Quality assurance and quality control of CO_2 observations

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Part of this programme: ACTRIS, EMEP, GAW, ICOS, IG3IS, NABEL

Keywords: atmospheric chemistry; air quality; trace gases; greenhouse gases; long-term monitoring

1. Project description

Empa launched its first atmospheric measurements at Jungfraujoch in 1973 as part of an early engagement of Switzerland in a programme organised by the Organisation for Economic Co-operation and Development (OECD). In 1978, Empa and the Swiss Federal Office for the Environment (FOEN/BAFU) initiated the Swiss National Air Pollution Monitoring Network (NABEL), with Jungfraujoch (JFJ) being one of the first 8 sites. In 1990/1991 the NABEL network was extended to 16 monitoring stations that are distributed across Switzerland. The monitoring stations represent the most important air pollution levels ranging from the urban kerbside to the remote background. The NABEL site at Jungfraujoch is such a remote site; it represents the lower free troposphere in central Europe.

The current measurement program at Jungfraujoch includes continuous in-situ analyses of ozone (O_3), carbon monoxide (CO), nitrogen monoxide (NO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), methane (CH_4), carbon dioxide (CO_2) and nitrous oxide (N_2O). Particulate matter is measured as PM10 (particles < 10 µm), PM2.5 (< 2.5 µm), PM1 (< 1 µm), and the particle number concentration (PNC) between 0.18 and 18 µm is also recorded continuously. All these data are stored as 10-min averages. An extended set of halocarbons (e.g. CFCs, HFCs), sulphur hexafluoride (SF_6) and a selection of volatile organic compounds (VOCs) (alkanes, aromatics) are measured with a time resolution of two hours. Daily samples are taken to quantify particulate sulphur and PM10.

A comprehensive calibration, quality assurance (QA) and quality control (QC) strategy is of utmost importance when performing atmospheric composition measurements. This is particularly true when measurements are long-term and part of a network of stations to ensure that the observed variability and trends are not due to changes in the instruments' sensitivity, and to allow for a best possible compatibility of the different time series within the network or across several networks, respectively. The latter also requires a well-documented traceability to internationally agreed scales, which are maintained by either National Metrology Institutes or assigned Central Calibration Laboratories in case of the Global Atmosphere Watch (GAW) programme of the World Meteorological Organisation (WMO). The required quality and quantity of the data are defined by so-called data quality objectives (DQOs). DQOs specify tolerable levels of measurement uncertainty and/or network compatibility based on the scientific question of interest or the decisions to be made (WMO, 2017). Within the context of GAW, DQOs are released as part of GAW reports (available via the WMO library, https://library.wmo.int/) or in the peer-reviewed literature as those publications often have a wider visibility in the scientific community. Sometimes, several resources are available, for example in the case of tropospheric ozone. There, DQOs for traditional GAW goals such as the detection of long-term changes in ozone background concentrations are given in a GAW report (WMO, 2013), but more explicit requirements for specific scientific questions, such as requirements for the validation of air quality models or satellite-borne ozone data, were released in a later publication (Tarasick et al., 2019).

DQOs are particularly demanding for carbon dioxide (CO_2) observations due to its long atmospheric lifetime, the strong interaction with the biosphere and consequently only small spatial gradients. The DQOs for greenhouse gases like CO_2 are regularly reviewed during the bi-annual Meeting on Carbon Dioxide, Other Greenhouse Gases and Related Measurement Techniques – GGMT (WMO, 2020). The desired compatibility goal, understood as "*the scientifically-determined maximum bias among monitoring programmes that can be included without significantly influencing fluxes inferred from observations with models*" for measurements in well-mixed background conditions is 0.1 ppm in the Northern hemisphere. To meet this goal, an internal reproducibility including instrumental imprecision, uncertainties in the traceability chain or uncertainties due to gas handling and drying of about 0.05 ppm (or roughly 0.1 permil at a level of 400 ppm) needs to be achieved (WMO, 2020). These specifications require high-precision instrumentation, a comprehensive QA/QC strategy, and a close and unbroken link to one of the internationally accepted primary scales. Operators of European greenhouse gas observations in pristine regions teamed up under the umbrella of the Integrated Carbon Observation System (ICOS) Research Infrastructure (www.icos-ri.eu). Members of ICOS, which is recognized as a contributing network to GAW, benefit from access to a Central Analytical

