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Article

ICOS Potenza (Italy) Atmospheric Station: A New Spot for the Observation of Greenhouse Gases in the Mediterranean Basin

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Abstract: The Integrated Carbon Observation System (ICOS) is the reference Research Infrastructure (RI) for the observation of greenhouse gases (GHGs) across Europe, providing standardised, long-term and high-precision measurements of the most relevant species (CO_2, CH_4, CO, etc.). The ICOS Atmosphere network currently extends throughout the continent, although the density of stations in the Mediterranean area is still low compared to Central and Northern Europe. In this context, the recently implemented class 1 continental station near Potenza in Basilicata, Italy—station code: POT—represents an important step forward in the extension of the ICOS atmosphere domain across the South, reducing the large spatial gaps existing between ICOS sites within the Mediterranean basin. Herein, we provide a description of the new ICOS POT station and the site where it operates, focusing mostly on the technical setup of the sampling system which plays a key role in GHG measurements. With a strong technical connotation, the present paper aims to be beneficial for the ICOS atmosphere community and those stations that intend to join the network in the future, providing an accurate description of the station at the level of single components. Moreover, a brief overview of the peculiarities of the site and the scientific perspectives to be pursued, together with very preliminary data collected at the new ICOS station, are presented. Preliminary data collected during a short campaign are compared with STILT (Stochastic Time-Inverted Lagrangian Transport) model results as a first test of the measurements and to provide a first insight of the specific Potenza situation in terms of GHG concentrations.

Keywords: ICOS; atmospheric station; tall tower; continental station; research infrastructure; GHG; monitoring; climate change

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1. Introduction

The full-blown effect of the rising levels of greenhouse gases (GHGs) on global warming, along with the necessity of retrieving GHG emissions with higher accuracy, is pushing the scientific community to constantly expand and improve observation networks all over the world [1,2]. In 2023, the World Meteorological Congress established the Global Greenhouse Gas Watch (G3W) initiative to support the goals set by the Paris Agreement by improving the monitoring of GHG net fluxes globally. To better guide the decisions of policymakers [3], it is necessary to monitor GHG emissions [4] at the national scale to investigate natural carbon exchanges between carbon reservoirs. The CEPI (Carbon Emission Performance Indicator) is a metric used to evaluate and quantify the effectiveness of policies and practices in reducing carbon emissions. Novel machine learning techniques are used to achieve an accurate prediction and optimization of CEPIs such as the multihead attention-based convolutional neural network (MHA–CNN) model proposed by Fenger Wu et al. [5]. Bottom-up, top-down [6] and inverse modelling [7] are the current methodologies used to estimate carbon fluxes. Each methodology is characterized by a number of advantages, as well as disadvantages (e.g., degrees of uncertainty). A synergistic combination of these methods can provide most robust and reliable estimates facilitating informed policymaking and effective planning of climate change mitigation strategies. Currently, several tall towers play a key role [8] by providing more accurate estimates on carbon cycles and the evaluation of bottom-up inventories [9]; these towers enhance the understanding of carbon fluxes at scales ranging from local to regional [10].

In Europe, the Integrated Carbon Observation System (ICOS) [11] is the pivotal Research Infrastructure (RI) for observations of GHGs, mainly CO_2, CH_4, N_2O and CO as tracers to discriminate natural GHG emissions and fluxes from combustion processes, and currently accounts for more than 170 measurement stations in three domains—atmosphere, ecosystem and ocean—across 16 countries within the continent. The main goal is to build a dense network, ranging from local to regional stations, to provide high quality long term and standardized GHGs data. The ICOS stations operate under the same technical and scientific standards and need rigorous assessment before being compliant, thus enabling the true comparability of data which is essential for high-quality research on climate change. Within ICOS, the atmosphere subdomain deals with the measurements of GHGs in terms of mole fractions and isotope-related quantities—needed to retrieve GHG emissions through inverse modelling—and to date, it includes 39 labelled stations in the European territory [12,13]. Despite its wide extension, the atmosphere network is mostly concentrated in the central part of the continent, with a minor density of stations in the Mediterranean area and even less in Eastern Europe. In this scenario, with the growing need to expand the ICOS observation network, the entry of new stations from the above-mentioned areas is highly desirable.

In this paper, we present the recently developed ICOS atmosphere station located near the city of Potenza—hence named POT—in the southern Italian region of Basilicata, implemented and run by the Institute of Methodologies for Environmental Analysis (*Istituto di Metodologie per l'Analisi Ambientale*, IMAA) of the National Research Council of Italy (*Consiglio Nazionale delle Ricerche*, CNR). The creation of the POT station was made possible by funding program PON issued by Italian Ministry of University and Research (*Ministero dell'Università e della Ricerca*, *MUR*). Located in the southern part of the Italian peninsula, the station occupies a central position in the Mediterranean basin which is currently not covered by other ICOS atmosphere sites (Figures 1 and 2); in fact, the closest ICOS sites are Lampedusa (LMP) in the South and Monte Cimone (CMN) in the North, both located more than 500 km away from POT. The new ICOS POT atmospheric station will help to make the Italian ICOS network more homogeneous. The continuous measurements, mainly at the highest level, from the POT station together with those achieved from remote sites will be very useful to provide measurements for regional and global inverse modelling systems. The Mediterranean basin is located between air masses coming from continental Europe, North Africa and Asia, in a transition zone subject to subtropical and mid-latitude weather regimes, which makes the basin prone to the influence of pollutants and highly sensitive to climate change [14–16]. Moreover, differences in pollutant concentrations have been found between central and eastern Mediterranean [17].

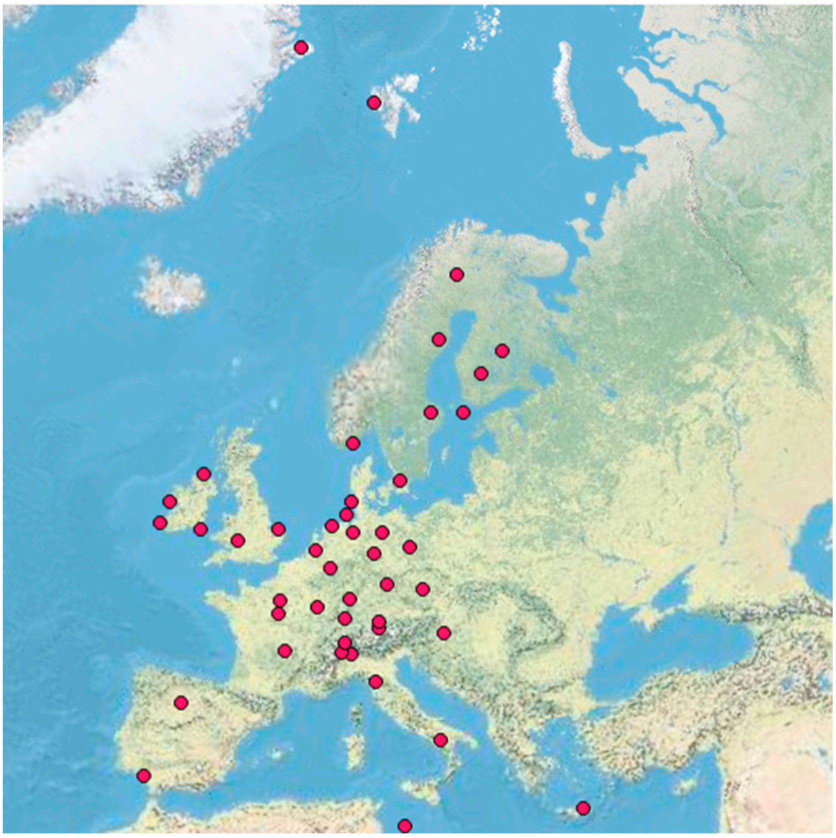

Figure 1. Spatial distribution map of the ICOS stations across Europe [18]. The atmosphere stations are flagged with red dots.

