PROJECT FINAL REPORT

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1.1 Executive Summary

Greenhouse gases (GHG) are the primary drivers of climate change. Accurate quantification of their fluxes is needed to tackle the climate change challenge. The required observations include essential climate variables such as carbon dioxide (CO2) and methane (CH4) in the atmosphere as well as complementary parameters describing the biogeochemical and dynamic environment such as the atmospheric boundary layer height. High precision surface measurements act both as primary data source and metrological reference, whereas satellite observations provide a complete geographical mapping of the key variables.

The fundamental objective of ICOS-INWIRE was to enhance capabilities of the ICOS infrastructure for GHG monitoring, in order to meet the needs of operational users in Copernicus (GMES in-situ coordination (GISC D2.1) requirements, EEA, 2010). ICOS-INWIRE aimed to develop 1) standardized sensors system that can be run with excellent autonomy in challenging environments, while remaining compliant with the ICOS high-accuracy requirements, and 2) software and database tools that will integrate ICOS data with data from other in-situ GHG networks for Copernicus users.

The project has achieved the development of the ecosystem (eddy covariance) and atmospheric (concentration) Near Real Time (NRT) measurements processing and evaluation, including the development of unsupervised algorithms for uncertainty estimation and flagging. This work led to the modification of the data lifecycle and definition of the official ICOS data products. New products developed and tested in ICOS-INWIRE also include multi-platform boundary layer height retrieval algorithm and total column greenhouse gas measurements from TCCON (Total Carbon Column Observing Network) in rapid delivery (3 weeks) to meet the Copernicus requirements. A NRT (3 day delivery) TCCON product delivered by the CIOS Atmospheric Thematic Center has been developed and showcased over a short period of 1 month.

The developments for robust, enhanced GHG atmospheric and ecosystem measurements systems in extreme environments have been fully implemented and tested in liaison with instrument manufacturers. An automated flask sampler has been implemented and initial field tests have been performed.

Towards the interoperability between the European ICOS network and other GHG networks an assessment of compatibility goals has been made, a design assessment for the atmospheric network has been performed, the comparability of TCCON measurements with in-situ measurements has been assessed, protocols harmonization has been elaborated and disseminated with ICOS, NEON and AmeriFlux representatives although ICOS is more advanced level in terms of implementing harmonized protocols than these other networks. A data discovery tool has been implemented to provide access to atmospheric GHG data from different networks and its sustainability for Copernicus users is discussed in report D6.9.

All this work was done in strong liaison with key stakeholder including ECMWF, TCCON international consortium, the WMO, (and other key players of Copernicus / MACC-II/III) and several other users (modelling groups, data for decision making), as well as instrument manufacturers. Notably, WMO

CIMO is now well engaged in the process leading to implement of a new WMO standard for eddy covariance in flux measurements.

These developments were successfully completed and demonstrated, and they directly benefit to Copernicus, ICOS and the wider community. ICOS-INWIRE enabled and extended the robust, enhanced provision of GHG data by merging new, in-situ GHG observations (ICOS) and surface remote sensing (TCCON) to validate satellite retrievals and data assimilation results within Copernicus.

1.2 Summary description of project context and objectives

Greenhouse gases (GHG) are the primary drivers of climate change. Accurate quantification of their fluxes is needed to tackle the climate change challenge. The required observations include essential climate variables such as carbon dioxide (CO2) and methane (CH4) in the atmosphere as well as complementary parameters describing the biogeochemical and dynamic environment.
Measurements started in the 1950's in Mauna Loa, Hawaii; now large surface networks and space-borne missions document the global GHG distribution. High precision surface measurements act both as primary data source and metrological reference, whereas satellite observations provide a complete geographical mapping of the key variables.
There has been remarkable progress over the past fifteen years in the development of in-situ GHG measurement techniques, modeling approaches and the creation of a global terrestrial and atmospheric GHG Observing System (GEO Carbon Strategy, 2010). Local ecosystem flux measurements recorded continuously by flux towers (Valentini et al., 2000), combined with concentration measurements made at atmospheric stations are now used to derive estimates of GHG fluxes over large regions of the globe (Janssens et al. 2003, Beer et al. 2010, Xiao et al. 2008, 2011, Chevallier et al. 2010). Global mapping of greenhouse gas fluxes delivers a major improvement in understanding how the biogeochemical cycles of greenhouse gases regulate the climate of the Earth. Importantly, this provides the scientific basis for the crucial development of emission reduction policies.
The GMES Atmosphere Core Service (Implementation Group) has identified as its two priorities the consolidation of in-situ GHG atmospheric monitoring through the Atmospheric component of the ICOS infrastructure in Europe and the harmonization of multiple-source datasets (GACS, 2009; GISC, 2011). In-situ GHG data are identified as critical information to "enable monitoring of long term trends" and to "ensure validation of global satellite retrievals".
The working paper on the GMES Global Land Monitoring Core Services (Dolman et al., 2010) identified among key Thematic Services "land data assimilation systems for the carbon and water cycles", and recognized the necessity to validate global data assimilation products using in situ networks such as FLUXNET, CARBOEUROPE, now integrated at the European level into the Ecosystem component of the ICOS Infrastructure (www.icos-infrastructure.eu).

ICOS is a large scale European infrastructure selected by the European Strategic Forum on Research Infrastructures (ESFRI) roadmap recently set up as a European organization (ERIC). ICOS consists of a network of GHG monitoring stations covering the European continent. The stations are equipped with sensor systems to measure online ecosystem fluxes (and air-sea fluxes) at local scale, or atmospheric GHG concentration and boundary layer height (using lidars) to verify GHG budgets over larger regions. The network of stations is complemented and supported for data processing and sensors system testing by Thematic Centres, for Atmospheric and Ecosystem data, respectively. The sensors systems that equip each ICOS station (intake line, calibration standards, instruments, and data transmission hub) required to be standardized, with all the stations sharing the same instruments and protocols. The data processing from raw measurements to elaborated GHG concentration or flux products is standardized at the Atmospheric and the Ecosystem Thematic Centre of the infrastructure. Prototype data processing chains at the Atmospheric and Ecosystem Thematic Centres where significantly enhanced in ICOS-INWIRE. A Central Analytical Laboratory (Germany) will provide flask air samples analysis for carbon cycle tracers. The preparatory phase of ICOS infrastructure setting up the concept was finished in 2013, and the ICOS networks will be formally operational in 2016. ICOS-INWIRE acted like a bridge for continued technical research and development over this period.

The strategic goal of ICOS-INWIRE was to enable and extend the provision of GHG data from relevant monitoring networks as identified in the GISC (2011) report to the GMES Atmosphere and Land Core Services. This includes enabling harmonized in-situ GHG measurements from multiple networks, including from stations in poorly covered regions, and from ground-based remote sensing stations of the Total Column Carbon Observing Network (TCCON). The concept was to enhance the capabilities of the ICOS Research Infrastructure jointly with the TCCON network, by developing new software and database tools, and autonomous GHG stations with intelligent sensor systems capable to collect and transmit continuous data from challenging environments to identified users, i.e. operational centers and data assimilation systems (e.g. ECMWF).
The convergence between in-situ and space GHG observations has to be demonstrated in ICOS-INWIRE through 1) combining ground-based remote sensing (TCCON) and surface in-situ measurements (ICOS) available to calibration and validation needs and 2) providing these data to the ECMWF assimilation system, that merges the in situ, total column and satellite data-streams in its forecast services.

The fundamental objective of the ICOS-INWIRE project was to enhance capabilities of the ICOS infrastructure for GHG monitoring, in order to meet the needs of operational users in the GMES Atmosphere and Land Core Service Elements. It achieved this by:

1. Developing and testing autonomous stations equipped with greenhouse gas concentration (WP2) and fluxes (WP3) sensor systems able to operate autonomously in remote areas and in technically challenging environments.
2. Enhancing the capabilities of the ICOS atmospheric and ecosystem networks through the ICOS Thematic Centers for producing new timely delivery and near real time data products as well as of GHG surface (ICOS) and total column (TCCON) concentration, boundary layer height from lidar (WP3), and eddy-covariance GHG fluxes (WP 5)
3. Developing integrated data-products combining ground-based upward looking remote sensing and surface in-situ measurements to validate satellite retrievals (WP 5 and WP6)
4. Improving inter-operability between ICOS and other in-situ GHG monitoring networks, through the development of innovative software and database tools (WP6) that will deliver data to the GMES Core services

The European contribution to global GHG in-situ monitoring

The construction of a global coordinated GHG Observing System is a priority of the Group on Earth Observation (GEO), and a 5-year implementation strategy has been drawn up (GEO-Community of Practice, 2010). The in-situ component is coordinated by the World Meteorological Organization (WMO) for atmospheric stations, and to a much lesser extent by the Global Terrestrial Observing System (GTOS) for ecosystem flux towers. The WMO has also recently launched an initiative toward an Integrated Global Greenhouse Gas Information System (https://www.wmo.int/pages/prog/arep/gaw/ghg/IG3IS-info.html). In-situ GHG monitoring is also a priority in the US, where the NEON ecosystem monitoring network is being build since 2011 on a budget of $430M (www.neoninc.org), and in China where carbon monitoring is a national science priority. The Copernicus priority for in-situ data as described by the GISC report (GISC, 2011) includes surface validated ("essential") and total column ("desirable") GHG measurements, including CO2 and CH4.

ICOS is a European contribution to global GHG Observing Systems. ICOS unites ecosystem, marine and atmospheric research communities across more than 15 countries. ICOS regroups all pre-existing GHG research networks in Europe such as CHIOTTO, CARBOEUROPE, EUROFLUX. In addition, European researchers contribute to the TCCON international network (www.tccon.caltech.edu) which provides an emergent but already crucial validation resource for space instruments, the Orbiting Carbon Observatory (OCO-2), IASI and GOSAT. ICOS complemented with TCCON sites, and reinforced through ICOS-INWIRE, is able to address the in situ GHG data requirements as established by the GISC report. We anticipate, on the face of the achievements in ICOS-INWIRE, that ICOS is soon able to provide routine in-situ GHG data from all globally available networks operationally to the Copernicus program.

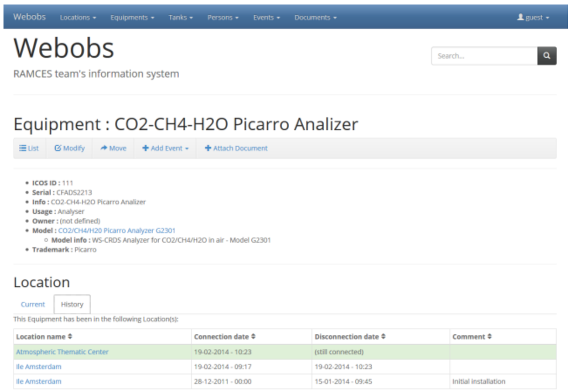
1.3 Description of main S & T results/foregrounds

1.3.1 WP2: Autonomous GHG atmospheric sensor systems

The goal of WP2 was to carry out the necessary R&D for the development of robust, low maintenance atmospheric GHG monitoring stations suitable for harsh environments, and the consolidation of the existing instrumental package at the atmospheric stations of the ICOS network, with the objective to enable a real time transmission of the data to the central database and then a seamless data provision to COPERNICUS. The work performed in this project concerns not only the high precision GHG analysers, but also the associated infrastructure needed for the data transmission, power supply, air inlet, etc….