Laboratory in Germany, which provides references gases directly traceable to the WMO scales maintained by GAW's Central Calibration Laboratories. For an optimum compatibility, ICOS also developed detailed specifications in terms of operation, like number of calibration gases, and specifies requirements in terms of sample periphery, like drying units, tubing material, models of pressure regulators etc. (ICOS RI, 2020). ICOS stations also undergo a rigorous assessment prior to acceptance to the network. The assessment procedure is documented in a recent publication by Yver-Kwok et al. (2021). A minimum of three high-pressure cylinders are required for a weekly to bi-weekly calibration, and two additional target tanks are used to track the short-term and longer-term performance of the instrumentation. Data from all ICOS stations are sent daily to the Atmospheric Thematic Centre (ATC) in France for centralized data processing. There, the data sets are split into subsets of in-situ (ambient air) data, target data and calibration data and further processed (see Figure 1 for illustration). Target data are measured up to once per day, are treated as unknowns in the same way as the in-situ data and are used as quality indicators and timely markers in case of problems.

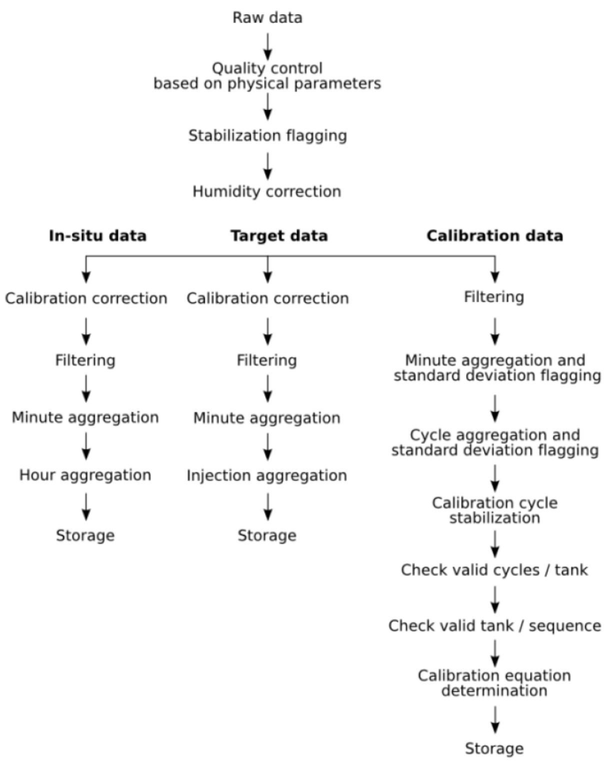

Figure 1. Schematic of data treatment during automatic processing at the ICOS Atmospheric Thematic Centre (taken from Hazan et al., 2016).

Standardized output is generated for visual inspection and quality control and is made publically available on the ICOS ATC panel board (https://icos-atc.lsce.ipsl.fr/dp). One of those plots is shown in Figure 2. The multi-panel figure shows the ambient air data on top, followed by the standard deviation of the ambient air data, the continuous measurement repeatability (CMR) defined as the monthly average of the standard deviations of short-term target raw data over 1 min intervals, the long-term repeatability (LTR) calculated as the standard deviation of the averaged short-term target measurement intervals over 3 days, and the difference of the calibrated short-term target data to its assigned value. The enhanced levels of LTR uncertainty and short-term target bias at the beginning of the period were caused by a problem with the sample drying. These numbers could be flattened when changing the drying unit in early November 2017. A series of other automatically generated plots are updated once a day and are made available on the ATC webpage.

