Surface Ocean Processes in the Anthropocene

Retrospect and Quintessence

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SOPRAN

Surface Ocean Processes in the Anthropocene

Retrospect and Quintessence

Edited by
Prof. Dr. Hermann W. Bange
GEOMAR

Kiel, 2015

Warnemünde, 2008

Kiel, 2009

Hamburg, 2010

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photo: H. W. Bange

Bremen, 2014

Heidelberg, 2011

Kiel, 2012

Leipzig, 2013

photo: J. Karstensen

 Deployment of long-term observation mooring from Meteor

Foreword

Hermann W. Bange

Dear Reader

In this brochure you will find descriptions of the scientific highlights from nine years of the SOPRAN project.

SOPRAN stands for Surface Ocean Processes in the Anthropocene and is a German contribution to the international Surface Ocean – Lower Atmosphere Study (SOLAS). SOPRAN started its work in February 2007 after some years of planning, meetings and proposal writing. It took quite a while until SOPRAN was born and it was the enthusiasm and endless energy of Douglas Wallace who laid the foundation for SOPRAN. Doug, who joined the former Institut für Meereskunde in Kiel in 1998, came to Germany with the vision of an interdisciplinary SOLAS project which should bring together the, by then well-separated, communities of atmosphere and ocean sciences. Consequently, Doug became the coordinator of SOPRAN from 2007 until 2011.

After nine years of work which included five ship campaigns, four mesocosm studies, two Aeolotron experiments, two land campaigns and countless lab studies and model runs we can say that the adventure of SOPRAN turned out to be a very successful one. And, indeed, the close collaboration between chemists, biologists, geoscientists and physicists working on both sides of the air-water interface look normal for us now, but this was not the case in the early days of SOPRAN.

Since its beginning, the backbone of SOPRAN has been the subprojects which were structured around varying scientific themes and platforms during the three funding phases of SOPRAN (2007-2009; 2010-2012; 2013-2015). We count now 73 subprojects and 58 principal investigators involved in SOPRAN over the years. 11 research institutions and universities from all over Germany, located in Bremen, Bremerhaven, Geesthacht, Hamburg, Heidelberg, Jena, Kiel, Leipzig, Mainz and Warnemünde, contributed to the success of SOPRAN. Up to now more than 250 publications based on the results from SOPRAN have been published and the number is still increasing.

SOPRAN also had the aim to train the next generation of SOLAS scientists. To this end SOPRAN organized its own Summer School and supported students' participation in the various SOLAS Summer Schools. Representing the spirit of SOPRAN, three young scientists who 'grew up' with SOPRAN are portrayed in this brochure.

Last but not least I would like to thank the students, technicians, project managers and scientists from all institutes and universities involved in SOPRAN for their work and enthusiasm for SOPRAN during the last nine years. SOPRAN also benefitted from the close and very fruitful cooperation with many national and international institutions, projects and colleagues; there are too many to list them here. Moreover, I would like to thank the PTJ for efficient and supportive project supervision. We are grateful for the generous financial support of SOPRAN by the German Ministry of Education and Research (BMBF, Bonn) during the last nine years.

I hope you find the information in this brochure informative and enjoy reading it.
Kiel, 7 September 2015

...First detection of transient low-oxygen zones in the surface ocean of the eastern tropical North Atlantic

...The coastal upwelling off Peru is site of extremely high oceanic emissions of nitrous oxide, N_2O, to the atmosphere

...The height of the marine boundary layer in combination with strong biological oceanic emissions and coastal sources determines the halogen budget of the atmosphere over upwelling regions

photo: H. Deneke

Theme 1

Climate relevant trace gas fluxes

Inga Hense, Christa Marandino, Birgit Quack

The compositions and processes of the Earth's ocean and atmosphere are undergoing fundamental transformations within the current Anthropocene epoch. This results in environmental changes on global and regional scales such as global warming and climate change, ocean acidification and deoxygenation as well as stratospheric ozone depletion. The surface ocean plays an important role for the Earth's climate and atmospheric chemistry through the release and uptake of trace gases that are radiatively and chemically reactive in the atmosphere. Therefore, we need to understand the natural background processes of trace gas production and consumption in the surface ocean. Moreover, we have to address the issue of how these processes may change due to human activities in order to improve our ability to predict future climate change.

The work in SOPRAN focused on selected important climate relevant trace gases involved in global warming (carbon dioxide, CO_2, and nitrous oxide, N_2O), stratospheric ozone-depletion (bromoform, $CHBr_3$) and atmospheric chemistry (bromine monoxide, BrO, and methyl iodide, CH_3I).

SOPRAN sought to improve our understanding of mechanisms and sources that determine the exchange of gases between ocean and atmosphere and how changes in atmospheric composition and climate can influence the oceanic release of trace gases. Varying temporal and spatial scales were investigated, combining marine and atmospheric chemistry, biological and physical oceanography, during measurement programmes on research cruises. Physical and biogeochemical processes in the surface ocean were investigated and these observational findings were complemented and integrated by numerical physical-biogeochemical modelling.

In order to decipher the biological, chemical, and physical processes which affect trace gas pathways in the surface ocean, SOPRAN used platforms such as research vessels and time series stations and performed complementary laboratory experiments and integrating modelling studies. Since trace gas production is mainly associated with biological productivity, oceanic high productivity areas such as the coastal upwelling regions off Mauritania and Peru as well as the equatorial upwelling in the Atlantic Ocean have been chosen for field studies. This was complemented with field studies in the Baltic Sea and at the Cape Verde Ocean and Atmosphere Observatories (CVOO, CVAO) in the eastern tropical North Atlantic Ocean.

During SOPRAN significant progress has been made in the application of new measurement techniques such as autonomous floats equipped with new sensors for the measurement of dissolved CO_2 and O_2 and new laser-based instruments for high-resolution underway measurements of atmospheric and dissolved N_2O during research cruises.


CO_2 Float

photo: B. Fiedler

CO_2

Changes in oceanic CO_2 concentrations are associated with changes in O_2 concentrations since both compounds are tightly linked through photosynthesis and respiration. The coastal upwelling region off Mauritania is of particular interest because, on the one hand, CO_2 enriched subsurface waters are brought to the ocean surface resulting in a high release of CO_2 to the atmosphere. On the other hand, the high productivity, which is based on the photosynthesis of phytoplankton, results in rapid uptake of CO_2 when the surface waters are 'aging' during moving towards the open eastern tropical North Atlantic (ETNA). In order to establish time series of concentrations as well as climatological air-sea fluxes from the ETNA surface ocean O_2 and CO_2 measurements have been compiled. Time series of CO_2 and O_2 show distinct seasonal cycles. On an annual scale, the observed seasonal changes of dissolved CO_2 revealed a weak net sink for atmospheric CO_2 in the ETNA.

By using various O_2 sensors on a mooring, gliders and profiling floats, extremely low O_2 concentrations right below the surface layer were found to occur occasionally at the Cape Verde Ocean Observatory (CVOO). Such extreme low-oxygen events, which have not been observed before in the ETNA, were related to a special type of oceanographic feature, so-called mesoscale eddies, which originate from the coastal region off northwest Africa.

