

Diurnal and seasonal cycles of trace gases and their year-to-year variability at Jungfrauoch

Martin Steinbacher ¹, David Steger¹, Beat Schwarzenbach¹, Christoph Hueglin ¹, and Lukas Emmenegger ¹

¹Laboratory for Air Pollution / Environmental Technology, Empa – Swiss Federal Laboratories for Materials Science and Technology, Duebendorf, Switzerland

martin.steinbacher@empa.ch

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

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

1 Project description

Empa launched its first atmospheric measurements at Jungfrauoch in 1973. In 1978, Empa and the Swiss Federal Office for the Environment (FOEN/BAFU) established the Swiss National Air Pollution Monitoring Network (NABEL), with Jungfrauoch being one of the first 8 sites. In 1990/1991, the NABEL network was expanded to 16 monitoring stations distributed throughout Switzerland (Hueglin et al. 2024). The monitoring stations represent the most important levels of air pollution, which range from the urban kerbside to the remote background. The NABEL site at Jungfrauoch is such a remote site; it predominantly represents the lower free troposphere in central Europe.

Empa's current measurement program at Jungfrauoch includes continuous in-situ analysis of air pollutants such as ozone (O₃), carbon monoxide (CO), nitrogen monoxide (NO), nitrogen dioxide (NO₂), sulphur dioxide (SO₂), and particulate matter. The latter are measured as PM₁₀ (particles <10 µm), PM_{2.5} (<2.5 µm), PM₁ (<1 µm), and the particle number concentration (PNC) between 0.18 and 18 µm. In addition, the greenhouse gases carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O) are monitored. All of these data are routinely stored as 10-min averages. An extended set of halogenated greenhouse gases, sulphur hexafluoride (SF₆) and a selection of volatile organic compounds (alkanes, aromatics) are measured with a time resolution of two hours. Bulk samples are taken to quantify daily PM₁₀ averages and to allow chemical characterization (nitrate, chloride and sulphate) of particulate matter.

2 Time series analysis

In this activity report, we look into diurnal and seasonal cycles and their interannual variability observed at Jungfrauoch over the last 10 years. The analysis focuses on O₃, CO, CH₄ and CO₂. The time series of these species are least subjected to sporadic and short-term events. Such events, when leading to extraordinarily high or low concentrations, may lead to less regular diurnal and seasonal patterns that are more difficult to interpret. This is, for example, the case for the records of

particulate matter that are sporadically impacted by strong Sahara dust events, which can dominate the shape and the year-to-year variability of the diurnal and seasonal cycles. Similarly, irregular signatures from regional emissions and processes are seen in the time series of nitrogen oxides (NO and NO₂), leading to less systematic diurnal and seasonal cycles.

2.1 Ozone

Figure 1 shows the time series of hourly averages (panel a), the seasonal cycles (panel b), and diurnal cycles (panel c) of the O₃ observations at Jungfrauoch for the 2015 to 2024 period. The O₃ trend for the last 10 years is close to zero but slightly negative (-0.1 ppb yr^{-1}), which corresponds to earlier findings by Cooper et al. 2020 and Parrish et al. 2020 who reported positive O₃ trends at Jungfrauoch and other Alpine sites in the 1980s and 1990s that turned into slightly negative trends after around 2005. The seasonal cycles for the individual years at Jungfrauoch show consistent patterns with summer maxima and winter minima, which are common for high-altitude monitoring stations in the Alps (Parrish et al. 2020). The seasonal cycle reflects the larger scale photochemical production of O₃ with stronger O₃ formation when the solar radiation is more intense. The year 2020, which experienced significant reductions in O₃ precursor emissions due to Covid-19 related restrictions (Gkatzelis et al. 2021), does, at first glance, not stand out very prominently neither in the time series nor in the seasonal cycles. However, lower than usual O₃ monthly mean mole fractions were observed at Jungfrauoch in May, June and July, and rather low O₃ mole fractions extended until summer 2021. These negative anomalies were also seen at other elevated monitoring stations in Europe, indicating a large scale phenomenon attributable to the widespread Covid-19 restrictions (Putero et al. 2023). The low surface O₃ mole fractions observed at elevated remote monitoring sites were also in agreement with the mid-troposphere O₃ mole fractions observed by ground-based remote sensing, O₃ soundings, and aircraft measurements (Steinbrecht et al. 2021).

