Cluster of Excellence / Exzellenzcluster

THE FUTURE OCEAN
OZEAN DER ZUKUNFT

2006 - 2019

EXC 80

Final Report / Abschlussbericht

CAU Kiel University Christian-Albrechts-Universität zu Kiel
ifw
muthesius kunsthochschule
GEOMAR

Final Report

Cluster of Excellence

The Future Ocean

Ozean der Zukunft

EXC 80

Excellence Initiative / Exzellenzinitiative

Final Report / Abschlussbericht

Cluster of Excellence / Exzellenzcluster

The Future Ocean

Ozean der Zukunft

Christian-Albrechts-Universität zu Kiel

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Final Report for Cluster of Excellence

The Future Ocean

Ozean der Zukunft

EXC 80

Host university: Kiel University

CAU – Kiel University
President
Prof. Dr. Lutz Kipp
Christian-Albrechts-Platz 4
24118 Kiel
E: praesident@praesidium.uni-kiel.de
T: +49 431 880-3000

Coordinator of the Cluster
Prof. Dr. Martin Visbeck
GEOMAR Helmholtz Centre for
Ocean Research Kiel
Düsternbrooker Weg 20
24105 Kiel
E: mvisbeck@geomar.de
T: +49 431 600-4100

Prof. Dr. Lutz Kipp

Prof. Dr. Martin Visbeck

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List of abbreviations

AGU	American Geophysical Union
AMOC	Atlantic Meridional Overturning Circulation
AvH	Alexander von Humboldt Foundation
CAU	Kiel University
CCS	Carbon Capture and Storage
CDR	Carbon Dioxide Removal
CE	Climate Engineering
CVOO	Cape Verde Ocean Observatory
ECO2	Sub-seabed CO_2 Storage: Impact on Marine Ecosystems
EdX	platform for education and learning founded by Harvard and MIT with more than 20 million learners
EEZ	Exclusive Economic Zone
EGU	European Geophysical Union
ERC	European Research Council
EU	European Union
FAO	Food and Agriculture Organization of the United Nation
GEOMAR	GEOMAR Helmholtz Centre for Ocean Research Kiel
IASS	Institute for Advanced Sustainability Studies e.V., Potsdam
ICES	International Council for the Exploitation of the Sea
IfW	Kiel Institute for the World Economy
IMAGES	International Marine Past Global Change Study
IOC	International Oceanographic Commission
IPCC	Intergovernmental Panel on Climate Change
IPN	Leibniz Institute for Science and Mathematics Education
ISOS	Integrated School of Ocean Sciences
IMAP	Integrated Marine Postdoc Network
INDP	Instituto Nacionale de Desenvolvimento das Pescas
JRG	Junior Research Group
KCM	Kiel Climate Model
KDMI	Kiel Data Management Infrastructure
KMS	Kiel Marine Science – Centre for Interdisciplinary Marine Science at Kiel University
KOB	Kiel-Outdoor-Benthocosms
LDEO	Lamont-Doherty Earth Observatory at Columbia University
MKH(S)	Muthesius University of Fine Arts and Design
MOOC	Massive Open Online Course
MSY	Maximal Sustainable Yield
NMR	Nuclear Magnetic Resonance
OSIS	Ocean Science Information System
ODP	Ocean Drilling Program
OMZ	Oxygen Minimum Zone
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
OUC	Ocean University of China, Qingdao
PETM	Paleocene Eocene Thermal Maximum
PI	Principle Investigator
RD	Research Divison
SCOR	Scientific Committee on Oceanic Research
SDG	Sustainable Development Goals
SDG 14	Conserve and sustainably use the oceans, seas and marine resources for sustainable development
SLR	Sea level rise
SML	Ocean Surface Microlayer
SOLAS	Surface Ocean Lower Atmosphere Study
SST	Sea Surface Temperature
TAC	Total Allowable Catch
UCLA	University of California
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Sea
UNEP-GRID	United Nations Enviroment Programme (UNEP) Collaborating Centre on Environmental Knowledge
UNESCO	The United Nations Educational, Scientific and Cultural Organization
WCED	World Commission on Environment and Development
WCRP	World Climate Research Programme
WOR	World Ocean Review
WSI	Walther Schücking Institute for International Law
ZBW	Leibniz Information Centre for Economics
ZMB	Center for Molecular Biosciences at Kiel University

1 GENERAL INFORMATION

1.1 SUMMARY

Covering about 70% of the earth's surface the ocean will play a pivotal role in achieving sustainable future of humanity. The ocean hosts our largest ecosystem, exerts a major influence on the global climate and provides living and non-living resources. The Cluster of Excellence "The Future Ocean" has used the results of multidisciplinary scientific research on the past and present ocean to predict the future of the Earth's marine environment. This involves understanding changes to the ocean as well as the interaction between society and the ocean with regards to marine resources, services and risks. This mission carries with it an obligation to develop and assess scientifically-based global and regional ocean governance options, taking their legal, economic and ethical aspects into account. Within the Cluster of Excellence "The Future Ocean" marine scientists across eight faculties at Kiel University and three partner institutions in Kiel have built up an integrated research environment, advanced world leading ocean science, published a large number of scientific paper, initiated new national, European and international initiatives to advance ocean science in the context of solutions to address the challenges on the changing ocean.

During the two phases, the Kiel research network has grown to 323 members of which 35% are female and 30% international, 55 PIs have worked within the Cluster, and in total the Cluster had 120 fulltime employees with 56% females. The first phase of the Cluster focused on investigating ocean change and reevaluating both the ocean's potential and the risks involved. New research teams have been established to bridge existing disciplines and encourage marine-related research across a broader range of disciplines and faculties. The second phase of the Cluster focused on achieving a deeper interdisciplinary understanding of the ocean system, predicting possible future states of the ocean, and advancing the science around improved ocean management regimes and made contributions to the ocean dimension of the UN's Sustainable Development Goals.

The Cluster has advanced public outreach and stakeholder dialogue in order to improve the understanding of the need for a more sustainable human-ocean interaction. The Cluster's structural impact on Kiel University has firmly established the Kiel Marine Science (KMS) as a research priority area within the University. KMS has established a productive partnership with other Kiel based institutions (GEOMAR, IfW and Muthesius University) and several of the Cluster's activities have provided successful role models for improved knowledge exchange, research-oriented education, and early career support. Moreover, the important role of early career scientists and challenging career perspectives and support within the German research system has been recognized.

ZUSAMMENFASSUNG

Im Exzellenzcluster „Ozean der Zukunft" erforschen Wissenschaftlerinnen und Wissenschaftler aus acht Fakultäten der Christian-Albrechts-Universität zu Kiel (CAU), dem GEOMAR, des Institut für Weltwirtschaft und der Muthesius Kunsthochschule gemeinsam die Veränderungen des Ozeans und seine Dienstleistungen mit einem fächerübergreifenden Ansatz und in einer einmaliger Breite. So wurde über die Clusterlaufzeit eine disziplinübergreifende Forschungsumgebung aufgebaut, in der Forschende aus den Bereichen Meeres- und Geowissenschaften, Umweltökonomie, den Rechts- und Nanowissenschaften, aus der Medizin, der Mathematik, Informatik, mit Ingenieuren und Wissenschaftlerinnen und Wissenschaftlern aus den Politik-, Gesellschafts- und Sozialwissenschaften eng zusammenarbeiten, zahlreiche wissenschaftliche Arbeiten veröffentlichten, und neue nationale, europäische und internationale Initiativen entwickelten, um nachhaltige Lösungen für die Herausforderungen des sich wandelnden Ozeans zu entwickeln.

Über die beiden Phasen ist das Kieler Forschungsnetzwerk auf 323 Mitglieder, davon 35% weibliche und 30% international, angewachsen. Im Cluster haben 55 PIs geforscht und insgesamt 67 Mitarbeiterinnen und 53 Mitarbeiter waren Vollzeit beschäftigt. In der ersten Förderphase (2006-2012) ging es vor allem darum, in verschiedenen Forschungsprojekten die grundlegenden Prozesse im Ozean besser zu verstehen. Ziel war es, den Ozeanwandel zu erforschen und die Risiken und Chancen seiner Ressourcennutzung neu zu bewerten; dazu wurden instituts- und disziplinübergreifende Forschungsteams eingerichtet.

In der zweiten Förderphase (2012-2019) lag der Fokus auf einer stärkeren interdisziplinären Ausrichtung. Dabei führte das grundsätzliche Verständnis des Ozeans zu wissenschaftlich fundierten Vorhersagen und Szenarien, um – in engem Dialog mit Entscheidungsträgern – zu einem nachhaltigen Management des Ozeans im Kontext der Ziele der Vereinten Nationen für nachhaltige Entwicklung beizutragen.

Der Cluster hat durch Öffentlichkeitsarbeit und den Dialog zwischen den Interessenträgern für meereswissenschaftliche Themen das Verständnis für die Notwendigkeit einer nachhaltigeren Interaktion zwischen Mensch und Ozean verbessert. Strukturell konnten die Kieler Meereswissenschaften innerhalb der Clusterlaufzeit als Forschungsschwerpunkt innerhalb der Universität fest etabliert werden: Kiel Marine Science (KMS). KMS hat eine produktive Partnerschaft mit anderen Kieler Institutionen (GEOMAR, IfW und Muthesius) etabliert und einige Clusteraktivitäten dienen erfolgreich als Vorbilder für einen verbesserten Wissensaustausch mit der Gesellschaft und mit Ozeanthemen befassten Akteuren aus Politik und Wirtschaft. Darüber hinaus wurde die wichtige Rolle von Nachwuchswissenschaftlerinnen und Nachwuchswissenschaftlern und herausfordernden Karriereperspektiven und -unterstützung innerhalb des deutschen Forschungssystems sichtbar gemacht und unterstützende Maßnahmen weiterentwickelt.

1.2 KEY DATA

1.2.1 HOST, SPEAKER AND OTHER PARTICIPATING INSTITUTIONS

Table 1: Participating institutions (second funding period)

Host university	Location
Christian-Albrechts-Universität zu Kiel	Christian-Albrechts-Platz 4 24118 Kiel
Participating university	**Location**
Muthesius Kunsthochschule	Legienstr. 35 24103 Kiel
Participating non-university research institutions	**Location**
GEOMAR Helmholtz-Zentrum für Ozeanforschung Kiel	Wischhofstr. 1-3 24148 Kiel
Institut für Weltwirtschaft Kiel (IfW)	Kiellinie 66 24105 Kiel