O_2


Recovering of glider

photo: M. Schneider


N_2O

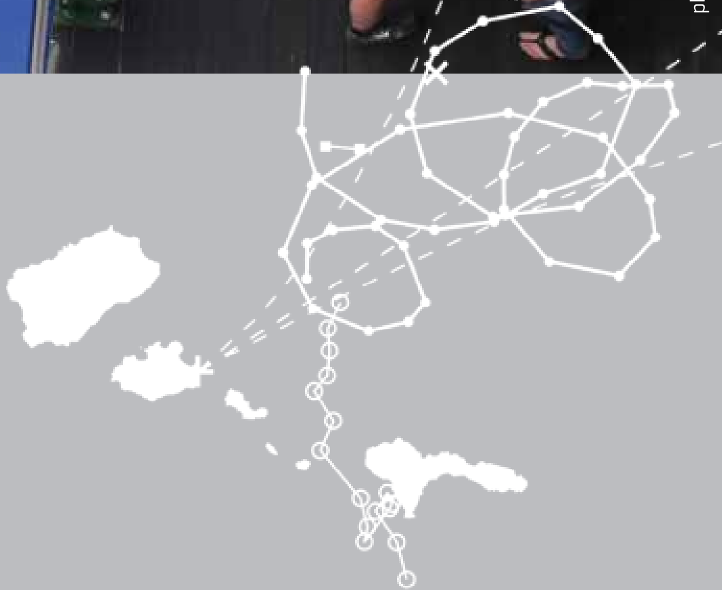
Water samples for NO_2 measurements

photo: E. Renz-Kiefel

Water sampling rosette onboard Meteor

photo: W. Huneke

N_2O



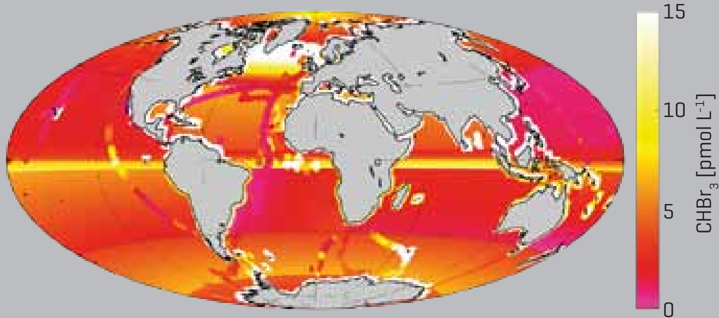
The ocean is a major natural source of atmospheric N_2O. Several new aspects of the oceanic pathways and the air-sea exchange of N_2O, in combination with the application of new measurement techniques, have emerged during SOPRAN, leading to a fundamental change in our understanding of oceanic N_2O pathways:

The longstanding paradigm of a predominant bacterial production of N_2O has been challenged by the fact that N_2O is mainly produced by nitrifying archaea. A study in the upwelling of Mauritania points to an underestimated role of surfactants in suppressing the release of N_2O to the atmosphere in areas of high biological productivity. A new laser-based absorption spectrometer coupled to a seawater/gas-equilibrator allows N_2O measurements in surface waters with an unprecedented high temporal and spatial resolution. The deployment of the new measurement set-up during a cruise to the coastal upwelling regions off Peru revealed remarkably high N_2O production resulting in the highest ever measured N_2O surface concentrations world-wide. This again underpins the pronounced role of coastal upwelling regions for the oceanic emissions of N_2O. However, global oceanic emission estimates are still associated with a high degree of uncertainty. This is partly caused by the fact that there was no database which could provide global oceanic N_2O data sets. To this end, MEMENTO (the MarinE MethanE and NiTrous Oxide database: memento.geomar.de/de) was established.

Bromoform ($CHBr_3$) is the most abundant bromine containing volatile halocarbon in the surface ocean and its oceanic emissions represent a significant source for reactive bromine species (such as BrO) in the atmosphere. Atmospheric BrO, in turn, plays an important role in chemistry of the Earth atmosphere because it is involved in ozone depletion in both the troposphere and stratosphere. On the basis of early measurements from two SOPRAN pilot cruises to the equatorial and tropical North Atlantic Ocean, it was suggested that, apart from the productive coastal upwelling region off Mauritania, additional coastal sources of $CHBr_3$ from salt marshes and seagrass beds might exist. Indeed, a SOPRAN field (land) study at the Mauritanian coast showed that coastal halophytes (plants that are coming into contact with saline water through its roots) release significant amounts of halocarbons to the atmosphere. Results from the SOPRAN cruises to the upwelling regions off Mauritania and Peru revealed for the first time that, additional to the upwelling and coastal sources, the interplay between the actual meteorological conditions (i.e. height of the marine boundary layer) and oceanic emissions strongly influence the atmospheric concentrations of $CHBr_3$. Moreover, the results from the SOPRAN cruise to the equatorial Atlantic Ocean showed that $CHBr_3$ production has to occur in the ocean surface layer to balance the release to the atmosphere and diffusion of $CHBr_3$ from the subsurface layer into the surface layer. In order to compile oceanic and atmospheric data of short-lived brominated and iodinated trace gases, the Halocarbons in the Ocean and Atmosphere database (HalOcAT: halocat.geomar.de/) was established.

$CHBr_3$

During SOPRAN the determination of the isotopic signatures (^{13}C) of dissolved and atmospheric halocarbons ($CHBr_3$ and others) was pioneered. In general an isotopic signature can be seen as a kind of chemical marker allowing the identification of characteristic source and sink processes for the compound of interest. A comprehensive set of isotopic fractionation factors, rate constants and signatures of source and sink processes of $CHBr_3$ and other halocarbons has been developed during SOPRAN.



Modelled Bromoform concentrations in the ocean surface layer

BrO

SOPRAN also enabled extensive measurements of the short-lived atmospheric intermediate bromine monoxide (BrO) during cruises to the Mauritanian and Peruvian upwelling regions as well as to the equatorial Atlantic Ocean and at the Cape Verde Atmospheric Observatory (CVAO). BrO was indeed detectable in the atmosphere above the coastal upwelling region off Mauritania and at the CVAO but not detectable above the upwelling off Peru and above the upwelling in the equatorial Atlantic Ocean. This shows that high atmospheric BrO concentrations are not characteristic for upwelling regions and that the interplay of oceanic sources of bromine containing compounds ($CHBr_3$), meteorological conditions (height of marine boundary layer) and other sources (BrO from aerosols) are more complex than thought at the beginning of SOPRAN.

CH_3I

The ocean is a natural, and by far the largest, source of methyl iodide (CH_3I) to the atmosphere. It plays an important role in atmospheric iodine chemistry and particle formation, which can result in tropospheric ozone destruction. In laboratory and process studies, as well as global ocean general circulation modelling performed during SOPRAN, evidence solidified that the observed CH_3I concentrations in the surface ocean are resulting mainly from photochemical degradation of dissolved organic molecules in the sunlit surface ocean. On a global scale, biological production accounts only for a minor fraction of the oceanic CH_3I concentrations.

Annette first came into contact with the SOPRAN project when she took part in the SOPRAN cruise Poseidon 348 in 2007. At that time, she studied chemistry at the Christian-Albrechts-Universität zu Kiel and measured methane concentrations in the Mauritanian upwelling region for her diploma thesis which she conducted at the IFM-GEOMAR. In September 2007, she started her PhD thesis within the SOPRAN project. During this time, she investigated the transport pathways of the greenhouse gas nitrous oxide from the subsurface ocean to the atmosphere using the data collected during P348 and many other ship campaigns to the eastern tropical Atlantic and Pacific Oceans that were part of the SOPRAN project. She successfully finished her PhD in 2012 and continued working in the project on nitrous oxide transport pathways. Since 2013, she is working in SOPRAN on the coordination of the MEMENTO (MarinE MethanE and NiTrous Oxide) database, which was initiated to collect and archive global oceanic measurements of nitrous oxide and methane. She now aims to combine the available global measurements of nitrous oxide with the new insights gained from the SOPRAN transport studies to improve global oceanic N_2O emission estimates. Working closely together with biologists, chemists, oceanographers and many other scientists from different fields, she particularly enjoyed the strong interdisciplinarity of the SOPRAN project and the opportunity it gave her to autonomously develop and pursue her own research ideas.

