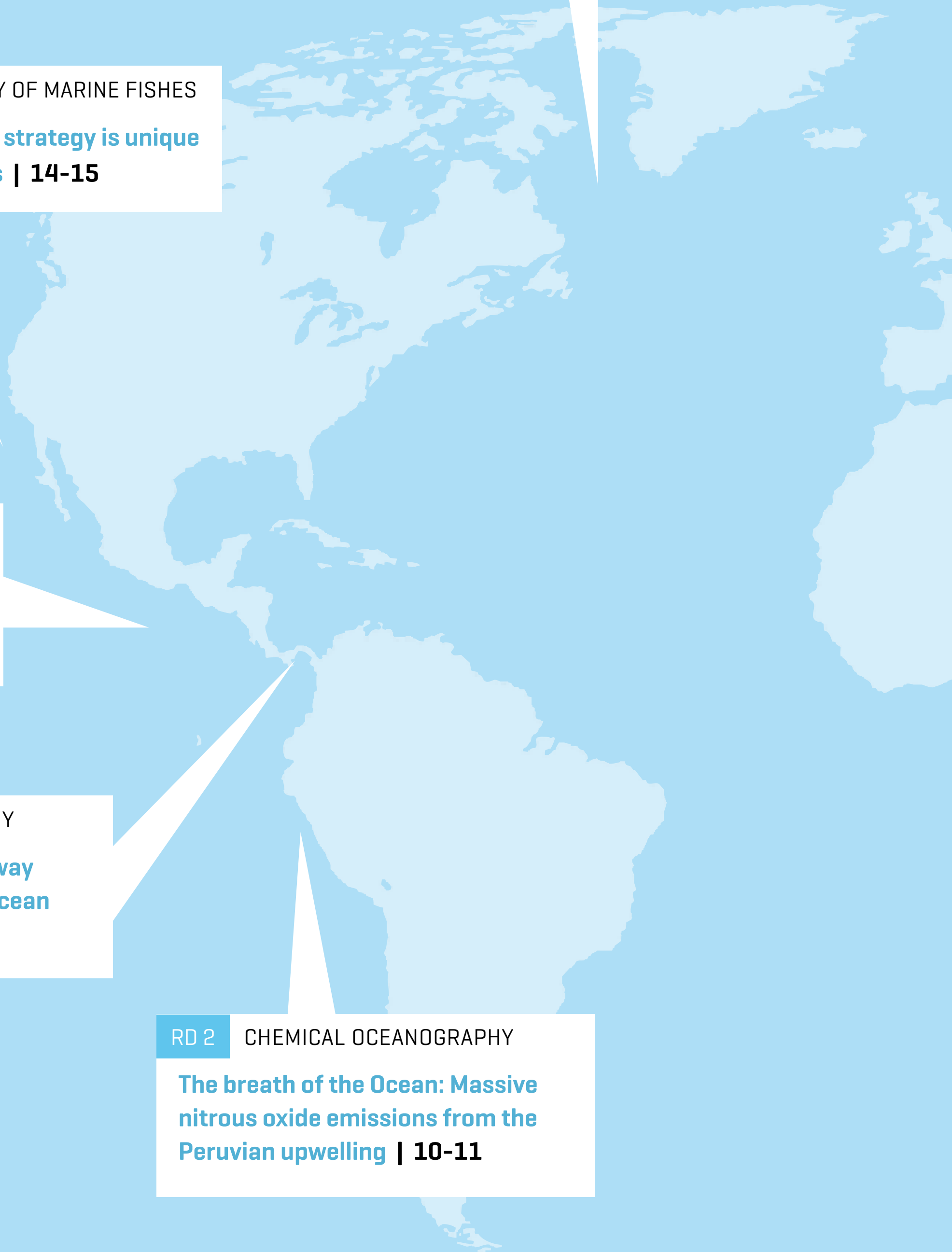
# GEOMAR Highlights | 02

Scientific Highlights from the GEOMAR Research Divisions


Image: Uli Kunz, uli-kunz.com

GEOMAR

# GEOMAR



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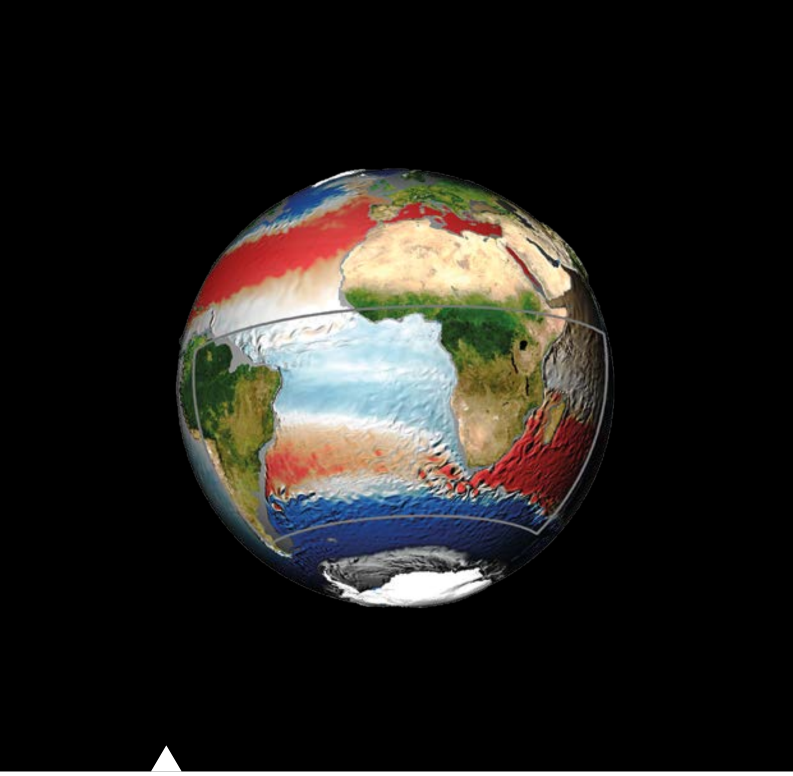
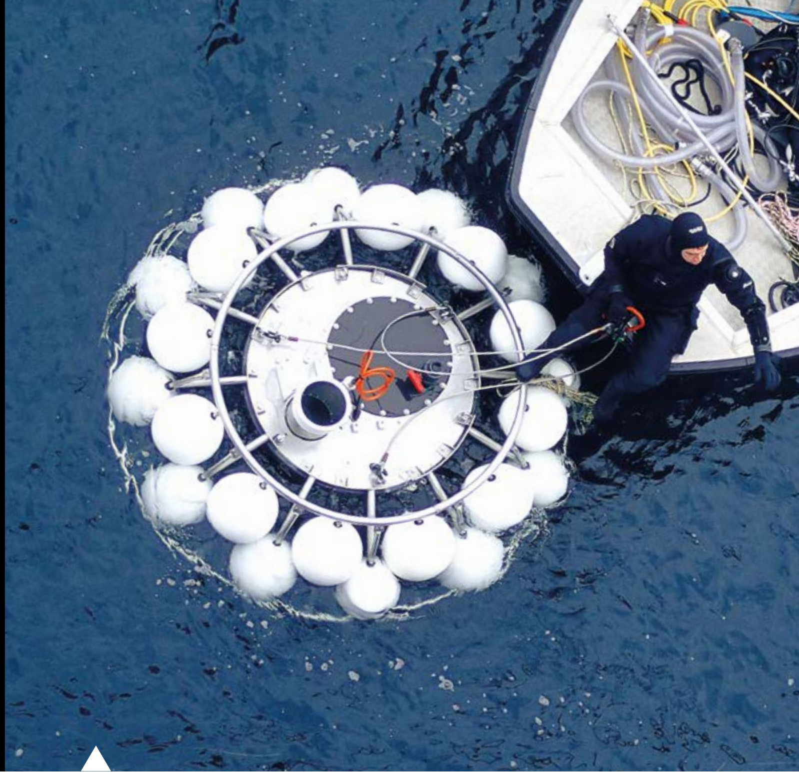
## Scientific Highlights from the GEOMAR Research Divisions



Snapshot of temperature and currents in 250-400 m depth in a high resolution ocean model. Simulation and graphics: ocean modelling group, GEOMAR



With a special collector, scientists collect deep-water for experiments on ocean acidification. Source: RD2-BI, GEOMAR



RD 1

RESEARCH DIVISION 1

## OCEAN CIRCULATION AND CLIMATE DYNAMICS

RESEARCH UNITS

- MARINE METEOROLOGY
- PALEO-OCEANOGRAPHY
- PHYSICAL OCEANOGRAPHY
- THEORY AND MODELLING

Climate variability can be externally induced or generated by Earth's atmospheric and oceanic processes. Research Division 1 develops the theoretical concepts required to understand and explore past and future climatic fluctuations and conducts the oceanographic, geological and meteorological experiments at sea to better constrain these models. Scientists in the division also undertake laboratory analyses, especially of the sediments of the ocean floor and their contained fossil organisms that are important marine climate archives. These studies are supported by sophisticated computer simulations of the complex Earth system.

**More:** www.geomar.de/en/research/fb1/overview/

RD 2

RESEARCH DIVISION 2

## MARINE BIOGEOCHEMISTRY

RESEARCH UNITS

- BIOGEOCHEMICAL MODELING
- BIOLOGICAL OCEANOGRAPHY
- CHEMICAL OCEANOGRAPHY
- MARINE GEOSYSTEMS

The chemistry of the oceans as we know them is hugely influenced by biogeochemical processes. Research Division 2 explores the biological, chemical and physical interactions between important chemical substances and their isotopes in the oceans, as well as the complex exchange between the oceans, atmosphere and sea floor. Major focal points of this research are the investigation of carbon fluxes from the atmosphere to the deep ocean, ocean acidification, so-called oxygen minimum zones and the study of gas hydrates.

**More:** www.geomar.de/en/research/fb2/overview/

15 mm-sized blue button jellyfish (Porpita *porpita*), found during the METEOR expedition M97 in the tropical Atlantic. Image: Uwe Piatkowski, GEOMAR

## RD 3

### RESEARCH DIVISION 3

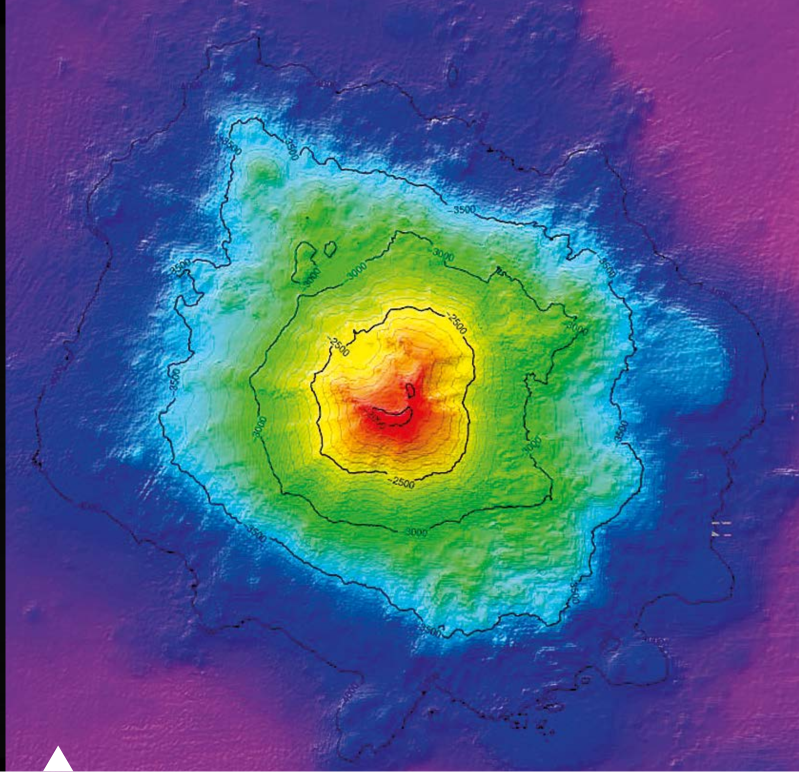
# MARINE ECOLOGY

RESEARCH UNITS

- EVOLUTIONARY ECOLOGY OF MARINE FISHES
- EXPERIMENTAL ECOLOGY
- MARINE MICROBIOLOGY
- MARINE NATURAL PRODUCTS CHEMISTRY

The responses of marine ecosystems to global environmental change are among the fundamental questions for the future oceans. Research Division 3 is examining how various marine species interact in changing food webs, how the composition, diversity and function of different ecosystems are affected by external influences, how biodiversity influences the ecosystem services, and whether rapid evolutionary adaptation mitigates the negative effects of global change.

