Many of the global biogeochemical cycles are reflected in the atmosphere by one or several trace gases such as carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O), or also aerosols. Spatio-temporal variations of these tracers (and other quantities linked to them such as their isotopic composition) contain important information on location, magnitude, and temporal variability of the various source and sink processes of the species of interest. The atmosphere thereby is used as a natural “integrator” of the complex pattern of surface fluxes because of the rapid mixing of air. Atmospheric measurements may thus be used to observe surface processes on a range of spatial and temporal scales, from a small-scale regional ecosystem to entire continents and the globe. Thereby, atmospheric transport by winds and mixing has to be taken into account by using three-dimensional numerical meteorological models in an inversion or data assimilation mode. In the Department of Biogeochemical Systems we develop and apply this “top-down approach” in four focus areas:

**Focus 1. Expansion of the atmospheric network of in situ measurements of high-accuracy biogeochemical trace species**

The current global atmospheric network for biogeochemical trace gases contains many gaps in important areas. An effort therefore is directed at the establishment of new measuring stations in undersampled locations, which constitute “hot-spots” in the Earth system. Geographically we pursue this along three directions: (1) A string of tall towers from Europe into the Eurasian taiga at 60°N including the 300 m high measurement mast in central Siberia (ZOTTO, Figure next page, left). (2) A line of stations along the eastern Atlantic Ocean on remote islands and coasts (e.g., Shetland, Cape Verde, Namibia) for monitoring oceanic processes and air leaving the African continent. (3) Jointly with the MPI for Chemistry

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**Portrait of the Director**

Martin Heimann is Director of the Department Biogeochemical Systems at the Max Planck Institute for Biogeochemistry since 2004. He is a member of the Max Planck Society, honorary professor at the Friedrich-Schiller-University of Jena, and elected member of the Academia Europaea. Over the last three decades Martin Heimann has worked on analyzing and modeling the global carbon cycle and its interaction with the physical climate system.

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in Mainz and partners in Brazil we will build and operate a 300 m tall measurement mast in central Amazonia (ATTO). A critical new development are quasi-continuous, concurrent observations of a whole suite of biogeochemical trace species, which allow us to discriminate between different source/sink processes.

Focus 2. Development of new measuring techniques and observing systems

The small spatial and temporal variability of long-lived biogeochemical atmospheric trace gases necessitates measurements with extreme accuracy. Ensuring this in remote areas under harsh environmental conditions poses a serious technical challenge. We explore new techniques, such as miniaturization of measurement devices for the deployment on routine civilian aircraft, application of ground-based Fourier Transformation Near-Infra-Red Spectroscopy of the sunlight, and, in collaboration with other partners, the development of new systems for space-based remote sensing of atmospheric biogeochemical trace gas concentrations.

Focus 3. Linking atmospheric point measurements with regional model grid averages

A critical “Achilles heel” in present regional and global inversion systems is the representation of point measurements in grid-based atmospheric models, especially if the measurements are taken over land covered by a heterogeneous mosaic of greenhouse gas sources and sinks. In order to bridge this gap, we conduct small and regional scale process studies by means of campaigns with a high density of observations using in situ stations, aircraft and remote sensing, together with high resolution regional meteorological modeling systems for the analysis.

Focus 4. Development and application of atmospheric inverse modeling and data assimilation frameworks

The determination of surface fluxes from atmospheric observations requires the use of realistic numerical models for the simulation of the atmospheric transport. Since in most cases observations from only a limited number of atmospheric stations are available, the underlying mathematical inversion problem is highly underdetermined. We attack this problem with a range of mathematical methods and by incorporating additional measurements: e.g. other atmospheric trace gas observations, surface properties such as the “greenness” of the vegetation seen from space, vegetation distributions and other geographical data. The ultimate goal is the development of a data assimilation framework consisting of land and ocean surface biogeochemical modules coupled to an atmospheric meteorological model. This is then being optimized in a consistent way by the wealth of available observations, similar to what is being done routinely in numerical weather forecasting. With these tools, we can quantify and monitor where and how biogeochemical trace gas budgets respond to climatic (e.g. heat, drought) and human (e.g. fossil fuel burning, fires, deforestation) impacts (Figure below). This provides important information for the improvement of modules of biogeochemical cycles in global comprehensive Earth system models.