The exceptionally low O₃ mole fractions at Jungfrauoch in 2020 become more apparent in the diurnal cycles because

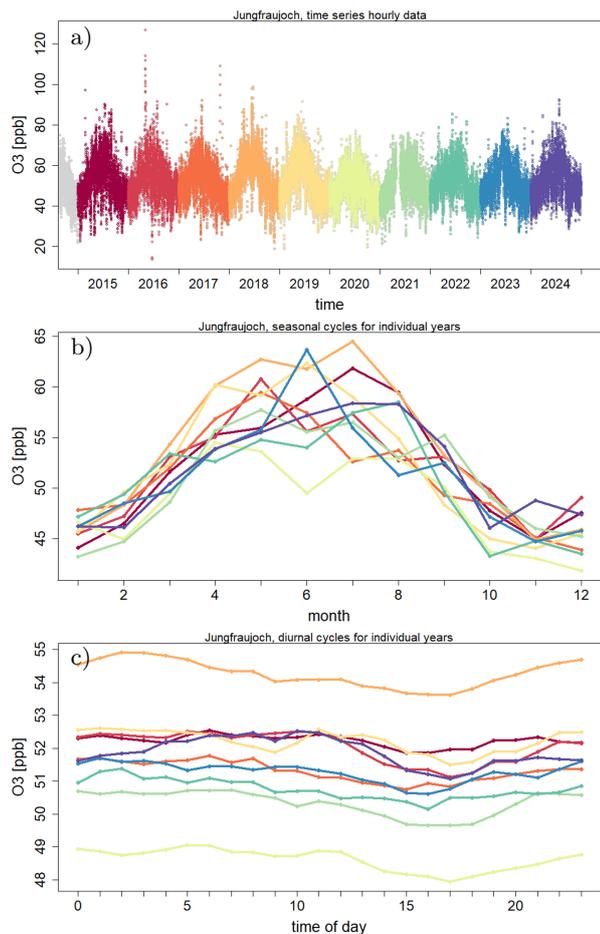


Figure 1: Time series of hourly averages (panel a), seasonal cycles (panel b) and diurnal cycles (panel c) for surface ozone observed at Jungfraujoch for the 2015 to 2024 period. Different colors represent different years.

