-03-18 02:17:00)	140515_FB03350	328.52	0.03	328.27	0.01	21	-0.25	-0.08
(15-03-18 02:56:30)	130423_FF30491	343.17	0.02	342.89	0.01	22	-0.28	-0.08

WCC-Empa Traveling Standards

Ozone

The WCC-Empa travelling standard (TS) was compared with the Standard Reference Photometer before and after the audit. The following instruments were used:

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

WCC-Empa TS: TEI 49i-PS #0810-153, BKG -0.1, COEF 1.008

Zero air source: Pressurized air – Breitfuss zero air generator – Purafil – charcoal – outlet filter

The results of the TS calibration before the audit and the verification of the TS after the audit are given in Table 13. The TS passed the assessment criteria defined for maximum acceptable bias before and after the audit (Klausen et al., 2003) (cf. Figure 20). The data were pooled and evaluated by linear regression analysis, considering uncertainties in both instruments. From this, the unbiased ozone mixing ratio produced (and measured) by the TS can be computed (Equation 6a). The uncertainty of the TS (Equation 6b) was estimated previously (cf. equation 19 in (Klausen et al., 2003)).

$$X_{TS} \text{ (ppb)} = ([TS] - 0.09 \text{ ppb}) / 1.0014 \quad (6a)$$

$$u_{TS} \text{ (ppb)} = \text{sqrt}((0.43 \text{ ppb})^2 + (0.0034 * X)^2) \quad (6b)$$

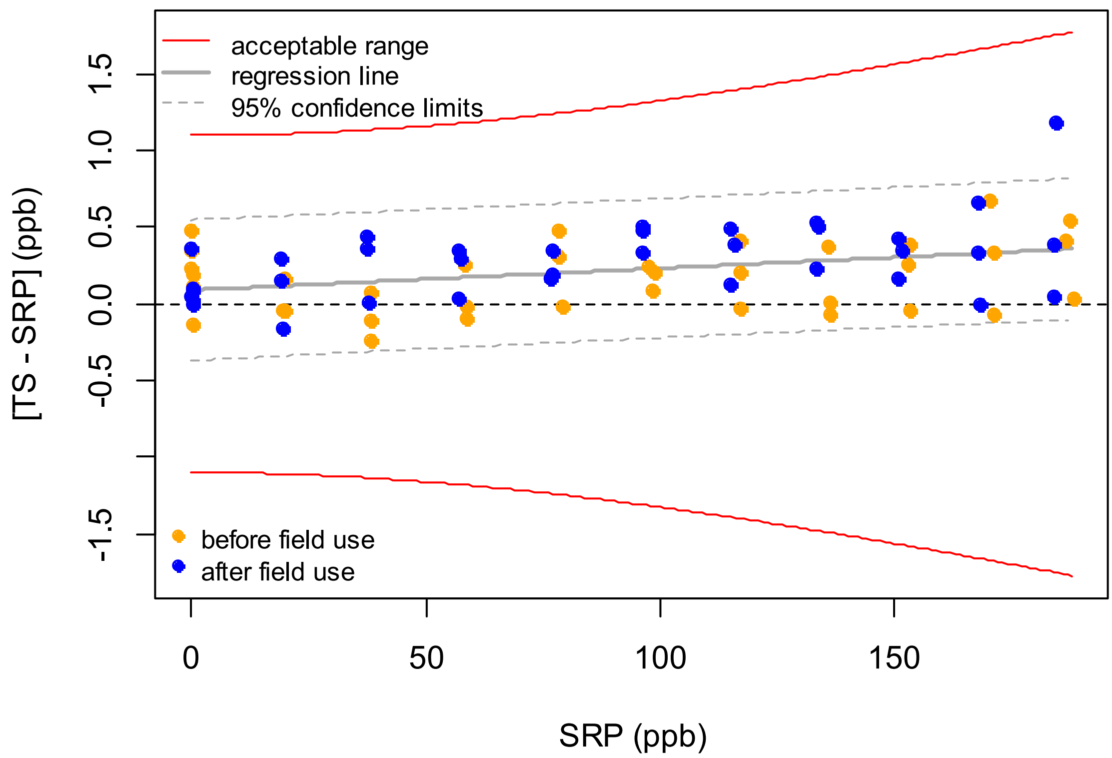

Figure 20. *Deviations between traveling standard (TS) and Standard Reference Photometer (SRP) before and after use of the TS at the field site.*

Table 13. Five-minute aggregates computed from 10 valid 30-second values for the comparison of the Standard Reference Photometer (SRP) with the WCC-Empa traveling standard (TS).

