



**3 x 6 months of quality
controlled turbulent fluxes of
co-emitted species (CO, NO_x,
CH₄, N₂O) from each city (CH-
Har, FR-Rmv, DE-Opd) as well as
quality-controlled results from
the experimental campaigns on
¹⁴C and COS fluxes**

Deliverable D3.10

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Introduction

Deliverable D3.10 provides and documents datasets on directly measured co-emitted species and isotopologue fluxes from three city pilot observatories - Zurich (Switzerland), Paris (France) and Munich (Germany). In each of the three observatories, a tall-tower supersite was established to monitor time-resolved emissions over a period of 24 months by means of eddy covariance (EC). The tall-tower EC measurements provide total carbon-dioxide (CO₂) net fluxes as part of Deliverable D3.9. However, total CO₂ net fluxes do not allow for a separation of biogenic and fossil fuel emissions, nor do they allow attributing EC measured fluxes to emission sectors.

The dataset presented here in D3.10 on co-emitted species and isotope fluxes is used to explore methods that overcome this limitation and hence contribute to two important goals of the project:

1. Improving attribution of EC measured fluxes to sectors (T3.4.2)
2. Partitioning EC measurements into biogenic and fossil fuel CO₂ (T3.4.3)

This report describes three datasets from three techniques:

1. EC fluxes of co-emitted species from each of the three pilot observatories over 6 months each (T3.4.2)
2. Fluxes of fossil and biogenic CO₂ using relaxed eddy accumulation in each of the three pilot observatories (T3.4.3)
3. EC fluxes of carbonyl sulfide (COS) from the Zurich pilot observatory (T3.4.3)

Brief descriptions of each of the three pilot cities and tall EC towers are given first (Site Descriptions) followed by detailed descriptions of the datasets.

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Site Descriptions

In each of the three pilot cities, a combined infrared gas analyser and sonic anemometer-thermometer (IRGASON, Campbell Scientific, Logan UT, USA) was operated on a tall EC tower (Deliverable D3.9). The combined infrared gas analyser and sonic anemometer-thermometer provided the meteorological variables necessary for calculation of eddy covariance (EC) fluxes of co-emitted species and isotopologue fluxes described in this Deliverable. At each of the three tall towers, the IRGASON was logged on a CR6 datalogger (Campbell Scientific, Logan UT, USA) and all systems used the same datalogger program (with different versions over time). The logger program is described and a version history is available at [github/logger_program](https://github.com/ICOS-Cities/logger_program) (<https://doi.org/10.5281/zenodo.13926681>). In all cases, the IRGASON oversampled at 60 Hz and measurements were recorded at 20 Hz. All systems were synced to UTC.

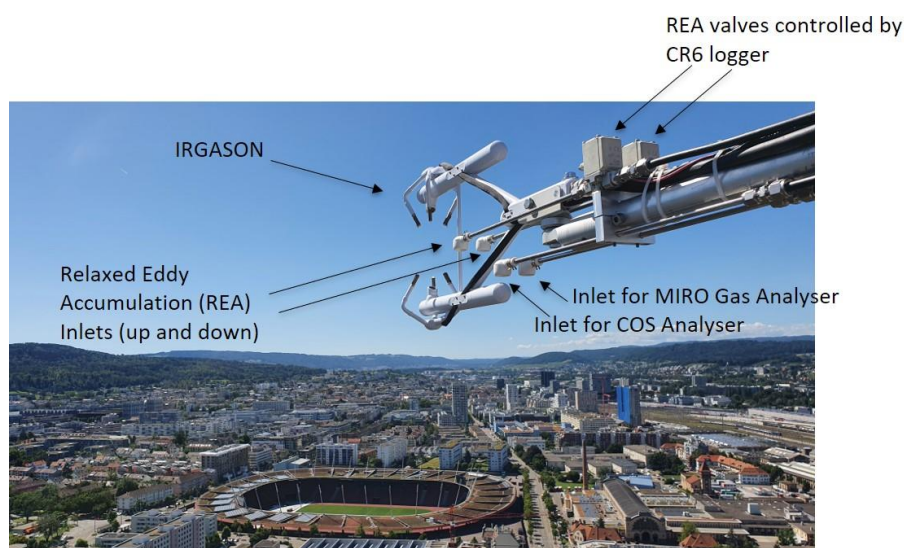


Figure 1: Overview of IRGASON and inlet arrangement. The photo is from Zurich but the mount, relative positioning, and inlets are the same across all three cities (Photo credit: R. Vogt, University of Basel).

At each of the three tall-towers, co-located with the IRGASON, were four inlets for use with closed-path analysers. The location of the inlets relative to the IRGASON is shown in Figure 1. The inlets with switching valves were used for relaxed eddy accumulation (Sec. ¹⁴C-based fossil fuel CO₂ fluxes) in all three cities. Two inlets had no switching valves. The MIRO gas analyser inlet was subsequently used for multi-species closed-path EC (Sec. CO₂ and co-emitted species fluxes) in all three cities. The final inlet was used for closed-path COS eddy covariance (Sec. Eddy covariance fluxes of carbonyl sulfide) in Zurich, and as an auxiliary/testing inlet for the relaxed eddy accumulation in Paris and Munich. Further details on the specific systems are found in their respective sections.

Zurich Hardau (CH-Har)

Measurements in Zurich, Switzerland were conducted from the Hardau II supersite (CH-Har, Bullingerstrasse 73: 47° 22' 52" N, 8° 30' 26" E), located in a flat, densely urbanized area west of the city centre. The building is 95 m tall and a communications antenna extends a further ~16.5 m above the roof. The measurement height for the IRGASON and the inlets was 112 m agl. A schematic is shown in Figure 2 along with a photo looking west from the measurement height.

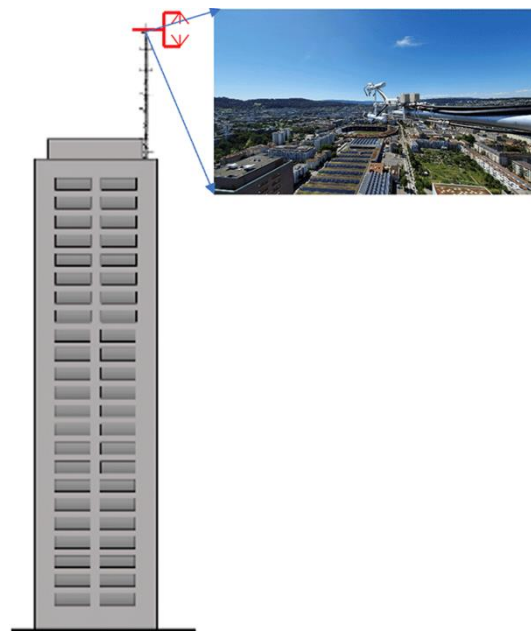


Figure 2: Schematic of the Hardau II tower and IRGASON/inlet location near the top of the building's communications antenna. Inset is a photo from the top of the antenna facing roughly west. Figure from Chen et al. (2024).

The building is the tallest of a cluster of four buildings (heights: 76 m, 85 m, 66m) located between 43 and 68 m horizontally to the S, SW, and N-NW. The tower itself is located 408 m asl. The azimuth of the IRGASON was 270° (W).

Analysers were located in a climate-controlled equipment room in the highest floor of the building, level with the base of antenna.

A summary of the Zurich Hardau tower and eddy covariance parameters is given in Table 1. Canopy height is the mean building height surrounding the tower determined from a digital surface model. Displacement height and roughness length are estimated as 0.7x and 0.1x the canopy height, respectively (Grimmond & Oke, 1997).

Table 1: Summary of eddy covariance parameters for the Zurich Hardau tower.

Parameter	Value	Units
Elevation	408	m asl
Measurement height	112	m agl

IRGASON azimuth	270	degrees from N
Canopy height	13.3	m
Displacement height	9.3	m
Roughness length	1.3	m

Paris Romainville (FR-Rmv)

Measurements in Paris, France were conducted at the Romainville supersite (FR-Rmv, Rue de la Résistance, Les Lilas, 48° 53' 7.6" N, 2° 25' 20.8" E), located north-east of Central Paris in a densely urbanized area. The tower is an active telecommunications tower with a wide platform at 91 m agl. The IRGASON and gas inlets were located 9 m above this level on a pylon at the edge of the platform. A schematic of the tower and photo of the IRGASON and inlets is shown in Figure 3.

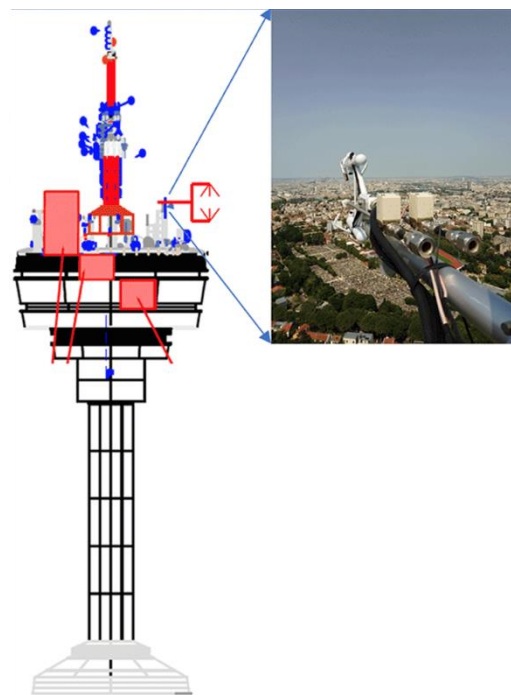


Figure 3: Schematic of the Romainville tower and IRGASON/inlet location on a pylon at the edge of the upper platform. Inset is a picture from the top of the pylon facing roughly W. Note that the pylon and IRGASON location and scale are misleading in the schematic, but the measurement volume of the IRGASON reached approximately to the outer edge of the platform. Figure from Chen et al. (2024).

