IUP Research Highlights 2013/2014









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Introduction

he IUP comprises four departments: Remote Sensing, Physics and Chemistry of the Atmosphere, Oceanography, and Terrestrial Environmental Physics.

The **Department of Remote Sensing** employs passive remote sensing instrumentation such as Fourier transform interferometers and microwave radiometers taking measurements in the spectral region from the infrared to the microwave. The instruments are located at various ground based sites ranging from the high Arctic (Svalbard) to the tropics (Surinam), as well as aboard research vessels (R.V. Polarstern) and aircraft (Falcon). Furthermore, operational satellite instruments are used to monitor atmospheric and earth surface properties. Among them are sea ice coverage, water vapour and clouds. A further research focus is the investigation of stratospheric and mesospheric processes including solar effects on the terrestrial atmosphere. These activities are supported by atmospheric modelling.

The research activities carried out in the **Department of Physics and Chemistry of the Atmosphere** aim at improving the understanding of the complex physical chemical processes in the atmosphere and its interfaces to land, ocean, ice, and deep space. Emphasis is placed on the impact of climate change of either anthropogenic or natural origin on the composition of the troposphere, stratosphere, and mesosphere, including greenhouse gases, pollutants and reactive gases. A particular focus has been the scientific support and direction of the Global Ozone Monitoring Experiment (GOME) and Scanning Imaging Absorption spectroMeter for Atmospheric ChartograpHY (SCIAMACHY) missions. These satellite sensors allow characterizing the chemical composition of the atmosphere remotely by means of spectroscopy in the ultraviolet, visible and near-infrared spectral regions using grating spectrometers. Similar instruments are operated ground-based (NDACC stations, BREDOM network), on ships (R.V. Polarstern), planes and balloons. Remote sensing is complemented by in-situ experiments, laboratory work on spectroscopy and reaction kinetics, and modelling of physical and photochemical processes in the lower, middle and upper atmosphere.

The main research topics of the **Department of Oceanog-**

IUP Mission Statement

The overarching objective of the Institute of Environmental Physics is to understand the mechanisms controlling the Earth System and its response to change. This is achieved by using physical methods and research focuses on the sub systems atmosphere, ocean, cryosphere, and their interfaces. This requires the development and use of remote sensing techniques from the ground, from ships, aircraft and satellite platforms and insitu measurements for process studies. The data are coupled with models to interpret the observations and improve the prediction of change.

raphy are the climate relevant processes in the Atlantic Ocean. The global meridional overturning circulation (MOC) plays an important role in the distribution of the heat received from the sun and thus for climate and climate change. Whether and how global warming will affect the circulation and how this will feed back on the climate is one of the central issues of marine research. The department studies - mainly with experimental methods - circulation, formation, and transformation changes in key regions of the Atlantic MOC, develops methods to infer the strength of the MOC, and improves and expands the tracer analysis techniques. Other interdisciplinary research themes are the role of vertical mixing in water mass transformation and at hydrothermal vents, the calculation of upwelling velocities at the equator and at the coast as well the dating of groundwater. The research is part of national and international pro-



grammes such as CLIVAR (Climate Variability and Predictability) and CARBOOCEAN (EU Integrated Project).

The **Department of Terrestrial Environmental Physics** of the IUP investigates transport processes in porous systems and soils and conducts research in the fields of radioecology and sediment chronology. It takes advantage of the excellent equipment available in the Bremen State Radioactivity Measurements Lab (as which it forms part of the state and federal nuclear emergency management networks) and of a unique Earth Field NMR apparatus.

The IUP is internationally well known for its participation in a number of advanced space-borne missions, like GOME and SCIAMACHY. Of particular importance is the Global Ozone Monitoring Experiment, GOME, which was the first satellite sensor to measure tropospheric trace constituents from space and has operated aboard ERS-2 for over 10 years. GOME is a smaller version of SCIAMACHY, which was launched successfully in 2002 and has provided almost a decade of successful measurements. Both sensors, GOME and SCIAMACHY, were proposed by the IUP, and the IUP acts as Principal Investigator. The IUP is also involved in many international projects with space-borne instruments for remotely measuring the surface, such as sea ice, the Wadden sea and land use. In addition the IUP runs instrumentation at research measurement stations worldwide. It has participated in many international and national research campaigns using ships, aircraft and ground-based instruments. Members of the IUP are actively involved in the international scientific organisations like COSPAR, IGBP-IGAC, WCRP-SPARC, CACGP and WMO-IGACO.

More than 100 Ph.D. students and postdocs work at the IUP. Students in general physics have the possibility to specialize in environmental physics. A variety of courses is offered at

the IUP, in cooperation with the colleagues from the Alfred-Wegener-Institut of Polar Research and Oceanography (AWI) in Bremerhaven. The aim of the environmental physics course is to provide a basic education in the areas of the ocean, the atmosphere and the solid Earth. Whereas other German universities cover parts of environmental physics, for example physical oceanography or meteorology as independent subjects. Bremen addresses all of them within the physics course fully integrated into the general physics. The students even have the opportunity to participate in exciting expeditions worldwide. To strengthen environmental physics as a course of study in its own

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right and also to motivate students from abroad to study in Bremen, a four-semester international course leading to a Master of Science (M.Sc.) in Environmental Physics and a two-semester postgraduate course for the Certificate in Environmental Physics have been offered since autumn 2000.

This document provides an overview of selected research highlights achieved by the members of the four IUP departments during the period 2013/2014.



Ten years of precise ground-based remote sensing of greenhouse gases

Thorsten Warneke, Christof Petri, Nicholas Deutscher and Justus Notholt

The increase of the atmospheric greenhouse gases carbon dioxide (CO_2) and methane (CH_4) results in an increase of global surface temperatures. Consequences of the temperature increase are already visible and severe consequences are predicted for the future, among them sea level rise, change of weather patterns, extreme weather events, extinction of certain wildlife species and the spread of diseases.

The increase of CO_2 in the atmosphere can be directly assigned to anthropogenic activities. Each year, several gigatons of CO_2 are emitted into the atmosphere by human activities. Fortunately, only about 50% of the emitted CO_2 remains in the atmosphere and thus contributes to global warming. The other 50% are taken up by natural sinks - the terrestrial biosphere and the ocean. Me-



Figure 1: FTIR-observatory at the University of Bremen

thane (CH_4), the second most important anthropogenic greenhouse gas after CO_2 , is emitted from highly variable and not well understood sources such as wetlands, rice fields, landfills, oiland gas-exploration and ruminants.

In order to reliably predict the future climate of our planet a good understanding of the sources and sinks of CO_2 and CH_4 is mandatory. Unfortunately, there are large gaps in our understanding of the natural sources and sinks of these gases. Key questions to be



Figure 2: Sites employing FTIR instruments in the TCCON and NDACC networks.

answered are: Where are the natural and anthropogenic sources and sinks? How strong are they? What are their characteristics? How will they respond to a changing climate?

The basis for understanding the atmospheric greenhouse gas budgets and answering the questions above are precise measurements of atmospheric CO_2 and CH_4 . The global atmospheric observing system for greenhouse gases consists of in situ measurements as well as ground-based and space-born remote sensing measurements. While high quality in situ measurements are available since almost 60 years, the technically challenging remote sensing measurements of CO_2 and CH_4 became possible only 10 years ago. In contrast to the in situ measurements, remote sensing measurements integrate through the whole atmosphere, and satellites provide global coverage.

The Total Carbon Column Observing Network (TCCON) represents the ground-based remote-sensing component in the global atmospheric observing system for greenhouse gases. It has been established in 2004. At that time it consisted of five sites: two in Europe, one in the US and two in Oceania. The only European founding member of TCCON was the Institute of Environmental Physics at the University of Bremen, operating the two European sites at Ny-Ålesund (Spitsbergen) and Bremen (Germany), see



Figure 2. Today the TCCON comprises more than 20 globally distributed sites and has established itself as a vital component in the global observing system for greenhouse gases. The University of Bremen has received EU-funding to build up two additional TCCON observatories, which are already fully operational since 2009. These observatories are located in Bialystok (Poland) and Orleans (France)

The ground-based remote sensing technique used within TCCON can be extended to different spectral regions, which allows the measurement of many gases. Currently we are investigating if simultaneous ground-based remote sensing measurements of CO_2 and OCS (carbonyl sulphide) allow differentiating between photosynthesis and respiration fluxes of CO_2 . This is not possible with CO_2 alone. OCS is taken up by plants during photosynthesis, but in contrast to CO_2 it is not released and therefore has the potential as a tracer for photosynthesis (Figure 3).

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Rivers in the carbon cycle

Thorsten Warneke, Denise Müller and Justus Notholt

The carbon cycle describes the exchange of carbon between different reservoirs. The fast component of the carbon cycle, which is relevant for the understanding of anthropogenic climate change, describes the exchange of carbon between the land, the ocean and the atmosphere. There, rivers play an important role by transporting carbon from the land to the ocean. The processing of carbon in rivers as well as the exchange of carbon between the rivers and the atmosphere have so far been ignored in carbon cycle modelling. Recent studies suggest that rivers play a



Figure 3: Simultaneous ground-based remote sensing measurements of CO_2 and OCS for three ground-based remote sensing sites of the University of Bremen compared with model simulations.

Chemistry and Physics, 13(18), 9447-9459, doi:10.5194/acp-13-9447-2013.

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crucial role for carbon processing and storage as well as greenhouse gas emissions and are therefore of large importance for establishing regional carbon balances.

One recent focus of our research are peat draining rivers in Southeast Asia. Southeast Asian peatlands store about 68.5 gigatons of carbon, which corresponds roughly to the amount of carbon emitted to the atmosphere by fossil fuel burning every 8 years. This large carbon store is currently under high pressure due to anthropogenic activity. The conversion of tropical peat swamp



forest to plantations (mainly oil palm) upsets both the water and the carbon balance in the peat soil. As a result, carbon that has been stored for centuries is lost to the atmosphere or the adjacent aquatic system. Consequently, rivers transporting peatderived carbon might be a mirror of the degree of disturbance in tropical peat ecosystems.

Since the vast majority of peatlands in SE-Asia is located close to the coast and many peatlands are drained by short rivers, the carbon is rapidly transported to the coastal ocean. We have investigated a river that drains an intact peat dome in Sarawak (Borneo, Malaysia). The entire river catchment is covered by peat swamp forest. Though such a scenario is relatively unique, it is ideally suited for a baseline study. Such baseline data is vital for the interpretation of carbon fluxes from disturbed peat areas.

The dissolved organic carbon concentrations in the river draining the undisturbed peatland are among the highest reported in the literature. The age of the dissolved organic carbon transported by the river was less than ten years, which shows that it is not derived from the peat-column, but from recently fixed biomass. Despite the very high organic carbon loads, the emission of CO_2 from the river to the atmosphere is not unusually high, but comparable to other tropical rivers. Most likely, this is a result of the short residence time of the carbon in the river, which is typical for peat-draining rivers in SE-Asia.

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Figure 4: Sampling trip on a small peat-draining river in Sarawak (Borneo, Malaysia)



Figure 6: This figure from Cole et al. (2007) shows a) the representation of rivers in current terrestrial models and b) an estimate of a more realistic representation of rivers)



Figure 5: Dissolved Oxygen (DO) vs Dissolved Organic Carbon (DOC) in a river draining an undisturbed peatland. DOC increases in flow direction due to the DOC input from the peat swamps. The decomposition of DOC produces CO_2 and consumes DO. For this river the DOC input exceeds DOC decomposition.



Increase of the chlorine load in the northern hemisphere between 2007 and 2012

Mathias Palm and Justus Notholt

Chlorine radicals in the stratosphere are the main cause of Ozone depletion. The main source of chlorine radicals in the stratosphere are Chlorofluorocarbons (CFCs) which are widely used for their properties, they are chemically very stable and not inflammable. Those properties, which made them the substance of choice as a cooling agent, as a propellant in cosmetics and other applications, make them so problematic, because they are not removed from the atmosphere and are transported to the upper stratosphere, where they are broken down by solar irradiation and release chlorine radicals.

A measure for the chlorine load in the stratosphere is the content of HCl, which serves as a reservoir gas for Cl radicals. With the rise of the sun above Polar Regions in spring, the Cl ions are released from HCl and enable catalytic Ozone depletion, which was first discovered in the Antarctic and published in 1985. The discovery of this mechanism led to the Montreal protocol which aimed at a complete ban of substances harming the Ozone layer.

Following the signing of the Montreal protocol, the Cl load in the stratosphere started to decrease as expected until 2007 (compare Figure 7), when it started to rise again. This caused great concern among the atmospheric scientist, because it was unclear what caused this increase (Mahieu, 2014). Using chemical transport models, this increase could be linked to a change in Brewer Dobson circulation, which transports the air containing CFC's from the tropical regions where tropospheric air enters the stratosphere, in the upper stratosphere and finally to the poles, the regions where ozone depletion is most severe. This circulation slowed down and therefor exposed the parcels containing CFC's longer to UVradiation in the upper stratosphere increasing the free Cl.

Whether or not this leads to a faster recovery of the ozone layer or hampers this recovery has yet to be studied.