Date	Run	Level#	SRP (ppb)	sdSRP (ppb)	TS (ppb)	sdTS (ppb)
2015-02-10	1	0	0.06	0.29	0.25	0.16
2015-02-10	1	80	78.97	0.25	78.95	0.18
2015-02-10	1	100	98.70	0.19	98.91	0.31
2015-02-10	1	20	19.84	0.32	19.81	0.18
2015-02-10	1	60	58.65	0.22	58.63	0.13
2015-02-10	1	135	136.34	0.28	136.26	0.12
2015-02-10	1	190	188.11	0.45	188.15	0.22
2015-02-10	1	155	153.34	0.55	153.73	0.11
2015-02-10	1	40	38.36	0.23	38.25	0.07
2015-02-10	1	170	171.07	0.40	171.40	0.29
2015-02-10	1	115	116.89	0.19	117.09	0.34
2015-02-10	1	0	-0.19	0.30	0.05	0.21
2015-02-10	2	0	-0.22	0.20	0.12	0.14
2015-02-10	2	20	19.69	0.32	19.85	0.60
2015-02-10	2	60	58.56	0.19	58.46	0.18
2015-02-10	2	40	38.26	0.22	38.33	0.33
2015-02-10	2	135	136.18	0.32	136.19	0.22
2015-02-10	2	170	171.18	0.14	171.12	0.41
2015-02-10	2	80	78.10	0.25	78.41	0.17
2015-02-10	2	115	117.06	0.20	117.03	0.20
2015-02-10	2	185	186.46	0.39	186.87	0.23
2015-02-10	2	155	153.00	0.28	153.26	0.32
2015-02-10	2	95	97.39	0.42	97.64	0.30
2015-02-10	2	0	0.13	0.27	0.00	0.23
2015-02-10	3	0	0.08	0.22	0.19	0.23
2015-02-10	3	100	98.23	0.21	98.32	0.17
2015-02-10	3	185	187.29	0.31	187.84	0.21
2015-02-10	3	135	135.85	0.24	136.22	0.34
2015-02-10	3	115	116.93	0.15	117.35	0.23
2015-02-10	3	170	170.19	0.30	170.87	0.16
2015-02-10	3	155	153.16	0.20	153.11	0.17
2015-02-10	3	40	38.24	0.32	38.01	0.24
2015-02-10	3	60	58.11	0.21	58.37	0.18
2015-02-10	3	20	19.59	0.20	19.55	0.11
2015-02-10	3	80	78.18	0.31	78.65	0.16
2015-02-10	3	0	-0.24	0.25	0.25	0.30
2015-06-05	4	0	0.03	0.32	0.14	0.24
2015-06-05	4	55	57.28	0.26	57.58	0.07
2015-06-05	4	185	184.57	0.37	185.75	0.35
2015-06-05	4	95	96.08	0.30	96.56	0.19
2015-06-05	4	20	19.08	0.23	19.23	0.24
2015-06-05	4	115	115.09	0.19	115.58	0.19
2015-06-05	4	135	133.61	0.35	134.12	0.22
2015-06-05	4	40	37.84	0.22	37.85	0.27
2015-06-05	4	170	167.95	0.20	168.61	0.25
2015-06-05	4	75	76.87	0.34	77.21	0.11
2015-06-05	4	150	150.78	0.23	151.21	0.31
2015-06-05	4	0	0.05	0.21	0.05	0.14
2015-06-05	5	0	0.03	0.24	0.06	0.20
2015-06-05	5	35	37.40	0.40	37.84	0.16

Date	Run	Level#	SRP (ppb)	sdSRP (ppb)	TS (ppb)	sdTS (ppb)
2015-06-05	5	20	19.32	0.19	19.15	0.27
2015-06-05	5	115	115.58	0.16	115.97	0.15
2015-06-05	5	95	96.15	0.33	96.65	0.14
2015-06-05	5	135	133.33	0.35	133.85	0.21
2015-06-05	5	55	57.04	0.38	57.39	0.24
2015-06-05	5	170	167.87	0.27	168.21	0.16
2015-06-05	5	75	76.82	0.21	77.02	0.35
2015-06-05	5	185	184.04	0.29	184.43	0.22
2015-06-05	5	150	150.93	0.41	151.11	0.21
2015-06-05	5	0	0.04	0.16	0.14	0.17
2015-06-05	6	0	0.00	0.32	0.04	0.08
2015-06-05	6	150	151.65	0.35	152.00	0.15
2015-06-05	6	95	95.99	0.37	96.33	0.26
2015-06-05	6	170	168.02	0.33	168.01	0.29
2015-06-05	6	35	37.32	0.16	37.68	0.20
2015-06-05	6	185	184.05	0.38	184.10	0.21
2015-06-05	6	115	115.10	0.29	115.23	0.12
2015-06-05	6	135	133.28	0.34	133.51	0.22
2015-06-05	6	75	76.76	0.27	76.93	0.24
2015-06-05	6	20	19.09	0.30	19.39	0.19
2015-06-05	6	55	57.08	0.28	57.11	0.24
2015-06-05	6	0	-0.19	0.30	0.17	0.15

#the level is only indicative.