The Romainville tower is located roughly 5 km NE from the Paris city centre and its base is at 130 m asl. There are no other similarly tall buildings located nearby, but the location of the pylon on a large (~30 m diameter) platform results in a large contribution to the turbulent flux footprint. The IRGASON was oriented 273° from N.

The analysers were located one floor below the observation platform in an equipment room. This measurement room was not climate-controlled in the summer but a heater was used in the winter.

Table 2: Summary of eddy covariance parameters for the Paris Romainville tower.

Parameter	Value	Units
Elevation	130	m asl
Measurement height	100	m agl
IRGASON azimuth	273	degrees from N
Canopy height	25	m
Displacement height	18	m
Roughness length	2	m

Munich Oberpostdirektion (DE-Opd)

Measurements in Munich, Germany, were conducted at the Oberpostdirektion supersite (DE-Opd, Blumenbergstrasse 1, 48° 8' 50.9" N, 11° 32' 59.3" E), located in a densely urbanized area north-west of the city centre. The tower is an active telecommunications tower located roughly 1.5 km NW of the city centre. The IRGASON and inlets were located 85 m agl. A schematic is shown in Figure 4. The IRGASON was oriented 180° from N. The analysers were located in a climate-controlled equipment room at the base of the tower.

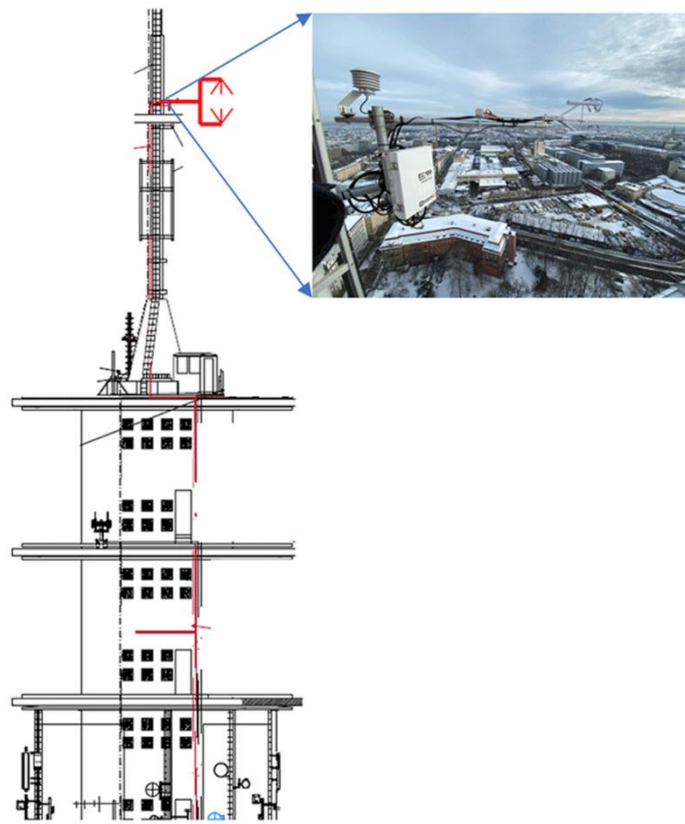


Figure 4: Schematic of the Oberpostdirektion tower and IRGASON/inlet location near the top of the tower. Note that the schematic only shows approximately the upper half of the tower. The uppermost platform shown is approximately 60 m agl. The inset shows a photo of the IRGASON and inlets facing roughly E-SE. Figure from Chen et al. (2024).

A summary of relevant parameters for the tower is given in Table 3.

Table 3: Summary of eddy covariance parameters for the Munich Oberpostdirektion tower.

Parameter	Value	Units
Elevation	520	m asl
Measurement height	85	m agl
IRGASON azimuth	180	degrees from N
Canopy height	20	m
Displacement height	14	m
Roughness length	3	m

CO₂ and co-emitted species fluxes

At each of the supersite towers of the three pilot cities a multi-species gas analyser was operated for 6 months as part of a closed-path eddy covariance flux measurement system to provide turbulent flux measurements of CO₂, H₂O, and the co-emitted species carbon monoxide (CO), nitrogen oxides (NO_x, comprising nitric oxide (NO) and nitrogen dioxide (NO₂)), methane (CH₄), and nitrous oxide (N₂O). The instrument used was a MIRO MGA7 (**M**ultispecies **G**as **A**nalysers, MIRO Analytical, Wallisellen, Switzerland). The MGA7 uses quantum cascade laser (QCL) spectrometry (Li et al. 2013) and four QCLs to measure gas concentrations at 10.3 Hz.

The MGA7 was operated in a thermally insulated environmental enclosure and sample air was drawn through the instrument at 10-12 SL min⁻¹ using a Kashiyama NeoDry30E vacuum pump. In Zurich the inlet length was 33 ± 2 m long with 5.7 mm inner diameter. In Paris the inlet length was 27 ± 2 m long with 9.5 mm inner diameter. In Munich the inlet length was 100 m long with 8.0 mm inner diameter. In Zurich the analyser operated with a 3-way valve and zeroing gas for reactive species. The valve and zeroing gas were removed for Paris and Munich.

The Zurich dataset comprises 1 August 2022 to 31 March 2023 (8 months). The Paris dataset comprises 19 January 2024 to 18 June 2024 (6 months). The Munich dataset comprises 27 June 2024 to 31 December 2024 (6 months).

Data Processing

Common to all cities

Raw data from the IRGASON system was logged at 20 Hz while raw data from the MGA7 was logged at 10.3 Hz. For EC calculation the raw MGA7 data were upsampled to 20 Hz using a nearest neighbour approach with 50 ms maximum search window. Raw concentration measurements in mol mol⁻¹ were converted to mmol mol⁻¹ (H₂O) or μmol mol⁻¹ (CO₂, CO, NO, NO₂, CH₄, N₂O).

Due to occasional significant clock drift of both the CR6 and the MGA7, the instruments were synced on a 30-minute basis directly based on the time lag of maximum covariance between the IRGASON and MGA7 concentrations rather than using search windows based on inlet dimensions and flow rate. The time series of time lags for each full campaign was despiked and linearly interpolated to remove erroneous estimates before being applied. No further time lag correction was made during flux calculation.

The IRGASON data were despiked prior to flux calculation following Mauder et al. (2013) but allowing >2 consecutive outliers to remain in the dataset.

Fluxes were calculated on a 30-minute basis using EddyPro (LICOR Biosciences, v7.0.9). Site parameters necessary for calculating fluxes are given in the site descriptions above. Further significant settings are: axis rotation was performed via double rotation; detrending was performed via block averaging; quality flagging was based on the 0-1-2 system of Mauder & Foken (2004). Low-pass filtering for the IRGASON was performed according to Moncrieff et al. (1997) and for the MGA7 according to Fratini et al. (2012).

Following the pre-processing described here no additional flagging of the L2 products is performed, with minor exceptions detailed below. Users are recommended to apply the following filters to ensure the best quality data and use fluxes for which:

1. The QC flag for a given species is 0 or 1;
2. The mean direction is not disrupted by the IRGASON body or other mounting infrastructure;
 - a. Zurich Hardau: mean wind direction $< 70^\circ$ or $> 100^\circ$
 - b. Paris Romainville: mean wind direction $< 70^\circ$ or $> 120^\circ$
 - c. Munich Oberpostdirektion: mean wind direction $< 340^\circ$ and $> 20^\circ$
3. Friction velocity $u_* > 0.2 \text{ m s}^{-1}$

Zurich Hardau

In Zurich, a 3-way switching valve was operated at the sample air inlet to allow periodic zeroing of reactive species. Use of L0 or L1 data from Zurich requires removing measurements where this valve is switch to the zeroing gas (given by variable VValve0=1, see below). This flag only records the instantaneous status of the switching valve however, and therefore a buffer around the valve flag must also be removed. In the L0 data no processing is applied. In the L1 data the 5 seconds before and after a valve actuation are masked. Each zeroing period is 45 seconds (without buffer). The switching valve and zeroing gas were removed for Paris and Munich.

The instrument erroneously logged in CEST (UTC+2) between 4 August 2022 and 17 August 2022. Users of L0 data should subtract 2 hours from the MGA7 timestamps on these days. This is fixed in L1.

Issues with fit window drift for the N_2O laser between 31 January 2023 and 20 February 2023 led to erroneous measurements of this species following zeroing and correct concentrations cannot be recovered. For L2 data the QC flag for N_2O fluxes during this period has been manually set to 2 and these data should not be used.

NO_x concentrations in Zurich were systematically too low by over 50%. A linear scaling correction for the raw concentrations was determined from a nearby air quality measurement station located in a park and away from heavy traffic (Zurich Kaserne, EMPA, [zue](#)). A correction factor of 2.33 was calculated based on linear best-fit between 1-hour averaged NO_x concentrations from the air quality station vs. the MGA7 during daytime unstable conditions where the mean wind was above 3 m s^{-1} . Because the scaling could only be applied to the total NO_x concentration the Zurich L2 data contain a combined NO_x entry rather than separate NO and NO_2 entries. The L1 product contains the original NO and NO_2 concentrations along with an extra column of scaled NO_x concentrations.

Paris Romainville

Following repairs and software updates in December 2023, the binary quality of each laser's fit window was recorded (good fit or bad fit). For Paris (and Munich) four extra columns are added for these flags. The L1 products for these cities replace flagged species with NaN on a per-laser basis and these are excluded from flux calculations during pre-processing.

From mid-April 2024 an additional CO₂ measurement mode was added to the IRGASON. L1 products for Paris (and Munich) contain this additional column throughout, though it is populated with NaN until 14 April 2024.

A direct comparison of MGA7 concentrations with a reference instrument was made after repairs and upgrades in December 2023 at the Dübendorf air quality measurement station ([due1](#), EMPA). Linear scaling factors for fluxes were determined based on this comparison and are summarised in Table 4. No reference data were available for N₂O and no correction is applied to this species. Correction factors are applied to calculated L2 fluxes. L0 and L1 concentration data are not corrected.

