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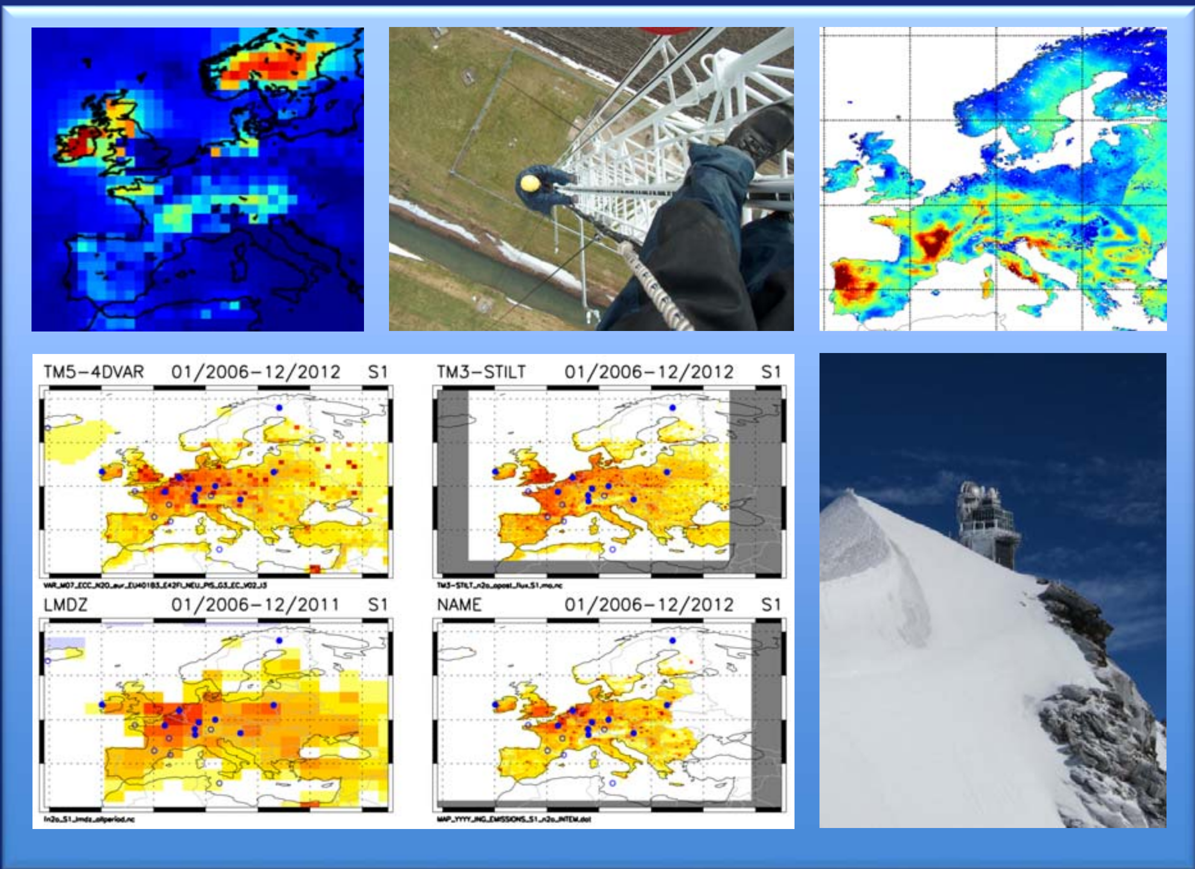
Integrated non-CO_2 Greenhouse gas Observing System

FP7-INFRASTRUCTURES–2011–1.1.11



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1. Project publishable summary

1.1 Executive summary

InGOS was an international EU Infrastructure project with almost 230 participating scientists and staff members from 14 European countries. InGOS, the acronym for "**I**ntegrated **n**on CO_2 **G**reenhouse gas **O**bserving **S**ystem", has developed a unique network in its scientific field of climate research. InGOS combined atmospheric, terrestrial and oceanic research and focussed on the main non–CO_2 greenhouse gases CH_4, N_2O, SF_6 and halocarbons, and H_2. The impact of InGOS is exceptional and based on the international and interdisciplinary character, which enables and support scientists in collaborating within a diverse consortium and to work "outside the box" of their own research field. For the first time a project included all relevant aspects to investigate climate change such as harmonization and intensive quality contraol of as well historical as actual data, long–term monitoring of relevant gas species on a European level, intercomparison of state–of–the–art measurement methods and development of new methods, provision of standards and standardized good–practise guidelines, combination and verification of several modelling techniques with remote sensing and measurement data, quantification of sources by using isotopes, or assessment of non–CO_2 GHG budgets at spatial scales by eddy covariance and flux–gradient techniques. The combination of these very different fields of natural sciences in one infrastructure project allowed establishing an overall picture of non–CO_2 greenhouse gas emissions over Europe. InGOS successfully reach its initial objectives, in particular InGOS has:

- Harmonized and standardized historical and actual European NCGHGs measurements by quality check and developing common QC/QA procedures
- Improved NCGHG flux measurements and linked European flux towers to the atmospheric observational network
- Improved measurement methods by testing&developing new innovative techniques and strategies
- Tested advanced isotope techniques for application in the network and enabled attribution of the atmospheric fractions to source categories
- Integrated marine observations of the NCGHGs with land-based observations
- Supported further development of the European NCGHG network and integrated data for network evaluation by using sophisticated, high–resolution inverse modeling, data-assimilation methods and developments in bottom up inventories
- Linked the network to remote sensing data from in-situ and satellite observations
- Generated a public European non-CO_2 GHG observation database
- Provided near-real time data of atmospheric CH_4, N_2O, SF_6, and H_2, and prepared data integration with the ICOS Research Infrastructure (Integrated Carbon Observation System), established as an ERIC in November 2015, to ensure operational, long–term monitoring perspectives
- Supported existing observation sites, transfer selected sites into supersites and provided access to key field stations and installations
- Expanded the current network with new stations in under sampled regions
- Stimulated atmospheric science knowledge transfer between experts and young scientists

With more than 300 dissimination activities, from wich up to now more than 150 peer–reviewed publications, InGOS creates significant output such as expertise and scientific advice, which could be used by policy makers.

InGOS made and make significant impact on many areas related to research and development, as well as the development of European environmental policies. InGOS supports informed decisions in climate change and international emission reduction protocols for non-CO_2 greenhouse gases and research strategies, to respond to both the future political, societal and economic challenges and the development of scientific knowledge. Several scientists of the InGOS network were not only involved in the 5th IPCC report (2014) but also in the new UNEP/WMO Ozone Assessment for Decision-Makers (2015) and finally contributed to the successful 2015 United Nations Climate Change Conference in Paris (COP21). The observation capabilities developed in InGOS allows independently verifying and also controlling the claimed emission reductions, and increasing the trust of the public and policy makers in the measures taken. Based on the excellent collaboration, the outcome and the need of such networks to scientifically support international climate relevant agreements (e.g.the Kyoto and the Montreal protocol or the new Paris agreement (COP-21)), the InGOS consortium expressed a clear commitment for a follow-up of the project.

1.2 Summary description of the project context and objectives

Project context: InGOS has been setup as an international infrastructure project to strengthen the European observation system of non-CO_2 greenhouse gases. The human induced increase in atmospheric greenhouse gases (GHGs) since the industrial revolution is causing significant changes in Earth's radiation balance. At present, the non-CO_2 GHGs (NCGHG) contribute about 37% (0.97 Wm^{-2}) of the global anthropogenic radiative forcing of all long-lived GHGs while 63% (1.66 Wm^{-2}) is attributed to CO_2. The increasing global atmospheric mixing ratios of CO_2 and the most important NCGHGs (methane (CH_4), nitrous oxide (N_2O), sulphur hexafluoride (SF_6) and halocarbons (with more than 40 different species) have been fairly well monitored by direct atmospheric observations. Systematic measurements of NCGHGs started in the 1980s, whereas CO_2 measurements were already initiated in the 1950s at the South Pole and at Mauna Loa, Hawaii.

Global monitoring of GHGs is performed by various research laboratories and national agencies (such as NOAA/ESRL). An important part of this network is coordinated within the World Meteorological Organization (WMO) Global Atmosphere Watch (GAW) program, and data are reported to the World Data Centre for Greenhouse Gases (http://gaw.kishou.go.jp/wdcgg/) by GAW participants. Currently, a significant limitation of this database is, however, that different networks or institutes report their measurements on different calibration scales. The lack of a common calibration is very severe in particular for N_2O, for which the standard measurement technique by gas chromatography exhibits a strong non-linearity, and comparison of measurements from different groups show significant offsets.

The emissions of NCGHG´s are very uncertain and it is unknown how future climate changes will feedback into the land use coupled emissions of CH_4 and N_2O. Nevertheless, the NCGHG atmospheric abundances will increase further in the future and the emissions of these gases are an attractive target for climate change mitigation policies. The monitoring of atmospheric GHGs with high accuracy and precision is essential to provide 'top-down' emission estimates, using inverse atmospheric transport models tracing back measured atmospheric mixing ratios to the regions where these GHGs were emitted.

Project objectives: InGOS aimed to support and integrate the observing capacity of Europe for NCGHG such as CH_4, N_2O, SF_6, halocarbons, and also hydrogen (H_2). InGOS aimed to improve the existing European observation system, which provide insight into the concentration levels and European and extra-European emissions of the NCGHGs. This allowed to detect the spatial and temporal distribution (hotspots) of the sources and changes in emissions due to mitigation and feedbacks with climate change. The data from the network enable to better constrain the emissions of NCGHGs within the EU and show whether emission reduction policies are effective. Thus, to strengthen the European observation system, the project had several objectives:

- Harmonization and standardization of historical and actual NCGHGs measurements in Europe by quality check and developing common QC/QA procedures
- Improvement of NCGHG flux measurements and linkage of European flux towers to the atmospheric observational network
- Improvement of measurement methods by testing and developing new innovative techniques and strategies
- Test advanced isotope techniques for application in the network to enable attribution of the atmospheric fractions to source categories
- Integrate and further integrate marine observations of the NCGHGs with land-based observations
- Support further development of the European NCGHG network and integrate data for network evaluation by using sophisticated, high-resolution inverse modeling, data-assimilation methods and developments in bottom up inventories
- Link the network to remote sensing data of column abundances from in-situ and satellite observations

- Generate a European non-CO_2 GHG observation database, which will be made available to the scientific community and general public
- Provide near-real time access to the atmospheric CH_4, N_2O, SF_6, and H_2 data, and prepare data integration with the ICOS Research Infrastructure (Integrated Carbon Observation System) to ensure operational, long–term monitoring perspectives
- Support existing observation sites, transfer selected sites into supersites and provide access to key field stations and installations
- Provide capacity building in new member states and countries with inadequate existing infrastructure and expand the current network with new stations in under sampled regions
- Stimulate atmospheric science knowledge transfer between experts, and between experts and young scientists

The overall strategy to achieve the objectives of improved data quality, coverage and availability was based on strengthening (using network activities), outreach/cooperation (using trans-national access and service activities) and innovation (using joint research activities). These activities were divided into 18 work packages, which are executed by 37 partners all over Europe. The relatively large number of participants was needed to have proper coverage of the European domain and to enable harmonization across different scientific fields of marine, terrestrial and remote sensing research. TNAs were designed to open up almost all available sites in Europe for visiting researchers, from boreal Finland down to Mediterranean Spain or Cyprus.

The **Networking Activities** enhanced the quality of the services provided by the participating infrastructures within the InGOS network. The strategy to attain such progress comprised co-operation between the participants through expert workshops, improved Near-Real-Time (NRT) data availability for quality check of instrument functionality, ongoing comparison programs and campaigns, working out of good practice recommendations, and harmonization of the concentration measurements by enhancing the availability of reference gases calibrated on the respective WMO and AGAGE scales.

The **TransNational Access Activities** enabled users to conduct high-quality research by offering access to different infrastructures such as measurement towers, airborne flux platform, calibration service, and isotope analysis service. Parts of the TNAs were used for campaigns that were related to the NAs and JRAs and facilitated scientists both in and outside InGOS to join these activities.

The InGOS data center was a **Service Activity** that provided access to non-CO_2 gas observations in Europe. This included near real time data to a wide audience as well as QA/QC controlled data for the international scientific community. The center was collocated with the CO_2 data center foreseen in preparation for ICOS (Integrated Carbon Observation System), providing a solid base for the future ICOS data center.

The **Joint Research Activities** contributed to improvements of the InGOS infrastructure. This included evaluation of the potential benefits of new available state-of-the-art instruments, methods or techniques, e.g. novel in-situ FTIR, CRDS and remote sensing (DIAL) techniques, remotely sensed CH_4, integration of NCGHG measurements on different spatial scales, new isotopologue instruments for CH_4, instrumentation for halocarbon measurements, or tower measurements to specify the effects of regional fluxes versus effects from sources further upstream.

The objectives and their progress were subject of internal and external reviews to ensure a high quality level. In December 2013 the responsible EU Project Officer (PO) Anna–Maria Johansson and Prof. Wilfried Winiwarter as an external reviewer evaluated InGOS. In the executive summary it has been stated that "The InGOS project has demonstrated excellent progress in its first period" and that "Measuring non-CO_2 greenhouse gases has been moved from individual scientists' achievement to a common activity".

Internally the Scientific Advisory Board (SAB) has monitored the progress of the project and gave scientific advice. During all General Assembly Meetings at least two members of the SAB were present and gave most valuable comments and advise during separate SAB / WP leader meetings.

The overall evolution was very positive and stated, that "InGOS is a well–organized project that made great progress with data harmonization, implementing standard procedures and testing new instruments" and that "InGOS is seen as solid and even world leading in the area of atmospheric measurements and particularly top-down emissions modeling. The process-orientated work provides solid descriptive information that broadens our understanding. The research that is done by InGOS bears directly on what many regards as the world´s most pressing environmental problem, anthropogenic climate change".

With respect to the end of InGOS the SAB also spent attention on focus and possibilities of a follow-on program. "Due to the fact, that 40% of the radiative forcing impact of anthropogenic GHG emissions comes from non-CO_2 GHGs, which play an immensely important role in the establishment and verification of policies to reduce anthropogenic climate change impacts, it would be foolish not to continue to support those aspects of InGOS that focus most directly on this problem". Three priorities on studying non-CO_2 GHGs have been mentioned:

- Continuing long-term measurements, because anthropogenic climate change cannot be studied without measurements that extend over time
- Continuing the modelling work, because one needs both observations and models to understand global and regional climate change
- Continuing support of process studies

1.3 Description of the main scientific and technical results / foregrounds

This chapter gives an overview of the main achievements of InGOS, based on the initial objectives. More details can be found in the public deliverables, available on the website, or in the publications (see chapter XX). Several publications will come in the near future.

Harmonization and standardization of historical and actual NCGHGs measurements in Europe by quality check and developing common QC/QA procedures

Data, which should be compared or merged for model calculation and consequently used as official validation for GHGs emissions changes, must have a well-known high-quality and reliability level. The aim was to evaluate and harmonize atmospheric and oceanic non-CO_2 greenhouse gas measurements in Europe, provide reliable uncertainty estimates for each individual data set, and make high-quality data available that can be jointly used in inverse modelling studies to estimate GHGs emissions and their changes. A retrospective of historical atmospheric European CH_4, N_2O and H_2 data sets and an improvement of comparability of actual atmospheric CH_4, N_2O, SF_6 and H_2 measurements from different European stations was an urgently needed, still unique exercise, since European in situ atmospheric greenhouse gas (GHG) monitoring is traditionally conducted by a multitude of national organizations and institutions, each with its own measurement procedure, quality control and link to the international GHG calibration scales. Adding realistic uncertainty estimates was particularly important for future use of these measurements e.g. for inverse modelling of European fluxes in other work packages of the project.