The station is classified as "continental"—i.e., placed in an inland area where a tall tower (above 100 m height) is needed to sample the air at altitudes where the impact of local phenomena is limited—and classified as class 1—i.e., measuring the largest number of parameters required by ICOS [19]. As of today, POT has been approved for Step 1 of the labelling process: this means that the site and the overall infrastructure have been approved by ICOS [12]. For becoming officially an operative ICOS station, a further step is needed, namely Step 2, which is currently ongoing. Step 2 involves a test period of measurement optimization and data evaluation performed under the supervision of ICOS Atmospheric Thematic Centre (ATC). The ATC also provide the digital infrastructure that collects data from the network and automatic data processing and archiving [20].

The main focus of the present paper is the technical description of the station, with a strong emphasis on the sampling system implemented with the guidance of the ICOS ATC. Indeed, the proper setup of the sampling scheme upstream of the instrumentation plays a key role in the accuracy and the comparability of GHG measurements across the network, thus constituting one of the major strengths of the ICOS RI.

The paper aims, therefore, at being useful for the ICOS community and especially to those stations that are on the verge of joining the atmosphere network, or anyhow to implement an ICOS-like measurement site, providing an up-to-date example of setup for a continental class 1 facility described at the level of single components. This work is divided as follows: Section 2 describes the measurement site; Section 3 provides details on POT infrastructure; Section 4 evaluates preliminary data gathered during a short campaign; Section 5 reports suggestions and conclusions.

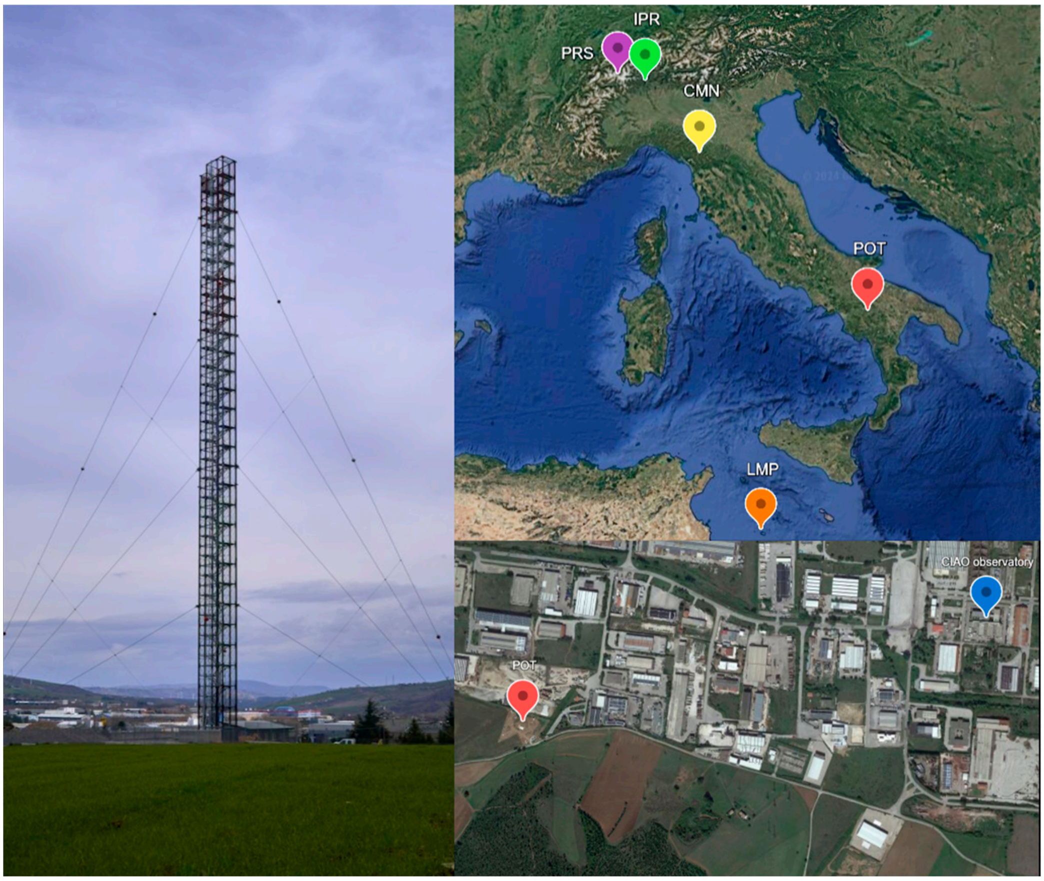

Figure 2. The new ICOS POT station (**left**) with the locations of ICOS sites (Potenza as red marker, Lampedusa as orange, Monte Cimone as yellow, ISPRA as green, Plateau Rosa as purple) within Italian territory (**top right**) and the Tito Scalo area (**bottom right**).

2. The Measurement Site

The ICOS POT atmosphere station is located on the Southern Apennine in Italy (Tito Scalo, 40.60° N, 15.72° E, 760 m a.s.l.). ICOS POT station is part of CIAO (CNR-IMAA Atmospheric Observatory) [21], one of the largest atmospheric observatories in the Mediterranean Basin and in Europe, which consists of a combination of advanced systems able to provide high-quality long-term observations of aerosol, clouds, and trace gases for the study of climate and weather [22,23]. In particular, the relevant role of CIAO in ACTRIS (Aerosol, Clouds and Trace Gases Research Infrastructure) as a reference station for aerosol remote sensing observations plus aerosol in situ and cloud and trace gas remote sensing observations was a key element for the ICOS Italian consortium and ICOS ERIC to propose first and accept the ICOS POT candidature as a new ICOS atmospheric site fostering scientific synergies, complementarities and progress [24].

The POT station is located in a plain surrounded by low mountains, less than 150 km away from the west, south and east coasts of the Mediterranean Sea. Therefore, it operates in a typical mountain climate strongly influenced by Mediterranean atmospheric circulation, resulting in generally dry and hot summers, and cold winters. Indeed, dew point temperatures measured at the station between 2018 and 2021 exceeded 15 °C only during the summer period as derived by our long-term time series measurements collected at CIAO.

Most of the surrounding land is classified as arable crops in non-irrigated areas, followed by broad-leaved woods and coniferous forests, sclerophyllous or wooded/shrubby areas and natural grazing areas and grasslands [25]. In line with ICOS recommendations, the site is not located near to large cities or heavy anthropogenic sources that could affect GHG observations. In fact, the closest urban centre to the station is the regional capital of Potenza (~9 km NE, 819 m a.s.l.; 64,100 inhabitants, 365 inhabitants/km^2), and some small villages (Tito, the most populous one, has less than 7500 inhabitants) can be found within 10 km of the site. A high-speed road is located 1 km north of the site while the nearest highway (A3) is about 30 km west of the site.