1.2.2 OVERVIEW OF THE CLUSTER'S STRUCTURE

Table 2: Structure of the Cluster

	Unit	Title	Research discipline & direction	Project leader, institute, location
E*	**A** **→R**	Research: Greenhouse Oceans	Atmospheric chemistry, benthic biology, biogeochemistry, computer sciences, ecology, economics, geochemistry, geology, geophysics, law, mathematics, medicine, meteorology, oceanography, physical chemistry, physiology	**Prof Dr. A. Oschlies** RD2 Marine Biogeochemistry, GEOMAR **Prof. Dr. F. Temps** Inst. of Physical Chemistry, CAU
E*	**B** **→R**	Research: Resources and Risks	Biogeochemistry, botany, chemistry, computer sciences, economics, fisheries, genetics, geochemistry, geography, geology, geophysics, geotechnology, hydrogeology, law, mathematics, molecular biology, oceanography, seismology, sociology, zoology	**Prof. Dr. T. Requate** Inst. of Economics, CAU **Prof. Dr. U. Sommer** RD3: Marine Ecology, GEOMAR
E*	**P** **→S**	Research Platforms	All disciplines of A and B with emphasis on: > Ocean Observing Systems > Isotope & Tracer Analysis > Molecular Bioscience Technologies > Numerical Simulation & Management	**Prof. Dr. T. Bosch** Inst. of Zoology, CAU **Prof. Dr. A. Eisenhauer** RD2 Marine Biogeochemistry, GEOMAR **Prof. Dr. A. Körtzinger** RD2 Marine Biogeochemistry, GEOMAR **Prof. Dr. A. Srivastav** Inst. of Informatics, CAU
	Z **Parts of Z** **→S**	*Central Management*		**Prof. Dr. R. R. Schneider,** Inst. of Geosciences, CAU **Prof. Dr. M. Visbeck** RD1 Ocean Circulation and Climate Dynamics, GEOMAR
N*	**R**	Research: Future Ocean	Applied mathematics, coastal geography, chemistry, computer sciences, economics, environmental ethics, fine arts, geophysics, international law, marine biogeochemistry, marine ecology, marine geology, medicine, meteorology, molecular biology, physical oceanography, politics, zoology	**Prof. Dr. G. Klepper** RD Environment and Natural Resources, IfW **Prof. Dr. M. Latif** RD1 Ocean Circulation and Climate Dynamics, GEOMAR **Prof. K. von der Decken (Odendahl)** WSI – Int. Law, CAU **Prof. Dr. T. Requate** Inst. of Economics, CAU **Prof. Dr. U. Riebesell** RD2 Marine Biogeochemistry, GEOMAR **Prof. Dr. R. Schmitz-Streit** Inst. of Microbiology, CAU **Prof. Dr. F. Temps** Inst. of Physical Chemistry, CAU **Prof. Dr. K. Wallmann** RD2 Marine Biogeochemistry, GEOMAR
N*	**S**	Science Support	> International Cooperation > Knowledge Exchange > Education & Careers > Research Platforms > Project Support, (see also Z)	**Prof. Dr. R. R. Schneider** Institute of Geosciences, CAU **Prof. Dr. M. Visbeck** RD1 Ocean Circulation and Climate Dynamics, GEOMAR

* Units included in second phase are marked with N(ew). Units that have not be continued past the end of the first funding phase are marked with E(nded).

2 RESEARCH

The two phases of the cluster of excellence "The Future Ocean" (from 2006 to 2012 and from 2012 to 2019) provide an asset of scientific achievements. The first phase of the Cluster focused on investigating ocean change and re-evaluating both the ocean's potential and the risks involved. Thirteen new research teams on dedicated research topics (A1→A7 and B1→B6, Fig.1) were established, headed by a fixed-term professor and equipped with a significant start-up package. These teams bridged existing disciplines and also expanded marine-related research into new disciplines and faculties.

The second phase of the Cluster focused on moving from multidisciplinary science to a deep interdisciplinary understanding of the ocean system, predicting possible future states of the ocean, and developing improved ocean governance regimes. A significant number of postdoctoral research projects, often involving teams with established scientists, have addressed specific questions on eleven scientific topics within the research programme (R1→R11, Fig.1). Groundbreaking publications have been included in Appendix A, section 7.1. The scientific achievements have further been published by means of a dedicated special publication (→ Appendix A, section 7.2).

Cluster Phase I (2006-2012)

Cluster Phase II (2012-2019)

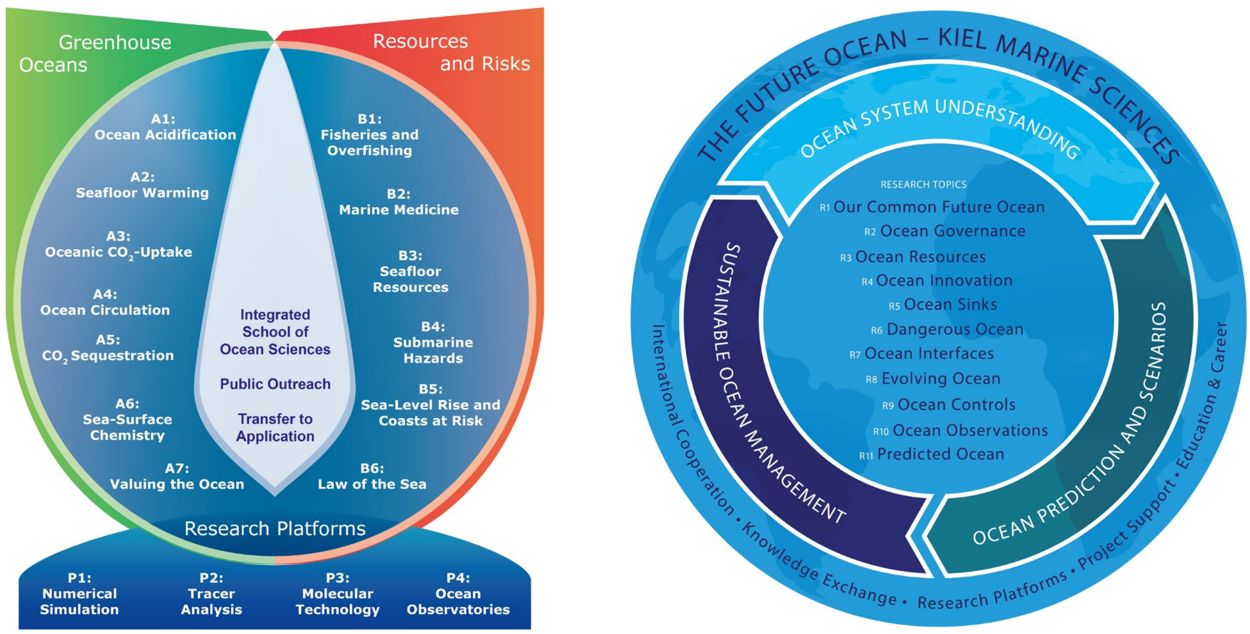

Figure 1: Research programmes with integrated research topics in the two phases of “The Future Ocean”.

Table 3: Major objectives and measures

Phase I & II Aims	Measures	Results of the 1st funding period	Results of the 2nd funding period
Establish new interdisciplinary marine research groups between the CAU, GEOMAR, IfW and MKH.	Identified 14 new research topics that required multidisciplinary investigation. Advertised 14 junior research group (JRG) tenure track professorships (W1/W2). Provided each JRG with a start-up package of 800 k€.	Installed 13 JRG leaders within the first 18 months. They immediately assembled multidisciplinary research teams and delivered exciting research results. All groups made significant progress and established new marine research areas in Kiel.	Established 11 research topics (R1-R11) that required interdisciplinary and partially transdisciplinary investigation. We executed 73 projects that were selected from a quality-controlled application process. The execution of these projects required the establishment of 51 postdoctoral research positions lasting usually two but in some cases up to five years. During the second phase some 5,000 peer-reviewed articles (137 in Science, Nature and Nature journals) were published from the Cluster's research with varying percentages of cluster funding.
Improve the understanding of ocean changes in response to human activities.	Support JRG with core resources. Provide internal mini-proposal funding to Cluster members. Enhance the observational, analytical and computing infrastructure.	New scientific findings include: a low risk of catastrophic gas hydrate melting and associated release of methane into the atmosphere by deep ocean warming, and testing climate models taking into account mismatches between simulations and proxy data for past climate change.	New scientific findings include: improved ocean observation technologies by interlinking different platforms. Establishment of new technology to observe the ocean. Improved understanding of the economic, legal and ethical dimension of human-ocean interactions.
Provide the scientific basis to develop, implement sound global and regional ocean management options.	Support JRG with core resources. Provide internal mini-proposal funding opportunities to Cluster members. Incorporate social science in Kiel Marine Science.	New findings include: Current fishing practices within the EU were found to be non-sustainable. New management options were developed based on the consideration of ecological economic, and legal aspects. The Cluster findings were well received by the EU regulatory bodies.	New findings include: identification of trade-offs from multispecies approach in fisheries management, characterization of the socially optimal exploitation paths for a resource stock.
Build capacity to reliably predict the risks associated with ocean change and natural hazards.	Support JRG with core resources. Provide internal mini-proposal funding opportunities to Cluster members. Enhance the computing and observational infrastructure.	New scientific findings include: Improved methods to assess the realism of biogeochemical models by optimally determining their action parameters. Reevaluation of large tsunami risks triggered by massive submarine mass flow.	New scientific findings include: determination of the long-term variability effects on sea level projections and their regional specificity. Risk assessments of tsunami prone regions and evaluation of emergency procedures.

Explore new marine resources and develop strategies for their sustainable use.	Support JRG with core resources. Provide internal mini-proposal funding opportunities; offer observational, computing and analytic facilities. Incorporate social science in Kiel Marine Science.	New scientific findings include: Analysis of gas-hydrate deposit formation allowed an improved estimate of their global abundance. Analysis of costs versus profits of submarine gashydrates or polymetallic deposit mining. Assessment of leakage risks for submarine CO_2 sequestration.	New scientific findings include: analysis of economic drivers of change for fisheries management, high-resolution and 3D-numerical modelling of the fundamental processes driving hydrothermal convection on the modern seafloor.
Enhance marine-oriented research and education in Kiel.	Establish a graduate school as a structural platform for doctoral education and training in interdisciplinary marine sciences and improve recruitment and mobility between German and international partners.	ISOS was implemented as an open graduate school with more than 120 PhD enrolled for multidisciplinary non-curricular marine science training. ISOS provides professional supervision, personal mentoring, and financial incentives. ISOS serves as a recruitment platform and facilitates international exchange of PhD. ISOS serves as a model for development of university graduate education.	In addition to graduate education in ISOS the Cluster expanded in marine-oriented research and education. An Ocean Education initiative was launched with the long-term objective to establish a cross-faculty Master School for Marine Sciences. Within the framework of cluster related semester topics, nine lecture series were offered crediting to the academic achievements of the students. ISOS together with the SDG Academy in New York and the International Ocean Institute in Malta developed the first Massive Open Online Course (MOOC) on the ocean. The Ocean MOOC has been broadcast twice, in 2016 and 2017, and reached a total of 6,500 registered participants from 62 countries.
Provide interfaces to the general public, stakeholders, non-governmental and scientific organizations as well as marine-oriented industry.	Communicate Kiel Marine Sciences in innovative ways. Promote new results in print, radio and film media. Publish books, brochures and web-based material produced for the public at large.	Developed an innovative marine science exhibition that successfully toured Germany, produced an assessment cooperation with the publisher *mare* and the International Ocean Institute (IOI) entitled 'World Ocean Review'; implemented first Kid's University in Kiel, and strengthened a range of school outreach activities. Regularly called upon to advise the German and EU administrators on marine issues. Initiated and conducted joint projects with industry partners to develop maritime technology.	Kid's university Kiel (with 53 lectures and 19,000 tickets sold) laid foundation stone for ocean:lab and Kieler Forschungswerkstatt with new forms of classroom education on marine topics. Conducted a number of citizen science projects, including an online platform to upload images of coasts to a world map, two data collection projects for pupils on marine plastics at the seashore and along riverbanks, a hybrid approach of machine learning and citizen science to identify plankton from 3 million individual images.