Annette Kock

Water sampling N_2O on board Littorina

photo: E. Renz-Kiefel

...Development of a new air-sea gas exchange model approach

...The accumulation of organic matter as well as bacterial diversity and activity in the surface microlayer, SML, depend strongly on the wind speed

...The organic matter in the SML is contributing to the composition of aerosols over oceanic regions

...Small (submesoscale) oceanographic structures have been overlooked so far but may significantly affect the air-sea gas exchange

photo: J. Lampel

 Cape Verde Atmosphere Observatory (CVAO), Mindelo, São Vicente

Theme 2

Air-sea exchange and the sea surface microlayer

Anja Engel, Bernd Jähne, Manuela van Pinxteren, Christian Stolle

The ocean and the atmosphere meet at the air-sea interface. In order to improve our understanding of how changes in the surface ocean are affecting the lower atmosphere and how changes of the lower atmosphere are affecting the surface ocean we need to investigate the biological, chemical, and physical interactions across the air-sea interface. On both sides of the air-sea interface tiny boundary layers are formed, in which molecular diffusion is the dominant transport mechanism. The thickness of these layers controls the speed of exchange (i.e. transfer) of heat and climate relevant gases. Wind blowing over the ocean surface is the main driving force for the exchange rate. On the air side, the boundary layer ranges from 100 to 1000 μm, whereas on the water side it is much thinner (20–200 μm). Even after thirty years of intensive research on air-water gas transfer semi-empirical relationships between the gas transfer velocity and wind speed are still in use to estimate the gas exchange across the air-sea interface.

On the waterside this interface is formed by the sea surface microlayer (SML), which is mainly composed of organic material. Phytoplankton and bacteria are the main sources of organic matter in the ocean. Among the organic compounds are large complex molecules that are released from the cell as dissolved organic matter. SML can modify gas exchange rates by changing sea surface hydrodynamics. Moreover, the organic matter in the SML determines the organic matter composition of sea-spray aerosols which can form cloud condensation nuclei.

During SOPRAN a unique set of research facilities and instruments to study the gas transfer processes across the water-atmosphere interface was used. The Heidelberg Aeolotron, a ring-shaped wind-wave tank, allows measurements under controlled conditions. It was used for several joint SOPRAN gas exchange experiments with both fresh water and natural seawater. The Aeolotron experiments were complemented with gas flux measurements using micrometeorological methods (i.e. eddy correlation) and radar backscatter measurements (to determine the influence of the sea surface roughness) on the German FINO 2 research platform which is located 33 km north of the island of Rügen in the southwest Baltic Sea. SOPRAN pioneered methods such as active thermography determining the heat exchange as a proxy for gas exchange and imaging optical instruments for measurements of the wind-wave parameters.

Moreover, the chemical composition of organic matter in the SML and aerosols as well as the bacterial diversity and activity in the SML were investigated during various SOPRAN cruises, mesocosm studies, at the Cape Verde Atmosphere Observatory (CVAO) and the Aeolotron experiments.

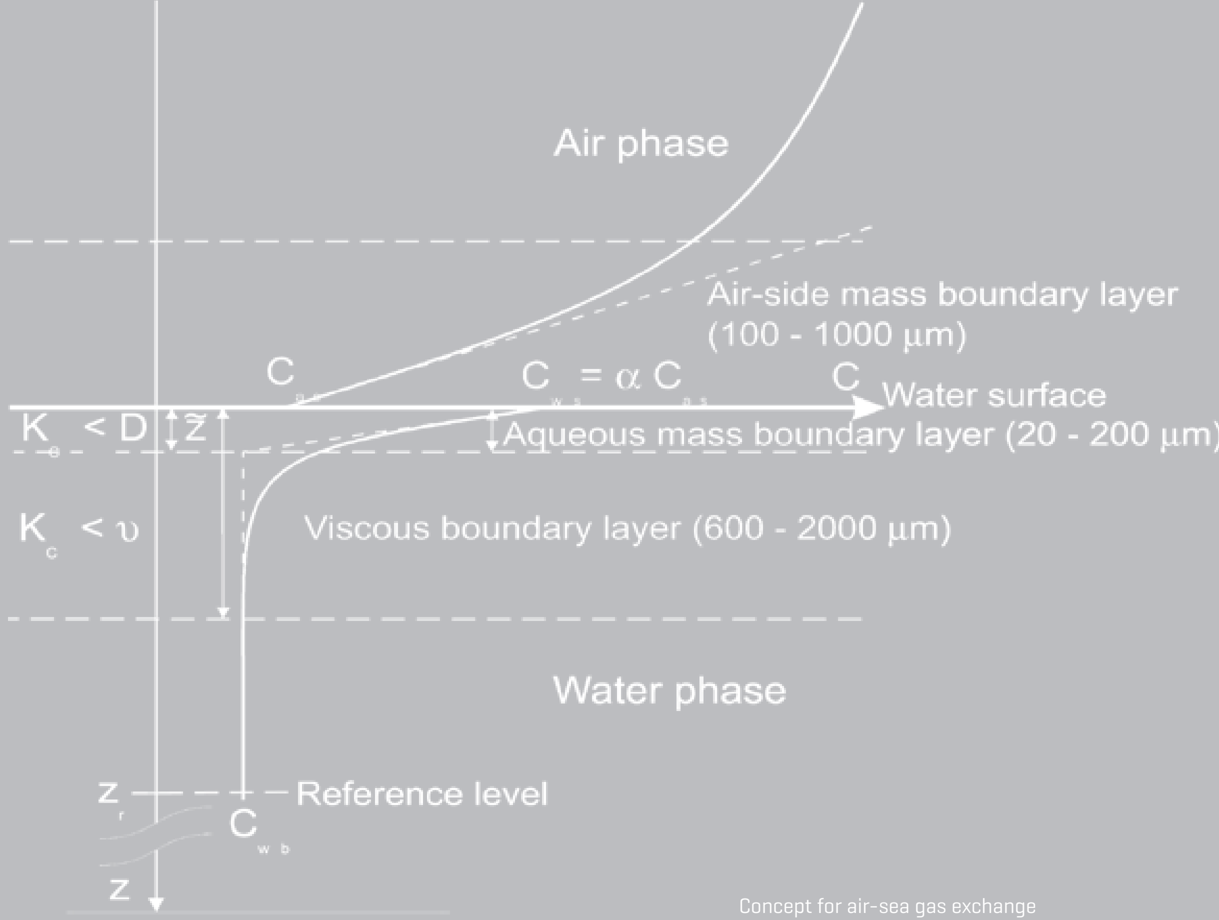
These measurements were complemented by a modelling study which implemented small (submesoscale) oceanographic structures (so-called mixed layer eddies with a radius of 100m to 10km) in a global ocean model in order to investigate their effects on the surface ocean and thus the air-sea gas exchange.


FINO 2 platform, Southern Baltic Sea

photo: M. Kaiser (DNV GL)


Active Thermography Instrument deployed during M91

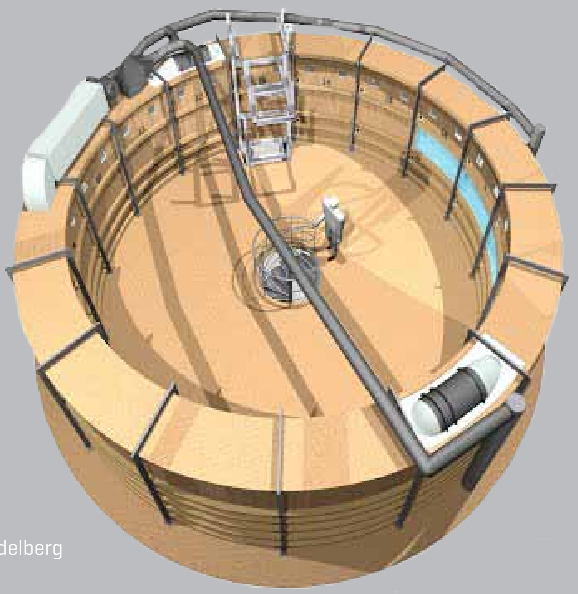
photo: H.W. Bange



Concept for air-sea gas exchange

During SOPRAN comprehensive studies of the air-water gas transfer of environmentally important compounds with solubilities ranging from low (e.g. nitrous oxide, N_2O) to moderate (e.g. dimethyl sulphide, DMS) and high (e.g. methanol) were performed in the Aeolotron. The measurements revealed that the gas transfer at low wind speeds is suppressed by surface films by up to a factor of three for fresh water (surface film mimicked with an artificial surfactant) and seawater with a natural surface film. At higher wind speeds, the gas transfer rate was still up to 30% lower. No evidence was found that a surface film monolayer is a direct barrier for the exchange of compounds with high solubility. On the basis of the field and Aeolotron measurements a novel air-sea gas exchange model was introduced.

