3rd Periodic Report

Project Summary

Covered period: 01/10/2014 – 31/12/2015
Grant Agreement Number 284274

Integrated non-CO_2 Greenhouse gas Observing System

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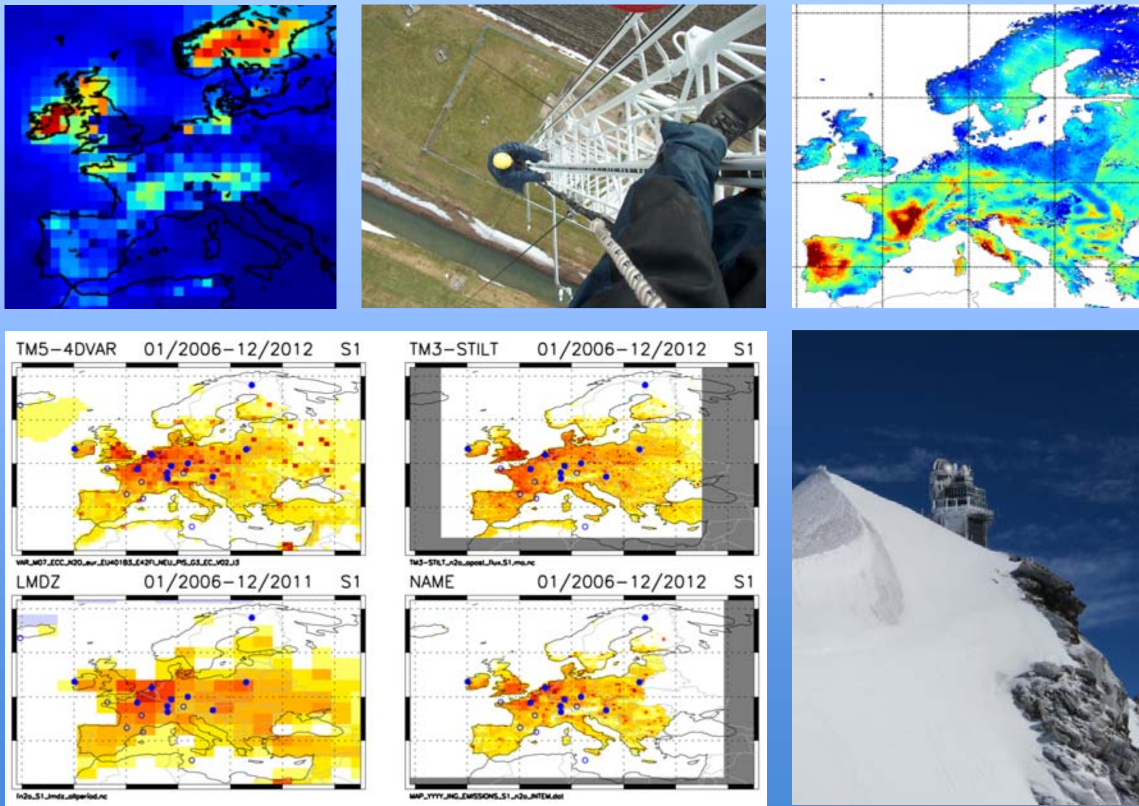

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Table of contents

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Project summary

1 Project background

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. Measurements of CO_2 were initiated in the 1950s at the South Pole and at Mauna Loa, Hawaii, while systematic measurements of NCGHGs started in the 1980s.

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.

2 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 allows 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 shows 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 Observing 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 demanded to ensure 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.