Global distribution of carbon dioxide sources and sinks determined from atmospheric measurements (black triangles: monitoring stations) with the Jena inversion system averaged from 1996 to 2007 (Rödenbeck et al., 2003, ACP, updated). Units: gC m⁻² yr⁻¹, blue colors denote sinks, yellow and red colors denote sources. The imprint of the emissions from the highly industrialized regions in the northern hemisphere is clearly visible.
Greenhouse gases like carbon dioxide, methane, or water vapor can be measured very accurately with in-situ instruments that sample the air around them. This becomes increasingly difficult for higher altitudes. However, the ability of greenhouse gases to absorb infrared radiation allows measuring them from a distance. When infrared radiation travels through the atmosphere, it is both absorbed and emitted by greenhouse gas molecules in a characteristic way. By detecting and analyzing this radiation, one can derive the abundance of many greenhouse gases. This can be done from above by a satellite as well as from the ground.

Remote sensing methods that observe natural electromagnetic radiation are called “passive” methods. Some constituents of the atmosphere like aerosols are better observed with “active” methods. For active remote sensing, an artificial light source, like a laser, is used to illuminate the part of the atmosphere to be sampled. The resulting scattered or absorbed light is then measured to derive, for example, the abundance of aerosols in the atmosphere.

**Focus 1. Greenhouse gas measurements with Fourier-Transform Infrared Spectroscopy**

The main project of the ARS group focuses on remote sensing of atmospheric greenhouse gases with a Fourier-Transform Infrared (FTIR) Spectrometer. This kind of instrument, which is also called FTS (Fourier-Transform Spectrometer), is able to observe a number of atmospheric trace gases at the same time. The main trace gases of interest are carbon dioxide (CO$_2$), methane (CH$_4$), water vapor (H$_2$O), carbon monoxide (CO) and nitrous oxide (N$_2$O). However, many more gas species as well as isotopes of these gases can be observed as well.

To measure these trace gases, the instrument uses a passive technique. When sunlight travels...
through the atmosphere, it is absorbed by the molecules of many trace gases, especially in the infrared region of the spectrum. When the molecules absorb light, they only do so at characteristic wavelengths. This way they produce spectral absorption lines that serve as a spectral fingerprint for each trace gas. The FTS analyzes the incoming sunlight and measures the strength of thousands of such spectral lines. From the position of the lines in the spectrum, one can identify the type of trace gas. The strength of the lines is a direct measure of the number of molecules between the sun and the FTS.

Because the light from the sun has crossed the whole atmosphere, the measurement provides information from the ground up to the top of the atmosphere. This is different from in-situ measurements which only measure the air directly surrounding them. Ground-based FTIR measurements are therefore very valuable to validate satellite measurements of greenhouse gases. Satellite instruments typically also sample the whole atmosphere, e.g. when they look at reflected sunlight that has passed through the atmosphere twice.

The FTS is part of the Total Carbon Column Observation Network (TCCON), an international network of FTS instruments that have been set up in different parts of the world. In 2010, our FTS was transported to the University of Wollongong, Australia, to make side-by-side measurements with another FTS. Both instruments are part of TCCON, and the intercomparison of the data produced from both instruments is very valuable to improve the overall data quality of the network. Our instrument has now been set up on Ascension Island, a small British overseas territory in the South Atlantic. The location is unique as it allows sampling of tropical air that comes mostly from Africa and under certain conditions also from South America - two continents where such measurements have not yet been made.

