White paper on research opportunities for Danish research arising from the Integrated Carbon Observation System (ICOS) infrastructure

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1 Preface

This document addresses the needs of Danish national and Danish international climate change related research for integration and access to larger research facilities and outlines a solution via the developing the European large research infrastructure the Integrated Carbon Observation System (ICOS).

2 Introduction

Denmark is one of the smaller EU countries with its large arctic dependency, Greenland. Early recognition of the vulnerability and limitation of natural resources together with being one of the most flexible and highly industrialized economies worldwide coins the ambitious Danish vision of sustainable development, i.e. environmentally and socially friendly development with competitive economic solutions. Research is the only key to conceptualize and invent sustainable technology. Larger research funds are being allocated to enable Denmark to become a leading global player in sustainable solutions and, thereby, the Danish economy to open areas of new economic growth (Ministry of Science Technology and Innovation 2009).

Science is one of the most globalised fields of human activities. The IPCC reports are prominent and highly visible products from global research integration. Being a small country, Denmark has recently responded to the requirements of globalization by forming fewer but larger and stronger research units. These research institutions need crosscutting thematic activities that enable them to form synergies and collaborate highly visible on the international research arena. Well proven and highly effective means to form intensive high quality research collaboration are large research infrastructures.

Research infrastructures bundle research - like other research instruments, too – and are in some cases the only means to provide the critical mass for visionary research projects. Like some member states, the European Commission has designed a road map for large research infrastructures to create unique research platforms for European and international scientists in different science areas (ESFRI). This strategy is supposed to strengthen Europe's research relative to competing science places America and Asia.

Climate change is the challenge for mankind of today and for at least several decades if not centuries in the future. The main causes for climate change are CO_2 emissions from fossil fuel, land-use and land-use change, processes that are essentially linked to economic and social activities. A change of the global economic system towards sustainable use of natural resources is as crucial as it is difficult, but the current opinion is that the not reacting now will be more costly and painful for mankind than mitigating climate change, i.e. abating dangerous climate change (Barker et al. 2007; Stern 2007). Nevertheless the magnitude of efforts restructuring global society and economy in order to manage the global carbon cycle within a couple of decades is unprecedented and will be costly. Managing the global carbon cycle needs careful scientific analysis, prediction and quality control. The enormous number of research projects during the last two decades has produced a large body of evidence on the global carbon cycle and its perturbation through human activities. The high demand on scientific guidance has forced scientist to generate state of the art guidelines and methods for greenhouse gas emission reporting and projection tools, mainly using available data from research projects that were not designed for this purpose. A criterion of the already high scientific standard is that whenever statements were made the uncertainty of this statement was estimated. This enables us today to identify major uncertainties in observing and understanding the global carbon cycle and to develop scientific approaches to investigate the carbon cycle at regional, continental and global scale.

The high costs of emission reduction require more accurate monitoring of the successes of global change mitigation than what is possible today. State of the art is that fossil fuel emissions can only be indirectly estimated from the economic statistics from those countries that take part in such assessments. Different monitoring protocols and implementation make the results more uncertain. The effects of land-use and land-use change are at best roughly estimated from emission factors that are based on sometimes just a few single flux rates that have been measured in a few places. Currently there is no control system at European scale that can consolidate the CO2 flux estimations, i.e. fossil fuel emissions and emissions from land use and land use change, with an independent approach. Such a approach is to simply measure the CO2 fluxes between the earth's surfaces and the atmosphere and follow the precise development of atmospheric CO2 concentration with necessary precision within a spatial domain. Existing continuous atmospheric CO2 concentration measurements are too scarce, located at the wrong places and not accurate enough. Some of the atmospheric approaches require accuracy of some tenth of a ppm CO2 and isotope composition in order to estimate the continental carbon flux components from an atmospheric station network. These accuracies can be reached with modern technology and careful sampling, but only if measurements are highly standardized is it possible to use them in continental scale CO2 flux calculations. Otherwise even relatively small differences in laboratory analyses will cause large systematic bias in continental flux estimates. A similar situation exists with carbon dioxide flux measurements at ecosystem scale. Large EU projects have developed a method that is able to measure fluxes between extended ecosystems and the atmosphere. Measurements show large seasonal and inter-annual flux variability of which the causes are not yet fully understood. Some ecosystems act even over large time scales as carbon sources others usually take up CO2 but release it during extreme weather events. Some of the research teams have been able to measure CO2 fluxes over now more than a decade on the basis of many short-term research projects. It was not possible to standardize these measurements, because this would mean a larger concerted action beyond the dimensions of current research funding. Attempts to

coordinate the atmospheric and ground based carbon cycle observations have been made on the basis of existing data and produced European scale flux estimates with yet large uncertainties(Ciais et al. 2008; Janssens et al. 2003; Martin et al. 1998). The uncertainties of these estimates are yet too large to use them as defensible argument to monitor and guide mitigation policies.

The Integrated Carbon Observation System (ICOS) aims at developing and building exactly such infrastructure that will generate the essential data that are needed to understand and monitor Europe's greenhouse gas budget with highest possible accuracy and precision.

2.1 The Integrated Carbon Observation System (ICOS)

The main objectives of ICOS is to provide long-term measured, high precision data to users of ICOS enabling them to investigate and to understand the European GHG budget and to produce higher level products like flux maps, trend analyses and case - effect studies that are needed to evaluate climate change mitigation measures.

ICOS follows a multi constraints approach, which means that scientific calculation of regional and continental GHG budgets is tackled from many different dimensions. The GHG flux, either GHG emission or GHG sequestration, can be measured directly at spatial scales of a few square kilometres or derived from its effect on atmospheric concentrations. Atmospheric concentrations and fluxes are linked by atmospheric transport processes, which are being routinely simulated for weather prediction at regional and continental spatial scales at 6 hours resolution. These information streams combined enables mapping of concentrations and fluxes independent from national statistics and reporting. ICOS will build three networks, the network of atmospheric stations (AS) and the network of ecosystem stations (ES). A third network, OS, will extend the terrestrial measurements over the marine area.

