


Department of Biogeochemical Systems

Biogeochemical cycles are represented in the atmosphere by several important greenhouse gases, such as carbon dioxide, methane and nitrous oxide. In the Department of Biogeochemical Systems we develop methods to measure these gases in situ and by remote sensing, we expand the measurement network to remote hot-spot regions such as Siberia and Amazonia, and we develop and apply numerical models to quantify the large-scale sources and sinks of the greenhouse gases.

Many of the global biogeochemical cycles are reflected in the atmosphere by one or several trace gases such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) 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 new 300 m high measurement mast in central Siberia (ZOTTO, Figure next page). (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

Portrait of the Director

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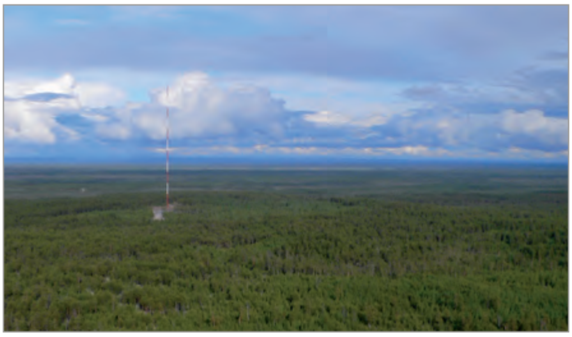
in Mainz and partners in Brazil we will build and operate a 300 m tall measurement mast in central Amazonia (ATTO). A critical new development are quasi-continuous, concurrent observations of a whole suite of biogeochemical trace species, which allow us to discriminate between different source/sink processes.



Zotino Tall Tower Observatory: a 300 m tall mast for the long-term monitoring of biogeochemical trace gases, aerosols and atmospheric chemistry established in central Siberia by the MPI for Biogeochemistry, the MPI for Chemistry and the Institute of Forest, Krasnojarsk; funded by the Max-Planck-Society.

Focus 2. Development of new measuring techniques and observing systems.

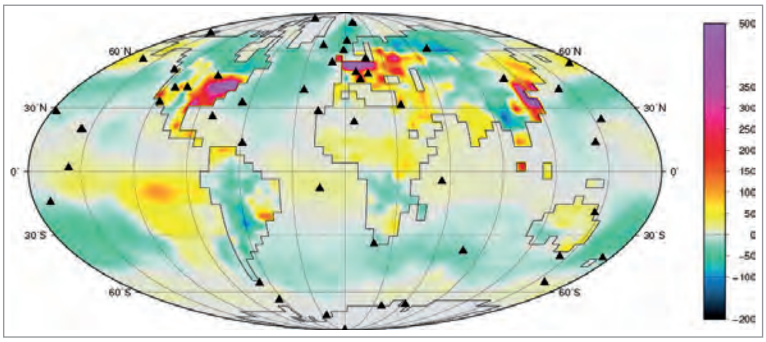
The small spatial and temporal variability of long-lived biogeochemical atmospheric trace gases necessitates measurements with extreme accuracy. Ensuring this in remote areas under harsh environmental conditions poses a serious technical challenge. We explore new techniques, such as miniaturization of 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 is 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.

Atmospheric Remote Sensing

The Atmospheric Remote Sensing (ARS) group investigates techniques that can measure atmospheric parameters from a distance. These remote-sensing techniques typically rely on electromagnetic radiation that has interacted with atmospheric constituents like greenhouse gas molecules or atmospheric particles (aerosols). From the analysis of the detected radiation one can derive atmospheric parameters that are important for the global carbon cycle.

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 diffcult 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_2O), carbon monoxide (CO) and nitrous oxide (N_2O). 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

Portrait of the Principle Investigator

Dietrich Feist studied Physics at the University of Heidelberg, Germany. In 1999 he received a PhD from the University of Bern, Switzerland, for a thesis on the retrieval of atmospheric parameters from a Space Shuttle experiment. He stayed in Bern as a postdoc, spent more than 300 hours on board research aircraft, and also worked in the USA, Japan and the UK during this time. He has been head of the Atmospheric Remote Sensing group at the Max Planck Institute for Biogeochemistry in Jena since 2006. His expertise is the remote sensing of atmospheric trace gases.