Focus 2. Remote sensing of atmospheric mixing layer height

Besides direct greenhouse gas measurements, there are other important atmospheric parameters that can be measured with remote sensing methods. One of these parameters is the height of the atmospheric mixing layer. The mixing layer is located between the surface and the free troposphere. It is strongly influenced by surface processes: for example the emission or deposition of particles or the exchange of greenhouse gases between the biosphere and the atmosphere.

The thickness of the mixing layer can range from a few hundred to more than two thousand meters. It is a crucial parameter for computer models that calculate the transport of greenhouse gas emissions from the surface through the atmosphere. However, the mixing layer height used in these models is often very inaccurate and leads to errors in the model results. This may also affect the interpretation of the atmospheric measurements from the Integrated Carbon Observing System (ICOS), a network of European stations for monitoring greenhouse gases, which is currently being established.

To improve this situation, we are evaluating remote sensing methods that can be used to measure atmospheric mixing layer height at the future ICOS stations. One way to measure the mixing layer height is to illuminate the atmosphere with a laser and analyze the backscattered signal (LIDAR principle). Since LIDAR systems are usually very expensive, we are investigating the possibility of using simpler instruments like ceilometers. Ceilometers are meteorological instruments that measure the cloud base height. With improved data analysis techniques, ceilometers can also be used to derive mixing layer height. The project is carried out in cooperation with the German Weather Service (Deutscher Wetterdienst, DWD) and JENOPTIK.

Overview of the methods used by the ARS group: passive measurements of greenhouse gases with an FTIR spectrometer (left), active measurements of mixing layer height with a ceilometer (right).
Atmospheric measurements of biogeochemical trace gases are made by ground stations, by aircraft, and by remote sensing. In order to retrieve information about surface-atmosphere exchange from atmospheric measurements of trace gases, a combination of atmospheric transport and surface flux models is required. These models need to resolve the trace gas patterns in the atmosphere, so that individual measurements can be represented. Transport models are usually a by-product of operational weather forecasting, which means that specific adaptations to the models in order to simulate long-lived trace gases are needed. Airborne measurements can best capture the 3-dimensional atmospheric distribution, and are hence ideal for testing and optimizing these models. In addition, airborne measurements are the only means to validate remotely-sensed atmospheric concentration data. Thus the Airborne Trace Gas Measurements and Mesoscale Modeling Group (ATM) has a focus on several research areas:

Focus 1. Development of high-accuracy airborne in-situ measurement systems

An airborne in-situ measurement system requires special instruments suited for the aircraft environment, taking into account vibrations, weight limitations, strict safety regulations etc. Therefore, commercially available instruments usually need significant modifications before they can be operated onboard aircraft. Several instruments are under development for application onboard airplanes: (1) Together with industry partners, a greenhouse gas analyzer using the cavity ring-down spectroscopy technique is being modified for deployment onboard commercial airliners. As part of the EU infrastructure project IAGOS-ERI (In-service Aircraft for a Global Observing System) the system is scheduled to monitor CO$_2$ and CH$_4$ around the globe with a fleet of airbus A340 aircraft. (2) ICON, the In-situ Capability for O$_2$/N$_2$ measurements, is designed to measure the oxygen to nitrogen ratio at very high precision.
onboard research aircraft. As oxygen is consumed/produced in processes that produce/consume CO$_2$ at a ratio specific for different processes, O$_2$/N$_2$ measurements provide information on sources and sinks of CO$_2$. (3) Within the EU infrastructure project ICOS (Integrated Carbon Observing System) an automated flask sampler suited for airborne and ground based collection of air samples for subsequent analysis of trace gases in the laboratory is under development in collaboration with other partners.

**Focus 2. Airborne measurement campaigns capturing atmospheric trace gas distributions for model validation and budgeting**

The atmospheric distribution of trace gases, derived from many vertical profile measurements during airborne campaigns, is an important constraint for regional budget studies and is used for validation of tracer transport models and remote sensing. Different types of airborne campaigns have been performed, including regional campaigns to study near-field effects on the CO$_2$ distribution in the vicinity of ground based stations, or the validation of ground-based Fourier-Transformation Near-Infrared Spectroscopy measurements such as those made within the Atmospheric Remote Sensing research group of our department. In addition, within the project BARCA (Balanço Atmosférico Regional de Carbono na Amazônia), the carbon balance of the Amazon basin has been investigated with partners from Brazil and the US using airborne campaigns during the dry and wet seasons (Figure below).