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Figure 7: Measurements of HCl since the mid 80ies. Figure a) shows measurements above Jungfraujoch. The blue line denotes the tropospheric chlorine as measured by in-situ instruments. The effect of the Montreal protocol can be observed from 1993, when the chlorine content starts decreasing. Due to the transport time scale the stratospheric decrease of chlorine starts around 1998. Figures b), c) and d) show the time from 1998 until 2012. It can clearly be observed, that in the northern hemisphere the HCl content increases after 2007. (from Mahieu et al., 2014)



Measurements of CO above Kiruna

Mathias Palm, Christoph G. Hoffmann, and Justus Notholt

S tratospheric and mesospheric profiles of CO can be used to study the vertical branch of the meridional circulation above the winter pole. CO is produced by the photodissociation of CO_2 and destroyed mainly by reaction with OH. In dark conditions, there is low supply of OH and the CO content is preserved. This leads to a strong gradient in the CO profile and makes CO an ideal tracer for the vertical branch of the mesospheric circulation because the shape of the CO profile is preserved and only moves downwards as the air above the pole descends (compare Figure 8).

The air above the pole is enclosed in the so called polar vortex which forms an effective barrier against mixing. As a result, the air above the pole becomes very cold and chemical species, like nitrogen and hydrogen containing radicals which would quickly break down in sun-lit conditions stay active a long time and can be transported into lower layers of the atmosphere.

The measured CO time series (see Figure 9) can be interpreted



Figure 8: Monthly averages of the Arctic CO profile measured by Fourier Transform spectroscopy above Ny-Ålesund.



Figure 9: Time evolution of the Arctic CO profile measured by Fourier Transform spectroscopy above Ny-Ålesund.

WACCM, shows however, that this is not always the case. For example, periods when the profile seems to be rising can also be caused by the mixing with CO poor air masses, for example in January and after the 10th of March in Figure 9.

Those various effects can be disentangled by detailed analysis using an atmospheric model. The CO gradient is a measure of how quickly air from the mesosphere, which may be enriched in ozone-depleting nitrogen oxide radicals, descends into the stratosphere, where ozone depletion may take place. This is called the electron-particle-precipitation indirect effect.

The properties of the ground based measurements of CO and their interpretation have been studied in detail by Hoffmann et al., 2011 and 2012.

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The chemistry of high altitude discharges

Holger Winkler and Justus Notholt

n addition to the well-known lightning flashes in the troposphere, there are electric discharges at higher altitudes. Different types of transient luminescent events (TLEs) have been observed between thunderstorm clouds and the ionosphere. The most famous of these events are the so called (red) sprites which occur in the mesosphere, typically in the altitude range 50 – 85km. Other TLEs are the elves in the lower ionosphere (~100km), blue jets in the stratosphere (15 - 40km), and gigantic jets (15 - 100km).

It is well established that atmospheric discharges have chemical effects. Energetic electrons cause ionisation, dissociation and excitation mainly of the highly abundant N_2 , and O_2 . As a result, reactive nitrogen and oxygen species are produced which initiate rapid ion-neutral reactions. Of particular interest from the atmospheric chemistry point of view is the for-



Figure 10: Simulated relative change of ozone in a sprite streamer at different altitudes. Shown are the results for (left) night-time, and (right) day-time conditions (solar zenith angle 65°).

mation of ozone, and the production of ozone depleting nitric oxide. In recent years, the chemistry of sprites has been investigated in a number of model studies. However, our understanding of the impact of sprites is still limited. Furthermore, there are only a few investigations on other TLEs including the blue jet events which occur in the altitude range of the stratospheric ozone layer.

In order to simulate the chemical processes in TLEs, a numerical plasma chemistry model has been developed at the IUP. It calculates the evolution of 91 neutral and charged species due to more than 1000 photochemical reactions. Recently, the model has been used to simulate the chemical processes in plasma filaments (streamers) of day-time sprites, and to investigate the reactions in blue jet discharges in detail.

Day-time sprite streamers

Sprites are mainly night-time phenomena. During the day, the ionospheric conductivity is higher, and the occurrence rate of sprites is smaller than at night. All previous model simulations on the chemical processes in sprite streamers had been performed for night-time conditions. The IUP plasma chemistry model has been used to study the chemical processes in day-time sprite streamers for the first time (Winkler and Notholt, 2014a). It was found that the chemical effects in streamers of day-time sprites. Figure 10 shows the relative change of the ozone mixing ratio in night-time and day-time streamers, respectively. In both cases there is an initial (weak) decrease of ozone



due to ionic processes followed by an increase of ozone due to atomic oxygen liberated by electron impact dissociation of O_2 . All this is very similar for day and night atmosphere. On longer time-scales, however, there are considerable differences between night and day. While the ozone increase is stable at night, there is a decrease of ozone in the day-time case. The reasons for these differences are catalytic ozone loss reactions with nitrogen radicals which only take place in the sunlit atmosphere.

Blue jets

These events are upward propagating discharges which originate from thunderstorm clouds. They consist of a so called leader (a high-temperature plasma channel) and a fan of streamers emitted at the tip of the leader. The IUP model results indicate that there is considerable impact on nitrogen species and ozone in the streamers. The chemical effects of the streamers predicted by our model are by orders of magnitude larger than in previous model studies (which used underestimated electric field parameters). Figure 11 shows the evolution of NO+NO₂ and Figure 12 the development of ozone in a streamer. Additionally, the chemical processes in the leader part of a blue jet have been simulated for the first time. Driven by high-temperature reactions, the concentration of N₂O and NO increases by several orders of magnitude, and there is a significant depletion of ozone (Winkler and Notholt, 2014b). The model results might gain importance by the fact that the chemical perturbations in blue jets are largest at altitudes of the stratospheric ozone layer.

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Figure 11: Simulated streamer $NO+NO_2$ mixing ratio as a function of altitude and time since the onset of the electric pulse.



Figure 12: Simulated ozone volume mixing ratio as a function of altitude and time since the onset of the electric pulse of a blue jet streamer.



Sea ice in the climate system

Georg Heygster, Christian Melsheimer and Justus Notholt

The inaccessible polar regions belong to those parts of the world of which the least information on weather and climate is available. On the other hand, the global warming is most pronounced in the Arctic (Arctic Amplification). In order to better understand these processes, which also influence the climate in mid-latitudes, as many as possible weather and sea ice parameters from the Arctic need to be collected on a regular basis. This is best done using satellite observations which may be obtained daily over the whole globe. For many years the IUP has been contributing daily



Figure 13: Arctic sea ice concentration of the 2014 minimum on 17 September

Universität Bremen

maps of the Arctic and Antarctic sea ice (www.iup.uni-

bremen.de:8084/amsr2) derived from observations of the passive microwave sensors AMSR-E on the satellite AQUA, (2002-2011) and AMSR2 on GCOM-W (since 2012) (Spreen et al. 2008).

Ongoing research develops daily maps of a series of other parameters such as the thickness of thin sea ice from the L-band microwave sensor SMOS, snow depth on sea ice and sea ice type from AMSR2, total water vapour from microwave humidity sounders like AMSU-B on the NOAA satellites, and albedo and melt pond fraction of Arctic sea ice in summer using the optical sensor MERIS on ENVISAT (Istomina et al. 2014).

The Arctic sea ice area varies seasonally between 4 and 12 million km². Figure 13 shows as an example the minimum of 2014 on 17 September. Figure 14 illustrates the regions of thin sea ice late in October of the same year, as obtained from observations of the ESA satellite SMOS (Soil Moisture and Ocean Salinity) with a procedure described



Figure 14: Thickness of thin ice on 29 Oct 2014

by Huntemann et al. (2014). Note the near match of the region of thick ice in late October (Figure 14) with the ice covered areas of the sea ice minimum on 17 September in Figure 13.

In Figure 15 (top), the time series of the Arctic sea ice extent since 1979 is shown as it can be derived from maps as depicted in Figure 13. The trends for each single month in Figure 15 (bottom) show that the decline is strongest in the months of low ice extent (August, September) and least in winter (February, March) when the sea ice extent is high. Does the sea ice reduction occur everywhere in the Arctic, or does it have a specific distribution? The map of the linear trend of the sea ice concentrations in Figure 16 gives the answer: The decline occurs mainly along the sea ice edge. There are even regions where the sea ice increases (Figure 16), such as in the Bering Sea in the months January to March. This unusual increase in sea ice cover has been explained by increasing temperatures in the same region, occurring as part of the Pacific Decadal Oscillation taking negative values in the last years.

Snow on sea ice reduces the heat transfer between ocean and atmosphere, and it strongly increases the friction of ships when traveling through snow covered ice. The snow depth on sea ice retrieved form AMSR2 data (Figure 17) was the contribution of IUP in a joint project (IRO-2, Ice Route Optimization) with several national partners about optimising ship routes in Arctic seas. For the first time remote sensing data of snow on sea ice, along with other remote sensing





Figure 15: Left: time series daily Arctic sea ice extent since 1979. Data: NSIDC. Bottom: monthly trends of sea ice extent, derived from the data shown in the top figure.



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Figure 16: Linear trend of Arctic sea ice concentration 1979-2013 for the months January, February and March.



Figure 17: Snow depth on Arctic sea ice (left) with variability within five days as estimate of the variability (right).



Influence of sea-ice changes on phytoplankton growth in the Fram Strait

Alexandra Cherkasheva, Astrid Bracher, Christian Melsheimer, Cornelia Köberle, Rüdiger Gerdes, Eva-Maria Nöthig, Eduard Bauerfeind, Antje Boetius

Phytoplankton, marine microalgae, is the main primary producer in the ocean and plays a key role in the marine food web in addition to its role in global biogeochemical fluxes. In the Arctic, climate change is already visible by the rapid decrease in sea-ice extent and thickness, and the freshening of the Arctic Ocean surface waters. These changes are likely to impact primary productivity and carbon export of the Arctic Ocean by altering solar radiation. The Fram Strait is the main gateway for water, heat and sea-ice exchanges between the Arctic Ocean and the North Atlantic. The complex physical environment results in a highly variable primary production in space and time.

In order to assess the effect of changing environmental con-

ditions in the Fram Strait, long-term data of good spatial coverage are necessary. Since from remote sensing only long-term information on phytoplankton abundance (chlorophyll-a concentration) and sea ice coverage is obtained, within this interdisciplinary study in situ field data, remote sensing and modelling techniques were combined to investigate in detail the influence of melting sea-ice and ocean properties on the development of phytoplankton blooms in the Fram Strait region for the years 1998-2009 (see monthly mean concentrations in Figure 18).

Satellite-retrieved chlorophyll-a concentrations from temporarily ice-free zones were validated with contextual field data. Those data were integrated per month on a grid size of



Figure 18: Monthly climatology of phytoplankton abundance as given in chlorophyll concentration (CHL) from measurements of the satellite instruments SeaWiFS, MODIS and MERIS and merged to the GlobColour product for the years 1998 to 2009.



20x20 km², resulting in 10 grids/fields (Figure 19). Factors tested, influencing spatial and temporal variation of chlorophyll-a, were: sea-ice concentration from satellite and seaice thickness, ocean stratification, water temperature and salinity time-series simulated by an ice-ocean circulation model.

The time series analysis for those ten ice-free fields showed everywhere a significant trend of increasing sea surface temperature (+1.6°C) but a regional separation according to different physical processes affecting phytoplankton biomass distribution (as shown in Figure 19). At the marginal ice zone the melting sea-ice was promoting phytoplankton growth the most by stratifying the water column and potentially seeding phytoplankton communities which resulted in enhanced chlorophyll concentrations in May. In the open ocean, the phytoplankton biomass variability was correlated mostly to thermal stratification by solar heating of the upper ocean layers. In the coastal zone around Svalbard, processes associated with the presence of shelf ice were rather suppressing than promoting the phytoplankton growth. During the twelve years of observations, chlorophyll concentrations significantly increased in the southern part of the Fram Strait, associated with an increase in sea surface temperature and a decrease in Svalbard shelf ice. Overall, the maxima of phytoplankton blooms tend to occur later in the summer since 2002.

Summary

This interdisciplinary investigation, linking in-situ and satellite observations with modelling, elucidates the coupling of phytoplankton growth to long-term changes in the physical environment observed in the main gateway for water, heat and sea-ice exchanges between the North Atlantic and the

Arctic Ocean, a rapidly changing region on Earth. Results reveal that the Fram Strait can be divided in three regions in terms of environmental conditions favouring phytoplankton growth: Stratification induced by sea ice melt at the marginal ice zone, stratification caused bv solar warming in the open ocean, and decline of shelf ice around Svalbard. The outcome of the study provides important evidence on the sensitivity of the Arctic marine ecosystem in respect to climate change beyond the region of the Fram Strait.

This study was done in collaboration between IUP and different groups at the

Alfred-Wegener-Institute Helmholtz Centre for Polar and Marine Research (AWI), Bremerhaven. It received the AWI Research Award in 2014.

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Figure 19: Satellite-derived map of sea ice concentration of July 2006 with circles in the map which show the location of the ten sites where the statistical analysis of physical and biological time series data from 1998 to 2009 was applied. The colours of circles indicate 1) orange: increasing trend in sea surface temperature (+1.6°C); 2) blue: marginal ice zone which is a light-limited region, with shallow stratified layers triggering phytoplankton growth; 3) violet: coastal sites (close to Svalbard) with a decreasing trend in phytoplankton chlorophyll concentration (+0.34 mg m⁻³). Circles D, E, H and I belong to the open ocean region (ice-free sites).