Phase I & II Aims	Measures	Results of the 1st funding period	Results of the 2nd funding period
Establish Marine Science as a research priority area at the CAU.	Promote marine research to CAU scientists traditionally not engaged in marine sciences. Place strategic working groups across institutes and faculties to develop, strengthen and sustain marine research at the CAU and its partner institutions.	The CAU has declared Marine Science as one of four research priority areas in 2009 and awarded nine times tenure for W1/ W2 professors held by Cluster JRG leaders in the areas of mathematics, coastal geography, physical chemistry, paleo-modeling, benthic biogeochemistry, marine medicine, resource economics, and seafloor resource modeling.	Kiel Marine Science, the Centre for Interdisciplinary Marine Science was formally established as a research priority area at Kiel University with a managing office as a central unit in the CAU administration.
Implement research management tools for interdisciplinary research priority areas across CAU and partner institutions.	Evolve the Cluster office to the central management of the Marine Sciences research priority area in Kiel by establishment of new governance, research communication, and academic training structures.	Established the Future Ocean Cluster Office at the Department for strategy and Research of the CAU administration to support the Cluster's implementation of science and new structural developments. Developed the concept for a Kiel Academy of Interdisciplinary Marine Sciences (KAIMS) and began its implementation in 2011.	CAU established the Schleswig-Holstein Alliance for Excellent Research as a science hub of the federal state of Schleswig-Holstein with two research universities and eleven non-university research institutions of the Leibniz Association, the Helmholtz Association and Max Planck Society and the European S-Ray Free-Electron Laser facility. The Kiel Alliance of Interdisciplinary Marine Sciences (KAIMS) is supporting the Future Ocean network building on the 12-year long cooperation resourced by the Future Ocean Cluster.

Phase II Aims	Measures	Results of the 2nd funding period
Establish a truly multidisciplinary integrated research network with a common focus on marine grand challenges and issues.	Identified 11 new integrated research topics that can only be addressed by multidisciplinary research. Endow those research topics with typically 3 postdocs and 2 PhD students selected by a centrally managed application process. Encourage additional multidisciplinary research by providing seed funding, hosting (international) workshops, organizing lecture series, and annual scientific retreats. Reappoint a junior research group leader (W2 tenure track) for the Law of the Sea. Appoint director for the Gustav Radbruch Center for environmental ethics (W3 professor).	Established 11 research topics (R1-R11) and strengthened the working groups with postdoctoral positions (*Mittelbau*), of which six were tenured at CAU and two at GEOMAR. Appointed two temporal professorships (W2) in marine social sciences and marine politics and tenured the professorship for the Law of the Sea.
Solidify the marine science research focus at CAU and partner institutions.	Fully establish the KAIMS concept to acquire new interdisciplinary research projects, implement joint analytical platforms and data management, as well as career support. Install strategic working groups across institutes and faculties at CAU, GEOMAR, IfW and MKH. Enhance exploitation of the joint research platform concept.	The Cluster Future Ocean will continue to exist within the Kiel Alliance of Interdisciplinary Marine Sciences from October 2019.
Strengthen multi-disciplinary marine sciences education in Kiel.	Sustain ISOS to support all PhD candidates whose research is concerned with the ocean. Provide complimentary courses on demand by PhD students and postdocs. Offer weekend seminars on a large range of 'soft skill' topics. Provide lab rotation opportunities for PhD students and postdocs. Improve attractiveness of Marine Science master education programs. Offer a variety of early research opportunities with selected schools in the region. Explore global classroom and similar curricula exchange opportunities with international research partners.	An Ocean Careers and Education initiative was launched with the long-term objective to establish a cross-faculty Master School for Marine Sciences, continue the successful graduate school ISOS and the post-doctoral network IMAP. Successful knowledge dissemination to global learners from 62 countries through a number of ocean literacy initiatives such as the World Ocean Review series, the Ocean Atlas and the now continuously available Ocean Sustainability MOOC on EdX.
Support marine sciences research careers and gender mainstreaming.	Increase the attractivness of Kiel for young researchers by fully establishing the IMAP postdoc network to support their career development and improve financial security and scientific independence for those at later stages of their career. Actively encourage the promotion of female scientists and continually monitor the Cluster's activities to overcome gender and minority biases in the decision-making structures to improve the gender literacy.	In addition to the ISOS, the IMAP network for postdoctoral researchers and the via:mento_ocean mentoring programme were established. Between 2006-2019, these structures supported PhD, postdoctoral researchers and woman scientists (up to 180 ISOS and 130 IMAP per year and in total 40 woman scientists). Organization of alumni events for an increasing number of alumni in New York, Kiel and Halifax and in context with the major scientific conferences (e.g. EGU European Geophysical Union, AGU American Geophysical Union).

Phase II Aims	Measures	Results of the 2nd funding period
Increase international visibility of Kiel Marine Sciences.	Expand current network of strategic partnerships with Ocean University Qingdao (China), Earth Institute of Columbia University (USA), Dalhousie University (Canada) by new collaborations with other universities and institutes engaged in marine multidisciplinary research. Host and cosponsor international workshops on topics of "The Future Ocean".	Enlarged the network of collaboration partners Bjerknes Center for Climate Research, Cluster of Excellence LabexMER Brest, National Oceanographic Centre in Southampton, and Cape Verde's National Institute for Fisheries Developement (INDP) in Mindelo; Regular science marketing at scientific conference at AGU together with Research in GermanyTM (annual), EGU (annual) and Ocean Sciences Meeting (every two years); Hosted and organized a series of joint workshops and conferences on interdisciplinary marine science and capacity building in the marine sciences in Kiel and abroad. Hosted UNESCO Chair in Integrated Marine Sciences since 2012; meetings in preparation of UN Conference to Support the Implementation of SDG 14.
Enhance transfer to application of Kiel Marine Science results to industry and decision makers.	Encourage researchers to offer their findings to a broad 'user' community. Develop a platform to match Kiel research capabilities with German and international industry research needs. Participate in national and international assessments, studies and position papers on marine science topics. Continue and enhance topical stakeholder dialogues.	Increased stakeholder engagement through implementation of formats, such as *Kieler Marktplatz* (Kiel Market Place), guided lab visits and fair presentations (e.g. Hannover Exhibition, Ocean Business) as networking platforms for knowledge exchange. Strengthing of regional networks (e.g. Maritimes Cluster Norddeutschland, Gesellschaft für maritime Technik) and successfully nuturing Kiel as regional innovation ecosystem for marine science and scientific applications. Introduction of Maritime Technology Platform (MaTeP) to conduct 8 R&D projects in cooperation with SMEs. Series of events (e.g. hearings at EU Commission, International Seabed Authority) and publications for decision makers (e.g. policy briefs) and 18 synthesis reports (World Ocean Review series, Ocean Atlas, Oil Spill Report).

2.1 HIGHLIGHTS OF INTEGRATED RESEARCH IN THE FIRST CLUSTER PHASE (2006-2012)

Highlight 1: Seafloor Warming and Methane Releases in the Arctic Ocean

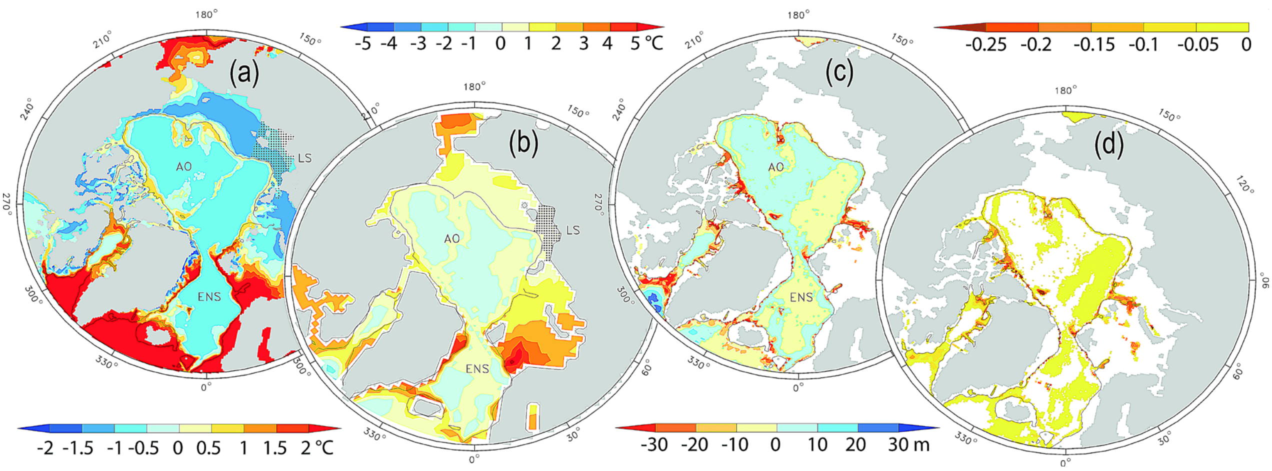

Figure 2: Impact of Global warming on Arctic methane hydrates within the next 100 years: (a) bottom temperatures in an ocean model (ORCA05), (b) changes due to global warming (KCM), (c) changes in the thickness of the gas hydrate stability zone (geophysical model), (d) changes in the near-bottom pH values by released methane (geochemical calculation). All figures from Biastoch et al. (2011).

Vast amounts of methane hydrates are stored in sediments along the continental margins. Their stability is due to the low temperature–high-pressure conditions found on the seafloor. Global warming could destabilize these hydrates and cause a release of methane (CH_4) into the water column and possibly the atmosphere. Since the Arctic has and will be warmed considerably, Arctic bottom water temperatures and their future evolution projected by a climate model were analyzed in a joint modeling effort by a group of physical and biological oceanographers, geologists, geochemists, and atmospheric scientists from the Cluster (A2). The seafloor warming was found to be spatially inhomogeneous, with the strongest impact on shallow regions affected by Atlantic inflow (Fig. 2). Within the next 100 years, the warming will affect 25 % of shallow and mid-depth regions containing methane hydrates. Release of methane from melting hydrates in these areas could enhance ocean acidification and oxygen depletion through aerobic microbial consumption in the water column. Contrary to wide spread previous estimates, the impact of methane release on global warming, however, was found to be insignificant within the time span considered.

Reference:

Biastoch, A., Treude, T., Rüpke, L.H., Riebesell, U., Roth, C., Burwicz, E.B., Park, W., Latif, M., Böning, C.W., Madec, G., Wallmann, K. (2011) Rising Arctic Ocean temperatures cause gas hydrate destabilization and ocean acidification. Geophys. Res. Lett. 38, L08602, DOI: 10.1029/2011GL047222.

Highlight 2: Sustainable Fisheries

Sustainable Fisheries applies a multidisciplinary approach toward fishery management by combining dynamic ecosystem interactions, stochastic processes, and climatic trends. Expertise from biology, resource economics, and law of the sea are combined to produce a new modeling framework. Failure analysis of current fishery management and harvest control rules for European fisheries management are examined. Further, a common modeling framework was designed, taking into consideration the age structure of fish stocks and multi-species interactions to develop new fishery management strategies (Fig. 3). Results from new, ecologically and economically sustainable fishery management strategies have been published in both biological and economic journals. The results were presented to the International Council for the Exploration of the Sea (ICES), which is a leading and active participant within the fishery management field. The interdisciplinary endeavor to develop strategies for sustainable fishery management has had a wide impact on fishery policy and has helped bring the issue to the attention of the general public. The success was documented in numerous TV, radio, and press interviews as well as in publications (e.g. World Ocean Review). Recently, a request was received from Nature for an Op-Ed article. The game table ecoOcean received an international award and has been displayed at several national and international exhibitions and was also used in a training workshop and a masters course. The Cluster's proposals for new sustainable fishery management were discussed with representatives from fishery policymakers in an expert hearing at the European Parliament and the European Maritime Day.