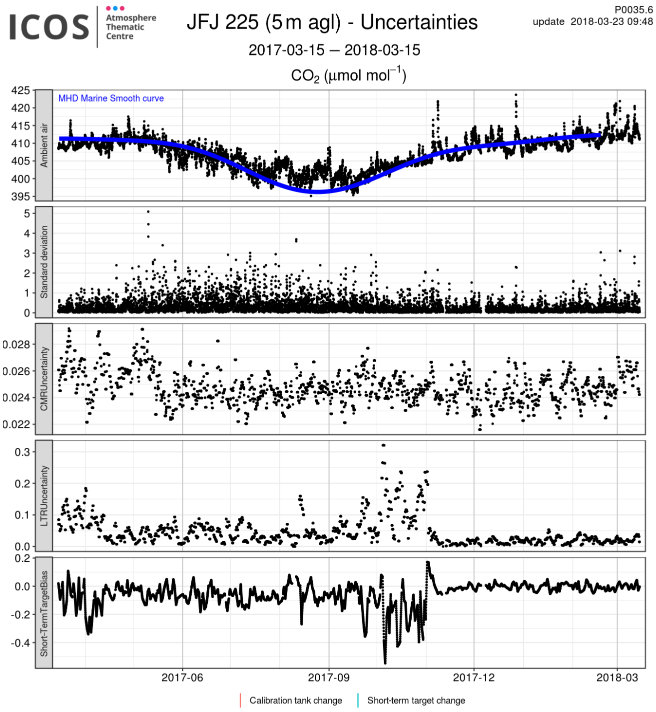

Figure 2. Standardized ICOS summary plot for atmospheric CO_2 data from Jungfraujoch. See the text for details. The smoothed curve for Mace Head (in blue) is added for visual guidance to the plots of all stations to simplify the comparison (taken from Yver-Kwok et al., 2021).

Next to the background station Jungfraujoch, CO_2 is also measured at the NABEL stations Haerkingen, Payerne and Rigi-Seebodenalp. The observations close to the highway in Haerkingen started in 2007 mainly as an indicator for the intensity of the traffic influencing the site. In more recent years, CO_2 measurements were also launched at Payerne and Rigi-Seebodenalp, partly facilitated through the availability of multi-species analyzers allowing to measure CO and CO_2 with the same instrument. In 2019, calibration and traceability of the CO_2 measurements at Payerne and Rigi-Seebodenalp were also implemented. Due to the rather large variability at Haerkingen, Payerne and Rigi-Seebodenalp (see Figure 3), a relaxed QA/QC strategy can be followed, and a simplified calibration scheme is applied. Instruments are regularly calibrated with CO_2-free air and one reference tank. Concentrations in the reference tanks are assigned by WMO/GAW's World Calibration Centre for CO_2 at Empa and are, thus, also traceable to the common GAW scale. The atmospheric variability on the Swiss plateau (observed at Haerkingen and Payerne) is largely driven by meteorology, such as the intensity of venting of the plateau or the occurrence of inversions. The measured CO_2 concentrations at Haerkingen are usually higher than at Payerne due to the vicinity of the highway, but persistent episodes with particularly low (e.g. in late February/ early March 2020) or high concentrations (e.g. in mid-March 2020) can be observed at both sites. The elevation of the Rigi-Seebodenalp station (1031 m asl) results in significant less variability than on the Swiss plateau but there is still more scatter than at Jungfraujoch, which is mostly exposed to free tropospheric air masses.

The CO_2 measurements at the four NABEL stations also serve as reference for the recently established Carbosense network (http://carbosense.wikidot.com). The Carbosense network is a uniquely dense CO_2 sensor network across Switzerland, which includes more than 250 low-cost sensors measuring CO_2. Due to the large number of sensors, network control and sensor calibration requires novel QA/QC approaches. Prior to deployment, all sensors are calibrated in a pressure and climate chamber as well as in ambient conditions when being exposed next to a reference instrument for several weeks. Once deployed, sensor data are corrected for interferences of atmospheric water vapour, followed by an outlier and drift correction and a final consistency check (Müller et al., 2020). The high-precision NABEL data are used for sensor calibration and assessment of the sensors' long-term performance as well as for correcting the sensor drifts during field operation.