The global model simulation with a new parameterisation of the submesoscale mixed layer eddies revealed that mixed layer depths are changing significantly in subtropical oceans of the North Hemisphere which implies that the gas exchange is affected as well.



Aeolotron, Heidelberg

Aeolotron, Heidelberg

photo: B. Jähne

Sampling of surface microlayer

photo: TROPOS

The studies during SOPRAN showed that the amount of plankton-derived dissolved organic matter and gel particles is affected by ocean acidification: Measurements during the SOPRAN mesocosm study in the Raunefjord (Bergen, Norway) revealed a higher abundance of organic components and gel particles in the SML at enhanced acidity (i.e. enhanced dissolved carbon dioxide concentration). During the SOPRAN cruise to the upwelling region off Peru the accumulation of organic substances in the SML was directly related to biological productivity. At higher wind speeds (> 5 m s^{-1}) mainly colloidal and particulate components were lost from the SML, suggesting that an effect of these 'insoluble' components on gas exchange is, if any, operating only at low wind speed. Independently of the wind speed, amino acids and proteinaceous compounds, which have the potential to affect air-sea gas exchange by dampening capillary waves, were more often enriched in the SML

Measurements in the southern Baltic Sea showed that the bacterial communities in the SML strongly depend on the dynamics of particulate organic matter in the SML and the prevailing weather conditions (i.e. wind speed, solar radiation): During calm weather conditions (low wind speeds and high solar radiation), the SML is characterised by a bacterial community which shows remarkably different diversity and higher activity compared to the bacterial communities found just a few centimetres below the air-seawater interface.

Small organic molecules such as aliphatic amines and carbonyl compounds (i.e. glyoxal, methyl glyoxal) often enriched in the SML were identified using high-sensitive analytical techniques during studies in the Baltic Sea and in the eastern tropical North Atlantic Ocean. These compounds were also found in associated aerosol measurements and thus demonstrated that the organic matter in SML can indeed contribute to the aerosol composition over oceanic regions.

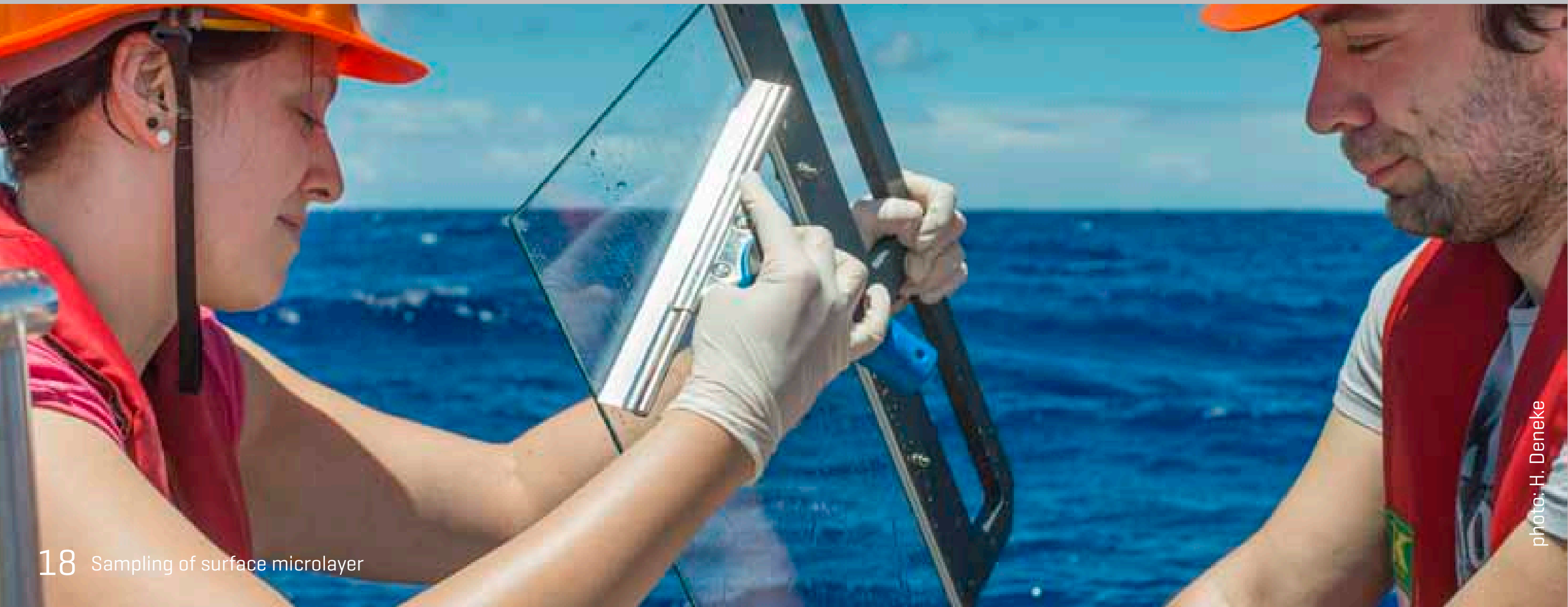


photo: H. Deneke

Kerstin studied physics at Ruprecht-Karls-University in Heidelberg. After finishing her diploma thesis in the field of particle physics, she joined the Institute of Environmental Physics to do her PhD thesis within the framework of the SOPRAN project. She is interested in the transfer of trace gases such as the noble gases, carbon dioxide, nitrous oxide, halocarbons and many more between the atmosphere and the ocean. A multitude of different mechanisms drive this gas exchange process, for instance wind, near surface ocean currents, rain as well as the contamination of the water surface with surface active material. Even after decades of research the interplay of these mechanisms and their relative importance is still poorly understood. Since Heidelberg is far from the ocean, Kerstin uses a so-called wind-wave tank, the Heidelberg Aeolotron, to mimic conditions at sea. This unique laboratory facility, being the world's largest annular wind-wave tank in operation, allows the study of gas transfer process and its governing mechanisms under very controllable environmental conditions with a precision not feasible at the open ocean. Kerstin enjoys working in a multidisciplinary environment, where close collaboration with chemists, biologists, oceanographers and scientists from other fields give her new insight into her own field of research and many new impulses for her own work.