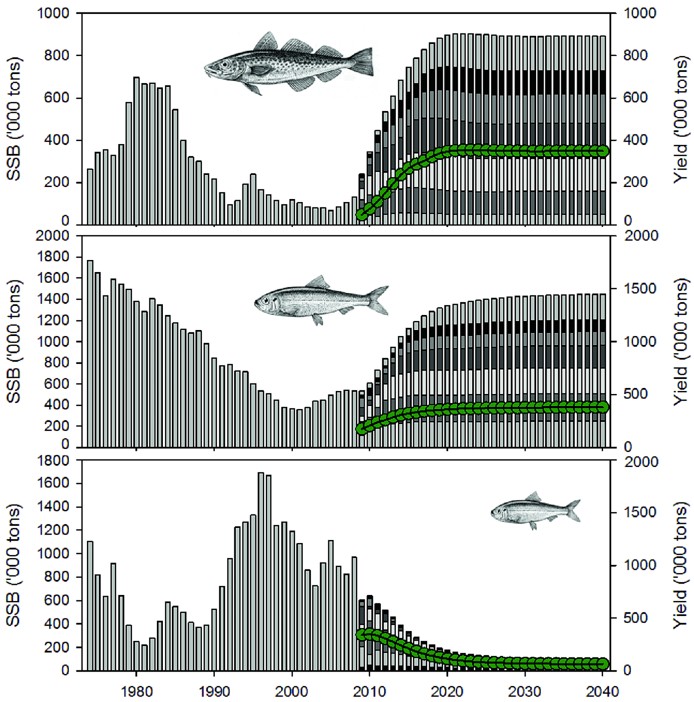

Figure 3: Historical spawning stock biomass and future development of spawning stock biomass and yield using an age-structured ecological-economic model comprising the most important fish species in the Baltic Sea. The results indicate that rebuilding the cod stock in an economically optimal way would reduce the (economically less valuable) stock of sprat, which is one of the cod's main prey species, while the effect on herring is less pronounced.

References:

Froese, R. (2011) Fishery reform slips through the net. Nature 475 (7), DOI:10.1038/475007a.

Froese, R., Proelss, A. (2010) Rebuilding fish stocks no later than 2015: Will Europe meet the deadline? Fish Fish. 11, 194 – 202. DOI: 10.1111/j.1467-2979.2009.00349.x.

Khalilian, S., Froese, R., Proelss, A., Requate, T. (2010) Designed for failure: A critique of the Common Fisheries Policy of the European Union. Mar. Policy 34 (6), 1178 – 1182. https://doi.org/10.1016/j.marpol.2010.04.001.

Voss, R., Hinrichsen, H.H., Quaas, M.F., Schmidt, J.O., Tahvonen, O. (2011) Temperature change and Baltic sprat: from observation to ecological-economic modeling. ICES J. Mar. Sci. 68 (6), 1244 – 1256. https://doi.org/10.1093/icesjms/fsr063.

Highlight 3: Ocean Iron Fertilization

At present time, the international community has accepted a 2°C temperature increase above pre-industrial levels as the maximum tolerable limit for global warming. Extrapolating from current global CO_2 emissions and results from current climate models, the equivalent emission budget will last only for little more than a decade. It therefore seems prudent to consider all possible options in addressing potentially dangerous climate change. Researchers from the Cluster have provided a comprehensive assessment that combines scientific, economic and legal issues of the potential and risks of one such option for enhancing the ocean carbon uptake: ocean iron fertilization (OIF).

From a scientific perspective, the potential of carbon sequestration of large-scale OIF is considerable (Fig. 4), but there is also evidence for significant perturbations of marine biogeochemistry and ecology. These are partly desired but may also have potentially significant unintended consequences including enhanced production of nitrous oxide (N_2O) and methane (CH_4) (Oschlies et al. 2010). From an economic perspective, the potential of OIF is significant in relation to other abatement options. First estimates of the costs associated with this technology are in the same order of magnitude as the estimates of the costs associated with forestation projects. OIF could also generate more carbon credits, even taking into account the possibility that emissions will shift to other regions or that the reductions are not permanent. As for the conformity of OIF with the requirements of public international law, the pertinent agreements dealing with the protection of the marine environment indicate that OIF is to be considered lawful to the extent to which it represents legitimate scientific research. According to Güssow et al. (2010), further scientific research must be permitted to explore the carbon sequestration potential of the ocean. Such research is necessary to make an informed decision on whether to reject ocean iron fertilization or to integrate it into the flexible mechanisms contained in the Kyoto Protocol.

References:

Güssow, K., Proelss, A., Oschlies, A., Rehdanz, K., Rickels, W. (2010) Ocean Iron Fertilization: Why Further Research is Needed. Mar. Policy 34, 911–918. https://doi.org/10.1016/j.marpol.2010.01.015.

Oschlies, A., Koeve, W., Rickels, W., Rehdanz, K. (2010) Side effects and accounting aspects of hypothetical largescale Southern Ocean iron fertilization. Biogeosciences 7, 4017–4035. https://doi.org/10.5194/bg-7-4017-2010.

Rickels, W., Rehdanz, K., Oschlies, A. (2010) Methods for Greenhouse Gas Offsets Accounting: A Case Study of Ocean Iron Fertilization. Ecol. Econ. 69, 2495–2509. DOI: 10.1016/j.ecolecon.2010.07.026.

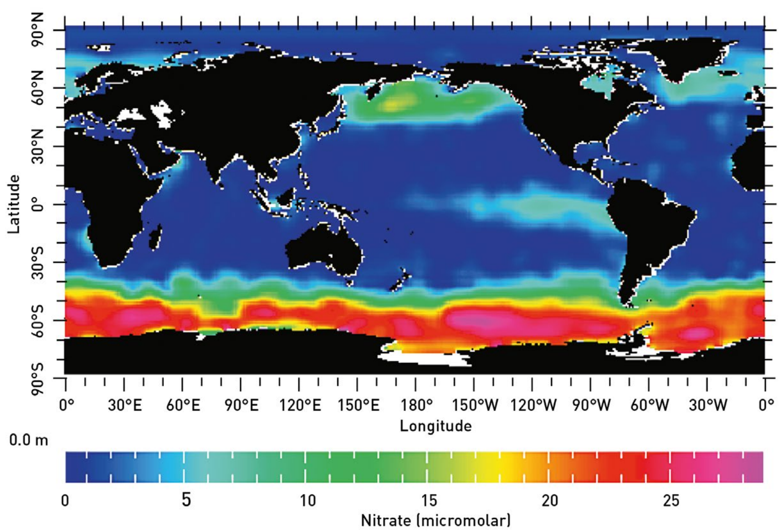

Figure 4: Annual average nitrate concentrations in the surface waters of the ocean. Source: http://www.atmosphere.mpg.de/enid/1vv.html

Highlight 4: Integrating Ocean Biogeochemistry, Paleoceanography and Climate Modeling

Numerical climate models are sophisticated tools used to predict the climate of the future. To be confident in their predictions, model simulations of the modern climate are usually compared with observational data from the last 50-100 years, the time period for which instrumental records exist. Another more rigorous test, however, is to apply the models to the climate of the geologic past, for which the boundary conditions are sufficiently known. The aim is to test whether the models are flexible enough to reproduce climate conditions distinctly different from today.

A multidisciplinary team combining expertise in ocean biogeochemical modeling, paleoceanography, and climate modeling achieved an unprecedented model-data synthesis of sea surface temperature (SST) changes over the last 10 kyrs (Holocene). Using paleo proxy SST-data based on (i) marine phytoplankton and zooplankton organisms, (ii) modern satellite data of SST and phytoplankton productivity, and (iii) a Holocene simulation of the Kiel Climate Model (KCM), it was shown that paleo-proxies may preferentially record seasonal signals instead of annual mean climate conditions, which is the usual interpretation. Furthermore, the respective seasons may differ between regions (Fig. 5 a). After taking seasonal preferences into account in model-proxy comparisons, the model-data agreement was considerably improved; however, the climate model still systematically underestimated the Holocene SST trends (Fig. 5 b).

Reference:

Schneider, B., Leduc, G., Park, W. (2010) Disentangling seasonal signals in Holocene climate trends by satellite-model-proxy integration. Paleoceanography 25, PA4217, DOI: 10.1029/2009PA001893.

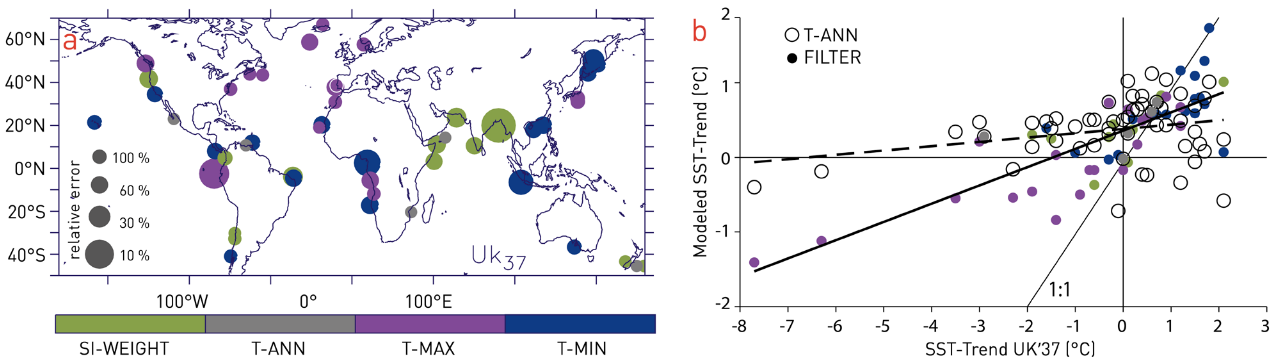

Figure 5: a. Climate signal that yields the best match for modeled and reconstructed Holocene SST trends for the phyto-plankton (UK'37) proxy data; green: SST weighted by the monthly primary productivity as obtained from the satellite data; grey: annual mean SST; purple: warmest month of the year; blue: coldest month of the year. The larger the symbol the better the match between model and proxy data. b. Seasonally sub-sampled SST trends from the model (colored dots) yield a better match with proxy data than annual mean SSTs from the model (open circles), although some systematic discrepancy remains.

2.1.1 RESEARCH AREA A – "THE OCEAN IN THE GREENHOUSE WORLD"

Under area A “The Ocean in the Greenhouse World”, the oceanic response to anthropogenic greenhouse gas emissions is investigated. The combined oceanic response to this forcing mechanism is complex and includes large-scale changes in ecosystem structure and ocean circulation. Ocean systems and parameters affected by anthropogenic greenhouse gas emissions and global climate changes include internal carbon cycling, nutrients, oxygen, physical exchange of greenhouse gases, heat, water, and movement across the air-sea and ocean-seafloor interfaces. Oceanic feedbacks may amplify anthropogenic forcing with largely unknown consequences for oceans, global climate, and human society. Cluster research area A encompasses basic and applied research on these subjects and studies oceanic responses in the Greenhouse World.

The overarching questions of research area A are:

- What are the biological and chemical responses of the ocean to changing atmospheric composition?
- How do ocean circulation and the ocean ecosystem interact with altered radiative forcing?
- What is the ocean’s capacity for current and future mitigation of atmospheric CO_2 increase?
- What are the implications of these changes to the marine system for human welfare and greenhouse gas management?