Table 1.3.1: overview corrected historical data per partner

Partner	Data	Partner	Data
NILU	N_2O, H_2	RHUL	H_2
FMI	N_2O, H_2	UHEI (UBA)	H_2O, H_2
ECN (MGO)	N_2O, H_2	AGH-UST	N_2O
CIO	N_2O	CEA	N_2O, H_2
MPG	N_2O	HMS	N_2O
UNIVBRIS	N_2O, H_2	EMPA	N_2O, H_2
UEA	H_2	JRC	N_2O
UNITUS	N_2O		

Comparability can be achieved by ensuring all measurement sites obtain calibration (or reference) standards from a laboratory maintaining a well-defined calibration scale (such as NOAA or AGAGE). Within InGOS partners obtained such reference standards from the MPG in Jena, Germany (N_2O, SF_6, H_2 and the stable isotopes of CH_4 and CO_2) and UNIVBRIS (in total 46 halocarbon species). In the case of halocarbon measurements, ambient air samples, pumped from the atmosphere at each measurement site, are related to a reference air sample from a cylinder. This cylinder has previously been measured at a recognised calibration centre and all compounds in the cylinder assigned a concentration.

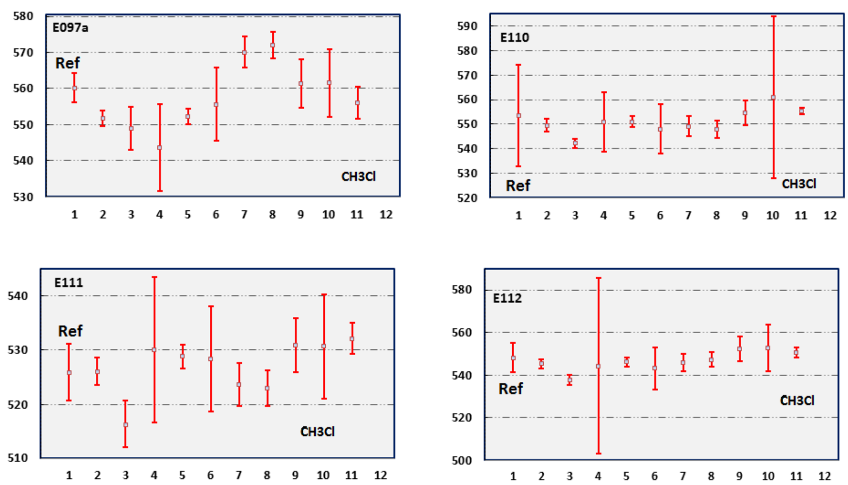

Figure 1.3.1: Round robin results for four tanks with CH_3Cl, showing mixing ratios (ppt) with error bars (±3 x standard deviation) for 11 different labs

The frequent comparison of ambient air to reference air allows accurate concentrations to be applied to the ambient air at each site, providing a consistency to the data. In addition, round-robin cylinders can also be used to determine any instrumental difference between sites, this is achieved by distributing a single set of reference cylinders that have been measured at a reference laboratory to all sampling sites and checking to see what differences between the sampling sites and reference laboratory occur. Fig. 1.3.1 gives an example of a round robin experiment for methyl chloride (CH_3Cl), a molecule involved in stratospheric ozone destruction. Results indicate that for the majority of the analyses the results are similar to the reference lab within the uncertainties with more labs/analyses deviating from the reference lab for the highest concentration tank. Such results ensure a comparability of data between different labs and also indicate where improvements are necessary. For the first time, "historical" atmospheric data, that means data of the last ten years before the start of the project, and also actual atmospheric data performed by up to 21 laboratories in different European countries have jointly been evaluated and rigorously quality controlled. Continuous measurements of CH_4 concentration have been performed at 21 existing stations in Europe whereas N_2O and H2 are measured at 18 and 13 stations respectively. Having such a dense collaborating measurement station network was a unique situation. To improve the harmonization of the measurements a good practice guideline and an error estimate algorithm have been applied to the CH_4, N_2O, and H_2 data, whereas additional graphical tools were developed to support the evaluation. Fig. 1.3.2 gives an example of such a graphical tool for Hungarian tower Hegyhatsal.

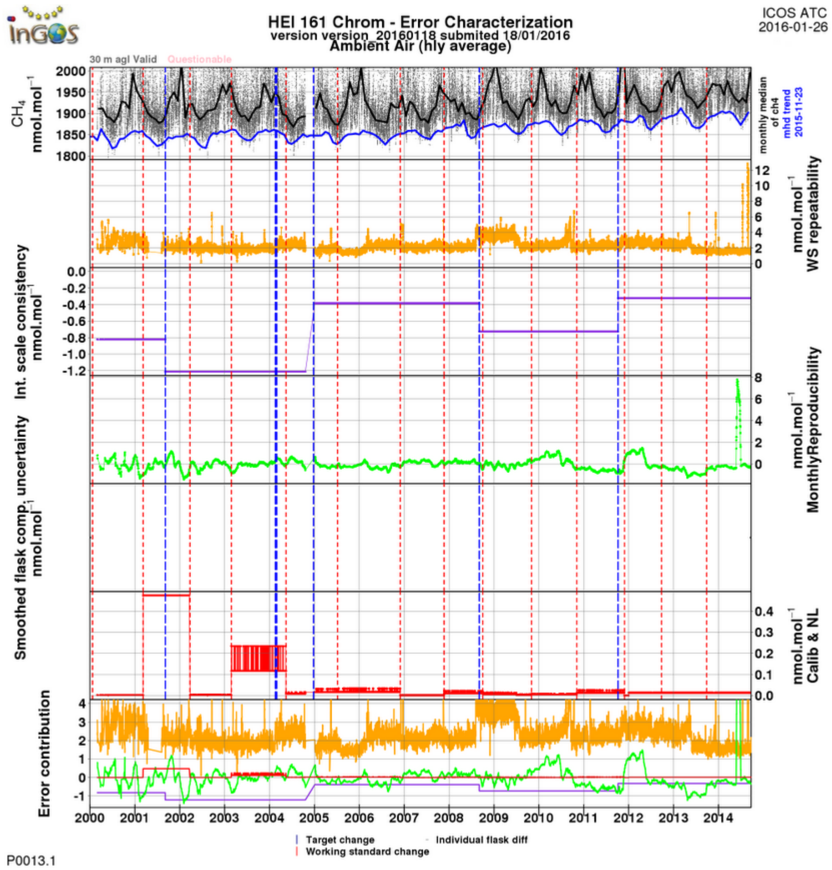

Figure 1.3.2: CH_4 measurements and their uncertainties at Hungarian tower Hegyhatsal at the 96m level. The upper panel shows the corrected hourly data (in black), together with the monthly mean observations at Mace Head station collected from the marine sector (blue line). The lower panels show the uncertainty estimates based on working standard repeatability, target gas deviations from assigned values and co-located flask results.

To survey the daily performance of the analyzers operated also at remote stations without permanent technical support on site, a near real time data transfer with a web interface was made available. On this web the atmospheric concentration of different trace gases is visible for 12 stations with a time delay of up to one day (Near-real-time). Two tasks address the topic of the comparison of the station within the network and how to prove the comparability. In the first task a classical approach to circulate a set of three high-pressure cylinders to 21 field stations was continued. 6 set of cylinders have been transported around Europe, between Zeppelin station (79° N) and Lampedusa (35°N), with the ultimate goal to visit at least each station once per year. For CH_4, the results agree within the recommendation of the WMO (world meteorological expert group) whereas for N_2O improvements is still needed. In a second task the concept of traveling comparison instrument (TCI) has been tested. A Fourier transform infrared analyzer (FTIR) was transported to Mace Head station (Ireland) and operated in parallel to the routine measurement systems there. The advantage of the TCI approach for comparison is that it covers the entire ambient air measurement system, including the sample intake system and the data evaluation process and mirrors also a longer time span. This comparison shows again a very good agreement for CH_4, and pointed to a small problem in N_2O. This feasibility study (Vardag et al., 2014) and will be included in the quality control procedure for the ICOS network. During InGOS most measurement stations have been upgraded with CRDS analysers for CH_4 following the ICOS protocol, with running the gas chromatographs for a sufficient long comparison period (6-24 months) in parallel. The network was extended with good quality data CH_4 from Voiekov operated by the group of St. Petersburg.

Also for the first time, methodologies have been developed and applied to estimate, for each data set, different types of uncertainty, i.e. precision, accuracy and compatibility. These uncertainty data were reported together with the quality-controlled measurements to a joint database (http://ingos-atm.lsce.ipsl.fr) after approval by all WP partners. The methodologies developed for future analyses and to estimate uncertainties will be taken over by the ICOS research infrastructure. This pioneer work is also highly recognized by the global GHG monitoring community.

For the marine community N_2O and CH_4 measurements were harmonized and standardized by developing methods as well as by executing laboratory inter-comparison exercises (both on board of research vessels and in the lab) and the setup of a European network. Oceanic regions covered by InGOS were the Strait of Gibraltar/Western Mediterranean Sea, the North Atlantic Ocean and the SW Baltic Sea. The activities and results of InGOS led to the establishment of the international Working Group #143 funded by the Scientific Committee on Oceanic Research (SCOR: www.scor-int.org). The SCOR WG #143 extends the activities of InGOS to an international level beyond Europe by including laboratories in Canada, Chile, China, India and USA. To this end the activities of InGOS and SCOR WG#143 will result for the first time in a global quality-checked data set of dissolved N_2O and CH_4 measurements of unprecedented high quality.

To support the modelling community, a ^{222}Radon and ^{222}Radon progeny comparison exercise was conducted, comprising nine European measurement stations. InGOS gives first estimates of disequilibrium between ^{222}Rn and its progeny and reports on ^{222}Rn progeny loss in long tubing, relevant when sampling ^{222}Rn progeny at tall tower stations as operated by the ICOS research infrastructure (Integrated Carbon Observing System, https://www.icos-ri.eu/). ^{222}Rn (emitted from soils) were used in model validation as an excellent tracer for vertical mixing owing to its short lifetime (half-life) of 3.82 days. An important achievement in this context is the generation of a novel, process-based ^{222}Rn flux map for Europe (Fig. 1.3.3), which enables significantly improved model simulations (and hence better model validation).

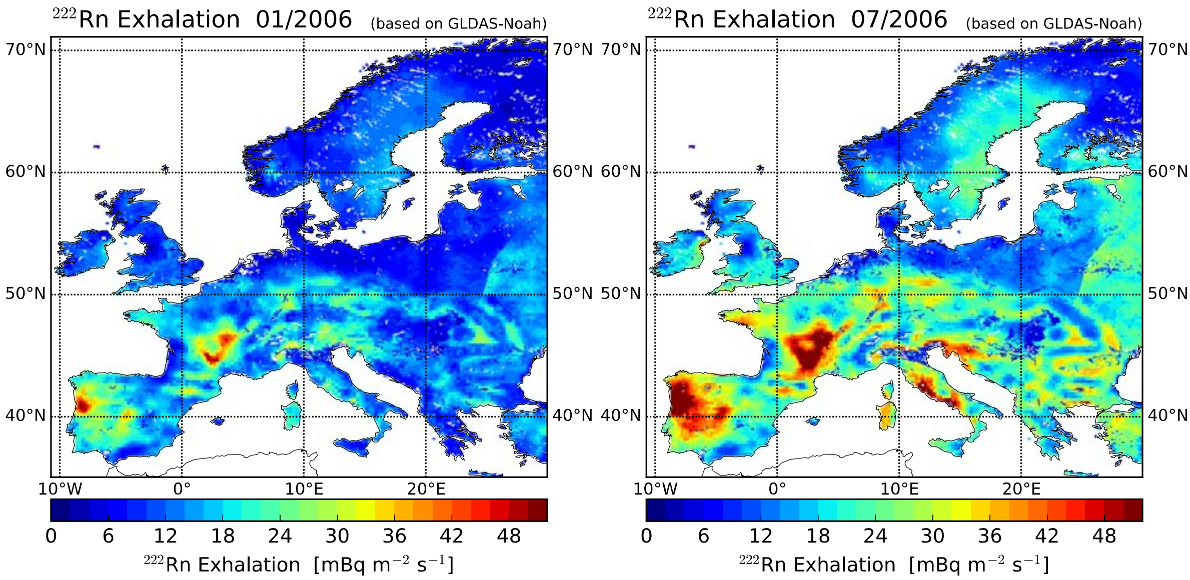

Figure 1.3.3: ^{222}Rn exhalation rate maps of European soils (based on monthly mean soil moisture estimates from the GLDAS Noah reanalysis) for January and July 2006 (Karstens et al., 2015)

Improvement of NCGHG flux measurements and linkage of European flux towers to the atmospheric observational network

Estimation of emissions of methane (CH_4) and nitrous oxide (N_2O) from soils and ecosystems (e.g. for reporting under IPCC and Kyoto agreements) requires a sound understanding of the processes that control these emissions and their dependence on meteorology, soil type and conditions, land (incl. agricultural) management etc. This understanding is developed by measuring fluxes of these compounds, ideally using the direct eddy-covariance technique, which derives the flux by correlating concentration with individual up- and down-draughts, making 10 measurements each second. The approach is well developed for carbon dioxide, but instrumentation for fast measurements of CH_4 and N_2O has only recently become available and fluxes are often very small. At the same time, simpler measurement approaches based on soil chambers, continue to be used widely, remain cost effective and sensitive and more suitable for flux measurements over smaller plots.