**More:** www.geomar.de/en/research/fb3/overview/



Bathymetric map of a seamount created with the deep-water multibeam echosounder system of RV SONNE during cruise SO239. Visualisation: Jens Greinert, GEOMAR

## RD 4

### RESEARCH DIVISION 4

# DYNAMICS OF THE OCEAN FLOOR

RESEARCH UNITS

- MAGMATIC AND HYDROTHERMAL SYSTEMS
- MARINE GEODYNAMICS

The dynamic processes of the ocean floor and ocean margins are the causes of natural hazards such as earthquakes, volcanic eruptions and tsunamis and the major control on the distribution of mineral and energy resources in the deep sea. Research Division 4 explores the fundamental links between the geological domains of the oceans – the oceanic ridges where new crust is formed, volcanic arcs such as the “Ring of Fire” at the plate margins, and the deep subduction zones where the oceanic plates sink back into the mantle – and the processes that influence the composition of the Earth’s crust and its stability.

**More:** www.geomar.de/en/research/fb4/overview/

**Figure 1:** Almost finished! A very wet mooring deployment (during Cruise METEOR 59) in the subpolar North Atlantic – which shows its other face – heavy winds and waves made further shipboard work impossible for days. This illustrates the importance of autonomous stations that are independent of such weather situations. Photo: Physical Oceanography, GEOMAR





# From Days to Decades: Variability of the western subpolar DWBC

**Jürgen Fischer, Johannes Karstensen, Martin Visbeck, Rainer Zantopp, and Patricia Handmann**

*The Deep Western Boundary Current (DWBC) is a key element of the Meridional Overturning Circulation (MOC) in the Subpolar North Atlantic (SPNA), and the Labrador Sea is the location where all of its North Atlantic Deep Water (NADW) constituents merge. Diverse pathways, underway modifications through ocean processes (e.g., convection, entrainment and mixing) and other forcing have modified the DWBC layers enroute. After exiting the Labrador Sea, the DWBC flows around Flemish Cap and the Grand Banks on its journey to the South Atlantic. Thus the DWBC at the exit of the Labrador Sea is directly connected to the subpolar MOC and its long term variation.*

This motivated the installation of a long-term moored observatory (the “53°N-Array”, Figure 1) in summer 1997 which is serviced nominally every two years. Typically, the array has 3-5 moored stations with current meters and temperature and salinity sensors in every NADW component, i.e. contributions from the Denmark Strait, the Iceland-Scotland Ridge, and the central Labrador Sea. With currently 17 years of data, the 53°N Array measured one of the longest full-ocean-depth boundary current records worldwide. The science associated with this observatory is embedded in German / European / Transatlantic programs, e.g., the BMBF RACE program, the EU NACLIM and the AtlantOS consortium, and the international OSNAP initiative.

The Deep Western Boundary Current at the exit of the Labrador Sea is remarkably stable in its general appearance (Figure 2). Near the shelf edge, the surface-intensified flow of the shallow Labrador Current dominates the boundary current system. A second, very stable current core with flow speeds of 20 cm/s and water mass properties associated with the lower NADW hugs the deep slope below 2000m water depth. At the intermediate level, the flow is more barotropic (i.e., has less vertical shear), parallel to the topography and directed out of the Labrador Sea. Farther offshore, about 150km off the shelf edge, the current reverses in a weak but relatively stable counter-current, and this current reversal terminates the DWBC throughout the water column.

Transports derived for water mass layers (indicated here by their isopycnal boundaries — red lines in Figure 2, left) show variability from days to decades, and there are two frequency bands dominating the deep transport. The first variance maximum at 10-20 day periods is due to topographic Rossby Waves (TRW’s; Fischer et al., 2015 — an international cooperation) tied to the steep Labrador shelf break (Figure 2, right), but these are also found all along the western margin of the SPNA, and the

TRW-frequency mainly depends on the steepness of the continental slope — the steeper the slope, the shorter the TRW periods. The principle axis of the variance associated with the TRW's (see red ellipses in the map — Figure 3) is in the direction of the mean DWBC flow, while the variability in the basin interior (Labrador- and Irminger Seas) is eddy dominated with no preferred variance direction and somewhat longer timescales near 50 day periods.

The high energy level of intra-seasonal velocity has the potential of causing strong aliasing of ship-based transport measurements and thus requires high time resolution sampling for example by moored observatories as in the 53°N Array, in order to detect the small changes on interannual and climate change time scales. It also sheds light on another major point of interest, namely the uncertainties of the associated quantities like heat or biogeochemical transports. While the time series are long with regard to the intra-seasonal variability, they are short regarding multiannual to decadal time scales. Great care must be taken to detect possible trends and to isolate them from internal oscillations and noise in this and similar time series.

Understanding and assessing the high frequency signal is very valuable in support of the ongoing analysis of the 53°N time series in the context of a quasi-decadal mode (8-10y time scale) that covers the second energy maximum of the DWBC variability at 53°N. Mass transports of the lower North Atlantic Deep Water (LNADW) are determined for the layer bounded by the isopycnal sigma2=36.95 kg $m^{-3}$ as its upper limit and the sea floor (Figure 4). This time series clearly shows the LNADW transport to be dominated by short-term fluctuations and multiannual to decadal periods. Both frequency regimes contain similar variances, but while the short-term fluctuations are treated as noise, the longer time scale variations are important contributions of the MOC variability. In addition to its direct relevance to the Atlantic MOC — this transport time series is important for validating ocean- and climate models and for their future improvements.

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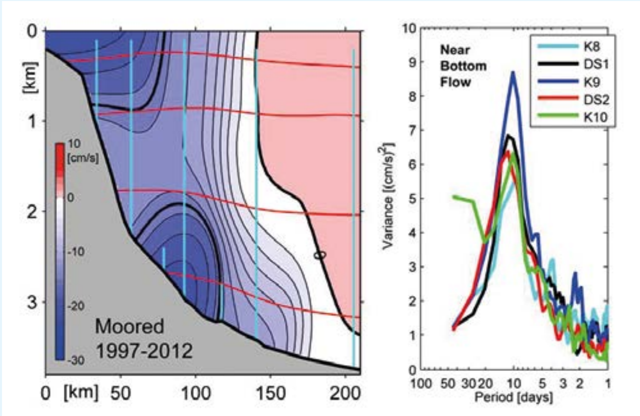


Figure 2: The mean structure of the DWBC at the exit of the Labrador Sea, from 15 years of moored instruments (left); blue colors for flow out of the Labrador Sea and red for the flow into the Labrador Sea; mooring locations are indicated by vertical line. Intra-seasonal variability dominates the variance of the near-bottom flow (right); with an energy peak around 10-20 day periods.

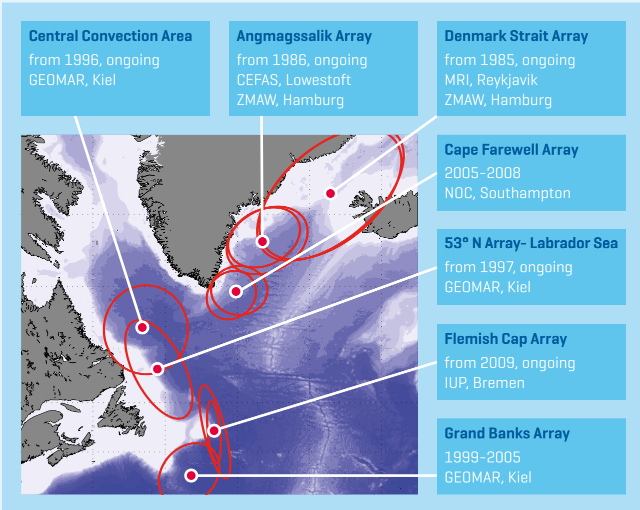


Figure 3: Elongated variance ellipses (red) of the flow within the DWBC in the western subpolar North Atlantic – for comparison variances from the central Labrador- and Irminger Seas are more circular. Data are from long term mooring initiatives from the mid-nineties until present.

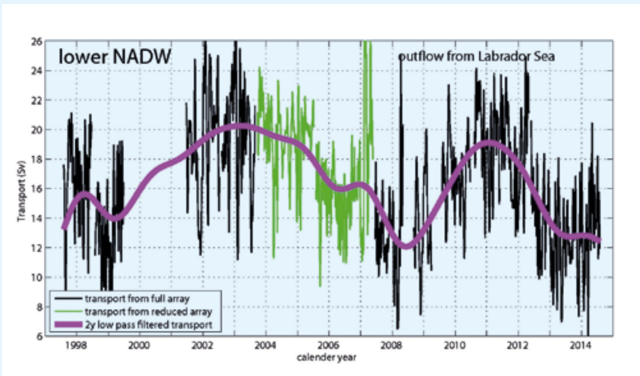


Figure 4: Mass transport of lower North Atlantic Deep Water (LNADW) defined below a density reference (i.e. sigma2=36.95 kg $m^{-3}$ located at approximately 1875m water depth). Thin black- and green lines include the noise generated by intra-seasonal variability through topographic Rossby Waves on the continental slope in the southern Labrador Sea. Heavy magenta line shows the low frequency variations of the DWBC.

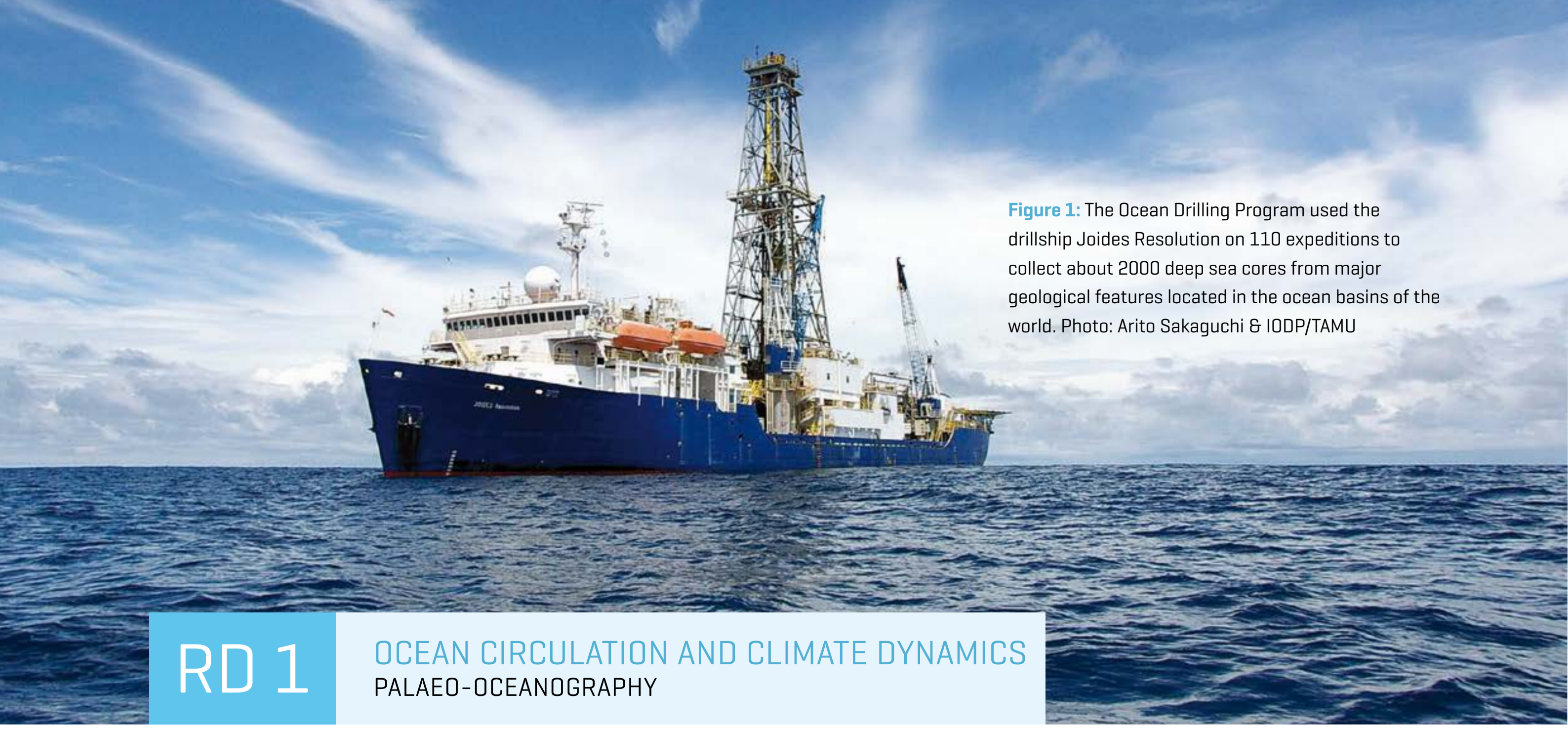

Figure 1: The Ocean Drilling Program used the drillship Joides Resolution on 110 expeditions to collect about 2000 deep sea cores from major geological features located in the ocean basins of the world. Photo: Arito Sakaguchi & IODP/TAMU



# Closure of the Panama Seaway and its impact on Atlantic Ocean Circulation

**Anne Osborne, Valeriia Kirillova (now at Marum, Bremen) and Martin Frank**

*The opening and closing of ocean gateways in the geologic past has had a huge impact on ocean circulation and thus on climate. The most recent of these events was the shoaling and final closure of the Panama Seaway, which ultimately stopped the flow of relatively fresh Pacific waters via the Caribbean into the North Atlantic 3 million years ago (Ma). Although tectonic changes of this magnitude are not important on human timescales, a better understanding of the sensitivity of the Atlantic circulation to salinity changes in the surface ocean in the past is relevant for the evaluation of future scenarios, which predict that there will be more melt-water runoff to the Atlantic Ocean in the high northern latitudes.*



Today, the Gulf Stream transports warm and salty water from the Caribbean warm pool to the northern Atlantic, where it cools and sinks to form North Atlantic Deep Water (NADW), which is responsible for the ventilation of the entire deep Atlantic basin. In contrast, until approximately 3 Ma, the Panama Seaway provided a direct connection between the eastern Pacific and the Caribbean [Keigwin, 1982] (Figure 2). It has been predicted that an open Panama Seaway and the inflow of low salinity waters would have prevented or reduced the amount of deep water forming in the north Atlantic and thus resulted in a fundamentally different climate.