Seven research topics were identified to study these questions. Topic A1 investigates effects of ocean acidification. It thereby creates new links between physiological and biochemical aspects of marine biology and geochemistry to characterize the response of marine organisms to elevated CO_2 and lowered pH levels. Topic A2 addresses the issue of temperature increases at the seafloor by combining benthic ecology and geochemistry with new observational technologies. Warming of intermediate-depth waters has the potential to drive major changes in seafloor processes, including accelerated decomposition of methane hydrates and as yet unknown effects on benthic ecosystems. In a new partnership, topic A3 builds on expertise in ocean modeling, marine carbon data observations and data synthesis with advanced numerical modeling techniques research. A major aim is to improve the quantification of the current and future oceanic uptake of anthropogenic CO_2. Topic A4 takes advantage of the existing knowledge in past ocean climate proxy research and uses ocean and climate models in order to reconcile observational records from past climates with dynamically consistent climate scenarios. Topic A5 proposes addressing the potential advantages and risks associated with CO_2 disposal in marine sediments. In topic A6, the physicochemical aspects of interactions at and near the air-sea interface are examined. These aspects are important for understanding the ocean’s response to changing compositions of the surface oceans and troposphere. Through this research, new links between physical and theoretical chemistry and marine sciences are being established. The economic and human welfare implications of future ocean change investigated in topic A1 through A6, and the focus of topic A7 combine economic and scientific expertise in the Cluster. A7 is strategically placed at the interface between basic scientific insight, quantitative assessment of data, and socio-economic understanding to evaluate human-dimension implications of future ocean change.

A1: Ocean Acidification

A1 studies basic mechanisms that contribute to marine animal sensitivity to future ocean acidification. Using ecological, physiological, biochemical, and biomolecular methods, both in laboratory and in field settings, A1 attempts to gain a cause-and-effect-based understanding of crucial processes that define vulnerability to elevated seawater pCO_2. One aim is to identify traits that promote sensitivity vs. tolerance, by comparing characteristics of more tolerant model groups (e.g., cephalopods) with those of more sensitive groups (e.g. bivalves). For this objective, a dual strategy is followed by carrying out laboratory based CO_2 perturbation studies to assess physiological responses and by simultaneously studying physiological adaptations of animals exposed to naturally elevated seawater pCO_2 levels.

A1 uses the Kiel Fjord as an acidic ocean model. Due to upwelling of CO_2-rich waters in summer and autumn, Kiel Fjord's shallow-water mussel-bed communities (blue mussel, *Mytilus edulis*) come into contact with 'acidified' water during large parts of the year. Laboratory studies showed that mussels maintain high rates of calcification at high pCO_2 of 1400 and 4000 µatm, i.e., in waters severely undersaturated with aragonite and calcite, despite not being able to control the pH value of their extracellular fluids (Thomsen et al. 2010). In addition, increased seawater pCO_2 leads to increased metabolic rates, potentially due to elevated energetic demands of cellular homeostasis (Thomsen and Melzner 2010). Other results and laboratory studies indicate that mussels are able to compensate for lower ambient pH when the food supply is high. Studies demonstrate that in relation to the large effects of nutritional supply within a given habitat, elevated pCO_2 constitutes a moderate stressor for blue mussel populations.

Selected publications:

Thomsen, J., Gutowska, M.A., Saphörster, J., Heinemann, A., Fietzke, J., Hiebenthal, C., Eisenhauer, A., Körtzinger, A., Wahl, M., Melzner, F. (2010) Calcifying invertebrates succeed in a naturally CO_2 enriched coastal habitat but are threatened by high levels of future acidification. Biogeosciences 7, 3879 – 3891. https://doi.org/10.5194/bg-7-3879-2010.

Thomsen, J., Melzner, F. (2010) Moderate seawater acidification does not elicit long-term metabolic depression in the blue mussel Mytilus edulis. Mar. Biol. 157, 2667 – 2676. https://doi.org/10.1007/s00227-010-1527-0.

A2: Seafloor Warming

A2 investigates consequences of global warming on processes at the seafloor, such as the stability of sub-seafloor gas hydrates, development of anoxia, and intensification of biofouling. In an interdisciplinary study with oceanographers, biologists, geologists, and geochemists from the Cluster, a prediction of future methane releases from submarine gas hydrates in the Arctic Ocean under global warming scenarios was formulated (→ section 2, highlight 1). In a second, more detailed modeling approach, members of A2 simulated the actual physical process of gas hydrate melting as well as the associated microbial methane consumption in the sediment. This model allows more realistic simulation of gas hydrate dissociation and its immediate consequences in the sediment after the initial warming effect. Besides modeling, major progress was achieved during fieldwork and laboratory campaigns exploring methane-related processes in sediments. Natural benthic systems were investigated in the Eastern Mediterranean (North Alex mud volcano), the Beaufort Sea (methane-rich sediments), and off Costa Rica and Chile (gas-hydrate bearing cold seeps). These expeditions, which were organized through major institutions and projects (RWE-DEA, Naval Research Laboratory, Collaboration Research Centre SFB 574), increased our understanding about the diversity and variability of benthic ecosystems with high methane levels. Laboratory studies with sediments retrieved during these expeditions showed: (1) how biogeochemical processes respond to changes in methane flux, (2) how microbial methane production and consumption react to increases in temperatures, (3) and how microbes facilitate the ultimate burial of methane-derived carbon as authigenic carbonates. On a more science-political level, members of A2 are participating in major initiatives to foster gas hydrate research and dissemination of knowledge such as the EU COST Action PERGAMON (Permafrost and gas hydrate related methane release in the Arctic and impact on climate change: European cooperation for long-term monitoring), the UNEP-GRID report on the 'Global Outlook on Methane Gas Hydrates', as well as the organization of gas hydrate sessions at international scientific conferences (EGU 2009, 2010).

Selected publications:

Treude, T. (2012) Biogeochemical reactions in marine sediments underlying anoxic water bodies. In: Altenbach, A., Bernhard, J., Seckbach, J. (eds.) Anoxia: Paleontological Strategies and Evidence for Eukaryote Survival. Cellular Origins, Life in Extreme Habitats and Astrobiology (COLE) Book Series, Springer. https://doi.org/10.1007/978-94-007-1896-8_2.

Treude, T. (2015) Methanhydrate: Erwärmung, Freisetzung und mikrobiologischer Abbau. In: Lozán, J.L. (Eds.) Warnsignal Klima: Die Meere– Änderungen und Risiken. Wissenschaftliche Auswertungen, Paul Parey: Berlin. http://www.klima-warnsignale.uni-hamburg.de/wp-content/uploads/2013/01/Treude.pdf.

Biastoch, A., Treude, T., Rüpke, L.H., Riebesell, U., Roth, C., Burwicz, E.B., Park, W., Latif, M., Böning, C.W., Madec, G., Wallmann, K. (2011) Rising Arctic Ocean temperatures cause gas hydrate destabilization and ocean acidification. Geophys. Res. Lett. 38, L08602, DOI: 10.1029/2011GL047222.

A3: Present and Future CO_2 Uptake

A3 applies mathematical optimization methods, couples ocean circulation and ecosystem models, high performance computing and uncertainty analysis, in order to investigate oceanic CO_2 uptake. State-of-the-art methods are used for parameter identification and estimation to obtain an improved fit of the model output to measurement data. This fit is a crucial step in the model validation process. A main part therein is to provide a software framework for flexible coupling and computationally fast simulation of the underlying systems of transport equations for a whole class of marine ecosystem models. This allows simulation of the tracer concentrations that determine marine photosynthesis and thus influence CO_2 uptake. A second important objective is the development of appropriate optimization methods to deal with the specific structure and characteristic problems as high computational effort and occurrence of local minima of the model-to-data fit cost function. For this, software for the fast spin-up of 3-D coupled models based on the Transport Matrix Method was established which replaces the usual pseudo-time stepping by a much faster Newton-Krylov method to obtain quasi-steady periodic states. Additionally, the software allows economical sensitivity computations. Several specific optimization strategies, including simultaneous iterative simulation and optimization (so-called one-shot methods) as well as Surrogate-based optimization were used. In developing a linearized model with periodic parameters, A3 finally succeeded in obtaining a nearly exact fit of data that up to now was regarded as 'unfittable' by marine biogeochemical models.

Selected publications:

Gauger, N., Griewank, A., Slawig, T., Hamdi, A., Kratzenstein, C., Özkaya, E. (2011) Automated Extension of Fixed point PDE Solvers for Optimal Design with Bounded Retardation. In: Leugering, G., Engell, S., Griewank, A., Hinze, M., Rannacher, R., Schulz, V., Ulbrich, M., Ulbrich, S. (eds.) Constrained Optimization and Optimal Control for Partial Differential Equations. Birkhäuser Int. Numer. Math. https://doi.org/10.1007/978-3-0348-0133-1_6.

Rückelt, J., Sauerland, V., Slawig, T., Srivastav, A., Ward, B., Patvardhan, C. (2010) Parameter Optimization and Uncertainty Analysis in a Model of Oceanic CO_2-Uptake using a Hybrid Algorithm and Algorithmic Differentiation. Nonlinear Anal. R. World Appl. 11, 3993 – 4009. https://doi.org/10.1016/j.nonrwa.2010.03.006.

A4: Biogeochemical Oceanography and Climate

A4 combines expertise from ocean biogeochemical and paleo-climate modeling in order to successfully link climate reconstruction and climate modeling. This has enhanced understanding of past, present and future mechanisms of climate variability and climate change. Several models that vary with regard to complexity are applied to simulate different warm climates from the present and the geological past. Simulations focus on ocean circulation, the atmospheric hydrological cycle, and marine biogeochemical cycles on a global scale. A central tool is the state-of-the-art Kiel Climate Model (KCM) that is forced by several mechanism such as (1) varying orbital configurations, (2) greenhouse gas (GHG) concentrations, and (3) varying continental distributions, e.g. to simulate the closure of the Indonesian and Panama Gateways during the Pliocene (5-2 Ma). Climate simulations are carried out as quasi steady states or as accelerated transient simulations. Further-more, an ocean biogeochemical model (PISCES) is used for sensitivity studies of the marine carbon sink to ocean acidification, focusing on $CaCO_3$ dissolution and the turnover of organic matter.

A model-data comparison of sea surface temperature (SST) trends over the Holocene (last 10 kyrs) revealed that systematic discrepancies between the two most established proxies for paleo SST can be assigned to different seasonal preferences of the proxies (→ section 2, highlight 4). It was also found that the amplitude of El Niño Southern Oscillation (ENSO) scales linearly with the SSTs of the tropical Pacific, indicating that in a future warmer climate, enhanced ENSO amplitude at constant frequencies can be expected. A combination of paleo-climate simulations with a global warming experiment revealed a warming-induced intensification of the Asian Monsoon, but with different moisture sources for solar and CO_2 forcing (Khon et al. 2010). The Pliocene restriction of the Indonesian Throughflow caused a cooling of the Indian Ocean subsurface waters and drying of the Australian continent, which is supported by our model results and proxy data. Furthermore, the sensitivity of $CaCO_3$ export (particle ballasting) to ocean acidification is strongly dependent on the kinetic expression of $CaCO_3$ dissolution, for which no unambiguous formulation exists.

Selected publications:

Schneider, B., Leduc, G., Park, W. (2010) Disentangling seasonal signals in Holocene climate trends by satellitemodel-proxy integration. Paleoceanography 25, PA4217, DOI: 10.1029/2009PA001893.

Khon, V., Park, W., Latif, M., Mokhov, I.I., Schneider, B. (2010) Response of the hydrological cycle to orbital and greenhouse gas forcing. Geophys. Res. Lett. 37, L19705, DOI: 10.1029/2010GL044377.

Krebs, U., Park, W., Schneider, B. (2011) Pliocene Aridification of Australia Caused by Tectonically Induced Weakening of the Indonesian Throughflow. Paleogeogr. Paleoclim. Paleoecol., accepted. https://doi.org/10.1016/j.palaeo.2011.06.002.