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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 may be very accurate but 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.

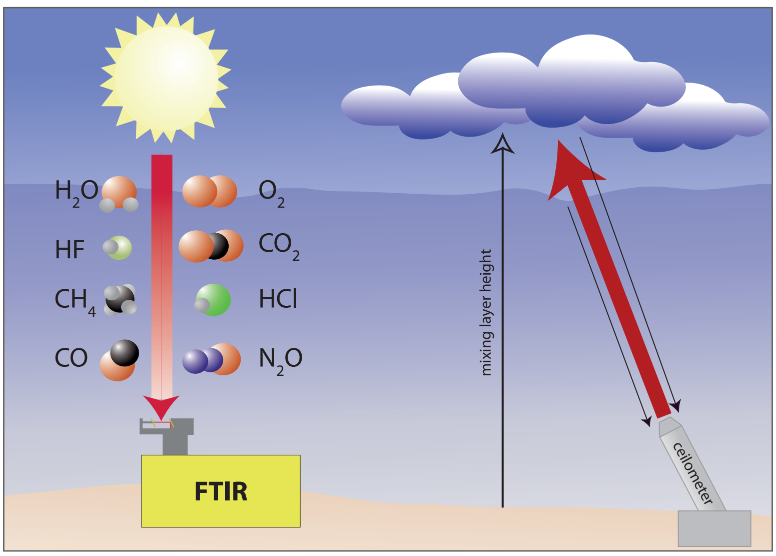
The FTS is part of the Total Carbon Column Observation Network (TCCON), an international network of FTS instruments that have been set up in different parts of the world. In 2010, the FTS was transported to the University of Wollongong, Australia, to make side-by-side measurements with another FTS. Both 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. Eventually, the instrument will be 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).

Airborne Trace Gas Measurements and Mesoscale Modeling

Aircraft campaigns measuring atmospheric greenhouse gases provide strong constraints for regional budgets, as they deliver a high density of data within a targeted region. In addition, they provide a 3-dimensional context for long-term measurements made at ground sites. Atmospheric transport modeling at high spatial resolution using weather prediction models in combination with biospheric flux models is used to interpret data from such airborne campaigns.

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 mean 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

Portrait of the Principle Investigator

Christoph Gerbig studied Physics in Aachen and Wuppertal, Germany, where he also received his PhD in Atmospheric Chemistry. He worked as a postdoc at Research Center Jülich and Harvard University, where he became interested in instrument development for atmospheric measurements, but also in application and development of atmospheric transport models. He has been head of the research group airborne trace gas measurements and mesoscale modeling since 2004.

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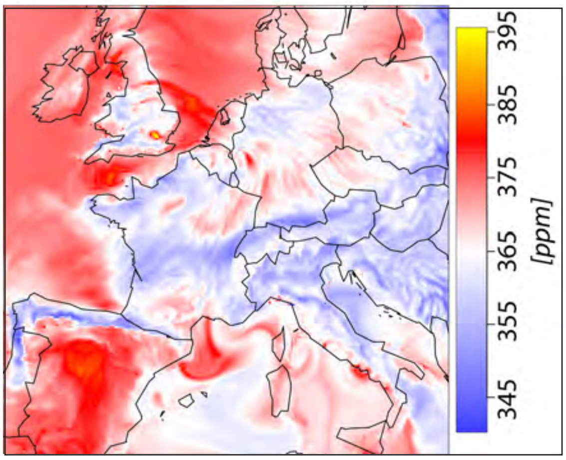
onboard research aircraft. As oxygen is consumed/produced in processes that produce/consume CO_2 at a ratio specific for different processes, O_2/N_2 measurements provide information on sources and sinks of CO_2. (3) Within the EU infrastructure project ICOS (Integrated Carbon Observing System) an automated 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.