According to GHG emission levels allowed by the Italian Ministry for Environment, Land and Sea Protection and reported in the EU ETS registry [26] (see https://www.ets.minambiente.it/, accessed on 1 October 2024), to date, three plants authorized to emit GHGs are located near the site: Siderpotenza S.p.A. (a steel plant, ~10 km ENE from the site), Lucart S.p.A. (a small paper mill, ~13 km NNE from the site) and Ageco S.r.l. (a small urban waste treatment plant, ~1 km ENE from the site). However, since all of them are located downstream of the prevailing wind direction W-WSW-SW (Figure 3), no significant effects are expected on GHG observations.

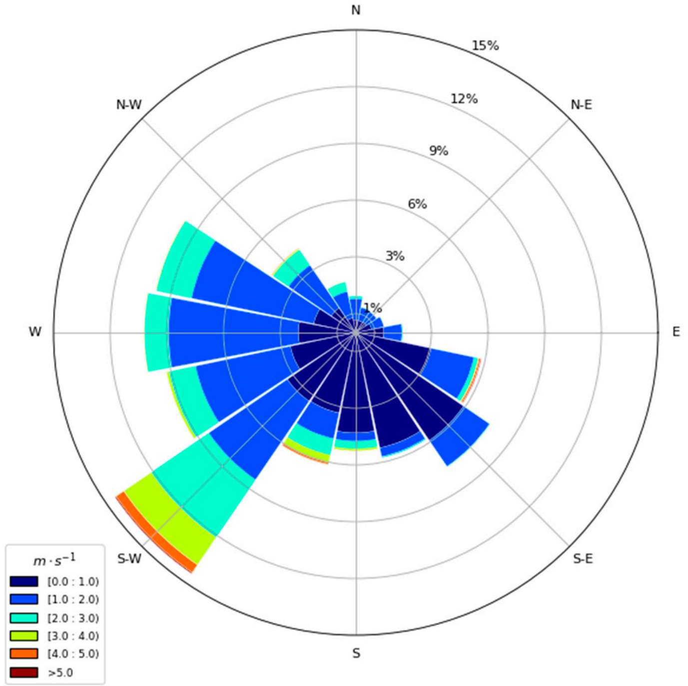

Figure 3. Wind rose measured near the ICOS site covering one year of continuous observations from October 2023 to September 2024. Wind measures have been collected by Vaisala AWS310 station.

In this sense, our expectations could be enlightened by STILT Footprint Tool [27] simulations. These products exploit model simulations in order to estimate greenhouse gases at station sites by considering atmospheric transport phenomena creating the so-called footprints. The station footprint can be analysed by open-source tools [28] on the ICOS Portal [29] to identify the regional station representativeness. The achieved results characterized the POT station in the context of the Mediterranean Basin and demonstrated its importance within the ICOS network, since it can play a fundamental role by linking the hints from atmospheric circulation from different European region domains.

We used the STILT on demand calculator to compute GHG footprints on a baseline of one year, by choosing the last available one, i.e., 2022, for our POT site. In order to have a reference for our site, we generated the same simulation for Monte Cimone station (CMN), selected for some similarities with our station. The CMN station is located at ~550 km NW from the POT site, and both places are located within the Italian Apennines which influence local conditions. These sites are not directly affected by the influence of the seas, which are located at distances greater than ~70 km. The noticeable difference is, however, the surrounding context: CMN is located in a wild, naturalistic context surround by coniferous woods and rocky soils while the POT site is located close to Tito Scalo industrial area, which does host some local emission sources and spots. In Figure 4, we present the simulations obtained for CO_2 (carbon dioxide) and CH_4 (methane) gases by considering all sources provided by the STILT footprint calculator: the behaviour of the concentration in the atmosphere at local sites for both gases appears to be quite similar. For CO_2, the annual trend predicted for the CMN site is higher than that of the POT site, within the period that goes from late autumn, i.e., from mid-November, to the beginning of summer, i.e., mid-June.

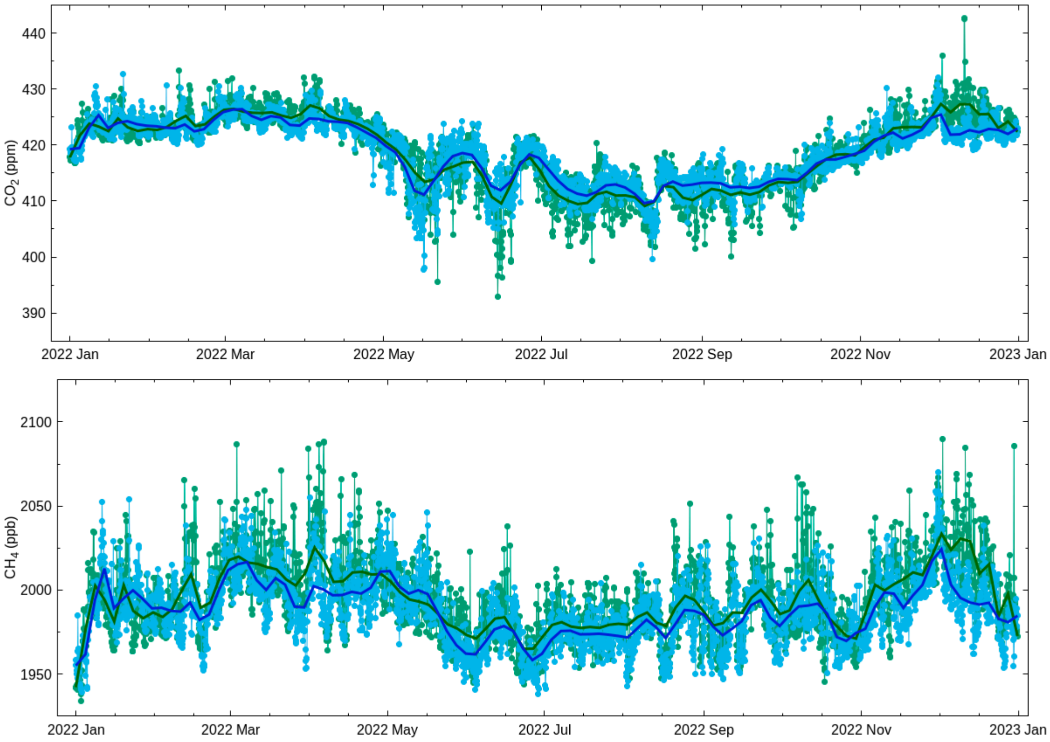

Figure 4. STILT predictions for CO_2 (**upper**) and CH_4 (**bottom**) over the year 2022. Single points and thin lines mark predictions for the Monte Cimone (light green) and Potenza (light blue) sites. The thick lines show average values of chemical species computed by smoothing single data points, dark green for CMN site while dark blue for POT site.

We can explain this annual trend with the vegetation cycle, corresponding to the periods in which woods, forests, and grasslands start to vegetate by absorbing carbon dioxide from the atmosphere which will be released in the autumn thanks to the actions of deciduous leaves. On the other hand, in the summertime, carbon dioxide shows an opposite trend at the POT site compared to CMN, which probably suggests the contribution of industrial activities and transportation. Conversely, the behaviour of CH_4 is quite challenging, resulting in a scenario not compatible with seasonal effects, and also presenting a quite noisy behaviour with important variations on small timescales. We limit our considerations by observing a higher level of CH_4 predicted for the CMN station without clear hints of seasonal cycles, thus resulting in a prevailing lower trend for the POT site over the annual baseline. We intend to investigate all the clues arising from STILT footprint predictions once we begin to collect observations at our station.