3 Project structure and description of work

The overall strategy to achieve the objectives of improved data quality, coverage and availability was based on strengthening (using network activities, NA), outreach/cooperation (using trans-national access, TNA and service activities, SA) and innovation (using joint research activities, JRA). These activities were divided into 18 work packages, which are executed by initially 34 partners all over Europe. 3 more were added in the course of the project. 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 (NA, work packages 1 to 6)** 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 (TNA, work packages 7 to 11)** 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 (SA, work package 12)** 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 (JRA, work packages 13 to 18)** 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 consortium got external scientific advise from the **Scientific Advisory Board.** Three international experts on this field were assessing the progress of the project and gave external advice. Members were Prof. Dr. Ray Weiss (Scripps Institution of Oceanography, San Diego), Prof. Dr. Adrian Simmons (European Centre for medium–range weather forecast, ECMWF), and Dr. Ed Dlugokencky (National Oceanic and Atmospheric Administration, NOAA).

4 Main results and achievements of the 3rd project period

4.1 Project Management (WP1)

- The **2nd Periodic Report** was submitted in time (30.11.2014) and the scientific part was accepted as it was. The TNA tables and the financial reports were accepted after corrections for some partners. Due to insufficient information content several deliverables were rejected, but accepted after adjustment. To ensure a consistent level of details an adjusted template was provided to the partners in charge.

- The third tranche of the budget was transferred to ECN in June 2015 and with some reallocations transferred to the partners in November 2015. The finances will be discussed in more detail in Chapter 6 (statement on the use of resources).
- Several **amendments** (eight in total) have been prepared during the 2nd period and finally accepted in March 2015. This process took more than a year and led to a delay in the TNA activities of the new beneficiaries. Mainly for this reason the project was prolonged by three months until 31.12.2015.
- **Communication strategies** were from the start of the project on focused on the InGOS website (http://www.ingos-infrastructure.eu) which has served well in informing the users and the partners on the project. The website is up–to date and includes, besides general project information a consortium restricted area for the participants with general project documents (e.g. Grant Agreement, Consortium Agreement), EU guidelines, deliverables, reports, presentations, and minutes of meetings. Besides the website as a more general communication platform, the consortium met annually on an inter– and intra–work package specific level to exchange information and knowledge (see overview table 3.3.2). For administrative issues a general management email address (management@ingos-infrastructure.eu) ensured reaching the whole management team.
- The **Final Project Meeting** was associated to the InGOS International Conference on non–CO_2 Greenhouse Gases, held 21. - 24.09.2015 in Utrecht, The Netherlands. In total, almost 120 participants followed the events, which successfully concluded the InGOS project. The Final Meeting concentrated on finalizing the project including organization of the last deliverables and the upcoming reports. Only a brief summary of the results was given to inform the consortium about the general outcome of project. The detailed scientific presentations were reserved for the conference. Next to four keynote speakers more than 50 plenary talks and 30 posters presented the impressive results of research within and outside InGOS during the following days. The conference, prior to the political summit in Paris (COP21) in December 2015, generated quite some media attention on national radio and newspapers.
- **Project dissemination** of InGOS results was intensified during the 3rd period. As during the first periods time was spent to plan and execute the experimental parts and to implement the networks, the data and results were published during the following periods and will be published beyond the project end. The number of peer–reviewed publications and scientific dissemination activities increased in the last period significantly to more than 300, from which more than 150 were peer–review publications. InGOS was well represented at numerous occasions (related meetings, conferences, etc.) Note: Presentations on InGOS meetings and the International InGOS conference were not counted here.

4.2 Networking Activities

During the 3rd reporting period, **WP2** (NA2) finalized the methodology for correction of all historical CH_4, N_2O and H_2 measurements and – where available – included corresponding uncertainty estimates. All PIs submitted their data sets, which have then been jointly evaluated during five teleconferences and partly approved. Final approval of all data until end of 2014 will be in February 2016 in the framework of WP3. CH_4 and N_2O data have been used by WP15 for respective atmospheric inversions to estimate European fluxes of these GHGs. The ^{222}Radon and ^{222}Radon progeny comparison exercise, comprising nine European measurement stations has been finalized. A report of the results, including first estimates of disequilibrium between ^{222}Rn and its progeny for those stations, where one-filter systems are in use, has been delivered in a revised version in January 2016. A manuscript on the outcome of the comparison has also been completed. It will be submitted to Tellus B in January 2016, together with a second manuscript reporting 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/).