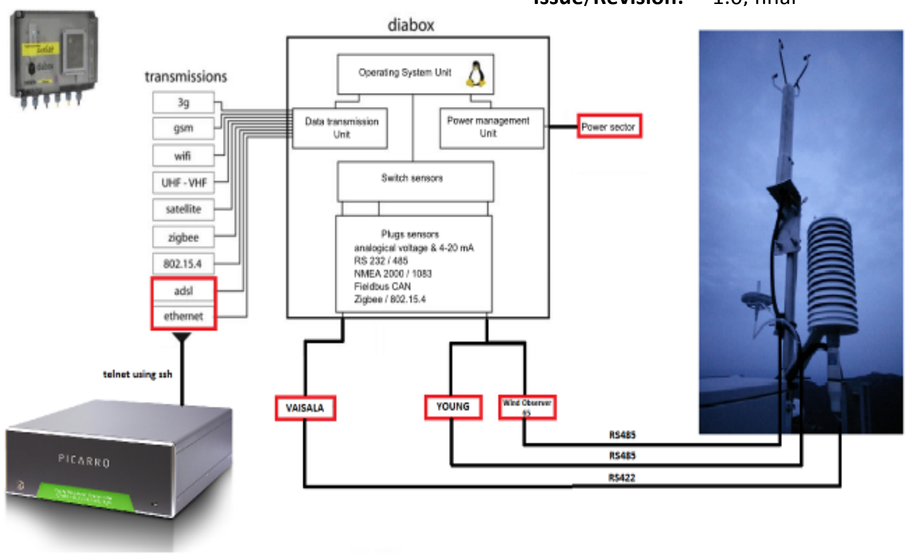
As a first step we have analysed the major troubleshooting problems encountered in GHG monitoring stations based on the experience acquired from several years at sites located in Europe, Arctic, and tropical regions. Three mains categories of problems have been identified linked with environmental conditions, human beings and instruments and sensors. As a result of the analysis of those problems, we have proposes recommendations and solutions to prevent and solve them (*D2.1*). This analysis gave the foundation for a knowledge basis about troubleshooting issues at GHG monitoring stations. In order to sustain the development of this basis we have develop a web based tool, called WEBOBS, giving the possibility to users to describe all the problems, their identified causes symptoms and solutions. Then a research by keyword enables the community to find all problems which have been already encountered for a given device (Figure 1).

Description of failure/ error message	Origin of failure Hardware / Sofware / others	Solution / Recommandation
Valve closed to protect cavity	Picarro pump Leak between pump and vacuum inlet	Pump membrane exchange Pump replacement with a new model
No data or not enough data	Laser tuning Laser failure	Retuning of the Laser1/2 Laser exchange *(> Manufacturer)*
Connectivity port	Software conflict with USB stick insertion	USB stick to be removed (drive not compatible with Picarro
Wire connection	Wire unplugged, cut	Replace wire and contacts.
Delay on data acquisition	Software problem, folder reached the limited size	Create a new folder and restart software
Analyzer not starting	Hardware disk out of order	Replacement of the hardware disk, externalization of the computer with no fans
Failure during starting mode; Analyser keeps freezing suddendly	Logic board failure	Replacement of the logic board (spare part from Picarro).



<u>Figure 1:</u> Left: Example of problems, with their causes and proposed solutions as compiled in this activity. Right: example of the information centralized in WEBOBS for one GHG analyser.

As expected, one of the issues identified in this analysis of troubleshooting is the need for a robust system to ensure real time data transmission as well as remote control of the analyzers, especially for isolated sites. A large percentage of the problems can be diagnoses or even solved thanks to the remote control. As a consequence of the deployment in the field of analyzers which are more and more reliable with limited maintenance, we can expect having less highly qualified operators. In this context it will be essential to provide a remote access to a central laboratory, and/or to the manufacturers, where more expertise will be available. In many cases the troubleshooting performed remotely by an expert could identified a simple maintenance feasible by local technicians, instead of shipping back the analyser to the manufacturer. We have collaborated with a SME in order to propose an integrated package (Figure 2) which can interact with the sensors installed at the station (GHG, meteorological, webcam, etc…) to gather and then transmit dataset using different way of transmission (RS232, RS485, Ethernet, NMEA; CAN BUS). A detailed description of this solution as well as a cost estimate is provided in the deliverable D2.2.



<u>Figure 2:</u> Diagram of the DIABOX system set-up at Ersa station for the data collection and transmission.

In addition to the in-situ measurements of greenhouse gases the ICOS Class 1 stations must also organize regular flask sampling program. The sampled flasks will serve as a quality control of the continuous measurements, and will provide measurements of additional trace gases like N2O, SF6, isotopes, etc…). As part of ICOS-INWIRE we had set-up the ambitious objective to develop a new flask sampling system that meets the high standard of the ICOS flask sampling strategy. Namely the specification of the flask sampler includes the following possibilities:

- Installation of at least 24 flasks for allowing diurnal cycle sampling
- Simultaneous sampling of at least 2 flasks for the comparison exercises with other laboratories as part of the ICOS QA strategy
- Sampling flasks via a buffer volume or in a low flow scenario that integrates air samples over ca. 1 hour to get more representative values
- Installation of flasks with different sizes in one sampler for allowing both trace gas analysis at the Central Flask Laboratory (CFL) which will be carried out with 2L flasks and 14C analysis at the Central Radiocarbon Lab (CRL) using larger 3L flasks.

A prototype has been designed and built during the project (Figure 3). The new flask sampler has the potential to set a new standard in automated sampling since the instrument provides a set of unique features, which cannot be provided by other auto sampling devices. The large set of 24 flasks that can be processed makes it possible to run the instrument 6 months without any user intervention provided that 2 flasks get filled on a bi-weekly schedule as it is foreseen for the ICOS flask sampling program. Further innovative features like purging the sampling line between sampling intervals help to ensure the ambitious aims with respect to the envisaged ICOS flask sample quality. Although the mechanical design of the instrument is finished and the manufacturing process is fully established, the work on the development of the sampler control software is not yet completed. Features for integrated sampling requiring the mass flow controller setup are still under implementation. In addition to this, experiments have indicated a malfunction in the individual control of the valve motors. This requires a partly revision of the motor control concept.

Figure 3: Left: picture of the automatic flask sampler prototype. Right: Flask overview screen of the sampler control software

During the duration of the ICOS-INWIRE project many specific tests have been performed both in laboratory and field conditions. The results of those tests have been explored by the partners of the project, as well as the scientific community thanks to presentation at international meetings, and the manufacturers of the analysers with whom collaborative efforts were established. As an example of the industry liaison developed with one manufacturer the Figure 4 shows the improvement of the CH_4 repeatability thanks to the redesigned of one electronic board used for the cell pressure regulation. The performance degradation on the CH_4 measurement of the new generation of analyzer (G2401, G2301) compared to the older generations (ESP1000, G1301) was identified by Yver Kwok et al, 2015, and the improvement implemented by Picarro was presented at the GGMT/WMO international conference (Leggett et al. 2015).

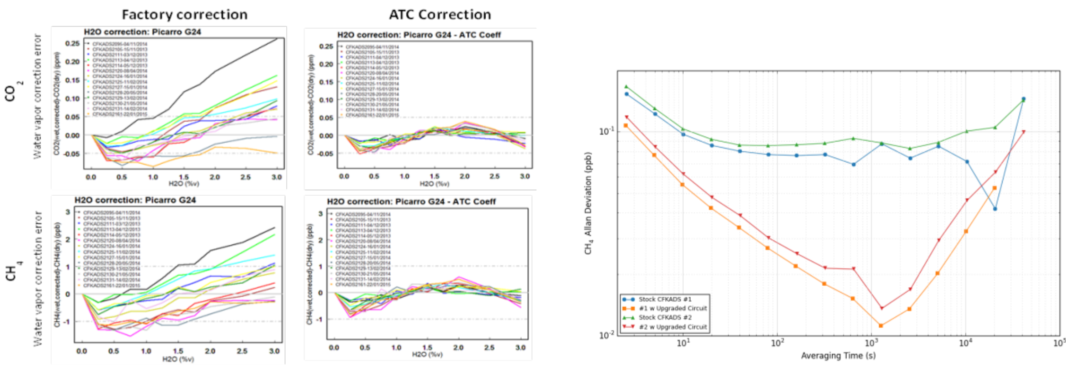


Figure 4: Left: water vapor correction bias comparison between factory (built-in) and ATC coefficients; dotted line represents half of the WMO compatibility goal [Laurent et al., 2015].Right: Picarro analyzer performance with (in red and orange) and without the hardware upgrade (in green and blue) [Leggett et al., 2015].

From the numerous tests performed in laboratory and in the field (tropical, arctic, desert environments and ship platforms) we have proposed an assessment of the sensibility of the greenhouse gases analysers to the temperature, pressure, water and dust content, icing conditions, power supply quality. According to the results, it appears that the GHG analyser selected in ICOS do not present a strong sensitivity to either the ambient temperature or pressure. Actually some analyzers were showing a strong CO sensitivity to the atmospheric pressure, but the problem was corrected by the manufacturer thanks to a hardware upgrade. Recommendations have been provided in the deliverable D2.5 to handle the dust and poor quality power supply (Figure 6). A lot of effort and tests have been dedicated to the sensitivity of CO_2/CH_4 measurements to the water vapor, which has been identified as a major potential source of bias. All the results which have been presented in ICOS and GGMT/WMO meetings and synthetized in the deliverable D2.5 will be published in 2016. The importance of the evaluation of the analyzer sensitivity to water vapor both before operations (tests performed at the ICOS ATC Metrology Lab), and regularly in the field have been demonstrated (Figure 4) and protocols have been proposed (Figure 5).

Figure 5: Protocol of the water vapor correction assessment with droplet method.

All the results and recommendations are synthetized in the deliverable D2.5 (Report on new sensor package capability in extreme environment) and in the following table (Figure 6). It is important to note that not only the results are crucial for the monitoring network, but also the rigorous approach which have been properly documented, and which will should be further pursued to guarantee the optimization of the measurement protocols in the long term.

Condition	Nature of problem	Solution	Test (field, lab)	Status
High variability and range of room temperature	Dependency of signal to the room temperature	Correction applied; coefficients to be determined	Controlled chamber	Now systematically implemented by ICOS ATC
High Humidity	GHG measurement need to be corrected from the dilution and the spectroscopic broadening effect of H2O	Either drying air or improving the determination of the H2O correction coefficients	ATC humidifying bench. Nafion dryer bias assessment test. Nafion setup with bypass system.	Now accurate H2O correction systematically determined at ATC Metrology Lab. Nafion with bypass setup successfully tested in Corsica.
Dust	Clogging of the analyser results in damage	Filter with large surface without inducing artefact on GHG measurement	GHG measurement compliancy test. Efficiency test in the field.	Now widely used in the ICOS network
Icing	Clogging the sampling lines	Insulating and/or heating the sampling lines	GHG measurement compliancy test of the insulated/heated sampling lines	Implemented in Norunda. Required further investigations for issue related to H2O
Poor quality of power supply	Risk of damage	Use of “online” UPS. UPS management System for appropriate instrument shutdown/start	Test of the UPS management system in the field in real conditions.	Successfully implemented in Corsica.