The Panama Seaway had been getting shallower since at least 15 Ma as a result of the tectonic collision between South and Central America [Montes et al., 2015]. However, there is disagreement as to how much restriction of the Seaway was necessary to have a major impact on Atlantic Ocean circulation, and if closure of the Seaway directly led to other changes in global climate, such as the build up of continental ice in the northern hemisphere.

We reconstructed the history of Atlantic Ocean circulation by analyzing the chemical composition of deep-sea sediments from the eastern equatorial Pacific, the Caribbean, and the Florida Strait.

The isotopic composition of the Rare Earth Element neodymium (Nd IC) of seawater, as recorded in the seawater-derived thin Fe-Mn-coatings of seafloor sediments can be used to reconstruct water mass mixing and circulation in the geological past. The distinct differences in Nd IC between water masses originating in the Pacific, the Southern Ocean, and those originating in the North Atlantic allow the evaluation of changes in their mixing proportions as a function of the closing of the Seaway. We measured the Nd IC in sediment cores from the eastern Pacific and the Caribbean spanning the period of time between 5 to 2 Ma (the Pliocene), and a longer record in a sediment core in the Florida Strait spanning 12 to 0 Ma, in order to investigate the history of Atlantic Ocean circulation as the Panama Seaway shoaled (Figure 3).

The results show that the seawater Nd IC in the Caribbean and the Florida Strait around 12 Ma was similar to the Pacific and distinct from any Atlantic water mass at that time, indicating that Pacific waters were transported through the open Panama Seaway and into the North Atlantic. The records from the Caribbean (green lines on Figure 3) then show a continuous change away from Pacific seawater composition (red line on Figure 4) until ~ 7 Ma [Newkirk and Martin, 2009, and this study]. The Florida Strait Site shows a stronger Atlantic influence than the Caribbean Sites between ~ 12 and 10 Ma but then converged with the Caribbean Nd IC signatures between ~ 10 and 8 Ma (blue line

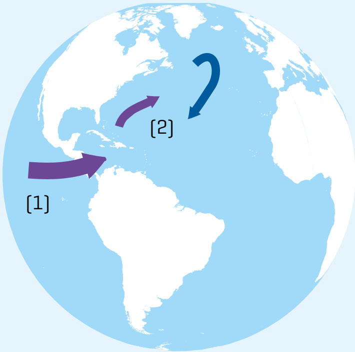


**Figure 2a:** Atlantic Ocean circulation before closure of the Panama Seaway.

[1] Lower salinity Pacific waters enter Atlantic. [2] Weaker or absent NADW production?

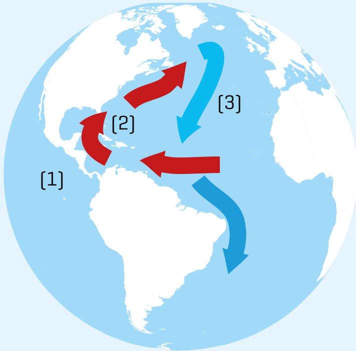


**Figure 2b:** Atlantic Ocean circulation after closure of the Panama Seaway.

[1] Evaporation in Caribbean increases salinity in surface waters. [2] Warm and salty Gulf Stream moves northwards. [3] Cold and salty waters sink to form NADW

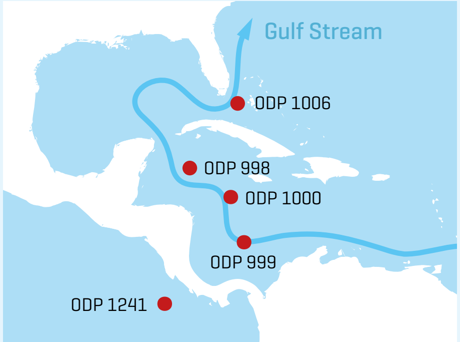


**Figure 3:** Location of Ocean Drilling Program Sites used in the study (red dots). The major current which becomes the Gulf Stream is also shown (blue line).

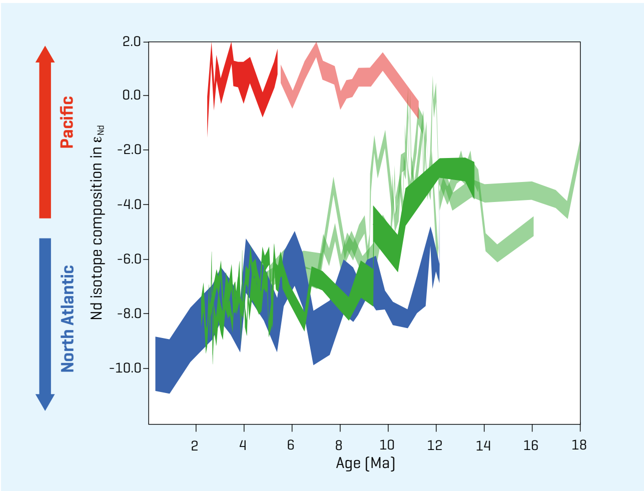


**Figure 4:** Evolution of seawater Nd isotope composition as extracted from sediments of Ocean Drilling Program (ODP) Sites in the Pacific (red line), the Caribbean (green lines), and the Florida Strait (blue line). The Nd isotope composition is reported in epsilon units (parts per 10,000 deviation of the measured $^{143}Nd/^{144}Nd$ isotope ratio from a standard). Bold lines are data from this study, pale lines are data from Newkirk and Martin (2009).

on Figure 4). There was also some variability in the Florida Strait thereafter, which we attribute to the complex tectonic history of the Caribbean, during which smaller gateways between the northern and southern parts of the basin opened and closed. From 6 Ma onwards, the trend towards more North-Atlantic-like Nd IC compositions in the Caribbean and Florida Straits sites continued at a slower rate but also showed a lot of short-term variability [Osborne et al., 2014]. Evidence from other studies shows that there was only a shallow connection between the Pacific and Caribbean during the Pliocene, repeatedly closing and opening due to sea-level changes, and thus the short-term variability in the Caribbean Nd IC is attributed to an increase in the production and inflow of NADW into the Caribbean at the expense of water masses originating in the Southern Ocean. The overall trend in Nd IC is consistent with other records that show that Caribbean waters became progressively better ventilated during this time [Haug and Tiedemann, 1998].

Our study confirms that a major step in Panama Seaway closure occurred between 12 and 7 Ma and affected circulation in the Caribbean. Prior to this, there had been a direct link between the Pacific and North Atlantic via the Florida Strait. Changes in ocean circulation continued at a slower rate during the Pliocene and were consistent with a gradual increase in the production of NADW. The major build up of ice in the Northern Hemisphere starting at ~ 2.7 Ma was apparently not directly linked to any major episode in Panama Seaway shoaling, as had been hypothesized in previous studies, but occurred during an overall trend towards stronger NADW production and Atlantic water inflow into the Caribbean.



## References

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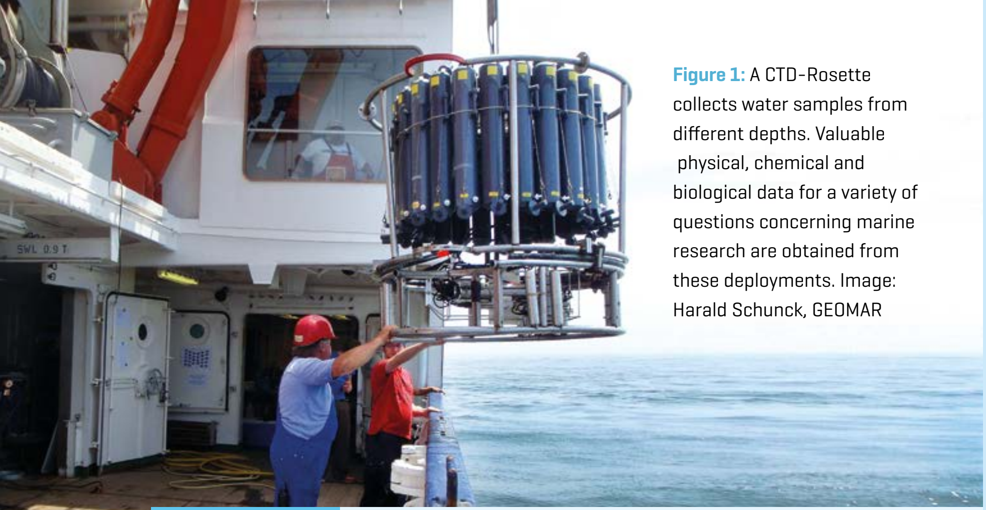


**Figure 1:** A CTD-Rosette collects water samples from different depths. Valuable physical, chemical and biological data for a variety of questions concerning marine research are obtained from these deployments. Image: Harald Schunck, GEOMAR

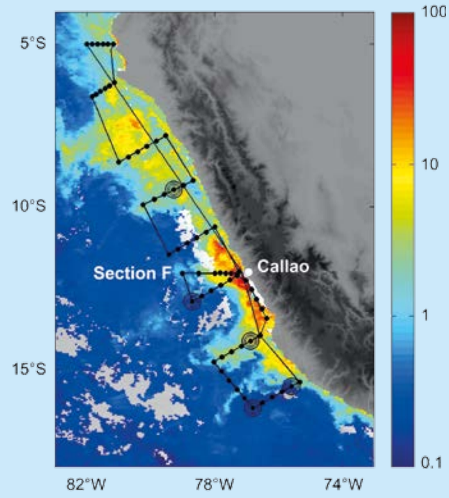



**Figure 2:** MODIS-Aqua mean chlorophyll *a* concentrations [in mg $m^{-3}$] off Peru in December 2012. The ship track and CTD-sampling stations during the M91 cruise are represented as black lines and points, respectively. Highlighted circles indicate the position of the 24 h stations carried out during M91. Chlorophyll *a* concentrations were retrieved from: http://oceandata.sci.gsfc.nasa.gov/MODISA/Mapped/Monthly/4km/chlor/.

RD 2 MARINE BIOGEOCHEMISTRY
CHEMICAL OCEANOGRAPHY

# The breath of the Ocean: Massive nitrous oxide emissions from the Peruvian upwelling

**Damian L. Arévalo-Martínez, Annette Kock, Carolin R. Löscher, and Hermann W. Bange**

*An integrated oceanographic and biogeochemical study on the Peruvian upwelling and the adjacent OMZ was carried out in order to assess their importance for the production and emissions of nitrous oxide ($N_2O$). For this purpose, a comprehensive survey of the surface and depth distribution of $N_2O$ was conducted during three RV Meteor cruises (M90, M91, and M93) in November 2012-March 2013. The M90 and M93 cruises were funded by the Collaborative Research Center SFB 754 (Climate-biogeochemistry interactions in the tropical ocean), and the M91 cruise was funded by the German BMBF project SOPRAN (Surface Ocean Processes in the Anthropocene) as a German contribution to the international SOLAS (Surface Ocean – Lower Atmosphere Study).*



The world's oceans play a fundamental role in the global biogeochemical cycles. It is therefore not too surprising that many climate-relevant trace gases are produced as intermediates or by-products of various microbiological processes in the marine environment. A significant fraction of biological productivity in the ocean depends on the concurrent availability of nutrients and light, and is therefore, restricted to the euphotic zone (i.e. the small sunlit upper part of the ocean water column). While light is usually available throughout the year in the eastern tropical South Pacific (ETSP), nutrient (i.e. nitrate and phosphate) concentrations are extremely depleted in large parts of the surface layer. Nutrient availability and, thus, the productivity of the ETSP depend on physical processes which inject nutrients into the upper ocean layer.