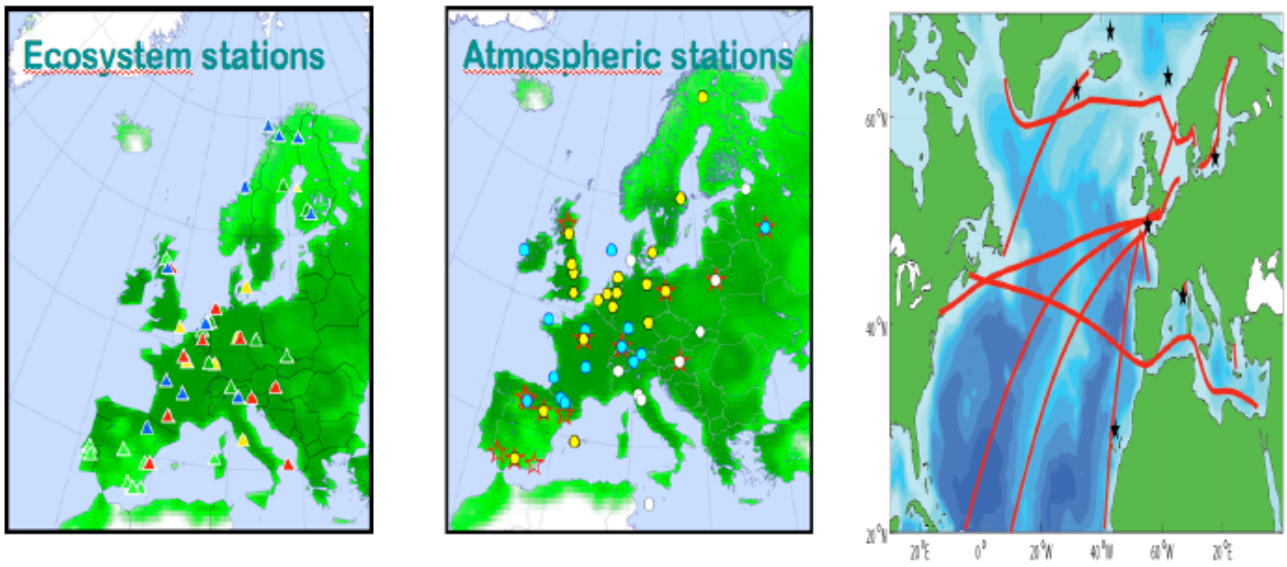

Figure 2-1 European coverage with ecosystem and atmospheric stations and possible marine atmospheric and flux observations.

These station networks will be coordinated by thematic centres, the ecosystem and atmospheric thematic centres, ETC and ATC, respectively. The coordination office administers and leads the different units of ICOS, collects the data from the thematic centres, combines them with other data streams and provides access to users, Figure 2-2.

The roles of the centres are to establish the networks, assess and control data quality assessment and manage data streams, to timely provide quality checked data to the users. Near real time transport (latest daily) enables quick scientific analyses of rare events (e.g. like the Central European heat wave in 2003 (Ciais et al. 2005)) and to produce automated higher level products of users (i.e. an online European or national flux map) at times when they are important for scientific investigation and political decision making (Figure 2-3).

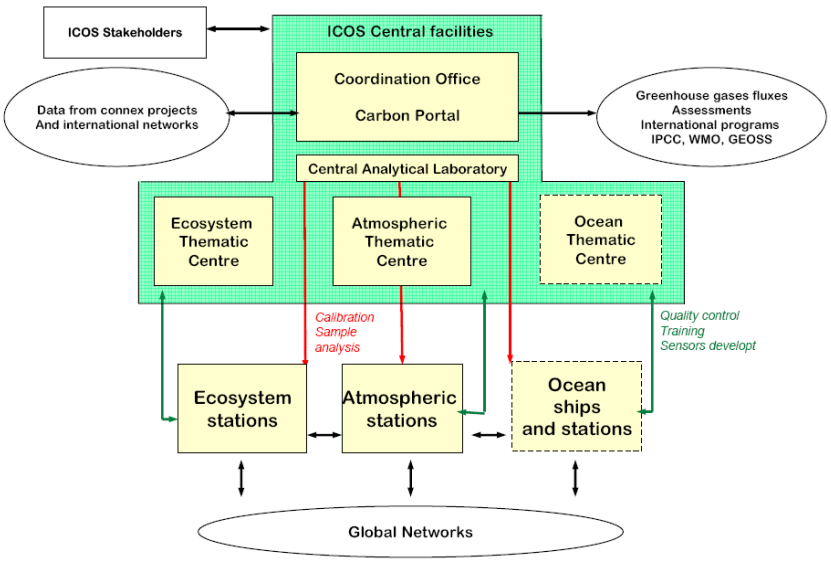

Figure 2-2: Structure of ICOS.

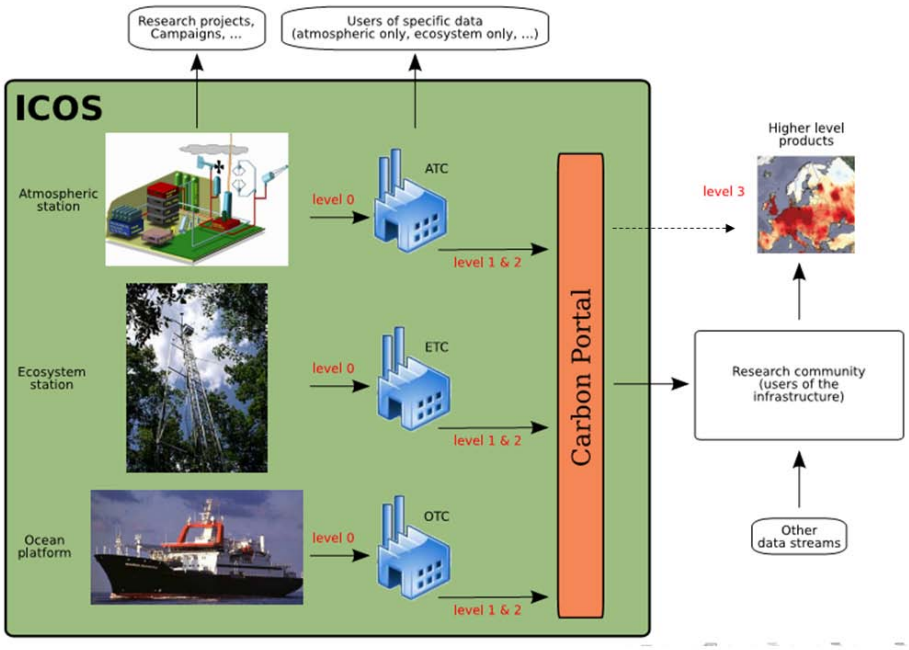

Figure 2-3: Data flow from station networks to users.

The high quality of data is essential for the success of ICOS. As an example, the identification of the fossil fuel contribution to fluctuations of CO2 concentrations can be traced by means of the radioactive ^{14}C isotope. Interaction with cosmic rays produces ^{14}C with regular rates from elementary nitrogen. Radioactive decay reduces the numbers of ^{14}C leading to an equilibrium between production and decay. Long-term storage over millions of years has depleted ^{14}C from fossil fuels. The fossil fuels signal can be traced by means of ^{14}C /^{12}C isotope ratios, typically 10^{-12} atoms ^{14}C per atom ^{12}C. Differences in this small number are the signal imposed by fossil fuel emission. Both analysis and sampling require highest care and precision when using this method. To guarantee stable and accurate chemical analysis ICOS establishes a Central Analytical Laboratory (CAL). Atmospheric, terrestrial and marine samples from the network will be chemically analysed by exactly the same methods and labs.