Carbon dioxide and methane from satellites

Michael Buchwitz, Maximilian Reuter, Oliver Schneising, Jens Heymann, Thomas Krings, Michael Hilker, Dhanyalekshmi Pillai, Vladimir Rozanov, Heinrich Bovensmann, and John P. Burrows

Carbon dioxide (CO₂) and methane (CH₄) are the two most important man-made ("anthropogenic") greenhouse gases (GHG) contributing to global warming. Despite their importance, our understanding of their variable natural and anthropogenic sources and sinks has large gaps. This limits the reliability of climate prediction, which requires a good understanding of natural sources and sinks. Furthermore, reported anthropogenic GHG emissions can typically not be verified by independent observations.

Most of our knowledge on CO_2 and CH_4 sources and sinks stems from accurate but sparse networks of surface observations performing local point measurements. Satellite observations of greenhouse gases add important information



Figure 20: Anthropogenic emission trends of nitrogen oxides (NOx) and carbon dioxide (CO_2) over major source areas as obtained from SCIAMA-CHY satellite observations. From: Reuter et al., Nature Geoscience, 2014a. See also link to ESA press release "Good and bad news for our atmosphere".

due to their global coverage. This however requires high measurement sensitivity to CO₂ and CH₄ concentration changes close to the Earth's surface. where the source and sink signals



Figure 21: Elevated methane (orange and yellow) over three major US oil and gas "fracking" areas as observed with SCIAMACHY. The satellite observations have been used to quantify the corresponding methane emissions as shown on the left (details: Schneising et al., 2014a; nightlights background figure: NASA).

are largest. For many applications it is also important to have long enough data sets covering ideally time periods of several years.

At present only data from two satellite instruments are available, which fulfil these requirements: These instruments are the IUP-Bremen led SCIAMACHY instrument on ENVISAT (2002-2012) and the TANSO-FTS on board the Japanese GOSAT satellite (2009-today). Selected results from SCIAMACHY and GOSAT are shown below.

The IUP is also involved in other greenhouse gas satellite missions. For example, the IUP is very active in preparing for the Sentinel-5-Precursor (S5-P) satellite mission. Furthermore, IUP-Bremen has proposed a new satellite, the "Carbon Monitoring Satellite" (CarbonSat), dedicated to improve our knowledge of the natural sources and sinks CO₂ and CH₄ as well as of localized emission sources. A short CarbonSat overview is given below.



Results from existing satellites derived from SCIA-

MACHY on ENVISAT and GOSAT

The IUP-Bremen is one of the leading institutes in the world in the relatively new area of satellite remote sensing of greenhouse gases (GHG). IUP-Bremen is leading the GHG-CCI project of ESA's Climate Change Initiative (CCI) which delivers the "Essential Climate Variable" (ECV) Greenhouse Gases (http://www.esa-ghg-cci.org/, Buchwitz et al., 2013a). At IUP retrieval algorithms are being developed and continuously improved (e.g., Heymann et al., 2012) to convert the spectra of reflected solar radiation as measured by SCIAMA-CHY (and more recently GOSAT) into atmospheric CO₂ and CH₄ concentrations ("column-averaged mixing ratios"). Among the highlights in 2012/14 were major results which have been obtained by analysing the SCIAMACHY and GO-SAT global GHG time series to obtain quantitative infor-



Figure 22: Strength of European terrestrial vegetation carbon uptake as derived from SCIAMACHY and GOSAT satellite data (different colors for different satellite data products) compared to NOAA's Carbon-Tracker (grey). As can be seen, the satellite CO_2 observations show that Europe appears to be a much larger sink for carbon than current assessments based on non-satellite observations suggest. From: Reuter et al., 2014b.



mation on anthropogenic methane (Figure 21) and anthropogenic CO_2 emissions (Figure 20) as well as CO_2 natural sink strengths (Figure 22 and Figure 23). The satellite data sets generated at IUP are delivered to and used within



Figure 23: Summary of the main conclusions of the study of Reuter et al., 2014b. For details see also Figure 22.

important European projects such as the EU's "Monitoring Atmospheric Composition and Climate" (MACC) project (Figure 25). The satellite derived atmospheric GHG-CCI CO₂ and CH₄ data sets are freely available via the GHG-CCI website (see Link given below) and the higher level data products generated within the MACC project are available via the MACC website (see Link given below).

Methane and carbon monoxide from Sentinel-5-

Precursor (S5-P)

The IUP is also strongly involved in the preparation of data processing for the Sentinel-5-Precursor (S5-P) satellite, which will be launched in 2016. See, for example, Krings et al., 2013a, for IUP activities related to the retrieval of methane and carbon monoxide vertical columns from S5-P.

Carbon Monitoring Satellite (CarbonSat)

To continue the global satellite derived GHG time series, which started with SCIAMACHY in 2002, the IUP has proposed the "Carbon Monitoring Satellite" (CarbonSat) to ESA. In November 2010 CarbonSat has been selected by ESA to be one of two candidate missions for Earth Explorer 8 (EE-8) to be launched around 2022 (see Links: CarbonSat). Currently, IUP is involved in optimizing the CarbonSat mission in cooperation with ESA and several European partners. In this context also several aircraft campaigns have been carried out with the MAMAP instrument (e.g., Krings et al., 2013b) as described in detail in the next section (see also CarbonSat related Links given below). CarbonSat will be the first GHG satellite mission optimized to detect and quantify localized anthropogenic and natural emission sources of CO_2 and CH_4 (see, e.g., Buchwitz et al., 2013b and Fig. Figure 24).



Figure 25: Timeseries of carbon dioxide (CO_2) from SCIAMACHY (black) and GOSAT (green) as retrieved at IUP, Univ. Bremen, compared to TCCON ground-based observations (green) at two Total Carbon Column Observing Network (TCCON) sites (top: Lamont, USA; bottom: Darwin, Australia). Clearly visible is the CO_2 increase primarily caused by anthropogenic CO_2 emissions, and the CO_2 seasonal cycle, primarily caused by regular uptake and release of CO_2 by terrestrial vegetation, i.e., land plants. These SCIAMACHY and GOSAT data product are generated at IUP and delivered to the European "Monitoring Atmospheric Composition and Climate" (MACC) project (see Links).

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Figure 24 Simulation of the CO_2 random error (or single measurement precision) for a CarbonSat overpass over Germany. As can be seen, CarbonSat will deliver many observations with high precision (~1.2 ppm). Note that gaps are due to clouds and the limited swath width (here: 500 km, which is Carbon-Sat's goal requirement). From: Buchwitz et al., 2013b.



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Links

GHG-CCI project: http://www.esa-ghg-cci.org/

MACC project: https://www.gmes-atmosphere.eu/

SCIAMACHY CO2 and NO2: ESA press release "Good and bad news for our atmosphere":

http://www.esa.int/Our_Activities/Observing_the_Earth/Space_for our_climate/Good_and_bad_news_for_our_atmosphere

CarbonSat: http://www.iup.uni-bremen.de/carbonsat/

CarbonSat airborne campaign: ESA press release "Pinpointing sources of greenhouse gases":

http://www.esa.int/Our_Activities/Observing_the_Earth/The_Livin g_Planet_Programme/Campaigns/Pinpointing_sources_of_greenh ouse_gases

CarbonSat airborne campaign: ESA press release "Paving the way for carbon mission":

http://www.esa.int/Our_Activities/Observing_the_Earth/The_Livin g_Planet_Programme/Campaigns/Paving_the_way_for_carbon_mi ssion

CarbonSat airborne campaign: NASA press release "NASA, ESA and Navy Scientists Fly Over California, Measure Greenhouse Gases": <u>http://www.nasa.gov/ames/nasa-esa-andnavy-scientists-fly-over-california-measure-greenhousegases/index.html#.VBcpMRbiKiO</u>



Carbon dioxide and methane from airborne observations

Heinrich Bovensmann, Michael Buchwitz, Thomas Krings, Konstantin Gerilowski, Sven Krautwurst, and John P. Burrows

The two most important man-made ("anthropogenic") greenhouse gases (GHG) carbon dioxide (CO₂) and methane (CH₄) have on small spatial scales (100 m to a few km) strong sources. These are for example CO₂ from power plants, volcanoes and cities, or CH₄ from fossil fuel production (coal, gas, and oil), landfills and geological seeps. Often the strength and/or the position of these sources is not well known and an independent verification of the emissions from observations is needed. Remote sensing of atmospheric GHG distributions, so-called greenhouse gas imaging, could close an important information gap on small spatial scales. In cooperation with the GeoForschungsZentrum (GFZ) in Potsdam, scientists at IUP developed an airborne spectrometer system called MAMAP (Methane Airborne MAPper), which allows demonstration that imaging the spatial distribution of atmospheric GHG concentrations in the vicinity of strong sources can be used to infer the emission strength of the source. The spectrometer uses solar absorption spectroscopy in the near and short-wave infrared, similar as the satellite sensors SCIAMACHY and GOSAT, to derive very accurate (precision better < 0.3%) gradients in atmospheric CO₂ and CH₄ with a spatial resolution of approx. 50 m over spatial scales of several km.

During the years 2012-2014 MAMAP was used in campaigns to demonstrate that with passive remote sensing of greenhouse gas distributions on small spatial scales the emission strength of selected sources can be quantified. These campaigns were (co-) funded by the European Space Agency in support of the development of the CarbonSat mission concept.

Carried on an aircraft from the Free University of Berlin, MAMAP measured during the C-MAPExp campaign in summer 2012 atmospheric carbon dioxide from power plants and methane from coalmine ventilation shafts in Germany. While MAMAP sensed gas concentrations from above, other instruments on a motor glider from the Swiss company MetAir flew through the gas plumes to take accurate in situ measurements to validate the remote sensing data.

An example of a CO_2 plume from a coal fired power plant is shown in Figure 26. Whereas the campaign in 2012 focused on targets with known emissions to demonstrate and validate the methodology, a campaign in summer 2014 focused on targets of not well known sources to demonstrate the added value of this new remote sensing technology.

In summer 2014 ESA and NASA joined forces, when carrying out the COMEX campaign that not only supported Carbon-Sat but also NASA's proposed Hyperspectral Infrared Imager, Hyspiri, mission. The campaign exploited passive remotesensing spectroscopy – the unique absorption signature that the gases leave in sunlight as it passes through the atmosphere. Measurements are taken from aircraft above, as would the satellite, and compared to other measurements



Figure 26 MAMAP aircraft observations of elevated CO_2 (red circles) compared to background concentrations (green circles) as measured over a coal fired power plant in Germany in summer 2012.



taken by aircraft and on the ground near the source of emissions. The measurements were taken in the San Joaquin Valley and around Los Angeles in California, USA – an area that features oil refineries, farms and landfill sites, which all release methane into the atmosphere.

The team equipped a Twin Otter aircraft with the MAMAP spectrometer (see Figure 28). The aircraft also carried instruments to sample greenhouse gases in situ– inside and outside greenhouse gas plumes. The flights were complemented by another aircraft that carried NASA's next-generation AVIRIS spectrometer, which can detect methane at a higher spatial resolution than MAMAP but with less sensitivity. An example of a MAMAP observed methane emission plume from a landfill in California is shown in Figure 27. In addition, the campaign was also able to capture a large scale methane plume over one of California's oil fields as depicted in Figure 27. A huge CH_4 plume of unknown origin was detected up to several miles downwind over the oil field for the first time by remote sensing only.



Figure 27: MAMAP aircraft observations of elevated methane (red circles) compared to background concentrations (green circles) as measured over a landfill in California, USA.

The data gathered during the campaigns in 2012 and 2014 demonstrate the power of imaging greenhouse gas concentration distributions to constrain emissions.

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Figure 28: Cabin view of the CIRPAS aircraft during COMEX in summer 2014 showing the flight scientists from University of Bremen at work.

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Links

ESA press release "Pinpointing sources of greenhouse gases":

http://www.esa.int/Our Activities/Observing the Earth/Th e_Living_Planet_Programme/Campaigns/Pinpointing_sourc es of greenhouse gases

ESA press release "Paving the way for carbon mission": http://www.esa.int/Our Activities/Observing the Earth/Th e Living Planet Programme/Campaigns/Paving the way f or_carbon_mission

NASA press release "NASA, ESA and Navy Scientists Fly Over California, Measure Greenhouse Gases": <u>http://www.nasa.gov/ames/nasa-esa-and-navy-scientists-</u> fly-over-california-measure-greenhouse-

gases/index.html#.VBcpMRbiKiO

CarbonSat: http://www.iup.uni-bremen.de/carbonsat/



Airborne mapping of tropospheric trace gas distributions with the AirMap instrument

Anja Schönhardt, Andreas Meier, Andreas Richter, and John P. Burrows

AirMap stands for Airborne Imaging DOAS Measurements of Atmospheric Pollution. The AirMap instrument was developed and assembled at the IUP Bremen specifically for operation on research aircrafts. It makes use of the Differential Optical Absorption Spectroscopy (DOAS) technique and is capable of detecting trace gases in the visible spectral range, and since recently also in the UV. Designed as an imaging instrument, AirMap makes measurements in many viewing directions (in practice up to 35) at the same time.