A5: Carbon Sequestration

The Cluster did not implement the research topic carbon sequestration as a distinct research group: As in 2007 increased funding for CCS projects became available, two offers for junior research group leader were rejected after long negotiations with another university and industry. Also, a large scale CO_2 sequestration project was launched in summer 2008 (SUGAR: Submarine Gas Hydrate Reservoirs) shortly after the successful funding of "The Future Ocean". The SUGAR project aims to produce natural gas from marine methane hydrates and to sequester carbon dioxide (CO_2) from power plants and other industrial sources as CO_2-hydrate in marine sediments. It has been funded with a 13 M€ grant for an initial period of three years from two federal ministries (BMWI and BMBF) and German industry. SUGAR is coordinated by GEOMAR and includes 30 institutional partners from German academia and industry. The proposal for the second SUGAR phase (July 2011 to June 2014 with total funding of 11 M€) was approved by the BMWI and BMBF. Moreover, the environmental risks of sub-seabed CO_2 storage were investigated by a multi-disciplinary group of Cluster scientists supported via the Cluster's internal 'mini proposal' scheme. Scientists leading this internal project group used the Cluster's seed funding to set up the large-scale European initiative ECO2. This initiative investigated the safety of existing and planned off-shore CO_2 storage sites and applied successfully for the 7th framework call by the EU addressing the environmental risks of sub-seabed CO_2 storage. The established ECO2 project was led by GEOMAR and includes 27 institutions from Norway and eight EU member states (funding period: May 2011 to April 2015, EU funding: 10.5 M€). The applied research on storage of CO_2 below the seabed has thus been established as a cornerstone of the Cluster's research portfolio.

A6: Physicochemical Methods for Ocean Surface Research

The biogeochemical coupling of the ocean and the atmosphere takes place at the air-sea interface, a vast chemical reactor where a range of heterogeneous and photochemical initiated processes occurs. In A6, modern optical detection tools are applied to resolve the structure, composition, and chemical reactivity of the atmosphere-ocean interface. Molecular-level resolution combined with high-detection sensitivity allows the study of ocean surface chemistry on a spatial scale and in concentration ranges where interface mediated processes eventually occurs. Whereas non-linear sum-frequency generation spectroscopy (VSF G) offers a unique detection capability to investigate the molecular structure and reactivity of the organic nanolayer, the ultrasensitive cavity-ringdown spectroscopy (CRDS) measures the absorption of trace gases with isotopic resolution. A new optical sensor has been developed to monitor the dynamics of biofilm formation on submerged substrates by autonomously logging biomass fluorescence.

The sum-frequency generation spectroscopy measurements show that partly soluble 'wet' surfactants form extremely dense layers of organic molecules at natural seawater interfaces. Observed spectral signatures are consistent with the predominance of lipopolysaccharides (surface active carbohydrate-containing molecules) or other lipid-like compounds embedded in colloidal matrices of polymeric material. In order to further clarify these preliminary conclusions, systematic studies on interfacial properties of lipopolysaccharides and on regional surface film abundance have been initiated, including first mesocosm test experiments. Substantial progress has been made in the implementation of both commercial and self-developed CRD spectrometers. In an interdisciplinary endeavor, a CO_2 isotopic analyzer has been successfully operated aboard the research vessel Polarstern on two Atlantic crossings.

For the first time, online data were collected over the course of ten weeks, recording variations and spatially dependent correlations between CO_2 partial pressure, pCO_2, and isotopic composition, δ13C(CO_2), these data are needed to work out details of global carbon cycling pathways. Another modular laboratory-based instrument capable of gas and surface sensitive measurements was applied to quantify the 'sitepreference' (SP) of N_2O samples. SP shows sources and sinks of environmental N_2O formed in microbial processes via denitrification and nitrification pathways.

Selected publications:

Laß, K., Friedrichs, G. (2011) Revealing structural properties of the narine nanolayer from vibrational sum frequency generation spectra. J. Geophys. Res., published online, DOI: 10.1029/2010JC006609.

Friedrichs, G., Bock, J., Temps, F., Fietzek, P., Körtzinger, A., Wallace, D.W.R. (2010) Toward Continuous Monitoring of Seawater 13CO2/12CO2 Isotope Ratio and pCO2: Performance of a Cavity Ringdown Spectrometer and Gas Matrix Effects. Limnol. Oceanogr.: Methods 8, 539–551. DOI:10.4319/lom.2010.8.539.

Fischer, M., Friedrichs, G., Wahl, M. 'Großflächiger Biofilmsensor / Large-area biofilm sensor'. Patent: DE 102011101934.4 (granted 2017).

A7: Valuing the Ocean

A7 investigates carbon management, ocean acidification impact assessment, shipping, energy and mineral resources. Different ecosystems in the ocean are integrated into economic models using economics, climate research, meteorology and oceanography. The ocean provides a number of ecosystem services used by mankind in multiple ways but which have not been systematically considered in economics. A7 evaluates services provided by the ocean by integrating them into economic models focusing on carbon management including aspects of ocean acidification, energy and mineral resources. Research concentrates on the interaction of climate, climate policy and the role of the oceans in the climate system. For example, the lack of success of the international community in reaching an agreement on measures to control the emissions of greenhouse gases increases the risk of climate change. This has led to a renewal of interest in directly manipulating the climate system through environmental engineering. Results of an interdisciplinary study on one engineering option, ocean iron fertilization, are presented in section 2.1, highlight 3. A7 has participated in two large-scale EU-FP7 projects (ECO2, ACCESS) and leads two BMBF projects.

Selected publications:

Bertram, C. (2010) Ocean iron fertilization in the context of the Kyoto protocol and the post-Kyoto process. Energy Policy 38 (2), 1130 – 1139. http://hdl.handle.net/10419/28353.

Güssow, K., Proelss, A., Oschlies, A., Rehdanz, K., Rickels, W. (2010) Ocean Iron Fertilization: Why further research is needed. Mar. Policy 34, 911 – 918. https://doi.org/10.1016/j.marpol.2010.01.015.

Rickels, W., Lontzek, T. (2011) Optimal global carbon management with ocean sequestration. Oxford Econ. Papers, DOI: 10.1093/oep/gpr027.

2.1.2 RESEARCH AREA B – "RESOURCES AND RISKS"

Research area B addresses questions raised by the use of living and non-living resources in the seas and includes the legal aspects and the risks generated by natural or anthropogenic impacts. The link between the six topics of research area B is the focus on resources and risks in connection with human benefits derived from the ocean. The economic and legal aspects of the topics create a unique network, which assists in the development of innovative and comprehensive approaches in the investigation and management of marine resources. Of particular interest are questions such as:

> Which physical, chemical, biological, and geological mechanisms lead to the evolution of certain resources?
> How should ocean resources be managed in a sustainable manner, and which institutional and legal frameworks are necessary for such endeavors?
> What are the mechanisms that lead to marine hazards threatening coastal populations?
> How can risks be assessed, how can damages from hazardous events be evaluated, and which countermeasures can be taken to mitigate these?
> Are ocean organisms a model system for human diseases providing a new tool in medical research?

These and related topics are addressed under research area B, which focuses on the understanding and management of marine resources and assessment of hazards.

In B1, fishery management is studied with the special focus on multispecies interaction and the link between commercial species, non-commercial species, and the ecosystem. In B2, Kiel-based scientists from medical and natural sciences joined forces for the first time to study marine organisms as a model system with the purpose of gaining a better understanding of the mechanisms which trigger human diseases, applying a genomics approach to investigate the evolution and function of orthologs to human susceptibility genes for barrier dysfunction in marine organisms from diverse phyla. Research topic B3 focuses on the study of the occurrence and formation of marine resources, such as gas hydrates and hydrothermal deposits, using modeling of fluid flow and coupled reactions to elucidate the formation of these deposits. Research topic B4 looks at the problems of submarine hazards at continental margins. Despite growing concerns regarding submarine earthquakes, submarine landslides and their consequences, such as the triggering of tsunamis, the individual processes causing these hazards are not well understood. Topic B5 brought in new expertise to analyzing physicalmorphological changes in coastal seas and to developing new tools to assess the vulnerability and resilience of coastal zone communities. Research topic B6 involves expertise in maritime law and contributes to the development of new laws for the sustainable use of marine resources based on a sound understanding of the oceanic ecosystem.

B1: Living Resources and Overfishing

B1 develops new fishery management strategies by combining the disciplines of natural resource economics and marine ecology with special focus on multispecies interaction and the link between commercial species, non-commercial species, and the ecosystem. B1 cooperates with A1, A4, A7, B5, and B6. The overall research objective of B1 is to provide the scientific basis for more sustainable use of marine ecosystem services, in particular for more sustainable fisheries. A JRG has been established to develop improved management strategies of fish stocks and fisheries, incorporating economic, legal, and scientific aspects. Pursuing the ecosystem approach to fisheries management, B1 studies the effects of the age structure of fish populations, multi-species interactions, uncertainty in fish recruitment, spatial heterogeneity and migration of fish. B1 integrates this with an economic approach, for two complementary reasons: First, economic incentives determine how resources are used in a market economy. Second, unlike ecology, economics provides sound methods normative societal objectives, such as welfare and sustainability. B1 has clarified what the economic contribution to questions of sustainability are and formulated general research questions on the sustainable use of ecosystem services addressed in the interdisciplinary collaboration between economists, ecologists and philosophers (e.g. Baumgärtner and Quaas 2010).

An age-structured ecological-economic model was developed for the Baltic Sea that includes the effects of cod predation on herring and sprat, the effect of climate change on the reproductive success of the fish, and computed the multi-species management strategy that optimizes economic welfare (e.g. Voss et al. 2011). On the basis of generic ecological-economic modeling analyses, new fishery management strategies were developed that adopt the ecosystem approach to fisheries management and take economic and legal aspects into account (e.g. Froese et al. 2010). Research results are continuously discussed with fishermen, politicians, NGOs, and the public to assure that the proposed measures are suitable for practical implementation.

Selected publications:

Baumgärtner, S., Quaas, M.F. (2010) What is sustainability economics? Ecol. Econ. 69, 445 – 450. http://dx.doi.org/10.1016/j.ecolecon.2009.11.019.

Froese, R., Branch, T.A., Proelß, A., Quaas, M.F., Sainsbury, K., Zimmermann, C. (2010) Generic Harvest Control Rules for European Fisheries. Fish Fish. 12(3), 340 – 351. DOI: 10.1111/j.1467-2979.2010.00387.x.

Voss, R., Hinrichsen, H.-H., Quaas, M.F., Schmidt, J.O., Tahvonen, O. (2011) Temperature change and Baltic sprat: from observations to ecological-economic modelling. ICES J. Mar. Sci. 68 (6), 1244 –1256. https://doi.org/10.1093/icesjms/fsr063.

B2: Marine Medicine: Interactions between Complex Barriers and Microbiota in the Ocean

Marine organisms are studied by scientists from medical and natural sciences for the purpose of gaining a better understanding of the mechanisms, which trigger human diseases. B2 cooperates with A1, A7 and B6. B2 applies a genomics approach to investigate the evolution and function of orthologs to human susceptibility genes for barrier dysfunction in marine organisms from diverse phyla. Evolution is a major unifying principle in biology and understanding evolution may serve as a fundamental basis for understanding health and the etiology of diseases. Over the past years it has become increasingly clear that most of the genes constituting the molecular risk maps of human diseases are of phylogenetically ancient origin. The fields of inflammatory disorders and cancer represent suitable precedents as many of the identified genes are involved in basic biological processes that evolved either at the unicellular or early multicellular level. Many of the cellular programs govern the interaction between the host and the environment and are pivotal for survival.