The other key word that describes the unique ICOS approach is *long-term* observation. It is well known that global climate change is a long-term process. Even if all anthropogenic emissions would stop today, there will be a lag of several decades conserving the atmospheric disturbance because of strong coupling of the atmosphere with the oceans and the biosphere. Terrestrial ecosystems respond from diurnal to multi centennial time scales to atmospheric forcing. Changing atmospheric CO2 concentrations and physical climate at the ground resolves changes in ecosystem dynamics that can only be observed on a long-term basis (see also 3.1.3). Because long-term investigations of carbon cycling in terrestrial ecosystems are lacking, one of the most

crucial questions, whether and if how long the biological CO2 sink will persist in a warmer world, can currently be only vaguely addressed. The operational phase of ICOS is expected to last at least 20 years.

Development of ICOS is sketched in Figure 2-4. It shows that ICOS is in midst of its development phase. The preparatory phase includes a EU project and many national preparatory projects. Negotiations with national stakeholders were successful and many nations expressed interest in hosting thematic centers or contribute to the station networks. Given the already documented national commitments it is not a question *if* but *how* ICOS will be launched, and, especially important here, in which way Denmark will contribute to ICOS.

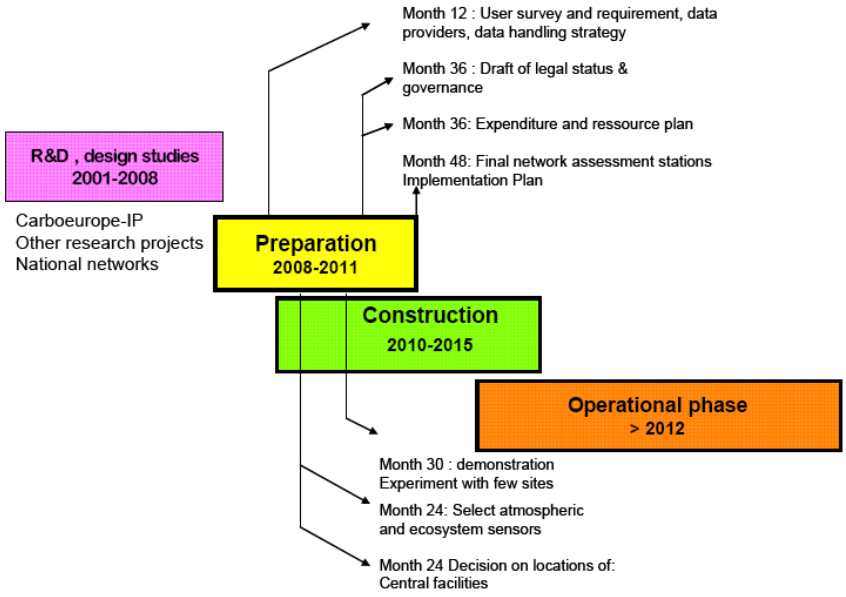

Figure 2-4: Roadmap for ICOS.

2.2 The Danish contribution to ICOS

A Danish participation in ICOS will be a natural continuation of a long-term partnership and success in the above mentioned EU projects. The members of the research team behind the Danish preparatory project have all been active within the research areas supported by the infrastructure. Apart from participation in the EU-projects, the present research team has formed the national part of the Nordic centre of excellence NECC (Nordic Centre for Studies of Ecosystem Carbon Exchange and its Interactions with the Climate System.). Members of the research team have also carried out flux measurements of greenhouse gases in areas outside of Europe (Africa, Siberia, and Greenland). The research team has published a large number of papers utilizing results from the research driven measurement stations (hereof 2 papers in Nature, one of which with a present total number of citations of 424 and an average citation rate of 53/year). Thus the existing team has demonstrated a high quality and productivity in research utilizing data that the ICOS infrastructure can provide in the future.

A Danish ICOS participation can be implemented as a continuation of existing ecosystem flux measurement stations. The station in a beech forest near Sorø has been operational continuously since June 1996 and has gained a position among the top 5 in Europe with respect to data coverage quality (see below). We have also been running flux stations in other land-use types (agricultural fields, grasslands, spruce forest).

We wish with the ICOS infrastructure also to enter the area of greenhouse gas concentration measurements. These measurements can be established at existing high masts within our organizations (e.g. the 125m Risø mast and/or the 116 m high mast at the test station for windmills at Høvsøre). Decisions within the team preparing ICOS at the European level might have other wishes to type and location of Danish measurement sites than the present. Currently a Danish national pre-project systematically scrutinizes the Danish landscape data resources for suitable locations for different types of ecosystems and source areas of greenhouse gases. Risø National Laboratory, DTU, has the technical skills and staff to provide national support for the infrastructure.

The Danish ICOS contribution is harmonised with the ICOS activities of the other Scandinavian countries thereby linking Central Europe with Scandinavia. Increase of the number of tall towers will increase the accuracy of flux estimation from inverse modelling for entire Scandinavia. The deciduous forest that is selected for the Danish contribution to the ICOS ecosystem station network is complementary to the Nordic conifer forests and will serve as a reference station not only for Denmark but as well for large parts of southern Sweden and Northern Germany. Close collaboration between the Nordic countries within ICOS will strengthen the Nordic research networks that have established during the last years, e.g. with The Nordic Centre for Studies of Ecosystem Carbon Exchange (NECC) and the newly established research network on the study of greenhouse gas exchange from northern ecosystems (NordFlux) and the Circumarctic Network of Terrestrial Field Bases (SCANNET).

At the time of the preparation of this white paper the ocean thematic centre and station network weren't yet designed. Given the existing large interest on marine research in Denmark it is anticipated to extend the Danish ICOS contribution to marine GHG flux research at a later stage of ICOS.

3 Use of ICOS for Danish research

Environmental research has high priority in Denmark. Until now this research has not yet been coordinated with respect GHG research, e.g. to assess the Danish GHG balance independently from Kyoto reporting. In almost every related field, strong research groups exist that form the scientific users of ICOS in Denmark. Individual national and European research projects have created the fundamental scientific capacity and existing infra-structure, like e.g. the Danish long-term CO2 flux station in a beech forest close to Sorø, which has been operating continuously since June 1996, and is run by Risø National Laboratory, DTU. Other similar stations have been operated by University of Copenhagen and Aarhus University. Danish Meteorological institute is a key player in regional climate assessment and there are scattered atmospheric modeling groups in all major Danish universities. Remote sensing is vital for spatial assessment and there is a lively development towards using remotely sensed spatially available data also for process monitoring (e. g., Grace et al. 2007).