Table 4: Linear correction factors determined from a direct instrument comparison during December 2023. Concentrations were compared at 1-minute averaging time for 13 days.

Species	Correction factor	RMSE of linear fit
CO ₂	0.98	3.6 ppm
CO	1.02	11.7 ppb
NO	1.07	2.0 ppb
NO ₂	1.04	1.0 ppb
CH ₄	0.97	10.1 ppb

Munich Oberpostdirektion

No scaling is applied to Munich L2 data in the present dataset.

File Format

Three data levels are described and made available with this report.

Level 0 / raw data is the raw data obtained directly from the MGA7 instrument. Consistency in the naming of columns is not guaranteed. L0 data are available as compressed archives of semicolon delimited plain-text (TXT) files (one archive per city). Each TXT file covers 24 hrs. There is one header row defining the column variable followed by one empty row. Units are not provided in the header of individual files.

Various software updates, especially during the early Zurich campaign, caused MGA7 columns to rename themselves. E.g., column “LD Cold Plate T C” may change name to “LD Cold Plate C” after a software update and restart. Users of L0 data are cautioned to double-check column names and order.

Level 1 data are combined 20 Hz IRGASON and MGA7 data. These data are time synchronised and the IRGASON has already been despiked. Additional processing may have been applied depending on city (see above). L1 data are available as compressed archives of 30-minute CSV files (one archive per city). Individual files contain one header row describing the column variable. Units are not provided in the header of individual files.

Level 2 data are the quality controlled fluxes which fulfil ICOS PAUL deliverable D3.10. The fluxes are in the form of EddyPro “full output” and “QC details” comma delimited plain-text (CSV) files. Two CSVs (one ‘full output’ and one ‘QC details’) are provided for each city. Detailed description of these files is [available from LICOR support](#). Each file contains three header rows: The first describes the broad category of the column; the second is the column variable; the third is the column units.

Metadata and Variable Description

Level 0 / raw data

Raw data file contents are summarised in Table 5.

Table 5: L0/raw variable description for the MGA7.

Variable Name	Description	Units	Notes
t-stamp	Timestamp	dd.mm.YYYY HH:MM:SS.SS	UTC
CO wet	CO molar fraction of wet air	mol mol ⁻¹	
CO2 wet	CO ₂ molar fraction of wet air	mol mol ⁻¹	
H2O	H ₂ O molar fraction	mol mol ⁻¹	
NO wet	NO molar fraction of wet air	mol mol ⁻¹	
NO2 wet	NO ₂ molar fraction of wet air	mol mol ⁻¹	
CH4 wet	CH ₄ molar fraction of wet air	mol mol ⁻¹	
N2O wet	N ₂ O molar fraction of wet air	mol mol ⁻¹	
LD Cold Plate C	Temperature of internal cold plate	°C	Column name may sometimes be slightly different
Outside T C	Ambient temperature	°C	Column name may sometimes be slightly different
Optics T C	Temperature of the optics	°C	Column name may sometimes be slightly different
p Cell	Pressure of the optical cell	mbar	
VValve 0	Status of switching valve	NA	Always 0 in Paris and Munich
FitWin 0 bad fit	Flag for bad spectral fit of laser 1	NA	Not available in Zurich. Laser 1 covers CO and CO ₂
FitWin 1 bad fit	Flag for bad spectral fit of laser 2	NA	Not available in Zurich. Laser 2 covers H ₂ O and NO

FitWin 2 bad fit	Flag for bad spectral fit of laser 3	NA	Not available in Zurich. Laser 3 covers NO ₂
FitWin 3 bad fit	Flag for bad spectral fit of laser 4	NA	Not available in Zurich. Laser 4 covers CH ₄ and N ₂ O

Level 1 data

Level 1 data file contents are summarised in Table 6

Table 6: L1 variable description for combined IRGASON and MGA7 data.

Variable Name	Description	Units	Notes
TIMESTAMP	Timestamp of the datalogger	YYYY-mm-dd HH:MM:SS.SSS	UTC
RECORD	Index record of the datalogger	—	
RAW_IRGASON_Ux	Longitudinal wind component of the sonic anemometer	m s ⁻¹	Unrotated
RAW_IRGASON_Uy	Lateral wind component of the sonic anemometer	m s ⁻¹	Unrotated
RAW_IRGASON_Uz	Vertical wind component of the sonic anemometer	m s ⁻¹	Unrotated
RAW_IRGASON_Ts	Acoustic temperature from the sonic anemometer	°C	
RAW_IRGASON_Dia gSonic	Diagnostic string for the sonic anemometer	—	
RAW_IRGASON_CO 2	CO ₂ density from the IRGA using the slow-response temperature	mg m ⁻³	
RAW_IRGASON_H2 O	H ₂ O density from the IRGA	g m ⁻³	
RAW_IRGASON_Dia gIRGA	Diagnostic string for the IRGA	—	
RAW_IRGASON_Cell T	Temperature of the IRGASON cell	°C	

RAW_IRGASON_Cell Prs	Pressure of the IRGASON cell	mbar	
RAW_IRGASON_CO 2SigStrgth	Signal strength of the IRGA CO ₂ measurement	—	
RAW_IRGASON_H2 OSigStrgth	Signal strength of the IRGA H ₂ O measurement	—	
RAW_IRGASON_CO 2_FastResp	CO ₂ density from fast-response temperature	mg m ⁻³	Not available in Zurich. Available in Paris from April 14 2024.
RAW_IRGASON_CO 2Dry	CO ₂ mixing ratio of dry air from the IRGASON	μmol mol ⁻¹	Before April 14 2024 the mixing ratio is determined using the slower-response temperature sensor and high-frequency density fluctuations are not well resolved.
REA_Flag	Status of the fast-response valves for relaxed eddy accumulation (see following section)	—	
CO wet	CO molar fraction of wet air	μmol mol ⁻¹	
CO2 wet	CO ₂ molar fraction of wet air	μmol mol ⁻¹	
H2O	H ₂ O molar fraction	mmol mol ⁻¹	
NO wet	NO molar fraction of wet air	μmol mol ⁻¹	
NO2 wet	NO ₂ molar fraction of wet air	μmol mol ⁻¹	
CH4 wet	CH ₄ molar fraction of wet air	μmol mol ⁻¹	
N2O wet	N ₂ O molar fraction of wet air	μmol mol ⁻¹	
LD Cold Plate C	Temperature of internal cold plate	°C	
Outside T C	Ambient temperature	°C	

Optics T C	Temperature of the optics	°C	
p Cell	Pressure of the optical cell	mbar	
VValve 0	Status of switching valve	—	Always 0 in Paris and Munich
FitWin 0 bad fit	Flag for bad spectral fit of laser 1	—	Not available in Zurich. Laser 1 covers CO and CO ₂
FitWin 1 bad fit	Flag for bad spectral fit of laser 2	—	Not available in Zurich. Laser 2 covers H ₂ O and NO
FitWin 2 bad fit	Flag for bad spectral fit of laser 3	—	Not available in Zurich. Laser 3 covers NO ₂
FitWin 3 bad fit	Flag for bad spectral fit of laser 4	—	Not available in Zurich. Laser 4 covers CH ₄ and N ₂ O
NO _x _scaled	Sum of NO and NO _x molar fraction scaled by 2.33	μmol mol ⁻¹	Only included for Zurich

Level 2 data

Level 2 data are provided in standard [EddyPro output format](#) and not described in detail here. Note that to obtain meaningful NO_x fluxes in Zurich it was necessary to sum the NO and NO₂ components before scaling them and calculating a combined NO_x flux. Therefore the Zurich L2 data contain a combined NO_x flux and associated QC columns. Paris and Munich contain individual NO and NO₂ columns.

Access and Download

Level 0 data are available as ZIP archives, one for each city:

- Munich: Hilland, R., Hammer, S., Holst, C., Kunz, A., Lan, C., Mauder, M., Zeeman, M., Christen, A. (2025). EC flux time series archive (raw data), Oberpostdirektion, 2024-06-27–2024-12-31, ICOS Cities, <https://hdl.handle.net/11676/NHoDcalgFxrErx-CGTd3YXqm>
- Paris: Hilland, R., Bignotti, L., Buysse, P., Hammer, S., Kunz, A., Loubet, B., Ramonet, M., Zeeman, M., Christen, A. (2025). EC flux time series archive (raw data), Romainville, 2024-01-19–2024-06-18, ICOS Cities, <https://hdl.handle.net/11676/veGwAPC2sBFZk3zpad57WF1v>
- Zurich: Hilland, R., Brunner, D., Emmenegger, L., Hashemi, J., Hammer, S., Kunz, A., Stagakis, S., Vogt, R., Zeeman, M., Christen, A. (2025). EC flux time series archive (raw data), Hardau, 2022-08-04–2023-03-31, ICOS Cities, <https://hdl.handle.net/11676/vRyrRhSLWcdDp4-eShQseiFh>

Level 1 data are available as ZIP archives, one for each city:

- Munich: Hilland, R., Hammer, S., Holst, C., Kunz, A., Lan, C., Mauder, M., Zeeman, M., Christen, A. (2025). EC flux time series archive (L1), Oberpostdirektion, 2024-06-28–2024-12-31, ICOS Cities, https://hdl.handle.net/11676/Uh94pi2sSjC7MlfePoNaut_j
- Paris: Hilland, R., Bignotti, L., Buysse, P., Hammer, S., Kunz, A., Loubet, B., Ramonet, M., Zeeman, M., Christen, A. (2025). EC flux time series archive (L1), Romainville, 2024-01-19–2024-06-18, ICOS Cities, https://hdl.handle.net/11676/A5znCKX9M-J_665MLb7E1GG7
- Zurich: Hilland, R., Brunner, D., Emmenegger, L., Hashemi, J., Hammer, S., Kunz, A., Stagakis, S., Vogt, R., Zeeman, M., Christen, A. (2025). EC flux time series archive (L1), Hardau, 2022-08-01–2023-03-31, ICOS Cities, <https://hdl.handle.net/11676/vjRXEq8turqnCbWvg7XgmY-w>