The coastal region off Peru belongs to the four major eastern boundary upwelling systems (EBUS). There, steady winds blowing parallel to the coast result in a westward movement of the upper water masses which are replaced by nutrient-rich subsurface water masses, triggering massive phytoplankton blooms. Hence, the Peruvian upwelling is one of the most productive regions of the global ocean. The high biological production, in turn, leads to a high flux of organic material from the euphotic zone into the subsurface ocean where it is respired by microorganisms, resulting in a zone with extremely depleted oxygen ($O_2$) concentrations (the so-called oxygen minimum zone, OMZ). Since the production of trace gases such as carbon dioxide ($CO_2$), nitrous oxide ($N_2O$), methane ($CH_4$) and others are either depending on phytoplankton or $O_2$-sensitive microbial processes, the Peruvian upwelling and the adjacent OMZ seem to be ideal study sites for trace gas cycling. Subsurface production of $N_2O$, for example, is particularly enhanced when low-$O_2$ waters prevail. Thus, transport of these $N_2O$-rich waters to the surface in the Peruvian upwelling can potentially create "hotspots" for significant emissions of this strong greenhouse gas to the atmosphere. However, the importance of this region for the production and atmospheric emissions of $N_2O$ and other climate-relevant trace gases is largely unknown.

To this end, we participated in three RV Meteor cruises (M90, M91 and M93) to the Peruvian upwelling between November 2012 and March 2013. The multidisciplinary team included scientists from various SOPRAN and SFB 754 subprojects as well as scientists from the Instituto del Mar del Perú (IMARPE, Callao). Our major objectives were: (i) to quantify the emissions of $N_2O$ and other trace gases from the upwelling region, (ii) to investigate the role of the sea-surface microlayer for the exchange of $N_2O$ across the ocean/atmosphere interface and (iii) to investigate the role of the coastal upwelling and the underlying OMZ off Peru as a source of $N_2O$. A combined approach was followed by conducting along-track measurements

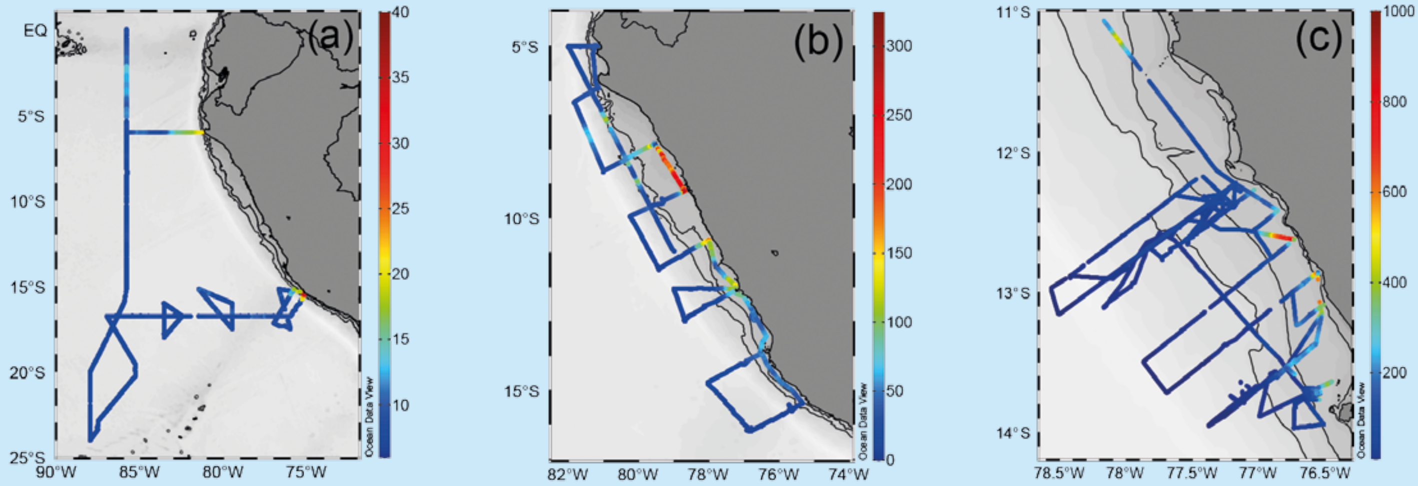



**Figure 3:** Surface distribution of $N_2O$ concentrations (in nmol $L^{-1}$) during the M90 (a), M91 (b) and M93 (c) cruises. Modified from Arévalo-Martínez et al. [2015].

of atmospheric and dissolved $N_2O$, vertical profiles of $N_2O$, in-situ measurements of nitrogen (N)-cycle processes as well as comprehensive hydrographic surveys. During the cruises, a north-south offshore transect along 86°W as well as several transects perpendicular to the Peruvian coast between 5°S and 16°S were sampled (Figure 2). In addition, during M91 we sampled the coastal time series stations off Callao (Section F). In total, 90 CTD/Rosette and 55 microstructure casts as well as 5 sampling trips with a zodiac were performed. Continuous underway atmospheric and surface ocean measurements were performed along the entire cruise tracks.

First results from this extensive survey in the ETSP are presented in Figures 2 and 3: Chlorophyll *a* concentrations were very high in the narrow band of upwelling along the Peruvian coast (Figure 2). The massive phytoplankton blooms result from nutrient-rich subsurface waters which are brought to the surface during upwelling events at the shelf. Mesoscale circulation structures (so-called eddies), which are a common feature of the ESTP, result in a transport of chlorophyll-rich surface waters away from the coast towards the open ocean. This is clearly visible as the ring-like structures of high chlorophyll *a* in Figure 2. The surface distribution of dissolved $N_2O$ is shown in Figure 3. Measurements were performed with a novel analytical system set up at GEOMAR, which allows measuring dissolved and atmospheric mixing ratios of $N_2O$ with unprecedented high resolution and accuracy. With this continuously operated underway system, even the small-scale variability of $N_2O$ in surface waters off Peru could be detected. We measured extremely high $N_2O$ concentrations, which are the highest ever measured in the surface ocean. In general, the highest $N_2O$ concentrations were associated with upwelling sites along the coast, where chlorophyll *a* was also high. Moreover, the vertical distribution of $N_2O$, nutrients and key molecular markers for N-cycling suggested that these high $N_2O$ concentrations resulted from combined microbial nitrification and denitrification within the water column, and subsequent transport to the surface by

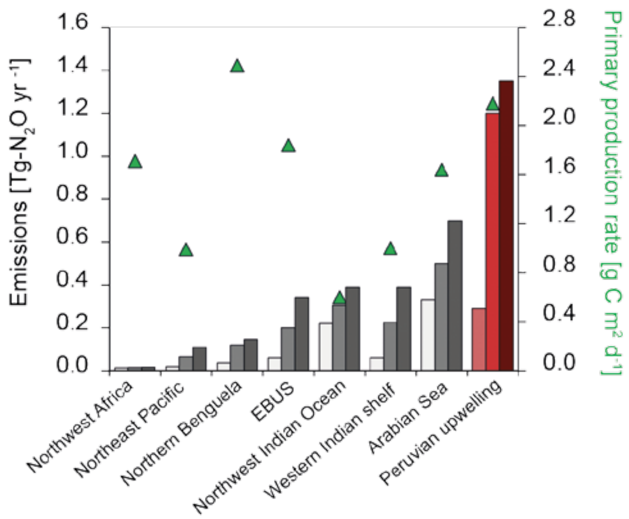



**Figure 4:** Comparison of $N_2O$ emissions from highly productive regions. The bars represent the $N_2O$ emissions (white = minimum, light grey = mean, dark grey = maximum), whereas the green triangles indicate the primary production rate. Our range of emission estimates for the Peruvian upwelling is highlighted in red. Modified from Arévalo-Martínez et al. [2015].

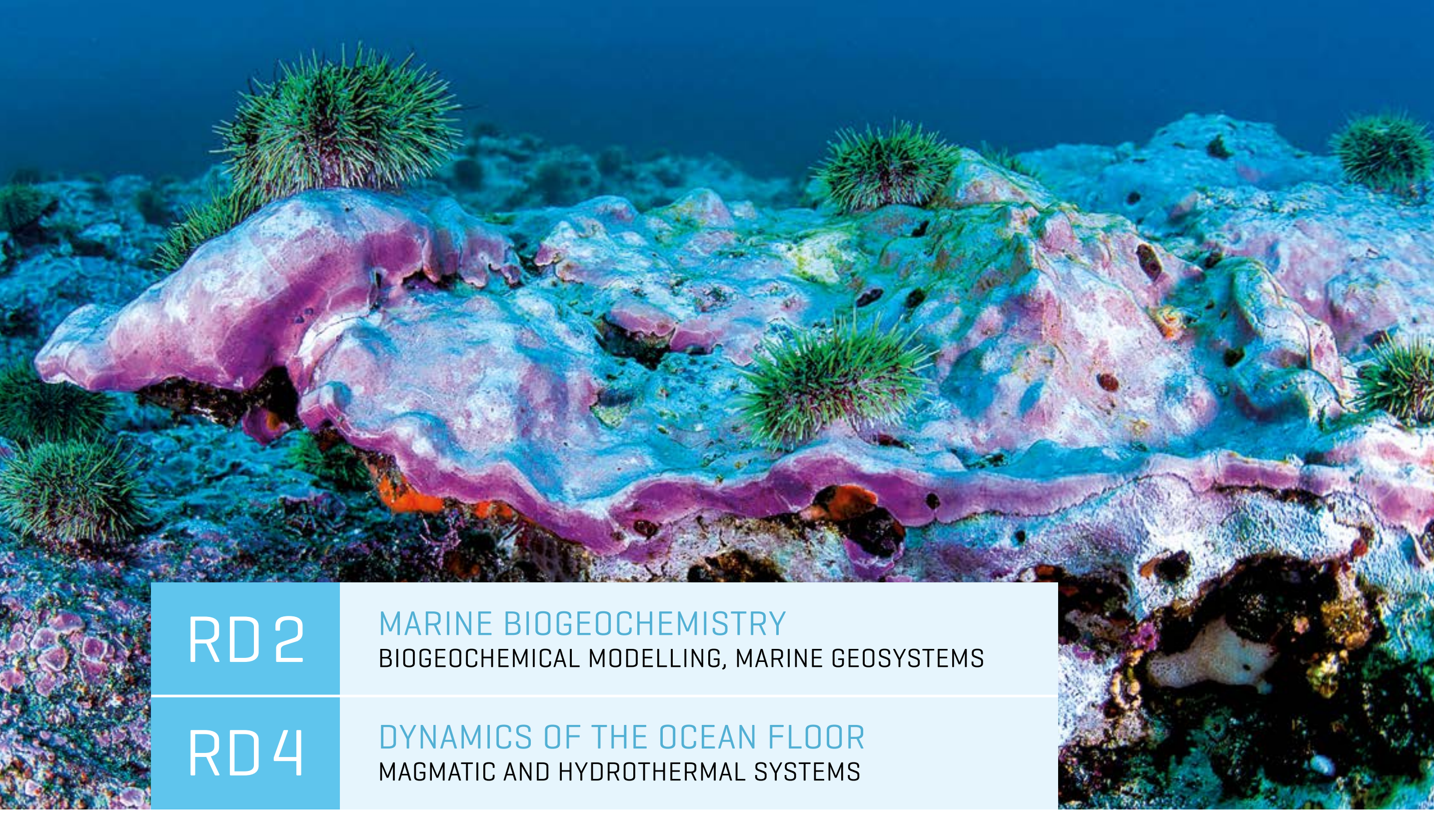
coastal upwelling. As a result, remarkably high emissions of $N_2O$ to the atmosphere (0.3-1.4 Tg-$N_2O$ $yr^{-1}$) could be observed off Peru, suggesting that the contribution of the Peruvian upwelling to the global ocean $N_2O$ emissions is higher than previously thought, also in comparison with other EBUS and similarly productive coastal upwelling regions worldwide (Figure 4). Thus, our contribution is relevant for future studies investigating the potential responses of the oceanic N-cycle to global warming and ocean deoxygenation.

## Reference


Arévalo-Martínez, D. L., A. Kock, C. R. Löscher, R. A. Schmitz, and H. W. Bange, 2015, Massive nitrous oxide emissions from the eastern tropical South Pacific Ocean, Nature Geosci., 8, 530-533.


## Acknowledgment


The field work conducted during the M90, M91, and M93 cruises was funded through a joint effort of the DFG-supported project SFB 754, the BMBF joint project SOPRAN II and III (FKZ 03F0611A and FKZ 03F662A), the Future Ocean Excellence Cluster at Kiel University (project CP0910), and the EU FP7 project InGOS (Grant Agreement # 284274).