Figure 6: Summary of the issues which have been evaluated, with related solutions and/or recommendations.

1.3.2 WP3: Enhanced operational capabilities of ICOS atmospheric network

To meet the needs of the GMES Global Atmospheric Core Service/Copernicus as prepared in the frame of MACC-II and MACC-III, high data availability rate and seamless in-situ Greenhouse gas (GHG) data transmission was required. Central to WP3's objectives was the timely delivery to MACC-II/III (ECMWF and partners) of the required parameters. The timeliness objective set in WP3 was one month. Estimates of the contribution from lidar (boundary layer height) and TCCON data (total column CO_2 and CH_4) were identified as crucial.

The general goal of this work-package was to consolidate the data flow coming from the ICOS atmospheric network through the ICOS Atmospheric Thematic Center (ATC) with enhanced measurement and data transmission/exchange capabilities of in-situ stations or networks. Ground based FTS (Fourier transform spectroscopy) measurements from TCCON were integrated in that package, updated at first, at a monthly frequency. The contribution of lidar and ceilometer was demonstrated to diagnose boundary layer height, a critical variable that defines the dilution of CO_2 and CH4 surface sources and sinks in the atmosphere. A data stream was implemented to provide an integrated data package with 1) Near Real Time (1-day) ICOS data, 2) Rapid delivery (1-month) ICOS data and 3) Rapid Delivery (1-month) TCCON data to the GMES MACC-II and other operational users. This was possible with the development of new capabilities for operational data processing enhancing the capabilities of the ATC, and a different approach to data processing within existing networks and communities.

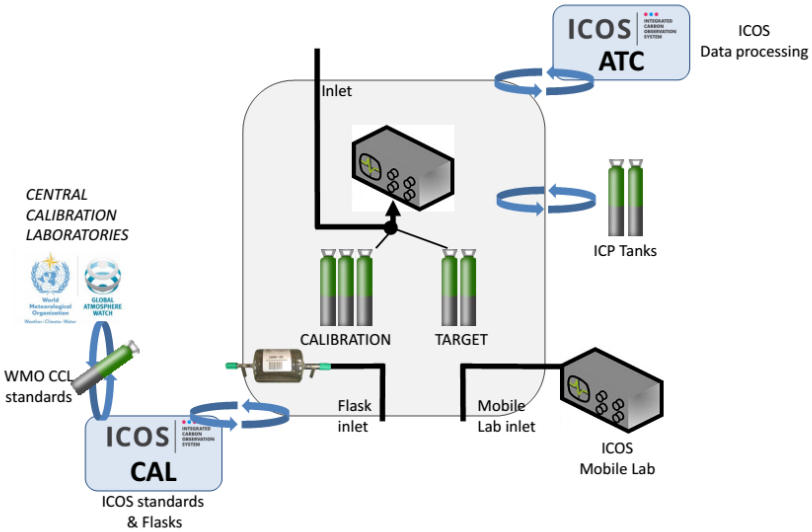


Figure 7 - schematic view of measurement protocol at ICOS stations.

As first step GHG concentration data processing was improved. In order to implement an automatic data filtering of GHG measurements in near real-time, possible parameters that can be used in non-human supervised data screening were identified, and data pre-processing with some automatic flags was applied, relaying on automatic thresholding during a pre-processing phase. In particular, a so-called "questionable data" flag (set on qualify in-situ data by PIs) has been added in data workflow. To facilitate PI's work at qualifying data, an automatic mail service on data processing when errors occur has been implemented. It allows alerting PIs when suspicious measurement are acquired at station and detected in the pre-processing phase of data.

In a concern for transparency and measurement traceability, full automatic processing of atmospheric CO_2 and CH_4 mole fractions at the ICOS Atmospheric Thematic Center has been documented (see ***Figure 7***) and is currently being reviewed for scientific publication [Hazan et al., 2016].

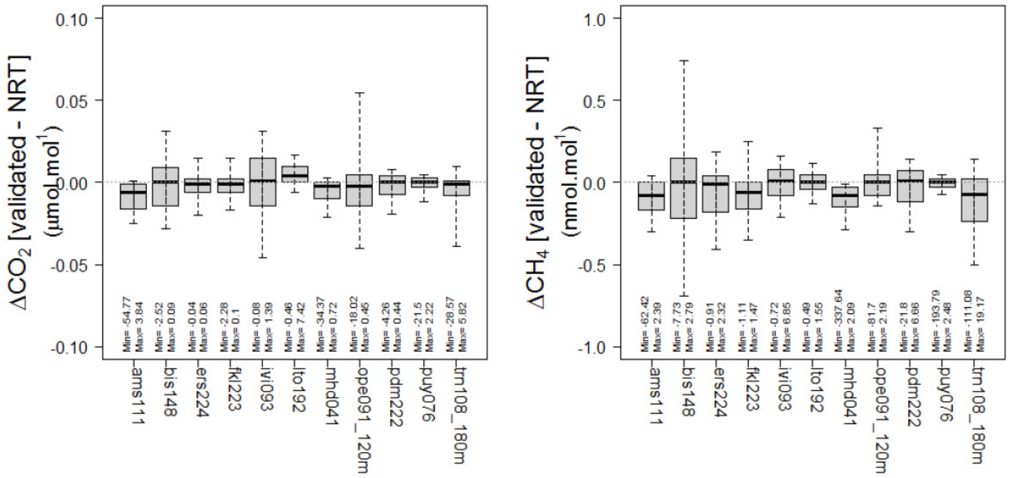


Figure 8 – Box-and-whisker plots of the validated minus near-real time differences of hourly means CO2 (left) and CH4 (right) mole fractions for 2014.

This paper describes the computing facility dedicated to the ICOS-ATC at LSCE, the different steps of the processing of CO_2 and CH_4 mole fractions including the automatic quality control of the raw data and the corrections due to water vapour interference and calibration in WMO reference scale. Most of the processing protocols and parameters are illustrated with few examples of instrument currently providing raw data to the ICOS-ATC as part of the ICOS extended Demo Experiment. In particular, the difference between validated and near real-time measurement of CO_2 and CH_4 was assessed (***Figure 8***). For the study of estimation of repeatability's based on target gas measurements, the calculation in near real time of the continuous monitoring repeatability (CMR) and the long term repeatability (LTR) have been implemented in the ICOS data processing and representativeness error assessment through hourly means has been calculated from discontinuous measurements

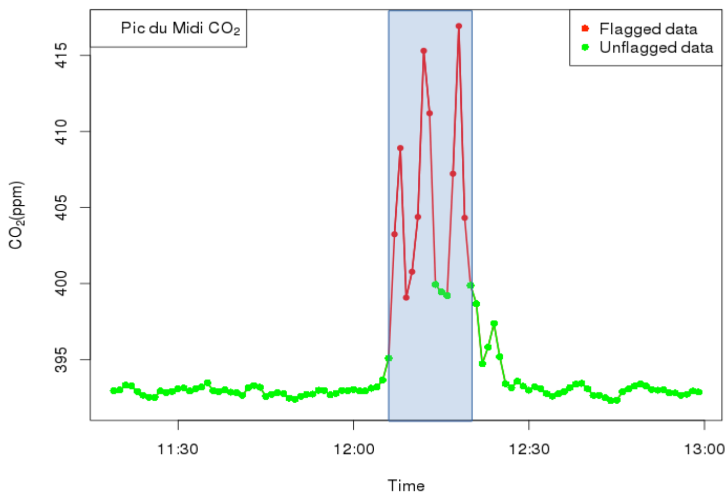


Figure 9 - Example of flagged and un-flagged data at Pic du Midi using the spike detection algorithm.

Last part of data processing improvement task 3.1 in this work package was to implement a method to identify the periods when measurements are strongly influenced by local emissions, typically within 1 or 2 km around the station. Such influence of local sources is characterized by short-term variations, which it was proposed to detect using spike detection algorithm. Two peak selection methods, namely the coefficient of variation method and the standard deviation method (Brantley et al., 2014) used to evaluate in situ emissions, local air quality trends, and air pollutant exposure were tested. The proposed algorithm detects CO_2 and CH_4 peaks, which are randomly emitted from unidentified sources (see ***Figure 9*** for CO_2).

One central task of work package 3 was also to have a better estimate of planetary boundary layer height (PBL), or better: mixing height (MH), which is a key parameter to link ground-based in-situ measurements of atmospheric trace gases to transport model results or total-column measurements. Because mixing height can usually not be measured directly, the goal of Task 3.2 was to develop an algorithm that could be used to derive MH from optical backscatter profiles of lidar systems as well as the less powerful but more cost-efficient ceilometers.

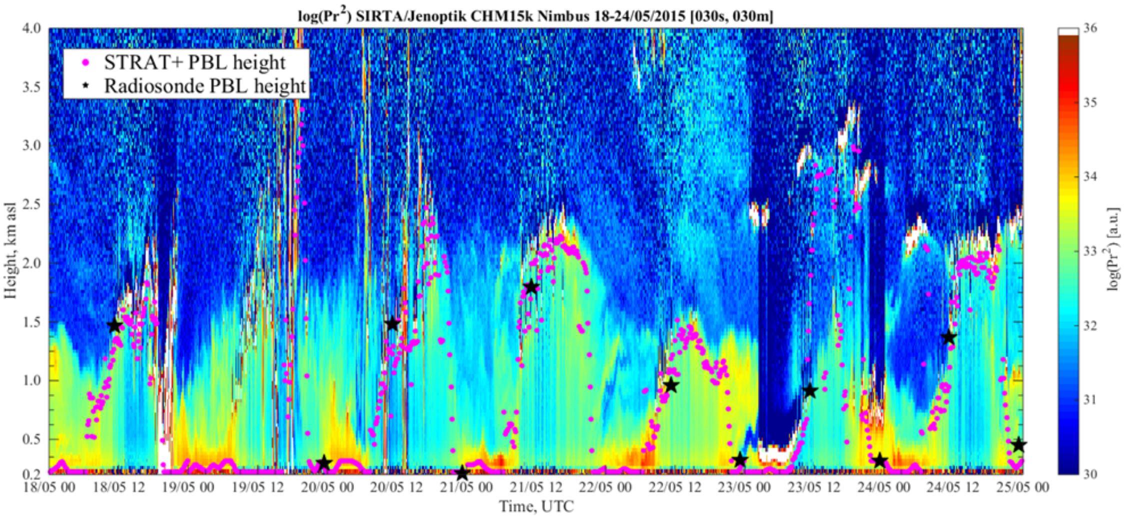


Figure 10 – Planetary Boundary Layer height retrieved from a Jenoptik Ceilometer (cyan points) and compared to those estimated from a near radiosonde (black stars) at SIRTA Observatory, Palaiseau, France during one week of May 2015.