AirMap mainly detects column amounts of nitrogen dioxide, NO₂. NO₂ is formed after emission of NO from combustion processes. After recent modifications of the instrument, now also sulphur dioxide, SO₂, may be detected above strong SO₂ sources. During the past research campaigns, AirMap has detected spatial distributions of NO₂, e.g. above cities, and from points sources such as power plants and even from single ships.

During research campaigns in 2011, 2013 and 2014, AirMap proved to be a reliable and useful instrument. AirMap has such a good spatial resolution, that point sources of pollution can be detected and distinguished, and mapping of trace gas distributions becomes possible on a small spatial scale down to below 100 m. At flight altitudes of about 1km and at full resolution, ground pixel sizes of around 30 m side length have been achieved. Typical temporal resolution is 0.5s so that changes in time can also be detected.

Research campaigns have taken the instrument to many different places around Europe, including Germany, the

North Sea, Scandinavia, and Romania. In addition to three airborne missions, the instrument was operated from ground at the shore of the Elbe River to detect shipping emissions, and from the roof of the IUP to perform rapid hemispheric measurements over Bremen.

As a typical target, AirMap has observed the exhaust plumes of several coal fired power plants. The high resolution measurements by AirMap reveal that NO_2 distributions within power

plant emission plumes are highly variable in space and time. The plume has a strongly inhomogeneous structure, often consisting of only loosely connected "bubbles" of high NO_2 amounts. Figure 29 shows the result of a measurement above the medium sized power plant in Wilhelmshaven, in Northern Germany. Amounts reach $1x10^{16}$ molecules/cm².

In the 2013 campaign above Northern Germany, AirMap has taken NO₂ photographs of single ship plumes, revealing the development and build-up of NO₂ behind the ship and the inner plume structure. The measurement in Figure 30 demonstrates that NO₂ amounts from single ships may be as large as from a coal fired power plant.

Latest achievements with the AirMap instrument are the mapping of NO_2 above the cities of Berlin and Bucharest. These measurements yield the amounts as well as the small



Figure 29: Wilhelmshaven power plant (Kraftwerk WHV). The exhaust plume is strongly inhomogeneous, it has a bubble-like structure with localised NO_2 maxima embedded in a plume of lower and variable NO_2 amounts

scale spatial variation of NO_2 within the cities. Similarly, AirMap is applied to resolve the spatial variation of trace gases within satellite pixels. Measurements by AirMap are extremely valuable as they lead to a better knowledge of the fine spatial variation of trace gases. The analysis includes also source detection and evaluation of source strengths. The results can be used for comparison and validation of small scale pollution models and hence they may increase our understanding of pollution processes and development.

In the future, AirMap will be used in further research campaigns for high resolution measurements of NO_2 , SO_2 and

further trace gases. An upgrade to an improved spectrometer is currently planned.

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Figure 30: NO₂ vertical column amounts observed by AirMap in August 2013 above a single container vessel in the North Sea. The NO₂ amounts are of comparable magnitude as above the power plant, demonstrating the strongly polluting effect of ship traffic.

MeSmarT: Measurements of Shipping emissions in the marine Troposphere

Folkard Wittrock, Lisa Kattner, Barbara Mathieu-Üffing, Enno Peters, Andreas Richter, André Seyler, John P. Burrows

Air pollution from ships contributes to overall air quality problems and has direct health effects on the population in particular in coastal regions, and in harbour cities. With the recent increases in international trading volume, the numbers of ships as well as their size have increased considerably. As a result, the importance of ship emissions for air quality is increasing.

The establishment of a Sulphur Emission Controlled Area (SECA) for North Sea and Baltic Sea based on the MARPOL Annex VI protocol by the International Maritime Organisation (IMO) has been a first step to control and reduce sulphur dioxide (SO₂) emissions by consecutively regulating the sulphur content of fuels. As part of the directive 2012/33/EC the EU member states shall take all necessary measures to check by sampling that the sulphur content of fuels used complies with the relevant limits. The sampling should be done periodically with sufficient frequency to be representative of the fuel used by the vessels while in relevant sea areas and ports. The analysis should be done without undue delay. However, up to now there is no regular monitoring system available to verify that ships are complying with the new regulations.

One of the main objectives of the project MeSMarT (Measurements of shipping emissions in the marine troposphere) is to develop, test and establish such a monitoring system for main shipping routes to support the surveillance of international emission regulations in a cost-efficient way. The project is carried out by IUP Bremen in cooperation with the German Bundesamt für Seeschifffahrt

und Hydrographie (Federal Maritime and Hydrographic Agency) with support of the Helmholtz Research Centre Geesthacht.

Within the project, pollution relevant gases like SO₂ and NOx are measured with in-situ and remote sensing techniques. Complementary meteorological data and AIS information of passing ships are also recorded by the whole setup. In order to demonstrate the different capabilities of the system two permanent measurement sites were set up in the year 2013. In Wedel near Hamburg measurements are performed in close distance to the Elbe River where ships entering the Hamburg harbour are passing by. Measurement results show that pollution peaks can be easily associated with individual ships, fulfilling the requirements of the EU directive mentioned above. On the island Neuwerk a second permanent measurement station is located 6 km south of the main shipping route through the German Bight. First results of the latter station illustrate the advantage of the remote sensing system compared to in situ measurements since this method is able to identify single ship plumes up to a distance of 10 to 15 km with sufficient accuracy. Furthermore these

Figure 31: MAX-DOAS telescope monitoring the German bight close to Neuwerk Island.

measurements are independent of the wind direction while in situ observations are only useful downwind of the shipping route. Further tests of the different techniques have been carried out during regular monitoring cruises of the BSH in the North and Baltic Sea aboard the RV Celtic Explorer.

Some technical details and results:

• In situ: Here a combination of commercial available standard instruments is used for monitoring NOx, SO₂, CO₂, and O₃. When detecting a shipping plume a simple algorithm taking into account the ratio of SO₂ to CO₂ is used to calculate the sulphur content in near real time. At the moment the detection limit for the sulphur content is roughly 0.1% which will be the limit for fuel used in emission control areas as from 1 January 2015. Further optimization of the instrumental sensitivity and the analysis is ongoing.

• Remote sensing: Here the MAX-DOAS (Multi-Axis Differential Optical Absorption Spectroscopy) technique is used which collects scattered sunlight in the UV and visible wavelength range to identify specific trace gases by their absorption features. Since this is a passive system only measurements during daylight are possible. An active system (having an artificial light source) would prevent this limitation but at least for remote stations close to shipping routes in the open sea (e.g. using off-shore platforms) the passive system is the only useful option. Since the remote sensing technique is not able to monitor the CO₂ the sulphur content is calculated by using ship information like size and engine technology. However, in the current status of the setup the detection limit for the sulphur content is roughly 0.2%, which is good enough to initiate further analysis of bunker oil from ships under suspicion.

Summary

Within the project MeSmarT a prototype of a cost-efficient monitoring system to support the surveillance of emission regulations has been introduced. It could be easily extended to a network covering the whole emission control areas, providing the possibility to sample the sulphur content in bunker oil with high frequency and adequate accuracy.

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Figure 33: Comparison between in situ and remote sensing observations for a single day at Neuwerk. The remote sensing instrument is showing more single ship peaks since due to the relative high distance to the shipping route not all plumes are reaching the location of the in situ monitor.

Estimating NOx emissions from biomass burning using satellite observations

Stefan F. Schreier, Andreas Richter, and John P. Burrows

arge vegetation fires, which are known to occur every single month on our planet, emit large amounts of trace species into the atmosphere, among them NOx. During the combustion process, nitrogen (N) present in the fuel is converted in part into oxides and N present in amino acids is converted to NO. However, NOx may also result from the reaction of molecular nitrogen (N₂) with O₂ at very high temperatures. The atmospheric composition over such biomass burning regions is strongly influenced by the release and subsequent chemical reactions of trace gases (e.g., NOx, O₃, and VOCs) as well as aerosols.

Global estimates of the importance of biomass burning for atmospheric composition are based on estimates of fire activity, usually based on satellite observations, assessments of the amount and type of biomass burned, and laboratory or field measurements of emissions per biomass burned. Recent studies estimate that the consumed biomass in the tropics accounts for 80% of the total biomass burned globally, with Africa and Australia accounting for more than 80% of the global burned area.

The estimation of emissions for large areas and long-term periods has to be carried out in a simplified way as the whole combustion process is complex and not well characterized. In Schreier et al., 2004a, an attempt is made to use satellite observations of tropospheric NO_2 from the GOME-2 and OMI instruments together with fire radiative power (FRP) observed from the MODIS instruments to estimate fire emission rates (FER).

The method is based on a simple statistical approach, linking fire radiative power and tropospheric verti-

Figure 34: Temporal variability of MODIS Terra (red) and MODIS Aqua (orange) satellite-derived FRP and GOME-2 (green) and OMI (blue) derived TVC NO₂ for selected regions (Schreier et al., 2014a)

cal NO₂ columns (TVC) over selected regions in a linear way. That this is possible is illustrated in Figure 34 where monthly time series of both quantities are shown for four selected regions. As can be seen, there is a high degree of correlation between FRP and NO₂ columns both in the morning (GOME-2 and MODIS on Terra) and in the early afternoon (OMI and MODIS on Aqua). As fire activity is more intense in the afternoon, NO₂ values are higher in OMI data, in particular in Africa. Correlation coefficients are high over all major biomass burning regions and exceed 0.8 over Africa (see Figure 36).

Using the slope of the correlation between FRP and NO₂, and assuming values for the NOx/NO₂ ratio as well as the NOx lifetime from literature, production rates of NOx from fires could be derived linking satellite observed FRP and NOx emissions. Good agreement was found between these satellite based estimates and the recent GFEDv3.1 fire emission inventory.

Using land cover data sets and appropriate filtering of data, region and biome specific fire emission rates could be determined (Figure 35). While overall the fire emission rates are similar between regions and biomes, there are significant differences with generally larger values in the African regions, except for croplands where the highest values are found in Southeast Asia. This is an important result for atmospheric models which rely on emission factors for model-ling of biomass burning.

Figure 35: Biome-specific FERs of NOx, averaged via the binning method, for the selected regions. Here, the best fitting least-squares regression lines of the morning observations (GOME-2 vs. MODIS Terra) are shown for evergreen broadleaf forest (green), open scrublands (beige), woody savannah (orange), savannah (yellow), and croplands (red) (Schreier et al., 2014a) The study could also be extended to boreal forests by using improved satellite NO₂ retrievals and better estimates for the NOx/NO₂ ratio by applying results from the MACC model (Schreier et al., 2014b). The main result is that fire emission rates from boreal forests are larger in Eurasia than in North America, presumably as a result of different N content in the two forest types.

Future applications of this method could reduce uncertainties by more detailed modelling of the radiative transfer in the atmosphere in the presence of biomass burning aero-

Figure 36: Correlation coefficients (r) of the local temporal relationship between FRP and TVC NO_2 based on monthly averages from 2007 to 2011 on a 1x1 grid. Data are shown for the linear relationship observed between GOME-2 TVC NO_2 and MODIS Terra FRP. (Schreier et al., 2014a)

sols. The next generation of satellite instruments will have much better spatial resolution, enabling better separation between biomes and also reducing cloud and smoke induced problems. Finally, the availability of NO₂ observations from geostationary satellites such as the Sentinel 4 will in the future allow the study of diurnal profile of biomass burning emissions.

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Satellite observations of the stratosphere

Mark Weber, Alexei Rozanov, Jan Aschmann, Lena Brinkhoff, John P. Burrows, Wissam Chehade, Florian Ernst, Claus Gebhardt, Katja Weigel

Until the end of the 1990s, ozone levels have declined on a global scale. In order to mitigate this ozone depletion caused by halogen compounds (CFCs and bromine containing species called halons), the Montreal protocol adopted in 1987 and a series of subsequent amendments phased out many ozone depleting substances. By the end of the 1990s stratospheric halogen load peaked and since then slowly declined.

Observations from SCIAMACHY and other satellite instruments show a modest increase in ozone in the upper stratosphere (40-50 km) (e.g. Gebhardt et al., 2014, Weber et al., 2014, see Figure 37) since the early 2000s which is consistent with the changes in stratospheric halogen load. In the lower stratosphere the picture is less clear since natural variability of other processes, such as solar variability (11-year solar cycle), circulation patterns (atmospheric dynamics, Brewer-Dobson circulation), and major volcanic eruptions also contribute to ozone changes. Nevertheless, in the lower stratosphere the long-term decline has been stopped and total ozone levels (representative of lower stratospheric ozone) remained stable since about 2000 (Chehade et al., 2014, Weber et al., 2014). At mid latitudes ozone total ozone levels are currently still about 3% (northern hemisphere) and about 6% (southern hemisphere) below average levels during 1964-1980.