Kerstin Krall

View from the Institute of Environmental Physics, Heidelberg

photo: K. Krall

- …Dry deposition of dust occurs mainly during winter time

- …Upwelling driven productivity dominates, whereas, nutrient deposition is of minor importance for productivity

- …Re-dissolution of particulate iron in the water column was identified as an important process which contributes to the dissolved iron distribution

- …The globally distributed, bloom-forming coccolithophore *Emiliania huxleyi* was unable to maintain its population size and lost the ability for bloom formation at high CO_2 concentrations

photo: NASA

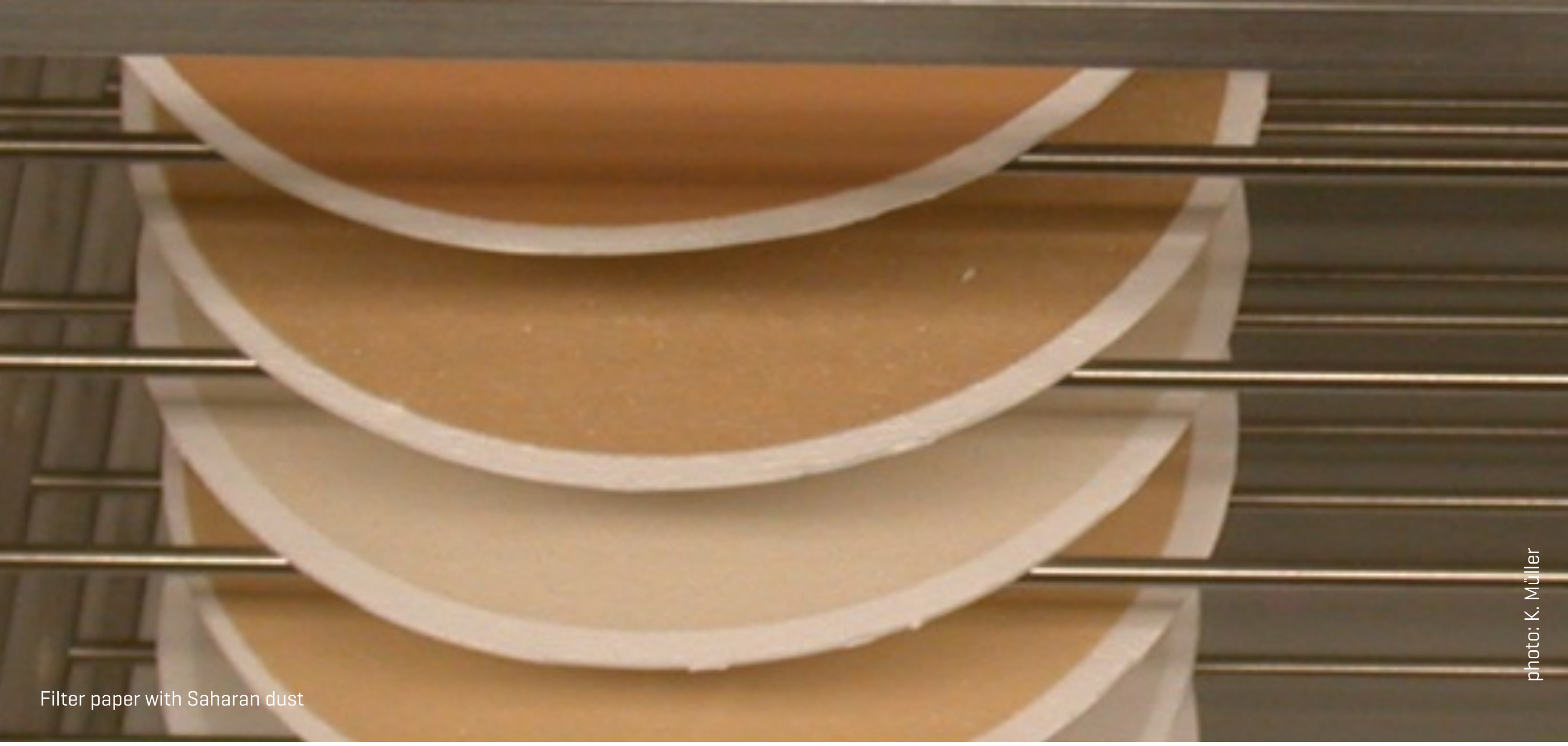
Theme 3

Oceanic responses to atmospheric drivers

Hartmut Herrmann , Ulf Riebesell

Dust deposition

The surface ocean takes up large amounts of atmospheric dust which, in turn, affects surface ocean processes and ecosystem responses.
The Sahara is the worlds biggest source of natural dust to the ocean. Especially the eastern Tropical North Atlantic Ocean (incl. the Cape Verde Islands), because of its close vicinity to the Sahara, experiences high dust deposition. The deposition of dust which contains iron is important for the ocean biota, because the lack of iron often limits biological production in the surface ocean. Major goals of SOPRAN were, therefore, to identify processes leading to the emission and transport of dust to the eastern tropical North Atlantic Ocean, to investigate the chemical modification of dust during transport and cloud contacts, as well as to study the dry and wet (i.e. rain) deposition of dust to the ocean. Furthermore, seasonal and inter-annual variability of the effect of dust on the radiation balance and optical properties of the upper ocean layers, as well as the fate of mineral dust in ocean were investigated. To this end model studies, field observations at the Cape Verde Atmospheric and Ocean Observatories and satellite observations were combined to improve our understanding of dust deposition and its consequences for the surface ocean processes.



Filter paper with Saharan dust

photo: K. Müller

A regional dust model, which provides a spatial context to the (micro-)physical and chemical aerosol measurements at the CVAO has been implemented to provide a detailed understanding of dust emission, transport and deposition of Saharan dust into the tropical eastern North Atlantic Ocean. The model results indicated that in the region around the Cape Verde Islands dry deposition dominates most of the year. Especially pronounced is this effect during winter time, due to the transport of dust close to the ocean surface (i.e. in the marine boundary layer). Dust transport in layers above the marine boundary layer takes place in the summer, resulting in lower deposition fluxes and an increasing importance of dust deposition by rain events. Nine years of (nearly continuous) time series measurements of the chemical composition of aerosol (dust) particles at CVAO resulted in a unique data set for this region. It revealed that Saharan dust outbreaks are accompanied with high concentrations of anthropogenic aerosol constituents such as elemental carbon, nitrates and sulfates. Enhanced ammonium concentrations in aerosols during spring corresponded often to chlorophyll-a (Chl-a) maxima in the Atlantic Ocean near São Vicente.

photo: K. Read

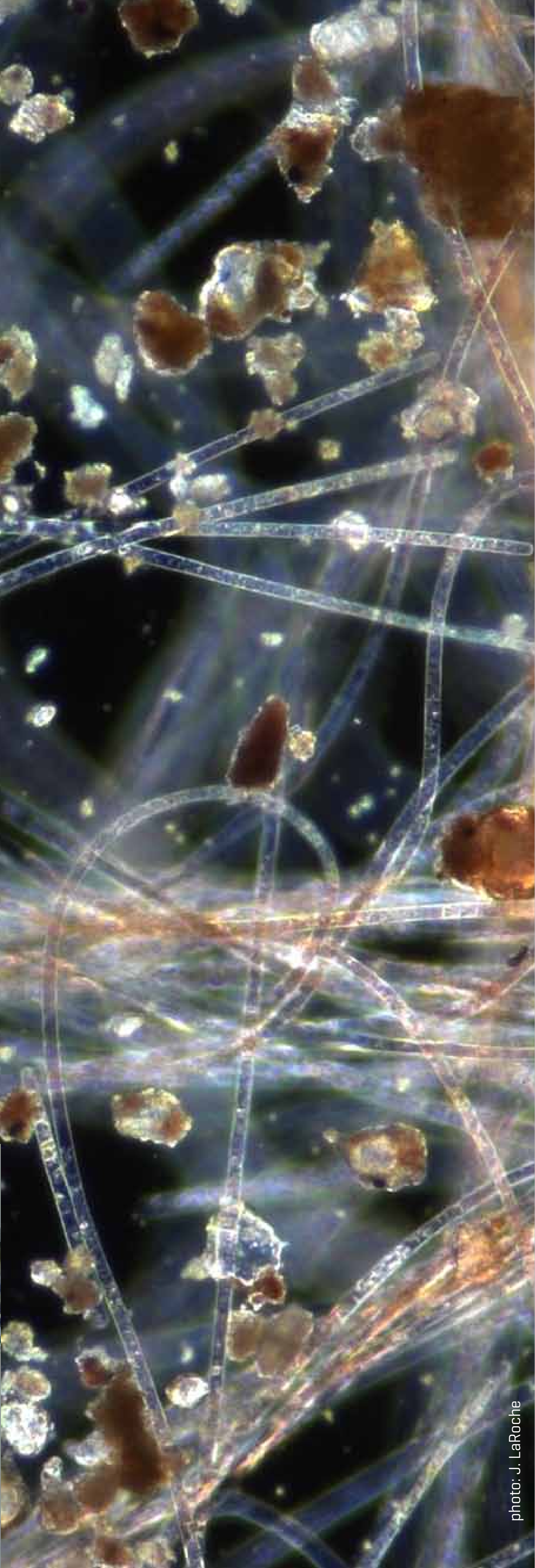
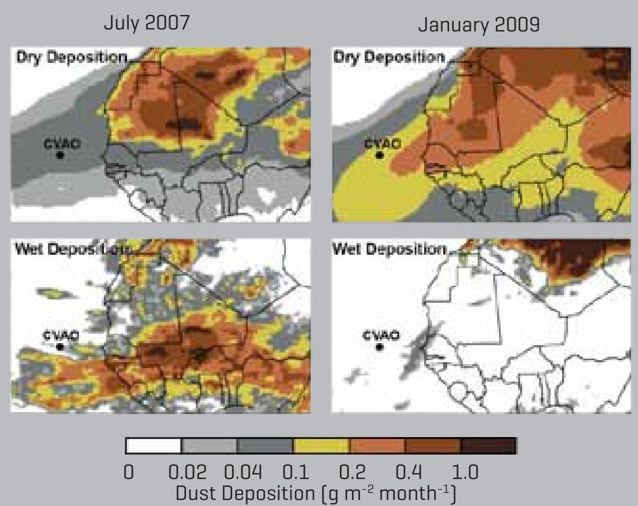