3. The ICOS POT Station

In order to ease the reading of this manuscript, the description of the station has been divided in three parts: in Section 3.1, the overall scheme of the station is presented with a focus on the sampling lines and the relative inlets; Section 3.2 continues the description by focussing on the components inside the shelter up to the instrumentation; lastly, Section 3.3 provides a short description of the tower structure and the meteorological stations deployed at the sampling levels.

3.1. Overview and Sampling Lines

The POT station consists of a 104 m tall tower, needed to bring the sampling points to the requested altitudes, and the shelter where the instrumentation for the analysis of sampled air is located.

According to the ICOS guidelines for continental stations (i.e., tall towers), the top sampling level on the tower is at 100 m from the ground and the other two mandatory sampling levels are located at 50 m and 10 m. The rationale behind the sampling at the top level (i.e., $\geq$100 m) is to avoid the influence of local phenomena and be exposed to atmospheric transport and processes covering larger areas [30–32]. Thus, integral information on regional sources and sinks of greenhouse gases can be retrieved, and a limited number of stations—nominally located at least 300 km from each other—provides coverage of large parts of the European continent. On the other hand, the air sampling at lower altitudes (i.e., 10 and 50 m) is intended to provide the vertical profile of GHG mole fractions on the site to ascertain the influence of local phenomena [33,34].

In compliance with ICOS recommendations, Synflex 1300 tubes manufactured by EATON (Dublin, Ireland) (see Table 1 for a complete list of components) have been used for the sampling lines. All tubes were deployed as single pieces without connectors: this is a recommended key feature, since it prevents the possibility of inherent leakages within the sampling lines. The pipes run along one side of the tower, from relative sampling height to the shelter, following parallel paths without overlapping in order to ease the recognition of each line and a possible visual inspection at any level. Considering tube lengths, their internal diameter (i.e., 12 mm), and the overall sampling flow rates generated by the downstream flushing pumps and instrument pumps, the residence time of air within the tubes is well below the recommended threshold of one minute. However, with the purpose of minimizing the residence time of sampled air within the tubes, the shelter has been placed just adjacent to the tower (i.e., at 2 m distance), with the instrumentation positioned close by the wall facing the tower.

The downstream instrumentation deployed to fulfil class 1 requirements includes: (1) a continuous analyser Picarro G2401 (Santa Clara, CA, USA) for the measurement of CO, CO_2, CH_4 and H_2O mole fractions; (2) the 24-port Flask-Sampler (designed and constructed at the Max Planck Institute for Biogeochemistry) for the periodical sampling of air to be analysed at the Flask and Calibration Laboratory (FCL) with independent analytical methods; (3) the Heidelberg $^{14}CO_2$ (Heidelberg, Germany) sampler for carbon dioxide in the form of carbonate solution meant to be analysed for its $^{14}C/^{12}C$ ratio at the Central Radiocarbon Laboratory (CRL). Furthermore, the continuous gas analyser Los Gatos Research GLA351 (ABB group, Mannheim, Germany) Series and the Mi.am Radon

Mapper (Piacenza, Italy) equipped with Pylon® Model TEL1 detector have been deployed for the measurement of the not-mandatory—but recommended—nitrous oxide (N_2O) and CO mole fractions and radon-222 (^{222}Rn) concentrations, respectively. To date, the Radon Mapper does not belong to the list of ICOS-compliant instruments for the measurement of Radon concentration, but this could be revised in the future.

Table 1. List of the main components of the POT station, from line types to multicomponent assembly elements. As guidance, we report type, manufacturer and short description.

Item	Element	Type/Manufacturer	Description
1	Tubes	EATON Synflex 1300 OD 12 mm	Connect intake heads to multicomponent assembly
2	12-position multiport valve	Vici EMT2CA-CE	Connected to sampling line (10, 50 and 100 m) through multicomponent node
3	2-way valve	Swagelok SS-43GS8	Protect inlet in cylindrical module
4	Flushing pumps	KNF N 815 KTE	Flush ambient air from 100 m lines, connect to multicomponent node
5	Flushing pumps	KNF N 811 KTE	Flush ambient air from 10/50 m lines, connect to multicomponent node
6	T union	Swagelok SS-400-3	Connect multicomponent node and flushing pump
7	Universal filter 2 mm porosity	M&C F2	Connected to multicomponent node
8	Gauge pressure	PGI-63B-BC1.5-LAQX	Connected to multicomponent node
9	Two-way valve	Swagelok SS-42GES4	Connect multicomponent node to flushing pump
10	Three-way valve	Swagelok SS-42GXLS4	Connect multicomponent node to quick-connect stem for shelter test
11	Quick-connect stem	Swagelok SS-QM2-D-200	Connect multicomponent node to cylinders for shelter test
12	Tubes	EATON Synflex 1300 tube OD 6 mm	Connect: multicomponent node to flushing pumps and Valco valve, Valco to Nafion, Nafion to continuous instruments
13	Flow switch	SMC PF2M711S-02-D	Connected all multicomponent nodes to flushing pumps
14	In-line filter 0.5 mm	Swagelok SS-4FWS-05	Connected to Valco and downstream to cylinders connections
15	Tubes	Stainless steel OD 3 mm	Connect cylinders to Valco and Valco to Nafion dryer
16	Reducer	Swagelok SS-200-R-4	Connect Valco to inline filters through stainless steel tubing
17	Nafion dryer	Perma Pure MD 070-144 S-4	Drying system, connected to Valco and continuous analysers
18	Flow switch	FESTO SFAH-1U-G14FS-PNLK-PNVBA-L1	Connected to upstream Picarro vacuum pump

The general scheme of the station with the main components is reported in Figure 5.