**Focus 3. Mesoscale modeling to bridge the gap between observations and global models**

Trace gas fluxes at the Earth's surface vary on small spatial scales, corresponding to patches of different land use and patterns of emissions from fossil fuel burning. The distribution of those gases in the atmosphere is variable on correspondingly small scales, albeit turbulence tends to remove some of this variability by mixing. In order to represent measurements made in the mixed layer (the lowest 1-2 km of the atmosphere) by stations such as tall towers, mesoscale models with resolution of 20 km or better are needed. Therefore there is a strong research focus on the following areas: (1) A high resolution modeling system that combines a mesoscale weather prediction model with flux models for CO$_2$ and other greenhouse gases has been developed and validated against campaign-based data. This system has been used to investigate the impact of the variability in atmospheric CO$_2$ on the interpretation of data from remote sensing and from mountain stations, and also to study the methane budget in the Amazon basin. (2) The Stochastic Time Inverted Lagrangian Transport model STILT was developed to study where and by how much measured air parcels are influenced by surface-atmosphere fluxes upstream. The model is implemented as a regional model within the Jena Inversion System to bridge the scale gap between observations and a global transport model. (3) Estimating surface fluxes from atmospheric observations requires accurate transport models. Thus an important research topic is the quantification and reduction of uncertainty in these models, especially in transport processes, such as turbulent mixing and moist convection through clouds that cannot be resolved but are described with parameterizations.
The major players of the global carbon cycle – the terrestrial biosphere, the oceans, human activity – exchange carbon dioxide (CO$_2$) and other greenhouse gases with the atmosphere, thereby influencing the climate through the greenhouse effect. The strength of the biospheric and oceanic exchanges strongly varies in space and time – from year to year, with season, from day to day, between day and night. This variability is, in turn, closely linked back to climatic influences. To comprehend the role of the carbon cycle in the climate system, we need to understand quantitatively how the carbon cycle processes on large spatial scales react to their climatic controls. As a prerequisite for such understanding, the temporal variability and spatial patterns of CO$_2$ exchange need to be quantified.

The research group “Inverse Data-driven Estimation (IDE)” focuses on such a quantification on the basis of measured data. Specifically, the following activities are currently pursued:

**Focus 1. Quasi-operational CO$_2$ flux estimation (“Jena CO$_2$ inversion”)**
Carbon dioxide is a direct tracer of the carbon cycle and its variability. Atmospheric CO$_2$ has been regularly measured by various institutions (including our MPI for Biogeochemistry in Jena) at more than 100 sites worldwide. Based on the gained data, CO$_2$ sources and sinks can be estimated quantitatively: CO$_2$ sources and sinks cause concentration gradients in the atmosphere, dependent on atmospheric transport processes. By measuring these gradients, the sources can be traced back using inverse methods in conjunction with a numerical transport model.

We perform such calculations with a focus on their interannual variations. By relating the year-to-year variations in the CO$_2$ sources or sinks to documented climate variations, we can reveal the driving mechanisms (Top figure, next page).

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**Portrait of the Group Leader**

Christian Rödenbeck studied physics at Leipzig University, where he also got his PhD. As a postdoc at the Max Planck Institute for Complex Systems in Dresden he worked on dynamical systems theory. In 2000 he joined the Max Planck Institute for Biogeochemistry in Jena.