Level 2 data are available as ZIP archives, one for each city:

- Munich: Hilland, R., Hammer, S., Holst, C., Kunz, A.-K., Lan, C., Mauder, M., Zeeman, M., Christen, A., 2025. EC flux time series archive (L2), Oberpostdirektion, 2024-06-28–2025-01-01. <https://doi.org/10.18160/3676-F51P>
- Paris: Hilland, R., Bignotti, L., Buysse, P., Hammer, S., Kunz, A.-K., Loubet, B., Ramonet, M., Zeeman, M., Christen, A., 2025. EC flux time series archive (L2), Romainville, 2024-01-19–2024-06-19. <https://doi.org/10.18160/KCTM-SKHM>
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[https://doi.org/10.1016/S0022-1694\(96\)03194-0](https://doi.org/10.1016/S0022-1694(96)03194-0)

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¹⁴C-based fossil fuel CO₂ fluxes

As part of Task 3.4.3, a novel relaxed eddy accumulation (REA) flask sampling system was built and operated for the first time at the Hardau II tall-tower in Zurich (CH-Har). It allows conditional sampling of air into ICOS glass flasks (one for updraft conditions, one for downdraft conditions), which can then be analyzed in the laboratory for a variety of gases, including ¹⁴CO₂. This enables the estimation of fossil fuel CO₂ (ffCO₂) fluxes and thus the partitioning of fossil and non-fossil CO₂ flux components. A detailed description of the system and its performance is given in Kunz et al. (2025). As quality control tests in Zurich showed an overall good performance of the system, it was decided to operate it also during the intensive campaigns in Paris (FR-Rmv) and Munich (DE-Opd). At each site, the REA inlets and fast-switching solenoid valves were mounted close to the sonic anemometer of the IRGASON (see Fig. 1). As for the MGA7, the inlet length was 33 ± 2 m long with 5.3 mm inner diameter in Zurich, 27 ± 2 m with 9.5 mm inner diameter in Paris and 100 m with 8.0 mm inner diameter in Munich.

For deliverable D3.10, we provide the flask CO₂ concentration measurements and the quality controlled ffCO₂ fluxes together with all relevant meta data for the 103 REA sampling periods analyzed in Zurich and the 93 periods selected in Paris. The results from Munich, which is still in operation, will be added later.

Data Processing

Derivation of ffCO₂ fluxes included the following steps:

1. Estimation of ffCO₂ concentration differences between updraft and downdraft flasks (ΔffCO₂):

Based on the assumption that any CO₂ difference measured between updraft and downdraft flasks is composed of a fossil fuel (ff), a non-fossil (nf, i.e., respiration and biofuels) and a photosynthetic (photo) component, the ffCO₂ difference can be calculated from the CO₂ and Δ¹⁴C flask measurements (for more details see Kunz et al., 2025):

$$c_{\text{meas}}^{\uparrow} - c_{\text{meas}}^{\downarrow} = (c_{\text{ff}}^{\uparrow} - c_{\text{ff}}^{\downarrow}) + (c_{\text{nf}}^{\uparrow} - c_{\text{nf}}^{\downarrow}) + (c_{\text{photo}}^{\uparrow} - c_{\text{photo}}^{\downarrow}) \quad (\text{Eq. 1})$$

$$c_{\text{meas}}^{\uparrow} \cdot {}^{14}\Delta_{\text{meas}}^{\uparrow} - c_{\text{meas}}^{\downarrow} \cdot {}^{14}\Delta_{\text{meas}}^{\downarrow} = (c_{\text{ff}}^{\uparrow} - c_{\text{ff}}^{\downarrow}) \cdot {}^{14}\Delta_{\text{ff}} + (c_{\text{nf}}^{\uparrow} - c_{\text{nf}}^{\downarrow}) \cdot {}^{14}\Delta_{\text{nf}} + (c_{\text{photo}}^{\uparrow} - c_{\text{photo}}^{\downarrow}) \cdot {}^{14}\Delta_{\text{photo}} \quad (\text{Eq. 2})$$

$$\Rightarrow \Delta \text{ffCO}_2 = c_{\text{ff}}^{\uparrow} - c_{\text{ff}}^{\downarrow} = \left[c_{\text{meas}}^{\uparrow} ({}^{14}\Delta_{\text{photo}} - {}^{14}\Delta_{\text{meas}}^{\uparrow}) - c_{\text{meas}}^{\downarrow} ({}^{14}\Delta_{\text{photo}} - {}^{14}\Delta_{\text{meas}}^{\downarrow}) + (c_{\text{nf}}^{\uparrow} - c_{\text{nf}}^{\downarrow}) ({}^{14}\Delta_{\text{nf}} - {}^{14}\Delta_{\text{photo}}) \right] \quad (\text{Eq. 3})$$

¹⁴Δ_{ff} is by definition -1000 ‰, whereas ¹⁴Δ_{photo}, ¹⁴Δ_{nf} and c_{nf}[↑] - c_{nf}[↓] are variable and need to be estimated as follows: ¹⁴Δ_{photo} equals the average atmospheric ¹⁴CO₂ signature measured during the REA run (average of updraft and downdraft samples). ¹⁴Δ_{nf}, on the other hand, is assumed to be 25 ± 12 ‰ enriched with respect to the mean atmospheric ¹⁴Δ_{meas} value in summer, when photosynthesis is most pronounced. The average of all flasks collected between 1 July and 1 October was -14 ± 10 ‰ in Zurich and -11 ± 8

‰ in Paris. $c_{nf}^{\uparrow} - c_{nf}^{\downarrow}$ is approximated as 5 ± 5 ppm. Table 7 summarizes the values used in Zurich and Paris. A detailed discussion of the choice of these parameters can be found in Kunz et al. (2025).

Table 7: Variables used to estimate the $ffCO_2$ concentration difference between updraft and downdraft flasks. $^{14}\Delta_i$ denotes the $\Delta^{14}C$ values of fossil fuels (ff), photosynthetic (photo) and non-fossil (nf) CO_2 , and flask measurements (meas). $\overline{^{14}\Delta_{meas}} = 0.5 (^{14}\Delta_{meas}^{\uparrow} - ^{14}\Delta_{meas}^{\downarrow})$ denotes the mean of the updraft and downdraft samples, which is different for each REA run. The atmospheric signature during CO_2 uptake by the biosphere $\overline{^{14}\Delta_{atmo}}$ is estimated by the mean value in summer (July to September). Also given are the specific values derived for the measurement campaigns in Zurich and Paris.

Variable	Unit	Approximation	Zurich Hardau value	Paris Romainville value
$^{14}\Delta_{ff}$	‰	-1000	-1000	-1000
$^{14}\Delta_{photo}$	‰	$\overline{^{14}\Delta_{meas}}$	$\overline{^{14}\Delta_{meas}}$	$\overline{^{14}\Delta_{meas}}$
$^{14}\Delta_{nf}$	‰	$\overline{^{14}\Delta_{atmo}} + 25$	9 ± 16	14 ± 15
$c_{nf}^{\uparrow} - c_{nf}^{\downarrow}$	ppm	$\sim (c_{meas}^{\uparrow} - c_{meas}^{\downarrow})$	5 ± 5	5 ± 5

The $\Delta ffCO_2$ uncertainty was derived according to Gauss' law of error propagation from Eq. (3). The $\Delta^{14}C$ measurement uncertainties were set to the analytical uncertainty of the individual measurements if updraft and downdraft sample pairs were analyzed in same AMS magazine. Otherwise, they were set to 1.9 ‰ (before May 2023) and 1.6 ‰ (since May 2023), corresponding to the long-term reproducibility of the quality control targets at the AMS to account for inter-magazine variability.

2. Estimation of $ffCO_2$ fluxes using EC-based CO_2 fluxes

With relaxed eddy accumulation, the mean turbulent $ffCO_2$ flux during the sampling interval F_{ffCO_2} is related to the concentration difference between updraft and downdraft sample $\Delta ffCO_2$ according to:

$$F_{ffCO_2} = \beta \rho \sigma_w \Delta ffCO_2, \quad (\text{Eq. 4})$$

where ρ is the mean molar air density and σ_w the standard deviation of the vertical wind velocity. Assuming scalar similarity between CO_2 and $^{14}CO_2$, the proportionality factor β was calculated from the total CO_2 difference between updraft and downdraft flask ΔCO_2 and the eddy covariance (EC) CO_2 fluxes of IRGASON and MGA⁷ near the REA inlets (Section CO_2 and co-emitted species fluxes). For this purpose, the 30 min CO_2 fluxes F_{CO_2} were averaged over the individual REA sampling periods. We provide $ffCO_2$ flux estimates using both the IRGASON and the MGA⁷ measurements where reliable measurements were available (i.e., no MGA⁷ data before 1 August 2022 in Zurich and before 19 January 2024 in Paris).

$$\beta = \frac{F_{\text{CO}_2}}{\rho \sigma_w \Delta \text{CO}_2} \quad (\text{Eq. 5})$$

$$\Rightarrow F_{\text{ffCO}_2} = \frac{\Delta \text{ffCO}_2}{\Delta \text{CO}_2} F_{\text{CO}_2} \quad (\text{Eq. 6})$$

The ffCO₂ flux uncertainty was again derived according to Gauss' law of error propagation, considering the measurement uncertainties of the flask concentrations and the random uncertainty estimates of the eddy covariance CO₂ fluxes.

3. Flagging of REA measurements

Like any other turbulent flux measurement technique, relaxed eddy accumulation is limited to certain micro-meteorological conditions, e.g., stationarity and well-developed turbulence (Rinne et al., 2021). Since, in contrast to the eddy covariance technique, the measurements cannot be processed retrospectively, e.g., cannot be corrected for changes in the mean vertical wind velocity, additional criteria are necessary. Table 8 provides an overview of the criteria considered relevant for ffCO₂ flux analysis.