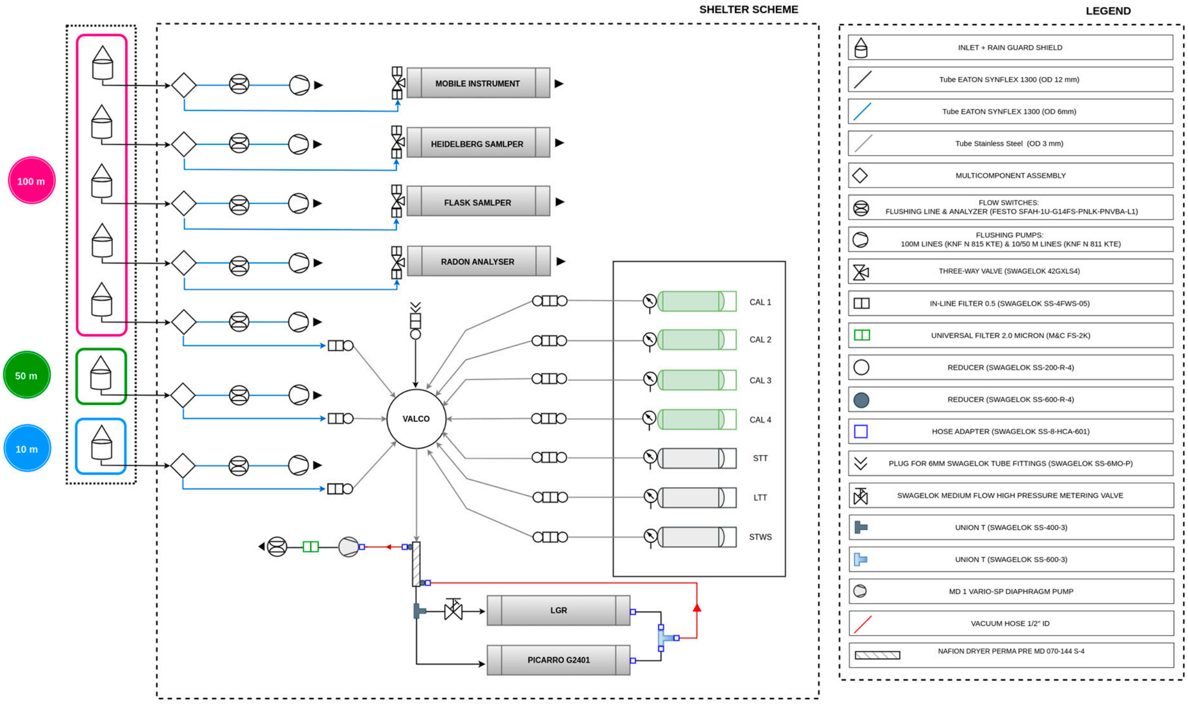

Figure 5. Overall scheme of the POT station with the main parts of multicomponent assembly (**left panel**). The legend with component symbols and model details is also reported (**right panel**).

All of the instruments/samplers listed above are fed only with the air sampled at the top level, with the exception of the continuous analysers which will collect air from 10, 50 and 100 m by means of the rotatory valve (Table 1, item 2) which selects the line of interest. Anyway, since the sampling at the top level is the one of primary interest to the ICOS network, most of the sampling time will be dedicated to the 100 m level. In view of this, the option of buffering volumes for the contextual time-integrated sampling of the air at the three levels has been discarded in favour of a simpler scheme with the lowest number of connectors and fittings possible.

Besides the seven operative lines reported in the scheme (Figure 5), three spare lines for the 100 m level and one spare line for each of the sampling levels at 10 and 50 m are also present. The inlet of the lines is schematically described in Figure 5. The conical-shaped rain guard provides protection from rain intrusion and ensures the slippage of water and/or snow; the underlying part of the inlet is further protected by a cylindrical module, inside which is located the 2-way valve (Table 1, item 3) necessary to perform the leakage test of the sampling lines, consisting of the verification of the capability of the line to maintain vacuum when the valve is closed and the downstream pump is shut off (Figure 5). The results related to the leak test of the lines show that the entire sampling system is not subject to significant leaks (see Table 2):

The tubes descend vertically along the tower parallel to each other—with an anchorage point every 10 m—until the height of 5 m, at which they start to deviate towards the shelter. The pipes approach the shelter from the tower with a gentle bending in order to prevent damage to the lines by avoiding sudden path folds. From the tower to the shelter front, a metallic structure sustains the lines to keep the paths fixed without the risk of wind vibrations or other unwanted movements.

The shelter is equipped with a series of linear holes by which the lines access the shelter without the need of other fittings, i.e., without cuts of the lines; this excludes unwanted possible leakages along the pipes. The holes have been sealed in order to avoid air mixing between the external environment and the shelter, which is properly conditioned and kept at a fixed and stable condition (see next section for details).

Table 2. Values of pressure obtained from sampling line leakage test.

Pressure After 24 h, Pump Off (bar)	Pressure After 20 min, Pump Off (bar)	Steady State Pressure (bar)	Sampling Line
−0.8	−0.8	−0.8	10 m
−0.8	−0.8	−0.8	50 m
−0.8	−0.8	−0.8	100 m
−0.7	−0.7	−0.8	Flask sampler
−0.8	−0.8	−0.8	Heidelberg sampler
−0.8	−0.8	−0.8	Radon analyser
−0.8	−0.8	−0.8	Mobile instrument

As shown in Figure 6, the top of the cylinder is 6 mm higher than the lower rim of the cone to prevent the possibility of rain infiltration.

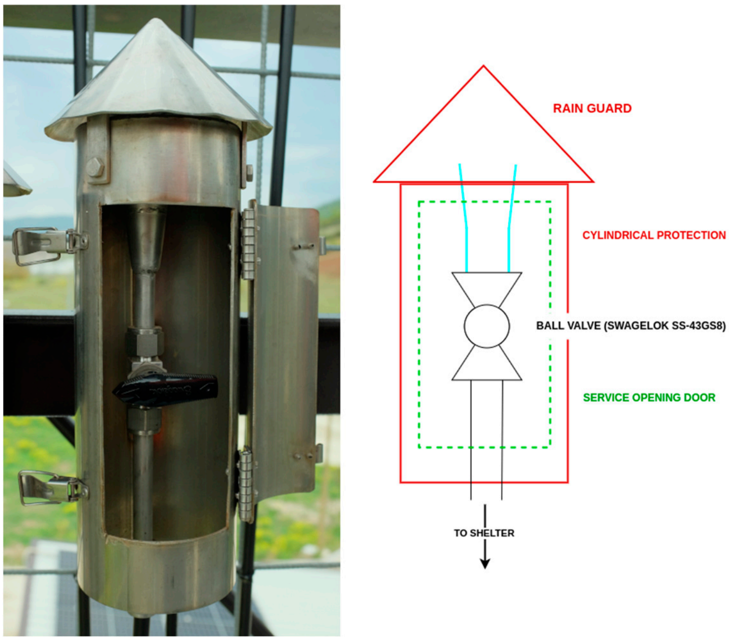

Figure 6. Sampling lines inlet (**left**) and related scheme (**right**).

The subsequent part of the scheme presented in Figure 5 (i.e., after the entrance of the pipes into the shelter) is described in the next subsection.

3.2. Setup of Components Inside the Shelter

After entering the shelter, the sampling lines go into the multicomponent assembly shown in the general scheme (Figure 5) and illustrated in detail in Figure 7. It is worth noting that no dryer (e.g., conventional fridge, Peltier cooler, heat-exchanger) has been used for the air entering the shelter since the dew point is well below the internal temperature of the shelter, which is set between 23 and 25 °C throughout the year. The internal conditions of the shelter are kept stable and fixed by two independent air conditioning systems with a power of 9000 BTU each, thus preventing thermal surges and ensuring stable global conditions of the equipment and instruments inside the laboratory.

The multicomponent node has a central role in the entire sampling system and serves different functions. In the first place, the sub-flow directed to the instrument/analyser is separated from the main flow generated by the flushing pumps (Table 1, item 4 for 100 m, and item 5 for 50/10 m) by means of a T union (Table 1, item 6). The universal filter M&C F2 (Ratingen, Germany) provides the first protection from particulates (2 mm porosity) and, at the same time, the external glass bulb allows a regular visual inspection to detect possible water intrusions (e.g., due to damage to the sampling lines); it is worth mentioning that the ICOS community is currently working on a liquid alarm sensor functioning also as flow diverter in the adverse case of water detection, which is the only way to constantly protect the downstream analysers when personnel are not present at the station. We designed our system accounting for the possible installation of liquid alarm sensors in the future as soon as the ICOS community release specific guidelines. The gauge pressure (Table 1, item 8)—installed through an analogous T union (Table 1, item 6)—allows in the first place constant monitoring of the pressure during the normal sampling of air and, in addition, assessment of the stability of vacuum during the line leakage test mentioned in the previous paragraph; during this test, the two-way valve at the end of the node (Table 1, item 9) must be closed to isolate the flushing pump and the T union for the flow split removed as shown in Figure 7 to disconnect the downstream analysers.