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Focus 2. Diagnostic data-driven models of the land biosphere

The information obtained by the atmospheric CO$_2$ measurements can also be combined with other sources of information, such as satellite-derived indices of vegetation state or meteorological data. This method has the advantage of exploiting both the small-scale structure in these data and the large-scale constraints from the atmospheric measurements. Through empirical models and again using inverse methods, the relation between surface CO$_2$ fluxes and climatic influences can be determined directly. The application of this method is currently being tested, with the aim of obtaining data-driven estimates of the climate sensitivity of the carbon cycle with respect to temperature, precipitation, or solar radiation.

Focus 3. Diagnostic data-driven models of the ocean carbon cycle

Carbon cycle processes do not only lead to gradients in atmospheric CO$_2$ but also to tiny variations in atmospheric oxygen. Oxygen measurements can thus provide additional information, in particular about ocean biogeochemistry (Figure right). At present, a diagnostic model is being developed that can incorporate further data streams, including carbon and oxygen measurements in the oceanic mixed layer, as well as sea surface temperature, sea-air heat fluxes, nutrient concentrations, and variables related to sea-air gas exchange and ocean-interior transport and chemistry. Estimates based on several independent data streams turn out to be mutually consistent, and thus corroborate each other. The diagnostic scheme can also be used to assess the information content of additional data, to help in the planning of new carbon cycle observations.

Focus 4. Regional inversions

Current-generation global models of atmospheric transport are much coarser in resolution than the actual variability of both atmospheric transport and carbon fluxes, particularly over continents. This leads to substantial errors in the inversion calculations. The problem can be tackled by focusing on a domain of interest over which fluxes and transport are more finely resolved. Strategies for such regional inversions are being developed and applied to various focus regions (Europe, Siberia).

Focus 5. Other tracers

The inverse methods developed for CO$_2$ are also applied to other atmospheric tracers, in particular the well-known greenhouse gases methane (CH$_4$) and nitrous oxide (N$_2$O). Another important tracer is carbonyl sulfate (COS), which is of interest both for its role in atmospheric chemistry and its link to the carbon cycle via photosynthetic uptake.
High precision ground-based and vertically resolved quasi-continuous atmospheric measurements of biogeochemical trace gases at coastal and continental sites are vital for the study of atmospheric transport, biogeochemical fluxes and human emissions. Our group develops and maintains atmospheric measurement sites and instrumentation with the objective of investigating global climate hot-spots and supporting the global atmospheric observational system.

High precision ground-based quasi-continuous atmospheric measurements and discrete (flask) samples are an important tool for the study of atmospheric transport, biogeochemical fluxes, and human emissions. They complement other types of atmospheric measurements such as ground- and space-based remote sensing and airborne measurements.

At our ground-based stations we measure alongside carbon dioxide (CO$_2$), the most frequently measured and most important anthropogenic greenhouse gas (GHG), also methane (CH$_4$), nitrous oxide (N$_2$O), and the synthetic GHG sulphur hexafluoride (SF$_6$). Additionally, the reactive non-GHG carbon monoxide (CO) is measured as it can serve as a tracer of human activity and has an influence on the concentrations of methane and ozone in the atmosphere. The isotopic composition of CO$_2$ (flask samples) and the O$_2$/N$_2$ ratio (continuous measurements and flasks) provide insight into the partitioning of the land and ocean portions of the carbon budget.

Despite substantial international efforts, the global GHG observational system is still far from adequately covering the entire globe. Particularly important are the critical gaps that still exist in so-called “hot-spot” areas, such as northern Eurasia, and the tropical regions of Africa and South America. These areas are considered as important climatic controls because of their large potential of carbon storage or loss in relation with land use and climate change (e.g., deforestation, permafrost thawing).

In contrast to atmospheric measurements close to the ground, a tall tower station offers the possibility to sample the atmosphere at different heights above the ground. This allows for measurement of vertical concentration gradients, local carbon flux estimation, and sampling of air masses above the

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**Portrait of the Group Leader**

Jošt V. Lavrič studied geology in Ljubljana and holds a PhD in stable isotope inorganic and organic geochemistry from the University of Lausanne. During his post-doctoral stays at LGGE (Grenoble) and LSCE (Gif-sur-Yvette) his focus moved to paleoclimatology and atmospheric research. His expertise includes high-precision instruments for gas measurements, and facilities for molecular and isotopic compound analysis. He has been head of the research group for ‘Tall Tower Atmospheric Gas Measurements’ since 2009.