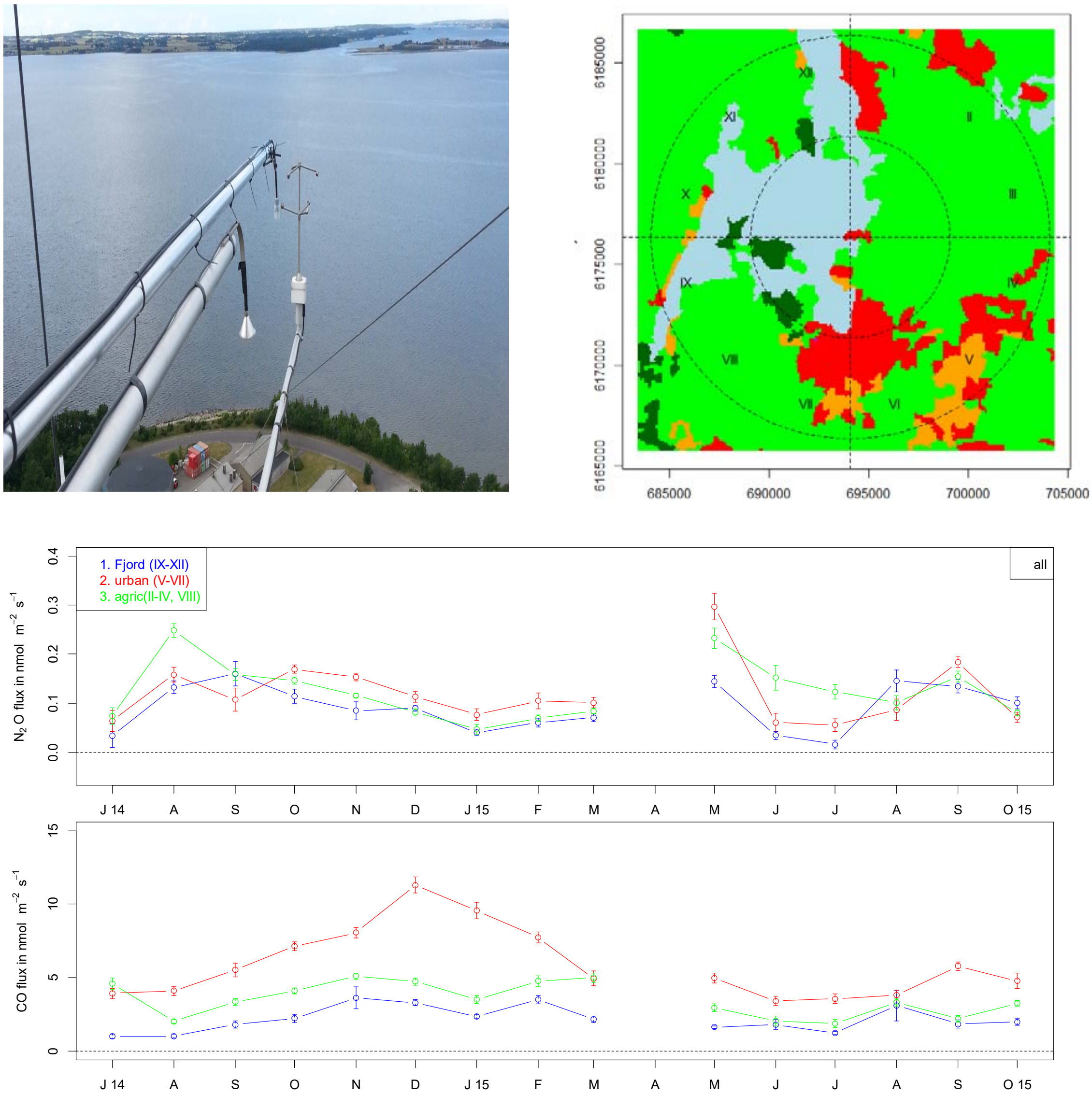

Figure 1.3.4: Above left: The view from the tower watching the Roskilde Fjord in the West direction. **Above right:** Land cover map around the Risø Tower: red, urban, orange, semi urban, dark green forest, light green, agricultural and blue, water. Roman numbers mark sectors that will be used in the analysis (see Figure 5.18.6.5). Data source CORINE (EEA, 2012), The reference lines indicate 5 and 10 km distances from the tower, which is located in the center of the graph. **Below:** Seasonal course of N_2O and CO fluxes from three different groups of sectors. The data are sorted in 30 ° slices (I to XII for 0-30 to 330-360° wind

direction, respectively). These were grouped according to certain dominant land cover features, i.e. Fjord, urban and agricultural area. The error bars represent the standard errors of the monthly mean values.

Within InGOS an infrastructure network methodology was developed enabling independent measurements of non-CO_2 GHG budgets from tall towers normally used for the concentration monitoring needed for the inverse modelling. This new type of measurements, done by using the eddy covariance and/or the flux-gradient technique, provides information on GHG emissions at the landscape scale. Data from different ecosystems (forest, urban, cropland, peatland) are available via InGOS database (http://gaia.agraria.unitus.it/ingos). Moreover, by using simultaneous measurements from short towers and/or chambers within the footprint of tall towers, new methodologies for studying the spatial variability of non-CO_2 GHG surface fluxes more systematically over landscape of a 1 to 5 km2 were proposed. Footprint modeling for tall tower and basic approaches for the attribution of the flux to a defined area and specific landscape elements were developed. Practical applications include the possibility to locate and quantify strong point sources in the landscape, to study the temporal variability of emissions, and to use these continuous and independent measurements for validation of emission inventories at regional scales as well as for model verifications and improvements (see Fig. 1.3.4).

Members of the InGOS consortium developed the first international protocol for eddy-covariance flux measurements and organized a number of instrument inter-comparisons, training events and expert workshops to support this development. For example, a campaign comparing up to 10 fast-response analysers for CH_4 was conducted in June 2012 in Cabauw, NL, and 6 fast-response N_2O analysers were assessed at agricultural grassland in Scotland in July 2013. A total of 13 European institutes took up the offer to participate in a flux chamber characterization exercise hosted by the Univ. of Helsinki at the Hyytiala field station. The results have highlighted important limitations of various instruments / approaches and led to further refinement of the data processing strategy. The outcomes of the activity have been discussed and provided to the ICOS research infrastructure in order to ensure an immediate impact on the measurements protocol and methods. This will help to promote and ensure the use of best practice and collection of all the ancillary measurements needed to fully exploit and interpret the results in particular in the developing research infrastructures.

Improvement of measurement methods by testing and developing new innovative techniques and strategies

Measurements of non-CO_2 greenhouse gases need instruments that are quite expensive (to buy and to handle) and need highly qualified operators. Within InGOS newly developed commercially available instruments were tested to see how they perform and how good they are to use in the field, and also how to apply them in new innovative measurements. Besides this, as industry continuously develops new compounds it is important to upgrade both measurement programmes and measurement instruments. Both have been advanced in the InGOS project.

In the comparison of instruments InGOS focused on the measurement of N_2O, the third most important greenhouse gas. For CO_2 and CH_4 instruments are already available that perform well. The specification of precision and accuracy to which the instruments should adhere is defined by the World Meteorological Organization-Global Atmosphere Watch (WMO-GAW). Also important is how big the drift of instruments is and whether they need high flows (expensive) and how often they need to be calibrated. The demands for measurements in a regional and/or global network are very high, and we strive for a minimal cost of maintenance and maximum reliability (data coverage) and robustness. The test results show that in fact none of the tested instrument fulfilled all demands, but some are close and should be able to reach the conditions after (minimal) adaptation.

An example of this is the Spectronus instrument that has been undergoing a large overhaul, for example by improving the measurement cell surface and the temperature control. This FTIR instrument performs simultaneous measurements of carbon dioxide, methane, nitrous oxide and carbon monoxide and also the $^{13}CO_2$ isotope ratio; recently it has been shown that also ^{18}O-CO_2 can be measured with this instrument (Vardag et al, 2015) and when sample air is not dried also H2O, $H_2^{18}O$ and HDO can be measured. An additional advantage is that the instrument measures and stores the complete infrared (IR) spectrum for each sample, so that later reanalysis (with improved spectral data or looking for other IR-absorbing gases) is possible. Having all measurements combined in one instrument reduces cost and will simplify the operation of a station compared to when using two or three instruments that would otherwise be needed. After these improvements the instrument has been deployed for a period of one year in a tall tower measuring vertical gradients. It showed excellent performance for all gases that it measures. The improvements designed and tested within InGOS have now been adopted by the manufacturer.

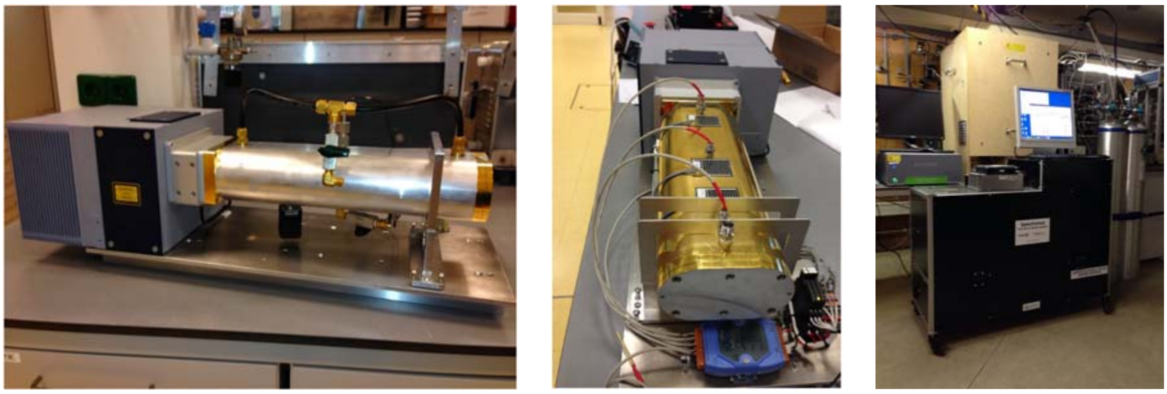

Figure 1.3.5: Spectronus aluminum measurement cell (and Bruker IR Cube FTIR detector (in gray/black)) before (left) and after (middle) upgrade of cell by braising, gold plating and implementing improved temperature control. Right: Spectronus instrument at the Cabauw control room.

An innovative remote sensing device has been developed on the basis of DIAL. This instrument has been designed to measure vertical or horizontal gradients of methane and carbon dioxide over a range of about 2 km. This proved to be very challenging, but large progress have been made, the proof-of-principle has led to a large follow-up grant and the formation of a startup company that will continue the development of this promising instrument.

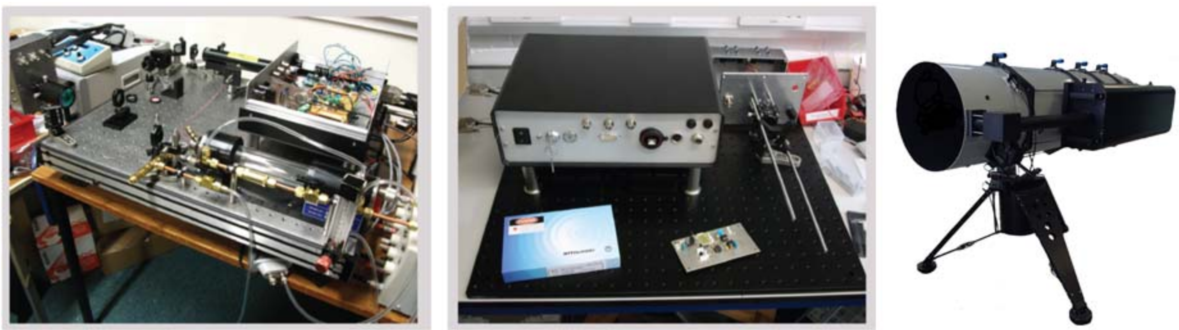

Figure 1.3.6: Seed modules (CO_2 on the left, CH_4 in the middle) for DIAL of greenhouse gases, a photograph on the right of the Mark 2 DIAL with the laser attached to the tripod-mounted Newtonian telescope

A low-cost GC has been designed and tested that enables measurements in conditions where high investments in instruments are not possible, also the running costs of this system are kept to a minimum. The system proved to run well for methane, but unfortunately only moderate performance for nitrous oxide was obtained and atmospheric measurements, where strict adherence to WMO precision and accuracy goals is required cannot be recommended at this stage.

Two instruments have been developed that can measure the isotopic composition of methane in the field. One is a system based on mass spectrometry and the other one is based on laser spectroscopy. Both systems were deployed during a short test campaign at the rural station Dübendorf in Switzerland and the main campaign at the CESAR site in the Netherlands.

Several new halogenated compounds have been detected for the first time worldwide by research groups within InGOS (Fig. 1.3.7).

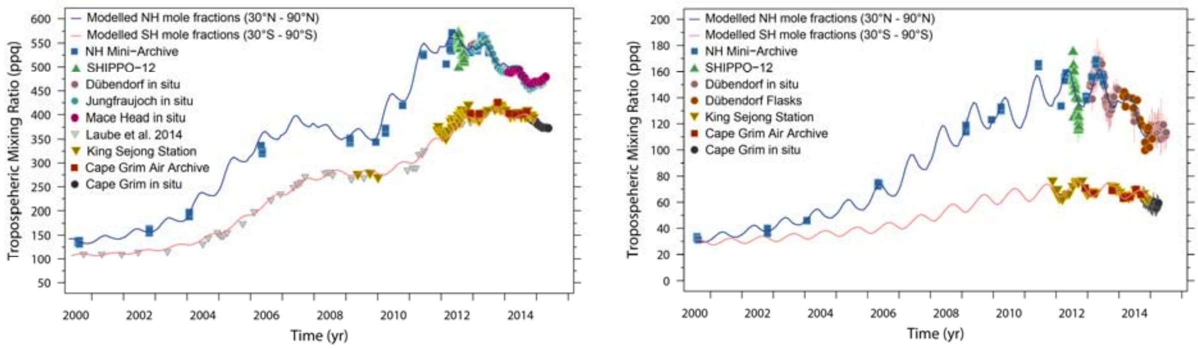

Figure 1.3.7: left panel: Mixing ratios of HCFC-133a in the Southern hemisphere and the Northern hemisphere. Measurements are an update of the measurements of HCFC-133a in the Southern hemisphere from Laube et al. (2014), which were the first atmospheric measurements of this compound. Right panel: Mixing ratios of HCFC-31 in the Southern hemisphere and the Northern hemisphere. In parallel with HCFC-133a, mixing ratios of HCFC-31 decline in recent years.

Remarkably only a part of these compounds were actually released as part of their usage in consumer products. Some of the newly found HCFCs and CFCs were identified as being by-products of the production of HFCs. Their calculated emissions undergo large fluctuations which indicate heavy emissions by only some very small number of point sources world-wide. Chlorofluorocarbons (CFCs), long-lived chlorinated solvents and brominated halons were used in many industrial applications from refrigeration to foam blowing and fire suppressants. However, these compounds were detected to destroy the stratospheric ozone layer and were globally banned from emissive usage in 2010. HCFCs (hydrofluorochlorocarbons) as their first replacement compounds still destroy stratospheric ozone (albeit to a lesser degree) and are therefore also on a global phase-out schedule. As a consequence, industry developed long-lived HFCs (hydrofluorocarbons), which do no longer destroy ozone but which are strong greenhouse gases. Therefore, political discussions are under way to curb also these gases. This lead to the invention of short-lived HFCs, which are destroyed within days in the atmosphere and which do not have an imminent effect on the climate anymore. All of these gases underlay to a certain degree international restrictions and therefore it is of utmost importance to measure these compounds in the atmosphere. Using long-term measurements, global emissions of these gases can be estimated. In addition, when these measurements are combined with meteorological transport models also regional emissions can be pinpointed. This information can then for example be used to verify emission inventories from different European countries for HFCs submitted under the Kyoto protocol.
Atmospheric halogenated compounds are normally analysed by gas chromatography using electron capture detection (GC-ECD) or by quadrupole mass spectrometry (GC-MS). In the course of InGOS it was shown that the application of a time-of-flight mass spectrometer (GC-TOFMS) has a very big potential to be used in future as the reference instrument for this kind of analyses. With the implementation of this technique research groups within InGOS are at the forefront of the global progress.

Test advanced isotope techniques for application in the network to enable attribution of the atmospheric fractions to source categories

Our understanding of the global cycle of non–CO_2 greenhouse gases still has many uncertainties, and innovative tools are needed to quantify the contributions from each process better. One interesting option is the use of isotope information, and within InGOS the focus was laid on CH_4 isotopes. Each source process emits CH_4 with a characteristic isotopic composition, and this signature is different for different source types, e.g. CH_4 from fires or coal mines tends to be rich in ^{13}C, while methane from cows or landfills has rather less ^{13}C, and methane from Arctic swamps is especially rich in ^{12}C. Therefore measurements of the isotopic composition of CH_4 in air samples can be used to quantify the contributions from the different sources (e.g. biogenic sources from agriculture, emissions from landfills or emissions associated with production, distribution and use of fossil fuels). Although the sampling is very simple, isotope ratio measurements are difficult and require sensitive instrumentation and very high precision. In InGOS, the RHUL and UU labs have been providing these analyses to research teams from across Europe to identify local and regional sources of methane. The provision of such transnational activities has been extremely valuable to so many European groups who hitherto have not had access to such high quality analytical facilities. In total 27 projects from 14 different European countries untilised the isotopic facilities. Particularly valuable data sets that have been generated include the data from Zeppelin station, Svalbard, which will be immensely valuable and of global importance in understanding the changing Arctic methane budget, and from Sodankyla Finland, in tracking wetland sources of methane, as well as results from intensive campaigns in various places, such as around Paris, or central in The Netherlands.