photo: J. LaRoche

Nutrient (namely nitrate and phosphate) supply in the area off northwest Africa is mainly regulated by two processes: coastal upwelling and deposition of nutrients by Saharan dust. Both processes were analyzed and evaluated by different statistical analysis of remotely sensed proxies. The results revealed that upwelling was the main physical driver accounting for nutrient supply for phytoplankton growth, whereas, the nutrient deposition was only of minor importance. A delay of up to 16 days in the surface Chl-a concentrations after the onset of upwelling was observed. Dust storms had two effets: a decrease of photosynthetically active radiation in the surface water and an increase in surface Chl-a concentrations after the dust storms passed the region.

The determination of soluble iron (which is the preferred form for biological uptake) from aerosol samples showed that different source regions of the dust and the atmospheric processing during transport have an important influence on the soluble iron content. It was suggested that, apart from particle size and photochemical reactions, there may be an additional factor (e.g. mineralogy) affecting the soluble iron content of dust aerosols. The bioavailability of soluble, dust-derived dissolved iron in seawater as well as its residence time in the ocean is strongly determined by the existence of organic iron-binding ligands. A model with a new parameterisations for ligand production and decay was developed in SOPRAN. The simulated profiles of dissolved iron were strongly influenced by both particle concentration and vertical distribution of particles in the water column. It turned out, that re-dissolution of iron attached to particles is prerequisite to reproduce the observed dissolved iron profiles at the Cape Verde Ocean Observatory.



Dry and wet deposition over the eastern Atlantic and Sahara from the regional dust model

Manuela studied chemistry with a focus on environmental chemistry at the University Leipzig and did her PhD thesis at the Helmholtz Centre for Environmental Research (UFZ Leipzig) on organic analytics. Since July 2011 she works at the Leibniz Institute for Tropospheric Research (TROPOS) within the SOPRAN project. She studies interactions between the ocean and atmosphere with a focus on marine aerosol particles; smallest airborne particles - the smallest airborne particles over the ocean, which contain, besides sea salt, high proportions of organic compounds. The chemical composition and concentration of these organic compounds are not well known, however both influence the properties of these aerosol particles and how they absorb or reflect solar radiation and thus influence the climate.

Of particular interest to Manuela are the measuring campaigns at the atmospheric station CVAO on the Cape Verde Islands. There she collects samples of aerosol particles and the marine surface microlayer as potential sources of organic substances. These samples are analysed at TROPOS laboratories in Leipzig. Differences in chemical composition between aerosol particles and the surface microlayer give information about the organic substances which cross the barrier between water and air and allow analysing the role of the microlayer itself in this transport.

Manuela van Pinxteren

photo: J. Rahlff

Mesocosm off Spitsbergen

photo: S. Klavsen (GEOMAR)

Ocean acidification

The ocean has taken up 28% of human made carbon dioxide, CO_2, witch through the formation of carbonic acidic causes seawater to acidify. This process, termed ocean acidification, affects marine organisms and ecosystems. It is the long-term response of communities, ecosystems and ecosystem services to ocean acidification along with other stressors that is of major interest to scientists, citizens, fishermen, ecosystem managers, and policymakers. To make progress in this direction, a seagoing mobile mesocosm platform, the Kiel Off-Shore Mesocosms for Future Ocean Simulations (KOSMOS), which can be employed to assess the impacts of ocean change on natural plankton communities and biogeochemical cycles, has been developed. A 6-unit mesocosm platform was built and deployed in a SOPRAN-supported study in the Gotland Sea in 2008. While this campaign failed due to heavy weather conditions, a follow-up deployment in 2009 in Kiel Bight was completed successfully. Further modifications in the technical design and handling then led to the 9-unit KOSMOS mesocosm system still in use today. This system has been successfully operated during two SOPRAN-funded campaigns in the Raunefjord south of Bergen, Norway in 2011 and in the Finish archipelago off Tvärminne in 2012. Further deployments included a SOPRAN co-funded first study in oligotrophic waters off Gran Canaria in 2014. Each campaign involved between 35 and 55 scientists, technicians, and students from a wide range of disciplines, covering research fields extending from molecular and evolutionary biology, to marine ecology and biogeochemistry, to marine and atmospheric chemistry.

Mesocosms in the Raunefjord, Norway

Floating basket for fish egg hatching and larval development. The larvae are then released into the mesocosms.

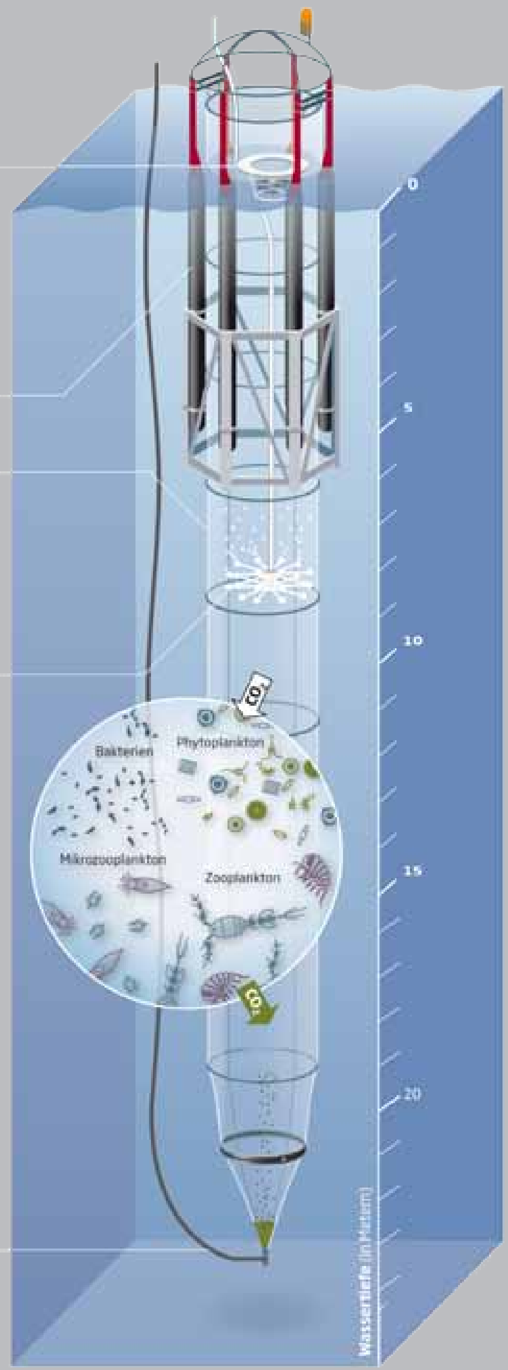
Floating frame, consisting of 6 glass-fiber tubes and a metal frame.