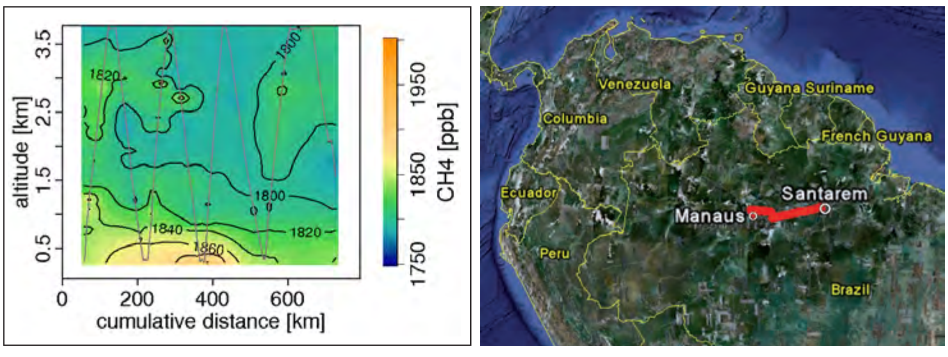
Focus 3. Mesoscale modeling to bridge the gap between observations and global models

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

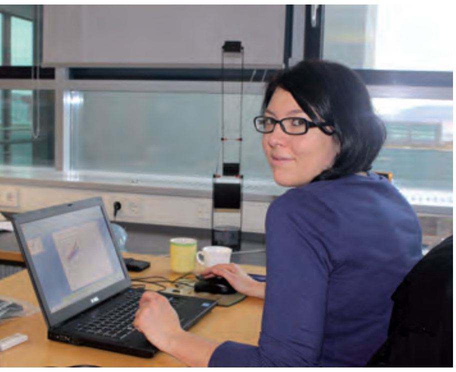


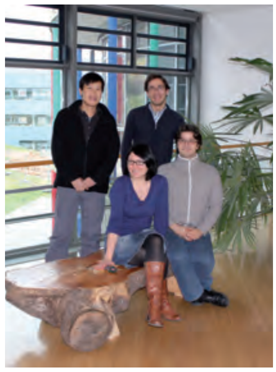
CO_2 mixing ratios at 150 m above ground over Europe during 12th July at 14:00 GMT, showing patterns of transport and fluxes.

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.



Enhanced CH_4 in the lower atmosphere shown in the altitude-distance cross-section measured during BARCA on 21st May 2009 (right: flight track).






Terrestrial Biosphere Modelling and Data Assimilation

Feedbacks between terrestrial biogeochemistry and climate are essential for understanding past and projecting future changes in atmospheric greenhouse gas concentrations and climate. Terrestrial biosphere models summarize current knowledge of the interactions between landsurface processes and climate on many timescales. Our group develops methods to test and improve these models with the objective of enhancing the predictive capacity of Earth System Models.

Terrestrial biogeochemical cycles are influenced by climate in many ways and on many timescales. They affect in turn the climate system through their control on atmospheric greenhouse gas concentrations. These interactions are essential for understanding observed past and present atmospheric and climatic changes, and for projecting future climate change as the consequence of anthropogenic greenhouse gas emissions. Studies of these interactions rely heavily on numerical models of the terrestrial biosphere (so called terrestrial biosphere models), linking processes at the scale of a single leaf to processes at the scale of individual ecosystems, biomes and continents. Terrestrial biosphere models can be driven with observed changes in land use, climate, and atmospheric composition to simulate recent trends in vegetation activity, and their controls on net land-atmosphere exchanges of energy, water and greenhouse gases such as carbon dioxide, to attribute these trends to their causes (Figure next page), and to project likely future developments. Being built on fundamental theories of plant and ecosystem functioning, the predicative capacity of terrestrial biosphere models depends on i) a comprehensive representation of the key processes that affect biogeochemical cycles at larger scales and ii) ecosystem observations that constrain the terrestrial biogeochemical cycles such as carbon and nitrogen and their relationships with land-atmosphere energy and water exchanges. The research of the Terrestrial Biosphere Modelling and Data Assimilation (TBM) group within the Department of Biogeochemical Systems focuses on the following areas:

Focus 1. Interactions between terrestrial carbon and nutrient cycles

The growth of plants and the decay of organic matter are limited by the availability of nutrients such as nitrogen and phosphorous. The flexibility of the stoichiometry of biological systems and the dynamics of these nutrients influence

Portrait of the Principle Investigator

Sönke Zaehle studied geo-ecology and environmental sciences in Braunschweig and Norwich, and holds a PhD from the University of Potsdam and the Potsdam Institute for Climate Impact Research. During his PostDoc at the Laboratoire des Sciences du Climat et de l'Environnement in Gif-sur-Yvette he became interested in studying the interactions between the terrestrial biosphere and the climate system using comprehensive numerical models. He has been head of the research group terrestrial biosphere modelling and data assimilation since 2009.

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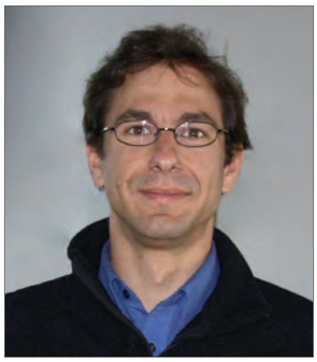
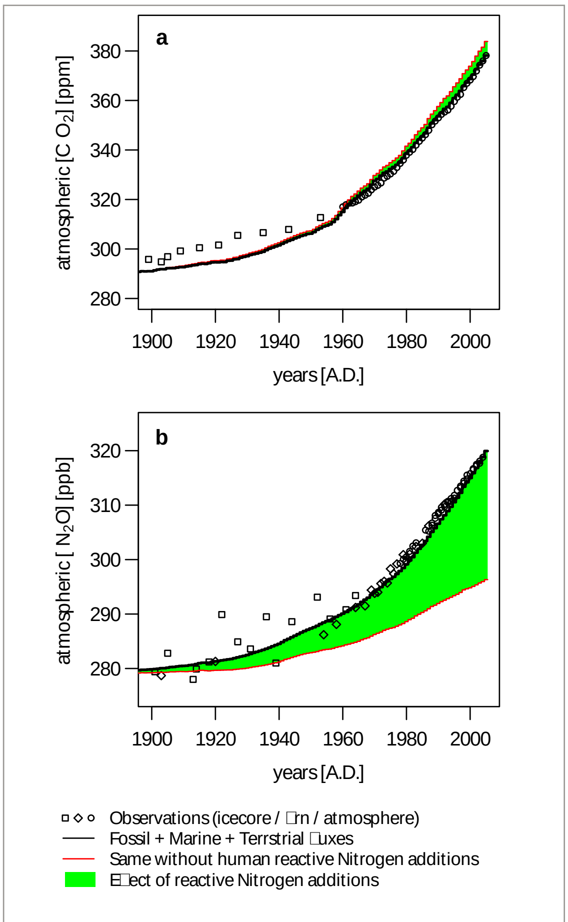


the responses of biosphere processes to changes in climate, atmospheric composition (such as the CO_2 concentration of the atmosphere) and disturbance. Ecosystem manipulation experiments, such as the elevation of atmospheric CO_2 levels, soil warming, and the addition of nutrients through atmospheric pollution, give information about how nutrient dynamics shape ecosystem responses to likely future environmental changes. As part of an international working group at the National Center for Ecosystem Analysis and Synthesis (NCEAS), TBM uses the results of Free Air CO_2 Enrichment (FACE) experiments to decipher key processes that control carbon and nutrient cycles, and to evaluate existing and derive novel model formulations. Together with supplementary information, for example provided by global databases on plant physiological characteristics, the aim of this work is to better represent ecological processes in the modeling of interactions between terrestrial biogeochemistry and climate.