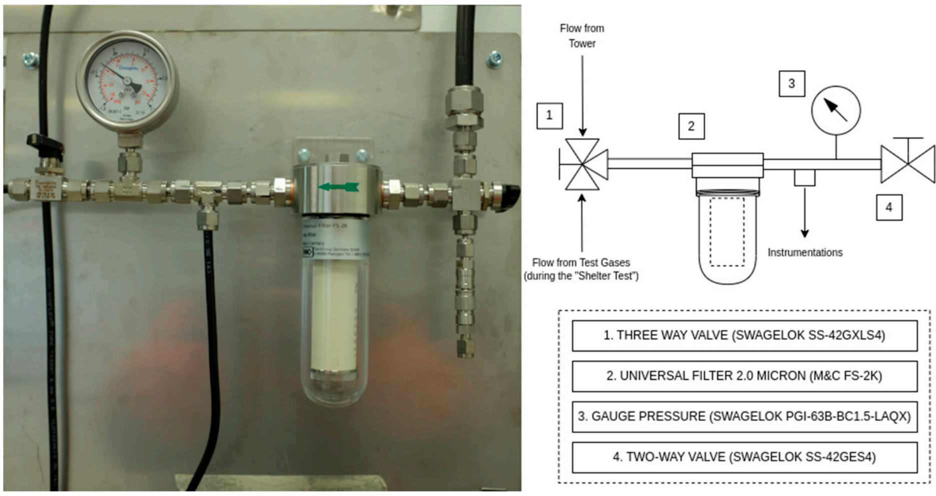

Figure 7. Multicomponent assembly (**left**) and related scheme (**right**). All the components are provided by Swagelok with the exception of the M&C FS-2K filter. The air samples coming from the inlets at different heights flow from thick black pipe (12 mm OD).

The three-way valve (Table 1, item 10) at the beginning of the multicomponent assembly is needed to perform another test, namely the "shelter test", which is aimed at detecting the leaks within the multicomponent assembly components up to the downstream inlet of the instruments. Briefly, a test gas (i.e., dry air within a cylinder) is flushed through the multicomponent assembly to the analysers by means of the quick connect stem (Table 1, item 11), with the three-way valve switched to isolate the sampling line, and the two-way valve at the end of the node closed to isolate the flushing pump.

The presence of leaks is detected via the monitoring of Picarro measurements: when blowing around all the fittings upstream of the instrument inlet, the analyser should not detect spikes or peaks, as the test gas provides a stable composition. Moreover, since the target gas is dry, if the water vapour mole fraction detected by the Picarro analyser is above 0.005% after stabilization, it may indicate the presence of a leak on the line.

The two sublines diverting from the multicomponent assembly—i.e., one to the flushing pump (Table 1, items 4–5) and one to the analyser—continue within a Synflex 1300 tube of lower diameter (i.e., OD 6 mm, Table 1, item 12) in order to match the inlets of the pumps and analysers. A flow switch (Table 1, item 13) is installed in the sublines directed to the flushing pumps for the constant monitoring of the flow rate. Regarding the sublines directed towards the instrumentation, the way down to the Flask-Sampler, the Heidelberg $^{14}CO_2$ sampler and the Radon Mapper is quite straightforward, with just an additional in-line filter of 0.5 mm (Table 1, item 14). Indeed, such instruments operate only at one height (100 m) and do not need a rotary valve to select the sampling level. In addition, both the Flask-Sampler and the Radon Mapper are equipped with their own dryer, while the need of drying does not arise for the Heidelberg $^{14}CO_2$ sampler which collects carbon dioxide as a carbonate aqueous solution.

The selected model of the in-line filter from the Swagelok (Solon, OH, USA) FW series (i.e., all-welded) has been chosen on the basis of ICOS expertise: such types ensure a lower pressure drop and a smaller surface if compared to the standard Swagelok F series.

The sublines towards the continuous analysers Picarro G2401 and LGR GLA351 are slightly more complex. In the first place, the rotary valve is needed to select the sampling height among 100, 50 and 10 m; since the inlet ports of the rotary valve require stainless steel tubing of OD 3 mm, the in-line filter of 0.5 mm (Table 1, item 14) is coupled with a reducer (Table 1, item 16) to switch from OD 6 mm (Synflex) to OD 3 mm (Table 1, item 15). It must be noticed that the pathway within the stainless steel tubing has been kept as short as possible due to higher risk of condensation with respect to the polyethylene-based Synflex tube.

Besides the sampling level selection, a VICI (Schenkon, Switzerland) Valco rotary valve is connected to the set of calibration and target gases for the correct operation of the gas analysers largely described within the latest ICOS atmosphere specifications [10].

Particular attention was reserved to disposition of calibration gas cylinders. In fact, in order to avoid potential bias induced by temperature variations, the cylinders and the relative pressure regulators have been installed within an enclosed rack which is expected to act as a temperature buffer in response to any sudden environmental change (e.g., air conditioning malfunction); moreover, in order to minimize the vertical stratification and fractionation effects, the gas cylinders have been placed in the ideal horizontal position.

The way-out stainless steel tube from the Valco valve splits into two separate sublines dedicated to the Picarro and LGR analysers through a T union, coupled with the same reducer described above to switch back to OD 6 mm (Synflex). Both the continuous analysers are configured with a Nafion Dryer (Table 1, item 17) placed in reflux mode: the external pump of the analysers is hence placed downstream at the exit of the Nafion counterflow and followed by a flow switch (Table 1, item 18) and an additional M&C FS-2K to monitor the end of the line. As described above, the Nafion operates in reflux mode, meaning that the humid ambient air flows in the Nafion tube while dry purge gas is pumped in counterflow. Since the partial pressure of water vapour in the dry gas is lower than in the ambient air, the Nafion membrane selectively transfers the water present in the sample air to the purge gas.

3.3. The Tower and Instruments Used for Meteorological Measurements

The tall tower is made of steel and is a cable-stayed type. We designed a complex structure for our tower due to the challenging characteristics of the site. Firstly, the areas of Potenza and Tito Scalo are classified as seismic Zone 1, the highest level of danger achievable within the Italian territory [35]. The second constraint arises from the nature of the soil around the station site, as preliminary studies performed in the area detected the presence of an aquifer just below the site, thus preventing the construction of deep foundations, which have been discarded in favour of a micropiles solution (see below for details). Accordingly, our station was designed with a tower-like structure accessible at each level from internal stairs by our personnel; this solution would ease the installation of new instrumentation in the future, which could be part of scientific topics far from environmental monitoring. Compared to the stations which adopt a pylon-like structure following a trellis scheme, our personnel do not require specific skills or training to perform general maintenance, being able to exploit a service elevator which allows them to reach different levels of the tower in a few minutes, easing transport and equipment handling.

The tower basement is 6.00 m × 3.00 m in size and extends up to a total height of 104 m with a stay rod system consisting of four stays reaching the ground at four separate foundations from four different levels along the tower (i.e., 23.61 m, 47.07 m, 70.53 m and 93.99 m). The stays are arranged along the bisector of the edges of the central nucleus of the tower, and small stabilizing spiral standard ropes (Ø 16) break the length of the stays to avoid resonance phenomena. The tall tower rests on an underlying reinforced concrete foundation plate, while the four levels of stays are tied to the ground by means of independent foundations, located approximately 45 m away from the tower along the corner bisector. The tall tower foundation has dimensions of 8.50 m × 5.50 m × 1.50 m (h) and is equipped with a system of 34 micropiles (tubular steel S275, Ø 88.8, thickness 10 mm, depth 15 m).