RD 2 MARINE BIOGEOCHEMISTRY
BIOGEOCHEMICAL MODELLING, MARINE GEOSYSTEMS

RD 4 DYNAMICS OF THE OCEAN FLOOR
MAGMATIC AND HYDROTHERMAL SYSTEMS

**Figure 1:** Massive coralline alga, *Clathromorphum nereostratum*, endemic to the Aleutian Islands and Bering Sea with associated green sea urchins, *Strongylocentrotus polyacanthus*. Photo taken by Joe Tomoleoni as part of NSF PLR-1316141, PI: Bob S. Steneck, Univ. of Maine

# Coralline algae record 120 years of Ocean Acidification in the arctic North Pacific

**Jan Fietzke (RD2, RD4), Heiner Dietze (RD2), Thor H. Hansteen (RD4) and Anton Eisenhauer (RD2)**



*Next to global warming, ocean acidification is considered as the second major impact on ocean surface waters resulting from anthropogenic $CO_2$ emissions. The uptake of $CO_2$ by surface waters shifts the carbonic acid equilibrium towards more acidic conditions. As a consequence of this chemical changes the saturation with respect to calcium carbonate in surface waters is decreasing. This ocean acidification effect challenges marine calcifiers´ ability to build shells and skeletons using biomineralized calcium carbonate.*

While intense research activities focused on this problem recently long-term records of e.g. seawater pH are scarce, both temporally and spatially. First continuous pH time-series measurements started in the early 1980´s. In an attempt to extend our knowledge base geochemical proxies play a key role. In particular the stable isotopes of boron incorporated in the calcium carbonate shells and skeletons of marine calcifying organisms can be used to reconstruct the seawater pH at the time of formation.

Using a new analytical method developed at GEOMAR boron isotope 2D images have been acquired via LA-MC-ICPMS (laser ablation multi-collector inductively coupled plasma mass spectrometry) from the skeleton of a long-lived crustose coralline alga. The algal specimen (*Clathromorphum nereostratum*, Figure 1) had been collected alieve from the shallow waters off Attu Island (Aleutian Islands, Alaska, Figure 2). The age model derived from counting annual growth increments (Figure 3) and confirmed by radiometric dating (U/Th) revealed a continuous growth over more than 120 years, covering the time interval most relevant to study man-made ocean acidification.

Boron isotope and Mg/Ca elemental ratio analyses allowed for the first time a detailed reconstruction of pH and temperature using crustose coralline algae covering both, long-term changes over the last century and intra-annual variations. The long-term decline of 0.08±0.01 pH units between 1890´s and 1990´s clearly demon-

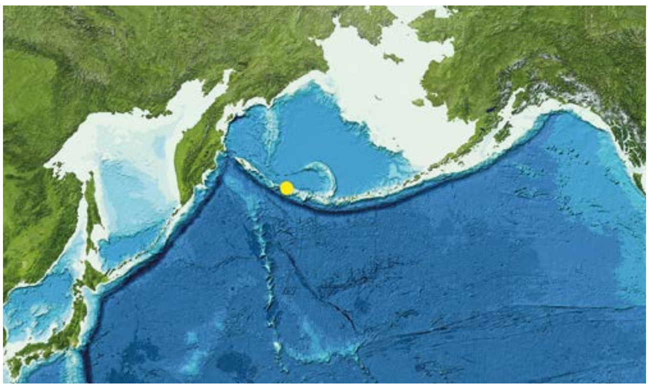


**Figure 2:** The samples for the current study came from the coastal waters of Attu Island (Aleutian Islands). Image reproduced from the GEBCO world map, www.gebco.net

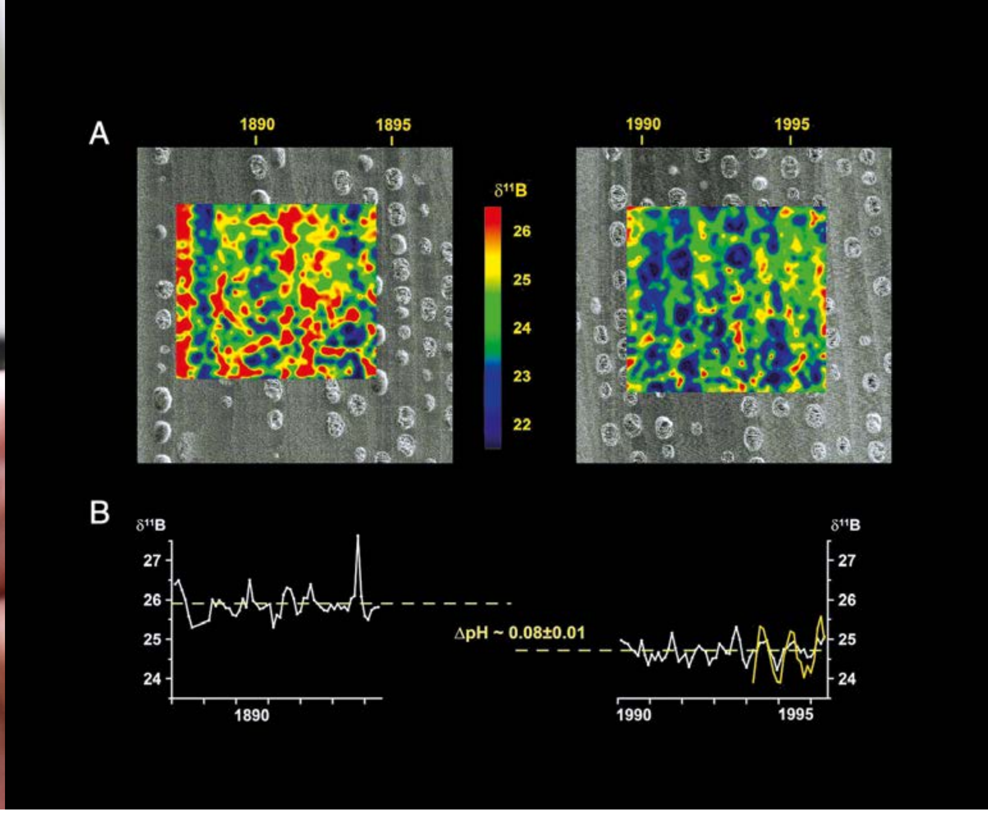



**Figure 3:** Sample of the coralline alga Alge *Clathromorphum nereostratum* in the laser-ablation lab of GEOMAR. Single growth rings are clearly visible. Photo: J. Steffen, GEOMAR

**Figure 4:** Stable boron isotope ratio ($\delta^{11}B$) images acquired by LA–MC–ICP–MS used for pH reconstruction. (A) $\delta^{11}B$ images (100 µm resolution) displayed as overlays on secondary electron images from the EMP measurements. (B) $\delta^{11}B$ time series showing a long-term decrease equal to 0.08 ± 0.01 pH units between the 1890s and 1990s in good agreement with atmospheric CO2 records. Additionally, a seasonal pH cycle of at least 0.1 pH units can be seen for the years 1994–1996 (yellow) using only data from the area least influenced by secondary calcite.



strates the presence of ongoing ocean acidification in this sub-polar coastal habitat. The amount of shift in pH is in good agreement with the expected change derived from the estimated increase in atmospheric $CO_2$ concentration for this period.

Besides the long-term trend seasonal cycles in seawater pH could be reconstructed, too. The latter underlines the exceptional value of crustose coralline algae as environmental archives. Individual lifespans can exceed centuries while annual growth is in the order of several hundreds of µm. Monthly resolution in pH reconstruction is presently possible using the above mentioned analytical methodology. New instrumentation (installed in early 2015) will allow further improvement with respect to temporal resolution.

Focusing on three 5-year-periods (from 1920´s, 1960´s and 1990´s) the present data set clearly reveals a pronounced annual cycle of 0.22±0.03 pH units, almost 3 times as large as the long-term shift over 100 years. The annual maximum in pH occurs during every year´s late spring onset of the growth season. This observation is interpreted as a consequence of the massive uptake of dissolved $CO_2$ by marine plants for photosynthesis. The habitat where the algal sample had been collected from is dominated by an annual kelp species (dragon kelp Eualaria fistulosa). The efficient uptake of vast amounts of dissolved $CO_2$ shifts the carbonic acid equilibrium resulting in an increase in pH.

The high natural variability in pH could explain a certain degree of adaptation/acclimation of the local biota to changing pH. E.g. annual growth indicated by the thickness of annual growth layers of the algal skeleton does not show significant changes related to ocean acidification. Nevertheless, a further reduction of pH in combination with warming could trigger changes in the habitats community favoring non-calcifying species outcompeting marine calcifiers. From our data a long-term increase in average water temperatures from 5.3°C to 6.2°C and a shift of the onset of annual growth season towards early times in the year could be observed comparing 1990`s and 1890´s.

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## Acknowledgement

This work was funded by the German Federal Ministry of Education and Research (BMBF) in the framework of the coordinated project BIOACID (Biological Impacts of Ocean Acidification).

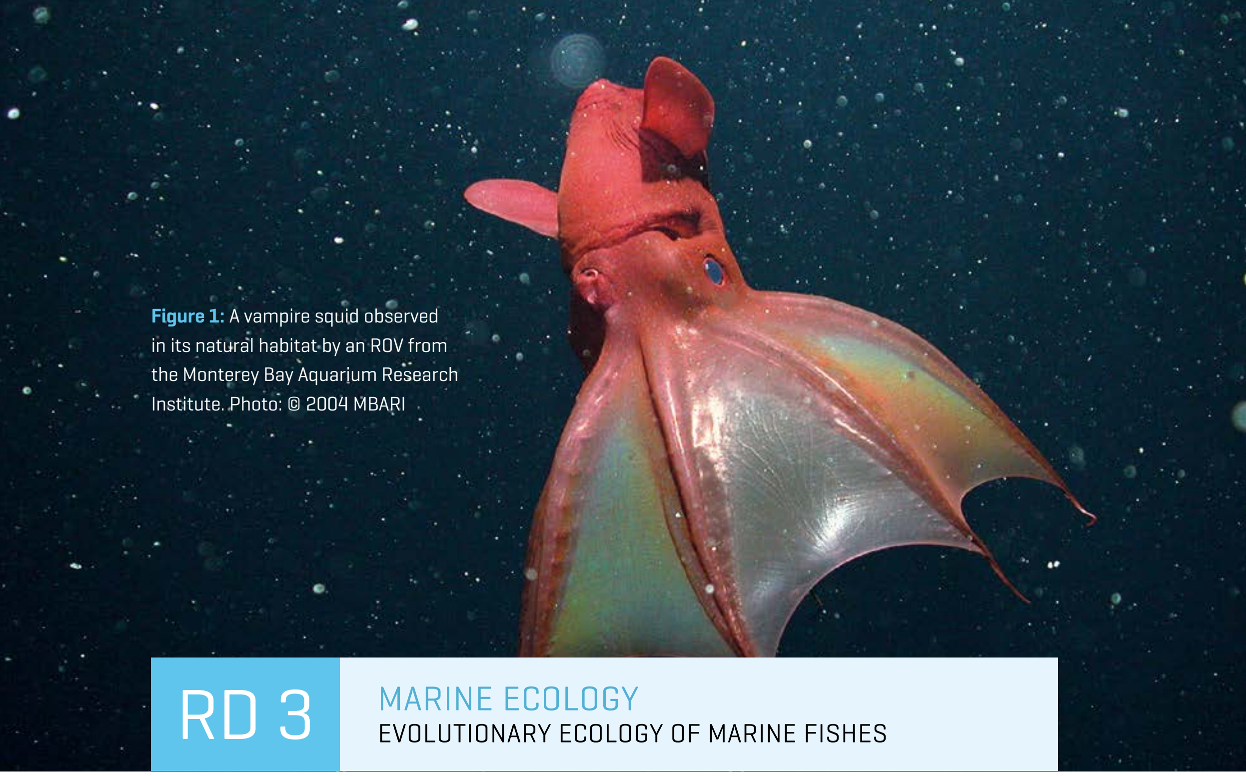

**Figure 1:** A vampire squid observed in its natural habitat by an ROV from the Monterey Bay Aquarium Research Institute. Photo: © 2004 MBARI



# Vampire squid reproductive strategy is unique among coleoid cephalopods

**Henk-Jan T. Hoving, Vladimir V. Laptikhovsky, Bruce H. Robison**



*The pelagic ocean, the water column above the ocean floor, is the largest yet least explored environment on the planet. While it is the habitat of vast numbers of organisms, all of which have a unique role in the ocean biogeochemical cycle and foodweb, for many species basic knowledge on their biology is still lacking. One group of organisms that is very abundant and successful in the pelagic and deep ocean, are cephalopods, a class of marine molluscs that are commonly known as octopus, squid and cuttlefish. As part of an ongoing international collaborative research effort to better understand the life history strategies of deep-sea cephalopods, the reproductive biology and life cycle length of vampire squid were investigated for the first time.*

The vampire squid *(Vampyroteuthis infernalis)* inhabits oceanic waters from 500-3000 m. Vampire squid have the lowest metabolic rates of all cephalopods, and an oxygen carrying protein with a relatively high binding affinity. They also have a reduced musculature compared to other, fast swimming, squids, suggesting that vampire squid are not strong swimmers. Unlike other cephalopods, which all hunt for living prey, vampire squid consume zooplankton and marine snow: dead and decomposing organic material that floats in the water column. This combination of biological traits likely enables vampire squid to live under low oxygen conditions, such as mesopelagic oxygen minimum zones. These zones are typically avoided by other fauna, resulting in a reduced abundance and diversity of zooplankton and nekton. Contrary to most other cephalopods, which generally have short life cycles and fast growth, the physiology and feeding ecology of the vampire squid suggest a slower pace of life, but to date no study had focused on the reproductive biology and longevity of this living fossil.