One goal of B2 is to apply the knowledge required in the marine model organisms to develop novel therapeutic or preventive strategies for human barrier disorders. Improved cell culture conditions for *Mytilus edulis* hemocytes have been developed, but the viability of cell cultures still range from a few days up to six months. Due to this instability the goal of creating a working long-term marine invertebrate cell culture could not be fully met. Nevertheless, short-term culture conditions have been improved and functional assays have been established, which are currently used in short-term experiments.

Selected publications:

Lipinski, S., Till, A., Sina, C., Arlt, A., Grasberger, H., Schreiber, S., Rosenstiel, P. (2009) DUOX 2-derived reactive oxygen species are effectors of NOD 2-mediated antibacterial responses. J. Cell. Sci. 122, 3522 – 3530. DOI: 10.1242/jcs.050690.

Franke, A., Balschun, T., Sina, C., Ellinghaus, D., Häsler, R., Mayr, G., Albrecht, M., Wittig, M., Buchert, E., Nikolaus, S., Gieger, C., Wichmann, H.E., Sventoraityte, J., Kupcinskas, L., Onnie, C.M., Gazouli, M., Anagnou, N.P., Strachan, D., McArdle, W.L., Mathew, C.G., Rutgeerts, P., Vermeire, S., Vatn, M.H., IBSEN study group, Krawczak, M., Rosenstiel, P., Karlsen, T.H., Schreiber, S. (2010) Genome-wide association study for ulcerative colitis identifies risk loci at 7q22 and 22q13 (IL17REL). Nat. Genet. 42, 292 – 294. DOI: 10.1038/ng.553.

Chalaris, A., Adam, N., Sina, C., Rosenstiel, P., Lehmann-Koch, J., Schirmacher, P., Hartmann, D., Cichy, J., Gavrilova, O., Schreiber, S., Jostock, T., Matthews, V., Haesler, R., Becker, C., Neurath, M.F., Reiss, K., Saftig, P., Scheller, J., Rose-John, S. (2010) Critical role of the disintegrin metalloprotease ADAM17 for intestinal inflammation and regeneration in mice. J. Exp. Med. 207 (8),1617-1624. DOI: 10.1084/jem.20092366.

B3: Fluid-Derived Seafloor Resources

B3 aims to deepen the knowledge on the occurrence and formation of marine resources, such as gas hydrates and hydrothermal deposits. For this purpose, a modeling-oriented JRG has been established. The objective of B3 is to study fluid flow and chemical processes to better understand the formation of seafloor resources. B3 cooperates with A2, A7 and B6.

The global ocean hosts sizeable natural resources of commercial interest. Gold, copper, and zinc can be found in massive sulphide deposits surrounding submarine hydrothermal vent sites. Methane hydrates, a potential future energy source, are abundant in the thick sedimentary covers of continental margins. B3 uses numerical modeling techniques to explore the geological processes controlling the formation of these natural resources and predict their global distribution and abundance.

Worldwide data sets are used to learn more about the global distribution of hydrothermal vent sites, their geodynamic relevance, and the volumes of seawater passing each year through the hydrothermal systems of the mid-ocean ridge systems. The inner workings of hydrothermal vent systems are explored using novel integrated models that resolve the interrelations between oceanic crust accretion at mid-ocean spreading centers and hydrothermal cooling zones. In addition, a new joint modeling framework has been established for studying marine gas hydrates. Newly developed reaction-transport models have been combined with high resolution ocean circulation models and the “Kiel Climate Model” in order to provide new global inventories of gas hydrates and to assess how marine hydrate deposits react to global change. Highlights include studies which show in situ degradation of organic is not an efficient hydrate forming process in the Holocene and that a warming climate will lead to hydrate dissociation and local ocean acidification in the Arctic over the next 100 years.

Selected publications:

Theissen, S., Rüpke, L.H. (2009) Feedbacks of sedimentation on crustal heat flow new insights from the Vøring Basin, Norwegian Sea. Basin Res. 22 (6), 976 – 990, DOI: 10.1111/j.1365 – 2117.2009.00437.x.

John, T., Medvedev, S., Rüpke, L.H., Andersen, T.B., Podladchikov, Y.Y. Austrheim, H. (2009) Generation of intermediate depth earthquakes by self-localizing thermal runaway. Nat. Geosci. 2, 137 – 140, DOI: 10.1038/ngeo419.

Iyer, K., Podladchikov, Y.Y. (2009) Transformation-induced jointing as a gauge for interfacil slip and rock strength. Earth Planet. Sci. Lett. 280 (1 – 4), 159 – 166. https://doi.org/10.1016/j.epsl.2009.01.028.

B4: Submarine Hazards at Continental Margins: Earthquakes, Submarine Slop Failure and Tsunami Generation

Earthquakes, submarine slope failures, and resulting tsunamis pose a major threat to coastal communities. Scientists involved in B4 have focused their activities on assessment of the link between the structure and dynamics of subduction zones and the mega earthquake cycle, and slope stability issues at continental margins. The objectives of B4 were to gain advanced insight into the generation of submarine earthquakes, slope failure, and tsunamis in cooperation with A2 and B5.

One main emphasis of B4 was the analysis of submarine slope failures and associated hazards. Numerous slides in different tectonic settings (active and passive margins, lakes) were investigated by means of hydroacoustic, seismic, and sedimentological methods. Along the passive Northwest (NW)-African continental margin, e.g., some sections show a large concentration of upper slope canyons but no indication for significant mass wasting, whereas other sections are characterized by large-scale mass wasting with no canyons. Several buried mass transport deposits are imaged beneath near-surface slides. These observations allow some general conclusions for the NW-African and other passive continental margins: (i) Open slope areas without major incisions allow rapid sediment accumulation beneath zones of high primary productivity, which in turn leads to sediment instabilities arising primarily from under consolidation of deposited sediments and lithological weak layers. In contrast, canyons and gullies act as effective pathways for regular downslope sediment transport by turbidity currents, preventing extensive slope failure. (ii) Vertical stacking of mass wasting events suggests that sediments deposited above buried scarps are potentially unstable. (iii) The large size of the slides off NW-Africa is caused by high sedimentation rates but infrequent triggers.

Mass wasting off NW-Africa is a geohazard but the probability for major events in the near future is low, with all major slides in the last 200 ka occurring during sea level lowstands or periods of sea level rise. This view, however, is challenged by recent observations showing a major reactivation of one headwall 1-2 ka ago. This reactivation resulted in the largest known Holocene submarine slide. Major headwall reactivations need to be considered for future risk assessments of this margin during the current period of a sea level highstand.

Selected publications:

Krastel, S., Wynn, R.B., Georgiopoulou, Geersen, J., Henrich, R., Meyer, M. and T. Schwenk (2012) Large scale mass wasting at the NW-African Continental margin: some general implications for mass wasting at passive continental margins. In: Submarine Mass Movements and their Consequences (eds: Y. Yamada et al). Advances in Natural and Technological Hazards Research 31. Springer Publications, pp. 189-199

Krastel, S., Wefer, G., Antobreh, A.A., Freudenthal, T., Hanebuth, T.J.J, Preu, B., Schwenk, T., Strasser, M., Violante, R., Winkelmann, D., and M78/3 shipboard scientific party (2011) Sediment Dynamics and Geohazards off Uruguay and the de la Plata River region (Northern-Argentina). Geo-Mar. Lett., DOI: 10.1007/s00367-011-0232-4.

Georgiopoulou, A., Masson, D., Wynn, R.B., Krastel, S. (2010) The Sahara Slide: Initiation and processes from headwall to deposit of a giant submarine slide. Geochem. Geophys. Geosys. 11 (7), DOI: 10.1029/2010GC003066.

B5: Sea Level Rise and Coasts at Risk

Two JRGs were established to study coastal processes, in particular sea level changes, coastal evolution and coastal risk assessment. JRG B5.1 analyzes physical-morphological changes in coastal seas, while JRG B5.2 develops new tools to assess the vulnerability and resilience of coastal zone communities. The objective of B5 is to improve the understanding of coastal changes and strategies for coastal risk management (sea level rise, coastal erosion, storm surges, tsunamis). B5 cooperates with B4 and B6.

B5.1 analyzes natural and anthropogenic influenced coastal processes, dynamics and their complex interactions, especially at the interfaces land-sea, water column-seafloor and freshwater-seawater. Rapid physical and morphological changes are studied using hydroacoustics and laser-optics to provide reliable information for high-quality coastal zone protection and management. Research programs with national and international partners are ongoing at different coastal hot spots and at the delta of the largest Brazilian river, where severe coastal erosion and systems adaptation from deltaic to estuarine conditions is situated. New results put further emphasis on the consequences of river damming (Traini et al, 2011). Studies on morpho- and sediment-dynamics in heavily engineered tidal estuaries deliver new insight on estuarine processes including the importance of internal waves on sediment mixing and particle flocculation as well as the impact of anthropogenic interferences, e.g. water injection dredging. Changes in the German Wadden Sea have been analyzed with new acoustics approaches (Bartholomä et al. 2011). New results are retrieved on coarse-grained sediment transport at coasts, which react to sea level change and storm impact, creating fast retreating cliff-coasts and adjacent coastal lowlands (May et al, 2010).

Selected publications:

Traini, C., Schrottke, K., Stattegger, K., Dominguez, J.M.L., Guimarães, J.K., Vital, H., d'Avila Beserra, D., da Silva, A.G.A. (2011) Morphology of subaqueous dunes at the mouth of the river dammed São Francisco (Brazil). J. Coastal Res., in press. https://doi.org/10.2112/JCOASTRES-D-10-00195.1.

Bartholomä, A., Holler, P., Schrottke, K., Kubicki, A. (2011) Acoustic habitat mapping in the German Wadden Sea – Comparison of hydro-acoustic devices. J. Coastal Res., SI 64, 1 – 5. https://www.researchgate.net/publication/256125798_Acoustic_habitat_mapping_in_the_German_Wadden_Sea.

May, H., Schrottke, K., Schwarzer, K., (2010) Coarse-grained sediment distribution in shallow water of the southwestern Baltic Sea (Germany). In: Schwarzer, Schrottke, Stattegger (eds.) From Brazil to Thailand – New Results in Coastal Research. Coastline Report 16 (2010), ISSN 0928-2734, ISBN 978-3-9811839-9-3 S. 55-57.

B5.2 examines the risks arising from the coupling of sea level rise (SLR) and other coastal stresses and assesses the potential impacts resulting from this coupling. Coastal processes are also investigated on spatial and temporal scales. Investigations provide input for policy and management support needed for issues and questions arising from accelerated SLR (increased flooding, displacement of lowlands and wetlands, salinization of surface and ground-water) and increased human activity. In cooperation with partner institutions, a significantly improved and updated version of the DIVA (Dynamic and Interactive Vulnerability Assessment) model has been compiled and a series of quantitative assessments of SLR impacts and vulnerability for various regions has been produced. These applications constitute the most up-to-date estimates of coastal impacts. They are the first results of this analysis type that consider different adaptation options (under various socio-economic and climatic scenarios) and which are consistent and comparable across regions. Regional studies (e.g. Coral Triangle, Europe, Africa) were carried out after requests from various international organizations (Nature Conservancy, European Environment Agency, Met Office UK). Further applications (Mediterranean, South America) are currently underway.

Selected publications:

Houghton, K., Vafeidis, A.T., Neumann, B., Proelss, A. (2010) Maritime Boundaries in a rising sea. Nat. Geosci. 3 (11), 803 – 806, DOI: 10.1038/ngeo1029.