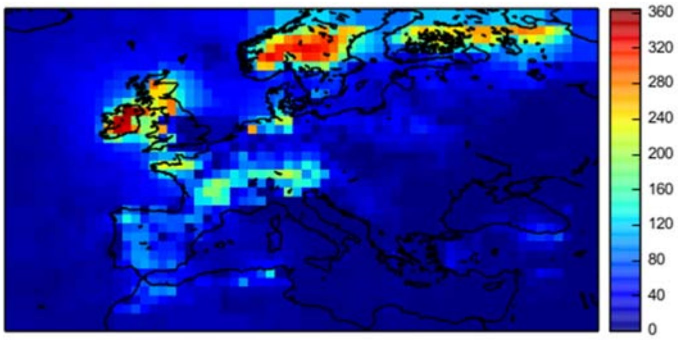

Figure 1.3.8: Number of days in the year where the uncertainty from CH_4 emissions lead to larger intervals in surface $\delta^{13}C$-CH_4 (interpolated at 15:00, local time) than the uncertainty in $\delta^{13}C$ source signatures (r>1).

Besides the access to the analytical facilities two instruments have been developed that can measure the isotopic composition of methane in the field. One is a system based on mass spectrometry and the other one is based on laser spectroscopy. Both systems were deployed during a short test campaign at the rural station Dübendorf in Switzerland and the main campaign at the CESAR site in the Netherlands. In Switzerland, the laser system was tested and a very good agreement was achieved with flask samples that were analyzed in the mass spectrometry laboratories of other partners. In Cabauw, the instruments measured the isotopic composition of methane for a period of more than 5 months with a temporal resolution of about 1 hour, which resulted in a dataset of more than 2500 measurements for both isotope signatures. Therefore Cabauw is now the site with the most extensive high–resolution information on the isotopic composition of methane worldwide. By analyzing the data it was found that agricultural CH_4 emissions from ruminants dominate the emissions at the Cabauw site (see Fig. 1.3.9).

Only occasionally elevated contributions from other sources were seen, such as natural gas and landfills reach the site. The data were also compared to model simulations to investigate whether the relative contributions from the different sources used in these models are realistic (Fig. 1.3.9). When two very different models (TM5 and FLEXPART-COSMO) used emissions from the EDGAR emissions inventory, they produced clearly too enriched isotope source signatures, which indicates that emissions from fossil fuel related sources are overestimated. The modeled source signatures were systematically more depleted and closer to the measured ones when the TNO-MACC inventory was used. Measurements at Cabauw reflect only one limited region of the European domain, and one single dataset is not sufficient to make a final decision on the quality of the emission dataset, but with the instruments for high frequency isotope observations developed within InGOS now methane emission inventories overall in Europe can be measured. Another important contribution within InGOS was the linkage of the isotope scale for methane isotope measurements to the international reference scales.

Integrate and further integrate marine observations of the NCGHGs with land-based observations

The global oceans cover more than 70% of earth surface and are a major source for atmospheric N_2O and a minor source for atmospheric CH_4. Both atmospheric trace gases play significant roles for the climate and atmospheric chemistry of the earth and the quantification of the oceanic release of N_2O and CH_4 is mandatory for our understanding of the Earth's climate and atmospheric pathways.

Within InGOS a European network of oceanic N_2O and CH_4 concentration measurements in different oceanic regions was setup, i.e. open ocean, coastal and coastal upwelling regions by using different platforms such as voluntary observing ship (VOS) lines, repeated hydrographic sections and open ocean and coastal time series stations. Oceanic regions covered by InGOS were the Strait of Gibraltar/Western Mediterranean Sea (see Fig. 1.3.10), the North Atlantic Ocean and the SW Baltic Sea.

During the InGOS period, data from different time series stations and expeditions have been collected, quality controlled and archived in the MEMENTO (MarinE MethanE and NiTrous Oxide) database (https://memento.geomar.de) which was launched in 2009 as a joint effort between SOLAS (Surface Ocean Lower Atmosphere Study) and COST Action 735 (European cooperation in the field of scientific and technical research). MEMENTO makes data available for the scientific community and provides a tool to identify key oceanic regions, which should be studied in order to improve the quality of air-sea flux estimates of methane (CH_4) and nitrous oxide (N_2O) as well as to assess their variability in different time scales. MEMENTO also provides a unique marine data set for model validation.

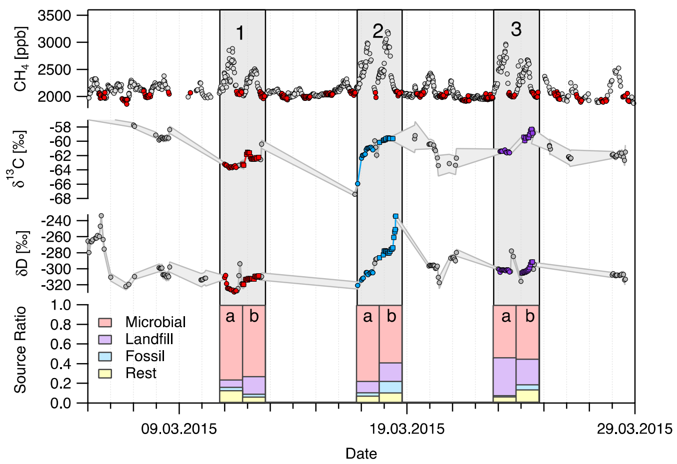

Figure 1.3.9: Detailed analysis of three 2-day periods with large CH_4 elevations in March 2015. The top panel exhibits CH_4 mole fraction (grey) with background values in red (10:00-18:00, >2100 ppb). The middle panels show the isotopic source signatures ($\delta^{13}C$-CH_4, δD-CH_4) derived with the 12-h MKP method. The color–coding in the middle panels (red, light blue, purple) indicates characteristic contributions from different sources; red-microbial, light blue-fossil, purple-waste.

The activities and results of InGOS in the marine network led to the establishment of the international Working Group #143 funded by the Scientific Committee on Oceanic Research (SCOR: www.scor-int.org). The SCOR WG #143 extends the activities of InGOS to an international level beyond Europe by including laboratories in Canada, Chile, China, India and USA. In order to produce comprehensive datasets for oceanic fluxes of N_2O and CH_4 it is likely that commercial vessels will need to be instrumental for these observations. This strategy has proved successful in obtaining data for CO_2 fluxes. The research undertaken brings forward the prospect of a much fuller description of the oceanic fluxes of these gases then is possible with research vessels alone. The use of commercial/research shipping systems to monitor greenhouse gas fluxes other than CO_2 will be an important future development within the marine activities of the European ICOS (Integrated Carbon Observation Systems) initiative and will lead to internationally set standards and protocols, and long-term, easy access of data and the ICOS data infrastructure.

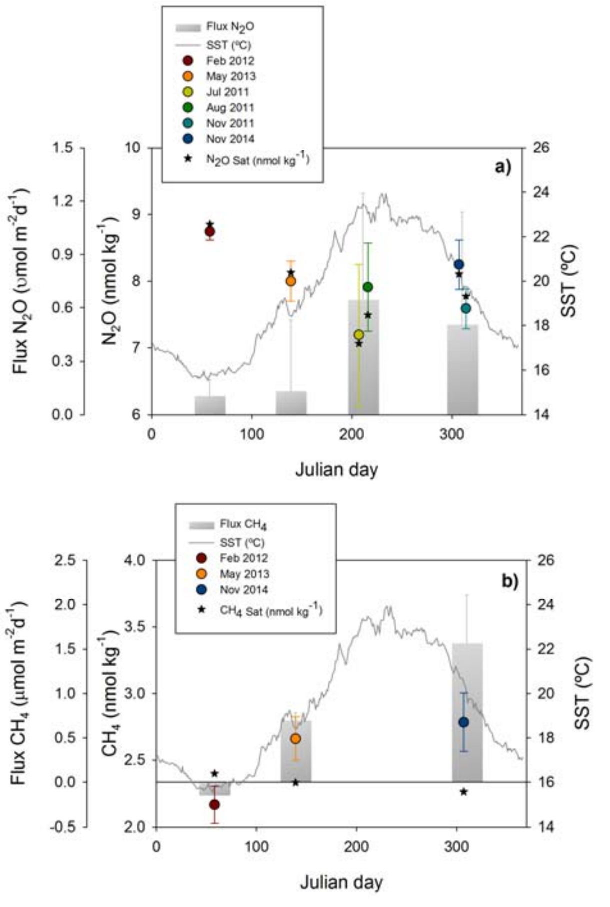

Figure 1.3.10: Annual cycle at the surface layer in the Strait of Gibraltar for: a) surface seawater temperature (SST), N_2O concentration, N_2O saturation and N_2O air-sea fluxes; and (b) SST, CH_4 concentration, CH_4 saturation and CH_4 air-sea fluxes

Support further development of the European NCGHG network and integrate data for network evaluation by using sophisticated, high–resolution inverse modeling, data-assimilation methods and developments in bottom up inventories

International agreements on reduction of greenhouse gas (GHG) emissions, such as the Kyoto protocol and the new Paris agreement (COP-21) under the United Nations Framework Convention on Climate Change (UNFCCC), require accurate accounting of GHG emissions.

GHG emissions reported to the UNFCCC are based on statistical activity data and measured or estimated emission factors.

However, for many 'non-CO_2 GHGs' (especially CH_4, N_2O and halocarbons), such 'bottom-up' emission inventories have considerable uncertainties, mainly due to the large uncertainties of emission factors, and various studies suggest that 'bottom-up' inventories may systematically underestimate real emissions.

Complementarily to 'bottom-up' estimates, emissions can be derived from atmospheric measurements using inverse atmospheric transport models ('atmospheric inversions', 'top-down'). The advantage of this technique is that it is based on observed atmospheric concentrations and is thus constrained by mass-balance, whereas emission-factor-based inventories are not and thus may not cover all sources. However, the 'atmospheric inversion' techniques rely on very accurate atmospheric measurements and are very sensitive to modelling errors.

Therefore, the harmonized high-quality datasets of atmospheric CH_4 and N_2O concentration measurements generated in InGOS provide the essential data input for the CH_4 and N_2O flux inversions performed for the period 2006-2012, using 7 different inverse models for CH_4 and 4 for N_2O (Fig. 1.3.11).

The inverse models derive in general higher total European CH_4 emissions (preliminary estimate for EU-28: 28.4 ± 6.4 (2σ) Tg CH_4 yr^{-1}) compared to anthropogenic CH_4 emissions reported to UNFCCC (19.0 - 20.9 Tg CH_4 yr^{-1}), which could point to an underestimate of reported CH_4 emissions. However, a potential alternative explanation for the discrepancy between the 'bottom-up' and 'top-down' estimates could be the contribution of natural sources, especially from wetlands, peatlands, and wet soils.

The hypothesis of significant natural emissions is supported by the finding that the inversions yield significant seasonal cycles of derived CH_4 emissions with maximum in summer, while anthropogenic CH_4 emissions are assumed to have much lower seasonal variability. However, emission estimates of natural sources have very large uncertainties and need to be better quantified in the future to close the gap between bottom-up and top-down emission estimates.

For N_2O, for which uncertainties of bottom-up inventories are extremely large - typically on the order of 100% for the total N_2O emissions per country (mainly due to N_2O emissions from agricultural soils) - the results demonstrate that atmospheric measurements and inverse modelling can significantly reduce the uncertainties. Despite the large uncertainties in the bottom-up inventories, our preliminary estimate of total European N_2O emissions (EU-28: 1.41 ± 0.54 (2σ) Tg N_2O yr^{-1}) agrees relatively well with reported total anthropogenic N_2O emissions (EU-28: 1.08-1.23 Tg N_2O yr^{-1}) and an assumed small contribution from natural soils (~0.1 Tg N_2O yr^{-1}).

Furthermore, within InGOS atmospheric inversions of two important halocarbons (HFC-125, HFC-134a) and SF_6 (which is a very potent GHG) have been performed for the year 2011. For HFC-125, the total for the 22 Western and Central European countries covered by the models was on average 30% higher than the sum of the national inventories reported to UNFCCC. A better consistency was found for HFC-134a for which the total was 8% lower than the total reported to UNFCCC. The largest national emitter of SF_6 in Europe is Germany, for which the model estimates agreed very well to the officially reported number, while for other countries the models estimated mostly higher emissions. The current network of only three regular monitoring sites is able to discover major discrepancies in national emission inventories for some of the large European countries, but more stations are clearly needed to serve as a reliable emission monitoring and verification tool for synthetic greenhouse gases, especially in Eastern and Southern Europe.

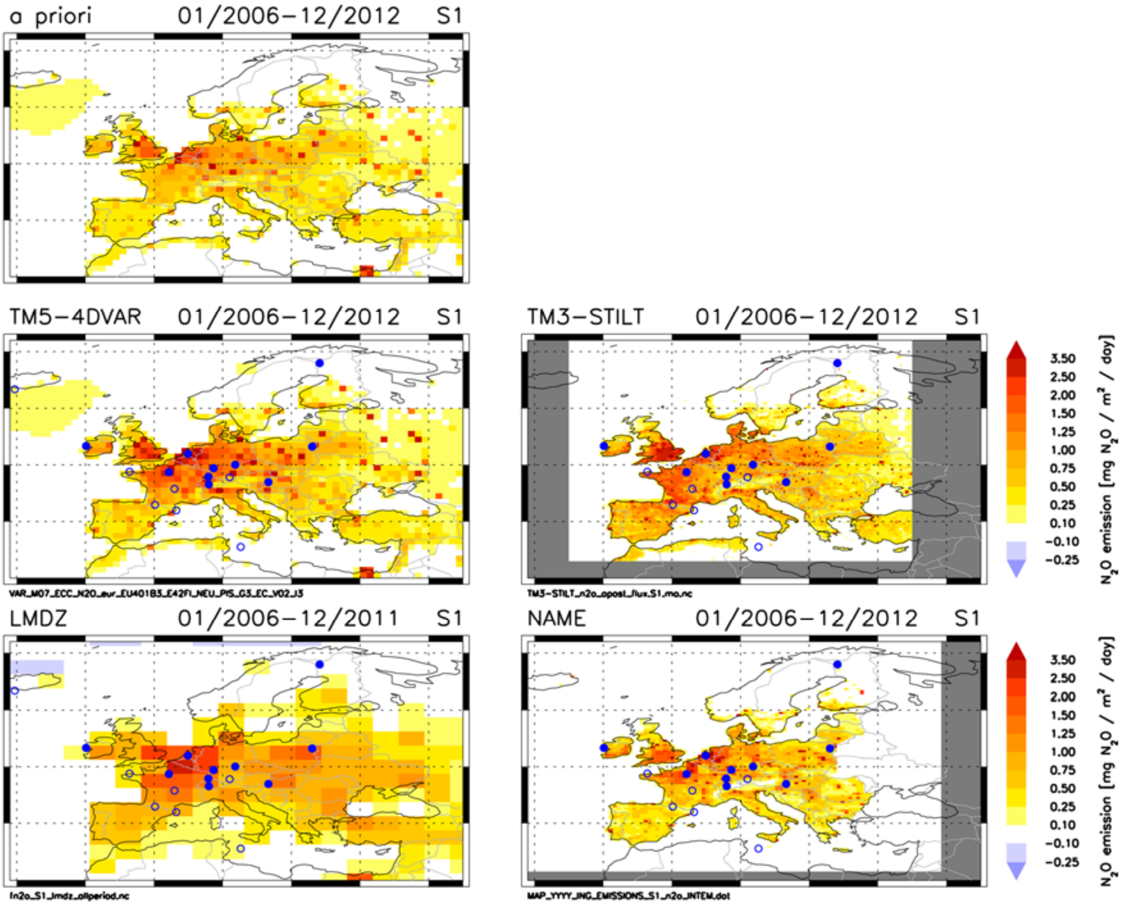

Figure 1.3.11: European N_2O emissions (average 2006–2012, inversion S1). Filled circles are InGOS stations with quasi-continuous measurements; open circles are additional discrete air sampling sites (NOAA and LSCE). A priori emissions shown in the upper left panel are as applied in TM5-4DVAR.