Two atmospheric boundary layer retrieval algorithms were selected (resp. PyBL & STRAT), and the choice was made to have them improved by their developers (resp. MPG & LMD) to meet the specific needs of ICOS-INWIRE in terms of BLH restitution and implementation on site in the ICOS. It results in two tuned versions (PyBL_ICOS & STRAT+) of original algorithms which were compared over a common dataset of measurement, thanks to standard data format for backscatter signals from lidar/ceilometers also developed in this work package (see ***Figure 10***). In order to assess algorithm and instrumental precision and variation, a set of 12 co-located ceilometers (six different types) and a lidar system were compared by applying STRAT+ on measurements (see ***Figure 11***). The results shows that the detected-to-potential BLH percentage for all systems is between 91% and 97% of the potential 10-min BLH during the whole period of comparison (i.e. 2 months). Regarding the instrument variability, all model of ceilometer show similar behaviour since the percentage of BLH deviation lower than 250 m (P<250) among the co-located ceilometers during the comparison was better that 80%. Comparison with collocated radiosondes showed $P<250m$ during night time is larger than 80% for all ceilometers. For daytime $P<250m$ drops to 25%-45% due to low signal to noise ratios.

Since optical systems are not necessarily be exactly collocated with atmospheric stations in the ICOS network, spatial and temporal interpolations of mixing heights were investigated. Nevertheless obtained results concerning interpolation of BLH value were still not mature enough to be used and more studies should be performed in order to combine radiosonde profiles, optical measurements and model data.

Both tuned algorithms are available for potential users and ICOS community upon request.

#	Instrument type	Instrument name	STRAT+ detected-to-potential BLH percentage (%)
1	CHM 15k Nimbus	CHM100110	97
2		CHM140101	96
3	CHX 15k Nimbus	CHX080082	96
4		CHXLMU	93
5	CL31	CL31RUB	91
6		CL31RAO	94
7	CL51	CL51RAO	96
8		CL51CG	94
9	CS135	CS1	94
10		CS2	92
11	LD40	LD40_002	94
12		LD40_003	95
13	PollyXT	RALPH	92

Figure 11 - List of 12 ceilometers and lidar systems participating in CEILINEX2015 at Lindenberg (Germany), on which BLH retrieval algorithm was applied and detection score as seen as STRAT+ detected-to-potential BLH percentage in %.

Along with lidar/ceilometers BLH products to complete data offering for Copernicus, one aspect of data provision in ICOS-INWIRE was to improve data workflow for TCCON stations, in order to fulfil GISC requirements in term of delay (i.e. 1 month). Within TCCON the routine processing of data is done in batches on a 6 months basis and most of the TCCON-data it is freely accessible only one year after the measurement. Within ICOS-INWIRE, data from four TCCON sites, including Ny Alesund (Spitsbergen), Trainou (France), Bialystok (Poland) and Réunion (France), are now processed and provided through the ICOS-ATC data server as Rapid Delivery TCCON products. For these sites the processing and data transfer has been automated and data is now available at least one month after the measurement, and most of the time the week after (see ***Figure 12***).

TCCON station	Acronym	Country	Data availability	#files	Upload frequency to server
Trainou	TRN	France	2014/02/04 →2015/11/23	252	~3days
La Réunion	RUN	France	2014/11/07 →2015/08/31	38	~1week
Ny-Ålesund	NYA	Norway	1 file for 2015[1]	1	-
Białystok	BIK	Poland	2014/10/18 →2016/11/23	194	~3days

Figure 12 – TCCON Rapid Delivery Product availability at ICOS ATC data center and mean upload frequency from station to data center. TCCON rapid delivery data are accessible via the landing page https://icos-atc.lsce.ipsl.fr/tccon hosted on ICOS ATC website. Access is subject to authentication. Login and password can be obtained by contacting ICOS ATC.

Last task of work package 3 was to improve data, metadata format, and data stream with MACC-II/III for Copernicus. Data protocols and formats for data distribution to MACC-II were defined and 3 open-ended datasets for CO_2 and CH_4 species were made available for ECMWF users. In 2015, 7 datasets from ICOS stations are pushed to Copernicus servers, in near real-time. Note that access is also given via ICOS ATC website, using https protocol (user and login on request). In order to characterize data transmission efficiency, short term and long term data availability are taken into account as performance indicator. Short term availability is ~70% because it is subjected to the stresses of operation and transmission in near real time operation mode. Long term availability is better, as expected, since PIs can resolve measurement issues (transfer, communication, calibration etc. …), and is ~90% post data processing and QA/QC (see **Figure 13**).

#	Station	Acronym	Species	Short term availability [CO2/CH4]	Long term availability [CO2/CH4]
1	Biscarrosse	BIS	CO_2 /CH_4	0.79/0.79	0.98/0.98
2	Cabauw	CBW	CO_2 /CH_4	0.09/0.09	0.66/0.66
5	Mace Head	MHD	CO_2 / CH_4	0.86/0.87	0.94/0.94
6	OPE	OPE	CO_2/CH_4	0.67/0.67	0.85/0.85
7	Puijo	PUJ	CO_2/CH_4	0.24/0.24	0.99/0.99
9	Pic du Midi	PDM	CO_2/CH_4	0.89/0.90	0.93/0.93

Figure 13 – Short term and long term availability for data provision for Copernicus. Short term indicator is computed from measurements actually transmitted to Copernicus the day after. The long term indicator is computed from hourly measurements of air availability, transmitted every six months. It does not take into account flagging of data. Note that long term availability at OPE station (a tall tower station, with 3 measurements levels) is 85%. This is due to the fact that inlet lines have to be flushed between each level. Covered period is January 2015 – November 2015.

1.3.3 WP4: Autonomous GHG ecosystem sensor systems

The purpose of WP 4 was to further standardise the methodology of the eddy covariance (EC) technique to monitor ecosystem greenhouse gas (GHG) fluxes and its associated quality control. To warrant a full coverage of the ICOS EC network, an autonomous and heavy duty EC ecosystem flux sensors system as be designed. This system should measure with similar quality and standards as the ICOS site 1 and 2 systems, in places to harsh or remote for these more conventional EC systems. As part of this design a wireless system for auxiliary variables was developed capable of measuring from -40^{0}C to +70^{0}C. The system was tested in remote conditions. We further developed a process for an internationally agreed protocol for eddy covariance measurements for the GMES, that is part of a UN (WMO-FAO) set of standards

Robust eddy covariance design and tests

One of the design choices was the use of of-the-shelf technology so third parties can readily implement the systems designs. This design choice had to be waivered for the wireless sensor communication as the state of currently commercially available radio motes is not sufficient for scientific use under extreme environments.

Thus wireless motes have been designed anew that can function under extreme conditions (-40^{o}C to +70^{o}C), are accurate enough for scientific data collection and are easy to use in the field. A user manual is available for potential users within ICOS.

All design choices and the systems characteristics can be found in deliverable 4.1 a Report on initial 'heavy-duty' EC flux sensors system design.

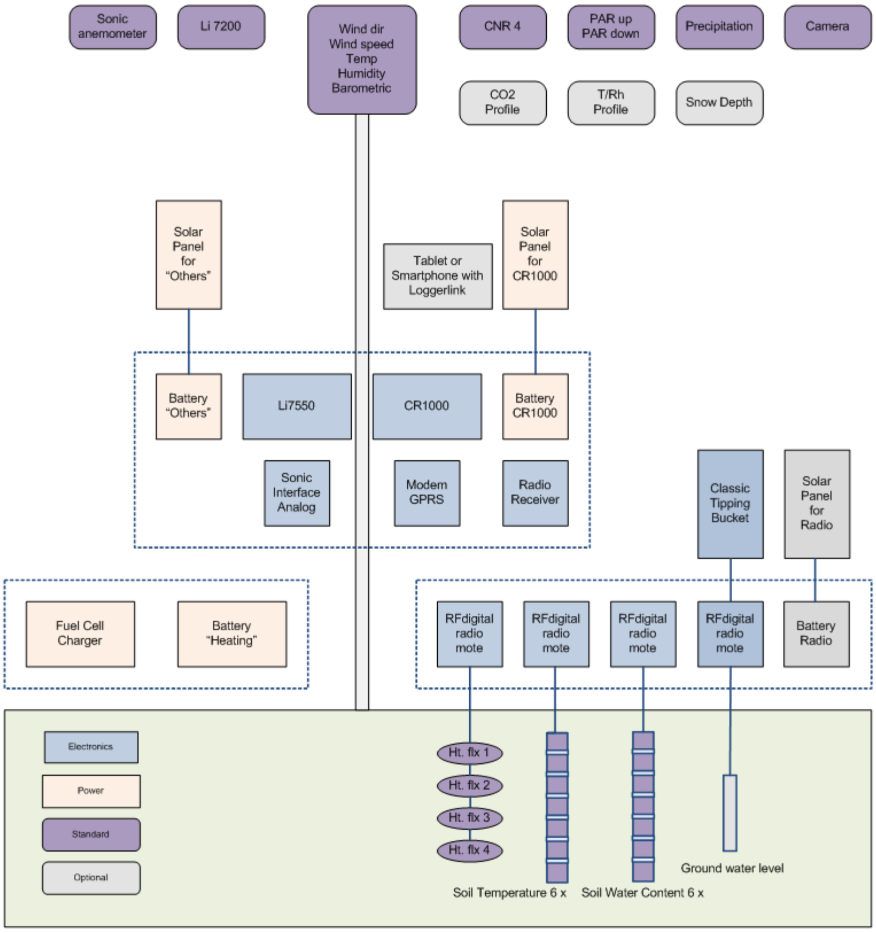


Fig 8. Design diagram for the robust eddy covariance system. The system block at the lower right corner is the wireless system soil moisture, temperature, and rainfall.

The system was built at successfully tested at 4 locations, from Spain to Northern Sweden. Some minor design details were corrected during this test, but overall the test proved satisfactory. In remote cold conditions we successfully tested a camera design that uploaded 10 times a day to check whether it was frozen. Through a remote telephone connection we were then able to defrost it.

Fig 9 Sonic anemometer above Swedish forest before and after defrosting.

An autonomous power supply developed by In Situ Instrument AB was installed in mid October 2025 at an eddy covariance flux site in northern Sweden in mid-October. The system is monitored continuously and it is working as planned. This opens up the possibility of using the eddy covariance system with the power system for remote conditions, with very low maintenance.

standardization of future measurements

We were invited at a CIMO (WMO Commission on Meteorological Observations) New Technology Workshop from 10-13 September 2014 in Geneva to present the ecological observatory/eddy covariance. Development of an EC standard was considered high utility and would be useful, and CIMO is the appropriate entity to manage the standard once it has been drafted by a group of experts drawn from the global EC community. The representatives met during AGU in San Francisco in December 2014 and agreed to proceed and tasked VUA to prepare an initial draft of the standard. This was scheduled to be ready by the end of July 2015, with assistance of NEON management. This draft standard, largely based on existing ICOS and NEON protocols is available and is currently under review by NEON. After that is will be made available to all FLUXNET organizations and open for review. After that a version will be submitted to CIMO for approval.