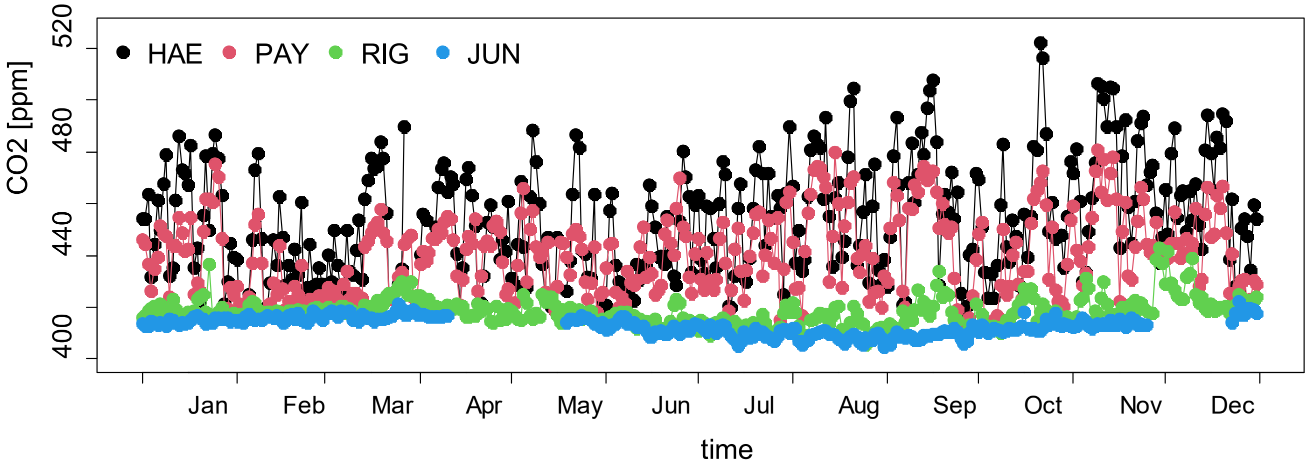

Figure 3. Daily averages of CO_2 mole fractions in 2020 at Jungfraujoch (blue) and other lower elevation sites of the Swiss National Air Pollution Monitoring Network, Haerkingen (HAE, black), Payerne (PAY, red), and Rigi-Seebodenalp (RIG, green).

Acknowledgements

We thank the International Foundation High Altitude Research Stations Jungfraujoch and Gornergrat (HFSJG) for providing access to the facilities and the custodians at Jungfraujoch for their dedicated support of the observations. The Swiss National air Pollution Monitoring Network is run by Empa in collaboration with the Swiss Federal Office for the Environment (FOEN). CO_2 observations at Jungfraujoch are also supported through ICOS Switzerland, which is funded by the Swiss National Science Foundation (grants 20FI21_148992 and 20FI20_173691) and in-house contributions. Carbosense is a joint effort of Empa, Swisscom and Decentlab and is supported by the Swiss Data Science Center (SDSC) (grant number 17-06) and the Swiss State Secretariat for Education, Research and Innovation.

References

ICOS RI, ICOS Atmosphere Station Specifications V2.0 (editor: O. Laurent), ICOS ERIC, https://doi.org/10.18160/GK28-2188, 2020.

Müller, M., P. Graf, J. Meyer, A. Pentina, D. Brunner, F. Perez-Cruz, L. Emmenegger, Integration and calibration of non-dispersive infrared (NDIR) CO2 low-cost sensors and their operation in a sensor network covering Switzerland, Atmospheric Measurement Techniques, **13**, 3815-3834. https://doi.org/10.5194/amt-13-3815-2020, 2020.