Greenhouse gases and carbon monoxide

WCC-Empa refers to the primary reference standards maintained by the Central Calibration Laboratory (CCL) for Carbon Monoxide, Carbon Dioxide and Methane. NOAA/ESRL was assigned by WMO as the CCL for the above parameters. WCC-Empa maintains a set of laboratory standards obtained from the CCL that are regularly compared with the CCL by way of traveling standards and by addition of new laboratory standards from the CCL. For the assignment of the mole fractions to the TS, the following calibration scales were used:

CO: WMO-X2014 scale (Novelli et al., 2003)
CO_2: WMO-X2007 scale (Zhao and Tans, 2006)
CH_4: WMO-X2004 scale (Dlugokencky et al., 2005)
N_2O: WMO-X2006A scale (http://www.esrl.noaa.gov/gmd/ccl/n2o_scale.html)

More information about the NOAA/ESRL calibration scales can be found on the GMD website (www.esrl.noaa.gov/gmd/ccl). The scales were transferred to the TS using the following instruments:

CO and N_2O: Aerodyne mini-cw (Mid-IR Spectroscopy using a Quantum Cascade Laser).
CO_2 and CH_4: Picarro G1301 (Cavity Ring Down Spectroscopy).

Table 14 gives an overview of the WCC-Empa laboratory standards that were used for transferring the CCL calibration scales to the WCC-Empa TS. For internal consistency among the available LS at WCC-Empa, new values have been assigned to the NOAA standards for some tanks. The results including estimated standard uncertainties of the WCC-Empa TS are listed in Table 15, and Figure 21 shows the analysis of the TS over time. Usually, a number of individual analysis results dating from before and after the audit was averaged. During these periods, the standards remained usually stable with no significant drift. If drift is present, this will lead to an increased uncertainty of the TS.

Table 14. NOAA/ESRL laboratory standards at WCC-Empa.

Cylinder	CO	sd	CH_4	sd	N_2O	sd	CO_2	sd	CO	sd	CH_4	sd	N_2O	sd	CO_2	sd
	NOAA assigned values								WCC-Empa assigned values							
	(ppb)		(ppb)		(ppb)		(ppm)		(ppb)		(ppb)		(ppb)		(ppm)	
CC339523	347.9	0.3	1854.60	0.13	322.52	0.12	396.88	0.06	350.9	0.3	1854.76	0.03	322.52	0.02	396.94	0.02
CC339524	390.7	0.2	1980.28	0.30	355.42	0.16	795.42	0.06	394.1	0.4	1981.18	0.04	355.42	0.02	796.36	0.04
CC311846	166.4	0.1	1805.24	0.12	338.27	0.11	377.86	0.04	167.2	0.3	1805.07	0.11	338.27	0.01	377.84	0.02

Table 15. Calibration summary of the WCC-Empa travelling standards.

TS	CO (ppb)	sdCO (ppb)	CH_4 (ppb)	$sdCH_4$ (ppb)	CO_2 (ppm)	$sdCO_2$ (ppm)	N_2O (ppb)	sdN_2O (ppb)
100212_FF31496	107.78	0.1	2122.57	0.06	331.04	0.02	298.42	0.02
130905_FB03358	71.37	0.4	1862.94	0.13	389.01	0.02	316.86	0.03
140515_FB03350	182.69	0.11	1965.65	0.07	413.4	0.03	328.52	0.03
130423_FF30491	247.76	0.05	2091.81	0.08	384.01	0.03	343.17	0.02
130819_FB03853	142.82	0.59	1943.01	0.13	399.48	0.04	327.52	0.02
140514_FB03930	236.06	0.13	1975.95	0.09	404.93	0.02	328.65	0.01