Focus 2. Evaluation of state-of-the-art terrestrial biosphere models

State of the art terrestrial biosphere models are



Simulated and observed concentrations of atmospheric CO_2 and N_2O using a terrestrial biosphere model (O-CN)

increasingly incorporated in Earth System Models (ESMs) as land model components to simulate the interactions between land, ocean, and atmosphere. These ESMs are emerging as the main tool with which to synthesize knowledge and predict the coupled behavior of climate and biogeochemical cycles. Terrestrial interactions with the atmosphere operating through biophysical and biogeochemical processes are amongst the key uncertainties in the coupled behavior of the Earth system. Within a European research network (Greencycles II), and as part of an international activity (International Land-Atmosphere Model Benchmarking Project, ILAMB) a comprehensive series of benchmarks and associated methodologies is being developed for the systematic and quantitative evaluation of ESMs and their terrestrial components. These projects emphasize the need to better quantify the links between current trends in regional and global biogeochemical cycles and climatic variability and changes. Foci are the compilation and harmonization of existing in situ measurements, inventories, atmospheric observations, and remote sensing datasets, and the development of evaluation techniques that provide rigorous constraints on future projections.

Focus 3. Development of a carbon cycle data assimilation system

The third pillar of the group's work is to bring the model evaluation a step further by integrating terrestrial biosphere models and Earth system observations systematically using an inverse modeling system. As part of the Max Planck Initiative on Earth System Modelling (ENIGMA), and in collaboration with the Max Planck Institute for Meteorology in Hamburg, such a system is being developed for the Jena Scheme for Biosphere-Atmosphere Coupling in Hamburg (JSBACH), the landsurface model of the COSMOS Earth System Model. The data sources considered for inverse modelling range from vegetation characteristics, in situ flux observations, and vegetation activity from remote sensing to measurements of atmospheric carbon dioxide concentrations from a global network of atmospheric monitoring stations. The inverse system will be used to systematically constrain important model parameters in JSBACH at different spatial and temporal scales. The aim of this work is to identify the need for improved representation of model ecosystem processes, but also to quantify and reduce model uncertainties, which will be directly useful for coupled climate-carbon cycle projections in the 21st century.




Inverse Data-driven Estimation

Quantification of the large-scale sources and sinks of CO_2 and other greenhouse gases is essential to understand the climate system and its feedbacks. Based on measurements of the atmospheric composition and various other data streams, inverse methods are used to obtain data-driven estimates of trace gas exchanges and their relation to climatic controls.

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:

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 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).

Portrait of the Principle Investigator

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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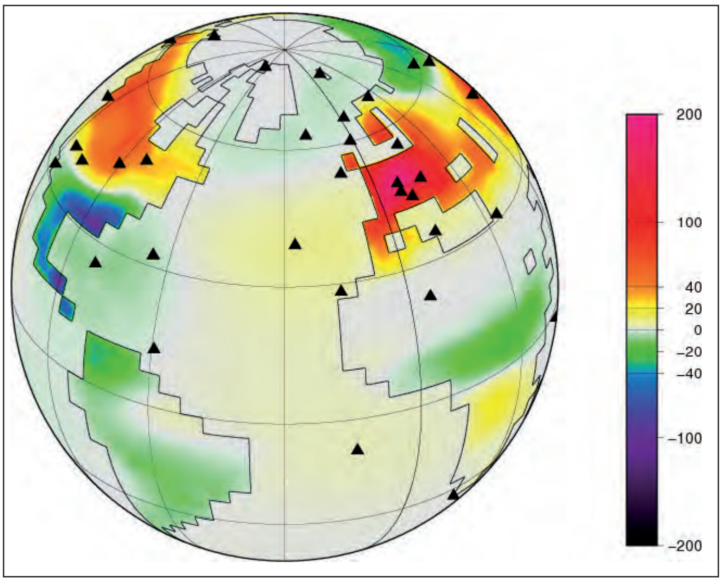


Anomalies of the CO_2 exchange in summer 2003 (May-September, in g/m2/year). In red areas, more CO_2 was released than on aver¬age (1999-2008). In Europe, the response to the record heat and drought is clearly visible. Black triangles indicate the atmospheric measurement sites used. The coarse continent outlines correspond to the spatial resolution of the tracer transport model.