Table 8: Flagging criteria for ffCO₂ fluxes

Flag name	Flag = 0	Flag = 1	Underlying data	Background
flag_FCO2qc	Quality control flags 0 and 1 according to Foken et al.(2004). The maximum of the 30 min EC fluxes is considered.	Quality control flag 2 according to Foken et al.(2004). The maximum of the 30 min EC fluxes is considered.	Integral turbulence characteristic test and test on stationarity obtained from the software EddyPro using the 20 Hz vertical wind and CO ₂ measurements of the IRGASON and the MGA7.	Quality control flags according to Foken et al. (2004) check for stationarity and well-developed turbulence during the sampling period (Foken et al., 2004). This is a prerequisite for taking turbulent flux measurements (Foken et al., 2012).
flag_ustar	Friction velocity $u^* \geq 0.2$ m/s or stability parameter $\zeta < -15.5$. The minimum of the	Friction velocity $u^* < 0.2$ m/s and stability parameter $\zeta > -15.5$. The minimum of the	Friction velocity u^* and stability parameter ζ obtained from the software EddyPro using the 20 Hz vertical wind measurements of	During time periods of low friction velocities, decoupling between the measurement height and the surface is likely.

	30 min EC output is considered.	30 min EC output is considered.	the sonic anemometer of the IRGASON.	Since u^* also becomes small during strong convective events with strongly negative stability parameter ζ , these periods are excluded.
flag_Fstrg	Absolute CO_2 storage flux during the sampling period $\leq 20 \mu\text{mol m}^{-2} \text{s}^{-1}$. The maximum of the 30 min EC fluxes is considered.	Mean absolute CO_2 storage flux during the sampling period $> 20 \mu\text{mol m}^{-2} \text{s}^{-1}$. The maximum of the 30 min EC fluxes is considered.	CO_2 storage flux obtained from the software EddyPro using a single-point vertical profile.	Storage fluxes, i.e., fluxes due to changes in storage below the measurement height, indicate a mismatch between measured turbulent fluxes and surface fluxes (Foken et al., 2012). Since we do not/ cannot correct for this in ffCO_2 flux estimation, these periods are flagged.
flag_betaCO2	Beta coefficient: $0.1 \leq \beta \leq 1$	Beta coefficient: $\beta < 0.1$ or $\beta > 1$	β coefficient obtained from EC CO_2 flux measurements and CO_2 flask concentration measurements (Eq. 5).	Negative or large β coefficients indicate vertical wind and CO_2 concentration statistics unsuitable for REA measurements (e.g., Grönholm et al., 2008). In accordance with Hensen et al. (2009) and Osterwalder et al. (2016), only

				measurements with $0.1 \leq \beta \leq 1$ are considered further.
flag_DffCO ₂	Relative Δ ffCO ₂ uncertainty $\leq 100\%$	Relative Δ ffCO ₂ uncertainty $> 100\%$	ffCO ₂ concentration differences between updraft and downdraft flasks and their uncertainties derived from CO ₂ and ¹⁴ CO ₂ flask analyses.	If the concentration difference is less than the measurement uncertainty, it is unclear whether the flux was actually small or whether it was a measurement error (Fotiadi et al., 2005).

File Format

For each city, there is one zip archive containing three files:

14C_REA_CH-Har_short / 14C_REA_FR-Rmv_short: Contains CO₂ and $\Delta^{14}\text{C}$ flask concentrations, derived ffCO₂ concentration differences and ffCO₂ fluxes, and the flags described in Table 8. The columns are described in Table 9.

14C_REA_CH-Har / 14C_REA_FR-Rmv, 129 columns: All data and meta data recorded for the individual REA sampling periods.

14C_REA_variable_description: A table containing the variable names, units, data types and descriptions of the 129 columns given in 14C_REA_CH-Har / 14C_REA_FR-Rmv.

Metadata and Variable Description

Table 9 describes the variables provided in 14C_REA_CH-Har_short / 14C_REA_FR-Rmv_short. The additional variables included in 14C_REA_CH-Har/14C_REA_FR-Rmv are described similarly in 14C_REA_variable_description.xlsx.

Table 9: Description of the variables given in 14C_REA_CH-Har_short / 14C_REA_FR-Rmv_short

Variable name	Unit	Description
REA ID	-	Unique identifier of the REA run
REStart(UTC)	UTC	Start time of REA run (flask sampler clock)
REEnd(UTC)	UTC	Start time of REA run (flask sampler clock)
REA_start_L1	UTC	Start of REA run, synchronized to level 1 IRGASON data
REA_end_L1	UTC	End of REA run, synchronized to level 1 IRGASON data
fsn_up fsn_down	-	Unique identifier of the "up" / "down" air sample
CO2_up CO2_down	ppm	CO ₂ concentration of "up" / "down" sample; MS measurements if available, otherwise GC
dCO2_up dCO2_down	ppm	Measurement uncertainty of the CO ₂ concentration of the "up" / "down" sample; MS measurements if available, otherwise GC
DCO2	ppm	CO ₂ concentration difference between "up" and "down" sample; MS measurements if available, otherwise GC
dDCO2	ppm	Measurement uncertainty of the CO ₂ concentration difference between "up" and "down" sample; MS measurements if available, otherwise GC
d14c_up d14c_down	‰	Final (including optional $\Delta^{14}\text{C}$ offset) decay corrected $\Delta^{14}\text{C}$ value of the "up" / "down" AMS target sample
dd14c_up dd14c_down	‰	Final error (AMS measurement and optional additional error) of the "up" / "down" AMS target sample

DffCO ₂	ppm	Estimated ffCO ₂ difference between "up" and "down" sample (Eq. 3)
dDffCO ₂	ppm	Measurement uncertainty of the estimated ffCO ₂ difference between "up" and "down" sample
FffCO ₂ _irga FffCO ₂ _mga	μmol m ⁻² s ⁻¹	Estimated ffCO ₂ flux during the REA run based on IRGASON / MGA ⁷ CO ₂ measurements (Eq. 4)
dFffCO ₂ _irga dFffCO ₂ _mga	μmol m ⁻² s ⁻¹	Measurement uncertainty of the estimated ffCO ₂ flux during the REA run based on IRGASON / MGA ⁷ CO ₂ measurements
flag_FCO ₂ qc	-	(Table 8)
flag_ustar	-	(Table 8)
flag_betaCO ₂	-	(Table 8)
flag_DffCO ₂	-	(Table 8)
flag_Fstrg	-	(Table 8)

Access and Download

The ZIP archives containing the data files and variable descriptions for each city are available on the ICOS Cities data portal (<https://citydata.icos-cp.eu/portal/>):

Paris:

Kunz, A.-K., Bevine, S., Bignotti, L., Borchardt, L., Bouillon, L., Buysse, P., Chanca, I., Christen, A., Della Coletta, J., Erirt, M., Foliot, L., Gaudry, C., Gutiérrez, X., Hashemi, J., Hilland, R., Jordan, A., Kneißl, R., Legendre, V., Levin, I., Loubet, B., Nief, G., Preunkert, S., Ramonet, M., Zeeman, M., Hammer, S., 2025. REA flux time series archive (L2), Romainville, 2023-07-08–2024-04-15.

<https://doi.org/10.18160/QKYX-AXA0>

Zurich:

Kunz, A.-K., Brunner, D., Borchardt, L., Christen, A., Della Coletta, J., Emmenegger, L., Erirt, M., Gutiérrez, X., Hashemi, J., Hilland, R., Jordan, A., Kneißl, R., Legendre, V., Levin, I., Preunkert, S., Rubli, P., Stagakis, S., Vogt, R., Zeeman, M., Hammer, S., 2025. REA flux time series archive (L2), Hardau, 2022-07-14–2023-03-29.

<https://doi.org/10.18160/62YQ-TSHN>

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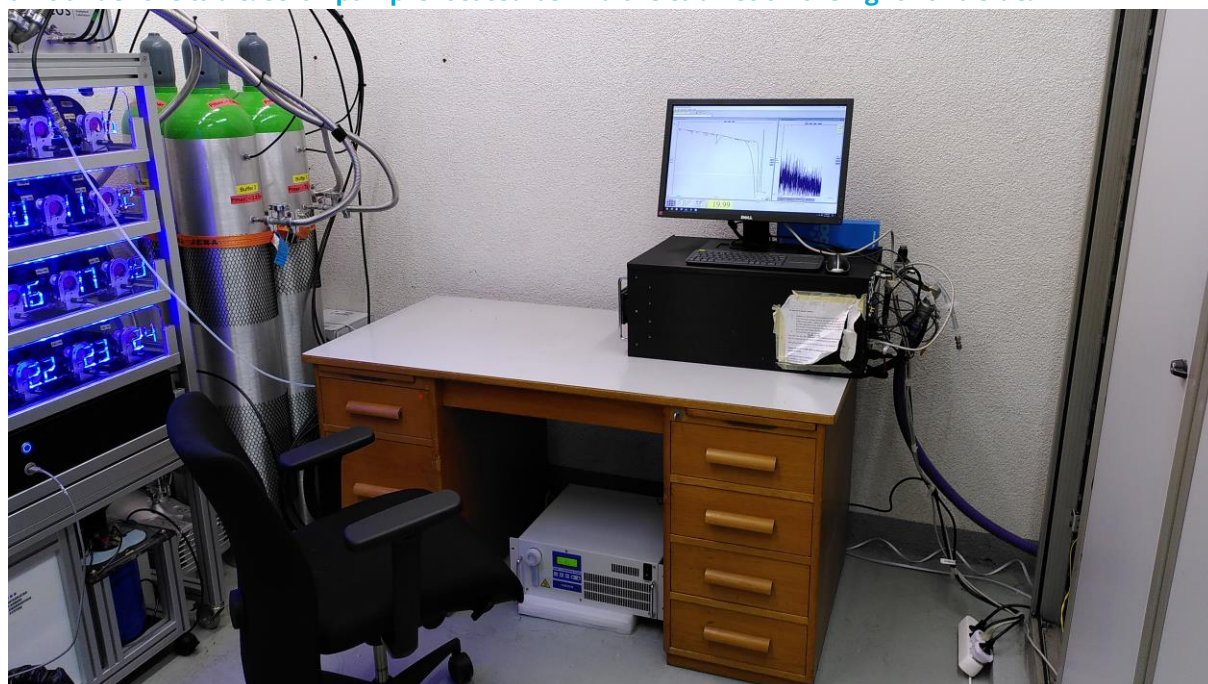
Eddy covariance fluxes of carbonyl sulfide

This section describes the dataset of eddy-covariance (EC) carbonyl sulfide (COS) fluxes measured at the Zurich-Hardau tall-tower EC site (CH-Har) in 2022/2023. The COS fluxes were measured to explore their potential for assessing the CO₂ uptake by photosynthesis of urban vegetation. In addition, also fluxes of carbon monoxide (CO) were measured and reported (as part of Task 3.4.3).