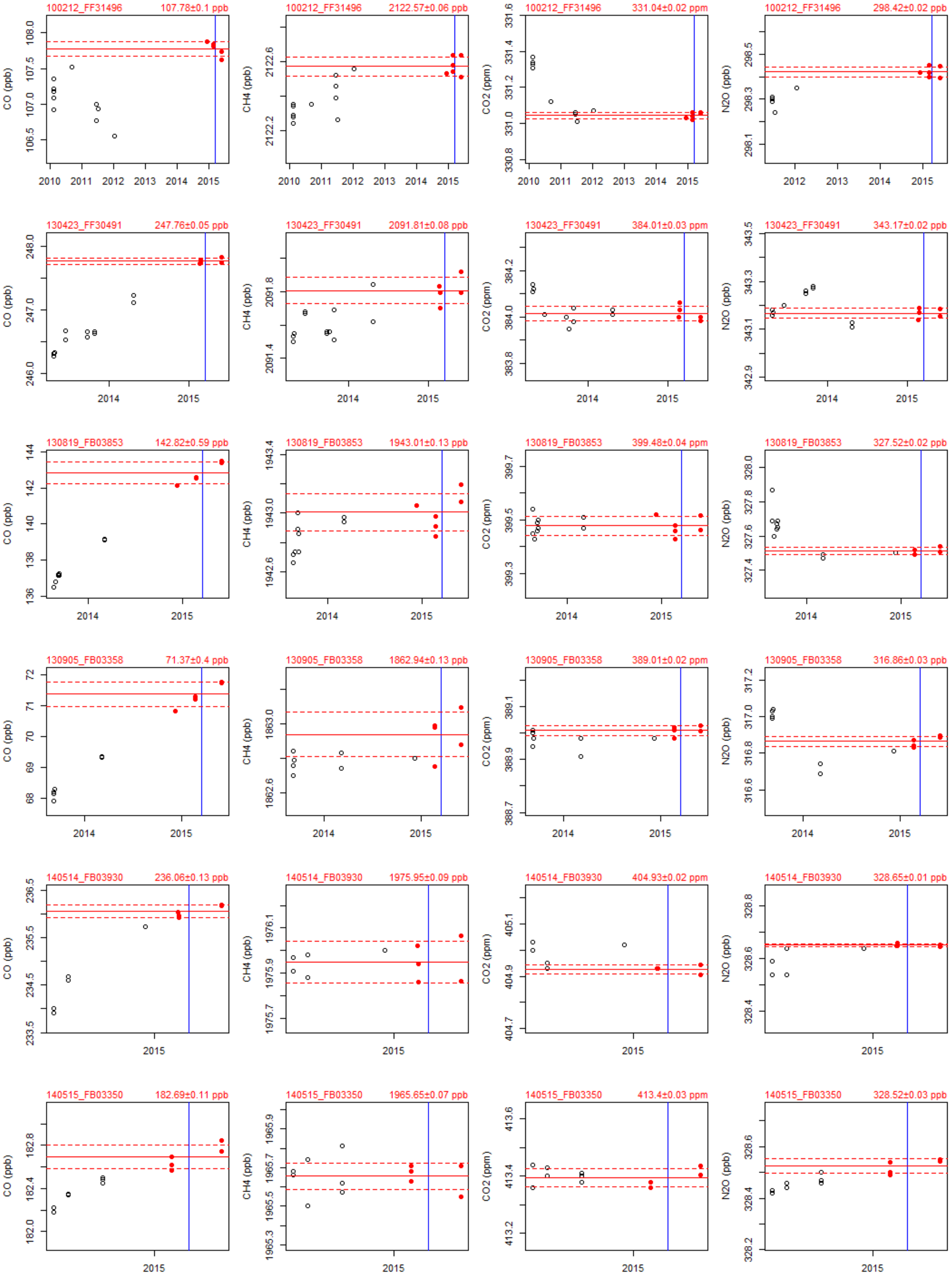

Figure 21. *Results of the WCC-Empa TS calibrations. Only the values of the red solid circles were considered for averaging. The red solid line is the average of the points that were considered for the assignment of the values; the red dotted line corresponds to the standard deviation of the measurement. The blue vertical line refers to the date of the audit.*

Calibration of the WCC-Empa 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 was calibrated every 1735 min using one WCC-Empa TS as a working standard, and two TS were used as targets. Based on the measurements of the working standard, a drift correction using a loess fit was applied to the data, which is illustrated in the figure below. The maximum drift between two WS measurements was approx. 0.7 ppb for CH_4 and 0.04 ppm for CO_2. Both target cylinders were within half of the WMO GAW compatibility goals for all measurements.