The speed of ozone recovery in the future strongly depends on the interaction of ozone with climate change and vice versa. Climate change may accelerate ozone recovery, e. g. stratospheric cooling due to enhanced greenhouse gases will lead to higher ozone production ('super recovery'). On the other hand increased tropical upwelling related, for instance, to increases in sea surface temperatures (SST), will continue reducing ozone in the tropical lowermost stratosphere (e.g. Aschmann et al., 2014). Because of changes in stratospheric greenhouse gases, in particular N_2O , CH_4 , and water vapour, background chemistry involving HOx and NOx radicals will play an increasing role in chemical ozone depletion globally. In the event of another major volcanic eruption with injection of large amounts of sulphate

Figure 37: Linear trends (%/decade) in ozone derived from SCIAMACHY limb observations between 2002 and 2012 as a function of latitude and altitude. Shaded areas indicate trends which are within 2σ not statistically significant different from zero trends. From Gebhardt et al. (2014)

aerosols into the stratosphere (like Mt Pinatubo in 1992) substantial ozone depletion may be observed in the future.

Important contributions to stratospheric ozone science:

• None of the different satellite total ozone datasets available show a statistically significant positive trend after 2000 (Chehade et al., 2014). The large year-to-year variability still masks the expected slow ozone recovery.

• The study by Gebhardt et al. (2014) highlighted the continuous decline in tropical middle stratosphere ozone (near 32 km altitude) observed by SCIAMACHY until 2012 (see Figure 37), which could be possibly linked to positive NO₂ trends in the same altitude region.

• Tropical lowermost stratospheric ozone as observed by SCIAMA-CHY and ozone sondes has leveled off since 2002 and this is believed to be due a hiatus in the continuous warming of the Pacific SST (Aschmann et al., 2014).

• Since the stratospheric halogen load is still fairly high (about 10% below peak values), substantial ozone losses are still observed dur-

ing cold polar winters. In particular, a record high polar ozone depletion was observed during Arctic winter 2010/11 (e.g. Hommel et al., 2014).

• Stratospheric aerosol properties have been derived for the first time from SCIAMACHY limb observations (Ernst et al., 2012). These observations highlight the potential role of minor volcanic eruptions contributing to stratospheric aerosols (Figure 38).

• Water vapour plays an important role in ozone chemistry, but also is a very useful tracer for transport processes in the tropical upper troposphere and lower stratosphere (UTLS). Water vapour in the altitude range from 10 to 23 km has been successfully derived from SCIAMACHY limb observations (Rozanov et al., 2011). The SCIAMACHY water vapour anomaly time series agrees well with other satellite data and shows an upward trend since 2001 following a sharp drop in the tropical lowermost stratosphere (Hegglin et al., 2014, see Figure 39).

Figure 38: SCIAMACHY aerosol extinction at 750 nm between 20°S and 20°N from 2002 to 2012. Volcanic events and locations are indicated in the bottom box

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Figure 39: Water vapour anomaly time series in the tropical lowermost stratosphere from different satellite datasets. The anomalies were obtained by subtracting the fitted seasonal cycle from each time series.

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Clouds and aerosols in the atmosphere

Marco Vountas, Luca Lelli, Vladimir Rozanov, Linlu Mei, Malte Jäger, John P. Burrows

Studies of global trends in top altitude of clouds

Tropospheric clouds are main players in the Earth's climate system. They serve not only as water reservoirs in the atmosphere, being a controlling factor in the hydrogeological cycle, but also modulate both incoming sunlight and outgoing terrestrial radiation. In this case, the cloud physical property of altitude is the parameter of interest. The sunlight reflected by the Earth has been globally and continuously measured by the three in-orbit spectrometers GOME, SCIAMACHY and GOME-2. Since the launch of GOME, back in 1995, more than 19 years of data are now available and they form the observational basis of current research. In particular, it has been seen that the satellite's ground pixel size impacts the calculation of mean values of cloud top height. Upon application of linear fitting methods, a global negative trend of -1.78 m/year has been estimated. The data have also been analysed with respect to underlying sur-

Trend β [m/yr]

ing clouds are found over ocean (-2.51 m/year), whereas rising clouds (+0.27 m/year) are

face, and sink-

Figure 40: The time series portrays the monthly averaged AOT signal extracted from adjacent boxes at the coast of West Africa and off-shore (for the same box size). The oscillations of both curves indicate that dust activity is more frequent in summer than in winter. Dust deposition is reflected by the difference between the red (off-shore) and black (at the coast) curves during the respective months.

found over land. Looking at the geographical patterns (Figure 41), we see higher clouds in the tropical belt and especially over the North African continent. Cloud top altitudes at mid latitudes as well as over oceans are decreasing.

Additional understanding of the terrestrial climate system can be obtained by looking at the quasi-periodic process of ENSO (El-Niño Southern Oscillation) across the Central-East Pacific. ENSO is found to be the main driver of clouds' altitude, reducing cloud top heights at a rate of approximately 2 m/year in the time window of data availability.

Dust deposition derived from optical satellite measurements

Desert dust (or dust aerosol) outflows off the West African coast impact offshore biogeochemical processes and can be regarded as natural hazards to human activities and ecosystems. For example, dust storms affect aviation operations by reducing flight visibility, by causing engine mechanical damages and through flight path reassessments. On the other hand, dust input adds nutrients to the surface of the seas which stimulate phytoplankton production, and higher particle flux can increase export fluxes of biomass from the surface waters to the sea floor and hence increase accumulation rates in the underlying sediments. For the above presented reasons, satellite retrievals of aerosol optical thickness (AOT, defined as the sunlight attenuation strength of dust particles, integrated over a vertical column through the atmosphere) over the Atlantic Ocean have been implemented to estimate the rates of dust deposition. First results (see the grey area in Figure 40, reflecting dust deposition by the difference between the red and black curves during the respective months) reveal higher dust deposition in summer than in winter.

Changes in atmospheric aerosol loading retrieved from space-based measurements during the past decade

The role and potential management of short-lived atmospheric pollutants such as aerosols are currently a topic of scientific and public debates. Our limited knowledge of atmospheric aerosol and its influence on the Earth's radiation balance has a significant impact on the accuracy and error of current predictions of future climate change.

A study has been performed to present an approach to minimize the uncertainties due to limited temporal sampling and cloud disturbance by use of weighted least-squares regression and multiple satellite-derived AOTs from four space-borne instruments, MODIS (on-board Terra from 2000 to 2009 and Aqua form 2003 to 2008), MISR (Terra from 2000 to 2010), and Sea-WiFS (OrbView-2 from 1998 to 2007). The output provides more convincing trend estimates for atmospheric aerosols during the past decade (Figure 42). It was found that the AOT decreases over Western Europe (by up to about -40% from 2003 to 2008). In contrast, a statistically significant increase (about +34% in the same period) over eastern China is observed and can be attributed to the increase in both industrial output and Asian desert dust.

The trends have been validated with the corresponding AOT trends at the available ground-based measurement stations

(AERONET). Significant decreases in AOT over Western Europe and the eastern USA, as well as increases over the Near/Middle East. southern and eastern Asia. are observed. In particular, the dramatic increases in AOT over the region of eastern China, associated with rapid industrial growth and desertification are revealed. The recent severe smog episodes in China during winter 2012/13 and 2013/14 could be a dramatic consequence of the increasing emissions resulting from economic growth, coupled with minimal environmental legislation.

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Figure 42: Weighted trends derived from satellite-retrieved AOTs for the selected regions. Each instrument has a different local sampling time; the equatorial crossing times for the satellites are 10:30 for Terra (descending node), 12:20 for Orb-View-2 (descending node), and 13:30 for Aqua (ascending node). Only statistically significant weighted trends are shown for each grid cell. Not significant trends are shown in grey.

Satellite observations of solar induced plant fluorescence

Marco Vountas, Narges Khosravi, Vladimir Rozanov, Astrid Bracher, Alexandra Wolanin, John P. Burrows

Terrestrial vegetation is the main sink of carbon-dioxide over land due to photosynthesis. Plants absorb sunlight (energy), water, and CO_2 from their environment and produce oxygen and sugar. However, not all of the absorbed energy is utilized by photosynthesis. The rest of the energy is re-emitted to the environment as thermal radiation or fluorescence. Accordingly the variation of fluorescence emission can be an indicator of photosynthesis efficiency.

Space-borne, global monitoring of solar-induced plant fluorescence is a very effective way to monitor vegetation regionally and globally. Moreover, it enables us to observe the effect of environmental stress (e.g. by drought, soil erosion, climate change) on plant's status. It can also serve as a potential source of information about the contribution of terrestrial plants to global carbon uptake.

A fluorescence retrieval method has been developed at IUP using reflected radiance measurements from SCIAMACHY (Scanning Imaging Absorption Spectrometer for Atmospheric ChartographY) and is applicable to other instruments as well. In presence of plant fluorescence emissions at ground level an additive signal is affecting the reflected radiance. Therefore, knowing the surface and atmospheric properties (e.g. ground reflectance, gaseous absorption features, aerosol optical properties and clouds) during a measurement enables us to decompose the signal into the radiance in absence of fluorescence and a fluorescence reference spec-

Figure 43: Seasonal variation of the retrieved solar-induced plant fluorescence power [mW $m^{-2}sr^{-1}$ nm^{-1}], based on 10 years of SCIAMACHY data (2002-2012). (Left top) for Northern winter (DJF); (right top) spring (MAM); (left bottom) for summer (JJA) and (right bottom) for autumn (SON) months.

trum. To calculate the atmospheric and measurement properties, a comprehensive radiative transfer model has been used. The net effect of fluorescence and the spectral features without accounting for fluorescence have been fitted to the measured radiances. The resulting fluorescence emitted power is shown in Figure 43. As fluorescence emission is closely connected to the presence of vegetation, the seasonal trend of fluorescence is highly correlated to the vegetation growth and decline during different seasons.

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Development of in situ airborne instrumentation for the measurement of reactive trace gases in the upper troposphere

Maria Dolores Andrés-Hernández, Markus Horstjann, Vladyslav Nenakhov, John P. Burrows

The accurate measurement of reactive trace gases in the upper layers of the troposphere requires the development and optimisation of particularly sensitive and robust measurement techniques (Andrés Hernández, 2013). In this context IUP-Bremen has long term experience with the measurement of peroxy radicals, very reactive and consequently short lived species which generate longer lived radiatively active (e.g. ozone, O_3) and chemically or toxicologically important pollutants. Following vertical and long-range transport, these in turn play a significant role in the chemistry of the Earth atmosphere both regionally and globally. In particular in-situ airborne measurements of peroxy radicals of high temporal and vertical resolution in different layers of the troposphere can provide unique information about the role of these species in determining O_3 abundance.

The PeRCEAS (peroxy radical chemical enhancement and absorption spectrometer) instrument has been developed at IUP-Bremen for operation on the new DLR (German Aerospace Center) research aircraft HALO (High altitude and long range research aircraft; see <u>www.halo.dlr.de/</u>). PeRCEAS provides a means to accurately measure peroxy radicals in altitudes of up to 13 km (Horstjann et al., 2014). It will be deployed in 2015 in the framework of the OMO mission (Oxidation mechanisms observations in the extra-tropical free troposphere) to determine the role played by peroxy radicals in the transport and transformation of pollution around

the globe, in particular addressing the outflow of continents under high convective conditions. In that context, flight tracks comprising a total of 100 flight hours will be carried out within a 5 weeks measurement campaign during the onset of the Asian monsoon anticyclone over South Asia, the Indian Ocean, the Arabian Peninsula and the eastern Mediterranean region. The research consortium has a strong track record in airborne atmospheric chemistry research and apart from the University of Bremen comprises 3 other universities and four institutions belonging to the Max Planck Society and the Helmholtz Association.

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Figure 44: Installation of the PeRCEAS in the HALO research aircraft in preparation of the OMO campaign

The 5th IPCC Report and the Ocean's role in Climate Change

Monika Rhein

The Intergovernmental Panel on Climate Change (IPCC) is an institution of the United Nations. Every seven years, thousands of scientists voluntarily collect, assess, summarize and review the present knowledge in climate research. None of them is paid by the IPCC. The results are published in three volumes: Working Group (WG) I is responsible for "The Physical Science Basis of Climate Change", WG II for "Climate Change Impacts, Adaptation and Vulnerability", and WG III for "Mitigation of Climate Change". The IPCC report is accepted by 195 nations and provides science- based knowledge for policymakers.

Scientists from the IUP mostly contributed to chapters of the WG I report ("The Physical Science Basis of Climate Change"). Monika Rhein was Coordinating Lead Author of Chapter 3 "Oceans: Observations" (Rhein et al., 2013), Lead Author of the Technical Summary, i.e. the Summary for scientists (Stocker et al., 2013), and Drafting Author of the Summary for Policymakers of WG I.

The most relevant topics of ocean research for society in WG I are the ocean's role in the energy budget and the storage of anthropogenic carbon, and - especially for coastal areas -the sea level rise caused by ocean warming and melt of glaciers and ice sheets.