The stay foundations consist of four foundation blocks in reinforced concrete (ballasts each measuring 5 m × 5 m and 2.5 m high), located approximately 42 m away from the tower itself. These blocks are anchored to the foundation ground through a system of four geotechnical anchor rods (Ø 140, L = 20.50 m). The tower is accessible via an internal staircase up to its top and is also equipped with a service lift with stops every 10 m in height.

The tower satisfies all requirements for active and passive flight safety, as it is authorized by ENAC (*Ente Nazionale per l'Aviazione Civile*, Italian Civil Aviation Authority) and AMI (*Aeronautica Militare Italiana*, Italian Air Force) which certified the absence of any interference with regular aviation traffic. Moreover, the tower adopts a specific high-visible colouring (by design); it is also equipped with plastic marker balloons which highlight the position of metallic tie-rods and has twelve red-light beacons located at three levels, which cover an angle of 90° at each level with a nocturnal minimum cycle of 40 flashes per minute. Hence, the position and the size of the tower during night-time is made clear by beacons in any weather condition, also accounting for occasional presence of fog, or during rain or snowstorms.

According to ICOS recommendations, the tower is equipped with three meteorological stations in order to measure air temperature, pressure, and relative humidity together with wind speed and direction at high temporal resolution. Meteorological parameters are essential for characterizing local wind patterns, vertical stability, and weather conditions. These parameters are used to analyse atmospheric signals and link them to regional and large-scale processes. The ATC applies quality control by filtering raw data based on valid ranges for these five parameters. Data are marked invalid if measurements remain constant for more than X minutes in a row (X is set to 10 for wind variables and 60 for the other species), except for relative humidity [12]. At 100 m and 50 m heights, we have two Vaisala DMU801 (Vantaa, Finland) meteorological stations equipped with HMP155 temperature/humidity sensors, Baro-1 A-class pressure sensors and WMT700 wind sensors (see Table 3).

At 10 m, the measurements are carried out by a Vaisala AWS 310 station equipped with the same sensors for temperature/humidity and wind only. The wind sensors are installed on a dedicated arm 3 m away from the structure. This arm can be folded and retracted to ease visual inspection and maintenance. The position of wind sensors detached from the tower body is also necessary in order to minimize wind shadow effect induced by the tower itself, and they are located facing the prevailing wind average direction assessed from one year of measurements. These wind shadow considerations do not concern the top of the tower; in fact, the meteorological station located at 100 m follows a vertical configuration installed on a metallic pole which allowed us to place the sensor on the top of the tower, thus avoiding any induced shield effect from the tower structure. Meteorological stations are connected via the Ethernet to the tower's internal network allowing real-time data collection and continuous performance checks.

Table 3. Measurement parameters of meteorological sensors.

Resolution	Observation Range	Parameter	Sensor
1%	0–100% RH	Relative humidity (%)	HMP 155
0.1 °C	−80–+60 °C	Temperature (°C)	
0.01 hPa	500–1100 hPa	Pressure (hPa)	Baro-1 class A-
1°	0–360°	Wind direction (°N)	WMT700
0.5 m/s	0 to 75 m/s	Wind speed (m/s)	

Finally, following the prescriptions for class 1 stations, our site is also equipped with a ceilometer (Vaisala CL51—Vantaa, Finland) for the continuous determination of the Planetary Boundary Layer height (PBLH) placed at the base of the tower at a distance of about 5 m.

4. Preliminary Data

In this section, we present preliminary data for our observation site gathered by the Picarro G2401 analyser in order to perform a very first snapshot of GHG variability at the POT site. We performed a short 25-day campaign by collecting measurements with Picarro G2401 using a mobile installation at the site. The analyser was located close to the shelter basement and was used with a temporary inlet located at about 3 m from the ground. At that time, the tower and shelter were under construction, so the site was characterized with a mobile configuration by using the analyser equipped with Nafion (Table 1, item 17) and the inlet only. As described above, for our station we chose a Picarro G2401 CRDS (Cavity Ring-Down Spectrometry) analyser, an instrument widely used across the ICOS network which provides a high degrees of precision ensured by the CRD principle [36] in measuring atmospheric mole fractions in ppm (parts per million) of gases, in this case CO, CO_2 and CH_4.

Preliminary data were gathered between August 16th (08:00 UTC) and September 9th (23:59 UTC) 2022, totalling 25 days of continuous measurements. The G2401 performs a measurement every 5 s with a precision of 1 ppb (part per billion); for this analysis, data have been aggregated on a daily basis and Standard Deviations (SD) have been calculated to monitor data variability. No calibration standards were available at that time; however, all data have been quality checked for instrument errors and optimal operating conditions (cavity pressure and temperature thresholds, status alarm flags). For CO_2 and CH_4, dry mole fractions corrected for residual water vapour were selected. Following the quality check procedure, only 34 out of 592 continuous hours (5.7%) were excluded.

In Figure 8, we present the data aggregated on a daily basis with a comparison of STILT predictions for CO_2 and CH_4; we excluded CO from the analysis since we cannot perform any comparison with STILT data due to the absence of CO in the model. The shaded area shows the 1σ variability for data measurements. In general, we found a good agreement between our measurements and STILT predictions. For CO_2, the average values predicted by models and those derived from our data differ by only 20 ppm on average, while measured data show a higher variability. The behaviour of CO_2 could be linked to photosynthesis or daily changes in wind patterns, also affected by local conditions, which in the case of another observation site located in the neighbouring southern Italian region of Calabria, result in a similar daily cycle of CH_4 [37]. It is worth recalling that these measurements are collected at ground level, therefore represent the conditions of a small area; we expect that air samples collected from the tower upper levels will be representative of progressively larger areas. Wind speed and atmospheric tracers will also be used to discriminate between local and remote sources of emissions to further assess contributions to measurements at various scales.