An Aerodyne quantum-cascade laser analyser (AD-QCL; Aerodyne Research Inc., Billerica, MA, USA) measured from 15 August 2022 until 21 April 2023. AD-QCL molar fractions of CO₂, CO, COS and H₂O with 10 Hz frequency (Kooijmans et al. 2016), from which eddy covariance (EC) fluxes were calculated together using data from an ultrasonic anemometer (IRGASON, Campbell Scientific Inc., Logan, UT, US). The collected data were saved both on the AD-QCL and remote servers at the University of Freiburg, from where it was subsequently transferred for EC calculations carried out at the University of Helsinki.

AD-QCL was installed inside the same room with the MGA7 and REA instruments designed to maintain stable measurement conditions. The setup is shown in Figure 5. The inlet from the anemometer was connected via a dual-part tube system, which consisted of a 33 ± 2 meter section with an inner diameter of 5.7 mm and a 4-metre section with a smaller inner diameter of 4 mm. Two Acro 50 filters (Pall, Port Washington NY, USA) were used to remove aerosols detrimental for the instrument from the sample air. The sample air was drawn in with a constant 7.5 l/min flow rate generated with an Agilent TriScroll600 pump (Agilent, Santa Clara, CA, USA). A constant pressure of 2.67 kPa (20 Torr) was maintained in the sample cell with an automatic pressure control valve integrated to the AD-QCL. Laser of the AD-QCL requires an external cooling unit, for which a SMC ThermoCon HECR cooling unit (SMC corp., Sotokanda, Chiyoda-ku, Japan) was used.

Figure 5: Setup of the AD-QCL at Hardau tower. AD-QCL is located on top of the table, and its cooling unit under the table. Scroll pump is located behind the cabinet on the right hand side.



To minimize background noise and interference during the measurement process, nitrogen gas was used regularly to measure the background absorption spectrum. The nitrogen tank bottle was initially installed on 17 October 2022. However, technical issues with the nitrogen supply persisted until 8 November 2022, which affected the quality and reliability of measurements during this period. The measurement cell was flushed once every four hours for 25 seconds, after which the absorption spectrum was measured for 10 seconds.

Data Processing

The gas analyser (AD-QCL) measured both CO₂ and COS with two different channels, marked as primary (pri) and secondary (sec). Even though both are displayed in the data, the primary channels on both gases have a more stable performance and should be of priority when analysing the data. AD-QCL acquired data at 10 Hz, whereas IRGASON recorded at 20 Hz. To harmonize datasets for flux computation, the IRGASON data were systematically downsampled to match the 10 Hz sampling frequency of the gas analyser. A linear detrending was used to account for drift and changing conditions within the averaging period. Spikes were detected and removed following existing protocols (Kohonen et al. 2020), and thresholds for sensible values were used (Sabbatini et al. 2018). A two-dimensional coordinate rotation was applied.

The AD-QCL internal clock initially operated in UTC+2 but was adjusted to UTC during the data preprocessing stage. The internal clock was synchronized daily with the *time.windows.com* server, ensuring accurate timing. The raw data from AD-QCL followed the same format as that used in the IGOR system, where time is stored as the number of seconds since January 1, 1904 (Macintosh epoch). Time lag correction between the gas analyser and the anemometer was performed to align their respective datasets accurately. Lags for CO, CO₂, and water vapour were computed by maximizing covariance within a predefined temporal window, ensuring precise synchronization for flux calculations. The time window used for assessing lag times was 3 seconds for all gases except for H₂O, for which it was 17 seconds. The window means were 6 and 20 seconds, respectively.

The signal-to-noise ratio of the COS signal was not sufficient to use that method for COS. Instead, the lag time of COS was assumed to be equivalent to that of CO₂, based on the shared characteristics of their transport and detection mechanisms (Kohonen et al. 2020). A problem in the IRGASON time synchronization caused a notable increase in the lag time between AD-QCL and IRGASON observations between 20 September and 20 October 2022. The increasing lag time during this period is showcased in Figure 5. This issue was addressed by increasing the window mean daily, and changing the window lengths to 4 seconds for CO₂ and CO and 8 seconds for water vapour. This way the drift could be accounted for while determining the covariances.

Data quality was assessed using a set of statistical metrics. Half-hourly distributions of the observations were used to assess kurtosis (Ku) and skewness (Sk)–or sharpness and asymmetry, respectively–of each variable. Additionally, flux stationarity (FS; Foken & Wichura 1996) and flux intermittency (FI; Mahrt et al 1998) were calculated.

Based on these parameters, a quality flagging system was applied to classify the data into three levels of reliability, as detailed in Table 10. This flagging framework was used to identify the high-quality data while highlighting moderate or poor-quality measurements for exclusion. Data flagged with “2” should be excluded from further analysis, and caution should be used when using data flagged with “1”. A flag of “0” indicates data good for further analysis.

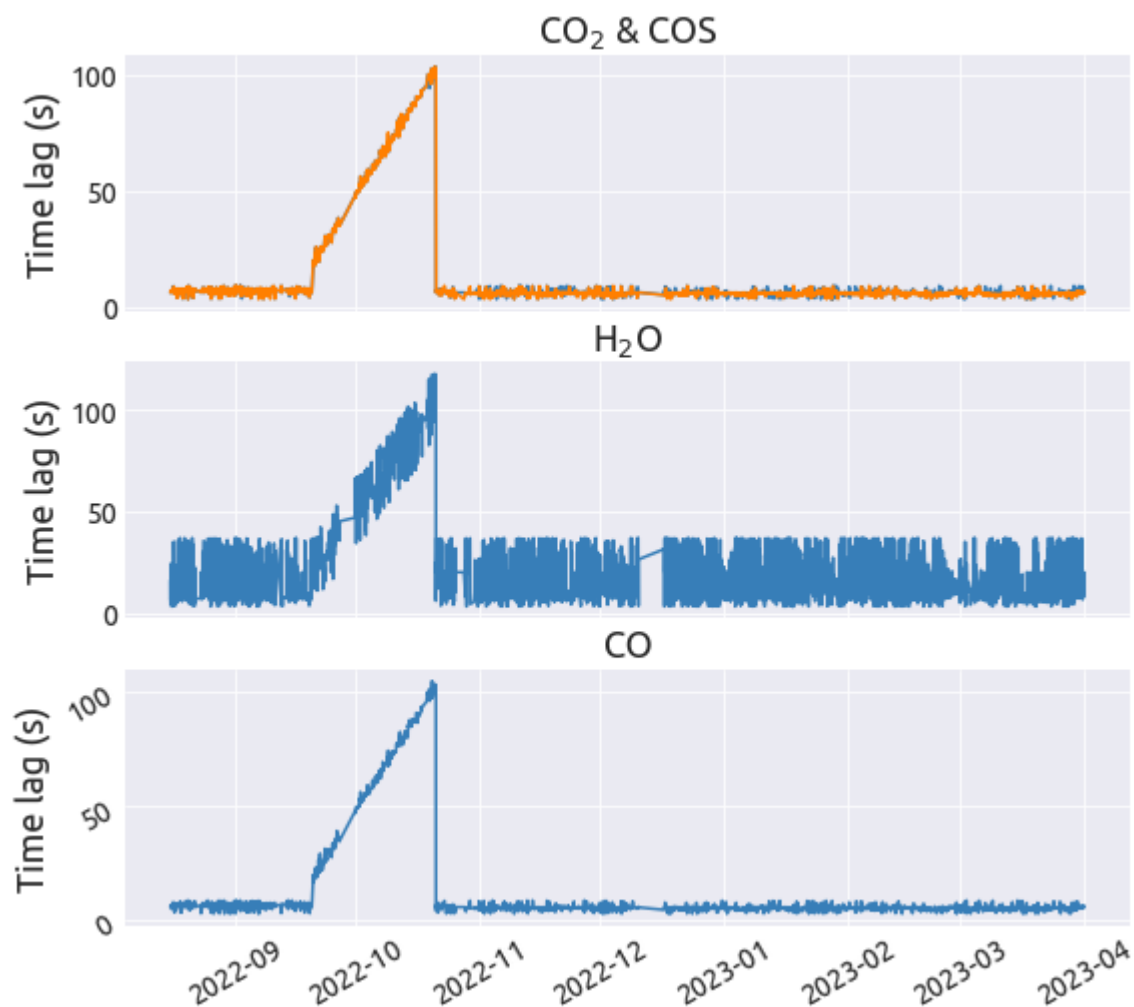


Figure 6: Lag times observed with AD-QCL for different gases.