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nocturnal planetary boundary layer. The composition of these air masses is representative of a much larger region compared to locally-influenced air masses closer to the ground.

Technological advancements in instrumentation lower the need for maintenance and increase the number of gas species that we can measure continuously in the field with high precision. This is particularly important for stations at remote locations.

As part of a cooperative effort, the Tall Tower Atmospheric Gas Measurements group (TAG) is establishing measurement sites along a west-east transect at about 60°N from the North Atlantic to Siberia, and along a north-south transect in the Eastern Atlantic Ocean. In addition, TAG is dedicated to the development and improvement of instrumentation and measurement techniques (See figure above). Currently, four continuous and two flask-only sites are operative (See figure below).

The Ochsenkopf station is located on a mountain in northern Bavaria (Germany) and measures air primarily influenced by central-northern Germany and Benelux. The Bialystok station (Poland) is located east of densely populated Western Europe, which has important implications for the monitoring of its anthropogenic emissions.

The Zotino tall tower observatory (ZOTTO) is a joint German–Russian scientific platform in central Siberia for observing and understanding biogeochemical changes in Northern Eurasia (http://www.zottoproject.org/).

The Cape Verde atmospheric observatory (CVAO) is an international effort to observe and investigate the complex West African upwelling system and the underlying low oxygen zone (http://ncasweb.leeds.ac.uk/capeverde/). Our measurements will be used for an assessment of the biogeochemical trace gas budgets in this region.

The TAG group has two major forthcoming projects: new stations for continuous atmospheric measurements of biogeochemical trace gases at Gobabeb (Namibia) and in the Amazonian forest (Brazil; ATTO project).

The Benguela current system off the Namibian coast drives one of the four major eastern-boundary upwelling ecosystems. Oceanic upwelling creates zones of intensive primary production and influences the budgets of atmospheric gases via the air-sea exchange. At the Namibia atmospheric observatory (NAO), located close to the southern African Atlantic coast, we started to continuously measure the O$_2$/N$_2$ ratio and biogeochemical trace gases (CO$_2$, CH$_4$, N$_2$O, CO). The site is ideally located to study the air-sea gas fluxes of the nearby Benguela Current system, and the natural and anthropogenic greenhouse and other gas fluxes on the southern subtropical African continent.

The construction of the Amazonian Tall Tower Observatory (ATTO) in the Amazonian forest (Brazil) is the result of a joint Brazilian-German research project. Our multi-level continuous GHG measurements at the more than 300 m tall tower will bridge the gap between flux tower, remote sensing and airborne measurements in a key global hot-spot area.

The MPI-BGC-BSY-TAG atmospheric network consists of coastal and tall tower-based continuous and flask atmospheric measurement sites.

At ZOTTO, the spherical buffer volumes (top left) allow a near-concurrent measurement of air from all six inlet heights with a single analyser.
Complex feedback processes between terrestrial ecosystem functionality and climate change constitute a major source of uncertainty for forecasting future climate scenarios. In order to improve future climate predictions, we need to better understand the interactions between all components affecting ecosystem functionality, and their sensitivity towards changing environmental conditions. In this context, scale poses a considerable challenge. The ‘big questions’ are posed on large scales (e.g., ‘What are the trends in annual atmospheric carbon budgets?’, ‘How much methane will be released from Arctic ecosystems over the next decade under a warming climate?’), and appropriate monitoring and modeling tools survey these domains in relatively coarse resolution (e.g., monthly timestep, grid resolution of several tens of km). While these tools can detect changes and trends in surface-atmosphere exchange processes, they often cannot provide information on the underlying mechanisms since many of these mechanisms take place on smaller spatiotemporal scales. Finer-scale observation techniques (timesteps of seconds to hours, spatial scales ranging between meters to a few km) can target these mechanisms and their feedback with climate, but these datasets are only representative for (very) small domains, and their suitability to answer large-scale questions may be limited.