For the first time the 5th IPCC report highlighted the role of the ocean for the global change of the **energy budget** in the climate system. Ocean warming dominates the global energy change inventory and accounts for about 93% of the increase in Earth's energy inventory between 1971 and 2010. Warming of the upper (0 – 700 m) ocean accounts for about 64% of the total. Melting ice (3%, including Arctic sea ice, ice sheets, and glaciers), warming of the continents (3%) and of the atmosphere (1%) account for the remainder of the change in energy (Figure 45). The estimated net increase in the ocean's energy storage between 1971 and 2010 is

equivalent to a mean uptake of 0.55 W m⁻² applied over the ocean's entire surface area, and this is each year more than eight times of the world's energy consumption of 2012. Before 1970, the observational data base is too small to reliably calculate the global oceanic energy change, but from the data available it is likely that the ocean has warmed since the 1870s. By this dominance of the ocean in the energy budget one can rightly say that global warming is ocean warming, and the observed interannual to decadal atmospheric temperature variability that overlies the warming trend is mostly caused by energy exchange between ocean and atmosphere.

The warming of the ocean and the additional mass through melting of glaciers and ice sheet leads to sea level rise. Since 1900, global mean sea level (GMSL) has risen by 0.19 [0.17-0.21] m. The mean rate was 1.7 mm yr⁻¹ between 1901 and 2010 and increased to 3.2 mm yr⁻¹ between 1993 and 2010. These results are based on the high agreement among multiple studies using different methods, long tide gauge records corrected for vertical land motion, and independent observing systems (tide gauges and altimetry) since 1993. Rates of sea level rise over broad regions can be several times larger or smaller than the global mean for periods of several decades due to fluctuations in ocean circulation. Examples are the anomalous sea level rise in the West Pacific Warm Pool and the decrease in sea level at Galapagos. Warming of the upper 700 m has been contributing an average of 0.6 mm yr⁻¹ of sea level rise since 1971, warming between 700 m and 200 m added 0.1mm yr⁻¹. and since the early 1990s, warming below 2000 m provided another 0.1 mm yr⁻¹ of sea level rise. Before the 1990s, the data coverage in the deep ocean is too low to calculate rates. It is very likely that the ocean mass has increased at a rate between 1 and 2 mm

yr⁻¹ (equivalent sea level rise) since 2002, based on high agreement between different studies using satellite gravity measurements and altimeter measurements after removing steric variations.

Another important role of the ocean is the storage of anthropogenic CO₂. Of the 555 Gigatons carbon released to the atmosphere from fossil fuel (375 Gt C) and land use emissions (180 Gt C) from 1750 to 2011, about 43% accumulated in the atmosphere. Based on high agreement between independent estimates using different methods and data sets (e.g., oceanic carbon, oxygen, and transient tracer data), the ocean stored 28% (155 Gigatons) of the anthropogenic carbon. This natural process of absorbtion in the ocean, the so-called "physical pump", has significantly reduced the atmospheric CO₂ level and minimized some of the impacts of global warming. The terrestrial biosphere stored 160 Gt C, i.e. about the same amount as it emitted (180 Gt C). The oceanic uptake of anthropogenic CO₂ results in gradual acidification of the ocean. The pH of seawater has decreased by 0.1 since the beginning of the industrial era, corresponding to a 26% increase in hydrogen ion concentration. Warming and oceanic uptake of anthropogenic carbon do not act independently. Ocean warming reduces the solubility of CO_2 , i.e. the ability to absorb CO_2 from the atmosphere, and warming increases the vertical stability of the ocean and limits the access of upper water with high levels of anthropogenic carbon to the storage area in the deep ocean.

Besides the direct influence of the ocean on climate and climate change, the oceanic salinity measurements provide a means to infer changes in the hydrological cycle that otherwise cannot be measured. Surface salinities are determined by the interplay between precipitation and evaporation: high salinities are found in the subtropical oceans, where evaporation dominates, and low salinities are observed in the rain band near the equator and in higher latitudes. River runoff has only a local influence. It is very likely that regional salinity trends have enhanced the mean geographical contrasts in sea surface salinity since the 1950s: saline surface waters in the evaporation-dominated mid-latitudes have become more saline, while relatively fresh surface waters in rainfall-dominated tropical and Polar Regions have become fresher. The spatial patterns of the salinity trends, mean salinity and the mean distribution of evaporation minus precipitation are all similar. This provides indirect evidence that the pattern of evaporation-precipitation over the oceans has been enhanced since the 1950s.

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Figure 45: Plot of energy accumulation in ZJ (1 ZJ = 1021 J) relative to 1971 and from 1971-2010 unless otherwise indicated. Ocean warming (heat content change) dominates, with the upper ocean (light blue, above 700 m) contributing more than the deep ocean (dark blue, below 700 m; including below 2000 m estimates starting from 1992). Ice melt (light grey; for glaciers and ice caps, Greenland and Antarctic ice sheet estimates starting from 1992, and Arctic sea ice estimate from 1979–2008); continental (land) warming (orange); and atmospheric warming (purple; estimate starting from 1979) make smaller contributions. Uncertainty in the ocean estimate also dominates the total uncertainty (dot-dashed lines about the error from all five components at 90% confidence intervals). From Rhein et al., 2013.

Oxygen trends over five decades in the North Atlantic and interannual to decadal oxygen variability in the middepth water masses of the eastern North Atlantic

Ilaria Stendardo, Dagmar Kieke, Monika Rhein, and Reiner Steinfeldt

issolved oxygen tends to respond very sensitively to Climate change because any warming in sea-surface temperature reduces the solubility of dissolved oxygen and increases ocean stratification, thus reducing the exchange of oxygen between thermocline and the mixed layer, which in fact amplifies the effect of solubility. Observations suggest that oxygen concentrations in the thermocline have declined globally since 1960 with the largest deoxygenation observed in the interior of the tropical ocean (Stendardo and Gruber 2012, Stendardo et al. 2015). Studying changes of oxygen in the subpolar North Atlantic is of particular interest since this is where deep, intermediate, and mode waters form. A better understanding of long-term oxygen variations and changes in the North Atlantic may also help to better decipher changes associated with the Meridional Overturning Circulation. Moreover, model simulations predict substantial decreases in the oceanic oxygen in the North Atlantic in response to anthropogenic climate change (Stendardo and Gruber 2012, Stendardo et al. 2015).

After the analysis of oxygen data from three different databases (CARINA, GLODAP and WOD05) multi-decadal changes in the oxygen concentration were assessed from 1960 to 2009 (Stendardo and Gruber, 2012) for eight sub-regions of the North Atlantic. Results from this analysis (Figure 46) show a significant decrease of oxygen in the Upper (UW), Mode (MW) and Intermediate (IW) waters in almost all regions over the last 5 decades. These water masses are large-

ly occupying the depth range between 100 and 700 m. Over the same period, oxygen increased in the MW of the southwest regions, in the Lower Intermediate Water (LIW) and Labrador Sea Water (LSW) throughout the North Atlantic. The LIW and LSW water masses are occupying mostly the depth range below 700 m up to 2750 m. The observed oxygen decreases in the MW and IW (Figure 46d and g) of the northern and eastern regions are largely driven by changes in circulation and/or ventilation (Figure 46f and i), while changes in solubility are the main driver for the oxygen decrease in the UW (Figure 46a-b) and the increases in the LIW and LSW (Figure 46j-o). Comparing the oxygen trends with those of the oceanic heat content, the O_2 to heat change

ratio is -4.3 ± 2.4 nmol J⁻¹ in the upper 700 m, and -1.6 ± 1.9

nmol J⁻¹ between 700 and 2750 m. These ratios are substan-

tially larger than those expected from solubility alone. Thus,

this analysis strongly supports the notion that if anthropo-

genic climate change continues to evolve unabated, the

Figure 46: O_2 concentration changes over the last 49 years for the five water mass (UW, MW, IW, LIW and LSW) and their drivers. The changes in oxygen (a, d, g, j, and m), the changes induced (b, e, h, k, and n) by solubility (represented by the ΔO_2 sat) and (c, f, i, l, and o) by changes in circulation/ventilation and remineralization (represented by the $-\Delta AOU$), respectively. Statistically significant concentration changes are represented with filled circles, while the not significant ones are plotted with open circles.

ocean is bound to deoxygenate with poorly understood consequences for marine life (Stendardo and Gruber, 2012).

Superimposed on the analysed long-term trend was a substantial amount of interannual to decadal variability in the MW and IW that remained poorly characterized in the previous analysis. We had the opportunity to address this gap by looking at interannual to decadal changes of dissolved oxygen from a repeated hydrographic section in the eastern North Atlantic (Stendardo et al. 2015). The hydrographic section is located at about 48°N and was occupied 12 times from 1993 through 2011. From 1993 to 2002 the oxygen concentrations of the water masses that are occupying the first 1500 m of the water column decreased. During this time period, the trends were mainly caused by a contraction of the subpolar gyre associated with a northwestward shift of the Subpolar Front (SPF) in the eastern North Atlantic (Figure 47b). This caused Subpolar Mode Water (SPMW) to be ventilated at lighter densities and its original density range being invaded by subtropical waters with substantially lower oxygen concentrations. The contraction of the subpolar gyre reduced also the penetration of IW of subpolar origin into the region in favour of an increased northward transport of IW of subtropical origin, which is also lower in oxygen (Figure 47b).

In the first work (Stendardo and Gruber, 2012) the significant decrease in the oxygen observed in the mode and intermediate waters during the last 50 years was related to a reduction in ventilation and circulation due to the positive trend observed in the North Atlantic Oscillation (NAO) after 1960s unti1990s with an emphasis on the reduction of ventilation due to buoyancy forcing especially in the mode water domain. While the role of the circulation on the oxygen

changes is emphasized more than the role of ventilation in Stendardo et al., (2015). First, similar changes of oxygen concentration were observed in the domain of IW. This water mass is not affected by local changes in ventilation since it forms elsewhere. Moreover, the observed shift of the NAO towards lower positive and sometimes negative values after 1997 would rather increase the ventilation within the eastern North Atlantic which would induce an increase in the oxygen concentration in the SPMW forming here. This raises the question to what extent these two mechanisms, ventilation and circulation, might interplay in determining the observed oxygen changes (Stendardo et al. 2015).

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Figure 47: Simplified sketch of the upper and intermediate North Atlantic circulation based on Sarafanov, 2009. Panel (a) represents the circulation during strong positive NAO with water of subpolar origin represented in yellow and water of subtropical origin represented in red. Panel (b) is the circulation during negative NAO. Both panels are zoomed-in on the eastern side of the North Atlantic and the main circulation of this area is sketched. For the complete figure caption including references see Figure 1 in Stendardo et al. 2015.

Decline of deep and bottom water ventilation and slowing down of anthropogenic carbon storage in the Weddell Sea, 1984–2011

Oliver Huhn, Monika Rhein

The Atlantic sector of the Southern Ocean is a key area for the formation of deep and bottom water. It is, hence, an important component of the Meridional Overturning Circulation and a significant sink for atmospheric gases. Climate relevant (anthropogenic) carbon (C_{ant}) is taken up at the atmospheric interface and exported from the atmosphere during Antarctic Bottom Water (AABW) formation. In turn, formation of these waters is influenced by climate change. Despite their importance, formation rates of AABW and related C_{ant} inventories in that area are not well known, and estimates of their temporal variability are quite uncertain.

We used a 27 year long time series of repeated transient anthropogenic tracer observations to investigate the evolution of the ventilation time scales and the related content of anthropogenic carbon in deep and bottom water in the Weddell Sea. This time series consisted of chlorofluorocarbon (CFC) observations from 1984-2008 together with first combined CFC and sulphur hexafluoride (SF6) measurements from 2010/2011 along the Prime Meridian in the Antarctic Ocean and across the Weddell Sea (Figure 48).

Transient tracers like the anthropogenic chlorofluorocarbons (CFCs) or sulphur hexafluoride (SF_6) enter the ocean by gas exchange at the ocean–atmosphere interface. These tracers carry time information due to their atmospheric evolution, which can be used to assess the time scales of the inner oceanic transfer or "age" of a water mass ("age" stands for the time elapsed since a water parcel has left the oceanatmosphere interface). The "TTD method" (TTD stands for "Transit Time Distribution" or "age spectra") is accounting for advection and mixing of all possible trajectories of water parcels and idealizes the inner oceanic transport to one dimensional advection and dispersion (e.g. Huhn et al., 2008).

Surprisingly, we found that all deep water masses in the Weddell Sea have been continually growing older and getting less ventilated during the last 27 years (Figure 49).

Figure 48: Map of the area of investigation. The dots indicate locations of 2010/2011 CFC measurements along the Prime Meridian and the Weddell Sea section; the colours represent CFC-12 surface water saturations. Geographic features as Mid Atlantic Ridge (MAR), Maud Rise, Antarctic (AA) Peninsula, Larsen and Filchner–Ronne Ice Shelf and South Scotia Ridge system are shown in italics. Water masses and schematic subsurface circulation are indicated by arrows and underlined abbreviations (see text) in the same colour.

The decline of the ventilation rate of Weddell Sea Bottom Water (WSBW) and Weddell Sea Deep Water (WSDW) along the Prime Meridian is on the order of 15-21%; the Warm Deep Water (WDW) ventilation rate declined much faster by 33%; lower Circumpolar Deep Water (ICDW) by 38%. However, about 88-94% of the age increase in WSBW near its source regions (1.8-2.4 years per year) can be explained by the age increase of WDW/ICDW (4.5 years per year).