Finally large projects are being launched to implement scientifically sound GHG emission monitoring for Denmark. Some of the research groups and institutions have already formed networks and collaborate in short-term research projects. Collaborated research on GHG-fluxes and budgets from local to regional scales will multiply the impact on Danish research through concentration and networking at Danish, European and global scale. As ICOS is a product of multiple flux projects it will also remain functioning as a core project in the European research area, meaning an essential window towards European GHG related research. Collaboration will increase the opportunity for Danish researchers to join EU research project initiatives and to involve strong partners in own EU project initiatives. Using ICOS as a concept and backbone for similar national approaches, will dramatically improve knowledge on the Danish GHG budgets and facilitate high quality, scientifically sound GHG reporting and management in Denmark.

The following chapters are short descriptions of research projects that document the benefits that Danish experts see arising from the large European infrastructure ICOS for their future research.

3.1 Ecosystem stations

Danish research has contributed to long-term CO_2 flux monitoring with various sites in Denmark and on Greenland. This introduction gives a short overview on how these flux observation sites have been used for Danish research.

The long-term CO2 flux station Sorø has operated since 1996 by a team from two divisions at Risø National Laboratory for Sustainable Energy (DTU), and has been used by many researchers. The site is already now part of a European infrastructure project, IMECC (EU-FP6), preparing both the site installations and teams to becoming a site of the ecosystem station network within ICOS. The consortium that manages the site is partner in three ongoing European research projects: on the effects of nitrogen cycling on the European GHG balance (NitroEurope, EU-FP7), the effects of future increased climatic variability and weather extremes (CARBO-Extreme, EU-FP7) and the effects of management on European GHG balances (GHG-Europe, EU-FP7). During the years Sorø has been part of at least 85 publications, including high level publications in Nature and Science (Ciais et al. 2005; Valentini et al. 2000). It was included in technological papers (Aubinet et al. 2001; Ibrom et al. 2007a; Ibrom et al. 2007b; Järvi et al. 2009), in processtudies (Ambus et al. 2006; Baldocchi et al. 2005; Beier et al. 2001; Davidson et al. 2002; Formánek and Ambus 2004; Hemming et al. 2005; Janssens and Pilegaard 2003; Pihlatie et al. 2005; Primé et al. 1996; Sevanto et al. 2003) atmospheric flow studies (Dellwik and Jensen 2005) site inter-comparisons (Granier et al. 2002; Lagergren et al. 2008; Pilegaard et al. 2006; Skiba et al. 2009) in flux up-scaling studies from plot to region (Boegh et al. 2009; Gryning et al. 2009) and even in environmental economics (Hultman 2006).

At the agricultural site of Risbyholm, Havdrup, the Department of Geography and Geology has been monitoring CO_2-exchange from 2001 to 2008. The site has been agricultural reference station within the CarboEurope IP programme (2004-2008) and test site for the Nordic centre of Excellence program (2003-2007). Apart from rapecrop in 2009 the large study field has been used for winter wheat production. Data from the site has been used in a number of international peer-reviewed publications (Boegh et al. 2009; Gryning et al. 2009; Houborg and Soegaard 2004; Houborg et al. 2007a; Houborg et al. 2007b).

Danish research within the Greenland Ecosystem Monitoring (GEM) programme includes GHG gas flux measurements in two areas on Greenland; at Zackenberg, a high arctic area in northeast Greenland, and at Nuuk, a low arctic area in southwest Greenland. Flux measurements in the Zackenberg valley have been performed by research teams from Copenhagen University, Aarhus University and Lund University since 1996 (cf. Soegaard and Nordstrøm 1999). Currently, turbulent flux measurements on the land-atmosphere CO_2 and H_2O exchange in a heath site and a wet fen site are maintained by the GeoBasis programme under Zackenberg Ecological Research Operations (ZERO) funded by the Danish Ministry of Energy and Climate. In 2006 and 2007 the gas flux monitoring programmes were extended to also include CH_4 flux measurements using automated chambers both at Zackenberg (Mastepanov et al. 2008) and Nuuk under the NERO (Nuuk Ecological Research Operations) initiative. In addition, a wide range of biological, climatological and geophysical studies are being conducted, which provide supportive information of the past, current and possibly future dynamics of the area. The three flux sites in Zackenberg and Nuuk uses state-of-the-art instrumentation and methodology for trace gas flux measurements, and are currently underway to become a part of IMECC and FLUXNET networks. the data have been published as part of different process, scaling and review projects (e.g., Christensen et al. 2000; Grøndahl 2006; Grøndahl et al. 2007; Mastepanov et al. 2008; Nordstrøm et al. 2001; Post et al. 2009; Soegaard and Nordstrøm 1999).

3.1.1 Development of flux observation technology

Turbulent flux measurements are the backbone technology of the ecosystem network in ICOS. The eddy covariance method has been developed in the 50ies of the last century, but only since the 90'es this method has made a huge development and is now the most widely used method to assess fluxes between ecosystems and the atmosphere. Long-term operation requires stable sensors with negligible or at least well known effects on the turbulence signals. The methodology to process the data is vitally evolving and new software is becoming available for a wider community offering a wide range of sophisticated analyses and correction methods. ICOS will use standardized equipment and data processing that will include the state of the art, but this will not be the end point of technological and theoretical developments. The group at Risø DTU has contributed much to these developments (Aubinet et al. 2000; Ibrom et al. 2007a; Ibrom et al. 2007b; Ibrom et al. 1996; Kaimal and Kristensen 1991; Kristensen 1998; Kristensen et al. 1989; Kristensen et al. 1997; Lenschow et al. 1994; Wilson et al. 2002) and will continue to design better sensors and postprocessing concepts.

Possible research proposals during the first five years of a Danish ICOS contribution

Applicant

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Research area: Turbulence flux measurement methodology

Research objectives

1. Test of new ICOS equipment and comparison with the equipment used at the Danish long-term beech forest flux observation site at Sorø.
2. Re-evaluation and correction of the existing 14 year turbulence data to harmonize the data series and to quantify the effects of new post-processing methods

Resources

- Number of research projects: 1
- Funding agency: The Danish Council for Independent Research (DFF)-FNU

- Senior scientific staff: 6
- Post Docs and young researchers: 12
- Technical staff: 24
- Students (PhD level): 36

3.1.2 Atmospheric flow in complex terrain

Both for micro- and mesoscale flow models, there is a constant need to improve the parameterizations of the surface. The microscale is the scale where variations in the landscape of 100-1000 m are important, whereas the mesoscale models focus on larger scales and assume that the effect of microscale variations are negligible. Results from flow modelling will serve as the basis for GHG flux footprint calculations that help interpret the measured turbulent flux estimates. For advanced microscale flow models currently in use at the Risø DTU's Wind Energy Division, such as the so called Reynolds Averaged Navier Stokes models, the surface energy balance will be included in the next five years for standard flow calculations. The flux measurements of greenhouse gases and water vapour taken at an ICOS flux station would provide a valuable source for validation data. For mesoscale models, tall tower profile measurements of greenhouse gases would likewise provide a direct and invaluable way of verifying the model output. This activity will improve the quality of flux measurements in Danish ecosystems and will serve as a model for other ICOS researchers on how to deal with complex terrain effects on their GHG flux measurements.