Within **WP3** (NA3) atmospheric measurements of CH_4, N_2O and H_2 have been continued at the InGOS stations following the good practice guideline developed in the 2nd Period. Quality controlled data from 18 stations including the year 2014 are available on the InGOS atmospheric database. These data have been evaluated during five teleconferences and were partly approved. Final approval of all data measured will be in February 2016. At most stations, new optical analysers, fulfilling the ICOS standards are operated in parallel or replacing the GC systems, which are difficult to maintain at remote stations.

The website for Near-Real-Time data is fully operational and hosts currently 12 stations. It turned out, that the realisation of the automatic transfer of computed concentration is more difficult for the station PIs than expected. The inter–comparison program circulating high pressure cylinders between three central lab and all InGOS stations runs routinely and results are reported on the webpage. During the annual meeting in Florence and Utrecht we discussed the results and the strategy for an inter–comparison program within ICOS.The feasibility study of a travelling instrument using a FTIR instrument for station audit is successfully documented in the paper from Vardag et al., 2014. Training activities have been carried out under Task 3.5 which are documented in the deliverable report D3.7

The halocarbon calibration gases, delivered by **WP4** (NA4) during the last period have been analysed and compared. A new tertiary standard is also compared with the working tertiary standard on-site, e.g. for SF_6 at Mace Head carried out for every compound (40 compounds) in every tertiary tank (16 tanks) and at each site (5 sites). Data from InGOS stations have been submitted to EBAS (Mace Head data is mirrored from CDIAC). In December 2015, the data for 2011, 2012 and up September 2014 are available through the database interface http://ebas.nilu.no. The data up to March 2015 will be submitted in February 2016. InGOS halocarbon data is also available in EBAS under the framework WMO GAW-WDCGG-node, which means that these datasets are made available for a WMO GAW-WDCGG ftp pull service. The round-robin activity is now complete, all stations have analysed the set of 4 comparison tanks. There were some unfortunate delays with this activity in reporting Period 3. The shipment of cylinder regulators did not arrive at UEA with the suite of Calibration cylinders, sent from GUF. This resulted in a considerable delay in carrying out the analysis at UEA. Eventually after 2 months, the courier company located and delivered the regulators. The cylinders were analysed (date) and then shipped to NILU. The inter-comparison results have been submitted to UoB. An online manual is available on the InGOS website. This manual is not a definitive guidebook, it is a compilation of methods and procedures carried out by experience research groups in the filed of halocarbon analysis.

During the 3rd project period **WP5** (NA5) has focused on the development of standardized protocols for flux measurements of N_2O and CH_4. For this InGOS initiated two new working groups within the framework of the ICOS Ecosystems Measurement Station Assembly (MSA) to make sure that the protocols are consistent with the requirements of the ICOS community and to maximize buy in into (and thus subsequently take-up of) the recommendations by the international flux network. An extra chapter into the protocol of flux chamber measurement was developed, further a draft protocol for the "Eddy-covariance flux measurement of non-CO_2 greenhouse gases", covering instrument requirements, system setup & maintenance, ancillary measurements as well as data processing and gap filling. In addition, analysis of the inter-comparison campaigns for N_2O eddy-covariance and chambers has continued.

WP6 (NA6) has continued the time series measurements at the Boknis Eck Time Series Station and the Gibraltar Fixed Time-Series Stations (GIFT). A publication about the data from GIFT has been published in 2015. Moreover, the results from the repeated hydrographic section OVIDE are currently in preparation for publication. Due to various technical and administrative difficulties the planned installation of underway trace gas OA–ICOS systems on Voluntary Observing Ship (VOS) lines in the North Atlantic Ocean had to be postponed to Spring 2016 (i.e. beyond the end of funding period of InGOS). A paper on a first long-term (proof-of-concept) deployment of an N_2O OA–ICOS/equilibrator system aboard a research vessel has been published in June 2015.