We found that C_{ant} is highest in WSBW on the slope of the Antarctic Peninsula (19.1±1.3 µmol/kg in 2011). The WSBW

further downstream from the sources, at the bottom of the basin and on the Prime Meridian has a C_{ant} of $9.4\pm1.7 \mu$ mol/kg (Figure 50). WSDW has about 7.6 -8.2 μ mol/kg on both investigated sections. The lowest values were found in WDW (6.6 $\pm1.4 \mu$ mol/kg) and ICDW (7.7 $\pm1.5 \mu$ mol/kg).

The increase of C_{ant} is highest in WSBW on the slope of the Antarctic Peninsula with 0.15±0.09 µmol/kg per year. Further away from the source regions, along the Prime Meridian in the WSBW and in WSDW with additional easterly sources, the C_{ant} increase is 0.06–0.10 µmol/kg per year (Figure 51). The C_{ant} in the upper and warmer deep waters (WDW and ICDW) seems to stagnate during the period of observations. However, as a consequence of the aging and reduced ventilation, the C_{ant} increase in the deep and bottom water formed in the Weddell Sea slowed down by 14-21% over the period of observations.

Declining ventilation of deep Antarctic waters and slowing down of C_{ant} uptake is a potentially very important phenom-

Figure 49: Trends [per year] for mean age τ from CFC based TTDs along the Prime Meridian for the entire period 1984 to 2011. To indicate positions of data points, data points from 2011 are marked by white dots as an example.

enon for the global oceans and climate. Whether this increase age will continue at its present rate or if it is only multidecadal variability can only be judged in the future and therefore it is absolutely necessary to extend the observational time series. Although we did not find evidence for changing WSBW formation rates, we cannot rule out that that may happen in the future due to changing environmental or climate conditions as observed or projected by models. Therefore, additional and detailed observations may give more clues as to the causes of the observed aging and ventilation reduction and slowing down C_{ant} storage.

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Figure 50: C_{ant} from CFC based TTDs along the Prime Meridian between the Antarctic Continent (left) and the Mid Atlantic Ridge (MAR) from 2011. Data points are marked by white dots.

Figure 51: Trends [per year] for the related C_{ant} from CFC based TTDs along the Prime Meridian for the entire period 1984 to 2011. To indicate positions of data points, data points from 2011 are marked by white dots as an example.

Circulation in the western subpolar North Atlantic

Christian Mertens, Monika Rhein, Maren Walter

n the northern North Atlantic the meridional overturning circulation at the boundary between the subpolar and subtropical gyre is superimposed by a system of strong currents and recirculations. Cold and fresh water flows southward in a deep boundary current along the continental margin, compensated by an adjacent northward flow that carries warm and salty water (e.g Mertens et al., 2014). These strong currents and their interchange control the deep water export from the subpolar gyre (e.g Kieke et al., 2009). The North Atlantic Current (NAC) is the northern extension of the Gulf Stream. At the southeastern tip of the Grand Banks of Newfoundland part of the Gulf Stream recirculates or continues in eastern direction, while the remaining fraction turns northward, now called the NAC. On its way north, the NAC follows the continental margin, thereby forming a number of small recirculation cells, to the so-called Northwest Corner, where it turns east. Satellite altimetry shows that the NAC crosses the Mid-Atlantic Ridge within different branches that align to the fracture zones in the ridge. Only a fraction of about 25% of the total NAC volume transport enters the East Atlantic, the remaining part recirculates within the Newfoundland Basin. Rhein et al. (2011) found that the fluctuations of the northward volume transport of the overturning circulation were dominated by variability west of the Mid-Atlantic Ridge.

The export of cold water from the subpolar gyre follows several pathways. The majority of the water is carried south within the Deep Western Boundary Current (DWBC) along the continental margin; it splits up north of 47°N, with one shallow branch flowing through Flemish Pass, mainly carrying (upper) Labrador Sea Water, and the other east of Flemish Cap. Evidence for additional interior pathways of deep water export comes from mooring data close to the Mid-Atlantic Ridge, where occasional southward flow of deep water was observed (Kieke et al., 2009). The interior pathways are likely sustained by a series of recirculation cells within the Newfoundland Basin.

The circulation and water mass properties east of Flemish Cap were studied using shipboard measurements from seven sections along 47°N, a two-year long time series of mooring data, satellite altimetry, and output of a highresolution numerical circulation model (Mertens et al., 2014). Observations and model results show

an alternating pattern of strong meridional currents east of Flemish Cap. Three major currents are located between 44° and 38°W. Directly at the continental margin cold deep water masses from the Labrador Sea are carried southward. The northward flowing North Atlantic Current is found farther offshore, followed in the east by its southward return flow. The transports of the main pathways are summarized in Figure 52.

Figure 52: Average absolute dynamic topography gridded on 1/3° from AVISO, bathymetry of the Newfoundland Basin, and schematic depiction of the circulation: southward flowing Deep Western Boundary Current (DWBC), northward flowing North Atlantic Current (NAC), and recirculation in the Newfoundland Basin (NBR). Arrows indicate mean paths of the DWBC and NAC. Hydrographic sections are shown as black lines. Red boxes: warm water transports above $\sigma_{\theta} =$

 $27.68~kg\,m^{-3},$ blue boxes: deep water transports below $27.68~kg\,m^{-3};$ numbers in Sv.

The deep western boundary current at 47°N has two distinct cores that are found in both observations and model, one with maximum at mid-depth directly at the continental slope, the other farther offshore and bottom intensified (Figure 53). The DWBC above the slope is rather stable, but in offshore direction the variability increases and (in the model) the bottom intensified DWBC core is strongly correlated to the NAC recirculation system. South of 47°N, part of the DWBC makes a hairpin turn and returns northward within the NAC. Mesoscale processes like eddies play an important role for the freshwater budget of the subpolar gyre, because they supply a regular exchange of water with different salinities between the boundary current and the NAC. Differences in the T/S properties in the deep water in DWBC, NAC, and NBR, where the T/S of the NBR is closer to the boundary current than to the NAC, imply an exchange of heat and salt across the subpolar front in the Newfoundland Basin.

The observed variability of the circulation ranges from synoptic to interannual; the coupling between the boundary and the interior makes it likely that the state of the circulation in the Newfoundland Basin determines the pathways of the NAC. The series of semi-permanent eddies between (and including) the Mann Eddy and the Northwest Corner is probably related to the number and position of branches crossing the Mid-Atlantic Ridge from the western to the eastern basin of the subpolar North Atlantic, thereby possibly affecting the eastward flow of Iceland-Scotland-Overflow Water in the Charlie-Gibbs Fracture Zone, as well as middepth diapycnal mixing patterns at the Mid-Atlantic Ridge (Walter and Mertens, 2013).

Figure 53: (a) Mean meridional velocity at 47°N between 44° and 36°W from LADCP measurements carried out on six different cruises. Superimposed are isopycnals σ_{θ} = 27.68, 27.74, 27.8, 27.88 kg m⁻³. (b) 47-year mean of meridional velocity along 47°N from model data.

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Temporal variability of the internal wave field and vertical mixing

Janna Köhler, Maren Walter, Christian Mertens, Monika Rhein

Turbulent vertical mixing in the deep ocean contributes an important part of the global overturning circulation by maintaining the stratification. Vertical mixing in the ocean is sustained by breaking waves in the ocean interior. These internal waves are excited by a variety of processes, e.g. atmospheric forcing at the surface, tidal motions, and mesoscale currents interacting with bathymetry as submarine ridges, canyons or seamounts. Temporal and spatial changes in the internal wave field and the associated vertical mixing have large effects on both local properties like the distribution of nutrients, and the large scale ocean system by their influence on vertical heat fluxes and stratification. This leads to the question whether changes in these forcing mechanisms (caused by natural variability or anthropogenic climate change) may have an impact on the overturning circulation by changing mixing patterns and strength. Understanding the processes involved in setting the strength and distribution of mixing in the ocean interior is crucial for its correct representation in climate models.

Two recent studies (Walter and Mertens, 2013; Köhler et al., 2014) have shown considerable temporal variability in the internal wave field associated with the paths of two major currents in the Atlantic, the North Atlantic Current (NAC) transporting water of subtropical origin across the North Atlantic, and the Deep Western Boundary Current (DWBC), which represents the southward return flow in the Atlantic overturning circulation.

The strength and position of this DWBC is highly variable over time in the tropical Atlantic off the Lesser Antilles (Rhein et al., 2004, 2005) which makes it an ideal region to study effects of variability in current strength and direction on the internal wave field and subsequently on vertical mixing rates (Stöber et al., 2008; Köhler et al., 2014). The analyses of a 5-year long mooring time series obtained in the flow path of the DWBC (Kanzow et al., 2006) shows significant variability in internal wave energy primarily in near inertial waves induced by the interaction of the DWBC with the slope to the west of the mooring location (Figure 54). Highest internal wave energy is found during times of strongest flow, emphasizing the importance of strong flows for the internal wave field (Köhler et al., 2014).

Vertical mixing intensities have been differentiated in dependence on background flow conditions and revealed high variability, especially in the deepest part of the profiles up to 1500 m above the bottom. Here, elevated mean values were observed during times when the DWBC was found close to

Figure 54: Top: Time series of low-pass filtered absolute velocities in the Deep Western Boundary Current at a depth of approximately 1500 m. Bottom panel: Internal wave available potential energy obtained from the integration of internal wave spectra (Köhler et al. 2014).

the continental slope. Enhanced energy content in the internal wave field and increased vertical mixing rates during strong DWBC phases strongly indicates an enhanced generation of internal waves due to interactions between the DWBC and the topography.

In the North Atlantic, the NAC crosses the Mid-Atlantic Ridge (MAR) between 48° and 54° N, shifting position and developing different branch modes in response to the prevalent wind field. The strength and positioning of the branches are determined by the eddy field and the topography: the main pathways correspond to the positions of the large fracture zones in the MAR. While mixing close to the seafloor is generally elevated over rough topography at oceanic ridges (e.g. Walter et al., 2005), observations of the internal wave energy and mixing from three years of a repeat transect along the flanks of the MAR (Walter and Mertens, 2013) could now demonstrate a mid-depth amplification that is linked to the mesoscale flow field and thus to the position of the NAC (Figure 55). Predominantly downward energy flux was observed in anticyclonic eddies, which may be a contributing factor to the amplification of internal wave shear at middepth by trapping and downward channelling of wind generated near-inertial energy in anticyclonic eddies.

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Figure 55: Section of normalized shear variance in the internal wave band (2008, 2010, 2011) with depthintegrated dissipation rate on top. White lines denote velocity speed (contour interval 0.1 m/s), positions of fronts are shown as vertical dashed (main front) and dotted (secondary front) black lines. Horizontal bars at the bottom of the figures denote approximate extent of anticyclones (red) and cyclones (blue) along section (Walter and Mertens 2013).

Quantifying Sedimentation and Mixing Processes using Radioisotopes

Daniela Pittauerová and Helmut W. Fischer

Marine or lake sediment cores (Figure 56) contain information needed to improve our understanding of past environmental conditions, such as climate variability. Therefore they serve as valuable archives of climate change. A better knowledge of the triggers, drivers and dynamics of past sedimentation processes, provides us with the necessary evidence that climate models and future climatic projections can be built upon.

An additional condition for the successful interpretation of information contained in sediment archives is reliable chronology - dating of individual sediment layers. For different time scales, different methods are used. These include radioactive nuclides such as radiocarbon (¹⁴C dating). Gamma emitting radionuclides play an important role in the chronology of sediments deposited during recent history. This is especially true since the beginning of 20th Century, when our living environment was affected by intensified industrial activities.

Sediment chronology of the last 100-150 years is constructed using the decay of ²¹⁰Pb, a member of the natural ²³⁸U decay chain. This isotope has a suitable half-life of 22.3 years and its origin within the sediment is two-fold: Firstly, radioactive decay from its long-lived parent nuclide ²²⁶Ra, being a common trace element in mineral grains in the sediment, is responsible for a part of ²¹⁰Pb, which is called "supported" ²¹⁰Pb. The second source is the deposition from the atmosphere, where ²¹⁰Pb originates from the gaseous intermediate decay chain member ²²²Rn, which escapes from the soil.

This additional ²¹⁰Pb contribution is called "excess" ²¹⁰Pb. With indepth creasing (and age) within undisturbed an sediment the "excess" ²¹⁰Pb decreases with a known rate. This enables us to date the sediment lay-

Figure 56: Sediment sampling on board RV Maria S. Merian, Amazon delta. Left: obtaining short sediment cores with a multi-corer. Right: documenting a long sediment core obtained by a gravity corer.

ers and therefore determine an age model for the sediment core.

There are several other radionuclide tracers which can be used to verify the accuracy of the age model: Those of natural origin – ²²⁸Ra and ²²⁸Th (both members of the ²³²Th decay chain), ²³⁴Th (a ²³⁸U decay product) or ⁷Be (of cosmogenic origin) – help to distinguish sedimentation processes from biological or physical mixing due to their wide range of halflives. Also, traces of anthropogenic radionuclides that are products of nuclear fission or activation in nuclear reactors or weapons, can be detected in certain sediment horizons as markers of nuclear fallout events. Examples of man-made isotopes with suitable half-lives are ¹³⁷Cs or ²⁴¹Am.