Possible research proposals during the first five years of a Danish ICOS contribution

Applicant

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Research area: Flow and surface flux modeling at meso- and microscale

Research objectives

1. Micro-scale flow model validation (flux station)
2. Simulation of greenhouse gases and surface energy balance in meso-scale models (tall tower profile)
3. Comparison of in-situ and remotely sensed data of water vapour and temperature (tall tower profile)

Resources

- Number of research projects: 2 possibly part of larger collaborated projects
- Funding agency: EU, Danish Research Councils
- Senior scientific staff: 18
- Post Docs and young researchers: 24
- Technical staff: 6
- Students (PhD level): 72

3.1.3 Ecosystem research including management

ICOS related ecosystem research in forests

The ICOS setup does not address the major unknown in the C cycle, the rate of C sequestration in the soil compartment. In ICOS this can only be assed as the difference between NEE and the change in biomass C; both

large numbers with a considerable uncertainty. Thus this needs to be assessed by other methods, which we are currently working on. To relate the ICOS site to these other research projects focusing on soil C sequestration a more thorough assessment of soil C and N pools and dynamics is needed.

Soil C and N stocks and their dynamics are only characterized to a limited extent at the Sorø site. Some work on soils has mainly been carried out by foreign project partners (Ph.D. students, post docs) and results have not been made available to any large extent. A thorough characterization of soil C and N pools within the whole soil profile is therefore needed. This characterization should be harmonized with the methodology currently employed in the Danish forest soil inventory for (SINKS) and long-term forest management experiments. Soil C and N stocks will be characterized in forest floors and mineral soil (0-10, 10-25, 25-50, 50-75 and 75-100 cm). In addition, nitrate concentrations in soil solution will be determined in a subsample from 75-100 cm depth. This information is needed for better modeling of soil C dynamics at the site, e.g. using the forests soil model Yasso for which other input variables are available at the site.

Possible research proposals during the first five years of a Danish ICOS contribution

Applicants

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Research area: Carbon and nitrogen cycling in forest soils

Research objectives

1. Soil C and N stocks and distribution at the Sorø site
2. Nitrate concentration below the root zone
3. Assessment of soil C turnover: Litterfall C/forest floor C ratio
4. Modeling of soil C stock change using Yasso (Liski et al.)

Resources

- Number of research projects: 3
- Funding agencies: Ministry of Climate and Energy, Villum Kann Rasmussen (VKR) Foundation, NordForsk
- Senior scientific staff: 6
- Post Docs and young researchers: 24
- Technical staff: 6
- Students (PhD level): 12

Atmospheric carbon dioxide emissions are the main agent driving global climate change. The global terrestrial biosphere absorbs substantial amounts of atmospheric CO2. Uncertainty in the determination and prediction of this sink contributes to a large extent to the uncertainty in climate prediction. At the example of a European research infrastructure, the Danish beech forest CO2 flux observation site, Sorø, we investigate the long-term carbon budget and its uncertainty with three independent approaches: long-term atmospheric flux measurement, carbon process modelling and carbon inventory. This unique multi constraints approach is only possible, because the site has been operated since many years and been part of a multitude of national and European projects. The only missing parts to reach this goal are the proposed measurements of carbon losses from vegetation together with their temperature dependency. The expected results will increase our

understanding how large the carbon uptake is, where the carbon will be stored in the forest and which processes determine the carbon budget.

Possible research proposals during the first five years of a Danish ICOS contribution

Applicant

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Research area: Carbon budgets of ecosystems, temperature sensitivities of carbon losses

Research objectives

1. Assessment of the forest carbon budget with three independent approaches
2. Measurement of aboveground autotrophic respiration
3. Investigation of temperature sensitivities of ecosystem respiration components

Resources

- Number of research projects: 1
- Funding agency: DFF-FNU
- Senior scientific staff: 12
- Post Docs and young researchers: 12
- Technical staff: 24
- Students (PhD level): 36

Forest ecosystems are expected to face significant pressures from climate change and air pollution in the future. Ozone is a significant air pollutant in Europe and the concentration will either level out or increase in the future. For estimating effects on the ecosystem it is important to determine the flux of ozone into the leaves (ozone uptake) under realistic conditions. This can e.g. be done by measuring the ozone concentration in the atmosphere and the sap flow in selected trees. From sap flow and meteorological parameters, which will be measured at the ICOS ecosystem station, canopy conductance will be estimated and in combination with ozone concentrations the uptake rate into the leaf interior can be calculated. The risk for ozone damage will be estimated by comparing ozone uptake rates with cellular detoxification rates and quantified in terms of limitations to carbon dioxide uptake and water use efficiency.

Possible research proposals during the first five years of a Danish ICOS contribution

Applicant

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Research area: Ecosystems services in polluted environment

Research objectives

1. Ozone canopy flux
2. Effects of ozone deposition on carbon uptake and water use.

Resources

- Number of research projects: 1
- Funding agency: EU, Danish Council for Strategic Research, DFF-FNU
- Senior scientific staff: 6
- Post Docs and young researchers: 6
- Technical staff: 6
- Students (PhD level): 36

ICOS related research in Danish shrublands

Shrublands are not planned to be part of the Danish ICOS contribution. However some ICOS related projects will disclose the need for model parameterization to include the Danish shrublands into Danish GHG budget assessment. This gap is expected to be filled with Danish national flux studies that can build on already established research infra structures (CLIMAITE and INCREASE).

Changes in atmospheric and climatic conditions with elevated CO2, elevated temperatures and changes in precipitation amounts and distribution will affect many ecosystem processes including processes responsible for capture/storage and release of green house gasses. The overall effect of these changes on the green house gas balance in shrubland ecosystems is difficult to assess, because it depends on the effects on a series of interconnected processes as well as interactions between all the involved drivers. It is generally not known what this overall effect will be on short and long terms. Therefore studies involving ecosystem manipulations of the involved factors to highlight the effects on individual processes as well as the overall system is necessary and are currently being conducted in Denmark. Such ecosystem experiments have clear advantages but are limited by the typically short term nature of the experiments, the generally small plot scales and methodological limitations to measure GHG exchange accurately. Therefore, collaboration between long-term monitoring sites like the ICOS network, which can highlight the long-term responses as well as take advantage of interannual variability and accurate GHG flux measurements, is a great advantage to build and test ecosystem models to improve our ability to forecast the fate of the sequestered atmospheric carbon dioxide and the persistence of the GHG sink strength in these ecosystems. Similarly, experiments in shrublands may be a great benefit to ICOS through highlighting effects of perturbations on GHG balances that are otherwise difficult to capture in the monitoring stations.