1.3.4 WP5: Enhanced operational capabilities of ICOS eddy covariance network

The ICOS Ecosystem Network monitors and measures a large number of parameters using standardized methods and approaches. The goal is clearly to serve the largest possible number of users with high quality data that can be used and integrated in particular in modelling activities. In this context the ICOS-Inwire activities in WP5 have been focussed on the data quality improvement and identification of the products characteristics requested in order to facilitate access and use to new potential users. The tasks performed covered some of the most critical aspects in the data dissemination and use, such:

1) The identification of the key ecosystem variables needed in model data assimilation and remote sensing data validation, their characteristics and frequency;
2) The test of the Near Real Time fluxes measurement processing and uncertainty estimation in order to evaluate their quality and potential use in modelling activities;
3) The verification of the compliance of the ICOS ETC metadata structure with the GEOSS requirements in order to increase the visibility of the ICOS data;
4) The development and definition of new metrics to evaluate the assimilation of the key ecosystem variables in land surface models, in order to suggest new approaches in the mode-data integration.

Characteristics of the variables needed in model-data assimilation

Which are the characteristics that modelers and remote sensing community want in the ecosystem measurements? This key question is crucial for a correct development of the ecosystem component in ICOS and the activities performed in Task 5.1 have been focused on finding the best possible answers. The first step has been the an expert meeting organized in Amsterdam by VUA in May 2013 where ECMWF modellers (Gianpaolo Balsamo and Anton Beljaars) participated as key Copernicus users together to ICOS and ICONS-Inwire people. The summary of the meeting results has been reported in Milestone MS16. the variables and sites characteristics needed to perform a model data assimilation exercise were identified, including their format and characteristics (quality filtering, uncertainty). One of the main outcome has been the definition of two different main type of activities based on ecosystem data:

- Retrospective data analysis
- Near Real Time (NRT) data ingestion

The difference between the two approaches is in the time frame and length of the data records used: in the first case the data have been acquired by sites in the past years while in the NRT data ingestion the measurements used in the modelling activity are acquired and made available almost in real time and for the previous 5 to 10 days.

In both the activities the same variables are requested and used (carbon, water and energy fluxes, net radiation and soil water content), although the quality of the NRT data is lower due to a number of corrections and filtering activities that are possible only when a long-time series is acquired and processed. It has been also clarified that what is more important is the clear indication of quality, uncertainty and measured versus gapfilled data and the use of a standard format stable in time.

Starting from these requirements on the variables it was suggested to identify datasets where the model-data fusion could be based on ecosystem and atmospheric measurements at the same time.

In addition also the climate regions where data are less available for model validation have been identified with the aim to analyze the availability of data collected in these regions (tropical, sub-tropical, artic).

These specific requirements (located in key areas, close to atmospheric measurement towers, collection of the requested variables, easy and open sharing of the data) have been used to search for possible study cases that respected all the characteristics requested. These areas have been identified and reported in Deliverable D.5.1

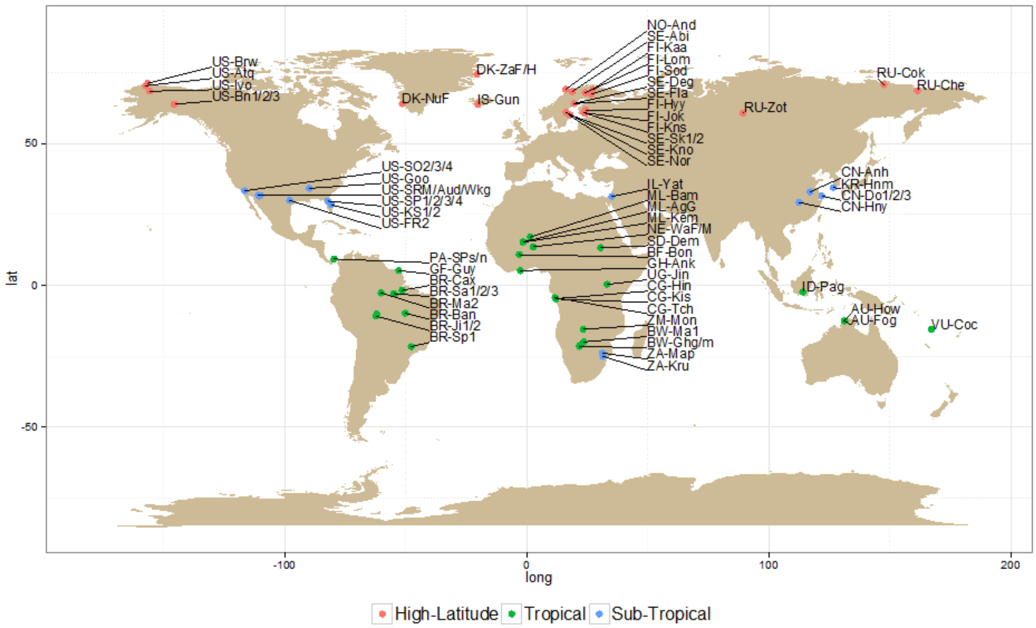


Fig 10: identification of the sites in the key climatic regions that matches the requirements in terms of key variables availability.

The main result obtained has been the identification of the needs from potential users of the ICOS infrastructure that can be used by ICOS in the design of the products and variables measured.

Near Real Time ecosystem data processing

Near Real Time data (NRT) can be defined as data that are received, processed and made available to the users in a short time, generally less than one day. The need of a fast processing based on short datasets can affect the quality of the results and for this reason NRT data have been in general considered “low quality” information available only for dissemination and general control of the measurements.

Also thanks to Task5.1 results it has been confirmed that however these data have potential scientific users interested to improve model data fusion (MDF) and in particular land surface model (LSM) to better understand the complex dynamic of terrestrial biosphere exchanges of matter and energy. This however requires an improvement of the data quality and the development of an uncertainty estimation that has been the core activity of Task 5.2.

The NRT processing was developed following the most recent recommendations on fluxes calculation (Foken et al, 2012), and the results obtained from previous researches (see Richardson et al, 2012 and reference therein). QA/QC procedures and uncertainty estimation are based on several processing option schemes, with the aim to provide information about both random (stochastic) and systematic (processing options) errors (Fig 11).

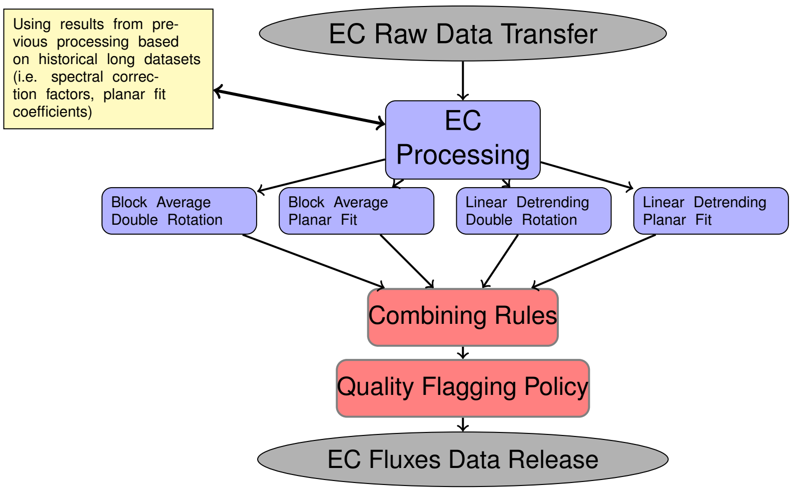


Fig 11: scheme of the steps involved in the NRT new processing and options selected for the uncertainty estimation

The methodology developed (fully described in Deliverable D5.2) has been implemented on the ICOS ETC portal (www.icos-etc.eu/icos/nrt-data) and applied in the last two years of the project to five candidate ICOS Ecosystem sites:

- BE-Lcr, Lochristi, Belgium; IGBP: DBF
- FI-Hyy, Hyytiala, Finland; IGBP: ENF
- FR-Fon, France, Fontainebleau, IGBP: DBF
- IT-SR2. San Rossore, Italy, IGBP: ENF
- SE-Nor. Norunda, Sweden, IGBP: ENF

The results obtained have been of crucial importance and impact in ICOS. NRT data from ecosystem sites were originally considered as temporary, low quality data but thanks to the new processing strategy they are now included in the official list of ICOS products and considered high quality data suitable for research activities.

As side result, the activity helped also to better understand and define the importance of the choice of a single standard data format. In the ICOS-Inwire context there was no standard and the conversion to a common format was performed by the data centre. This approach resulted to be too complex and more important not enough robust and following these results ICOS decided to standardize the raw data format.

This activity has been one of the most successful on the deliverable and of the project and in Fig. 12 are summarized the main conclusions.

Strenghts	**Weaknesses**
- Real time monitoring - Uncertainty quantification and separation - Multiple processing	- Computational efforts - Need of standardization in raw data format
Opportunities	**Threaths**
- Increase the number of sites and gases - Optimize the selection of the processing options	- Data quality remain lower respect to the processing of long time series and this needs to be documented

Fig. 12 main lessons learned with the NRT data processing development in ICOS Inwire

Compliance with GEOSS

The main characteristics of the data (in terms of variables but also format) were discussed in the meeting with the modelers (Milestone M16) and the analysis of requirements did not evidence particular issues. The characteristics requested are in general already available in the data provided by ICOS and include and easy identification of measured and gapfilled data, a full metadata set to interpret the data, a number of ancillary information (LAI, biomass, chambers etc.) that although not used in the first phase will be useful in a second stage and to have both a long-term and a NRT data product.

To increase the visibility of the ICOS data, although the activity is covered by the Carbon Portal, it has been discussed and tested a method to include the ICOS Near Real Time data in the GENESI portal in order to test the information flow and communication format. The work has been done following a scheme suggested by the GENESI experts through simple XML files that in future can be further developed to include more information. This experience has been presented and discussed with the ICOS Carbon Portal that is in charge of this activity and is developing the strategy considering also the experience from ICOS-Inwire.

A similar system, based on xml files, has been also set up to link the ICOS Ecosystem database with the FLUXNET network, a global database of metadata on ecosystem eddy covariance sites. The xml is automatically generated at the address http://gaia.agraria.unitus.it/siteslist2.aspx and it is imported in the FLUXNET database available here: http://fluxnet.ornl.gov/

New model validation parameters

The last activity in the WP has been focused on the definition of new metrics to evaluate model data integration. In fact, the best use of the data is reached not only when they become available with the highest possible quality but also where they are used in the best possible way. In this context a number of possible alternative evaluations of them model results against measurements have been created and tested using existing models runs. The group of metrics applied (described in Deliverable D5.4) are:

Descriptive statistics: after a visual inspection of the data, calculation of basic descriptive statistics to summarize the data should give the researcher insight into their data. Simple descriptive statistics include the Mean, Media and Mode. The Mode should be calculated as the value where the probability density function reaches its peak and not as the most frequent numberdue to the random component in data and model outputs. When computing statistics for model outputs whenever possible biomes should be analysed separately due to their large heterogeneity.