4.3 TransNational Activities

The provision of facilities through the TNA work packages was very successful, although some diversity exist. Within **WP7** (TNA1) and **WP8** (TNA2) almost 100 projects were executed. Several stations provided most of their capacity for access, only a few stations were less attractive for users and as a result some of their TNA budget has been reallocated to other stations. Due to the accepted amendments we could welcome two new beneficiaries proving access to their stations: the University of Granada (UGR) with the station "*Padul*" and the Institute for Climate Science (IC3) with the station "*Ebre Delta*". **WP9** (TNA3) provided access for the ULUND airplane, here 2 more projects have been accepted and executed.

As during the previous periods the TNA facilities for providing calibration gases (WP10) and the isotope analyses (WP11) have been used extensively by both external and project internal users, up to and beyond the capacity of the providers. **WP10** (TNA4) got continuous request for real air standard gases calibrated for InGOS related tracers. One focus was the support to groups involved in the activities of WP2 and WP3 with hydrogen measurements. Five of the laboratories that had not yet used InGOS TNA for calibrated hydrogen standards were served. In addition, the hydrogen calibration laboratory at CSIRO of an important international user group, the AGAGE (Advanced Global Atmospheric Gases Experiment) monitoring network, has adopted the WMO hydrogen calibration scale based on InGOS Transnational Access calibrations. In **WP11** (TNA5) intense activity has shown at RHUL and at UU. Demand for analyses has been very high, and from a wide range of national partners; indeed, requests were well above expectations and increased significantly as the project continued. The work has included a large number of new and continuing projects and sampling campaigns at Cabauw, around Paris, and in Switzerland. A wide variety of projects were supported across Europe, at many different latitudes, from Spitsbergen to Italy and Spain, and investigating both natural wetland and urban/industrial sources. TNA visits to the RHUL lab provided training in sampling methodology and campaign planning.

4.4 Service Activities

The Service Activity of **WP12** (SA1) has become operational during the 1st Period, and during the 2nd Period data have been flowing into the databases. During the last period data continued to flow in the databases and database developments in relations with associated work packages went on. The databases are organized in three different Data Centers and provide several date sets: Near Real Time data (NRT data), historical validated level 2 data, intercomparison data, or chamber data. The Atmospheric Database was filled with updated version of historical hydrogen data with uncertainties. The historical methane datasets were enlarged to include 2014 data for most of the stations. The automatically daily–generated data products on historical data have been further developed to include additional statistics to help the WP members to analyze their data. The Ecosystem Database has been further developed to include the information and metadata that are defined as relevant by the WP5 activities. The data now also includes the chambers comparison experiment results that can be an important contribution to the ICOS discussion on the standard chambers to be used in the network. The Halocarbon Database, located at http://ebas.nilu.no, is populated with the newest version of the AGAGE halocarbon data, originally sent to CDIAC. The datasets now consists of 144 quality assured parameters from 4 stations (Zeppelin, Mace Head, Jungfraujoch and Mt.Cimone) from 2010-2014, the datasets that constitute the complete InGOS halocarbon dataset. The InGOS complete dataset is quality controlled according to AGAGE standards, and is an important contribution to studies of the behavior of halocarbons in the Northern Hemisphere.

4.5 Joint Research Activities

In WP13 (JRA1) the improved Spectronus instrument has been tested in the lab and showed a significant improvement in performance and usability for deployment at tall towers. The instrument has been run for a year now at Cabauw tall tower and performed well. The improvements have been taken over by the manufacturer in a new version of the instrument. A peer–reviewed paper on this work is in preparation. The test of seven new laser instruments at CEA has been concluded and led to a publication in AMTD. A novel instrument for $^{13}CH_4$ measurements in extensive tests at UHEI shows excellent performance. The results have been published in AMT. The low cost GC has been tested in the field at two measurements locations. Performance was excellent for CH_4, but sub-optimal for N_2O. Nevertheless the instruments can still be considered for applications in cases where financial resources are limited and manpower is relatively cheap. The experiments with is-FTIR at several locations and configurations for measurements of horizontal and vertical gradients and eddy accumulation for use in flux measurements have been very successful and led to a successful PhD defence and several articles in press. The innovative DIAL instrument led to a completely new design of the telescope. The instrument will be further developed by a new SME company as a direct result of the innovations started in InGOS.