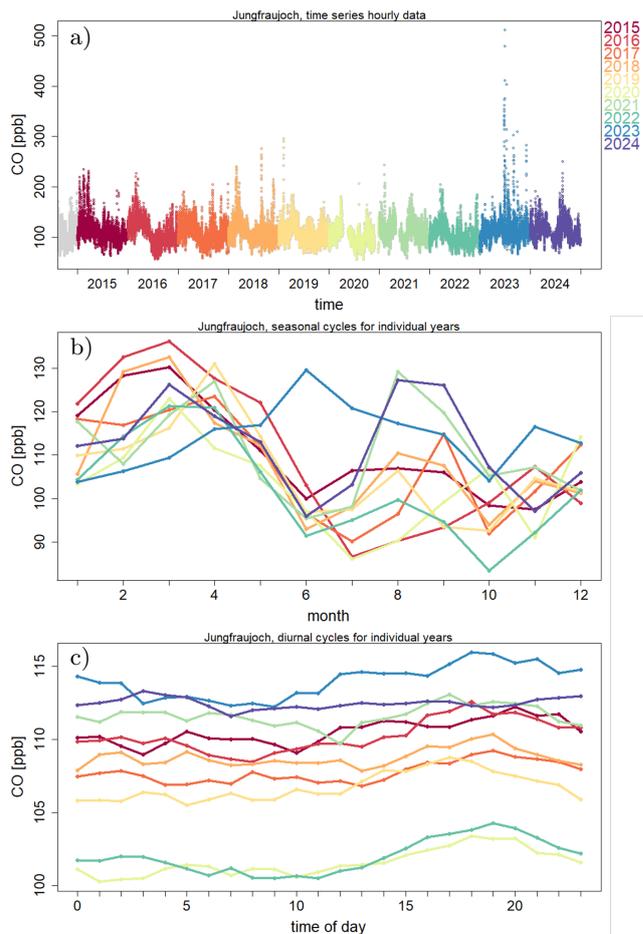


Figure 2: Time series of hourly averages (panel a), seasonal cycles (panel b) and diurnal cycles (panel c) for carbon monoxide observed at Jungfraujoch for the 2015 to 2024 period. Different colors represent different years.

the diurnal cycles usually reveal a low year-to-year variability. Systematic diurnal cycles are particularly developed in summer, while hardly any dependence on the time of the day is seen in winter. O_3 mole fractions in summer tend to reach minimum levels in the late afternoon, which coincide with the arrival of convective air masses from the planetary boundary layer (PBL) at Jungfraujoch (Baltensperger et al. 1997). On average, the air masses from the PBL reaching Jungfraujoch contain lower O_3 mole fractions than the free troposphere conditions, which are usually predominant at Jungfraujoch during nighttime. Therefore, diurnal O_3 cycles at Jungfraujoch feature minimum values in the late afternoon.

2.2 Carbon monoxide

Exceptionally low mole fractions were also observed in 2020 for CO, as can easily be seen in the yearly separated diurnal cycles (see Figure 2, panel c). A similarly low diurnal cycle was recorded for 2022, while the pattern in 2021 was similar to pre-pandemic years.

Overall, diurnal patterns at Jungfraujoch show late afternoon

maxima, which can again be explained by the prominent advection of PBL air masses during this time of the day. The seasonal patterns for CO are less consistent than for O_3 due to the impact of occasional events leading to elevated CO mole fractions. This is well illustrated for the year 2023, when large scale forest fires from Canada reached the European continent (Byrne et al. 2024) and led to hourly CO mole fractions at Jungfraujoch of up to 500 ppb (see Figure 2, panel a), which were unprecedented compared to previous years. These episodes also altered the common seasonal cycle with CO minima in the summer season because the Canadian fires were strongest in June 2023 (Jones et al. 2024). Due to the intercontinental advection of CO emissions from Canada to Europe during summer, there was no systematic seasonal cycle of CO observed at Jungfraujoch for 2023 (see Figure 2, panel b). Despite the signature of this event, a negative trend of -0.1 ppb yr^{-1} was observed over the last 10 years. It is lower than the mean global long-term trend for CO at remote locations of -0.8 ppb yr^{-1} for the 1991–2020 period (Patel et al. 2024), but also confirms the findings of Patel et al. 2024 that there was a slowdown in CO decline in the most recent decade.

2.3 Carbon dioxide

The CO₂ record at Jungfraujoch (see Figure 3) shows a striking persistent increase with an average growth rate of 2.5 ppm yr⁻¹. This is well in line with the global mean annual of 2.4 ppm yr⁻¹ increase over the past 10 years, as reported in the latest edition of the WMO Greenhouse Gas Bulletin (WMO 2024).