Tarasick D., I. E. Galbally, O. R. Cooper, M. G. Schultz, G. Ancellet, T. Leblanc, T. J. Wallington, J. Ziemke, X. Liu, M. Steinbacher, J. Staehelin, C. Vigouroux, J. W. Hannigan, O. Garcia, G. Foret, P. Zanis, E. Weatherhead, I. Petropavlovskikh, H. Worden, M. Osman, J. Liu, K.-L. Chan, A. Gaudel, M. Lin, M. Granados-Munoz, A. M. Thompson, S. J. Oltmans, J. Cuesta, G. Dufour, V. Thouret, B. Hassler, T. Trickl, J. L. Neu, Tropospheric Ozone Assessment Report: Tropospheric ozone from 1877 to 2016, observed levels, trends and uncertainties, Elementa, **7** (39), doi: https://doi.org/10.1525/elementa.376, 2019.

WMO, Guidelines for Continuous Measurement of Ozone in the Troposphere, by Galbally, I. E., M. G. Schultz, B. Buchmann, S. Gilge, F. Guenther, H. Koide, S. Oltmans, L. Patrick, H.-E. Scheel, H. Smit, M. Steinbacher, W. Steinbrecht, O. Tarasova, J. Viallon, A. Volz-Thomas, M. Weber, R. Wielgosz, C. Zellweger, GAW Report No 209, ISBN 978-92-63-11110-4, Geneva, Switzerland: World Meteorological Organisation, https://library.wmo.int/index.php?lvl=notice_display&id=14537, 2013.

WMO, GAW Implementation Plan (IP) 2016-2023, GAW Report No 228, ISBN 978-92-63-11156-2, Geneva, Switzerland: World Meteorological Organisation, https://library.wmo.int/doc_num.php?explnum_id=3395, 2017.

WMO, 20th WMO/IAEA Meeting on Carbon Dioxide, Other Greenhouse Gases and Related Measurement Techniques (GGMT-2019), Crotwell, A., H. Lee, M. Steinbacher (eds), WMO/GAW report #255, World Meteorological Organisation, https://library.wmo.int/doc_num.php?explnum_id=10353, 2020.

Internet data bases

http://empa.ch/web/s503/nabel
https://www.bafu.admin.ch/bafu/de/home/themen/luft/zustand/daten.html
https://www.icos-cp.eu/
https://icos-atc.lsce.ipsl.fr/JFJ

Collaborating partners / networks

Bundesamt für Umwelt (BAFU) / Federal Office for the Environment (FOEN)
Belgian Institute for Space Aeronomy, Brussels
Climate and Environmental Physics, University of Bern
Environmental Geosciences, University of Basel
Institut d'Astrophysique et de Géophysique, Université de Liège
Institute for Atmospheric and Climate Science, ETH Zurich
Laboratory for Atmospheric Chemistry, Paul Scherrer Institut
MeteoSchweiz
World Meteorological Organisation (WMO)
ACTRIS – Aerosol, Clouds, and Trace Gases Research Network
EMEP – European Monitoring and Evaluation Programme
GAW – Global Atmosphere Watch
ICOS – Integrated Carbon Obervation System Research Infrastructure
IG3IS – Integrated Global Greenhouse Gas Information System
NABEL – Swiss National Air Pollution Monitoring Network
RINGO – Readiness of ICOS for Necessities of Integrated Global Observations

Scientific publications and public outreach 2020

Refereed journal articles and their internet access

Boleti, E., C. Hueglin, S.K. Grange, A.S.H. Prévôt, S. Takahama, Temporal and spatial analysis of ozone concentrations in Europe based on timescale decomposition and a multi-clustering approach, Atmospheric Chemistry and Physics, **20**, 9051-9066, 2020.
https://doi.org/10.5194/acp-20-9051-2020