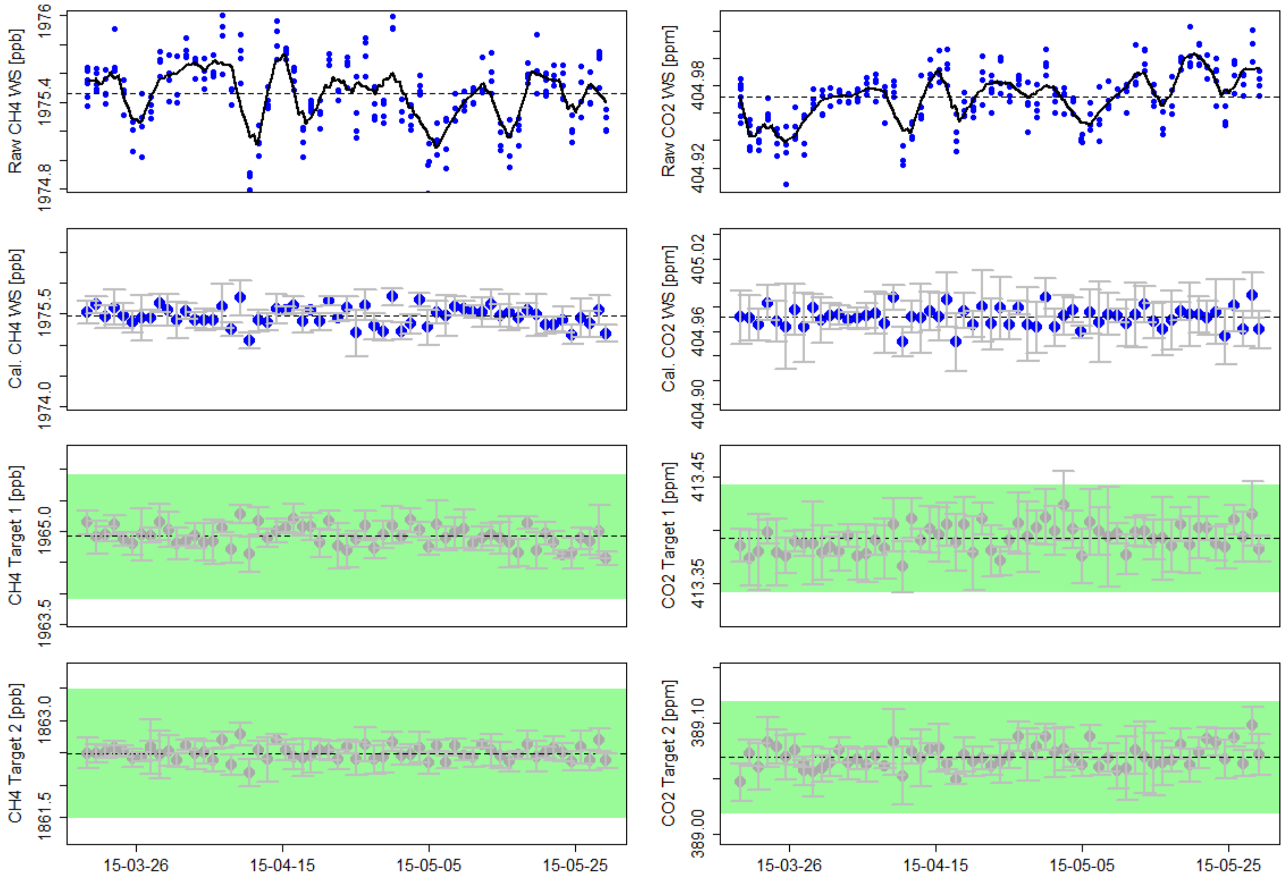

Figure 22. *CH_4 (left panel) and CO_2 (right panel) calibrations of the WCC-Empa-TI. The upper panel shows raw 1-min values of the working standard and the loess fit (black line) used to account for drift. The second panel shows the variation of the WS after applying the drift correction. The two lower most panels show the results of the two target cylinders. Individual points in the three lower panels are 5 min averages, and the error bars represent the standard deviation. The green area represents half of the WMO/GAW compatibility goals.*

For CO, the Picarro G2401 was calibrated every 1735 min three WCC-Empa TS as a working standards. Based on the measurements of the working standards, a drift correction using a loess fit was applied to the data, which is illustrated in the figure below.

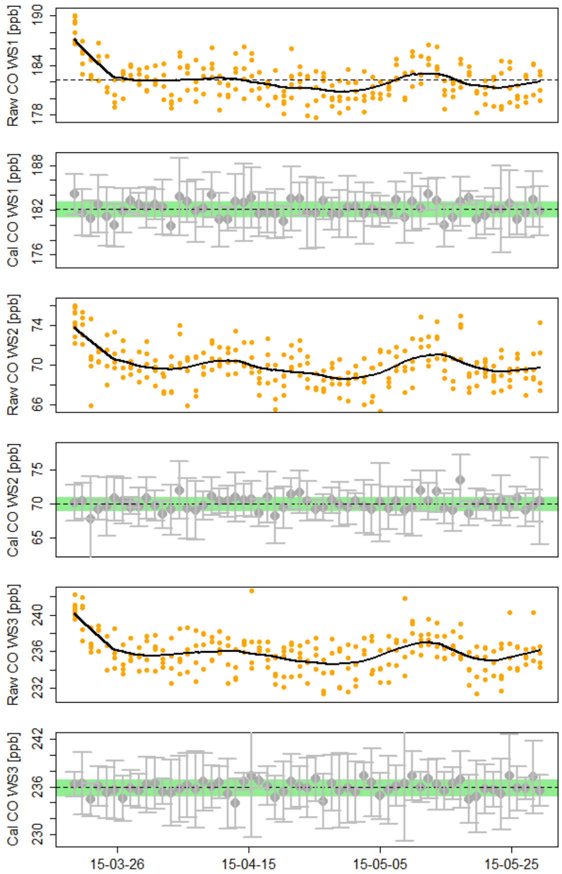

Figure 23. *CO calibrations of the WCC-Empa-TI. The panels with the orange dots show raw 1-min values of the working standards and the loess fit (black line) used to account for drift. The other panels show the variation of the WS after applying the drift correction. Individual points in these panels are 5 min averages, and the error bars represent the standard deviation. The green area represents half of the WMO/GAW compatibility goals.*

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CH-8600 Dübendorf, Switzerland
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Ozone Audit Executive Summary

0.1	Station Name:	Jungfraujoch
0.2	GAW ID:	JFJ
0.3	Coordinates/Elevation:	46.54749°N 7.98509°E (3580m a.s.l.)
Parameter:		Surface Ozone

1.1	Date of Audit:	2015-03-17/18
1.2	Auditor:	Christoph Zellweger
1.3	Station staff involved in audit:	Martin Steinbacher, Simon A. Wyss
1.4	Ozone Reference [SRP]:	NIST SRP#15
1.5	Ozone Transfer Standard [TS]	
1.5.1	Model and serial number:	TEI 49i-PS #0810-153, BKG -0.1, COEF 1.008
1.5.2	Range of calibration:	0 – 200 ppb
1.5.3	Mean calibration (ppb):	[TS] = (1.0014±0.0006) • [SRP] + (0.09±0.06)
1.6	Ozone Analyser [OA]	
1.6.1	Model:	TEI 49i #CM08320009
1.6.2	Range of calibration:	0 – 100 ppb
1.6.3	Coefficients at start of audit	BKG = +0.0; COEF = 1.008
1.6.4	Calibration at start of audit (ppb):	[OA] = (0.9960±0.0017) • [SRP] + (0.32±0.10)
1.6.5	Unbiased ozone mixing ratio (ppb) at start of audit:	X_{O3} (ppb) = ([OA] – 0.32 ppb) / 0.9960
1.6.6	Standard uncertainty remaining after compensation of calibration bias (ppb):	u_{O3} (ppb) = sqrt (0.37 ppb^2 + 2.87e-05 * X_{O3}^2)
1.6.7	Coefficients after audit	NA
1.6.8	Calibration after audit (ppb):	NA
1.6.9	Unbiased ozone mixing ratio (ppb) after audit:	NA
1.6.10	Standard uncertainty remaining after compensation of calibration bias (ppb):	NA
1.7	Comments:	NA
1.8	Reference:	WCC-Empa Report 15/2