Possible research proposals during the first five years of a Danish ICOS contribution

Applicant

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Research area: Effects of climatic change on biological processes and ecosystem functioning

Research objectives

1. Quantify short and long-term responses of ecosystems to changing climate with ongoing ecosystem manipulation experiments (mono factor and full factorial design) in shrublands. Shrublands serve as case studies for other systems like forests.
2. Identification of ecosystem responses to real climate change in ICOS long-term observations in forests.
3. Develop generalized dynamic ecosystem models for shrublands and forests and test them with ecosystem manipulation and long-term observation data.

Resources

- Number of research projects: 2
- Funding agency: EU, DFF-FNU
- Senior scientific staff: 60
- Post Docs and young researchers: 60
- Technical staff: 36
- Students (PhD level): 360

ICOS related research in Danish agricultural systems

Sources of agricultural emissions of N_2O, CH_4 and CO_2 have been investigated in experimental and full-scale settings for a number of years. Among the focus areas are: Effects of organic vs. conventional management, effects of reduced tillage, effects of manure pre-treatments such as anaerobic digestion or acidification, on GHG emissions from livestock manure. Most recently, as part of the SINKS program, this department has in collaboration with NERI in Silkeborg determined annual emission factors from organic soils managed by agriculture, using a stratified monitoring strategy covering three regions and three land use categories. Measurements have been conducted with static chambers systems developed for measurement of CH_4/N_2O/R_{eco} and NEE of CO_2, respectively. In addition a wide range of supporting data were obtained at each site. The results have demonstrated a need for spatially integrated measurements at the field level to cover microscale, as well as variation related to land use and local soil and climatic conditions.

Possible research proposals during the first five years of a Danish ICOS contribution

Applicant

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Research area: Effects of climatic change on biological processes and ecosystem functioning

Research objectives

1. Effect of tillage strategy on annual balances of N_2O, CH_4 and NEE of CO_2
2. Manure management practices and GHG emissions
3. Importance of aerenchymous plants for CH_4 emissions from wetlands
4. Effects of cover crops and residue management on annual N_2O emissions

Resources

- Number of research projects: 4
- Funding agency: Danish Food Insdustry Agency (DFFE), ICROFS, Ministry of the Environment, EU
- Senior scientific staff: 36
- Post Docs and young researchers: 48
- Technical staff: 40
- Students (PhD level): 48

ICOS related research in arctic systems

Danish research within the Greenland Ecosystem Monitoring (GEM) programme includes trace gas flux measurements in the High Arctic (Zackenberg in northeast Greenland) as well as in the Low Arctic (Nuuk in southwest Greenland). Ecosystem measurements have been performed by research teams from Copenhagen University, Aarhus University and Lund University since 1996. The flux sites in Zackenberg and Nuuk uses state-of-the-art instrumentation and methodology for trace gas flux measurements and a proposal for the Danish Research Council has recently been submitted to include nitrous oxide (N2O) measurements in the trace gas research at the Zackenberg site.

The combined data set from Zackenberg and Nuuk on trace gas fluxes and other environmental variables provide unique information on ongoing climate change, which is expected to be most prominent in high latitudes. Inclusion of the GEM sites into the ICOS frame strengthens not only the general Danish ecosystem modelling community but also allow for stronger models that includes the important Arctic component. The recently funded new atmospheric station for Greenland further strengthen the arctic part of ICOS and allows for spatial up-scaling to a large parts of the Arctic. Parallel to the monitoring at the GEM sites there are currently several individual research projects that are dedicated to the understanding of the dynamics of the trace gas budgets.

Possible research proposals during the first five years of a Danish ICOS contribution

Applicant

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Research area: GHG gas fluxes in arctic ecosystems

Research objectives

1. Estimations of the carbon budget in high and low arctic ecosystems and its vulnerability to climate change
2. Dynamic global vegetation modeling studies
3. Up-scaling trace gas fluxes using remote sensing techniques

Resources

- Number of research projects: 5
- Funding agency: Danish Ministry for Energy and Climate, DFF-FNU, EU
- Senior scientific staff: 45
- Post Docs and young researchers: 30
- Technical staff: 50
- Students (PhD level): 72

3.1.4 Ecosystem modeling and prediction

Large focus is currently placed on model-data fusion techniques, i.e. the approach to find model parameter values and their uncertainties from Bayesian calibrations and other MCMC approaches (Svensson et al. 2008; Van Oijen et al. 2005). Longer CO_2 flux observation including new climatic episodes and sporadic forestry management activities will increase the value of the Sorø flux time series to test dynamic ecosystem models. These models do not only simulate the current fluxes at a given ecosystem structure but construct the stand from simulated stand history, dynamically. Currently 5-10 modelling groups from outside Denmark are working with data from Sorø. The team of Risø DTU takes part in these studies and will use the models for systematic site specific analysis of carbon cycling, carbon-nitrogen and carbon-water interactions. The Danish ICOS contribution will help to form a Danish ecosystem modelling community that will provide ecosystem models and parameters with known uncertainties for spatial analyses and future projection. We do not expect individual projects that are only dedicated to modelling, but rather collaborated projects that create new field data and use models for interpretation and extrapolation.

Possible research proposals during the first five years of a Danish ICOS contribution

Applicant

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Research area: Ecosystem modeling and prediction

Research objectives

1. Multi model studies of the carbon, water and energy exchange between the Sorø beech forest and the atmosphere
2. Simulation of carbon-water and carbon-nitrogen interactions
3. Long-term dynamic ecosystem modeling

Resources

- Number of research projects: 2
- Funding agency: EU, Danish Council for Strategic Research, DFF-FNU
- Senior scientific staff: 18
- Post Docs and young researchers: 24
- Technical staff: 6
- Students (PhD level): 72

3.2 Atmospheric station network

3.2.1 Atmospheric measurements

RAQS (Risø Atmospheric Quality Station) is a joint initiative between National Environmental Research Institute (NERI) at University of Aarhus (AU) and Risø National Laboratory for Sustainable Energy at the Technical University of Denmark (Risø DTU). The purpose of the initiative is to establish an advanced measurement station for air pollutants and greenhouse gases that can be used as Danish contribution to the atmospheric station network of ICOS.