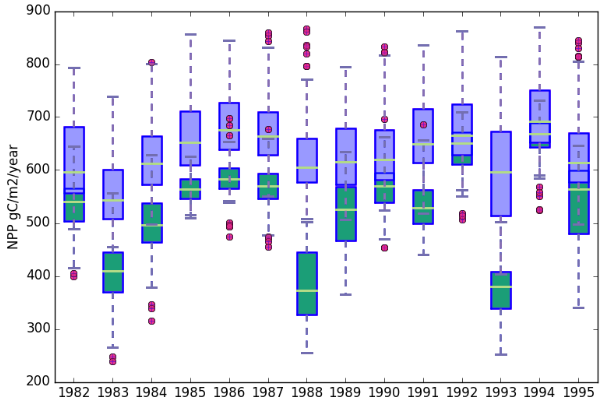


Fig. 13: example of descriptive statistical analysis where distribution, median and percentiles are compared between a model (purple) and direct measurements (green)

Regression analysis: also regression analysis between variables is another important step, easy to follow because implemented in all the software for data analysis. It includes for example the R2 and the Root Mean Square Error (RMSE) that give info on the spread of the model versus measurement data. The regression analysis however should not be considered as only applicable to the final model output; there are cases where partial output of a model can be verified against data and in this case this should be done. For example, a model predicting forest biomass starting from a simulation of the tree number, diameters and height could be possible validated not only on the final result but also on the intermediate products (diameter, tree number and tree height) at the basis of the calculation (and often more easily available as direct measurements and with lower uncertainty)

Seasonality and trend: simulating correctly the annual budget doesn't mean that the model is correct. It is always possible to get the right answer for the wrong reason and this is why it is important to validate also the model temporal variability at different frequencies. A simple method could be looking at maxima of a variable that is sensitive to seasonal variation and analyzing the timing of this maxima between model and observation. However, other methods are today available to better analyze the model behavior in time, like the decomposition of the timeseries. The principle behind the decomposition of a time series is that a time series consists of 3 elements: a trend, seasonality and random variance. Taking atmospheric CO2 concentrations as an example, the yearly increase in CO2 concentration as a result of anthropogenic carbon emissions is a long term positive trend. The yearly carbon fluctuations as a result of the growth season and winter are a season cycle.

Al the other leftover variation is quantified as random variation. Seasonal cycles can be extracted by for example a Fourier transformation followed by as smoothing of the data after which the transformation is reconstructed without the smoothed seasonal cycle. A next step will then be a regression to extract the trend from the data. Subtracting this extracted trend will leave the random variation. The different components from model and data can be then directly compared in order to check if the match between the two is conserved at all the time scales.

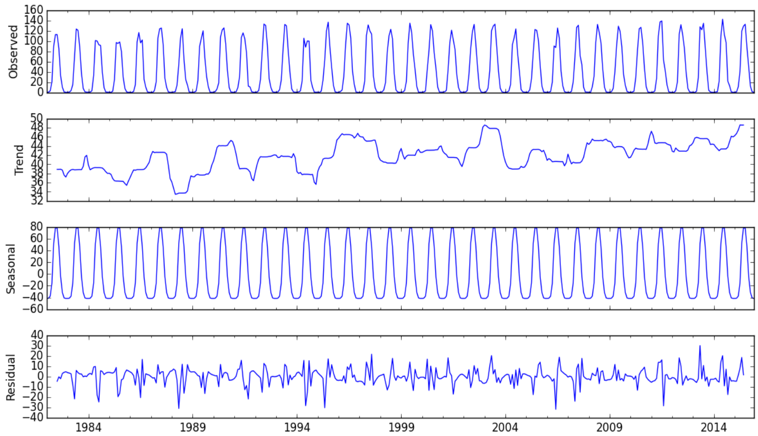


Fig. 14: example of timeseries decomposition in the three main components. Here as example NPP of deciduous forest from Casa model.

As final conclusion of this task, on the basis of the example of application reported in the deliverable D5.4, is that the time decomposition is one of the most promising approaches. This may imply that the current ICOS observation schemes need to be adjusted to address the really critical issues, rather than “measure everything”. This calls for flexibility in the standardisation of the program in the long term.

1.3.5 WP6: Towards interoperability between the European ICOS network and other GHG networks

A growing number of networks for monitoring atmospheric mixing ratios by tall towers and surface-atmosphere fluxes of greenhouse gases by eddy covariance towers are in operation around the world. In the atmospheric domain, NOAA-GMD started in the early 1990s with a tall tower program across the US, and by now operates about eight tall tower observatories. Various countries in Europe operate a network of now about 30 stations, many of which were introduced within ICOS, and additional stations to be started within the next years. The current European network includes around 15 tall towers, with the remaining stations at the coasts or on top of mountains. Earth Networks (EN), a private company, has started investing into a measurement network for CO_2 and CH_4 in the beginning of 2011, with a plan to instrument 50 towers in the US. Furthermore, a substantial network is being implemented in China. The rapid growth of in situ networks within Europe needs to be accompanied by careful planning of atmospheric site locations in order to maximize synergies, to provide the desired spatial coverage required for wall-to-wall monitoring of

GHG emissions and sinks, and to develop and agree on common protocols and methods in ecosystem monitoring activities.

Networks for ecosystem observations have been developed strongly in the last 10 years on different continents, following different standards and harmonized criteria. In the US, NEON developed a network of highly standardized ecosystem sites that will run in parallel to the Ameriflux network. Similarly, organized networks in the major countries in Asia (China, Japan, Thailand) and Australia are established. All these networks, including ICOS, are partially integrated under the FLUXNET international initiative, but without any inter-operability or agreement about protocols and standards. Data acquisition protocols, methods and standards have been developed or are under development independently in the different ecosystem networks, but without coordination. It is thus crucial to ensure compatibility and interoperability of measurements acquired by these different networks, by developing common protocols and products definition and characteristics.

The objectives of the work performed under WP6 are to:

• Assess the compatibility requirements of different GHG atmospheric networks, using high resolution inverse modelling tools

• Provide a coordinated atmospheric network design assessment over Europe, targeting maximum reduction of flux uncertainties

• Ensure network compatibility between atmospheric in-situ networks from ICOS and EN, and between ICOS and the Total Carbon Column Observing Network (TCCON), a network for ground based remote sensing of columns

• Develop and document common protocols and methodologies that ensure inter-operability between the different ecosystem (eddy covariance GHG fluxes) networks.

• Develop database software tools that ensure the data availability to the GMES Atmosphere Core Service and other users

• Demonstrate improvement in the cal-val of satellite data using TCCON

6.1 Assessment of compatibility requirements

The compatibility recommended by WMO of 0.1 ppm for CO_2 and 2 ppb for CH_4 was not originally intended for measurements over continental areas with strong and variable fluxes of GHGs affecting the measurements. To assess the usefulness of this compatibility target for ICOS atmospheric observations, targeted uncertainties for spatially resolved land-atmosphere fluxes have been assumed for CO_2 (15 $gC/m^2/y$ to allow for resolving interannual variations in the biospheric flux signals) and for CH_4 (5% of emissions, corresponding to year to year variations in emissions), and the Jena regional inversion system STILT-TM3 was applied using a full year of simulated transport to determine the impact of measurement bias.

The results show that measurement biases of 0.1 ppm for CO_2 and 2 ppb for CH_4 (i.e. within the WMO compatibility goal) are compatible with uncertainty targets for retrieved spatially resolved fluxes that require flux signals to be resolved on annual to inter-annual time scales (see Fig. 15 and 16). However, for future modelling systems with a better representation of atmospheric observations (higher resolution transport and a priori fluxes), results reported in deliverable report D6.1 indicate that the compatibility requirements are a useful upper limit for measurement biases within the network. These results have been communicated to and taken up by ICOS-ERIC, as they underpin the current atmospheric station requirements set up by ICOS.

However, the assessment also indicated that a clear definition of the targets for any monitoring and verification activity addressing greenhouse gas exchange is of crucial importance. This has initiated a stronger involvement of the reporting community within future projects surrounding the ICOS-ERIC, with the intention to get their advice on how to best verify GHG emission reporting, i.e. to identify the spatial and temporal scales at which information is most useful.

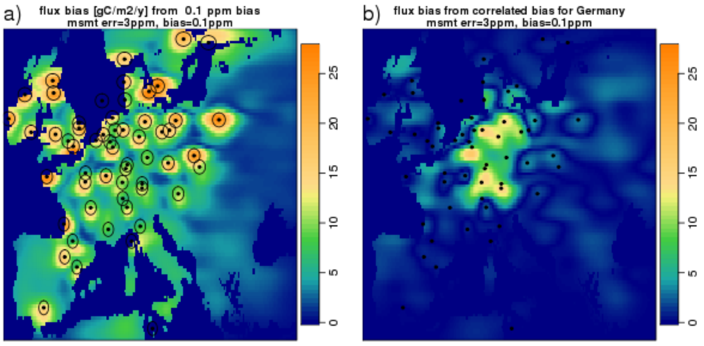


Figure 15: Impact on flux bias for CO_2 in units of gC/m^2/y, in the case of independent bias errors of 0.1 ppm at each station (left), and in case of a 0.1 ppm bias in all ICOS stations within Germany. Black filled circles correspond to the station locations, and black circles indicate the area around each station within one spatial correlation length of the prior uncertainty (~66 km).

6.2 Coordinated network design over Europe with mesoscale models

In order to assess the (current and future) ICOS atmospheric network's performance in terms of the amount of information gained through the observing network, through individual stations, and regarding the impact of spatial gaps in the observing network, a network design study with different regional scale inversion systems (the STILT-TM3 system and the VUA regional inversion system) focusing on CO_2 was performed. For this, the prior flux uncertainty was harmonized, with an error structure that resembles the mismatch between prior fluxes and eddy covariance flux observations from ecosystem stations. Resulting uncertainty reductions (Fig. 17) show a strong spatial inhomogeneity in the uncertainty reduction for seasonally or annually integrated fluxes, which is a consequence of the short prior error correlation scales. Typical uncertainty reductions for seasonal fluxes are around 30-50% near observing sites for the pixel scale (50 km), and around 50% for national scales. The regional inversion systems gave a similar answer regarding the pattern of uncertainty reduction at the national scale. A comparison to a coarse-resolution global inversion system clearly indicated that such regional systems are needed to provide information on sub-continental scales.

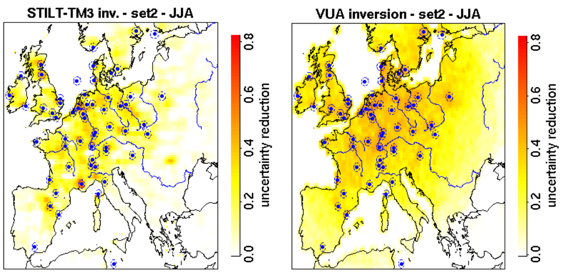


Figure 16: Uncertainty reduction maps for the future ICOS network for summer 2007 for STILT-TM3 (left) and the VUA inversion system (right).

Note that model-data mismatch uncertainties are chosen that are typically used in current inversion systems, such that the observational constraint for future (improved) models is likely to increase. Differences in the uncertainty reduction between the STILT-TM3 and the VUA inversion systems are partially related to the differing implementation of a long-term flux bias component, resulting in larger prior uncertainty for the VUA system (and thus larger uncertainty reduction) at large spatiotemporal scales, but could also reflect differences in optimization approach.