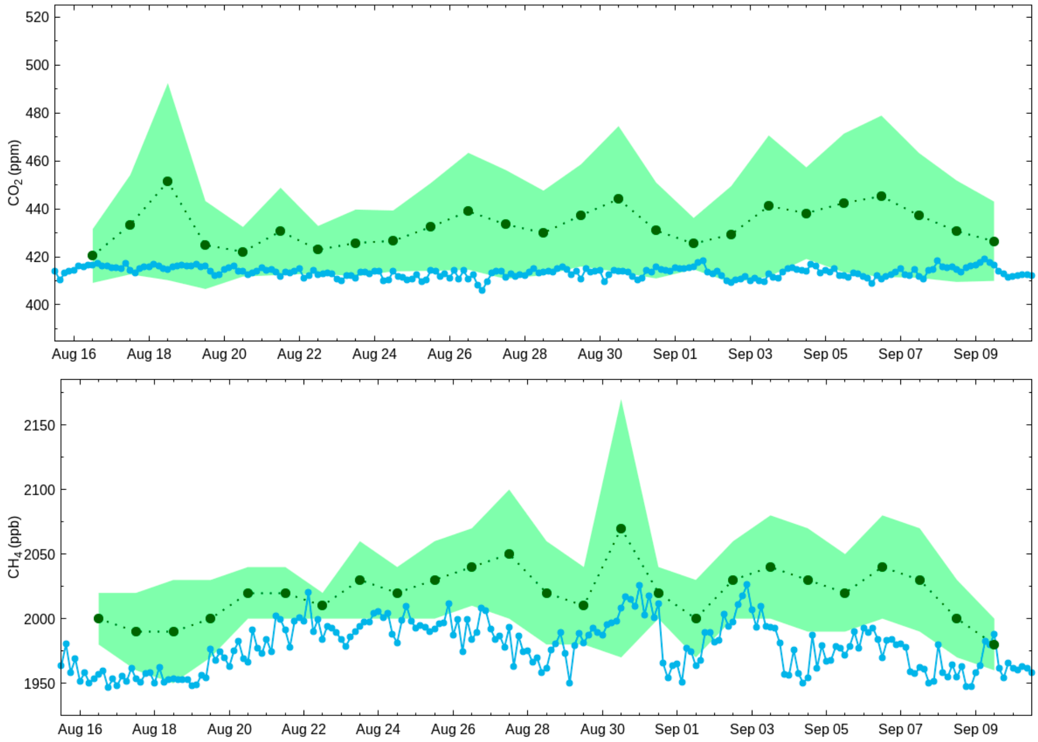

Figure 8. Comparison between CO_2 (**upper**) and CH_4 (**bottom**) measurements collected under the short campaign performed during 25 days of measurements, from 16 August to 9 September 2022, and STILT predictions. Dark green points mark the daily average value reported at 12:00 UTC, light-green shaded areas highlight 1σ variability for data averaged within each day. STILT predictions have been reported for both chemical species as light-blue lines.

A lower 1σ variability is observed for CH_4 measurements but with very good agreement with STILT predictions. Interestingly, the model was able to provide a very precise forecast for the global behaviour of methane over a period of 25 days, able to reproduce in particular the two bumps observed on August 30th and September 3rd. This is an interesting feature which can be seen also for CO_2. In any case, the duration of our campaign was so short that no other clues could be derived from measurements.

However, in the summer period, the concentrations of certain greenhouse gases in southern Italy are generally lower compared to winter concentrations, as demonstrated by findings of a WMO/GAW (World Meteorological Organization—Global Atmosphere Watch) observation site in the neighbouring region of Calabria [37–39]. Other studies highlighted that contributions derived from domestic heating and fossil fuel burning may play an important role [40]. It will therefore be important to carry on investigations in the boreal cold season when domestic heating (often relying on wooden fuels) systems are active.

These preliminary findings highlight the importance of integrating data on atmospheric mole fractions with additional tracers meant to pinpoint emission sources. In this direction, we plan to implement a Picarro G2201-i carbon isotope analyser of $\delta^{13}CO_2$ and $\delta^{13}CH_4$, which will improve source apportionment by linking peaks of either isotopologue to either natural or anthropogenic sources in conjunction with Heidelberg $^{14}CO_2$ measurements [41,42]. G2201-i analysers are already in operation at other Italian stations such as Lampedusa (LMP) and Lamezia Terme (LMT); cross-analyses of findings from these stations in conjunction with POT will provide the first assessment on carbon isotope variability in the Italian peninsula.

5. Conclusions and Perspectives

In this paper, we provided a comprehensive description of the ICOS POT atmosphere station in Potenza (Basilicata, Italy), with an unprecedented level of detail for the technical setup of the sampling system which is crucial for high-accuracy measurements of GHGs. This is expected to be useful for the ICOS community and those stations planning to join the network in the future, providing a detailed manuscript that should enlighten those interested in building up complex structures like tall towers on the necessary steps to achieve the goal.

We presented a global view of each aspect of our station, from the site chosen for the installation to several aspects concerning the structure of the tower itself, the shelter which hosts the instruments, and technical solutions adopted to realize the multicomponent assembly and related sampling system. Particular care has been paid to system design by following all prescriptions and suggestions provided by ICOS guidelines, also choosing only allowed and/or compliant materials, sensors and instrumentations.

Besides that, we reserved great attention to all phases of the construction of our station. As concerns multicomponent assembly and pipes placement, a continuous monitoring of the system is necessary to guarantee a constant high quality of the measurements. By design, our system is ready for visual inspection for each component, whether it belongs to the tower or to the shelter which hosts the laboratory equipment. This is also practically supported by two crucial tests required by ICOS for checking possible leakages within the sampling system, i.e., the so-called line test and shelter test, which we described in detail. These tests allow us to exclude the absence of any leakage in the pipes and in the multicomponent assembly, respectively. These tasks, which must be performed at least twice a year, are not trivial since they are the only way to guarantee that the analysed gases and the collected data are truly representative of GHGs sampled by the station.

The co-location at CNR-IMAA of the multi-component ACTRIS National Facility offers in addition unprecedented integration and synergistic possibilities. Indeed, CNR-IMAA hosts ACTRIS aerosol remote sensing in situ, and remote-sensing observational instruments for clouds and trace gases. As a future perspective, we are evaluating the possibility of integrating studies derived from the ICOS facility with ACTRIS in situ measurements, with the possible installation of other instruments at the POT station, namely a nephelometer, aethalometer and particle sizer; these instruments will be of the same type and models already available at the ACTRIS laboratory for proper data comparison. Among the different circumstances for potential synergistic investigation, two are reported: smoke characterization from local wildfires in summer, performed primarily using lidar and aethalometer measurements, will be complemented by CO, CO_2, and CH_4 molar fraction analysis with Picarro G2401. This will provide key information on the fire's progression, such as the CO/CO_2 ratio and modified combustion efficiency MCE [43]; also, aerosol source apportionment from residential heating (wood and fossil fuel burning) in winter using an aethalometer and OC/EC analysis will be enhanced with radiocarbon analysis of $^{14}CO_2$, performed by the Heidelberg sampler and Picarro G2201i, sampled and quantified within the ICOS research infrastructure. Future perspectives appear encouraging, with room to probe atmospheric phenomena in time and space domains (two aerosol sites 1 km apart) accounting also for the vertical dimension (three sample heights + profiling capabilities at ACTRIS). The station's characteristics may even suggest a more exciting scenario due to challenging local conditions with a mix of urban areas and natural areas with woods and grasslands apart from some industrial facilities located within a few kilometres.

In this sense, the data collected during the small campaign of about 25 days performed between August and September 2022 highlighted a good agreement non only with STILT model predictions but also for the trends observed at the Lamezia Terme station (LMT), in the neighbouring region of Calabria, another site with peculiar characteristics dominated by local conditions and global effects arising from Mediterranean basin, which itself is considered in the literature as a hotspot for climate and environmental studies. In the future, GHG mole fraction measurements will be integrated by carbon isotope analyses, thus contributing to the differentiation between anthropogenic and natural sources of CO_2 and CH_4.

For all of these reasons, the tall towers cover a particular importance within the ICOS network, since they provide an essential tool for a continuous monitoring of gases in the lowest part of the atmosphere directly connected to the ground. The possibility of having several measurements at different heights, even above 100 m as provided by other stations within the network, give us the opportunity to probe in great detail the behaviour and evolution of GHGs. In this sense, the POT station may complete the ICOS network coverage within the Southern European area, since it will be an outpost in the Mediterranean basin to characterize the effects of climate changes on a continental scale.

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