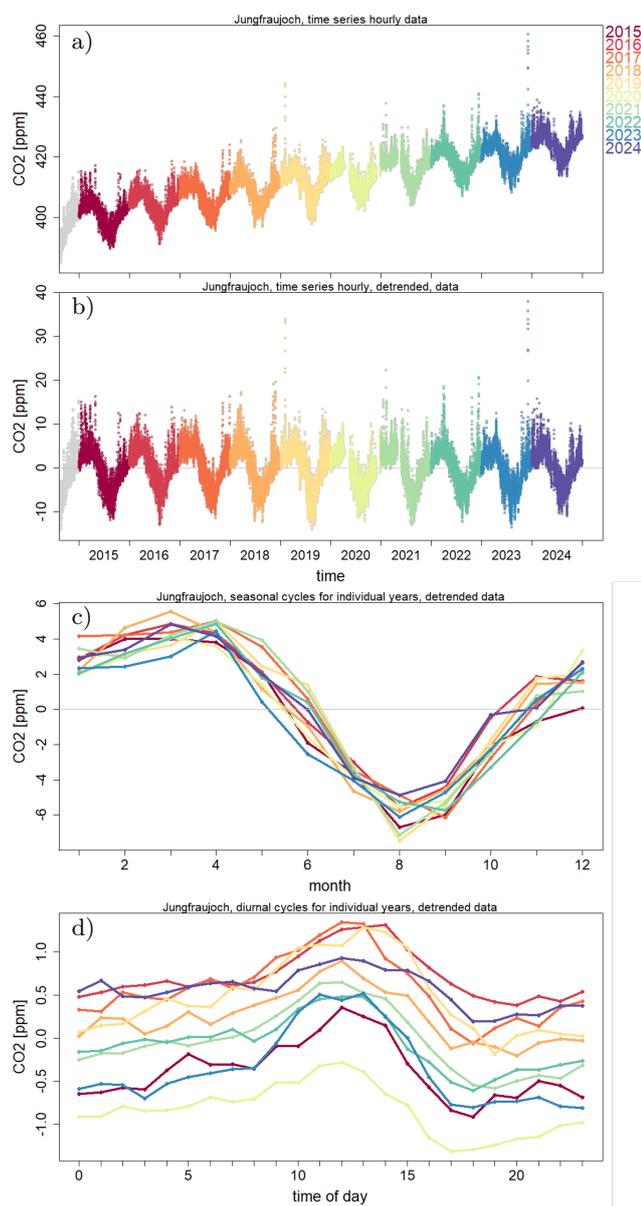


Figure 3: Time series of hourly averages (panel a), detrended hourly averages (panel b), seasonal cycles (panel c) and diurnal cycles (panel d) for carbon dioxide observed at Jungfraujoch for the 2015 to 2024 period. Different colors represent different years.

The increase of atmospheric CO₂ levels can be attributed to emissions from human activities, especially the burning of fossil fuels, cement production and carbonation, land-use, land-use change, and forestry (Friedlingstein et al. 2024).

The CO₂ time series was detrended prior to the analysis of the interannual variation of the diurnal and seasonal cycles. This was done by using a combination of a low pass filter and decomposition into a fitted long-term trend and seasonal cycle (Thoning et al. 1989) and by subtracting the intercept and the linear term. The seasonal cycles of the detrended data show a systematic pattern with a regular yearly minimum at the end of the summer (August, September) as a result of the net uptake of atmospheric CO₂ by the vegetation during the growing season. Globally, the natural positive (emissions) and negative (sinks) fluxes of the atmosphere-biosphere exchange on land are more than one order of magnitude larger than the anthropogenic fossil fuel emissions (Friedlingstein et al. 2024). Therefore, the year-to-year variability in the atmosphere-biosphere interaction, e.g. driven by persistent large-scale meteorological patterns, can lead to anomalies in the seasonal cycles. The dominant role of the biosphere with regard to the seasonality and year-to-year variability of the atmospheric CO₂ mole fractions was discussed in the European Greenhouse Gas Bulletin of the ICOS Research Infrastructure (Ramonet et al. 2022). In 2021, for example, a more pronounced than usual summer minimum in atmospheric CO₂ mole fractions was observed over large areas of Western Europe. This was attributed to rather cool and humid meteorological conditions, which favored carbon uptake by vegetation. Due to the lack of vegetation in the vicinity to Jungfraujoch, the effect is only weakly pronounced there and is less visible than at less elevated locations. Nevertheless, the non-negligible role of vegetation on CO₂ concentrations at Jungfraujoch was also emphasized in the study by Pieber et al. 2022, which investigated the regional contributions to CO₂ concentrations at Jungfraujoch. Due to the remote location of the station and the low anthropogenic contributions, the CO₂ signal at Jungfraujoch is most strongly influenced by the uptake and respiration of CO₂ by the biosphere, especially in summer. The study by Pieber et al. 2022 confirms the unique role of the Jungfraujoch as a central European background station, which is primarily subject to integrated signals from a large catchment area. The diurnal CO₂ cycles again reflect the varying influence of PBL air masses at Jungfraujoch with air masses slightly depleted in CO₂ in the late afternoon due to uptake of CO₂ by the local vegetation during transport from the surrounding valleys to the station. It cannot be ruled out that the increase in CO₂ during daytime (~ 9 am to 3 pm) partly originates from local emissions related to the infrastructure and the touristic facilities (Affolter et al. 2021). However, diurnal cycles do not look different since 2023 when the inlet of the greenhouse gas measurements was moved from the top of the Sphinx laboratory to the end of the Jungfraujoch ridge, about 30 m northeast of the tourist platform (Vollmer et al. 2021). There – based on long-term parallel measurements and an analysis of the high resolution CO₂ data – no influence from local emissions could be seen anymore (Steinbacher et al. 2023).