Table 10: Description of the data flagging of the fluxes measured with AD-QCL

Flag	Description	FS	FI	Sk	Ku
0	Good quality	$FS < 0.6$	$FI < 1.0$	$ Sk < 1$	$1 < Ku < 8$
1	Moderate Quality	$FS < 1.0$			
2	Poor quality	$FS \geq 1.0$	$FI \geq 1.0$	$ Sk \geq 1$	$Ku \leq 1$ OR $Ku \geq 8$

Similar data flagging was made for the average molar fractions of COS, CO₂, CO, and water vapour. Flag criterion 0 is fulfilled as default, flag 1 is assigned for data considered as spikes or outside of the reasonable range, and flag 2 was assigned for moments of time, when the background signal removal

with nitrogen gas was not functioning as wished. Values used to assign flag 1 are shown in the Table 11. Only the highest flag for each gas per averaging period is shown in the final data files.

Table 11: Limits used to assess flags for molar fractions measured with AD-QCL. Spike limit refers to the maximum difference allowed for consequent molar fractions. Minimum and maximum values mean the average over the averaging period, not momentary values.

Gas	Spike limit	Minimum allowed	Maximum allowed
COS	200 ppt	300 ppt	600 ppt
CO ₂	20 ppm	380 ppm	600 ppm
CO	100 ppb	60 ppb	500 ppb
H ₂ O	3 mmol mol ⁻¹	0 mmol mol ⁻¹	50 mmol mol ⁻¹

File Format

Level 0 / raw data was obtained directly from the AD-QCL output. The files are delivered as an individual zip archive "ICOS-CITIES_ZURICH_AD-QCL_RAW.zip". Files are named according to the beginning of a data collection period (in UTC+2), which was started either manually after maintenance or automatically every midnight. File name followed convention "YYMMDD_hhmmss.str": two digits for year, month, day, hour, minute, and second each. The columns in the file are separated with individual spaces. The raw data occupies a total of 21 GB of data when extracted.

Level 1 data combines the IRGASON and AD-QCL observations into single csv file. The data have been despiked and the times synchronised (lag time has not been taken into account yet). Files have been created for each half-hourly period. Naming convention is "Zurich_AD-QCL-IRGASON_YYYYMMDD-hhmm.csv", where YYYY is the year, MM the month, DD the date, hh the hour, and mm the minute. Time indicates the start of the half hour period. The data is available in monthly zip archives, which are named after a similar convention as "Zurich_AD-QCL-IRGASON_YYYYMM.zip".

Level 2 data contain the processed and quality checked fluxes in monthly CSV files. Data is provided with both hourly and half-hourly resolution. File names follow convention "Zürich_AD-QCL_YYYYMM_avg.csv", where YYYY is year in four digits, MM the month in two digits, and avg is either 30m or 60m depending on the averaging period length (in minutes) in question. Column names are provided as the first row of each file, the units are not provided in the files. Columns with their units are described below in Table 14.

Metadata and Variable Description

Level 0 / raw data

The molar fractions of each measured gas are provided in units of parts per billion (ppb). Variables of level 0 data from AD-QCL are shown in Table 12.

Table 12: Description of the columns of raw data from AD-QCL

#	Description	Explanation
1	Timestamp	Seconds since IGOR Pro epoch (1st January 1904), UTC+2.
2	COS primary channel	Molar fraction of COS measured at wave number 2050.397 cm ⁻¹
3	CO ₂ primary channel	Molar fraction of CO ₂ measured at wave number 2050.566 cm ⁻¹
4	CO ₂ secondary channel	Molar fraction of CO ₂ measured at wave number 2050.422 cm ⁻¹
5	H ₂ O	Molar fraction of H ₂ O measured at wave number 2050.638 cm ⁻¹
6	CO	Molar fraction of CO measured at wave number 2050.854 cm ⁻¹
7	COS secondary channel	Molar fraction of COS measured at wave number 2050.865 cm ⁻¹

Level 1

For the level 1 data, the molar fractions were changed to more sensible units for each gas as shown in Table 13: Description of the data columns in the L1 data, which combines the anemometer data of IRGASON and the molar fractions of AD-QCL Table 13.

Table 13: Description of the data columns in the L1 data, which combines the anemometer data of IRGASON and the molar fractions of AD-QCL

#	Column header	[Unit]	Description
1	Timestamp	[-]	Time in UTC, YYYY-MM-DD hh:mm:ss.S
2	Record	[-]	Anemometer running number of records
3	u	[m s ⁻¹]	Horizontal wind component in x direction
4	v	[m s ⁻¹]	Horizontal wind component in y direction
5	w	[m s ⁻¹]	Vertical wind direction
6	Ts	[°C]	Sonic temperature from the anemometer
7	Pc	[kPa]	IRGASON cell pressure
8	Diag	[-]	IRGASON anemometer diagnostic output
9	COS_pri	[ppt]	Molar fraction of COS in the primary channel
10	COS_sec	[ppt]	Molar fraction of COS in the secondary channel

11	CO2_pri	[ppm]	Molar fraction of CO ₂ in the primary channel
12	CO2_sec	[ppm]	Molar fraction of CO ₂ in the secondary channel
13	H2O	[mmol mol ⁻¹]	Molar fraction of H ₂ O
14	CO	[ppb]	Molar fraction of CO

Level 2

An overview of the fluxes calculated from the IRGASNO and AD-QCL observations are shown in Table 14.

Table 14: The columns, units, and descriptions of the fluxes measured with AD-QCL.

#	Column header	[Unit]	Description	Device 1	Device 2
1	Year		Year with 4 digits		
2	Month		Month without the leading zero, [1,12]		
3	Day		Day of the month without the leading zero, [1,31]		
4	Hour		UTC, 24h format, [0,23]		
5	Minute		Center of the averaging period		
6	U	[m s ⁻¹]	Average wind speed	IRGASON	
7	wind_dir	[°]	Average wind direction	IRGASON	
8	eta	[°]	Horizontal rotation angle which sets u along the main wind	IRGASON	
9	theta	[°]	Vertical rotation angle	IRGASON	
10	beta	[°]	Third rotation angle (zero in two-dimensional coordinate rotation)	IRGASON	
11	H_sonic	[W m ⁻²]	Sensible heat flux from sonic temperature	IRGASON	
12	tau	[m ² s ⁻²]	Momentum flux	IRGASON	
13	u_star	[m s ⁻¹]	Friction velocity	IRGASON	
14	MO_length	[m]	Monin-Obukhov length	IRGASON	
15	cov_wu	[m ² s ⁻²]	Covariance of vertical wind and u component of horizontal wind	IRGASON	

16	cov_wv	[m ² s ⁻²]	Covariance of vertical wind and u component of horizontal wind	IRGASON	
17	cov_wT	[°C m s ⁻¹]	Covariance of vertical wind and sonic temperature or kinematic heat flux	IRGASON	
18	F_COS_pri	[pmol m ⁻² s ⁻¹]	COS flux on primary channel	IRGASON	AD-QCL
19	F_COS_sec	[pmol m ⁻² s ⁻¹]	COS flux on secondary channel	IRGASON	AD-QCL
20	F_CO2_sec	[μmol m ⁻² s ⁻¹]	CO2 flux on secondary channel	IRGASON	AD-QCL
21	F_CO2_pri	[μmol m ⁻² s ⁻¹]	CO2 flux on primary channel	IRGASON	AD-QCL
22	F_CO	[nmol m ⁻² s ⁻¹]	CO flux	IRGASON	AD-QCL
23	LE	[W m ⁻²]	Latent heat flux	IRGASON	AD-QCL
24	E	[mmol m ⁻² s ⁻¹]	H2O flux	IRGASON	AD-QCL
25	av_u	[m s ⁻¹]	Average u component of wind speed	IRGASON	
26	av_v	[m s ⁻¹]	Average v component of wind speed	IRGASON	
27	av_w	[m s ⁻¹]	Average w component or vertical of wind speed	IRGASON	
28	av_T	[°C]	Average sonic temperature	IRGASON	
29	av_RH	[%]	Average relative humidity of air	IRGASON	
30	av_P	[hPa]	Average cell pressure	IRGASON	
31	av_COS_pri	[ppt]	Average molar fraction of COS_pri	AD-QCL	
32	av_COS_sec	[ppt]	Average molar fraction of COS_sec	AD-QCL	
33	av_CO2_sec	[ppm]	Average molar fraction of CO2_sec	AD-QCL	
34	av_CO2_pri	[ppm]	Average molar fraction of CO2_pri	AD-QCL	
35	av_H2O	[mmol mol ⁻¹]	Average molar fraction of H2O	AD-QCL	
36	av_CO	[ppb]	Average molar fraction of CO	AD-QCL	
37	std_u	[m s ⁻¹]	Standard deviation of u component of wind	IRGASON	
38	std_v	[m s ⁻¹]	Standard deviation of v component of wind	IRGASON	

39	std_w	[m s ⁻¹]	Standard deviation of w (vertical) component of wind	IRGASON	
40	std_T	[°C]	Standard deviation of sonic temperature	IRGASON	
41	std_P	[hPa]	Standard deviation of ambient air pressure	IRGASON	
42	std_COS_pri	[ppt]	Standard deviation of COS_pri	AD-QCL	
43	std_COS_sec	[ppt]	Standard deviation of COS_sec	AD-QCL	
44	std_CO2_sec	[ppm]	Standard deviation of CO2_sec	AD-QCL	
45	std_CO2_pri	[ppm]	Standard deviation of CO2_pri	AD-QCL	
46	std_H2O	[mmol mol ⁻¹]	Standard deviation of H2O	AD-QCL	
47	std_CO	[ppb]	Standard deviation of CO	AD-QCL	
48	FS_wU	[-]	Stationarity of cov_wu	IRGASON	
49	FS_wT	[-]	Stationarity of cov_wt	IRGASON	
50	FS_wCOS_pri	[-]	Stationarity of wCOS_pri	IRGASON	AD-QCL
51	FS_wCOS_sec	[-]	Stationarity of wCOS_sec	IRGASON	AD-QCL
52	FS_wCO2_pri	[-]	Stationarity of wCO2_pri	IRGASON	AD-QCL
53	FS_wCO2_sec	[-]	Stationarity of wCO2_sec	IRGASON	AD-QCL
54	FS_wH2O	[-]	Stationarity of wH2O	IRGASON	AD-QCL
55	FS_wCO	[-]	Stationarity of wCO	IRGASON	AD-QCL
56	FI_wU	[-]	Intermittency of cov_wu	IRGASON	
57	FI_wT	[-]	Intermittency of cov_wt	IRGASON	
58	FI_wCOS_pri	[-]	Intermittency of wCOS_pri	IRGASON	AD-QCL
59	FI_wCOS_sec	[-]	Intermittency of wCOS_sec	IRGASON	AD-QCL
60	FI_wCO2_pri	[-]	Intermittency of wCO2_pri	IRGASON	AD-QCL
61	FI_wCO2_sec	[-]	Intermittency of wCO2_sec	IRGASON	AD-QCL
62	FI_wH2O	[-]	Intermittency of wH2O	IRGASON	AD-QCL
63	FI_wCO	[-]	Intermittency of wCO	IRGASON	AD-QCL