As mentioned above, the atmospheric inversions are very sensitive to potential model errors. Therefore, a comprehensive model validation have been performed, including a detailed analysis of the capabilities of the models to simulate the boundary layer height dynamics realistically. The model validation includes the use ^{222}Rn (emitted from soils), which is an excellent tracer for vertical mixing owing to its short lifetime (half-life) of 3.82 days. An important achievement in this context is the generation of a novel, process-based ^{222}Rn flux map for Europe (see Fig. 1.3.3), which enables significantly improved model simulations (and hence better model validation).

Finally the usefulness of using stable isotopes in CH_4, in order to constrain emissions from specific CH_4 sources, has clearly shown. The isotopic signatures represent 'fingerprints' which are characteristic for specific sources, and allow e.g. to distinguish between 'biogenic' sources (e.g. agriculture), e.g. from leakage in natural gas distribution networks.

Link the network to remote sensing data of column abundances from in-situ and satellite observations

Sufficiently accurate remote sensing measurements of CH_4, from the ground as well as from satellite, are only available since about 10 years. These remote sensing measurements started a new era in atmospheric greenhouse gas monitoring and are widely used nowadays. It can be expected that technical as well as retrieval developments enhance the precision and accuracy of the remote sensing measurements in the future and that these measurements will become increasingly important for greenhouse gas monitoring. Remote sensing observations of CH_4 from the ground as well as from space are fundamentally different from in situ observations. The remote sensing measurements of CH_4 measure solar radiation that has passed through the atmosphere and contains the spectral absorptions of the atmospheric molecules. From these characteristic absorption features the abundances of the gases in the atmosphere are retrieved. Thereby remote sensing observations sample vertically the whole atmosphere, which is in contrast to the in situ measurements, which sample at one point in space. This difference is important for use of the data, because current models are designed for use of in situ measurements as well as for the calibration since the atmospheric column cannot be bottled up and therefore calibration of remote sensing measurements with respect to in situ standards cannot be done directly.

InGOS contributed to the further development of the remote sensing measurements of CH_4 and demonstrated the usefulness of remote sensing observations for model validation. A tropospheric CH_4 data product for ground based solar absorption measurements in the near-IR (available from any TCCON site) was developed. It allows separating the stratospheric and tropospheric CH_4 provides a direct link to the in situ measurements. This link is difficult to establish with the column averaged data product because of the uncertainties of stratospheric CH_4, which is commonly not measured by the in situ measurements. This data product was compared to vertical in situ aircraft profiles, showing a very good comparison (see Fig. 1.3.12). A QA/QC activity based on circulation of gas cells was established in TCCON Europe.

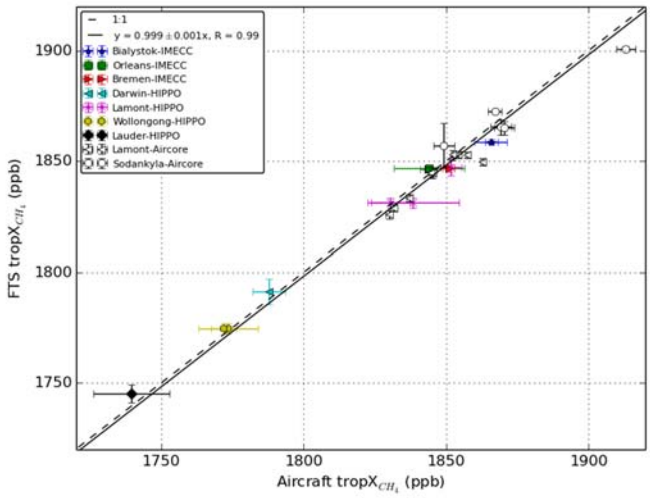

Figure 1.3.12: Calibration results of FTS-derived tropospheric column-averaged CH_4 mole fractions with in situ measurements. The in situ profiles are smoothed using GFIT CH_4 averaging kernels in troposphere as described in Wang et al. (2014). The FTS data are averages during the in situ measurement periods.

Since this activity demonstrated to be successful, it was adopted by the global network. Satellite retrievals of CH_4 were validated using TCCON data. Remote sensing observations from satellite and the ground were used to validate model data. The comparisons showed a systematic latitudinal dependent bias between model and measurement. The newly developed tropospheric data product was used to show that the stratospheric representation in the models as well as vertical transport in the troposphere is responsible for the bias. It is recommended to include the European part of TCCON into ICOS, since TCCON observations have established as a vital component in the global observing system of greenhouse gases and the observations have to be secured long term.

Generate a European non-CO_2 GHG observation database, which will be made available to the scientific community and general public

Measurements and data collection within an international and interdisciplinary project, aiming on collaboration and joint activities to increase knowledge, are useless for the scientific community without availability and accessibility of the data. Therefore an InGOS Data Center was setup, which guarantees free access of the InGOS data to the scientific community and also to the general public. The interdisciplinary character of InGOS led to heterogeneity of the data collected and different expertise, so the InGOS Data Center has been structured into three distinct data centres for I) non-halocarbon atmospheric data, II) halocarbon data, and III) ecosystem data.

The atmospheric database collected CH_4, N_2O, and H_2, and is hosted by the same laboratory responsible of the Atmospheric Thematic Center (ATC) of ICOS ensuring a good standardization between non-CO_2 greenhouse gas data and CO_2 data as well as a good long–term storage and distribution of the atmospheric data (http://ingos-atm.lsce.ipsl.fr/). The data collected during the course of the project are of two types: historical validated data with associated error estimates and metadata and daily Near Real Time data. The setup of a NRT transmission is part of a preparation for those stations, which will eventually integrate ICOS quality strategies. The final historical validated data release along with the computed uncertainties will be available to the community after the end of the project.

Table 1.3.2: Available atmospheric data sets

Station name	Country	Latitude	Longitude	Altitude	Parameter1	Sampling heights	Current scale	Data period (start)	Data period (end)
Angus	UK	56.555	-2.986	313	CH_4	50, 222	NOAA-2004	2006-01-10 17:00:00	2012-10-13 21:00:00
	UK	56.555	-2.986	313	N_2O	50, 222	NOAA-2006A	2006-01-10 17:00:00	2012-10-13 21:00:00
Bialystok	PL	53.229	23.013	183	CH_4	5, 30, 90, 180, 300	NOAA-2004	2005-07-19 10:00:00	2012-12-31 23:00:00
	PL	53.229	23.013	183	N_2O	5, 30, 90, 180, 300	NOAA-2006A	2005-07-19 10:00:00	2012-12-31 23:00:00
Cabauw	NL	51.97	4.926	0	CH_4	20, 60, 120, 200	NOAA-2004	2005-01-01 01:00:00	2015-12-31 23:00:00
	NL	51.97	4.926	0	CO	20, 60, 120, 200	WMO CO X2004	2005-01-01 00:00:00	2013-12-31 22:00:00
	NL	51.97	4.926	0	N_2O	20, 60, 120, 200	NOAA-2006A	2005-01-01 01:00:00	2015-12-31 23:00:00
	NL	51.97	4.926	0	SF_6	20, 60, 120, 200	NOAA-2006	2005-01-01 00:00:00	2015-12-31 22:00:00
Ebre River Delta	ES	40.744	0.787	0	CH_4	10	NOAA-2004	2013-01-09 15:00:00	2015-11-30 23:00:00
	ES	40.744	0.787	0	N_2O	10	NOAA-2006A	2013-01-09 15:00:00	2015-11-30 23:00:00
Egham	UK	51.426	-0.563	45	CH_4	10	NOAA-2004	2008-09-01 00:00:00	2008-12-31 22:00:00
	UK	51.426	-0.563	45	H_2	10	WMO H2 X2009	2008-09-01 00:00:00	2015-06-30 23:00:00
Gif sur Yvette	FR	48.71	2.148	160	CH_4	7	NOAA-2004	2013-06-25 00:00:00	2015-06-30 23:00:00
	FR	48.71	2.148	160	H_2	7	WMO H2 X2009	2013-06-25 00:00:00	2015-06-30 23:00:00
	FR	48.71	2.148	160	N_2O	7	NOAA-2006A	2013-06-25 00:00:00	2015-07-01 23:00:00
Hegyhatsal	HU	46.956	16.652	248	CH_4	10, 48, 82, 115, 96	NOAA-2004	2006-01-01 00:00:00	2014-12-31 21:00:00
	HU	46.956	16.652	248	N_2O	10, 48, 82, 115, 96	NOAA-2006A	2006-01-01 00:00:00	2014-12-31 21:00:00
	HU	46.956	16.652	248	SF_6	10, 48, 82, 115, 96	NOAA-2006	2014-04-10 11:51:05	2012-12-31 21:00:00
Heidelberg	DE	49.417	8.675	113	CH_4	30, 30	NOAA-2004	2000-01-01 01:00:00	2014-09-23 11:00:00
	DE	49.417	8.675	113	H_2	30, 30	WMO H2 X2009	2014-01-01 00:00:00	2014-09-23 11:00:00
	DE	49.417	8.675	113	N_2O	30, 30	NOAA-2006A	2014-01-01 01:00:00	2014-09-23 11:00:00
Ispra	IT	45.807	8.63	223	CH_4	16	NOAA-2004	2007-10-12 16:00:00	2014-12-31 20:00:00
	IT	45.807	8.63	223	N_2O	16	NOAA-2006A	2010-09-15 20:00:00	2014-12-31 21:00:00
Jungfraujoch	CH	46.55	7.983	3580	CH_4	5	NOAA-2004	2004-12-31 23:00:00	2015-07-31 22:00:00
	CH	46.55	7.983	3580	H_2	5	WMO H2 X2009	2005-01-01 00:00:00	2014-12-31 23:00:00
	CH	46.55	7.983	3580	N_2O	5	NOAA-2006A	2004-12-31 23:00:00	2015-07-31 22:00:00
Kasprowy Wierch	PL	49.233	19.983	1987	CH_4	2	NOAA-2004	2009-01-30 19:00:00	2015-06-30 23:00:00
	PL	49.233	19.983	1987	N_2O	2	NOAA-2006A	2013-01-09 13:00:00	2015-06-30 23:00:00
Lampedusa	IT	35.518	12.632	45	CH_4	8	NOAA-2004	2014-01-01 09:00:00	2014-12-29 21:00:00
Lutjewad	NL	53.404	6.353	1	CH_4	7, 40, 60	NOAA-2004	2013-01-01 00:00:00	2015-01-01 04:00:00
	NL	53.404	6.353	1	N_2O	7, 40, 60	NOAA-2006A	2006-05-01 00:00:00	2015-01-01 00:00:00
Mace Head	IE	53.326	-9.904	5	CH_4	24, 10	Tohoku University	2000-01-01 02:00:00	2014-10-01 00:00:00
	IE	53.326	-9.904	5	H_2	24, 10	WMO H2 X2009	2000-01-01 02:00:00	2014-10-01 00:00:00
	IE	53.326	-9.904	5	N_2O	24, 10	SIO-98	2000-01-01 01:00:00	2014-10-01 00:00:00
Ochsenkopf	DE	50.03	11.808	1022	CH_4	23, 90, 163	NOAA-2004	2006-05-31 08:00:00	2012-08-15 10:00:00
	DE	50.03	11.808	1022	N_2O	23, 90, 163	NOAA-2006A	2006-05-31 08:00:00	2012-08-15 10:00:00
Pallas	FI	67.973	24.116	565	CH_4	7	NOAA-2004	2012-10-18 00:00:00	2014-12-31 22:00:00

	FI	67.973	24.116	565	N_2O	7	NOAA-2006A	2004-02-25 22:00:00	2014-12-31 21:00:00
Puy de Dôme	FR	45.772	2.966	1465	CH_4	10, 10	NOAA-2004	2010-07-27 00:00:00	2015-07-01 23:00:00
	FR	45.772	2.966	1465	N_2O	10	NOAA-2006A	2010-07-27 00:00:00	2015-07-01 23:00:00
Schauinsland	DE	47.917	7.917	1205	CH_4	8	NOAA-2004	2001-01-01 01:00:00	2014-12-31 23:00:01
	DE	47.917	7.917	1205	H_2	8	WMO H2 X2009	2009-01-01 01:00:00	2014-12-31 23:00:00
	DE	47.917	7.917	1205	N_2O	8	NOAA-2006A	2001-01-01 01:00:00	2014-12-31 23:00:00
Trainou	FR	47.965	2.112	131	CH_4	50, 100, 180, 5	NOAA-2004	2007-01-29 00:00:00	2012-06-01 23:00:00
	FR	47.965	2.112	131	H_2	50, 100, 180, 5	WMO H2 X2009	2008-01-01 00:00:00	2012-12-31 23:00:00
	FR	47.965	2.112	131	N_2O	50, 100, 180, 5	NOAA-2006A	2007-01-29 00:00:00	2012-06-01 23:00:00
Weybourne	UK	52.95	1.121	31	CH_4	6, 10	NOAA-2004	2015-09-08 16:21:28	2015-07-31 21:00:00
	UK	52.95	1.121	31	H_2	10	WMO H2 X2009	2008-03-06 00:00:00	2015-06-30 21:00:00
Zeppelin	NO	78.908	11.881	474	CH_4	15	NOAA-2004	2012-04-20 00:00:00	2014-12-31 22:00:00
	NO	78.908	11.881	474	H_2	15	WMO H2 X2009	2009-01-01 00:00:00	2014-05-01 22:00:00

*non-beneficiary contributors HFSJG: International Foundation High Altitude Research Stations Jungfraujoch and Gornergrat, UBA: Umweltbundesamt, ENEA: Italian National Agency for New Technologies, Energy and Sustainable Economic Development

Note: All stations are groundbased with ongoing, continuous sampling and a sampling frequency of 1h. All stations fall in the WMO GAW Category „contribution“.

The InGOS Halocarbon Data Center is a subject to the EMEP database EBAS (http://ebas.nilu.no), which is hosted, operated and maintained by NILU – Norwegian Institute for Air Research. EBAS is used by a number of other national and international monitoring programs including all near-surface data from the RI ACTRIS, WMO Global Atmosphere Watch (World Data Centre for Aerosols), EMEP, Arctic Monitoring and Assessment Programme (AMAP), OSPAR, HELCOM, and more than 50 different EU research projects. EBAS provides the final long-term archive for the data. EBAS has an open data policy, offering free and easy access to the data, and there is a strong link to the end users. In InGOS, EBAS is offering access to all halocarbon data from the 4 stations Zeppelin (Norway), Mace Head (Ireland), Jungfraujoch (Switzerland) and Mt.Cimone (Italy). The InGOS halocarbon dataset is defined as the 5-year period from January 2010 to December 2014, and includes 36 different halocarbon components. The quality control of the data is performed in the AGAGE network, which ensures up-to-date and harmonized quality control according to well-described and documented standard operating procedures.