The CO_2 flux estimates from the "Jena inversion" are regularly updated and made available to collaborating research groups (for documentation and download see http://www.bgc-jena.mpg.de/~christian.roedenbeck/download-CO2/).

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.

Diagnostic data-driven models of the ocean carbon cycle

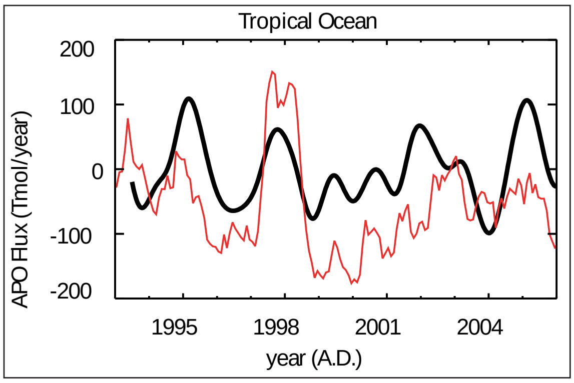
Carbon cycle processes do not only lead to gradients in atmospheric CO_2, but also to tiny variations in atmospheric oxygen. Oxygen measurements can thus provide additional information, in particular about ocean biogeochemistry (figure right). At present, a diagnostic model is being developed that can 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, und 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.

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).

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_2O). 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.



Interannual variations in the oxygen exchange between the tropical ocean and the atmosphere (black), compared with an El Niño index (red). In El Niño years (increased index) the oxygen outgassing tends to increase, too.

Tall Tower Atmospheric Gas Measurements

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_2O), 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

Portrait of the Principle Investigator

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.

At ZOTTO, the spherical buffer volumes (top left) allow a near-concurrent measurement of air from all six inlet heights with a single analyser.

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 above). Currently, four continuous and two flask-only sites are operative (see 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.

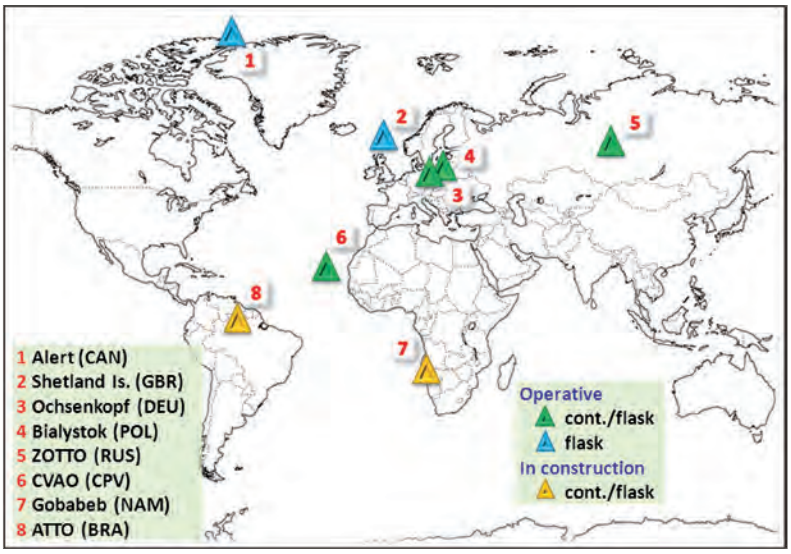
The Zotino tall tower observatory (ZOTTO) is a joint German–Russian scientific platform in central Siberia for observing and understanding biogeochemical changes in Northern Eurasia (http://www.zottoproject.org/).

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 will continuously measure the O_2/N_2 ratio and biogeochemical trace gases (CO_2, CH_4, N_2O, 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.