2.4 Methane

CH₄ is the second most important long-lived greenhouse gas, following CO₂. Similar to CO₂, the CH₄ time series at Jungfraujoch shows a significant mean growth rate, which was 10.9 ppb yr⁻¹ over the last 10 years (see Figure 4). The trends at Jungfraujoch are again very similar to the global growth

rate of 10.7 ppb yr^{-1} (WMO 2024). Therefore, the CH_4 time series was also detrended by trend estimation according to Thoning et al. 1989 and subtraction of the linear trend. The most important anthropogenic CH_4 emissions in Switzerland are agriculture, livestock farming, fossil fuel exploitation, landfills, and wastewater treatment (Henne et al. 2016).

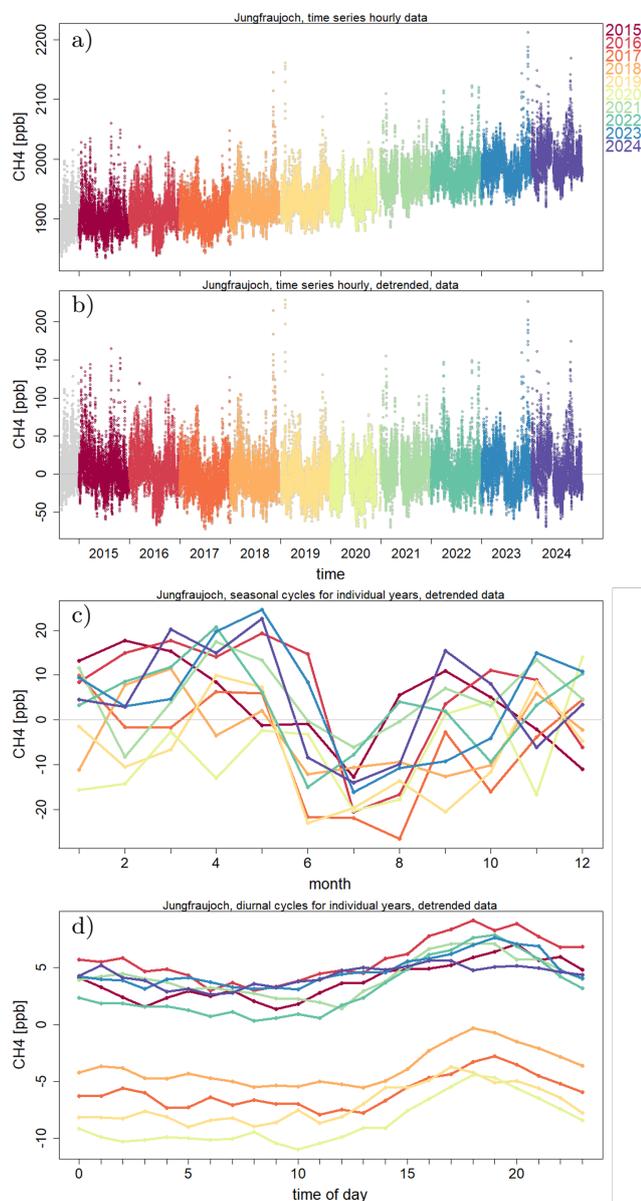


Figure 4: Time series of hourly averages (panel a), detrended hourly averages (panel b), seasonal cycles (panel c) and diurnal cycles (panel d) for methane observed at Jungfrauoch for the 2015 to 2024 period. Different colors represent different years.

CH_4 has an atmospheric lifetime of ~ 10 years and its main removal process in the atmosphere is the reaction with hydroxyl (OH) radicals in the troposphere. The concentrations of OH radicals are highest in summer because they are mainly formed through the photolysis of ozone and recycling from its reaction products (Li et al. 2018). Seasonal variations of the OH concentration lead to a changing CH_4 sink throughout the year and, consequently, to a seasonal CH_4 cycle with

the lowest mole fractions in summer. However, changes in the magnitude of the emissions are largely responsible for the year-to-year variability as reported for the exceptionally strong CH_4 growth rate, which was observed in 2020 and 2021 around the globe (Feng et al. 2023). According to Feng et al. 2023, the reduced OH radical concentrations during the Covid-19 lockdown in 2020 played only a smaller role in the strong CH_4 increase. Diurnal CH_4 cycles at Jungfrauoch are usually rather flat for most of the day but show an increase in mole fraction in the late afternoon with the arrival of PBL air masses (see Figure 4, panel d), which is similar to the diurnal CO cycle.