Table 1.3.3: Available halocarbon data sets

Station	Measurement principle	Instrument type	No. Comp.	Time res.	Time frame
Jungfraujoch	online GC	MEDUSA	36	2h	2010-2014
Mace Head	online GC	MEDUSA	36	2h	2010-2014
Mt.Cimone	online GC	GC-ADS	36	2h	2010-2014
Zeppelin	online GC	MEDUSA	36	2h	2010-2014

The InGOS Ecosystem database worked as platform for the exchange of all the InGOS ecosystem data that where of two types: the measurements of non-CO_2 greenhouse gases fluxes between ecosystems and atmosphere (including an urban site in London) and the results, including measurements and metadata, of the specific InGOS campaigns that were organized with the aim to better develop and estimate the uncertainty in CH_4 and N_2O flux measurements using eddy covariance and chambers.

Table 1.3.4: Available Ecosystem data sets

Station	Measurement principle	Instrument type	Time Res.	Time frame
Cabauw CH_4 eddy comparison campaign	Eddy covariance	different	30 min	2012
Edinburgh N_2O eddy comparison campaign	Eddy covariance	different	30 min	2012
Cabauw CH_4 second eddy campaign on spatial variability	online GC	different	30 min	2012
N_2O chambers intercomparison	Chambers	different	variable	2012
CZ-wet	Eddy covariance and meteo	different	30 min	2005-2009
FI-Hyy	Eddy covariance and meteo	different	30 min	1996-2014
RU-Fyo	Eddy covariance and meteo	different	30 min	1998-2014
DE-Lnf	Eddy covariance and meteo	different	30 min	2002-2012

UK-LBT	Eddy covariance	different	30 min	2011-2014
NL-Hor	Eddy covariance and meteo	different	30 min	2004-2011
DK-RCT	Eddy covariance and meteo	different	30 min	2014-2015
FI-Kns	Eddy covariance and meteo	different	30 min	2004-2009
DK-RCW	Eddy covariance and meteo	different	30 min	2012-2013
FR-Gri	Eddy covariance and meteo	different	30 min	2004-2014
SE-Nor	Eddy covariance and meteo	different	30 min	1996-2012

These data are shared on a specific InGOS webpage in the database (http://www.europe-fluxdata.eu/ingos) and they will be available also after the end of the project because can be used as reference for future standard selections in the context of ICOS.

Additionally to the InGOS Data centres the MEMENTO (MarinE MethanE and NiTrous Oxide) database (https://memento.geomar.de), launched in 2009, gives the InGOS community access to marine CH_4 and N_2O data and provides a tool to identify key oceanic regions, which should be studied in order to improve the quality of air-sea flux estimates of methane (CH_4) and nitrous oxide (N_2O) as well as to assess their variability in different time scales. MEMENTO also provides a unique marine data set for model validation.

Provide near-real time access to the atmospheric CH_4, N_2O, SF_6, and H_2 data, and prepare data integration with the Integrated Carbon Observation System infrastructure to ensure operational, long–term monitoring perspectives

The need for a real-time, high-frequency measurement network is very strong and the observations and their interpretation are recognized widely for their importance to ozone depletion and climate change studies and to verification issues arising from the Montreal (ozone) and Kyoto and successor (climate) Protocols. InGOS is distinguished by its capability to measure regionally, at high frequency, all the important species in the Montreal Protocol and all the important non-CO_2 gases in the Kyoto Protocol and to document accurately the European manmade and natural distribution and behavior over time, provide information about the accumulation rates, and determine estimates of the regional emissions of these gases. Within InGOS several stations were operated remotely without permanent technical support on site. A near real time (NRT) transfer of data with a web interface can help to survey the daily performance of the analyzers and to identify possible problems with measurements promptly. Besides this, NRT data are used for the validation of short–term forecast assimilation models, satellites and total column FTIR measurements. Especially NRT data of CH_4 are useful for the atmospheric service of the European GMES programme (Monitoring Atmospheric Composition and Climate (MACC). InGOS succeeded in the challenge of the automatic transfer of computed concentration, which costs more effort than expected.

InGOS implemented a near-real time data transmission from the measurement stations in addition to the normal data acquisition. With an automated routine, the stations made calculated mixing ratios of CH_4, N_2O, SF_6 and H_2 available, a few hours after data acquisition. Mixing ratios were automatically transferred to a FTP server once per day, with an intermediate quality and a lower target precision as a compromise for the timely provision of data. In order to automate the data processing, the data files send to the atmospheric database server comply with InGOS defined file formats. To provide a more powerful tool the database accept now also additional trace gases like CO_2 and CO. These gases are plotted in the same way as CH_4 and N_2O and offer a better view if the analyser function correctly or local if possible contaminations occurred.

The website for NRT data is fully operational and hosts currently data of the last 20 days of in total 12 stations, available to the scientific and public community. The web page is accessible at http://ingos-atm.lsce.ipsl.fr/NRT. To enhance the visual clarity the available data records are also shown as individual graphs of the trace gases per station. An example of the graphical NRT interface for Gif-suy Yvette station is given in Fig. 1.3.13. Users can also browse through an interactive time series line chart with optional annotations from the last measurements of submitted data for all NRT stations. Directly below the time series of each molecule the zoom range selection area is given.

The long term improved datasets for non-CO_2 greenhouse gas atmospheric concentrations and their uncertainties gathered in InGOS connect directly to the high quality datasets that will be gathered in the ICOS RI and will allow the modellers to analyse from its start already long term trends in the greenhouse gas budget of Europe for CH_4 and N_2O. A similar exercise is urgently needed for CO_2 and the methods developed and experiences gathered in InGOS for the non-CO_2 gases will be very valuable in working on the historic CO_2 concentration timeseries.

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Support existing observation sites, transfer selected sites into supersites and provide access to key field stations and installations

InGOS enabled users to conduct high-quality research by offering access to several infrastructure facilities such as measurement towers, the calibration facilities or aircraft sampling. These open access activities fostered interdisciplinary collaboration and knowledge transfer, opened the network and broadened dissemination activities. Particularly the knowledge transfer on several levels – national/international, junior/senior scientists, between different disciplines and sectors – is an important aspect of such infrastructure projects. It ensures and increases the quality of research and is the base for new inventions and networks, which both are necessary to Europe at the scientific forefront of this field. In total 29 facilities were offered within InGOS, including access to a number of core stations which were used for intercomparison campaigns. Beside the core stations access to other European facilities cooperating in the program and to an airborne flux platform was offered. Three services were provided through the calibration service and provision and analysis of calibration standards and the isotope analysis service. These activities facilitated measurement comparability

Table 1.3.5: List of station with regular NRT data transfer to the IngOS data base and the gases presented in the graphs.

Nr.	Station	Trigram	Type	Species
1	Cabauw	CBW	Tall tower	CH_4, N_2O, SF_6
2	Gif-sur-Yvette	GIF	Ground	CH_4, (CO_2), N_2O, SF_6
3	Heidelberg	HEI	Ground	CH_4, (CO, CO_2,) H_2, N_2O, SF_6
4	Hegyhatsal	HUN	Tall Tower, one level	CH_4, N_2O, SF_6
5	Ispra	IPR	Ground	CH_4, N_2O
6	Kasprowy	KAS	Ground	CH_4, N_2O, SF_6
7	Lutjewad	LUT	Ground	CH_4
8	Pallas	PAL	Ground	CH_4
9	Puy de Dôme	PUY	Ground	CH_4, (CO_2) N_2O, SF_6
10	Trainou	TRN	Tall tower	CH_4
11	Voeikov	VKV	Ground	CH_4

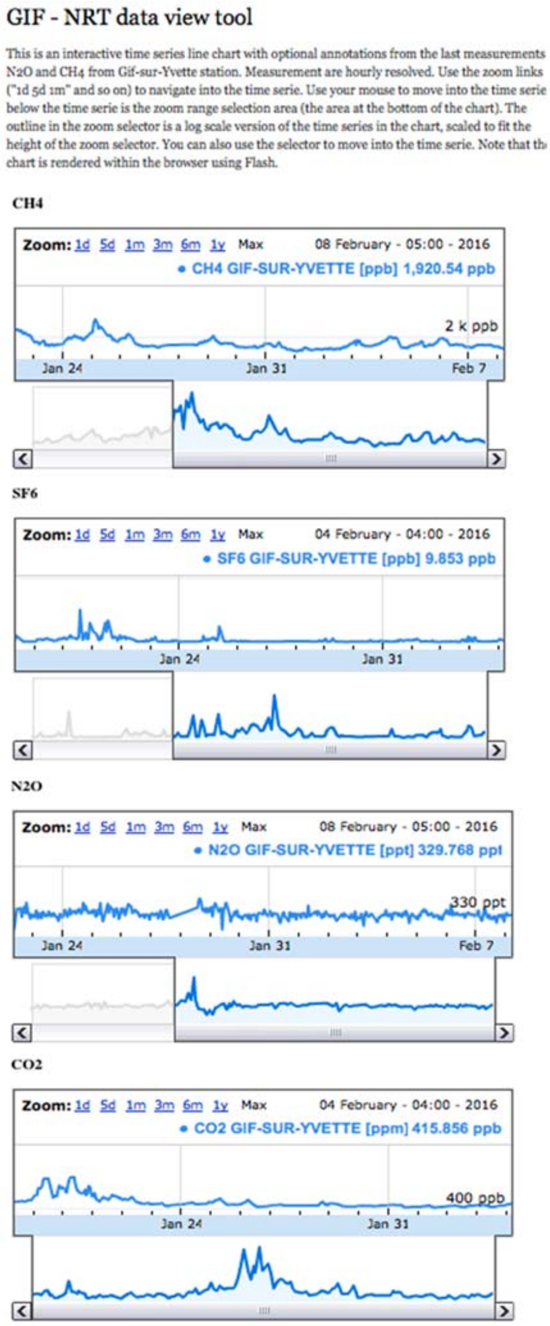

Figure 1.3.13: Example of the NRT data for Gif-sur-Yvette station.

and the interaction between the individual sites and teams, and fostered a culture of co-operation. They led to unique data sets, which were harmonized and comparable for the first time, and also several good practice guidelines. InGOS developed a long-term perspective by preparing the integration of the NCGHG measurements into the Integrated Carbon Observation System (ICOS). Almost 130 Scientists from 18 European Countries joined these activities, from which 40% came from institutes and companies outside the InGOS consortium (see Fig. 1.3.14).

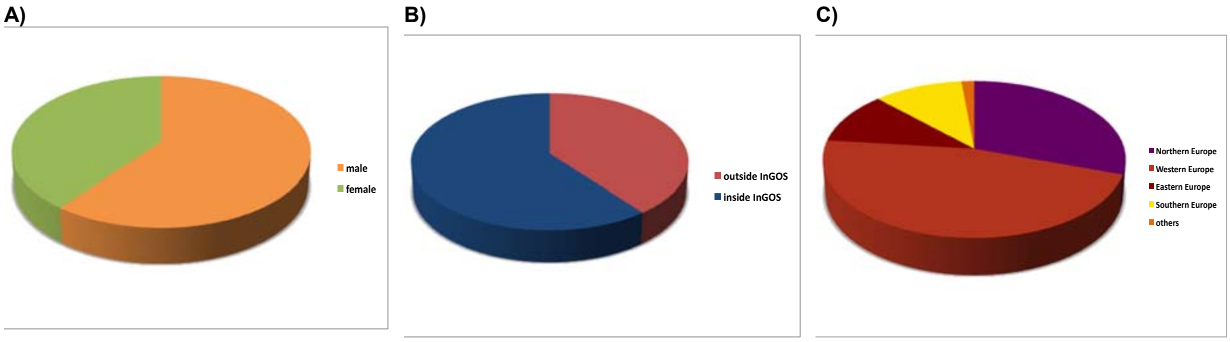

Figure 1.3.14: statistical overview of users regarding A) gender, B) InGOS affiliation, C) country grouping.

The gender of participating scientists was almost balanced with 40 % female and 60 % male. A clear majority of 47%, respectively 30% came from Western (NL, FR, DE, CH, BE, and AU) and Northern (SE, NO, GB, IE, FI, and DK) Europe, particularly Germany and Great Britain, 11% each from Southern (PT, IT, and ES) and Eastern (PL, HU, and CZ) Europe, dominated by the Czech Republic and Poland, respectively Spain and Italy.

The provision of facilities was quite successful, but showed some diversity (Fig. 1.3.15). In total more than 2800 research days were offered by the measurement sites. Several stations had provided most of their capacity for access already at the end of the second reporting period. A few stations were less attractive for users, which resulted in a reorganization of duties and budgets within the last project period. The facilities for providing calibration gases and the isotope analyses have been used extensively by both external and project internal users, up to and beyond the capacity of the providers.

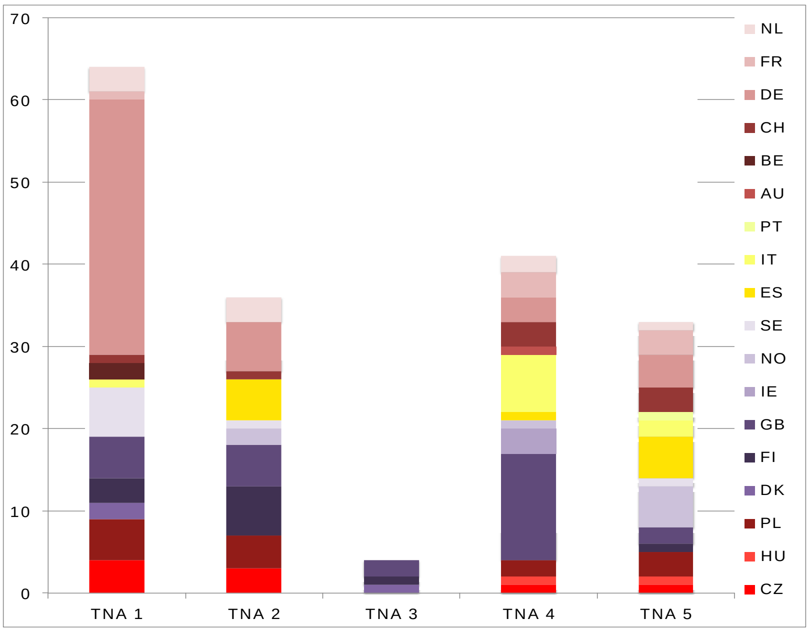

Figure 1.3.15: statistical overview of users projects, the number of scientific projects are separated by Transnational Activities. The country grouping is based on the statistics of the United Nations: https://unstats.un.org/unsd/methods/m49/m49regin.htm

More than 2300 isotope measurements have been done, and more than 200 calibrations of standard gases or re-assignments of them. The airborne observation platforms generated quite some interest, and although the one planned by WUR was inoperable and has finally be canceled, more than 50 flight hours were realized.

Provide capacity building in new member states and countries with inadequate existing infrastructure and expand the current network with new stations in under sampled regions

InGOS started with a consortium of 34 partners from 14 European countries. It is obvious from Fig. 1.3.16 that Southern and especially Eastern Europe are less involved than Western and Northern Europe.

Figure 1.3.16: a) country distribution and number of partners within the consortium

During the project the consortium expanded the transnational measurement facilities by two more stations in Spain, maintained by the University of Granada (UGR, http://ecologia.ugr.es/?lang=en, Padul) and the Institut Catalá de Ciéncies del Clima (IC3, http://www.ic3.cat, Ebre Delta).

Figure 1.3.17: Padul station and instruments

The two new stations Padul and Ebre Delta complemented the original stations, and were visited quite well.