The background for the initiative is to provide the scientific basis for evaluating the changes in atmospheric quality in Denmark following attempts to mitigate climate change and air pollution. The interplay between these is complicated; changes in energy use towards more bioenergy may lead to increased air pollution; conversely reduction of air pollution can affect global temperature in both positive and negative ways. RAQS will provide data to assess the evolution in atmospheric quality over Denmark and enable evaluation of mitigation towards reduction of atmospheric pollutants and climate change. The station will be centered on the Risø meteorological mast. The mast is 125m tall and was erected as part of the Risø radioactivity surveillance program in the late 1950's. There is a laboratory building at the base of the mast. A detailed meteorological record exists with profile measurements of temperature, wind speed and wind direction. During the years 1990-2010, NERI has used the station at Lille Valby (established by Risø DTU) as a background station for air quality in Denmark. In order to have better facilities these activities are moved to the Risø mast in spring 2010.

Possible research proposals during the first five years of a Danish ICOS contribution
Applicant
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Research area: long-term atmospheric station
Research objectives
1. Tall tower reference atmospheric station for air pollutants and GHG
Resources
• Number of research projects: 1
• Funding agency: Danish ICOS contribution
• Senior scientific staff: 30
• Post Docs and young researchers: 24
• Technical staff: 10
• Students (PhD level): 0

3.2.2 Landscape scale validation experiments

Three GHG monitoring sites have been established in the Skjern Å catchment in western Denmark to establish a long-term estimation of catchment wide GHG budgets within the framework of the HOBE hydrology project (www.hobecenter.dk). In the western part of the basin (Skjern Enge) focus is directed towards Methane and

CO2 exchange over the largest restored wetland in Denmark (Herbst et al. 2009). At Voulund in the Eastern part of the basin N2O and CO2 exchange is monitored in the middle of a large agricultural area. At Gludsted Plantation in the NE corner of the basin the CO2 fluxes above and below the canopy of one of the largest spruce forest stands in Denmark are permanently monitored. Likewise N2O fluxes will be monitored continuously at this site from summer 2010. All three sites will be excellent ground reference sites for a future atmospheric station approach, calculating fluxes through inverse modelling.

Possible research proposals during the first five years of a Danish ICOS contribution

Applicant

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Research area: Catchment wide ecosystem monitoring and modelling

Research objectives

1. Continuous CO2 exchange over three different ecosystems within the Skjern Å basin
2. Continuous CH4 exchange over a managed/restored wetland within the Skjern Å basin
3. Continuous N2O exchange over agricultural and spruce forest ecosystems within the Skjern Å basin

Resources

- Number of research projects: 1
- Funding agency: VKR-foundation
- Senior scientific staff: 24
- Post Docs and young researchers: 24
- Technical staff: 6
- Students (PhD level): 24

3.2.3 Forward and inverse atmospheric modelling

The distribution of CO2 in the atmosphere is controlled not only by the sink and source processes acting on local to regional scales, but also by the meteorological processes and dynamics driving the mixing and transport in the atmosphere. Model inter-comparisons show that regional models (0.5°x0.5°) capture the observed spatial-temporal variability of atmospheric CO2, somewhat better than global models with lower resolution (4°x5° to 1°x1°) (Geels et al. 2007). These inter-comparisons show, however, also that part of the observed variability cannot be simulated by even the regional models due to the complexity of both the mesoscale circulation and the exchange with the biosphere.

In recent years a few experiments with focus on CO2 at the regional scale (here defined as a few hundred km long and wide) have been carried out (Dolman et al. 2009; Gerbig et al. 2003). They all suggest that high accuracy measurements in combination with advanced models are necessary in order to understand the involved processes. In principle inverse methods could be applied on such forward high-resolution mesocale models in order to determine the regional source pattern. However, at first it is essential to develop and validate such models against appropriate data, in order to minimize and quantify e.g. the transport uncertainty (Dolman et al. 2009).

Generally, the tendency in carbon cycle research is directed towards a more regional approach, where high-resolution atmospheric models in combination with continuous CO2 measurements, ecosystem models and

inverse techniques potentially can be an excellent tool (Gerbig 2009). The Danish ICOS contribution will be an essential step towards developments of such a pilot system for e.g. a region in Denmark or Northern Europe.

The Department of Atmospheric Research at NERI/AU has a strong record in developing air pollution models from hemispheric to local scales as well as in monitoring air concentrations and fluxes of various atmospheric components. An atmospheric model for CO2 has been developed an applied for studies of the spatial-temporal variability of atmospheric CO2 (e.g., Geels et al. 2004). Interdisciplinary collaboration is needed in order to include the ICOS data in new model developments and improvement as well as in developing a new inverse modelling system.

Possible research proposals during the first five years of a Danish ICOS contribution

Applicant

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Research area: Atmospheric modelling

Research objectives

1. Improve our understanding of the interaction between the carbon cycle and land use at the regional scale by developing high-resolution atmospheric models in combination with continuous CO2 measurements, ecosystem models and inverse techniques.
2. Accurate regional carbon budgets for e.g. Denmark, northern Europe, Europe.

Resources

- Number of research projects: : 2-3 e.g. as part of larger collaborated projects
- Funding agency: VKR-foundation, EU, Danish Council for Strategic Research, DFF
- Senior scientific staff: 18
- Post Docs and young researchers: 20
- Technical staff: 6
- Students (PhD level): 72

3.3 Higher level data products

3.3.1 Development of remote sensing technology

Climate model scenarios conducted in the beginning of this century showed that land ecosystems might sequester carbon fast enough to help counteract CO2 emissions from human activities (Watson et al. 2001). However, mechanisms related to carbon-nutrient interactions and vegetation dynamics are not well represented in large-scale ecosystem and climate models, and ecosystem carbon accumulation rates might be constrained by nitrogen (N) availability (Denman et al. 2007). In addition to the insufficient representation of regional and global N availability for Net Ecosystem CO2 Exchange (NEE) modelling, results from FACE and CO2 experiments show that the photosynthetic capacity and N concentration of leaves are often decreasing at elevated atmospheric CO2 concentrations(i.e., Del Pozo et al. 2007). The loss in photosynthetic activity has been attributed to a reduction in the amount and activity of the enzyme Rubisco which is closely related to leaf N contents. Due to the characteristic spectral signature of leaf chlorophyll, and the close relationship between leaf chlorophyll and leaf N contents, satellite remote sensing can be used to map spatial variations in leaf N. ICOS affiliated research at ENSPAC aims to develop remote sensing based techniques to map land use, leaf area

index and leaf N contents, and to use such products for the modeling and upscaling of NEE from field to regional scales (i.e., Boegh et al. 2002; Hougaard and Boegh 2008)