3 Conclusions

The present discussion highlights the value of high-precision long-term time series. It is planned to compare Jungfrauoch's diurnal and seasonal cycles with the recurrent patterns from other high-altitude stations.

Acknowledgements

We acknowledge financial support of the Swiss National Air Pollution Monitoring Network (NABEL) by the Swiss Federal Office for the Environment. Greenhouse gas observations at Jungfrauoch are also supported by ICOS Switzerland which had been funded by the European Commission (Preparatory Phase, 2008–2012), and since 2013 by the Swiss National Science Foundation, in-house contributions and the State Secretariat for Education, Research and Innovation (Phase 1: 2013–2017; Phase 2: 2017–2021, Phase 3: 2021–2025).

References

- Affolter, S. et al. "Assessing local CO_2 contamination revealed by two near-by high altitude records at Jungfrauoch, Switzerland". *Environmental Research Letters* **16**, 4 (2021), 044037.
- Baltensperger, U. et al. "Aerosol climatology at the high-alpine site Jungfrauoch, Switzerland". *Journal of Geophysical Research: Atmospheres* **102**, D16 (1997), 19707–19715.
- Byrne, B. et al. "Carbon emissions from the 2023 Canadian wildfires". *Nature* **633**, 8031 (2024), 835–839.
- Cooper, O. R. et al. "Multi-decadal surface ozone trends at globally distributed remote locations". *Elementa: Science of the Anthropocene* **8** (June 2020), 23.
- Feng, L. et al. "Methane emissions are predominantly responsible for record-breaking atmospheric methane growth rates in 2020 and 2021". *Atmospheric Chemistry and Physics* **23**, 8 (2023), 4863–4880.
- Friedlingstein, P. et al. "Global Carbon Budget 2024". *Earth System Science Data Discussions* **2024** (2024), 1–133.
- Gkatzelis, G. I. et al. "The global impacts of COVID-19 lockdowns on urban air pollution: A critical review and recommendations". *Elementa: Science of the Anthropocene* **9**, 1 (Apr. 2021), 00176.