Cooper O.R., M.G. Schultz, S. Schröder, K.-L. Chang, A. Gaudel, G. Carbajal-Benitez, E. Cuevas, M. Fröhlich, I.E. Galbally, S. Molloy, D. Kubistin, X. Lu, A. McClure-Begley, P. Nedelec, J.O'Brien, S.J. Oltmans, I. Petrapavlovskihk, L. Ries, I. Senik, K. Sjöberg, S. Solberg, G.T. Spain, W. Spangl, M. Steinbacher, D. Tarasick, V. Thouret, X. Xu, Multi-decadal surface ozone trends at globally distributed remote locations, Elementa, **8**, 23, 2020. http://doi.org/10.1525/elementa.420

Cristofanelli P., F. Fierli, F. Graziosi, M. Steinbacher, C. Couret, F. Calzolari, F. Roccato, T. Landi, D. Putero, P. Bonasoni, Decadal O3 variability at the Mt. Cimone WMO/GAW global station (2,165 m a.s.l., Italy) and comparison with two high-mountain "reference" sites in Europe, Elementa, **8**, 1, 2020. https://doi.org/10.1525/elementa.00042

Laj P., A. Bigi, C. Rose, E. Andrews, C. Lund Myhre, M. Collaud Coen, A. Wiedensohler, M. Schultz, J. A. Ogren, M. Fiebig, J. Gliß, A. Mortier, M. Pandolfi, T. Petäjä, S.-W. Kim, W. Aas, J.-P. Putaud, O. Mayol-Bracero, M. Keywood, L. Labrador, P. Aalto, E. Ahlberg, L. Alados Arboledas, A. Alastuey, M. Andrade, B. Artíñano, S. Ausmeel, T. Arsov, E. Asmi, J. Backman, U. Baltensperger, S. Bastian, O. Bath, J.P. Beukes, B.T. Brem, N. Bukowiecki, S. Conil, C. Couret, D. Day, W. Dayantolis, A. Degorska, S.M. Dos Santos, K. Eleftheriadis, P. Fetfatzis, O. Favez, H. Flentje, M.I. Gini, A. Gregorič, M. Gysel-Beer, G.A. Hallar, J. Hand, A. Hoffer, C. Hueglin, R.K. Hooda, A. Hyvärinen, I. Kalapov, N. Kalivitis, A. Kasper-Giebl, J.E. Kim, G. Kouvarakis, I. Kranjc, R. Krejci, M. Kulmala, C. Labuschagne, H.-J. Lee, H. Lihavainen, N.-H. Lin, G. Löschau, K. Luoma, A. Marinoni, F. Meinhardt, M. Merkel, J.-M. Metzger, N. Mihalopoulos, N.A. Nguyen, J. Ondracek, N. Peréz, M.R. Perrone, J.-E. Petit, D. Picard, J.-M. Pichon, V. Pont, N. Prats, A. Prenni, F. Reisen, S. Romano, K. Sellegri, S. Sharma, G. Schauer, P. Sheridan, J.P. Sherman, M. Schütze, A. Schwerin, R. Sohmer, M. Sorribas, M. Steinbacher, J. Sun, G. Titos, B. Tokzko, T. Tuch, P. Tulet, P. Tunved, V. Vakkari, F. Velarde, P. Velasquez, P. Villani, S. Vratolis, S.-H. Wang, K. Weinhold, R. Weller, M. Yela, J. Yus-Diez, V. Zdimal, P. Zieger, N. Zikova, A global analysis of climate-relevant aerosol properties retrieved from the network of Global Atmosphere Watch (GAW) near-surface observatories, Atmospheric Measurement Techniques, **13**, 4353-4392, 2020. https://doi.org/10.5194/amt-13-4353-2020

Müller, M., P. Graf, J. Meyer, A. Pentina, D. Brunner, F. Perez-Cruz, L. Emmenegger, Integration and calibration of non-dispersive infrared (NDIR) CO2 low-cost sensors and their operation in a sensor network covering Switzerland, Atmospheric Measurement Techniques, **13**, 3815-3834, 2020.
https://doi.org/10.5194/amt-13-3815-2020