The assessment indicates that the density of stations is a critical parameter in obtaining a homogeneous uncertainty reduction in surface-atmosphere exchange fluxes. Analysis of a hypothetical network with a gap in the area of Germany indicates a significant impact for the immediate area, including neighbouring countries. For the development of the ICOS atmospheric network this means that it is crucial to expand into currently under-sampled regions, especially Southern and Eastern Europe.

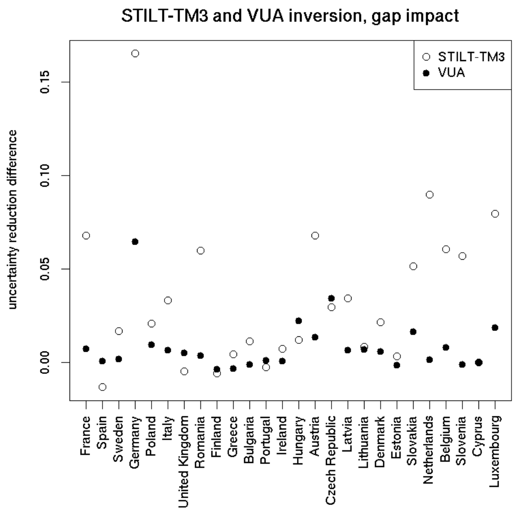


Figure 17: Difference in uncertainty reduction for seasonally averaged CO_2 fluxes for a full network and one with a gap over Germany, showing the impact of a gap on uncertainty reduction for different countries.

6.3a QA/QC evaluation at TCCON sites

As a first step towards combining ground-based remote sensing data with in-situ observations from ICOS, TCCON observations of column-averaged dry air mole fractions of CO_2 for two sites (Bialystok and Orleans) were compared with a combination of tall-tower based in-situ profile observations for the PBL, boundary layer height data, and TM3-simulated CO_2 mixing ratios for the free troposphere. In general, the dry-air mole fractions retrieved by the different methods (TM3 model, synthetic model + tall-tower in-situ, TCCON) agreed within limits. The model-derived columns are likely biased high vs. TCCON during winter and also possibly during summer, pointing to a too low age of air in the stratosphere in the TM3 model.

6.3b QA/QC evaluation for atmospheric stations using flask sampling

Analysis of air samples are collected at the two AGAGE sites JFJ (high altitude research station Jungfraujoch) and CGO (Cape Grim Observatory) have been compared to local continuous measurements for the gases CO_2, CH_4, CO, and N_2O for time periods from 2003 up to the end of 2013. In general, good agreement was found for the different gases. However, in some cases and for some time periods, significant differences (bias) between continuous and flask sample analysis were found that exceed the WMO recommended compatibility goals. This shows that flask sampling is an essential element of quality assurance, as it provides a common link between different stations and networks using the same flasks and analysis methods across all observing stations. Future regular flask sampling using the automated sampler will simplify this procedure for the continuous greenhouse gas measurements made at ICOS class 2 stations, and regular intercomparisons at sites from different networks (such as AGAGE or NOAA-GMD) will help ensuring that compatibility goals according to WMO are met across different networks.

6.4 Harmonization and interoperability of GHG ecosystem networks

High accuracy and quality of collected data is one of the main objectives of the ICOS ecosystem network, for which standards have to be defined from the selection of the sites to the release of the data. Protocols defining best options in the different fields of research have been developed to this end, involving an experts meeting with representatives from AmeriFlux and NEON. Eddy covariance (EC) methodology plays the largest role in the monitoring activity. Four protocols have been developed within ICOS community related to EC, concerning: 1 – setup of the tower; 2 – sonic anemometer; 3 – gas analyser; 4 – raw data processing. These protocols are summarized in the report D6.6, highlighting the contribution of ICOS INWIRE in their definition, and indicating the importance of standardization and the role of collaboration with other existing consolidated GHG networks such as AmeriFlux and NEON. The official ICOS protocols distribution and publication is under the control of ICOS and its bodies, however the plan is to publish a book containing all the protocols, and reference and acknowledgment to the ICOS-Inwire contribution.

The first step towards interoperability of different networks is a consistent and common system of labelling of variables and processing levels. The proposed labelling system, common to ICOS and AmeriFlux, and developed within ICOS-INWIRE, is detailed in the report D6.7. The report emphasizes the importance of a common system of labelling shared by initially two different GHG monitoring networks, in the perspective of developing future higher standardisation levels between worldwide GHG networks. The role of collaboration and interoperability with other larger networks such as OzFlux in Australia, ChinaFlux, and AsiaFlux is crucial, and has been initiated within ICOS-INWIRE.

6.5 Database and software tools to provide data from different GHG networks to GMES services

A new discovery tool has been implemented at the ICOS ATC (Atmosphere Thematic Centre), accessible to users through url https://icos-atc.lsce.ipsl.fr/databrowser/. It allows users such as CAMS (Copernicus Atmosphere Monitoring Service) and inverse modellers to discover and access atmospheric greenhouse gas (GHG) observations from different networks, through a simple and easy-to-use interface. Sustainability of the tool is granted through the support by ICOS-ATC.

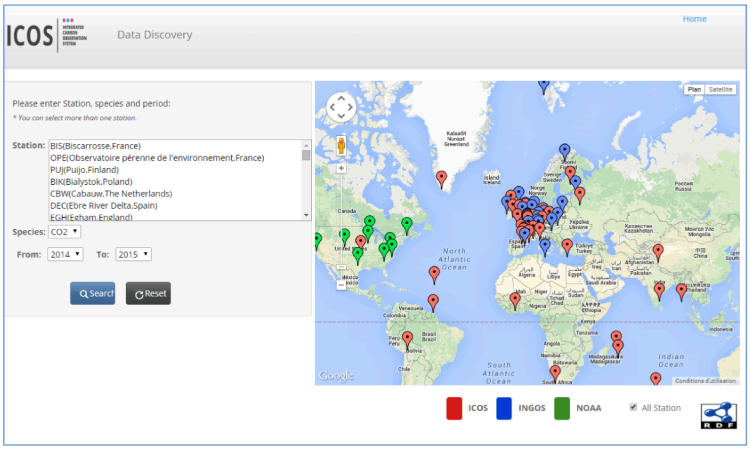


Figure 18: General view of the data discovery tool, giving access to atmospheric measurements from the ICOS, InGOS, and NOAA-GMD networks.

6.6 Demonstration of improvement in the cal-val of satellite data using TCCON

Ground-based column measurements from TCCON sites are vital for validation of satellite retrievals. However, it has been realized within the satellite community that for validation time-lags of one year (as standard TCCON provision) are not acceptable, and for future satellite missions such as the Sentinel 5 precursor (S5p) rapid delivery (RD-TCCON) data is needed. The feasibility of RD-TCCON has been demonstrated and implemented for 4 sites.

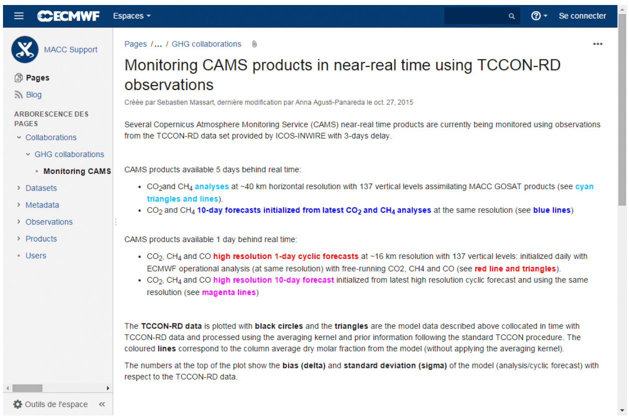


Figure 19: Landing page of demonstration experiment at ECMWF for very fast delivery TCCON product, acknowledging the ICOS-INWIRE data provision.

1.4 Potential impact and main dissemination activities and exploitation results

1.4.1 Potential impact

The EU's target of reducing greenhouse gas emissions by 20% relative to 1990 levels by 2020 embodies its objective to fight climate change and is at the heart of the Europe strategy for sustainable growth. Both policy-induced and voluntary actions can help reduce carbon emissions and

increase carbon sinks, but significant changes in the carbon budget are likely to require policy interventions. This is called for by European citizens.
The improvement of the ICOS research infrastructure through ICOS INWIRE has wide-ranging socio-economic implications: not only improving the measurement systems on regional carbon fluxes available to the public and decision makers, but also technological externalities (innovation required to meet the needs of the infrastructure's development), general socio-economic benefit of public investment in infrastructure projects, and potential improvement to climate prediction models. European companies serving the requirements of the Infrastructure can benefit from the development of ICOS by gaining competitive advantages on the global market.
ICOS INWIRE supported the research and development needed to keep ICOS at the forefront of carbon observations. Now the task will be to secure the uptake of ICOS-INWIRE results in the ICOS decision making frame.

1.4.2 Main dissemination activities

The ICOS INWIRE project maintained a dedicated website with access to documents, generated 20 published scientific papers, and 6 more are going to be submitted. The coordinator and other participants participated in several conferences and meetings to promote the achievements in the project. But most importantly, the connection with the ICOS research infrastructure has been actively maintained.
Close contact and collaboration with the ICOS HQ, ATC, ETC and Carbon Portal as well as TCCON network is ensured. The ICOS director (Dr W. Kutsch) participated to all the ICOS-INWIRE annual meetings. The coordinator of ICOS-INWIRE has been nominated to participate to the ICOS Research Infrastructure management committee teleconferences on an ad hoc basis. In addition, the ICOS-INWIRE Executive Board includes responsible persons from the ICOS atmospheric and Ecosystem Thematic Centers. More activities are described in D7.3.
The collaboration with TCCON is close through the activity of the beneficiary UBREMEN. We demonstrated in ICOS-INWIRE, that TCCON data could be delivered within one week or less. This has been validated with the decision body of the international TCCON network, with the establishment of a dedicated data fair use policy in WP3. Data delivery 3 days after the measurement would be possible. The quality control for this fast data product should be enhanced in the future, pending appropriate level of funding. If funding for the operation of the 4 TCCON sites can be obtained, the fast data product can be delivered beyond the duration of ICOS-INWIRE.
It is striking that at the last ICOS assembly of Principal investigators, ICOS-INWIRE was directly or indirectly associated to half of the presentations. 3 presentations were entirely made of ICOS-INWIRE results; therefore the uptake of ICOS-INWIRE results in the ICOS community is now considered as totally engaged.
The project has been presented at conferences and associated information material has been developed and distributed. These dissemination activities are explained in the report.
The project website has been updated to follow the intermediate review's recommendations.

A very user friendly Document Management Software (webpage is WP7) has been installed through the website and made available to the partners. After the lifetime of ICOS-INWIRE, all documentation (reports, deliverables, material) will be transferred to the ICOS document management system.