The 2 m diameter, 20 m long transparent **mesocosm bag** (made of thermo-plastic urethane) encloses 55000 litres of seawater.

The **spider** distributes CO_2-saturated seawater into the mesocosms while slowly being lowered down in the bag.

The enclosed **plankton community** ranges from viruses, bacteria, phyto-plankton, micro- and mesozooplankton up to small juvenile fish.

Sinking material is collected in the **sediment trap**, which is sampled regularly via a sampling hose.



The extent to which the sensitivity of a single key species to ocean acidification can alter ecological and biogeochemical processes under elevated CO_2 conditions became evident in the 2011 campaign in the Raunefjord. The globally distributed, bloom-forming coccolithophore *Emiliania huxleyi* was unable to maintain its population size and lost the ability for bloom formation at CO_2 partial pressures above ~650 µatm. A small CO_2/pH-induced decline in growth rate deteriorated *E. huxleyi*'s ability to maintain positive net growth prior to bloom formation. Thus, a bottleneck for the future success of *E. huxleyi* may lie in the upkeep of seed population densities large enough to induce bloom formation. With most non-calcareous phytoplankton being either unaffected or stimulated by rising CO_2/declining pH, *E. huxleyi* may thereby loose its competitive fitness in an acidifying ocean.

Emiliania huxleyi

photo: U. Riebesell

The failure of *E. huxleyi* bloom development under high CO_2 conditions caused major changes in biogeochemical processes in the mesocosms. The sinking rates of particle aggregates and fecal pellets were significantly reduced in the absence of *E. huxleyi* bloom formation, which can be attributed to lower $CaCO_3$ ballasting. The reduced vertical fluxes of $CaCO_3$ correlated with a lower rate of organic matter sedimentation in the high CO_2 treatments. The CO_2-induced failure of *E. huxleyi* bloom formation also affected the production of dimethylsulphoniopropionate (DMSP) and its break-down product dimethylsulphide (DMS) for which *E. huxleyi* is known to be one of the predominant producers in the ocean. When emitted to the atmosphere, DMS is considered to act as a cooling agent in the atmosphere. DMSP and DMS were reduced in high compared to low CO_2 treatments by 30% and 60%, respectively. The observed 30% decline in particle sinking velocities and up to 25% reduction in sedimented organic matter due to the decline in *E. huxleyi* abundance under high CO_2 along with strongly reduced concentrations of the climate-active sulphur compound DMS have the potential for positive feedback to the climate system, potentially amplifying the greenhouse effect.

photo: M. Nicolai

Sampling of a mesocosm

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Glossary

Aerosol...air containing an assembly of suspended (solid or liquid) particles. For the studies of atmospheric aerosols, the particles are collected often on filters.

Anthropocene...is the (proposed) geological epoch that begins when human (i.e. anthropogenic) activities started to have a significant global impact on Earth's climate and ecosystems.

Coastal upwelling...wind blowing parallel to a coastline pushes water away and then deep, cold water rises up from beneath the surface replacing the surface water. Deep water is nutrient-rich "fertilizing" surface waters, increasing biological productivity.

Dust...solid particles in the atmosphere are called dust. It is formed by the erosion of minerals on the Earth's surface (e.g. in the Sahara) and is kicked up in the air by the wind.

Emiliania huxleyi...is a single-celled phytoplankton covered with uniquely ornamented calcite ($CaCO_3$) disks called coccoliths. *E. huxleyi* is globally distributed and often forms massive blooms in temperate and sub-polar oceans, which can reach a size of >100,000 km^2 and can be seen by satellites in space.

Equatorial upwelling...occurs when easterly trade winds blow from the northeast and southeast and converge along the equator blowing west. This triggers upwelling just north and south of the equator and results in an uplift of nutrient-rich waters from 200 m to the surface.

Float/Drifter...is an oceanographic device floating on the surface or at a given water depth to investigate ocean currents and other parameters like temperature or salinity. The depth of a drifter is defined by its neutral buoyancy. The device stops sinking when its buoyancy force is in equilibrium with its gravitational force.

Glider...is a type of autonomous underwater vehicle that uses small changes in its buoyancy in conjunction with wings to convert vertical motion to horizontal, and thereby propel itself forward.

Marine atmospheric boundary layer (MABL)...is that part of the atmosphere that has direct contact and, hence, is directly influenced by the ocean. Thus the MABL is where the ocean and atmosphere exchange heat, moisture, momentum and compounds (trace gases and aerosols).

Ocean mixed layer...is the layer between the ocean surface and a depth usually ranging between 25 and 200m, where the density is about the same as at the surface.

Sea spray...over the ocean provides a source of liquid drops, which upon evaporation produce sea salt crystals or a concentrated solution thereof.

Sea surface microlayer (SML)...is found at the interface between the atmosphere and ocean. On both sides of the interface, viscous and mass boundary layers are formed. The overall thickness of these layers (<1000 µm on the air side and <2000 µm on the water side) controls the speed of exchange (i.e. transfer velocity). Moreover, organic (macro)molecules can accumulate to form a loose gel of tangled macromolecules and colloids in the SML.

Stratosphere...is the second major layer of Earth's atmosphere, just above the troposphere. Here ozone (O_3) absorbs high energy (UVB and UVC) radiation from the sun.

Trace gas...is a gas which makes up less than 1% by volume of the Earth's atmosphere and it includes all gases except nitrogen (78.1%) and oxygen (20.9%).

Troposphere...is the lowest portion of Earth's atmosphere. It contains approximately 75% of the atmosphere's mass and 99% of its water vapour and aerosols. The average height of the troposphere is approximately 17 km.

SOPRAN measurement campaign in the coastal region of the Banc d'Arguin National Park, Mauritania, in September 2007

photo: F. Rommerskirchen

P348 Mauritania

The major objectives of the R/V Poseidon cruise P348 (February 2007) to the eastern tropical North Atlantic Ocean and the coastal upwelling region off Mauritania were to investigate the cycling of climate relevant trace gases between the ocean mixed layer and the atmospheric boundary layer, the aerosol input to the ocean and the turbulence structure and biological setting of the upper water column.

ATA03 Mauritania

The R/V L'Atalante cruise ATA03 took place in February 2008. The cruise combined a wide spectrum of biological, chemical and physical oceanography work packages as well as atmospheric chemistry with a regional focus on Cape Verdean waters and the coastal upwelling off Mauritania.

P399 Mauritania

The DRIVE (Diurnal and Regional Variability of Halogen Emissions, P399) campaign to the eastern tropical North Atlantic Ocean and the upwelling off Mauritania (NW Africa) took place in June 2010 with R/V Poseidon. The major objective of DRIVE/P399 was to investigate the regional and diurnal atmospheric and oceanic variations of halogenated compounds in the eastern tropical North Atlantic Ocean with a special focus on the Mauritanian upwelling. Cruises in Mauritanian waters were done in cooperation with the Institut Mauritanien de Recherches Océanographiques et des Pêches (IMROP, www.imrop.mr/).

MSM18/3 equatorial tropical Atlantic

The R/V Merian cruise MSM 18/3 to equatorial upwelling in the tropical Atlantic took place in June/July 2011. MSM 18/3 investigated the contribution of physical processes to the emission of climate relevant trace gases and short lived halogenated gases and to decipher the effects of atmospheric dust deposition on phytoplankton productivity, nitrogen fixation and export of organic matter.