The general reproductive strategy of coleoid cephalopods (all cephalopods except the chambered Nautilus) is semelparity: there is one reproductive cycle after which the individual dies. Interspecific differences in spawning strategies do exist within the semelparous life history strategy; some species spawn batches of eggs or even individual eggs, sometimes over a protracted period of time, while other species spawn all their eggs at once and brood them for an extended period. Regardless of the number of spawning events, it is typical for the semelparous strategy in cephalopods that once the female produces eggs, she does not stop until she dies. In coastal cephalopods this single reproductive cycle is relatively short and completed in approximately 0.5-1.5 years. Semelparity is the opposite of iteroparity, which means that organisms have multiple reproductive cycles. After spawning, the gonads of iteroparous organisms return to a resting phase during which they accumulate energy (e.g. during a feeding migration) for a new reproductive cycle. Iteroparous organisms are typically longer-lived than semelparous organisms.

Using a rare collection of the Santa Barbara Museum of Natural History we performed a detailed analysis of the reproductive systems of more than 40 female vampire squid that were captured by pelagic trawl in the deep waters off southern California in the 1960s-1970s. We counted and measured the ovarian oocytes and eggs, as well as any empty follicles (empty sheets in which the ripe egg was covered before ovulation) inside the ovary of females of various sizes and reproductive states.

**Figure 2:** The deployment of a midwatertrawl, a similar but smaller version of the trawls with which the vampire squids were collected in southern Californian waters in the 60s and 70s. Image: Susan von Thun, MBARI

**Figure 3** The deep-sea cephalopod *Chiroteuthis calyx* brought back on board after being collected by MBARI's ROV Doc Ricketts. Image: Todd Walsh, MBARI



In many females, we found large numbers of empty follicles, which are evidence of previous spawning activity. However, these mature individuals did not have any ripe eggs in the ovary or oviducts, as would be expected in a mature female semelparous cephalopod. Instead the ovaries of these vampire squid were in a resting state. Such a reproductive condition has not been described for coleoid cephalopods, but is known from iteroparous fishes. Therefore vampire squid are not semelparous, but iteroparous with multiple reproductive cycles that are separated by a gonadal resting phase. The finding of a gonadal resting phase and hence iteroparity in vampire squid shifts the paradigm that all coleoid cephalopods are semelparous, and supports the slow pace of life suggested by its physiology and diet. But how long do vampire squid live?

**Figure 4:** Some of the preserved vampire squid which were used for this study, in jars ethanol, and accessioned in the Santa Barbara Museum of Natural History. Image: David Schultz

Our analyses showed that vampire squid could spawn approximately 100 eggs per spawning event. The most advanced female in our study had already spawned close to 3800 eggs, probably in 38 spawning events, and still had about 6500 eggs left for future spawning. If we estimate the time between the spawning events to be at least 1 month (gonadal resting time plus the time for ripening of the eggs) this would mean that the length of the period of the first 38 spawning events would be at least 3 years, with the potential 65 future spawning events further extending the life time of the vampire squid. These estimates of the life cycle length are much higher than what we know from shallow water cephalopods. They are, however, in line with recent observations that benthic deep-sea octopuses brood their eggs for longer than 4 years. Deep-sea octopuses and vampire squid may therefore have record lifespans among cephalopods.

We can only speculate about the selective pressures that have resulted in iteroparity and a relatively high longevity in vampire squid. The slow physiology, and the low-calory food on which vampire squid feed, may not enable the species to mobilize enough energy to produce the high short term fecundity characteristic for semelparity. We suggest that only the spreading of reproductive events, each separated by gonadal resting during which new energy for reproduction is accumulated, may allow the species to secure a sufficient life time reproductive output. According to life history theory, iteroparity is favored when adults are exposed to reduced mortality rates. With the ability to inhabit low oxygen environments, where predators are fewer, vampire squid may experience reduced adult mortality rates allowing for multiple reproductive cycles at low reproductive cost.

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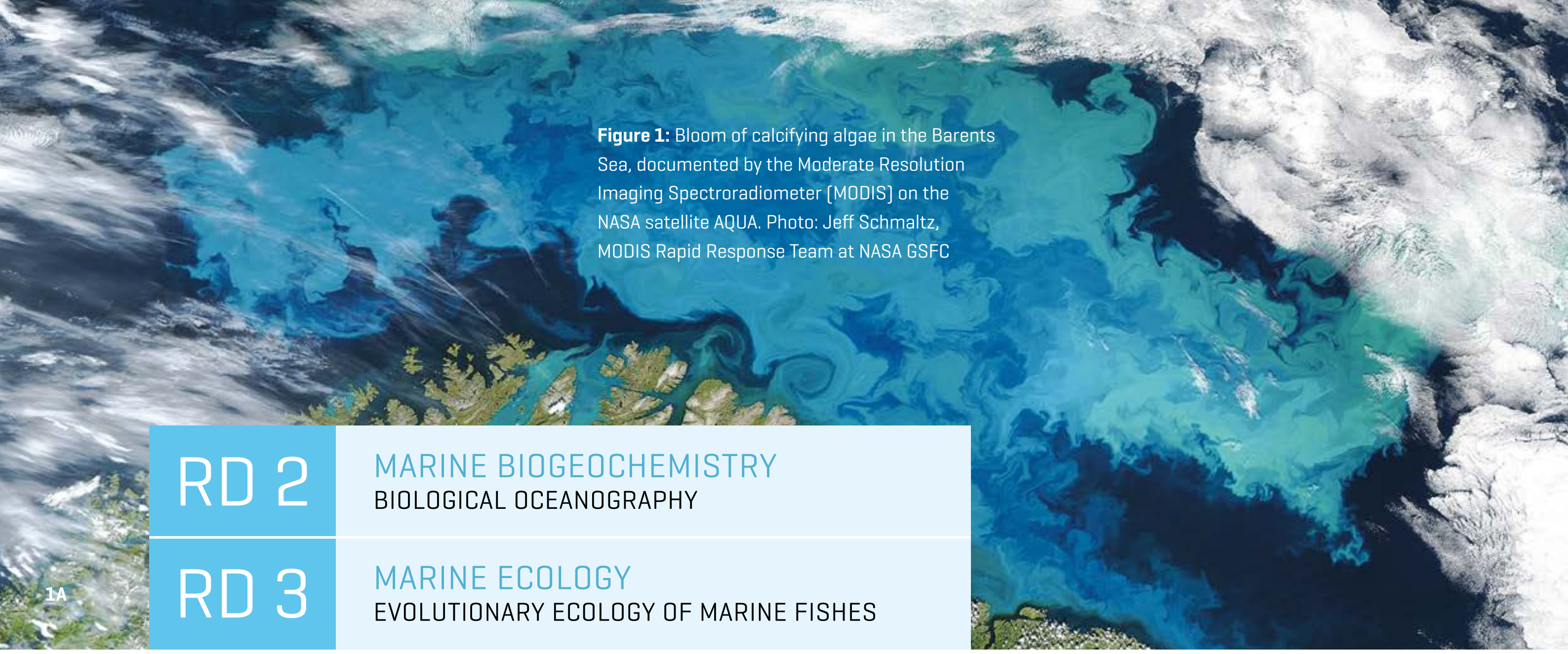


**Figure 1:** Bloom of calcifying algae in the Barents Sea, documented by the Moderate Resolution Imaging Spectroradiometer (MODIS) on the NASA satellite AQUA. Photo: Jeff Schmaltz, MODIS Rapid Response Team at NASA GSFC

RD 2 MARINE BIOGEOCHEMISTRY
BIOLOGICAL OCEANOGRAPHY

RD 3 MARINE ECOLOGY
EVOLUTIONARY ECOLOGY OF MARINE FISHES

# The organisms of tomorrow in today's experiment

## Unique laboratory experiment shows rapid evolutionary adaptation to ocean acidification and warming in the coccolithophore *Emiliania huxleyi*

**Lothar Schlüter (RD3), Kai T. Lohbeck (RD3), Magdalena A. Gutowska (RD2), Joachim P. Gröger, Ulf Riebesell (RD2) and Thorsten B. H. Reusch (RD3)**

*The single most important calcifying plankton algae of the world's oceans is able to simultaneously adapt to rising water temperatures and ocean acidification through evolution. A unique long-term experiment with the species Emiliania huxleyi at GEOMAR Helmholtz Centre for Ocean Research Kiel shows that the evolutionary potential of the algae is much greater than previously thought. In their laboratory evolution experiment, a group of scientists led by Prof Thorsten Reusch have shown for the first time that evolutionary adaptations to multiple stress factors do not necessarily interfere with each other. Further work will reveal how evolution in ocean microbes may affect the function of the ocean in removing carbon dioxide to the deep sea and whether or not laboratory findings can be translated into the natural ocean environment.*

In an unprecedented evolution experiment scientists from GEOMAR Helmholtz Centre for Ocean Research Kiel and the Thünen Institute of Sea Fisheries have demonstrated for the first time, that the single most important calcifying algae of the world's oceans, *Emiliania huxleyi*, can adapt simultaneously to ocean acidification and rising water temperatures. In their study, the researchers found no evidence for the widespread idea that evolutionary adaptations to these two aspects of climate change would interfere with each other.

Even although the experiment was conducted under laboratory conditions, it clearly shows the high potential for evolutionary adaptation in an oceanic microbe such as *Emiliania huxleyi*. Thus, predictions about the future ocean definitely have to take such adaptive changes into account.

The study was funded by the Kiel Cluster of Excellence "The Future Ocean" and the German research network BIOACID (Biological Impacts of Ocean Acidification).

Evolution experiments were initiated by isolating a single cell of *Emiliania huxleyi* from the Raunefjord in Norway in 2009. Since the alga reproduces by cell division about once per day in the laboratory, numerous genetically identical cultures could be derived from the isolate. Five cultures each were kept under control conditions (15°C) and at elevated water temperature (26°C) in combination with three different concentrations of carbon dioxide ($CO_2$): a control value with today's conditions, the conditions of the Intergovernmental Panel on Climate Change's worst case scenarios for the years 2100 and 2300.

After one year – corresponding to about 460 algae generations – the scientists tested how the adapted and the control populations reacted to the high temperature. Before growth responses and cell composition were assessed, care was taken that the control and the long-term temperature adapted populations were acclimatized to their test conditions so as to only address genetic changes but not plasticity. Within five-day test intervals, the high-temperature adapted populations grew significantly faster than the non-adapted at 26°C – regardless of the carbon dioxide level. The adapted cultures produced even more new biomass and about twice as many calcite platelets than the control group under the high temperatures.

In one part of their experiment, the researchers came to the surprising conclusion that the cultures that had been exposed to the highest $CO_2$ value and the highest temperatures at the same time for one year adapted fastest to the newly higher temperatures. Over several hundred generations, apparently those new mutations that are advantageous in conditions of both ocean acidification and warming

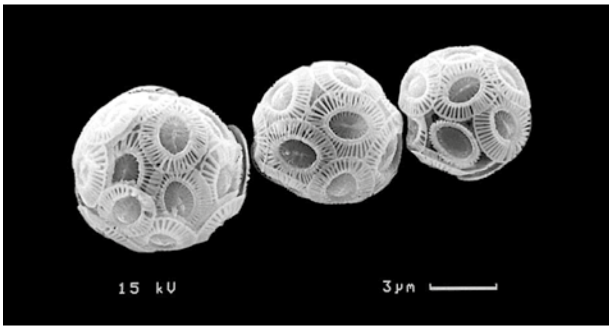


**Figure 2:** Three cells of *Emiliania huxleyi*. Photo: Kai T. Lohbeck, GEOMAR

emerged and swept through the population. $CO_2$ adaptation, which was shown previously in a study by Lohbeck et al. (Nat Geosci 2012) thus seems to pre-adapt populations to also adapt to warming.

Unicellular calcifying algae such as *Emiliania huxleyi* play an important role in the transport of carbon to the deep ocean. Therefore, the researchers analysed the mass ratio of the inorganic calcite platelets to the organic carbon inside the cells after the adaptation phase. It was nearly the same as that of the control population under current ocean conditions, implying that the evolutionarily adapted algae display the same specific weight as the original, isolated cultures under present-day conditions. The density of individual cells along with the overall productivity of the coccolithophore populations determine the ballast effect - the accelerated sinking of aggregates and fecal pellets by $CaCO_3$. Along with the restored population growth rate, this will help maintaining the ocean as a carbon sink. However, results should not be taken face value since in the real ocean the production of calcite platelets may also serve different functions such as protection against viruses or grazing.