Within **WP14** (JRA2) a tropospheric XCH4 data product has been developed for ground-based remote sensing observations in the near infrared spectral region. This region is covered by all TCCON sites. The data product has been validated by aircraft in situ profiles. Regular gas cell measurements and circulation of the cells have been implemented within TCCON-Europe. This activity quantifies the instrumental differences at different sites and has established as an essential QA/QC component within the global network. The observations within InGOS have widely used for the validation of satellite retrievals. Specifically the influence of different parameters on GOSAT satellite retrievals has been investigated. Modeled 3D CH_4 fields (provided within JRA3) have been thoroughly compared with ground-based as well as satellite retrievals of CH_4. The results show the need for TCCON data for model validation.

In **WP15** (JRA3) the CH_4 and N_2O flux inversions have been completed for the period 2006-2012 according to the defined modelling protocols, using the new harmonized CH_4 and N_2O dataset generated in the InGOS work package WP2 and WP3 ('2014 InGOS data release'). Seven different inverse models were applied for CH_4, and four models for N_2O. The CH_4 and N_2O flux inversions were analyzed in detail and derived European CH_4 and N_2O emissions compared with bottom-up CH_4 and N_2O inventories reported to UNFCCC. The generated CH_4 and N_2O model data sets have been compiled and documented. In parallel, flux inversions of halocarbons (HFC-125, HFC-134a) and SF_6 for the year 2011 have been completed using four different inverse modelling systems and the derived European emissions analyzed and compared with national inventories reported to UNFCCC. The ^{222}Rn flux map has been updated and this has resulted in a scientific publication. Furthermore, the $\delta^{13}CH_4$ analysis has been completed and documented. A first comparison has been made between model simulated $\delta^{13}CH_4$ and measurements performed in WP16, resulting in a publication which is close to being submitted. Finally, also the analysis of the sensitivity of the existing network network (and potential future extensions) has been completed.

During the 3rd period WP16 (JRA4) organized the main InGOS WP16 field campaign at the Cabauw tall tower station, where the innovative isotope instruments from UU and EMPA were successfully deployed for a period of 5 months. The campaign resulted in a worldwide unique high temporal resolution dataset of methane isotopic composition. The measurements from the two instruments were combined to yield a dataset with 2610 data points for $\delta^{13}C$ and 2673 data points for δD. The campaign was followed by an intensive period of data interpretation involving all partners, where strong synergies were achieved with the modeling activities (WP15) within InGOS. A major finding is that the emissions are dominated by agricultural sources, and that particularly fossil sources contribute only a minor fraction to the methane emissions at this site. This was also used to test different emission inventories. A manuscript has been submitted to Atmospheric Chemistry and Physics Discussions. A second major aim was the link of methane isotope measurements to the international isotope scales for carbon and hydrogen isotopic composition. This work has been successfully concluded by MGP and a second manuscript has been submitted to Atmospheric Measurement Techniques Discussions.

Within **WP17** (JRA5) significant progress was made on new halogenated gases. Vollmer et al. (2015a) and Schoenenberger et al. (2015) could show that the increase of HCFC-133a and HCFC-31 has recently stopped and emissions declined in parallel. This was potentially caused by changed processes in the production of HFCs, which is the most likely source of these compounds in the atmosphere. In addition to these unintentionally emitted substances, also fluorinated anesthetics and the newly produced HFOs (hydrofluorolefines) were measured for the first time within the InGOS project (Vollmer et al. 2015b, 2015c). Besides this GUF showed the ability to use the Time-of flight (TOF) mass spectrometer technology for electronically archiving halogenated trace gas abundances in the atmosphere and UEA installed their newly acquired TOF-MS for long-term usage. A feasibility study for the use of this state-of-the art instrument was published by Obersteiner et al. (2015). WP17 made also progress in the development of standard GC-MS sampling for larger and smaller volumes of atmospheric samples. With the help of this development it was possible to lower the detection limit for halocarbons to ~2 ppq (fmol/mol). Furthermore, continuous measurements of the strong greenhouse gas NF_3 were started at Jungfraujoch.