Padul (Fig. 1.3.17), at 37˚N, 3˚W, is an experimental site at a wetland of about 0.7-0.8 km2 near El Padul, a village in the province Granada, southern Spain, and located within the Sierra Nevada National Park. This wetland lies in the Padul valley at an elevation of 744m and has recently been included in the Ramsar Convention for Wetlands. The vegetation cover is dominated by Phragmites sp. There is a lake resulting from discontinued peat extraction activities that now provides a valuable bird habitat. Below the surface and drainage channel network, the wetland contains peat layers of close to 100 m thickness in the North-East. The wetland area has been altered over the past decades including drainage for small-scale agriculture, peat extraction, and eutrophication from surrounding human activities. A highly variable water table during the annual cycle is a result of strong seasonal discharge from spring snow melt in the mountains, human intervention (changes in hydrology), and the semi-arid warm climate including an extensive dry period in summer. An eddy covariance tower was installed the beginning of 2013 for measuring ecosystem CO_2, H_2O, CH_4 and energy fluxes, together with meteorological and soil state instruments for measuring net radiation, photosynthetic photon flux density, air temperature and humidity, soil temperature, soil heat flux and water table level.

Figure 1.3.18: Ebre River Delta station and instruments

The station at the Ebre River Delta Natural Park (Fig. 1.3.18) is located in the province of Tarragona (Catalonia), in northeastern Spain (40°N, 1°E). It is a costal site and the region can be described by a typical Mediterranean climate: high temperatures (25.4 ºC average temperature in July 2012) and drought in summer (29.5 L/m2 rainfall between June and August 2012). The station was inaugurated in May 2012 and since then it is up and running. It is a site for greenhouse gases, ecosystem and climate observations. Ebre River Delta Natural Park is one of the largest wetland areas (over 300 km2) in the western Mediterranean region. It is a flat area characterized mostly by rice fields, which is the main agricultural product of the area, and reeds. The station is located next to the Canal Vell biological station where all year round scientists work to preserve the Mediterranean wildlife. The industrial pole of the city of Tarragona is located at 80 km from the station.

Besides this, CzechGlobe (http://www.czechglobe.cz/en/) and RADO (entered the InGOS consortium as an associated partner, actively participating and collaborating in the project by joining activities. Especially CzechGlobe, which is also involved in several other EU projects such as ICOS, GMOS and ACTRIS, participated in measurement campaigns and offered access to their atmospheric station facilities K□ešín and Pacova, and also to the Ecosystem station facilities Tr□bo□ and Lan□hot.

In the InGOS/ICOS/TTorch Summer Schools in 2013 and 2015 several students and scientists from non-InGOS and/or non-ICOS member states participated, thereby contributing to the build up of capacity in these countries (Lithuania, Estonia, Iceland, China, Japan, Hungary, Poland, Denmark, United Kingdom, Czech republic)

An additional desirable expansion would have been into the direction of the neighboring countries of the Baltic Sea and the Adriatic Sea

Stimulate atmospheric science knowledge transfer between experts, and between experts and young scientists

Knowledge transfer is a key issue of international projects and indispensable to increase quality and progress of science. InGOS fostered the knowledge transfer on several levels and by different activities such as networking and the availability of research communities. InGOS involved more than 200 scientists within Europe, from different disciplines and with different experiences. Within the project scientists were open for questions and discussions and therefor the threshold for getting in contact was relatively low. An important role of InGOS was to integrate the communities that deal with different observing platforms. InGOS also integrated communities that until now focused on one or more clusters of different greenhouse gases (group of (CO_2,) CH_4, N_2O, SF_6 resp. halocarbons, resp. Hydrogen, resp. related tracers). Furthermore the network made a significant contribution in the combination of very different fields of science, e.g. measuring and modelling, in one infrastructure project, which allowed establishing an overall picture of NCGHG emissions over Europe.

The use of international measurement stations and the unique combination of marine, terrestrial ecosystem, satellite and tall tower research brought teams of senior and junior scientists together with maintaining staff members from other labs, other experiences and scientific approaches. In InGOS the main focus was a solid infrastructure foundation as a common basis for all groups and research. Joint harmonization, quality control and improving data quality and accessibility for current and future research were the main tools to establish this. InGOS actively promoted young/new scientist to participate, either through the capacity building transnational activities or otherwise by joining the several workshops and meetings held during the project.

Also the InGOS/ICOS/TTorch Summer Schools in 2013 and 2015 formed an excellent opportunity for exchange of scientific knowledge between experts and young scientists. While preparing the InGOS periodical meetings the organising committee always reserved about 50% of the plenary talks for young scientists.

Another measure to ensure knowledge transfer is the public access to the InGOS data, ensured by the InGOS data centers and the close connection to other data bases or European projects such as ICOS, TCCON, AGAGE, MEMENTO, Fluxnet and ACTRIS

1.4 Potential impact and the main dissemination activites

InGOS as a project with more than 200 participating scientists and staff members from 14 countries has developed a unique network in its scientific field of climate research. InGOS combined atmospheric, terrestrial and oceanic research and focussed on the main non-CO_2 greenhouse gases CH_4, N_2O, SF_6 and halocarbons, and H_2. The impact of InGOS is exceptional and based on the international and interdisciplinary character, which enables and support scientists in collaborating within a diverse consortium and to work "out of the box" of their own research field. For the first time a project included all relevant aspects to investigate climate change such as harmonization and intensive quality contraol of as well historical as actual data, long-term monitoring of relevant gas species on a European level, intercomparison of measurement methods and development of new methods, provision of standardized good-practise guidelines, combination and verification of several modelling techniques with remote sensing and measurement data, quantification of sources by using isotopes, or assessment of non-CO_2 GHG budgets at spatial scales by eddy covariance and flux-gradient techniques. The combination of these very different fields of science in one infrastructure project allowed establishing an overall picture of non-CO_2 greenhouse gas emissions over Europe.

Synergy with policy makers

InGOS supported informed decisions in climate change and international emission reduction protocols for non-CO_2 greenhouse gases and research strategies to respond to both the future political, societal and economic challenges and the development of scientific knowledge. InGOS made significant impact on many areas related to research and development, as well as the development of European environmental policies. InGOS delivered relevant scientific results and involved scientist functioned as authers and reviwers of international reports and assements. They were engaged with policy makers on local governmental, national and international level to advise them, e.g. on

- Stratospheric ozone–depletion and mitigation strategies to protect the ozone layer
- General greenhouse gas emissions and mitigation strategies
- Monitoring and emission verification of greenhouse gases
- Briefing of the DG Climate Action on verification of greenhouse gas inventories reported to UNFCCC
- Environmental regulation of greenhouse gases and mitigation options for agriculure

Several scientists of the InGOS network were not only involved in the 5th IPCC report (2014) but also in the new UNEP/WMO Ozone Assessment for Decision-Makers (2015) and finally contributed to the successful 2015 United Nations Climate Change Conference in Paris (COP21).

It is likely that emission reduction in non-CO_2 greenhouse gases will be more cost-effective than most CO_2 emission reduction measures and will lead to quicker wins in actual decrease of global warming. The observation capabilities developed in InGOS allows to independently verify and also control the claimed emission reductions, and increasing the trust of the public and policy makers in the measures taken. By this InGOS clearly creates output such as expertise and scientific advice, which could be used by policy makers.

Building scientific knowledge and knowledge transfer

InGOS played an important role in integrating communities dealing with different observing platforms and those focused on one or more clusters of different greenhouse gases, and supporting their collaboration. Furthermore the network made a significant contribution in providing data for satellite data validation. Bringing these teams together in dedicated RTD projects has proven to be difficult, because of the cutting-edge scientific questions these RTD projects are addressing. In InGOS however the main focus was a solid infrastructure foundation as a common basis for all groups and research. Joint harmonization, quality control and improving data quality and accessibility for current and future research were the main tools to establish this. The unique combination in InGOS of marine, terrestrial ecosystem, satellite and tall tower scientists contributed to the advancement of science in a broad sense and enhanced further the leading position of Europe. In the course of the project the number of peer-reviewed publications and other dissemination activities increased significantly to more than 300 and will also last beyond the project (Fig. 1.4.1, see also Chapter 2 for a list of publications and dissemination activities). Due to on-going experimental work, data evaluation and writing activities several publications are expected in the near future.

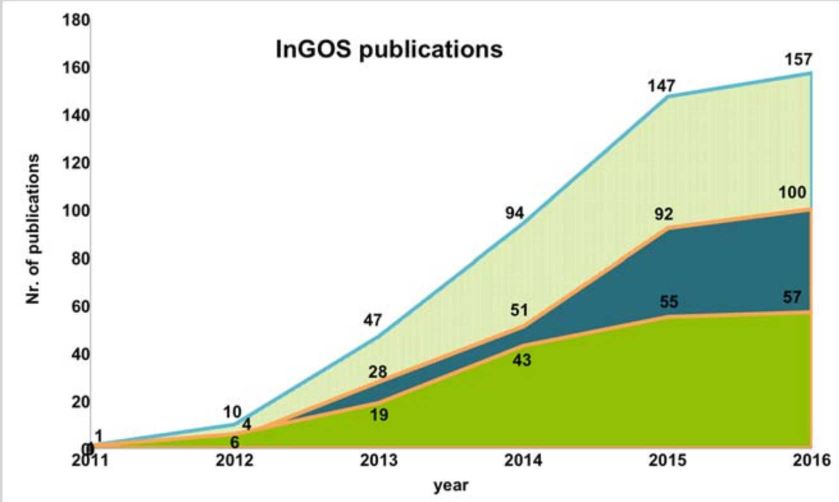

Fig. 1.4.1: Number of peer–rewieved publications until January 2016, Please note: here we differentiated between publications acknowledging InGOS for financial support (blue field) and InGOS related publications (green field). Although InGOS is not officially acknowledged in “related” publications for financial funding, several PI´s of InGOS were either involved as co–authors or collaborates with the authors, or facilities or data bases of InGOS were used. So these publications are closely connected to InGOS by contributions of the InGOS consortium. The total number of InGOS publications (light green field) sums up to 157 in January 2016.

The reached network and its scientific results are outstanding and the work of InGOS, particularly the interdisciplinary collabora-tions, has led to significant development in all disciplines and is not limited to InGOS. As an example, the access to measurement facilities was also appreciated by researchers outside the consortium and led to several new collaborations, and the developed guidelines of good practice or the recommendations for instrumentations have been taken up by other projects such as ICOS, e.g. for consideration of instrument choices or measurement methods. Knowledge transfer was also provided by offering workshops, summer schools and training at the measurement sites and labs in observation techniques and data processing, open also for participants outside the InGOS consortium. This snowball effect leads to an on-going scientific synergy, which could never be reached by individual projects.

InGOS created not only scientific synergy but also educational synergies and a close engagement with civil society. The most common synergy was the education and supervision students. The society was invited to participate in several public events, e.g the Royal Research Ship Discovery (http://www.nerc.ac.uk/press/releases/2015/06-discovery/), the Royal Holloway Science Festival (https://www.royalholloway.ac.uk/science/sciencefestival/home.aspx), or several University researcher nights. Climate change was also a topic at LONCON3, the 72nd World Science Fiction Convention (http://www.loncon3.org/documents/ReadMe_LR.pdf). Those activites ensure not only the education of future scientist but also attract the interest of the public for important subjects such as climate change and will led to a better knowledge and understanding, and an increased acceptance of needed measures.

Despite the more research orientated character of the project, InGOS has quite a few exploitable products. For the application of automated flux measurement chambers as an exploitable foreground the University of Amsterdam did engage with nature conservancy organizations Landschap Noordholland and Natuurmonumenten. For a mobile CH_4 source mapping system, they engaged in 2014 with the municipality of Amsterdam, Amsterdam Firebrigade and a gas distribution company. Following on from InGOS support, the University of Edinburgh has received an additional one million euros from Research Councils UK to support the development of our Differential Absorption LiDAR. This has included funds to combine the InGOS CH_4 laser system with a laser capable of detecting atmospheric CO_2. We have also had support to ruggedise the system so it is field deployable. Scottish Enterprise (a non-departmental public body of the Scottish Government) has recently awarded the university of Edinburgh with Phase 1 funds to become part of their ‘High-Growth Spin-Out Programme’ with a view to becoming a spin-out company with a turnover target of at least 7 million euros by 2018-19.

The improvements of the Spectronus instruments have found their way into a new version of the instruments and other findings have led to major improvements and new instrument versions at several of instruments (Picarro, LGR).

Data provision to a broad scientific community

As mentioned above, measurements and data collection within an international and interdisciplinary project aiming on collaboration and joint activities to increase knowledge are useless for the scientific community without availability and accessibility of the data. The archiving of the data, metadata and uncertainties in the atmospheric data center ensure the traceability and the documentation of several European historical and actual time series, and the INGOS datasets will be available to the whole scientific community also outside the InGOS consortium. The data collected in the context of InGOS are now part of a larger database and infrastructure that will ensure their availability also in the future. This guarantees a higher impact of the project results, in particular for the comparison campaigns. The development of specific components of the ecosystem database dedicated to the non-CO_2 GHGs exchanges measurements forms an important basis for the ICOS ETC development where non-CO_2 gas fluxes are also an important component.

Making the multi-species concentration and flux data available the InGOS data centers were facilitated through research on the NCGHG budgets, transport mechanisms and ecosystem/atmosphere interactions throughout Europe. The databases of integrated projects like CarboEurope-IP, CarboEocean and NitroEurope-IP are already being used by researchers all over the world, leading to many new insights in the Earth System. These data are used to make environmental assessments, validate model calculations or evaluate effectiveness of greenhouse emission reduction options, and providing these data was an important role of the InGOS data center. InGOS added both the halocarbons and new CH_4, N_2O, SF_6, H_2, and CO data to the already available data and became a ‘gateway’ to European measurements of the non-CO_2 greenhouse gases.

Independent emission evaluation

International agreements on reduction of greenhouse gas (GHG) emissions require accurate accounting of GHG emissions and therefore rely on very accurate atmospheric measurements and are very sensitive to modelling errors. Both issues were addressed in InGOS.
InGOS offers unique harmonized and quality controlled datas sets which are of particular importance since they show global trends of greenhouse gas concentrations and emissions, and can reliably be merged for inverse model calculation of regional or continental-scale GHGs fluxes. The data produced within InGOS significantly increase the quality of monitoring activities and also of modeling approaches, which are used as official validation for GHGs emissions changes. The ^{222}Rn data harmonization as well as the implementation of correction factors that can be applied to future measurements, e.g. in the framework of ICOS-RI, improve the reliability of regional transport models. InGOS enhances the capabilities of the inverse modeling work and demonstrate both the importance and the feasibility to verify bottom-up inventories of non-CO_2 GHGs emissions by atmospheric observations and inverse modelling. This necessary for independent assessments of European emission and concentration levels as a valuable tool both for policy development and evaluation of implemented measures.

Understanding trends and linking satellites

InGOS supported key representative measurement stations and ensured comparability of results, both leading to a better understanding of flux and concentration trends at the continental level. InGOS further developed innovative ground-based measurements complementary to satellites. Remote sensing observations of atmospheric greenhouse gases from the ground as well as from space are available since about 10 years and their potential (retrieval as well as information content) is not fully exploited. Within InGOS ground-based data and satellite fields were integrated in advanced simulation models and led to new data products for non-CO_2 greenhouse gases. The results have major impact on the development of the remote sensing measurements of atmospheric greenhouse gases and their improvement.