In 2012, evolutionary ecologists at GEOMAR showed for the first time that *Emiliania huxleyi* is able to adapt to ocean acidification by means of evolution. Since then, the laboratory experiments were continued and refined. In fact, the world's longest and most complex experiment on this issue is running in GEOMAR laboratories. The lab results are now being integrated into biogeochemical models, which calculate the productivity of the ocean of the future and the limits of carbon storage. In addition, the findings on the evolutionary adaptation are being incorporated into an investigation of future phytoplankton species shifts. Finally, genetic DNA sequencing is underway to pinpoint those mutations that confer adaptation to warming and /or acidification.

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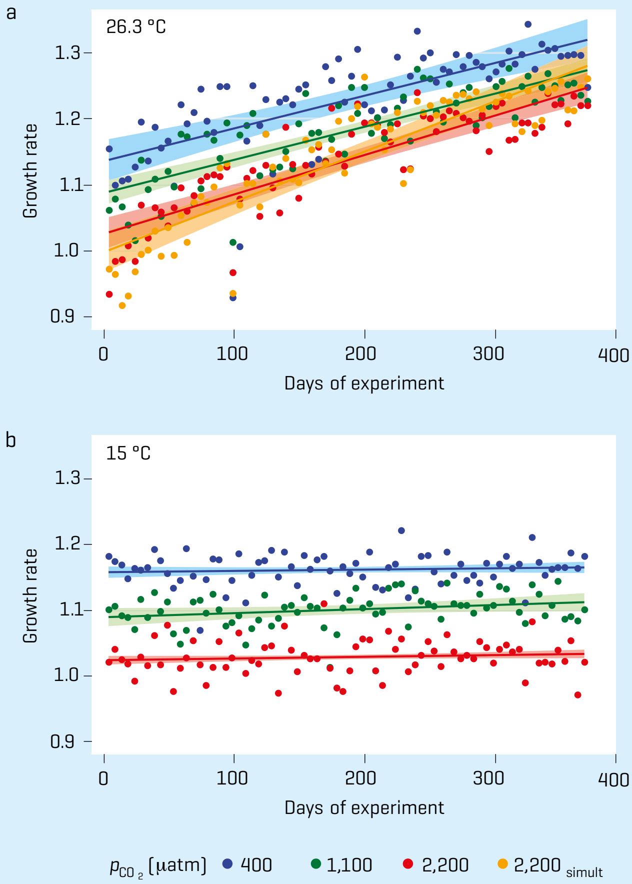


**Figure 3:** Time course of exponential growth rates in *Emiliania huxleyi* over one year subjected to different combinations of temperature and $CO_2$ concentration. Two temperatures, 26.3 °C (a) and 15.0 °C (b) were used in combination with three levels of $CO_2$ concentration simulating ocean acidification. Growth rates were calculated every five days. Fitted lines are based on an autoregressive moving average model that incorporates significant autocorrelation terms, shaded areas depict ±95% prediction intervals. All lines at 26.3 °C reveal highly significant slopes, whereas none of the slopes is significant at 15.0 °C.



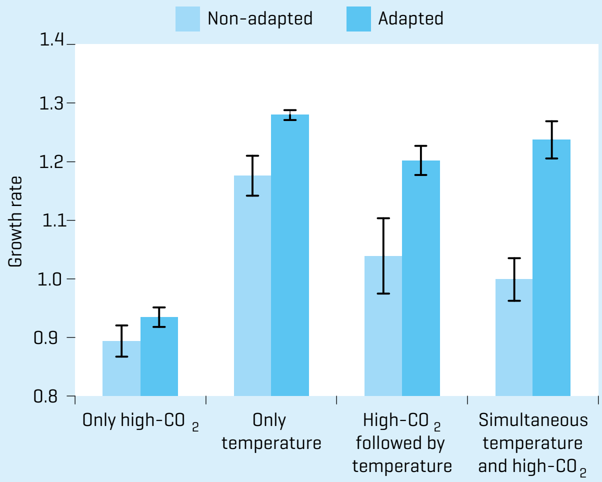


**Figure 4:** Evolutionary adaptation in *Emiliania huxleyi* to ocean acidification and to temperature alone, and to a combination of both factors. Mean growth rates of adapted asexual populations ±1 s.d. (dark bars) relative to their respective control treatments (light bars).

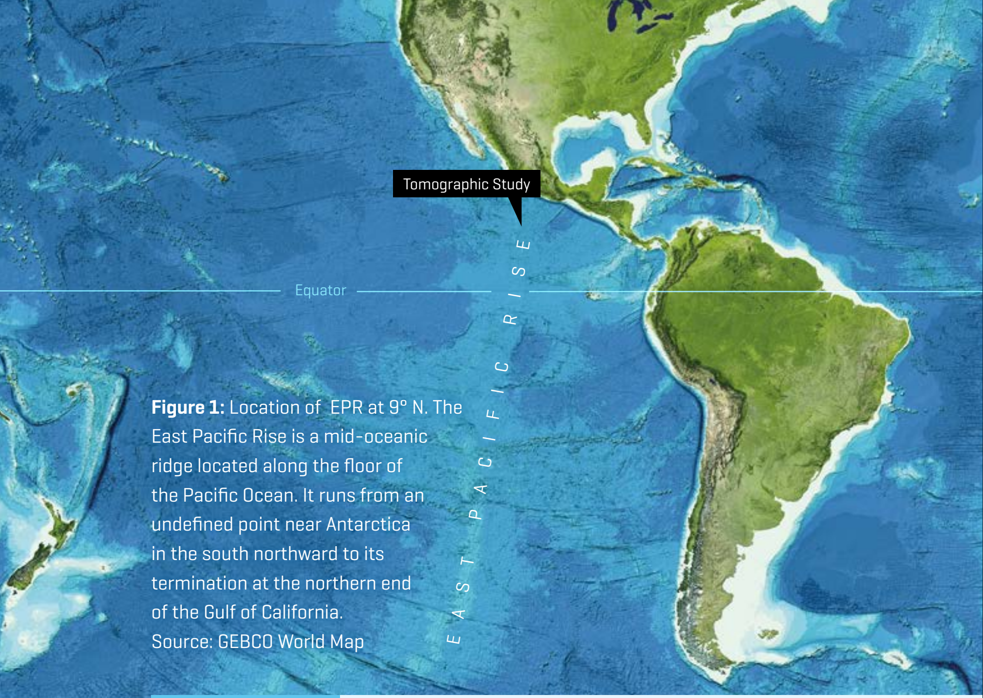


**Figure 1:** Location of EPR at 9° N. The East Pacific Rise is a mid-oceanic ridge located along the floor of the Pacific Ocean. It runs from an undefined point near Antarctica in the south northward to its termination at the northern end of the Gulf of California. Source: GEBCO World Map

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**Figure 2:** Hydrothermal vent in the deep sea. They occur along the boundaries of tectonic plates along the submarine volcanic chains. Where and how deep does seawater penetrate into the seafloor to take up heat and minerals before it leaves the ocean floor at these "Black Smokers"? Image: ROV-Team, GEOMAR

# Hybrid shallow on-axis and deep off-axis hydrothermal circulation at fast-spreading ridges



**Jörg Hasenclever, Sonja Theissen-Krah, Lars H. Rüpke, Jason P. Morgan, Karthik Iyer, Sven Petersen and Colin W. Devey**

*Hydrothermal flow at oceanic spreading centres accounts for about ten per cent of all heat flux in the oceans and controls the thermal structure of young oceanic plates. It also influences ocean and crustal chemistry, provides a basis for chemosynthetic ecosystems, and has formed massive sulphide ore deposits throughout Earth's history. Despite this, how and under what conditions heat is extracted, in particular from the lower crust, remains largely unclear.*

The fast-spreading East Pacific Rise (EPR) at 9° N is one of the best-studied ridge sections worldwide. Multichannel seismic studies between 9° N and 13° N image a nearly continuous sub-axial melt lens at depths of about 1.2 – 2.4 km. A tomographic study at 9° 30' N shows a narrow P-wave anomaly below the melt lens that is best modelled as a 4 – 5-km-wide, high-temperature region extending through the whole crust and only widening at depths below the crust – mantle boundary (Fig. 3a). Isotherms are steep near this 'hot slot' but become nearly horizontal further off-axis, consistent with field observations from the Oman ophiolite. Previous ridge-perpendicular two-dimensional (2D) hydrothermal flow models show that this implies hydrothermal convection through the entire crust that thereby alters the lower gabbros at some distance away from the ridge axis. This is in contrast to the conclusion, drawn from microearthquake distributions at EPR 9° N, that hydrothermal cells develop predominantly above the melt lens—a concept apparently supported by vent fluid chemistry studies and previous three-dimensional (3D) simulations of hydrothermal flow at fast-spreading ridges.

In Hasenclever et al. (2014) we present high-resolution, whole-crust, 2D (Fig. 3b,c) and 3D (Fig. 3d,e) simulations of hydrothermal flow beneath fast-spreading ridges that predict the existence of two interacting flow components that merge above the melt lens to feed ridge-centred vent sites. Shallow on-axis flow structures develop owing to the thermodynamic properties of water, whereas deeper off-axis flow is strongly shaped by crustal permeability, particularly the brittle – ductile transition. About 60 per cent of the discharging fluid mass is replenished on-axis by warm (up to 300 °C) recharge flow surrounding the up to 450 °C hot thermal plumes. The remaining 40 per cent or so occurs as colder and broader recharge up to several kilometres away from the axis that feeds very hot (500 – 700 °C) deep-rooted off-axis flow towards the ridge. Despite its lower contribution to the total mass flux, this deep off-axis flow carries about 70 per cent of the thermal energy released at the ridge axis, because of its higher temperatures compared to the on-axis thermal plumes.

This new hybrid (shallow on-axis plus deep off-axis) hydrothermal flow structure reconciles previously incompatible observations and models that suggested either strong on-axis or deeper ridge-perpendicular hydrothermal circulation. We find that both modes exist and naturally merge into a single hy-

[3b]

[3a]

[3c]

[3e]

[3d]

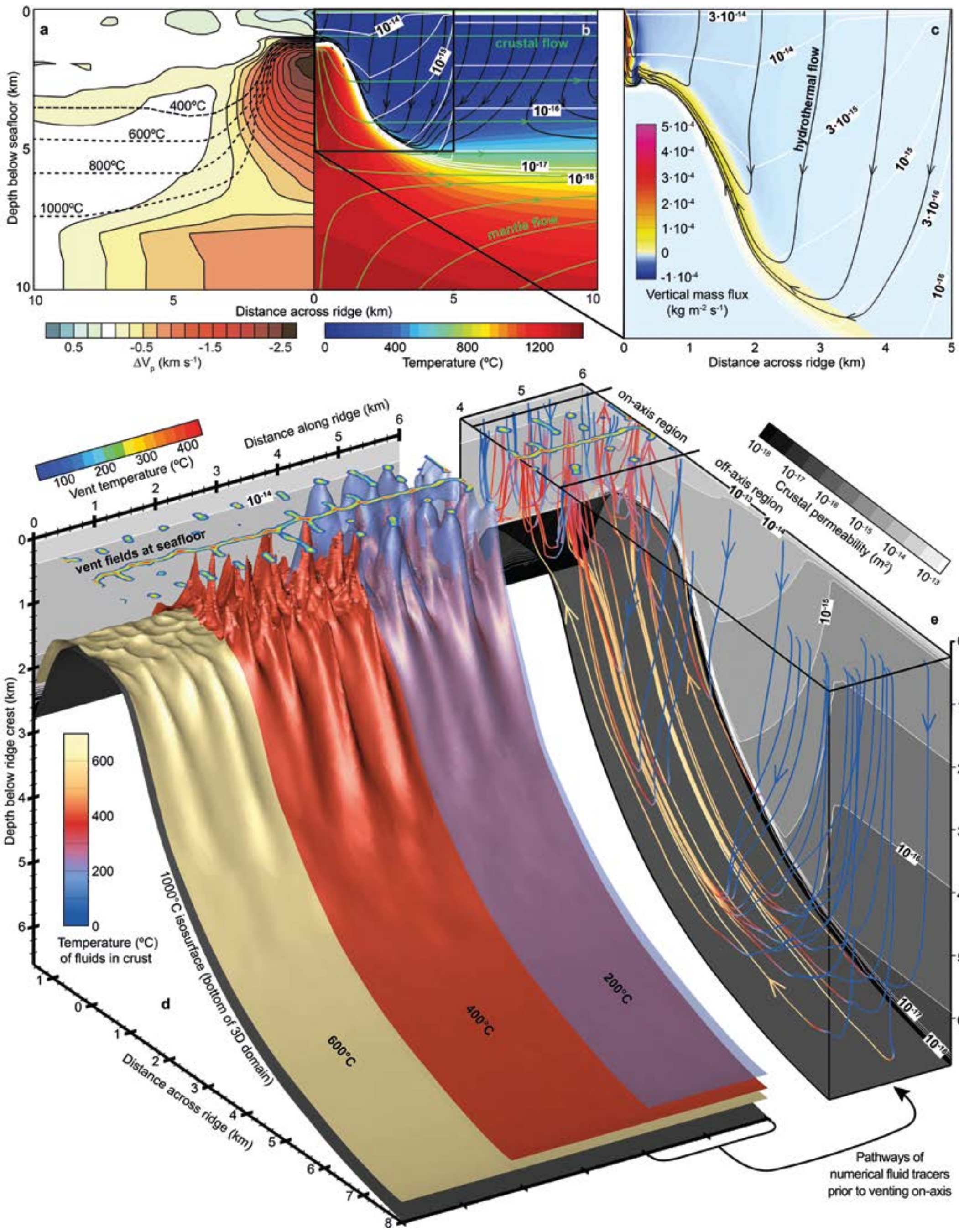


**Figure 3:**

[3a] Seismic and inferred thermal structure beneath the EPR at 9°N (re-drawn after Dunn et al., 2000)