64	Sk_u	[-]	Skewness of u distribution within the averaging period	IRGASON	
65	Sk_v	[-]	Skewness of v distribution within the averaging period	IRGASON	
66	Sk_w	[-]	Skewness of w distribution within the averaging period	IRGASON	
67	Sk_T	[-]	Skewness of t distribution within the averaging period	IRGASON	
68	Sk_wCOS_pri	[-]	Skewness of COS_pri distribution within the averaging period	AD-QCL	
69	Sk_wCOS_sec	[-]	Skewness of COS_sec distribution within the averaging period	AD-QCL	
70	Sk_wCO2_pri	[-]	Skewness of CO2_pri distribution within the averaging period	AD-QCL	
71	Sk_wCO2_sec	[-]	Skewness of CO2_sec distribution within the averaging period	AD-QCL	
72	Sk_wH2O	[-]	Skewness of H2O distribution within the averaging period	AD-QCL	
73	Sk_wCO	[-]	Skewness of CO distribution within the averaging period	AD-QCL	
74	Ku_u	[-]	Kurtosis of u distribution within the averaging period	IRGASON	
75	Ku_v	[-]	Kurtosis of v distribution within the averaging period	IRGASON	
76	Ku_w	[-]	Kurtosis of w distribution within the averaging period	IRGASON	
77	Ku_T	[-]	Kurtosis of t distribution within the averaging period	IRGASON	
78	Ku_wCOS_pri	[-]	Kurtosis of COS_pri distribution within the averaging period	AD-QCL	
79	Ku_wCOS_sec	[-]	Kurtosis of COS_sec distribution within the averaging period	AD-QCL	
80	Ku_wCO2_pri	[-]	Kurtosis of CO2_pri distribution within the averaging period	AD-QCL	

81	Ku_wCO2_sec	[-]	Kurtosis of CO2_sec distribution within the averaging period	AD-QCL	
82	Ku_wH2O	[-]	Kurtosis of H2O distribution within the averaging period	AD-QCL	
83	Ku_wCO	[-]	Kurtosis of CO distribution within the averaging period	AD-QCL	
84	Fa_COS_pri	[-]	Flux attenuation of F_COS_pri	IRGASON	AD-QCL
85	Fa_CO2_pri	[-]	Flux attenuation of F_CO2_pri	IRGASON	AD-QCL
86	Fa_CO2_sec	[-]	Flux attenuation of F_CO2_sec	IRGASON	AD-QCL
87	Fa_H2O	[-]	Flux attenuation of E	IRGASON	AD-QCL
88	Fa_CO	[-]	Flux attenuation of F_CO	IRGASON	AD-QCL
89	Fa_COS_sec	[-]	Flux attenuation of F_COS_sec	IRGASON	AD-QCL
90	det_COS_pri	[pmol m ⁻² s ⁻¹]	Detection limit of F_COS_pri	IRGASON	AD-QCL
91	det_CO2_pri	[μmol m ⁻² s ⁻¹]	Detection limit of F_CO2_pri	IRGASON	AD-QCL
92	det_CO2_sec	[μmol m ⁻² s ⁻¹]	Detection limit of F_CO2_sec	IRGASON	AD-QCL
93	det_H2O	[mmol m ⁻² s ⁻¹]	Detection limit of E	IRGASON	AD-QCL
94	det_CO	[nmol m ⁻² s ⁻¹]	Detection limit of F_CO	IRGASON	AD-QCL
95	det_COS_sec	[pmol m ⁻² s ⁻¹]	Detection limit of F_COS_sec	IRGASON	AD-QCL
96	RE_COS_pri	[pmol m ⁻² s ⁻¹]	Random error of F_COS_pri	IRGASON	AD-QCL
97	RE_CO2_pri	[μmol m ⁻² s ⁻¹]	Random error of F_CO2_pri	IRGASON	AD-QCL
98	RE_CO2_sec	[μmol m ⁻² s ⁻¹]	Random error of F_CO2_sec	IRGASON	AD-QCL
99	RE_H2O	[mmol m ⁻² s ⁻¹]	Random error of E	IRGASON	AD-QCL
100	RE_CO	[nmol m ⁻² s ⁻¹]	Random error of F_CO	IRGASON	AD-QCL
101	RE_COS_sec	[pmol m ⁻² s ⁻¹]	Random error of F_COS_sec	IRGASON	AD-QCL
102	COS_pri_lag	[s]	Time lag between the vertical wind and COS_pri signals	IRGASON	AD-QCL
103	COS_sec_lag	[s]	Time lag between the vertical wind and COS_sec signals	IRGASON	AD-QCL
104	CO2_sec_lag	[s]	Time lag between the vertical wind and CO2_sec signals	IRGASON	AD-QCL

105	CO2_pri_lag	[s]	Time lag between the vertical wind and CO2_pri signals	IRGASON	AD-QCL
106	H2O_lag	[s]	Time lag between the vertical wind and H2O signals	IRGASON	AD-QCL
107	CO_lag	[s]	Time lag between the vertical wind and CO signals	IRGASON	AD-QCL
108	flag_av_COS_pri	[-]	Quality flag for av_COS_pri	AD-QCL	
109	flag_av_COS_sec	[-]	Quality flag for av_COS_sec	AD-QCL	
110	flag_av_CO2_pri	[-]	Quality flag for av_CO2_pri	AD-QCL	
111	flag_av_CO2_sec	[-]	Quality flag for av_CO2_sec	AD-QCL	
112	flag_av_H2O	[-]	Quality flag for av_H2O	AD-QCL	
113	flag_av_CO	[-]	Quality flag for av_CO	AD-QCL	
114	flag_F_COS_pri	[-]	Quality flag for F_COS_pri	AD-QCL	
115	flag_F_COS_sec	[-]	Quality flag for F_COS_sec	AD-QCL	
116	flag_F_CO2_pri	[-]	Quality flag for F_CO2_pri	AD-QCL	
117	flag_F_CO2_sec	[-]	Quality flag for F_CO2_sec	AD-QCL	
118	flag_LE	[-]	Quality flag for LE	AD-QCL	
119	flag_E	[-]	Quality flag for E	AD-QCL	
120	flag_F_CO	[-]	Quality flag for F_CO	AD-QCL	
121	CT2	[°C ² m ^{-2/3}]	Temperature-structure parameter calculated from the raw temperature data	IRGASON	
122	Spikes_gas_analyzer	[-]	Number of spikes observed	AD-QCL	

Access and Download

Level 0 data are available as a ZIP archive:

- Soininen, J., Brunner, D., Emmenegger, L., Rubli, P., Stagakis, S., Järvi, L. (2025). EC flux time series archive (raw data), Hardau, 2022-08-15–2023-04-21, ICOS Cities, <https://hdl.handle.net/11676/RmmFTFqA6h3IMSpoZrDi9-lz>

Level 1 data are available as a ZIP archive:

- Soininen, J., Brunner, D., Emmenegger, L., Rubli, P., Stagakis, S., Järvi, L. (2025). EC flux time series archive (L1), Hardau, 2022-08-15–2023-04-21, ICOS Cities, <https://hdl.handle.net/11676/UjiwSPcHzsUoRjzc0XUUX5gn>

Level 2 data are available as two ZIP archives, one for each averaging period:

- 30 minutes: Soininen, J., Brunner, D., Emmenegger, L., Rubli, P., Stagakis, S., Järvi, L., 2025. EC flux time series archive (L2), Hardau, 2022-08-15–2023-04-21. <https://doi.org/10.18160/G039-HZT1>
- 60 minutes: Soininen, J., Brunner, D., Emmenegger, L., Rubli, P., Stagakis, S., Järvi, L., 2025. EC flux time series archive (L2), Hardau, 2022-08-15–2023-04-21. <https://doi.org/10.18160/AFX5-2DG3>

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Abbreviations

Abbreviation	Description
AD-QCL	Aerodyne quantum-cascade laser analyser
agl	Above ground level
AMS	Accelerator mass spectrometry
asl	Above sea level
CEDT	Central European Daylight Time
CH-Har	Zurich Hardau site
CH ₄	Methane
CO	Carbon monoxide
CO ₂	Carbon dioxide
COS	Carbonyl sulfide
CSV	Comma separated values
DE-Opd	Munich Oberpostdirektion site
EC	Eddy covariance
FR-Rmv	Paris Romainville site
GC	Gas chromatography
IRGA	Infrared gas analyser
L0	Level 0 data (www.icos-cp.eu)
L1	Level 1 data (www.icos-cp.eu)
L2	Level 2 data (www.icos-cp.eu)
MGA7	Multi-species gas analyser (7 species)
MS	Mass spectrometry
NO	Nitric oxide
NO ₂	Nitrogen dioxide
NO _x	Nitrogen oxides
N ₂ O	Nitrous oxides
REA	Relaxed eddy accumulation
UTC	Coordinated Universal Time