Currently the first generation of satellite instruments dedicated to atmospheric greenhouse gas observations is in orbit and the data products developed in InGOS will help future satellite missions to provide atmospheric greenhouse gas data with higher precision and accuracy. The new data product allows separating the stratospheric and tropospheric CH_4, which has been proven useful for model validation and also provides a direct link to the in situ measurements. This link is difficult to establish with the column averaged data product because of the uncertainties of stratospheric CH_4, which is commonly not measured by the in situ measurements. It has been shown that remote sensing measurements are able to detect deficiencies in the models that are tailored to in situ data and a common use of in situ as well as remote sensing data should be used to constrain models. The results of InGOS cleary improved the quality of this methodological approach. Besides this a QA/QC procedure for the instrumental characterization using gas cells has been developed and implemented. This procedure has now been adopted by the global network, which demonstrates the impact of InGOS on the international community.

Within InGOS also the influence of scene specific parameters on the satellite retrievals has been investigated. The dataset produced during InGOS is widely used, especially for the validation of satellite retrievals, which have improved accordingly.

Enhancing the observational capacity of Europe

„Taking emission reduction measures without monitoring is like going on a diet without weighing yourself" (Ray Weiss, SAB member InGOS).

Without long-term monitoring it is not possible to quantify and verify measures of climate change mitigation strategies. Mitigation of climate change is a key scientific and societal challenge. The 2015 United Nations Climate Change Conference in Paris (COP21) agreed to significantly limit global warming and reaching this target requires massive reductions of greenhouse gas emissions. However, several greenhouse gas emissions, e.g. CH_4 are not well quantified and there are significant discrepancies between official inventories of emissions and estimates derived from direct atmospheric measurement. Therefore, new advanced combinations of measurement and modelling are highly needed as well as a long-term observation of greenhouse gas emissions and fluxes. Both are indispensable to ensure quantification and verification of emission reduction and mitigation efforts. InGOS contributed to the latter by the expansion of the observation capacity of NCGHGs in Europe on several levels: I) through access to a dense network of more than 20 European measurement facilities, II) calibration and measurement services, III) including isotopic analysis, eddy covariance measurements and footprint models to verify greenhouse gas sources and sinks, or VI) knowledge transfer by training activities also for external participants. The provision of working standards and participation in intercomparison experiments together with the data harmonization activities allowed the build-up of a dense operational European measurement network, significantly improved the provision of international comparable data and ensured that new monitoring stations were linked to the required QA/QC level of InGOS.
Last but not least InGOS contributed also to keep several European measurement stations such as the TCCON sites operational. The European part of TCCON relies financially on short-term projects, which makes needed long-term oberservations difficult. Currently the European part of TCCON has funding problems. Neither the Copernicus programme, nor ESA nor the national space agencies are currently supporting the operation of the European TCCON sites. Hence some of the sites could only be operated partly due to support received through InGOS, by freeing resources for actual operations.

Verification of sources and detection of new climate relevant gases

Effective emission reduction can only be achieved if sources are properly quantified, and tools exist to independently verify mitigation efforts. The analytical developments to measure isotopic compositions achieved in INGOS allow a better quantification of the relative contributions of different source categories to the atmospheric greenhouse gas budgets, and contribute to verification of mitigation efforts that are required to reach the global warming targets. The development of instruments that are capable of measuring the isotopic composition of e.g. methane in the field is a key step forward towards a better quantification of the European and global CH_4 budget and are expected to find wide use in the future. E.g.

the measured CH_4 emissions at the Cabauw tall tower are dominated by agricultural sources, but variations in the source signatures allow identification of events with increased contributions from fossil fuel and landfill sources. The implementation of isotope data in models show that modeled source signatures could cause an over– or underestimation of different sources, whereas the differences in the source signatures appear to originate from differences in the inventories and not from differences in the models. By those result InGOS helps to improve the validation of variations in the source mix and therefor the control of mitigation measures.

Besides the verification of sources also new climate relevant gases were found, which has social impacts in several aspects. The detection of previously unidentified CFCs and HCFCs by Laube et al. (2014) marked a turning point in the analysis of these ozone-depleting substances in the atmosphere. Until then only CFCs and HCFCs were detected which had been released either during the production or usage of consumer goods, such as foams and refrigerators. However, with the detection of CFC-112, 112a, 113a, and HCFC-133a this paradigm has changed. These gases were never produced in large quantities for consumer products and hence the conclusion was made that they were unintentional by-products of the production of HFCs. Disturbingly, emissions of some of these gases were found to have been increasing in recent years, which might be caused by less careful production processes. Second, a new class of compounds (HFOs, hydrofluorolefines) was detected within InGOS by Vollmer et al. (2015c) for the first time in the atmosphere at Jungfraujoch. HFOs have a very small atmospheric lifetime and are therefore foreseen as the major replacement compounds for the long-lived HFCs, with their large impact on climate. Measurements of HFOs, which started in 2011, showed no detectable background concentrations for these compounds. However, within the course of the InGOS project the picture changed completely. From being detected only during sporadic pollution events, two of these compounds (HFO-1234yf and HFO-1234ze(E)) can now regularly be measured above the background and concentrations are rising constantly. This example shows in a striking way the ability of the measurements of halocarbons within InGOS to detect new gases and to act as an early-warning tool both on the European and the global scale.

1.5 Website

The website of the project was maintained by the project coordinator and served as a central platform within and outside the consortium. It ensured the dissemination of project relevant information, results, and access to TNA´s.

For sensible information the website contained a to the consortium restricted area, including general project documents (e.g. Grand Agreement, Consortium Agreement), deliverables, reports, presentations, and minutes of meetings. The website can be found at: http://www.ingos-infrastructure.eu/.

1 **Figure 1.5.1: start page of the InGOS website**

2. Use and dissemination of foreground

In the course of the project the number of peer-reviewed publications and other dissemination activities increased significantly to more than 300 and will also last beyond the project (see also Fig. 1.4.1).

InGOS was very successful regarding publications and dissemination actitivies. A full list of dissemination activities is shown in the 3rd Periodic Report, here only peer-reviewed publications are listed because of page limitation. Due to on-going experimental work, data evaluation and writing activities several publications are expected in the near future.

Please note: it has been differentiated between publications acknowledging InGOS for financial support and InGOS related publications. Although InGOS is not officially acknowledged in "related" publications for financial funding, several PI´s of InGOS were either involved as co-authors or collaborates with the authors, or facilities or data bases of InGOS were used. So these publications are closely connected to InGOS by contributions of the InGOS consortium.

Section A: publications

Peer-reviewed publications (InGOS acknowledged)

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Peer-reviewed publications (InGOS related)

Although InGOS is not officially acknowledged in “related” publications for financial funding, several PI´s of InGOS were either involved as co-authors or collaborates with the authors, or facilities or data bases of InGOS were used. So these publications are closely connected to InGOS by contributions of the InGOS consortium.

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Section B: exploitable foreground

Two public exploitable foregrounds resulted from InGOS, a pneumatic chamber system for CO_2 and CH_4 flux measurements, and a data logging system for cavity ring–down laser systems.

Type of exploitable foreground	Exploitable foreground (description)	Exploitable products of measures	Sector of application	Timetable comercial / any other use	Patents / IPR exploitation (licenses)	Owner / other beneficiaries involved
General advancement of knowledge	Pneumatic automated chamber system for measurement of CO_2 and CH_4 fluxes from wetland soils. Measurement of greenhouse gas fluxes from wetland soils is difficult because of the high risk of measurement disturbance by induced ebullition of soil gases due to people moving around at the measurement location. This causes overestimation of fluxes. An automated, pneumatic system reduces this risk considerably by preventing any disturbance of soft soils during measurements.	Pneumatic automated chamber system for measurement of CO_2 and CH_4 fluxes from wetland soils.	Greenhouse gas flux measurements of wetlands	Ready for use, application in measurement projects ongoing	None	VU University, Noordhollands Landschap, Natuurmonumenten (Nature conservancy organizations)
General advancement of knowledge	Data logging system for mobile application of cavity ringdown laser systems for measurement of CH_4 including CH_4-C stable isotope ratio	Data logging system for mobile application of cavity ringdown laser systems for measurement of CH_4 including CH_4-C stable isotope ratio	Landscape scale greenhouse gas source mapping	Immediate use	None	Owner, Municipality of Amsterdam, Gas distribution company Liande

3. Report on societal implications

A detailed report on the societal implications of InGOS has been submitted electronically. Please find here a short summary of the relevant key themes.

Ethics

InGOS was not involved in research related to any ethical issues.

Workforce statistics

Almost 230 scientists and staff members were involved in InGOS, from which approximately 20% non-scientific staff members and 80% researchers. 25% of the researchers were early stage researchers (PhD students), the marjority were experienced researchers. Only a small number of people were specifically hired for the project (13%).

	women	%	men	%	total	%
scientific coordinator	0	0	1	1	**1**	0
WP leader	3	4	14	10	**17**	7
experienced researcher (postdoc)	36	43	82	56	**118**	52
PhD student	24	29	18	12	**42**	18
other	20	24	31	21	**51**	22
total	83	36	146	64	**229**	
Extra hired for InGOS	14	6	16	7	**30**	13

Gender aspects

Several partner institutions have gender equality programs and gender balance is promoted in general. InGOS as a project has not specifically implemented dedicated gender balance activities, but promoted equal opportunities. The number of specifically recruited researchers is almost gender balanced with 47% women and 53% men. However, this gender balance is not given for the marjority of already recruited researchers. Here InGOS shows a distribution of 36% women and 64% men.

Synergies with Science Education

InGOS actively promoted young/new scientist to participate, either through the capacity building TNA or otherwise, joining workshops and meetings. Most partners showed a clear synergy with scientific education and an engagement with civil society. The most common synergy was the education of bachelor and master students by lectures, practical excersices and excursion and the supervision of PhD students. Students were involved in the on-going research work or invited to scientific presentations. They learned about project organization, measurement methods and got familiar with equipment. Besides this several partners participated in visiting high schools to e.g. discuss greenhouse effects and new gases or giving interactive experimental lectures on solar radiation. The society was invited to participate in several public events, e.g the Royal Research Ship Discovery with guided tours for policy makers and groups of pupils, researcher nights, or the Royal Holloway Science Festival (https://www.royalholloway.ac.uk/science/sciencefestival/home.aspx).

Climate change was also a topic at LONCON3, the 72nd World Science Fiction Convention (http://www.loncon3.org/documents/ReadMe_LR.pdf)

Interdisciplinary

InGOS was highly interdisciplinary, and the main scientific disciplines belong to natural sciences, engineering and technologies, and agricultural sciences. Especially within natural sciences all associated disciplines were involved, i.e. mathematics and computer sciences, physical, chemical and biological sciences, and earth and related environmental sciences. To a smaller amount also electrical engineering and electronics as well as agricultural and allied sciences were involved.

Engaging with civil society and poliy makers

See chapter 1.4.

Use and dissemination

InGOS is related to more than 150 peer–reviewed publication, the marjority provides open access. The main reason for not providing open access are unavailable funds for open access and that the publisher´s licensing agreement would not permit publishing in a repository. Within InGOS were no patents or trademarks created. One spin–off company has resulted from technical inventions.

Media and communication to general public

Within InGOS no beneficiaries were professionals in communication or media release and only a few have received training or advice, however, not dedicated by InGOS but by their own institutions. Project results and information have been communicated mainly via the project website (http://www.ingos-infrastructure.eu). Besides this communication took place by several print and internet based media: via youtube (https://www.youtube.com/watch?v=gPGbl5zpb1w), TV/radio coverage, and coverage in general/national/international press. Press releases were related to relevant events such as the InGOS International Conference on non–CO_2 Greenhouse Gases (2015, or important scientific findings, e.g. the findings of new ozone–depleting compounds (http://www.theguardian.com/environment/2014/mar/09/ozone-hole-antarctica-chemicals) or unexpected high N_2O concentrations in the Southeast Pacific (http://phys.org/news/2015-06-southeast-pacific-nitrous-oxide-previously.html).

4. Statement on the use of resources

InGOS was an international EU Infrastructure project running for 4 years. It included almost 230 scientists and staff members at 37 partners and had a total EU contribution of 8 million €. Approximately 2 million € were contributed by the partners. Table 4.1 gives an overview of the initial budget; Table 4.2 shows the percentage of recources claimed in the specific cost categories and activities. In the course of the project the budget was predominantly used as foreseen, whereas most of the budget was spend for salaries and for indirect costs, which are structural and support costs of administrative, technical and logistical nature (overheads). These costs were overspent according to Annex I, especially in the RTD cost category. Access costs were less than expected, as well as the management costs. In total the budget is balanced.

Table 4.1: initial overview of total resource use per cost category and activity category

Original budget according to Annex I	RTD (A)	Coordination (B)	Support (C)	Management (D)	Other (E)	Total (A+B+C+D+E)
Personnel costs	2048346.00	1532618.00	0	343856.00	0	3924820.00
Subcontracting	37000.00	120000.00	0	59500.00	0	216500.00
Other direct costs	392439.00	358572.00	259423.00	339378.00	0	1349812.00
Indirect costs	1661986.20	1068917.20	87580.40	255398.00	0	3073881.80
Access costs	0	0	1540916.98	0	0	1540916.98
Lump sums/flat rate/scale of unit declared	0	0	0	0	0	0
Total	4139771.20	3080107.20	1887920.38	998132.00	0	10105930.78
Maximum EU contribution	3047326.65	2143085.84	1811454.69	998132.00	0	7999999.18

Table 4.2: percentual overview of used resources per cost / activitiy category according to the original budget (Annex I)

Percentage of claimed budget according to Annex I	RTD (A)	Coordination (B)	Support (C)	Management (D)	Other (E)	Total (A+B+C+D+E)
Personnel costs	119	100	*	117	0	116
Subcontracting	100	68	0	92	0	80
Other direct costs	110	110	56	42	0	82
Indirect costs *	113	100	158	85	0	108
Access costs	0	0	85	0	0	85
Lump sums/flat rate/scale of unit declared	0	0	0	0	0	0
Total	116	100	93	81	0	103
Maximum EU contribution	116	100	90	81	0	101

* a previously unallocated amount of 157k€ for personell costs have been spent in “support”

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InGOS consortium:

Number	Name	Country
1	Energy research Centre of the Netherlands	NL
2	Max Planck Gesellschaft	DE
3	Swiss Federal Laboratories for Material Science and Technology	CH
4	Atomic Energy and Alternative Energies Commission	FR
5	University of Bristol	UK
6	University of East Anglia	UK
7	Ruprecht Karls University Heidelberg	DE
8	Utrecht University	NL
9	Royal Holloway University of London	UK
10	University of Bremen	DE
11	University of Helsinki	FI
12	Technical University of Denmark	DK
13	University of Edinburgh	UK
14	Joint Research Centre of the European Commission	BE
15	Natural Environment Research Council	UK
16	Finnish Metereological Institute	FI
17	Tuscia University	IT
18	Johann Wolfgang Goethe University of Frankfurt am Main	DE
19	Norwegian Institute for Air Research	NO
20	Kalsruhe Insitute of Technology	DE
21	University of Lund	SE
22	National Institute of Agronomic Research	FR
23	Met Office	UK
24	AGH University of Science and Technology	PL
25	University of Leicester	UK
26	VU University of Amsterdam	NL
27	Hungarian Metereological Services	HU
28	University of Groningen	NL
29	Poznan University of Life Sciences	PL
30	Leibniz Insitute of Marine Sciences	DE
31	Spanish National Research Council	ES
32	University of Bergen	NO
33	Service Agricultural Sciences	NL
34	University of Granada	ES
35	University of Exeter	UK
36	Institute of Marine Sciences of Andalusia	ES
37	Catalan Institute of Climate Sciences	ES