[3b] Temperature field, flow of crust and mantle (green streamlines) and hydrothermal flow (black streamlines) predicted by a best-fitting 2D simulation

[3c] Vertical fluid mass flux in the 2D model

[3d] Thermal evolution and vent field locations in the 3D hydrothermal flow simulation

[3e] Flow paths of fluid tracers, colour-coded for temperature in a subsection of the 3D domain

brid flow structure in our whole-crust numerical experiments. The on-axis flow component is more vigorous and contributes slightly more to the total mass flux. It controls the depth of the axial melt lens and explains why high-temperature vent systems associated with fast-spreading ridges have so far been observed only directly on-axis. The deeper off-axis flow component carries most of the hydrothermal energy and is what makes the overall thermal structure of the young oceanic crust consistent with seismic tomography data and the pervasive crustal-scale hydrothermal circulation inferred from in situ analysis of the Oman ophiolite. Our results imply that the entire oceanic crust experiences extensive high-temperature hydrothermal circulation, providing a mechanism to scavenge elements not only from the upper but also from the lower crust.

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**Figure 1:** The west coast of Spitsbergen. Here the international research team investigated methane seeps on the ocean floor in the summer of 2012. Photo: Helge Niemann, University of Basel

**Figure 2:** Carbonate crusts at the observing site HYBIS at 385 metres water depth. For comparison: the white organisms in the right part of the picture have a length of about 15 cm. Carbonates of this size require several 100 years to build-up. Source: GEOMAR



# Gas hydrate dynamics off Svalbard

**Christian Berndt, Gareth Crutchley, Nathan Bangs and Matt Hornbach**

*Marine methane hydrate is an ice-like substance that is stable at high-pressure and low temperature in continental margin sediments. Since our discovery of a large number of gas flares at the landward termination of the gas hydrate stability zone off Svalbard in 2008 [Figure 1], there has been concern that warming bottom waters have started to dissociate large amounts of marine gas hydrate and that the resulting methane release may possibly accelerate global warming.*

This spurned a major collaborative program between the GEOMAR, the National Oceanography Centre Southampton, IFREMER, the University of Tromsø, MARUM (Bremen), and the University of Basel, Switzerland. In 2010 we deployed a sea floor observatory using the Norwegian vessel Jan Mayen. In 2011 we serviced the observatory with the British vessel RRS James Clark Ross, and we retrieved it during a Maria S. Merian cruise in 2012. At the same time we conducted a larwge number of marine geophysical and geological experiments including dives with the manned submersible JAGO, heat flow measurements, seismic investigations, sediment coring, and water column sampling.

The results show that hydrates play a role in the observed seepage of gas, but by analyzing carbonate samples collected by JAGO (Figure 2) and with gravity cores, we could show that seepage off Svalbard has been ongoing for at least three thousand years and that seasonal fluctuations of 1-2°C in the bottom-water temperature cause periodic gas hydrate formation and dissociation, which focus seepage at the observed gas flare depth.

Our findings imply that decadal scale warming of the West Svalbard Current is at most of minor importance for the observed seepage and that the seeps in Svalbard do not necessarily represent the beginning of large-scale hydrate dissociation in the Arctic. But, it also shows that hydrate is highly sensitive to bottom water temperature changes and that bottom water warming will affect the stability of any large hydrate accumulations in the uppermost sediments on a short time scale. Thus, the observation of gas flares off Svalbard is not proof that anthropogenic warming of the ocean is already affecting the gas hydrate system, but it is possible that part of the escaping methane results from long-term warming of the gas hydrate system in addition to the seasonal changes.

Building on these findings we have successfully secured funding and ship time to drill the gas hydrate system off Svalbard in the summer of 2014. We will attempt to take pressure cores at the edge of the gas hydrate stability zone to sample hydrate and prove that the gas flares are related to the hydrate system. The pressure cores will also allow to determine the amount of hydrate in the part of the margin that is sensitive to bottom

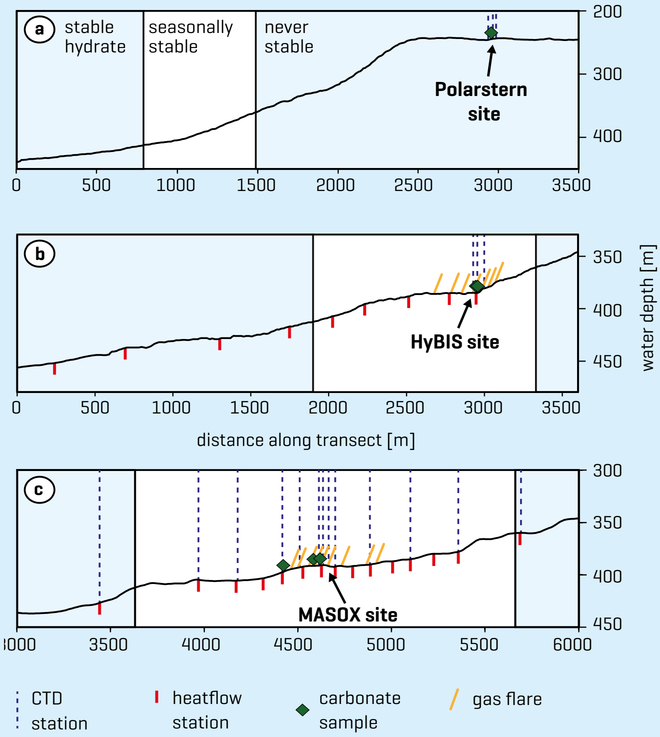


**Figure 3:** Off the coast of Svalbard the submersible JAGO is lowered into the water from the research vessel MARIA S. MERIAN. Photo: Karen Hissmann, GEOMAR

water temperature changes which will be the basis for robust assessments of the amount of methane that may be released, and it will allow to determine the distribution of hydrate in the sediment which is the main control on the time that it takes to dissociate hydrate. Finally, the drilling will provide information on the long-term temperature history of the area to establish if has already started to warm as suggested by paleoceanographic studies.

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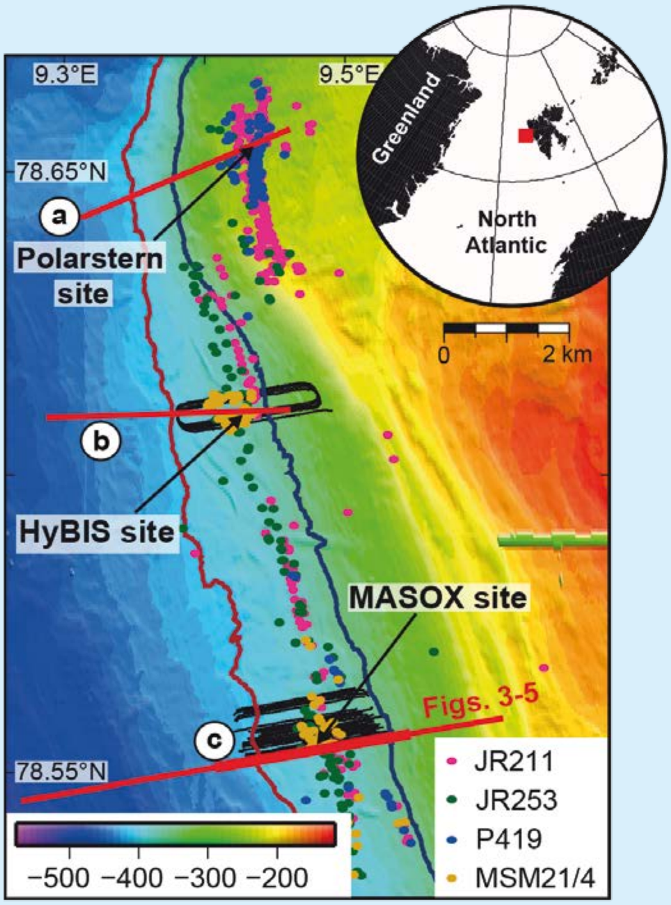
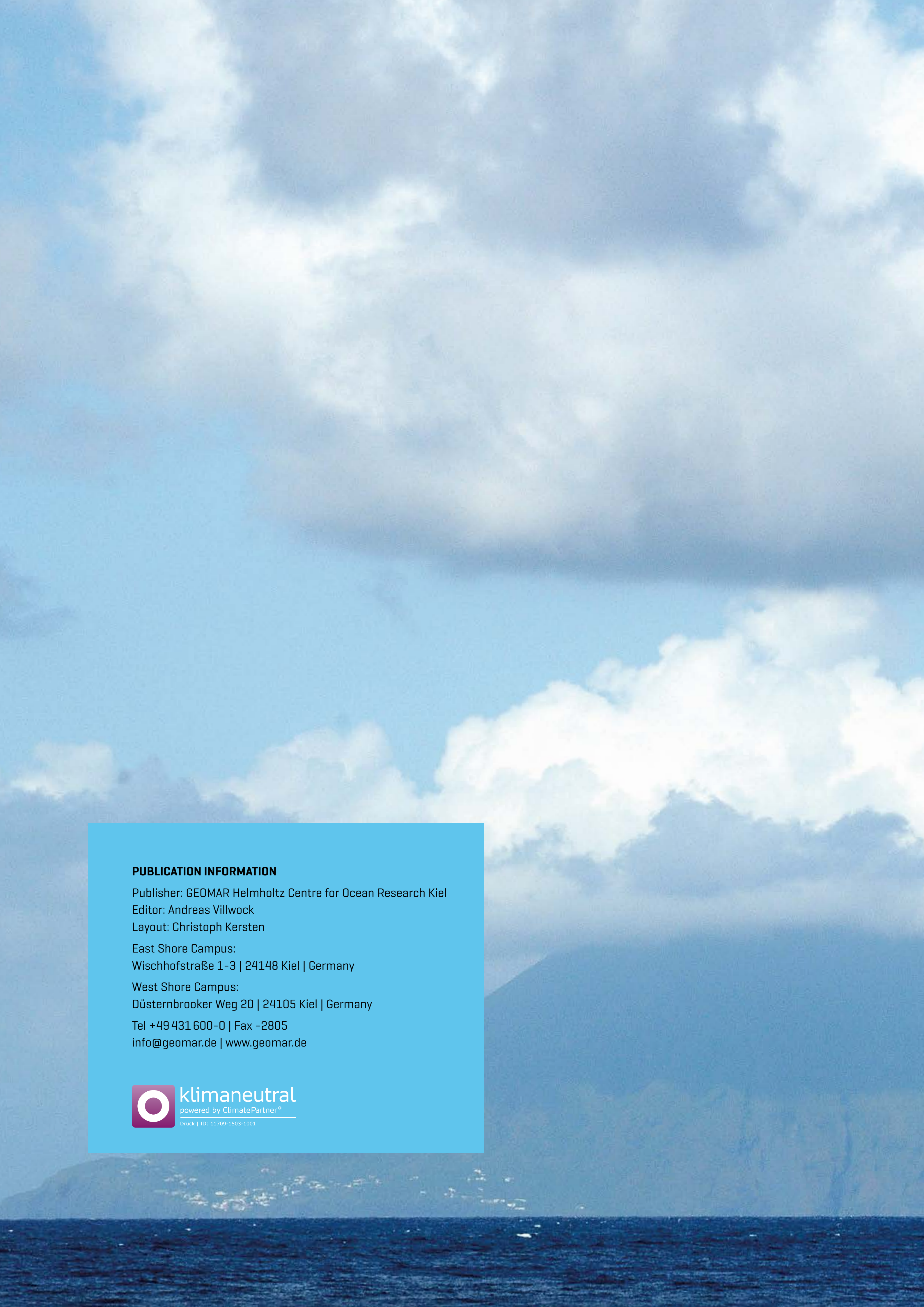



**Figure 4:** Area of investigations west of Svalbard. During several expeditions observations were performed. The colored dots mark gas seeps, the three named sites mark locations where dives took place. Source: GEOMAR

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