- Henne, S. et al. “Validation of the Swiss methane emission inventory by atmospheric observations and inverse modelling”. *Atmospheric Chemistry and Physics* **16**, 6 (2016), 3683–3710.
- Hueglin, C., B. Buchmann, M. Steinbacher, and L. Emmenegger. “The Swiss National Air Pollution Monitoring Network (NABEL) – Bridging Science and Environmental Policy”. *Chimia* **78**, 11 (2024), 722–727.
- Jones, M. W. et al. “State of Wildfires 2023–2024”. *Earth System Science Data* **16**, 8 (2024), 3601–3685.
- Li, M. et al. “Tropospheric OH and stratospheric OH and Cl concentrations determined from CH₄, CH₃Cl, and SF₆ measurements”. *npj Climate and Atmospheric Science* **1**, 1 (2018), 29.
- Parrish, D. D. et al. “Zonal Similarity of Long-Term Changes and Seasonal Cycles of Baseline Ozone at Northern Mid-latitudes”. *Journal of Geophysical Research: Atmospheres* **125**, 13 (2020), e2019JD031908.
- Patel, A. et al. “Revisiting regional and seasonal variations in decadal carbon monoxide variability: Global reversal of growth rate”. *Science of The Total Environment* **909** (2024), 168476.
- Pieber, S. M. et al. “Analysis of regional CO₂ contributions at the high Alpine observatory Jungfrauoch by means of atmospheric transport simulations and δ¹³C”. *Atmospheric Chemistry and Physics* **22**, 16 (2022), 10721–10749.
- Putero, D. et al. “Fingerprints of the COVID-19 economic downturn and recovery on ozone anomalies at high-elevation sites in North America and western Europe”. *Atmospheric Chemistry and Physics* **23**, 24 (2023), 15693–15709.
- Ramonet, M. et al. “The importance of CO₂ variations for informed climate action”. *Fluxes – The European Greenhouse Gas Bulletin* **1** (2022), 8–14.
- Steinbacher, M., D. Steger, L. Emmenegger, and H. C. *The effect of sampling location on CO₂ and CH₄ mole fractions at Jungfrauoch*. Activity Report 2022, pp. 31–35. International Foundation High Altitude Research Stations Jungfrauoch and Gornergrat, Bern, Switzerland, 2023.
- Steinbrecht, W. et al. “COVID-19 Crisis Reduces Free Tropospheric Ozone Across the Northern Hemisphere”. *Geophysical Research Letters* **48**, 5 (2021), e2020GL091987.
- Thoning, K. W., P. P. Tans, and W. D. Komhyr. “Atmospheric carbon dioxide at Mauna Loa Observatory: 2. Analysis of the NOAA GMCC data, 1974–1985”. *Journal of Geophysical Research: Atmospheres* **94**, D6 (1989), 8549–8565.
- Vollmer, M. K., M. Steinbacher, M. C. Leuenberger, and L. Emmenegger. *The new 2020 air sampling inlet system at Jungfrauoch*. Activity Report 2020, pp. 4–8. International Foundation High Altitude Research Stations Jungfrauoch and Gornergrat, Bern, Switzerland, 2021.
- WMO. *WMO Greenhouse Gas Bulletin – The State of Greenhouse Gases in the Atmosphere Based on Global Observations through 2023*. Vol. 20. WMO, 2024, pp. 1–11.
- FOEN/BAFU. <https://www.bafu.admin.ch/bafu/de/home/themen/luft/zustand/daten.html>.
- GAW-WDCGG. <https://gaw.kishou.go.jp/>.
- ICOS Carbon Portal. <https://www.icos-cp.eu/>.
- SRF-Klimamonitor. <https://www.srf.ch/news/schweiz/klimamonitor-am-puls-des-planetens-taegliche-zahlen-und-fakten-zum-klima>.