Possible research proposals during the first five years of a Danish ICOS contribution
Applicant Eva Boegh, ENSPAC, Roskilde University, Universitetsvej 1, 4000 Roskilde, Denmark, email: eboegh@ruc.dk
Research area: Remote sensing based upscaling of Net Ecosystem CO2 exchange rates **Research objectives** 1. Remote sensing based mapping of chlorophyll and leaf nitrogen of forest canopies 2. The role of leaf nitrogen for upscaling Net Ecosystem CO2 Exchange rates 3. Spatial upscaling of Net Ecosystem CO2 Exchange rates using Earth Observations and agro/ecosystem modelling
Resources • Number of research projects: : 1-2 (participation in EU-FP6 project NitroEurope in 2006-2011) • Funding agency: EU, national Danish research councils or VKR foundation • Senior scientific staff: 6 • Post Docs and young researchers: 24 • Technical staff: 3 • Students (PhD level): 36

3.3.2 Spatial modeling at the landscape scale

The regional fluxes over an inhomogeneous area add up in a non-linear way from their equilibrium fluxes at plot scale over the types of homogeneous terrain found. A budget method has been developed and applied on a few datasets only that allows derivation of the effective fluxes over an inhomogeneous terrain. In short it consists of setting up the mass balance for the evolving unstable boundary layer. The method was for the first time used to derive the regional fluxes of CO2 on two days of measurements to during an experimental campaign over Sjælland in 2006 (Gryning et al. 2009). In order to use the method a profile of CO2 is needed as well as measurements on the developments of the growth of the daytime boundary layer. Considerable research is presently devoted for measurements and monitoring of the height of the boundary layer and thus this application of ICOS fit into related activities carried out in other research areas.

Possible research proposals during the first five years of a Danish ICOS contribution
Applicant *Sven-Erik Gryning, Risø DTU, sveg@risoe.dtu.dk*
Research area: Atmospheric mesoscale modelling **Research objectives** 1. Measurements of CO2 profiles by airplane. 2. Derivation of methods to determine the boundary layer height based on aerosol lidar profiles and/or radio soundings.

Resources

- Number of research projects: 1
- Funding agency: The Danish Council for Independent Research (DFF)
- Senior scientific staff: 18
- Post Docs and young researchers: 18
- Technical staff: 24
- Students (PhD level): 72

3.3.3 National GHG emission reporting

GHG emission reporting is a relatively novel, mandatory political commitment to those countries that have signed the Kyoto protocol to the United Nations Framework Convention on Climate Change. The reporting methods need to be applicable for all nations, and default methods are therefore based on simplified emission factor approaches and generalized conversion tables from national economic statistical data to technical GHG emission rates. Limited economic, technological and scientific capacity precludes a number of nations from using state of the art methods to monitor GHG fluxes between land surfaces and the atmosphere, such as direct flux estimations, spatial and dynamical ecosystem modelling and atmospheric inversion approaches. To overcome this limitation, highly developed countries are starting state of the art scientific programmes to both constrain the reported national emission estimates and to demonstrate the progress in GHG emission reduction and its effect on climate change mitigation on a long-term basis at larger spatial scales. ICOS will provide the infrastructure for such GHG flux observations on a European scale. A Danish ICOS contribution will involve Danish scientists in this process, develop new scientific capacity and increase the data availability for Denmark such that ICOS projections will cover Danmark more realistically. It is obvious that ICOS cannot cover the whole complexity of GHG emissions from Danish landscapes. This requires targeted local research in Danish landscapes to address specific land uses and mitigation strategies, e.g., such as proposed in the earlier chapters. Integration of the results and development of a national Danish GHG flux assessment that meets the high scientific standards of ICOS will lead to defensible, science based GHG budgets estimates for Denmark.

Possible research proposals during the first five years of a Danish ICOS contribution

Applicant

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[2]Copenhagen University , Copenhagen Denmark

[3]Århus University, Århus, Denmark

[4]Roskilde University Center, Roskilde, Denmark

Research area: National GHG flux programme for Denmark (DANFLUX)

Research objectives

1. Assimilate approaches and integrate data from ICOS and supplemental Danish national research into a online Danish GHG flux estimation system

Resources

- Number of research projects: 1
- Funding agency: Danish Council for Strategic Research
- Senior scientific staff: 90
- Post Docs and young researchers: 72
- Technical staff: 36
- Students (PhD level): 72

4 Summary and conclusions

This white paper addresses the benefits for future Danish research on greenhouse gas (GHG) and climate research from contribution to the large scale European infrastructure ICOS (Integrated Carbon Observation System (www.icos-infrastructure.eu).

ICOS is designed to assess GHG fluxes on the European continent with a dual constraint approach, direct measurement of GHG fluxes between terrestrial and marine ecosystems and the atmosphere and atmospheric inversion modeling from high precision GHG concentration fields from a tall tower network across Europe. The methods used have been developed and tested in a large number of prominent European research projects in which a large number of Danish researchers were participating. Key for the use of such data are: high precision, high degree of standardization, near real time data dissemination and long-term operation.

Many countries, e.g. France, Finland, Sweden, UK and Italy, have already bindingly committed themselves to support ICOS and applied to host central ICOS facilities. The ICOS focal point in Denmark has prepared a Danish contribution to the ICOS ecosystems and atmospheric station networks, with maintaining two ecosystem observation sites and building up and maintaining two tall tower, high precision atmospheric observation sites. Especially the ecosystem observation sites will be built upon an existing site, the beech forest site at Sorø, where fluxes have been monitored for more than 10 years, thereby extending the scope of ICOS to more than 30 years of continuous GHG flux and climate observation.

Based on this a workshop was held introducing the concept to Danish researchers with proven records of ICOS related research. The participants demonstrated their expectations to such Danish contribution to ICOS for their future research with project sketches that build the body of this white paper.

In total this white paper has collected ideas for 27 research projects from all major Danish Universities that benefit from a Danish contribution to the ICOS infrastructure during its first 5 years operation. These projects will in total dedicate 10 person years of Danish senior researchers to ICOS related research, will give about the same amount of resources for career development of young scientists and Post Docs, and will offer ca. 25 students possibility to in depth training and qualification in this vitally developing science area. The benefits from a Danish contribution to ICOS to the sketched projects arise from either using the ICOS infrastructures and methods of ecosystem flux observation directly or improving the use or extending the ICOS infrastructure to get more detailed picture of GHG exchange between the Danish ecosystems and the atmosphere. The

atmospheric network stations open new grounds for Danish research, which is possibly the reason, why there are only a few projects that directly addresses the benefits from these stations. This emphasizes that there is a large potential and evolving interest for capacity building in atmospheric measurements and modeling in Danish research institutions. This white paper documents, that Danish scientists have realised that Danish GHG fluxes research needs to be integrated and taken on a higher scientific level in order to contribute substantially to a scientific GHG emission monitoring and management in Denmark, Europe and at global scale. The Danisch contribution to the ICOS infrastructure will act as the condensation nucleus towards an integrated Danish GHG research that is vitally embedded in international, European and global, research.

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