[OA]: Instrument readings; [SRP]: SRP readings; X_{O3}: mixing ratios on SRP scale

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GAW QA/SAC Switzerland
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Ozone Audit Executive Summary

0.1	Station Name:	Jungfraujoch
0.2	GAW ID:	JFJ
0.3	Coordinates/Elevation:	46.54749°N 7.98509°E (3580m a.s.l.)
Parameter:		Surface Ozone

1.1	Date of Audit:	2015-03-17/18
1.2	Auditor:	Christoph Zellweger
1.3	Station staff involved in audit:	Martin Steinbacher, Simon A. Wyss
1.4	Ozone Reference [SRP]:	NIST SRP#15
1.5	Ozone Transfer Standard [TS]	
1.5.1	Model and serial number:	TEI 49i-PS #0810-153, BKG -0.1, COEF 1.008
1.5.2	Range of calibration:	0 – 200 ppb
1.5.3	Mean calibration (ppb):	[TS] = (1.0014±0.0006) • [SRP] + (0.09±0.06)
1.6	Ozone Analyser [OA]	
1.6.1	Model:	TEI 49C #429508925
1.6.2	Range of calibration:	0 – 100 ppb
1.6.3	Coefficients at start of audit	BKG = +0.5; COEF = 1.026
1.6.4	Calibration at start of audit (ppb):	[OA] = (1.0081±0.0016) • [SRP] + (0.31±0.08)
1.6.5	Unbiased ozone mixing ratio (ppb) at start of audit:	X_{O3} (ppb) = ([OA] - 0.31 ppb) / 1.0081
1.6.6	Standard uncertainty remaining after compensation of calibration bias (ppb):	u_{O3} (ppb) = sqrt (0.34 ppb^2 + 2.74-05 * X_{O3}^2)
1.6.7	Coefficients after audit	NA
1.6.8	Calibration after audit (ppb):	NA
1.6.9	Unbiased ozone mixing ratio (ppb) after audit:	NA
1.6.10	Standard uncertainty remaining after compensation of calibration bias (ppb):	NA
1.7	Comments:	NA
1.8	Reference:	WCC-Empa Report 15/2

[OA]: Instrument readings; [SRP]: SRP readings; X_{O3}: mixing ratios on SRP scale

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Carbon Monoxide Audit Executive Summary

0.1	Station Name:	Jungfraujoch
0.2	GAW ID:	JFJ
0.3	Coordinates/Elevation:	46.54749°N 7.98509°E (3580m a.s.l.)
Parameter:		Carbon Monoxide

1.1	Date of Audit:	2015-01-17
1.2	Auditor:	Christoph Zellweger
1.3	Station staff involved in audit:	Martin Steinbacher, Simon A. Wyss
1.4	WCC-Empa CO Reference:	NOAA laboratory standards (WMO-X2014 scale)
1.5	CO Transfer Standard [TS]	TS calibrated against the WCC-Empa laboratory standards, WMO-2014 scale
1.6	Station Analyser:	
1.6.1	Analyser Model:	Picarro G2401 #CFKADS2133
1.6.2	Range of calibration:	71 – 248 ppb
1.6.3	Coefficients at start of audit	NA
1.6.4	Calibration at start of audit (ppb):	CO = (1.0078±0.0014) • X_{CO} - (3.9±2.4)
1.6.5	Unbiased CO mixing ratio (ppb) at start of audit:	X_{CO} (ppb) = (CO + 3.9) / 1.0078
1.6.6	Standard uncertainty after compensation of calibration bias at start of audit (ppb):	u_{CO} (ppb) = sqrt (9.7 ppb^2 + 1.01e-04 * X_{CO}^2)
1.6.7	Coefficients after audit	NA
1.6.8	Calibration after audit (ppb):	NA
1.6.9	Unbiased CO mixing ratio (ppb) after audit:	NA
1.6.10	Standard uncertainty after compensation of calibration bias after audit(ppb):	NA
1.7	Comments:	NA
1.8	Reference:	WCC-Empa Report 15/2

[CO]: Instrument readings; X: mixing ratios on the WMO-X2014 CO scale.