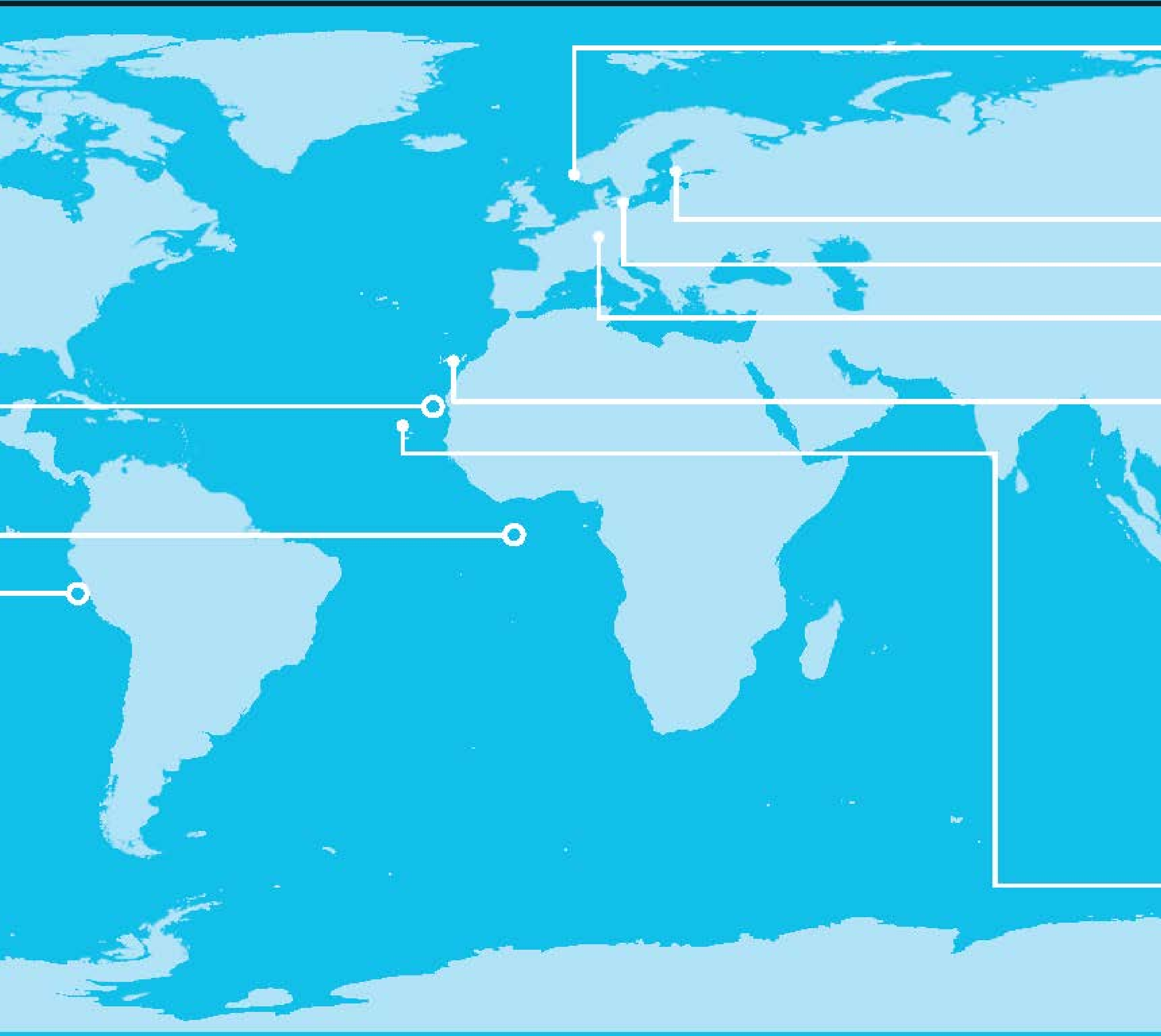
M91 Peru

The R/V Meteor cruise M91 took place off Peru in December 2012. The overall goal of M91 was to conduct an integrated biogeochemical study on the upwelling region off Peru in order to assess its importance for the emissions of various climate-relevant atmospheric trace gases and tropospheric chemistry. Cruises in Peruvian waters were done in cooperation with the Instituto del Mar del Peru (IMARPE, www.imarpe.pe/imarpe/).

www.sopran.pangaea.de/expedition

PI H.W. Bange, February 2007

PI A. Körtzinger, February 2008



PI H.W. Bange, June 2010

PI A. Körtzinger, June/July 2011

Global map of cruises and major experiments as of 2015

Raunefjord: 60° 16′ N, 05° 12′ E, Spring 2011

This mesocosm field experiment investigated the effect of ocean acidification on the carbon cycle with a special emphasis on the reaction of the calcifying algae *Emiliania huxleyi*. SOPRAN cooperated with the EU project MESOAQUA and the Marine Biological Station Espeland of the Bergen University (www.uib.no/en/bio/53898/espeland-marine-biological-station).

Tvärminne: 59° 50′ N, 23° 12′ E, Summer 2012

A European team of scientists investigated the impacts of ocean acidification on a post-bloom plankton community. The focus on this study was on the response of N_2-fixing cyanobacteria. The SOPRAN-led mesocosm field experiment took place at the Tvärminne Zoological Station. (luoto.tvarminne.helsinki.fi/english/).

FINO 2 Plattform: 55° 00′ N, 13° 09′ E

FINO 2 is a research platform in the SW Baltic Sea 33km north of the island of Rügen. On FINO 2 SOPRAN performed eddy co-variance measurements of CO_2 fluxes, measurements of dissolved pCO_2 and radar backscatter measurements of the sea surface.

Air-Sea Interaction Facility (Aeolotron), Heidelberg

The Heidelberg Aeolotron is an unique ring-shaped wind/wave tunnel with a diameter of 10 m. Two multidisciplinary experiments to investigate the mechanisms of air-sea gas exchange were performed by SOPRAN in the Aeolotron in February/March 2011 and November 2014.

Gran Canaria: 28° 7′ N, 15° 25′ W, Autumn 2014

This long-term field study investigated the ecological and biogeochemical impacts of ocean acidification on an nutrient-poor ecosystem in the subtropical North Atlantic. SOPRAN cooperated with the German BIOACID project (Biological Impacts of Ocean Acidification, www.bioacid.de), the Spanish research station Plataforma Oceánica de Canarias (PLOCAN, www.plocan.eu/index.php/en/) and the University of Las Palmas de Gran Canaria (ULPGC, www.english.ulpgc.es).

Cape Verde Atmospheric Observatory (CVAO): 16° 51′ N, 24° 52′ W and Cape Verde Ocean Observatory (CVOO): 17° 36′ N, 24° 18′ W

SOPRAN performed aerosol and trace gas measurements, measurements of solar irradiance and optical thickness as well as measurements of reactive halogen species at the two sites of the Cape Verde Observatory in cooperation with the Instituto Nacional de Desenvolvimento das Pescas - Cabo Verde (INDP).

PI H.W. Bange, December 2012

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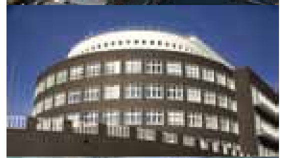
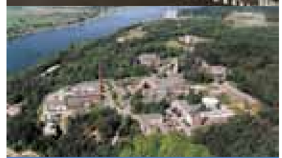
Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, www.awi.de/en.html



Helmholtz Centre Geesthacht, Centre for Materials and Coastal Research, www.hzg.de/index.php.en



IOW Leibniz Institute for Baltic Sea Research Warnemünde, www.io-warnemuende.de/en_index.html

TROPOS Leibniz Institute for Tropospheric Research, www.tropos.de/en/

Max Planck Institute for Chemistry, www.mpic.de/en/top-navigation/home.html

Max Planck Institute for Biogeochemistry, www.bgc-jena.mpg.de

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