All mentioned isotopes can be quantified in individual sediment samples by gamma spectrometry within a single spec-

trum. The method is non-destructive, and the samples therefore remain preserved for further analyses. Resulting chronologies using ²¹⁰Pb together with other gamma emitting tracers, provide high temporal resolution and are complementary to radiocarbon based chronologies, which are not suitable for the last century, but in turn, can cover history of several millennia. In our laboratory mathematical efficiency calibration was introduced recently and verified against a more classical experimental method. This approach, which is rather innovative for environmental radioactivity samples, brings more freedom for sample matrix and measurement geometry and in effect, the measurement efficiency can be optimized and lower detection limits achieved. We co-operate with other national or international institutions and provide sediment chronologies within paleoclimate or environmental studies.

Anthropogenic input of particulate Phosphorus in the Gulf of Eilat

(in co-operation with: University of Kiel; Israel Oceanographic and Limnological Research, Haifa, Israel)

In this project we studied a possible connection of eutrophication of the gulf and consequential environmental changes with industrial pollution caused by phosphorus ore mining and processing and transporting of fertilizers. For the first time, sedimentation and mixing rates in this region were quantified.

Australian-Indonesian summer monsoon variability

(in co-operation with: MARUM – Center for Marine Environmental Sciences, University of Bremen)

A deep sea sediment core taken off the Indonesian island of Sumba was studied in order to reconstruct the Australian– Indonesian

summer monsoon variability in the last 6000 vears (see Figure 57). Assuming that riverine detrital input is linked to the summer monsoon rainfall, we selected used element main ratios as a measure for relative monsoon intensity. Interpretation of the natuand manral made gamma emitters' depth

Figure 57: Chronology of a sediment core taken off the Indonesian island of Sumba extending to 6000 years before present. It is based on 39 radiocarbon ages (Steinke et al., 2014). The youngest section of the core covering the latest 160 years, for which the use of ¹⁴C method is obviously restricted, was dated using gamma emitting ²¹⁰Pb and ²⁴¹Am (see insert), providing a reliable age model.

profiles provided a solid base for high resolution chronology of the youngest core section.

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Coil cooling

Coils correcting magnetic field inhomogeneity ("shim coils") Polarization-

and measuring coil with sample

Shielding against electromagnetic radiation

Figure 58: NMR measuring device (electronics not shown)

Application of Earth field Nuclear Magnetic Resonance (NMR) to porous systems

Volker Hormann and Helmut W. Fischer

or analyzing open porous materials, NMR (or more correctly: Nuclear Induction) of protons in the Earth's magnetic field is an attractive alternative to conventional Mercury Porosimetry because the pores are filled with non-toxic substances (usually water) and the method will not cause destruction or structural changes in the sample. It has also advantages in comparison to conventional NMR methods, because the Earth's field has a low strength while exhibiting an extraordinary homogeneity which means that neither expensive magnets nor heavy cooling are needed. Furthermore, it permits the usage of large samples up to a volume of 25 ml.

Figure 58 shows the measuring device, developed at the Physics Department of the University of Bremen.

Figure 59: Pore size distribution of a waterfilled ceramic sample analysed by Mercury Porosimetry (grey bars) and NMR Relaxometry (black line)

NMR porosimetry is based on the fact that the decay time constant (T_2) of the induced transverse magnetization in the pore-filling fluid depends on the probability of interaction of the fluid molecules with the pore surfaces and hence on the pore size (small pores will provide a high interaction probability, resulting in short T_2 , and vice versa). The magnetization signal decay of a water-filled porous system having a distribution of pore sizes is normally multiexponential and can then be analysed by using numerical regularization techniques, leading to a T₂ distribution. This distribu-

tion can easily be transformed to the effective pore size distribution of the sample using a calibration curve obtained previ-

ously on well-characterized samples with single pore radii.

Figure 59 shows the comparison of the Mercury Porosimetry analysis of a ceramic sample with a bimodal pore size distribution (meaning it has two different predominant pore sizes, in this case around 0.2 and 8 μ m), manufactured and measured by the Advanced Ceramics Group at the Engineering Science Department of the University of Bremen, with the NMR analysis performed in our lab.

The distributions are remarkably similar and differences can be explained by the characteristic property of Mercury Porosimetry yielding the distribution of pore throat sizes whereas the NMR distribution is connected to the "true" volume/surface ratio of the porous system.

This result shows that NMR porosimetry in the Earth's field is a promising method for analysing porous systems.

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Fukushima emissions in regional sewage sludge

Helmut W. Fischer

Catastrophic nuclear events can release large amounts of radioisotopes into the environment. From the last decades, Chernobyl and Fukushima are the most prominent examples. Both events had a large impact on the living circumstances of the regional population, as soil, water and food became heavily contaminated. The IUP radiometric laboratory has been and is involved in the management and follow-up of both these and of other radiological events, and conducts research in the field of radioecology.

Apart from investigating terrestrial pathways of radionuclides, the focus lies also on transport processes in the

Figure 60: Sewage sludge concentration data for Fukushima City for 137 Cs (red) and 131 I (blue). In addition, daily rainfall data are shown in black. The 137 Cs initial deposition density was approx. 300 kBq/m².

wastewater chain. Medically used radioisotopes can routinely be found in high concentration in wastewater treatment sludges and currently serve us as tracers for studying transport processes. The same processes affect radioactive materials washed out from the atmosphere with rain, or eroded from the Earth's surface after deposition. Wastewater treatment sludges range therefore among the most highly contaminated materials after nuclear accidents.

A collaboration with the Institute of Symbiotic Science and the newly founded Institute of Environmental Radioactivity, both of Fukushima City University, offered the possibility to investigate time series originating from routine surveillance of sewage sludge for the prominent isotopes ¹³⁷Cs, ¹³⁴Cs and ¹³¹I from fallout-affected areas in Japan, and to compare them with historical data from Europe after the Chernobyl releases. The results of the analysis show that

fortunately and astonishingly, sludge contamination levels for Cs isotopes are lower (max. 6 kBq/kg) than in central Europe 1986 (max. 70 kBq/kg), despite higher surface deposition levels in Japan (300 kBq/m² vs. 25 kBq/m²). The reason lies in the usage of separate sewer systems for rainfall and wastewater, common in Japan, but not in Europe. Separate sewer systems direct most surface runoff and erosion products directly to surface waters, avoiding contamination of sewage sludge.

- the decay of sludge caesium concentration with time has similar time and seasonal patterns in Japan after 2011 and in Europe after 1986 – the initial decay half-life is lower than 1 year, later it becomes slower in both cases (see guiding line in Figure 61). This can be explained by comparable types of land use and climate, leading to similar erosion mechanisms for isotopes after their deposition on the ground. The finding helps to predict future radioisotope levels in sewage sludge in Japan.
- the surprising detection of the short-lived isotope ¹³¹I (radioactive half-life: 8 days) even years after the accident (and resulting end of the nuclear chain reaction and of fission product generation) can be explained by the medical usage of ¹³¹I for thyroid therapy, which leads to a well-known continuous input into the sewer system through excretion from patients. It shows the necessity to carefully discriminate between possible nuclear and medical origin of this isotope.
- sludge Cs concentration varies strongly from day to day, with a high dependence on rainfall pattern – after each significant rainfall event the sludge concentration rises by up to a factor of 10 – see the corresponding spikes in Figure 60. This finding opens the possibility to study urban surface runoff, erosion and sewer transport processes, complementary to our current work on medical (¹³¹I), natural (²¹²Pb, ²¹⁰Pb) and cosmogenic (⁷Be isotopes, to be found in rainfall, surface water and/or wastewater.

Figure 61: Sewage sludge concentration data for 137 Cs (upper line) and 134 Cs (lower line), measured at Ingolstadt, Germany after the Chernobyl accident. The 137 Cs initial deposition density was approx. 25 kBq/m². The thin guiding line corresponds to a decay half-life of 1 year.

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Teaching activities

Annette Ladstätter-Weißenmayer, Holger Winkler, Anja Gatzka, und Lars Jeschke

Today's graduate and postgraduate education in the field of Earth System and Environmental Science is a highly interdisciplinary and inter-institutional challenge. The existing research infrastructure at the University of Bremen (UB) and the Alfred Wegner Institute Bremerhaven (AWI) offers a unique research environment in north-western Germany to study past, present and future changes of the Earth system. The education and qualification of Master and PhD students is carried out on an internationally competitive level.

Since 2000 the international Master program "Postgraduate Program Environmental Physics" (PEP), accredited by the German Accreditation Council is offered in collaboration with the AWI. Since its start, 81 students successfully finished this program with a Master degree, 12 with a Certificate. The foci of this program are on the atmosphere, ocean, land and climate as well as on remote sensing and dynamics. In the winter terms 2013/14 and 2014/15, 43 students (incl. 5 guests) started this study-program at the University of Bremen. The students came from Bangladesh, Brazil, China, Colombia, Croatia, Germany, Ghana, Greece, India, Iran, Italy, Nepal, Nigeria, Pakistan, Sweden, Turkey, USA and Yemen.

In 2006 a very successful collaboration between the University of Bremen and the Ocean University of Qingdao of China (OUC) started with the aim to offer Master double degrees of both universities. In this program, Chinese students start their studies in China, participate one year in the PEP program in Bremen and then complete their studies at OUC. The German students start with one year of the PEP program and then study one year at OUC in Qingdao. Following this double degree program, in addition to the "normal" PEP students, 19 pre-selected excellent students came in the winter terms 2006/07 until 2009/10 from the OUC to study one year in the PEP program to get a certificate. After finishing their Master program at the partner university in China (OUC) they get a double degree from both universities (OUC and UB). From 2007 up to 2010, 19 students finished successfully with a Certificate, 18 students with their master double degree (in addition, one PEP student finished with a double degree). Seven of the OUC students started with a PhD thesis at IUP or AWI Bremerhaven and 5 of these students have already finished their PhD successfully.

In 2006 in the context of the excellence initiative the Bremen International Graduate School for Marine Sciences GLOMAR was launched and funded by the Deutsche Forschungsgemeinschaft (DFG). This Graduate School is carried out with the following partners: University of Bremen, DFG Research Centre Ocean Margin (RCOM), Centre for Marine Environmental Science (MARUM), Research Centre for Sustainability Studies (ARTEC), AWI, German Maritime Museum (DMS), Max Planck Institute for Marine Microbiology, Centre for Tropical Marine Ecology (ZMT). For excellent PhD students GLOMAR provides an optimal student research environment and fosters excellence in education and research. In general the Graduate School's educational concept allows the PhD students to develop into excellent interdisciplinary researchers, with international contacts and a publication record in peer-reviewed international journals, skills in conducting research and in communication (on disciplinary and

interdisciplinary levels to both experts and students as well as to the public), and in project management.

From 2008 to 2014, the University of Bremen, AWI, and Jacobs University Bremen offered a Helmholtz-PhD program named ESSReS (Earth System Science Research School) and since 2009 a second one named POLMAR (Polar and Marine Research). The Helmholtz Graduate School POLMAR is carried out with the following partners: AWI (host institution), University of Bremen, Jacobs University Bremen, Max Planck Institute Bremen, University of Potsdam, Institute for Marine Resources (IMARE), and Hochschule Bremerhaven. Twelve internal and 12 external students started in 2008 and the same number of students followed in fall 2011 within the ESSReS program. Up to now, more than 100 PhD students are within POLMAR.

Since 2013 and for a time period of nine years, the International Research Training Group ArcTrain educates three cohorts of twelve PhD students each in an interdisciplinary environment that combines the strength in marine geosciences and environmental physics in Bremen with complementary skills and expertise in sea-ice and ice-sheet modelling. ArcTrain is a collaborative project led by scientists from MARUM, Faculty of Geosciences and Faculty of Physics/Electrical Engineering at the University of Bremen and colleagues from the Alfred Wegener Institute for Polar and Marine Research in Bremerhaven. In addition ArcTrain consists of a consortium of eight Canadian universities led by the GEOTOP cluster at the Université du Québec à Montréal and including Dalhousie University, McGill University, Memorial University of Newfoundland, University of Alberta, University of British Columbia, University of Calgary and Université du Québec à Rimouski.

These programs enable PhD students from a variety of disciplines to cooperate and exchange views on the common theme of linking "data and modelling", leading to a better understanding of local processes within a global context. It provides a structured framework for education and qualification for excellent PhD students dealing with the challenging questions in Earth System Science and Polar and Marine Research. Developing all categories of skills needed for analysing complex climate and environmental systems and the development of integrated solutions in a supportive network of collaborating research institutions fosters outstanding career options. Structured training and supervision supported by a broad range of soft skill courses is indicative for the entire concept.

The IUP Bremen regularly welcomes students from high schools in Bremen and surrounding cities for carrying out practical exercises. During these internships, students have the opportunity to work together with scientists in different research groups for a time period of 2 weeks to get a first impression of research work.

In addition, the members of IUP are actively involved in the public outreach activities "Day of Physics" and "Saturday Morning Physics" to offer the general public an insight into current scientific work at IUP.

IUP Bremen Staff, December 2014

Visit us on http://www.iup.uni-bremen.de/index e.html

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