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Carbon Monoxide Audit Executive Summary

0.1	Station Name:	Jungfraujoch
0.2	GAW ID:	JFJ
0.3	Coordinates/Elevation:	46.54749°N 7.98509°E (3580m a.s.l.)
Parameter:		Carbon Monoxide

1.1	Date of Audit:	2015-01-17/18
1.2	Auditor:	Christoph Zellweger
1.3	Station staff involved in audit:	Martin Steinbacher, Simon A. Wyss
1.4	WCC-Empa CO Reference:	NOAA laboratory standards (WMO-X2014 scale)
1.5	CO Transfer Standard [TS]	TS calibrated against the WCC-Empa laboratory standards, WMO-2014 scale
1.6	Station Analyser:	
1.6.1	Analyser Model:	LGR-23r #12-0066
1.6.2	Range of calibration:	71 – 248 ppb
1.6.3	Coefficients at start of audit	NA
1.6.4	Calibration at start of audit (ppb):	CO = (1.0083±0.0015) · X_{CO} - (1.4±0.3)
1.6.5	Unbiased CO mixing ratio (ppb) at start of audit:	X_{CO} (ppb) = (CO + 1.4) / 1.0083
1.6.6	Standard uncertainty after compensation of calibration bias at start of audit (ppb):	u_{CO} (ppb) = sqrt (0.3 ppb^2 + 1.01e-04 * X_{CO}^2)
1.6.7	Coefficients after audit	NA
1.6.8	Calibration after audit (ppb):	NA
1.6.9	Unbiased CO mixing ratio (ppb) after audit:	NA
1.6.10	Standard uncertainty after compensation of calibration bias after audit(ppb):	NA
1.7	Comments:	NA
1.8	Reference:	WCC-Empa Report 15/2

[CO]: Instrument readings; X: mixing ratios on the WMO-X2014 CO scale.

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Methane Audit Executive Summary (JFJ)

0.1	Station Name:	Jungfraujoch
0.2	GAW ID:	JFJ
0.3	Coordinates/Elevation:	46.54749°N 7.98509°E (3580m a.s.l.)
Parameter:		Methane

1.1	Date of Audit:	2015-03-17
1.2	Auditor:	Christoph Zellweger
1.3	Staff involved in audit:	Martin Steinbacher, Simon A. Wyss
1.4	WCC-Empa CH_4 Reference:	NOAA laboratory standards (WMO-X2004 scale)
1.5	CH_4 Transfer Standard [TS]	TS calibrated against the WCC-Empa laboratory standards
1.6	Station Analyser:	
1.6.1	Analyser Model:	Picarro G2401 #CFKADS2133
1.6.2	Range of calibration:	1863 – 2123 ppb
1.6.3	Coefficients at start of audit	NA
1.6.4	Calibration at start of audit (ppb):	CH_4 = (0. 99919±0.00054) • X_{CH4} + (1.9±1.1) ppb
1.6.5	Unbiased CH_4 mixing ratio (ppb) at start of audit:	X_{CH4} (ppb) = (CH_4 – 1.9 ppb) / 0.99919
1.6.6	Standard uncertainty after compensation of calibration bias at start of audit (ppb):	u_{CH4} (ppb) = sqrt (0.1 ppb^2 + 1.30e-07 * X_{CH4}^2)
1.6.7	Coefficients after audit	NA
1.6.8	Calibration after audit (ppb):	NA
1.6.9	Unbiased CH_4 mixing ratio (ppb) after audit:	NA
1.6.10	Standard uncertainty after compensation of calibration bias after audit(ppb):	NA
1.7	Comments:	NA
1.8	Reference:	WCC-Empa Report 15/2

[CH_4]: Instrument readings; X: mixing ratios on the WMO-X2004 CH_4 scale.

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Carbon Dioxide Audit Executive Summary (JFJ)

0.1	Station Name:	Jungfraujoch
0.2	GAW ID:	JFJ
0.3	Coordinates/Elevation:	46.54749°N 7.98509°E (3580m a.s.l.)
Parameter:		Carbon Dioxide

1.1	Date of Audit:	2015-03-17
1.2	Auditor:	Christoph Zellweger
1.3	Staff involved in audit:	Martin Steinbacher, Simon A. Wyss
1.4	WCC-Empa CO_2 Reference:	NOAA laboratory standards (WMO-X2007 scale)
1.5	CO_2 Transfer Standard [TS]	TS calibrated against the WCC-Empa laboratory standards
1.6	Station Analyser:	
1.6.1	Analyser Model:	Picarro G2401 #CFKADS2133
1.6.2	Range of calibration:	331 – 413 ppm
1.6.3	Coefficients at start of audit	NA
1.6.4	Calibration at start of audit (ppm):	CO_2 = (0. 99975±0.00081) • X_{CO2} +(0.10±0.32) ppm
1.6.5	Unbiased CO_2 mixing ratio (ppm) at start of audit:	X_{CO2} (ppm) = (CO_2 – 0.10 ppm) / 0.99975
1.6.6	Standard uncertainty after compensation of calibration bias at start of audit (ppm):	u_{CO2} (ppm) = sqrt (0.011 ppm^2 + 3.28e-08 * X_{CO2}^2)
1.6.7	Coefficients after audit	NA
1.6.8	Calibration after audit (ppm):	NA
1.6.9	Unbiased CO_2 mixing ratio (ppm) after audit:	NA
1.6.10	Standard uncertainty after compensation of calibration bias after audit(ppm):	NA
1.7	Comments:	NA
1.8	Reference:	WCC-Empa Report 15/2

[CO_2]: Instrument readings; X: mixing ratios on the WMO-X2007 CO_2 scale.