Our working group focuses on the design of networks of greenhouse gas observation systems covering multiple spatiotemporal scales, and the assimilation of these new datasets into flexible modeling frameworks. One major focus is placed on approaches to optimize a hierarchy of observation platforms across scales to constrain surface-atmosphere exchange fluxes of unknown, but presumably highly variable spatiotemporal distribution (e.g., methane fluxes in permafrost ecosystems). A second major focus, intimately related to the first, is to mine all information available on...
ecosystem feedbacks to climate variability, ranging from small scale soil chambers to large scale satellite data, from high-frequency eddy-covariance data to long-term biometric inventories, in order to improve the representation of underlying mechanisms in process models.

Focus 1. Carbon fluxes in permafrost ecosystems

As one of several collaborating institutes across Europe in the EU-funded project PAGE21, we coordinate a long-term experiment to monitor exchange fluxes of carbon dioxide and methane near Chersky, Northeast Siberia (68.7N, 161.4E). The new network, which will start operating in early summer 2013, comprises soil chamber measurements, eddy covariance towers, taller towers to produce highly accurate time series of atmospheric mixing ratios, and airborne sampling to integrate signals over very large areas. Data analysis will focus on the characterization of flux variability across multiple scales in both time and space, involving detailed studies on flux components on the microscale using isotope data. For macroscale analyses on the pan-Arctic scale, we will integrate our observations with datasets from collaborating research groups operating similar systems in Northwestern Siberia (Lena delta) and the Alaskan North slope (Barrow). Upscaling procedures will involve a framework of biosphere process models, source weight function modeling and atmospheric inverse modeling.

Focus 2. Data assimilation based on high-resolution regional scale inverse modeling

Atmospheric inverse modeling provides an approach to extract information on regional to global scales from atmospheric trace gas observations, while at the same time allowing to assimilate data from various other sources. A major challenge in this context is to find the most suitable setup for integration and weighing of different data sources. We are testing and evaluating conceptual strategies to handle the assimilation of various data sources into atmospheric inverse modeling frameworks, including geostatistical inverse modeling approaches that allow extracting information from atmospheric observations without placing constraints through prior assumptions, or rigid model structures. Part of this research will be carried out under focus 1; in addition, we are involved in an atmospheric inverse modeling study focusing on the state of Oregon in the Pacific Northwestern USA that is part of the North American Carbon Program. In this domain, a network of currently seven observation towers, the tallest of which reaches 283 m a.g.l., has been set up to monitor mixing ratio time series of CO$_2$ and CO in an effort to constrain biosphere and anthropogenic Carbon budgets.

Focus 3. Carbon capture and storage monitoring

Carbon capture and storage (CCS) is a growing industry that is supposed to provide an interim solution for dealing with growing greenhouse gas emissions by pumping exhausts as liquefied CO$_2$ into geological reservoirs. At present, monitoring, verification and accounting approaches are lacking behind advances in CCS technologies, with little rigorous research available that could guide CCS operators to set up the most suitable tools. We are involved in a pilot project focusing on two CCS sites in Canada where several surface based monitoring approaches will be tested, evaluated and finally integrated into a comprehensive network. This research aims at providing a tool to detect potential leaks, thus verifying how much of the injected greenhouse gas actually stays underground. Similar to the work focusing on permafrost carbon fluxes, we will use a suite of soil chambers, eddy covariance towers and mobile as well as stationary trace gas observation platforms to monitor the unknown, highly variable flux emission fields across different scales. Special attention will be paid here to the integration of a suite of different techniques into the framework, including multi-scale modeling approaches for biosphere flux activity, atmospheric transport, as well as observations of ancillary trace gases and isotope signals that characterize the injected gas mixture.