1.4.3 Exploitation of results

The expoitation of ICOS-INWIRE results into ICOS is secured by several elements:

- Adhesion: direct participation of key ICOS staff to ICOS-INWIRE (director of the ICOS Ecosystem Thematic center and several national networks coordinators are members of the ICOS-INWIRE executive board, the ICOS director has been participating to the last 2 annual meetings of ICOS INWIRE)
- Community awareness: regular presentation of ICOS INWIRE results at internal ICOS meetings (including the PI meetings, the science meetings)
- Decision-making: plans are under preparation to include several of the ICOS INWIRE achievements into ICOS in a formal way. A new activity is set up to inform the inclusion of TCCON into ICOS within a 3 year horizon. Lidar BLH characterization operational product is being prepared by the ICOS ATC. Webobs will be formally promoted as the network information system in a new proposal in INFRADEV.
- In some cases the achievements of ICOS INWIRE will be promoted beyond ICOS to the Research Infrastructure Cluster ENVRIPLUS. For example, robust instrument testing methodology and power provision are being currently proposed as services to the community of environmental research infrastructures.

More details are given hereafter for key achievements.

1.4.3.1 WP2: Robust testing in harsh environments

ATC/ICOS will profit from the work done to evaluate several technical options in the atmospheric stations (e.g. Nafion drying, CRDS analysers field testing, heating of the sampling line, data transmission, etc.). The results of the tests performed in ICOS-INWIRE will be used to improve the **ICOS Atmospheric Stations Specifications document**, which summarize the guidelines for the ICOS sites. Details can be found in Deliverable 2.1 (Requirement specifications for GHG atmospheric stations in extreme environments) and D2.4 (Report on the test at 4 sites).

1.4.3.2 WP2: Development of WEB interface to manage the station and instruments

The WEBOBS interface enables to centralize the trouble shooting of several stations and instruments. The information centralized through this tool will be used by the ICOS atmospheric community as a knowledge base of the problems which can arise and how to solve them. This Web-based software also serves as an interface to exchange metadata between stations and the ICOS database at ATC and CP. This system is currently being **proposed for deployment across ICOS in the frame of a new proposal**.

1.4.3.3 WP3: NRT data processing

ICOS-INWIRE has improved the ICOS data processing scheme in several points: warnings and errors information are sent to the station PIs on a daily basis, calibration interpolation interruptions of the regular scheme are better managed, automatic detection and flagging of local exhaust plumes with 2 methods is under test and will be implemented in the ICOS ATC database.
Thanks to developments in task 3.1, sufficient QC can now be applied automatically in almost real-time and the NRT data is processed in a more consolidated way. NRT data are therefore ready to be

considered as a high-quality data product that **will be distributed in the ICOS official data products list, as now included in the ICOS RI data lifecycle plan document**.

1.4.3.4 WP3: BLH product from LIDAR

Through task 3.2 ICOS-INWIRE provides a step towards a release candidate of a unified algorithm for BLH retrieval, and a framework for lidar/ceilometers test and performance evaluation, which is essential to complete "ICOS Atmospheric Station Specifications" document. On this basis, ICOS ATC will continue its coordinating role in the development of robust algorithm for mixed layer depth computation. Recommendation has been made and a **2-year roadmap to implement operationally the best algorithm is now available based on proposition by the CNRS partner**.

1.4.3.5 WP3: TCCON data processing

Through Task 3.3 we achieved GISC requirement in term of data delivery (i.e. 1 month) and data processing improvement on 4 experimental TCCON stations to Copernicus. In the context of Copernicus, TCCON and ICOS ATC are additionally able to deliver column averaged mole fractions of CO2 and CH4 from specific TCCON sites within 3 days, for specific model assimilation, and/or satellite validation. ICOS-INWIRE brought together these teams and developed a new service but long term support to this activity needs to be endorsed. To this effect, **a science requirement and feasibility study for operational inclusion into ICOS will be launched in 2016**.

1.4.3.6 WP3: Data uncertainties

The calculation of time-varying short and long term repeatability's developed during ICOS-INWIRE has been included recently in the operational ICOS data processing. Spike detection algorithms are now being evaluated, and the results **will be presented at the next ICOS MSA for community uptake**, with the objective to implement the most appropriate one in the ICOS processing chains by 2016-2017.

1.4.3.7 WP4: Wireless sensors system

Wireless motes allow for easy wireless communication between sensors and datalogger. They constitute the innovative core of the ICOS-INWIRE autonomous robust ecosystem eddy covariance system. These motes have been designed to be easy to use and match many types of instruments. At the end of this project **blueprints of these radio motes and assembly service is made available to ICOS partners**, with the fine electronics department of the VUA.

During these three years many new components have appeared that can enhance the initial design. Therefore beyond ICOS-INWIRE the improvement and further development of these radio motes will continue at VUA. As an example we are currently investigating possibilities to replace the radio component with new parts that have only recently become available, these parts should extend the range of these radio motes even further. The inclusion of wireless sensor technologies in environmental science is relatively new, and will in the future offer great freedom and new methods of collecting data.

1.4.3.8 WP4: Eddy covariance standard with WMO/CIMO

The agreement with WMO to develop an EC standard has been met early on in the project during a meeting with the commission for instruments and methods of observation (CIMO), which agreed that a common EC standard is desirable. This need for an EC standard of measurements has been echoed by all of the representatives of EC networks during the AGU fall meeting in 2014, where the participants also expressed their willingness to cooperate in creating one. This meeting included members of ICOS, NEON, Ameriflux, Chinaflux, INPE, Ozflux and ICOS-INWIRE.

A first draft for this EC standard has been written within ICOS-INWIRE and is currently receiving improvements by selected experts to form a robust document that can form the basis for a final standard to be endorsed by the larger flux community. Creating a standard requires consensus and takes time, this is reflected in the D4.4 deliverable*: Report on proposed definition of international WMO/FAO standard on eddy covariance.* This proposed definition has been written, however the completion of such a standard requires more time than possible within the three years of the ICOS-INWIRE project.

Beyond the scope of ICOS-INWIRE the formation of this EC standard will continue to the benefit of ICOS and other networks globally. The people responsible for this EC standard are longstanding members of the flux community and prominent members of ICOS and are thus are in a perfect position to continue the development of this EC standard that has already gained some traction.

1.4.3.9 WP4: Power supply (fuel cell)

The concept and design of a robust and autonomous power supply system for eddy covariance flux measurements in harsh winter conditions has been developed in cooperation between ICOS-INWIRE partner ULUND and a small company, In Situ Instrument AB located in Ockelbo, Sweden. The people at In Situ Instrument AB (www.insitu.se) are experts in environmental measurement techniques with a specialty to integrate different components into functioning state-of-the-art systems. They also perform field installations and provide services in management of measurement systems as well as data handling.

The final design solution of the ICOS-INWIRE power supply is based on a system consisting of dual fuel cells for production of electric power and to provide backup in case of failure of one of the fuel cells. This is important since a fuel cell become damaged if it freezes. Therefore one of the fuel cells is dedicated to this preventive safety issue. The two fuel cells will be placed in a specially designed weatherproof and insulated container with specially designed air intakes and water drainage system to cope with snow drift and low temperatures. The system will be continuously monitored and communication with the internet will be done through flexible communication solutions. One of the key components of the system is a big methanol fuel tank that will provide the necessary capacity to run the system for minimum 6 months in cold climates. Field installation and tests in the north of Sweden will commence in October 2015 and continue throughout the winter.

Since we believe that it is important to make innovations available to the market, **the system will be fully CE certified and introduced to the market after finalization of the ICOS-INWIRE field tests**.

1.4.3.10 WP5: Definition of the GMES Land core services requirements

Defining the needs of general ICOS data users is a key step to better define the ICOS products and to provide the best possible service from the Research Infrastructure. The activities performed in the WP5 started with a meeting with expert users from ECMWF that has been the basis for the Deliverables 5.1, 5.3 and 5.4 where the data characteristics and best sites to use in the modelling activities were described. **These elements will be transferred to the ICOS Carbon Portal and ICOS Ecosystem Thematic Centre**. The modelling activities were also a key result for the NRT data production described here below.

1.4.3.11 WP5: Ecosystem NRT data product

In the context of WP5 a new methodology to calculate Near Real Time eddy covariance fluxes has been developed. For this first time the raw data (10Hz) were submitted daily to a centralized server where a combination of processing methods are applied in a standardized way. The results are then published online every day and directly accessible to the users. The data include uncertainty estimation and a number of flags for the most important quality tests (see Deliverable 5.2). These data have been also used in a first data-model fusion activity by ECMWF. In fact, the new processing and quality tests, in addition to a practical example of scientific data user were the basis for a discussion in the **ICOS Interim Research Infrastructure Committee that recognized the Ecosystem NRT data as ICOS data products** (before they were only envisaged for dissemination activities and not for scientific use). This is an important step forward in the ICOS data products definition and a major ICOS-INWIRE contribution to ICOS.

1.4.3.12 WP6: Network design and Harmonisation

Elements of the network design study performed within WP6 are being made available to users such as station PIs and also the general interested public through the ICOS CP (Carbon Portal). Specifically, the sensitivities (so called footprints) of measurements made at atmospheric stations to surface-atmosphere fluxes are used to create interactive visualizations of what the network can “see”. For this, the ICOS CP has started implementing the STILT transport model in a way that allows users to interactively visualize station footprints. This way, station PIs or also the interested general public can see how atmospheric transport modulates the way a given site is influenced by different geographic regions.
Furthermore, biospheric fluxes and anthropogenic emissions for CO_2, CH_4, and CO, used as a-priori emissions for inverse modelling, are combined with these footprints to generate time series information of simulated atmospheric signals and their partitioning into e.g. different emission sectors and fuel types. This enables users to assess for each station the expected contribution to the observed signal from specific sources, which is useful e.g. for further network planning. The necessary code modules and inventory data have been provided to ICOS CP by the MPG group and the EDGAR emission inventory group at JRC. This will be especially useful to evaluate also potential new sites in the context of verification of anthropogenic GHG emissions reporting.

The results from the network design activities (ICOS-INWIRE D6.1) were frequently communicated to ICOS Station PIs and other ICOS participants during several ICOS Monitoring Station Assemblies for

Atmosphere. This allowed for improved coordination within the network regarding the requirement of homogeneous station coverage across the domain, and regarding the proximity of stations to areas of strong local emissions (which are more problematic to represent in models). The results obtained in the assessment of compatibility goals for atmospheric GHG observations (ICOS-INWIRE D6.1) provided scientifically based reasoning to the required measurement precision and accuracy as well as to the required compatibility of measurements made throughout the ICOS atmospheric network.

A central element developed in this network design, the so-called "**footprints" are currently being transferred to the ICOS Carbon Portal** (ICOS-CP). Footprints represent sensitivities of measurements made at each station at a given time to upstream sources and sinks, This will allow for on-going activities regarding the impact of stations on the estimation of surface-atmosphere exchange fluxes in atmospheric inversions, and provides further guidance on station selection and network design.

1.4.3.13 WP6: Protocol improvements

In the ecosystem component, it is crucial to standardize and harmonize the methodologies, definitions, and protocols as much as possible among different networks. ICOS aims to be a reference Research Infrastructure. The comparison of protocols and the work on sharing of protocols, in particular between ICOS, AmeriFlux, and NEON, contributed to a common development of the basic structure of the data product and the definition variables. **This helped supporting the development of the ICOS ecosystem definitions considering also the compatibility and harmonization with other RIs.**

1.5 Address of project public website and relevant contact details

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