Parrish D.D., R.G. Derwent, W. Steinbrecht, R. Stübi, R. van Malderen, M. Steinbacher, T. Trickl, L. Ries, X. Xu, Zonal Similarity of Long-term Changes and Seasonal Cycles of Baseline Ozone at Northern Mid-latitudes, Journal of Geophysical Research Atmosphere, **125**, 2020. https://doi.org/10.1029/2019JD031908

Ramonet, M., P. Ciais, F. Apadula, J. Bartyzel, A. Bastos, P. Bergamaschi, P.E. Blanc, D. Brunner, L. Caracciolo di Torchiarolo, F. Calzolari, H. Chen, L. Chmura, A. Colomb, S. Conil, P. Cristofanelli, E. Cuevas, R. Curcoll, M. Delmotte, A. di Sarra, L. Emmenegger, G. Forster, A. Frumau, C. Gerbig, F. Gheusi, S. Hammer, L. Haszpra, J. Hatakka, L. Hazan, M. Heliasz, S. Henne, A. Hensen, O. Hermansen, P. Keronen, R. Kivi, K. Komínková, D. Kubistin, O. Laurent, T. Laurila, J.V. Lavric, I. Lehner, K.E.J. Lehtinen, A. Leskinen, M. Leuenberger, I. Levin, M. Lindauer, M. Lopez, C. Lund Myhre, I. Mammarella, G. Manca, A. Manning, M.V. Marek, P. Marklund, D. Martin, F. Meinhardt, N. Mihalopoulos, M. Mölder, J.A. Morgui, J. Necki, S. O'Doherty, C. O'Dowd, M. Ottosson, C. Philippon, S. Piacentino, J.M. Pichon, C. Plass-Duelmer, A. Resovsky, L. Rivier, X. Rodó, M.K. Sha, H.A. Scheeren, D. Sferlazzo, T.G. Spain, K.M. Stanley, M. Steinbacher, P. Trisolino, A. Vermeulen, G. Vítková, D. Weyrauch, I. Xueref-Remy, K. Yala, C. Yver Kwok, The fingerprint of the summer 2018 drought in Europe on ground-based atmospheric CO2 measurements, Philosophical Transactions of the Royal Society B, **375**, 20190513, 2020. http://dx.doi.org/10.1098/rstb.2019.0513

Yu, L., E. Harris, S. Henne, S. Eggleston, M. Steinbacher, L. Emmenegger, C. Zellweger, J. Mohn, The isotopic composition of atmospheric nitrous oxide observed at the high-altitude research station Jungfraujoch, Switzerland, Atmospheric Chemistry and Physics, **20**, 6495-6519, 2020. https://doi.org/10.5194/acp-20-6495-2020

Conference Papers

Henne, S., D. Brunner, M.K. Vollmer, M. Steinbacher, S. Reimann, L. Emmenegger, Simulating atmospheric tracer transport towards and concentrations at the high altitude observatory Jungfraujoch, 5th VAO Symposium, Bern, Switzerland, February 4-6, 2020.

Henne, S., D. Brunner, M.K. Vollmer, M. Steinbacher, M. Leuenberger, J. Mohn, S. Reimann, L. Emmenegger, Top-down Estimation of Swiss non-CO2 Greenhouse Gas Emissions in Support of National Inventory Reporting to UNFCCC, 18th Swiss Geoscience Meeting, virtual, November 6, 2020.

Henne, S., M.K. Vollmer, M. Steinbacher, M. Leuenberger, F. Meinhardt, J. Mohn, L. Emmenegger, D. Brunner, S. Reimann, Top-down Support of Swiss non-CO2 Greenhouse Gas Emissions Reporting to UNFCCC, EGU General Assembly 2020, virtual, May 4-8, 2020.