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Carbon Dioxide Audit Executive Summary (JFJ)

0.1	Station Name:	Jungfraujoch
0.2	GAW ID:	JFJ
0.3	Coordinates/Elevation:	46.54749°N 7.98509°E (3580m a.s.l.)
Parameter:		Carbon Dioxide

1.1	Date of Audit:	2015-03-17
1.2	Auditor:	Christoph Zellweger
1.3	Staff involved in audit:	Michael Schibig
1.4	WCC-Empa CO_2 Reference:	NOAA laboratory standards (WMO-X2007 scale)
1.5	CO_2 Transfer Standard [TS]	TS calibrated against the WCC-Empa laboratory standards
1.6	Station Analyser:	
1.6.1	Analyser Model:	Sick Maihak S710
1.6.2	Range of calibration:	383 – 413 ppm
1.6.3	Coefficients at start of audit	NA
1.6.4	Calibration at start of audit (ppm):	CO_2 = (1.00907±0.00683) • X_{CO2} -(3.62±2.72) ppm
1.6.5	Unbiased CO_2 mixing ratio (ppm) at start of audit:	X_{CO2} (ppm) = (CO_2 + 3.62 ppm) / 1.00907
1.6.6	Standard uncertainty after compensation of calibration bias at start of audit (ppm):	u_{CO2} (ppm) = sqrt (0.060 ppm^2 + 3.28e-08 * $X_{CO2}{}^2$)
1.6.7	Coefficients after audit	NA
1.6.8	Calibration after audit (ppm):	NA
1.6.9	Unbiased CO_2 mixing ratio (ppm) after audit:	NA
1.6.10	Standard uncertainty after compensation of calibration bias after audit(ppm):	NA
1.7	Comments:	NA
1.8	Reference:	WCC-Empa Report 15/2

[CO_2]: Instrument readings; X: mixing ratios on the WMO-X2007 CO_2 scale.

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Nitrous Oxide Audit Executive Summary

0.1	Station Name:	Jungfraujoch
0.2	GAW ID:	JFJ
0.3	Coordinates/Elevation:	46.54749°N 7.98509°E (3580m a.s.l.)
Parameter:		Nitrous Oxide

1.1	Date of Audit:	2015-01-17/18
1.2	Auditor:	Christoph Zellweger
1.3	Station staff involved in audit:	Martin Steinbacher, Simon A. Wyss
1.4	WCC-Empa N_2O Reference:	NOAA laboratory standards (WMO-X2006A scale)
1.5	N_2O Transfer Standard [TS]	TS calibrated against the WCC-Empa laboratory standards, WMO-2006A scale
1.6	Station Analyser:	
1.6.1	Analyser Model:	LGR-23r #12-0066
1.6.2	Range of calibration:	298 – 343 ppb
1.6.3	Coefficients at start of audit	NA
1.6.4	Calibration at start of audit (ppb):	$N_2O = (0.99654 \pm 0.00223) \cdot X_{N2O} + (0.87 \pm 0.82)$
1.6.5	Unbiased N_2O mixing ratio (ppb) at start of audit:	X_{N2O} (ppb) = $(N_2O - 0.87) / 0.99654$
1.6.6	Standard uncertainty after compensation of calibration bias at start of audit (ppb):	u_{N2O} (ppb) = sqrt (0.022 ppb^2 + 1.01e-07 * X_{N2O}^2)
1.6.7	Coefficients after audit	NA
1.6.8	Calibration after audit (ppb):	NA
1.6.9	Unbiased N_2O mixing ratio (ppb) after audit:	NA
1.6.10	Standard uncertainty after compensation of calibration bias after audit(ppb):	NA
1.7	Comments:	NA
1.8	Reference:	WCC-Empa Report 15/2

[N_2O]: Instrument readings; X: mixing ratios on the WMO-X2006A N_2O scale.

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LIST OF ABBREVIATIONS

ATC	Atmospheric Thematic Center
BKG	Background
COEF	Coefficient
CRDS	Cavity Ring-Down Spectroscopy
DQO	Data Quality Objective
ESRL	Earth System and Research Laboratory
FOEN	Federal Office for the Environment
FMI	Finish Meteorological Institute
GAW	Global Atmosphere Watch
GAWSIS	GAW Station Information System
GHG	Greenhouse Gases
LS	Laboratory Standard
ICOS	Integrated Carbon Observation System
JFJ	Jungfraujoch GAW Station
NA	Not Applicable
NABEL	National Air Pollution Monitoring Network
NOAA	National Oceanic and Atmospheric Administration
NDIR	Non-Dispersive Infrared
OA-ICOS	Off-Axis Integrated Cavity Output Spectroscopy
SOP	Standard Operating Procedure
SRP	Standard Reference Photometer
TI	Travelling Instrument
TS	Traveling Standard
WCC-Empa	World Calibration Centre Empa
WDCGG	World Data Centre for Greenhouse Gases
WMO	World Meteorological Organization