Collaborating partners / networks

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

Refereed journal articles

- Hueglin, C., B. Buchmann, M. Steinbacher, and L. Emmenegger. “The Swiss National Air Pollution Monitoring Network (NABEL) – Bridging Science and Environmental Policy”. *Chimia* **78**, 11 (2024), 722–727.
- Laj, P. et al. “Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS): The European Research Infrastructure Supporting Atmospheric Science”. *Bull. Amer. Meteor. Soc.* **105**, 7 (2024), E1098–E1136.
- Osterwalder, S. et al. “Spatial and seasonal dynamics of gaseous elemental mercury concentrations over Switzerland observed by a passive air sampler network”. *Environ. Sci.: Atmos.* **4** (8 2024), 848–860.
- Patel, A. et al. “Revisiting regional and seasonal variations in decadal carbon monoxide variability: Global reversal of growth rate”. *Science of The Total Environment* **909** (2024), 168476.

Internet data bases

- ACTRIS. <https://dc.actris.nilu.no/>.
- EBAS & GAW-WDCRG. <https://ebas-data.nilu.no/>.
- Eionet. <https://www.eea.europa.eu/data-and-maps/data/aqereporting-9>.
- Empa. <http://empa.ch/web/s503/nabel>.

Conference papers

- Steinbacher, M. “NO and NO₂ measurements at Jungfrauoch”. *ACTRIS NO_x/VOC Quality Assurance workshop 2024* (online). Apr. 11, 2024.

- Steinbacher, M., C. Amman, I. Feigenwinter, and U. Krieger. "Session 'Atmospheric Composition and Biosphere-Atmosphere Interactions'". *22nd Swiss Geoscience Meeting* (Basel, Switzerland). Nov. 9, 2024.
- Steinbacher, M., D. Steger, et al. "CO₂-Messungen im globalen bis städtischen Kontext". *ERFA-Immissionen* (Lucerne, Switzerland). Sept. 5, 2024.
- Steinbacher, M., B. Steger, D. amd Tuzson, and L. Emmenegger. "Update from ICOS-CH Atmosphere Network and Jungfrauoch". *ICOS-CH National Meeting* (Bern, Switzerland). Sept. 3, 2024.

Contact

Dr. Martin Steinbacher
 Tel: +41 58 765 40 48
 E-mail: martin.steinbacher@empa.ch

Data books and reports

- ICOS RI, F. Apadula, S. Arnold, et al. *ICOS Atmosphere Release 2024-1 of Level 2 Greenhouse Gas Mole Fractions of CO₂, CH₄, N₂O, CO, meteorology and ¹⁴CO₂, and flask samples analysed for CO₂, CH₄, N₂O, CO, H₂, SF₆ and ¹⁴C*. Data Release 2024-01. ICOS ERIC – Carbon Portal, 2024.
- ICOS RI, F. Apadula, T. Biermann, et al. *ICOS Atmosphere 2024.3 FastTrack release of Level 1.5 Greenhouse Gas Mole Fractions of CO₂, CH₄, N₂O, CO and meteorology*. Data Release 2024.3. ICOS ERIC – Carbon Portal, 2024.
- Luftqualität 2023*. Bundesamt für Umwelt BAFU, Eidgenössische Materialprüfungs- und Forschungsanstalt (Empa), 2024.

Magazine and newspaper articles

- "CO₂-Messungen in Echtzeit: Empa-Daten für den SRF Klimamonitor". *DMZ Die Mittelländische Zeitung* (May 8, 2024).
- "Empa-Daten für den SRF Klimamonitor". *EmpaIntern* (Aug. 15, 2024).
- "SGM Members Visit the Jungfrauoch Research Station: A Day of Science and Scenic Beauty". *Webpage of the Swiss Society for Meteorology* (Aug. 30, 2024).

Radio and television

- BBC. *Can Scientists Save the World?* BBC Panorama. Nov. 18, 2024.

Address

Empa
 Laboratory for Air Pollution/Environmental Technology
 Ueberlandstrasse 129
 8600 Dübendorf
 Switzerland