Pieber, S.M., B. Tuzson, S. Henne, U. Karstens, D. Brunner, A. Jordan, H. Moossen, M. Rothe, M. Steinbacher, L. Emmenegger, Nine years of continuous CO2 and δ13C stable isotope ratio measurements at Jungfraujoch interpreted with atmospheric transport simulations, 5th VAO Symposium, Bern, Switzerland, February 4-6, 2020.

Pieber, S.M., B. Tuzson, S. Henne, U. Karstens, D. Brunner, M. Steinbacher, L. Emmenegger, Simulations of atmospheric CO2 and δ13C-CO2 compared to real-time observations at the high altitude station Jungfraujoch, EGU General Assembly 2020, virtual, May 4-8, 2020.

Pieber, S.M., B. Tuzson, S. Henne, U. Karstens, H. Moossen, A. Jordan, M. Rothe, D. Brunner, M. Steinbacher, L. Emmenegger, A decade of atmospheric CO2 mole fraction and stable isotope ratios at Jungfraujoch measured by QCLAS, GC-FID and IRMS, Swiss Chemical Society Fall Meeting, virtual, August 25, 2020.

Pieber, S.M., B. Tuzson, S. Henne, U. Karstens, D. Brunner, M. Steinbacher, L. Emmenegger, Simulations of atmospheric CO2 and δ13C-CO2 compared to real-time observations at the high altitude station Jungfraujoch, , ICOS Science Conference, virtual, September 15-17, 2020.

Steinbacher, M, Updates on ICOS RI, ICOS CH National Meeting, virtual, September 3, 2020.

Steinbacher, M., WMO/GAW Quality Assurance / Science Activity Centres, Joint GAW Web Meeting of Expert Team- Atmospheric Composition Measurement Quality (ET-ACMQ) and QA-Central Facilities (QA-CF's), virtual, September 29, 2020.

Steinbacher, M., Long-term observations of atmospheric trace gases: challenges, implementation and operation, BMKG focus group discussion, virtual, November 12, 2020.

Steinbacher, M., The Importance of Quality Assurance and Quality Control for long-term in-situ atmospheric composition observations, GAWTEC webinar, virtual, December 7, 2020.

Steinbacher, M., C. Hueglin, S. Reimann, D. Brunner, B. Buchmann, L. Emmenegger, 45 Years of Atmospheric in-situ Trace-Gases Observations at Jungfraujoch, 5th VAO Symposium, Bern, Switzerland, February 4-6, 2020.

Steinbacher, M., D. Steger, S. Pieber, B. Tuzson, R. Rüfenacht, L. Emmenegger, Update from ICOS-CH Atmosphere Network and Jungfraujoch, ICOS CH National Meeting, virtual, September 3, 2020.

Steinbacher, M., C. Zellweger, L. Emmenegger, B. Buchmann, The importance of training for long-term operation of atmospheric greenhouse gas observations, ICOS Science Conference, virtual, September 15-17, 2020.

Edited books

Crotwell, A., H. Lee, M. Steinbacher (eds), 20th WMO/IAEA Meeting on Carbon Dioxide, Other Greenhouse Gases and Related Measurement Techniques (GGMT-2019), WMO/GAW report #255, World Meteorological Organisation, 2020.

Data books and reports

BAFU, Empa (eds) – Luftqualität 2019, Messresultate des Nationalen Beobachtungsnetzes für Luftfremdstoffe (NABEL), pp. 28, Bundesamt für Umwelt, Bern, Umwelt-Zustand Nr. 2020, 2020.

ICOS RI: ICOS Atmosphere Release 2020-1 of Level 2 Greenhouse Gas Mole Fractions of CO2, CH4, CO, meteorology and 14CO2, ICOS ERIC - Carbon Portal, doi:10.18160/H522-A9S0, 2020.

Magazine and Newspaper articles

"Sky-high science", National Geographic, vol. 237, no. 1, January, 2020.

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