During the 3rd reporting period, **WP18** (JRA6) continued on CH_4 and N_2O flux and concentration measurements in the involved tall tower sites, and data have been submitted to the InGOS database. The work focused on the completion of regional scale estimates of CH_4 and N_2O balances and the assessment of ecosystem–active periods of CH_4 and N_2O, in particular related to tall tower flux measurements and linking short–tower EC and tall tower measurements. Two detailed reports have been delivered about this: In the first report (D18.8) the CH_4 and/or N_2O budgets at spatial scales have been evaluated, which fall between the regular eddy covariance (EC) towers (field scale,~1 ha) and inverse modelling (~100–500 km^2) at five tall tower sites. At the same time the application of installing EC measurements on tall towers have been assessed, which are established for the concentration monitoring needed for the inverse modelling in order to simultaneously provide information on emissions at the regional and at the landscape scale. Such studies could help bridge the gap between these two methods and may help understand why bottom-up and top-down estimates for large-scale CH_4/N_2O emissions often disagree. The objective of the other report (D18.9) was to assess the CH_4 and N_2O flux dynamics during the ecosystem-active periods and to compare the bottom-up fluxes with tall tower integrated fluxes. In particular, the link between small–scale fluxes (measured by short-towers eddy covariance (EC) and/or chambers), and large–scale fluxes (measured by EC and/or gradient at tall tower) was investigated using tall tower flux footprint estimates (D18.1), process based models and available flux measurements at six sites.

5 Expected final results and their potential impact and use

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 most 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.

5.1 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 and 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 5^{th} 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.

5.2 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. 1.5.1, see also Chapter 4 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.

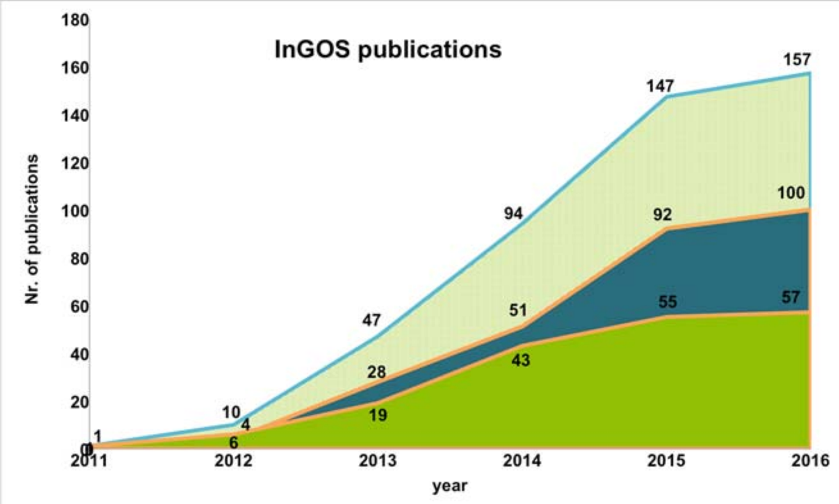

Figure 1.5.1: Number of peer-rewieved publications until January 2016, Please note: here we differentiated between publications acknowledging InGOS for financial support (blue field) and InGOS related publications (green field). Although InGOS is not officially acknowledged in "related" publications 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 quitea 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 their Differential Absorption LiDAR. This has included funds to combine the InGOS CH_4 laser system with a laser capable of detecting atmospheric CO_2. They 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).

5.3 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.

5.4 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.

5.5 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.

5.6 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.

5.7 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.

6 Website

Figure 1.6.1: start page of the InGOS website

The website of the project is 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/

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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