Vafeidis, A.T., Nicholls, R.J., McFadden, L., Tol, R.S.J., Hinkel, J., Spencer, T., Grashoff, P.S., Boot, G., Klein, R.J.T. (2008) A new global coastal database for impact and vulnerability analysis to sea-level rise. J. Coastal Res. 24 (4), 917 – 924, DOI: 10.2112/06-0725.1.

Nicholls, R.J, Tol, R.S.J., Vafeidis, A.T. (2008) Global estimates of the impact of a collapse of the West Antarctic Ice Sheet: An application of FUND. Climatic Change 91 (1 – 2), 171 – 191. https://doi.org/10.1007/s10584-008-9424-y.

B6: Law of the Sea and Marine Resources

B6 strengthens the expertise in the field of international law of the sea at CAU Kiel. A JRG contributes to the development of new laws for the sustainable use of marine resources based on a sound understanding of the oceanic ecosystem. B6 cooperates with A2, A3, A4, A7, B1, B2, B3 and B5.

When and under which circumstances ocean activities can be undertaken requires a detailed examination of the legal issues linked to these activities. These activities may include the carrying out of marine scientific research, fishing, shipping, and exploitation of resources, laying pipelines or cables on the seafloor or ocean environmental protection. The legal framework is provided by the international law of the sea, which constitutes one of the oldest and most relevant areas of public international law.

B6 analyzes the existing legal framework for ocean activities in light of challenges resulting from climate change, energy resource scarcity and the increased exploitation of the seas. B6 collaborates closely with other research groups within the Cluster. For example, aspects of fishery biology and economics played a central role in a recent proposal of harvest control rules. The proposed rules are economically sound, comply with international fishery agreements, are based on relevant international observations, support ecosystem-based fishery management, and are compatible with fish stock biology. The need for a multidisciplinary approach is also reflected in JRG involvement in the 'Sub-seabed CO_2 Storage: Impact on Marine Ecosystems (ECO2)' EU project. The JRG was responsible for dealing with the legal prerequisites of properly applying the precautionary principle. In addition, B6 delivered a legal opinion on the legality of iron fertilization experiments, which was requested by the Federal Ministry of Education and Research (BMBF). Following this project, B6 was engaged by the Ministry to give a general opinion on the legal regulation of climate engineering. Interdisciplinary cooperation is also required for the question of sea level rise impact on maritime boundaries.

Selected publications:

Froese, R., Branch, T.A., Proelß, A., Quaas, M.F., Sainsbury, K., Zimmermann, C. (2010) Generic Harvest Control Rules for European Fisheries. Fish Fish., 1 – 12, DOI: 10.1111/j.1467-2979.2010.00387.x.

Güssow, K., Proelss, A., Oschlies, A., Rehdanz, K., Rickels, W. (2010) Ocean Iron Fertilization: Why further research is needed. Mar. Policy 34, 911 – 918. https://doi.org/10.1016/j.marpol.2010.01.015.

Houghton, K., Vafeidis, A.T., Neumann, B., Proelss, A. (2010) Maritime Boundaries in a rising sea. Nat. Geosci. 3 (11), 803 – 806, DOI: 10.1038/ngeo1029.

2.1.3 RESEARCH AREA P: PLATFORMS

A platform concept has been established to provide technical infrastructure and resources for all scientists within cluster "The Future Ocean". Platform P1 Numerical Simulation addresses all Cluster requirements for access to high performance computing facilities and modern numerical techniques. Platform P2 Isotope and Tracer Analysis supports research through highly specialized and accurate instruments for isotope and trace element measurements. Platform P3 High-Troughput Molecular Bioscience Technologies comprises high throughput molecular techniques with the new Center for Molecular Biosciences (ZMB). Platform P4 Ocean Observatories offers support for in-situ measurements of chemical and physical properties of current conditions and ongoing change in the ocean. The platforms allow for a more efficient use of technical infrastructure and expertise of lab personal and will be further developed into the KAIMS Science support unit Research Platforms.

P1: Numerical Simulation

Numerical simulations play a key role in the Cluster. They require an infrastructure for high-performance computing, development of interfaces for algorithms and software from different areas, in particular marine science and numerical mathematics, the ability to store and manage data in an efficient way, and to provide expertise from mathematics and computer science for large-scale numerical problems. The computing infrastructure, a vector machine NEC SX-8 located in the computing center of CAU, was extended by an additional node for applications computed in Cluster projects. P1 extended the Opteron-Parallel Machine in the computer center and acquired a dedicated server for the processing of seismic data together with various hardware upgrades to high performance computer facilities. The platform also provided software for algorithmic data assimilation. The platform has been used predominantly by groups simulating oceanic CO_2 uptake as well as ocean circulation and warming.

P2: Isotope and Tracer Analysis

The study of spatial and temporal changes of the ocean's chemical composition and the interaction between marine biology and seawater as well as the ocean's interaction with atmosphere and sea floor at their respective interfaces is crucial to marine science and a strategic task within Future Ocean.

Therefore, the platform P2 Isotope and Tracer Analysis was established in order to give advice to Cluster members on all existing facilities of trace element and isotope measurements which may be necessary for Cluster-related research. Furthermore, P2 supported inter-laboratory networking and synergy between Cluster laboratories and provided a platform for the discussion on strategic investments for new state-of-the-art analytical equipment, such as new gas scource mass spectrometers, in marine sciences. As a consequence, Cluster investments focused on the replacement of outdated instruments and the purchase of new, complementary and innovative analytical equipment. Strategic investments were made in support of a new organic geochemistry department and to strengthen the inorganic micro-analytical capabilities.

P3: High-Throughput Molecular Bioscience Technology

Platform P3 mainly serves the research topics A1:Ocean Acidification, A2:Seafloor Warming and A3: Marine Medicine in Future Ocean by providing high-throughput molecular technologies to marine biology projects. The Center for Molecular Biology provides automated technologies in life sciences. It offers in particular (i) (ultra)high-throughput analyses of genetic diversity, (ii) systematic expression profiling, (iii) robot-assisted cell-based assays including automated genome-wide siRNA transfection protocols, (iv) competitive proteome analysis techniques, and (v) high-throughput live imaging facilities. The new infrastructure consists of a DNA Analyzer for high-throughput, walk-away DNA purification from a variety of biological specimen. These large-scale sequencing capabilities are important for all Cluster research related to marine genomics. A Biacore X100 System allows studying biomolecular interactions in real time where protein-protein interaction, protein-ligand interaction or any biomolecule of interest interacting with a specific binding partner can be studied with high sensitivity. Sea-going equipment has been acquired for on-board execution of the nucleic acid extraction step in the processing of field samples for normal and qPCR and a automatic purification system for genomic DNA, RNA and proteins, a metagenomic filtration system to rapidly collect size fractions of planktonic organisms.

P4: Ocean Observatories

Platform P4 has the mandate to provide multi-facetted observational capabilities that meet the wide range of requirements for research to be carried out within in the Kiel Marine Sciences Network. Platform P4 is mainly used by the research groups working on ocean acidification and warming, sea level rise and coasts at risk, submarine hazards, as well as seafloor resources. The platform holds instruments deployed at the sea floor, surveying the water column, or observing the surface from floating platforms at various depths. Available instruments are i.e. mesocosms for replicated shipboard plankton experiments, including a controlled aeration system for CO_2 manipulation, benthic mesocosms with oxygen exchange systems integrated into existing bottom landers, an ‘Ocean Tracer Injection System’ (OTIS) for artificial tracer injection, a continuous imaging flow cytometer (FlowCAM) for real time monitoring of particles in fluids. For hydroacoustic imaging in shallow waters, a side-scan sonar and mini-boomer, a parametric sub-bottom profiler, an Acoustic Doppler Current Profiler (ADCP), and an optical instrument for in-situ measurement of particle size spectra (LISST -100) for characterisation of suspended matter were purchased. Seismometers with 8,000 m depth capability, a Benthos C3D side-scan sonar for seabed mapping, and various special upgrades to the ROV ‘Kiel 6000’ complement the P4 infrastructure.

2.2 HIGHLIGHTS OF INTEGRATED RESEARCH IN THE SECOND CLUSTER PHASE (2012-2019)

In phase I the Cluster research was organized in two major areas: (A) Greenhouse Ocean and (B) Ocean Resources and Risks, covering 13 research topics. These had been identified with great potential to integrate existing Kiel Marine Science expertise and at the same time deliver new interdisciplinary marine research. Inspired by our internal, EU and international discussion on grand challenges for marine research, the current Cluster research in phase II has evolved towards a more natural, issue driven and fully integrated research structure with eleven research topics that aimed to connect Ocean System Understanding – Ocean Prediction and Scenarios – Sustainable

Ocean Management and Governance while still addressing the three main ocean challenges: Global Change, Hazards and Resources (→Fig. 1).

As scientific progress is required in basic ocean system understanding, which in turn enables us to better interpret past and ongoing future changes and develop science based predictions and scenarios, the prospects for future ocean uptake of CO_2, exploitation of an increasing number of ocean resources and their sustainable management and governance have been assessed. The development and assessment of science based sustainable governance options poses specific requirements on the accuracy, timeliness and quality of ocean information, predictions and scenarios and basic understanding. This process allows to set priorities on new demands for more basic marine science. The new structure of fully integrated research within the Cluster has enabled this feedback loop to operate between improved basic ocean system understanding, improved prediction and scenarios, and improved ocean governance models.

Program of research areas R1-R11

The research areas A and B from phase I formally terminated and merged into fully integrated research areas “R”. Based on existing Kiel talent and experience, the possibility for new strategic hires and the Marine Sciences Grand Challenge context, eleven integrated multidisciplinary research topics have been developed under descriptive titles (Fig. 6).

Figure 6: Integrated multidisciplinary research topics in the second phase of “The Future Ocean”.

Strategically, interdisciplinary research has been established that follows and closes the integrated marine sciences innovation cycle (→ Fig. 1) to address a range of marine grand challenges. The research topics R7: Ocean Interfaces, R8: Evolving Ocean, and R9: Ocean Controls have achieved a certain level of ocean system understanding, that forms the basis for developing models or similar statistical procedures that enable science-based scenarios, projections and predictions of the future ocean, which has been done for instance in R10: Ocean Observations and R11: Predicted Ocean. Based on a range of future scenarios and, where possible, the likelihood of their respective occurrence, management and governance concepts have been developed to promote sustainable development of the marine system in R1: Our Common Future Ocean and R2: Ocean Governance. In most cases it becomes apparent that the range of likely outcomes is large and more basic information and more precise forecasts are highly desirable. This usually is only possible with an increased level of understanding of the underlying marine system or the need to develop alternative ways to ‘use’ the oceans as it has been done in R3: Ocean Resources and R4: Ocean Innovation. This integrated marine sciences innovation cycle provides a prioritized request for specific basic research.

All new integrated research topics built directly on current Cluster research, but strived to increase the level of multidisciplinary cooperation. An initial assessment of the level of integration between the areas of Ocean System Understanding – Ocean Prediction and Scenarios – Sustainable Ocean Management and Governance is provided by Fig. 1. Clearly the level of integration varied, however, the aspiration was to take advantage of the broad Kiel Marine Sciences knowledge base where it made scientifically sense. All research topics addressed one or two overarching broad research questions and have developed typically three initial research foci. The work in each research topic was executed by the Cluster proponents supplemented by typically three postdoctoral researchers and two PhD students.

The research topics built on existing activities, already funded by the Cluster or by a range of additional sources (e.g. DFG, BMBF, EU, industry partners). The Cluster contributions targeted the interfaces between the disciplines and work toward the generation of integrated science that provides reliable knowledge for stakeholders and decision makers to act upon. In addition to the eleven Cluster research topics with their explicit initial research foci, new teams had the possibility to apply for small amounts of seed funding (typically 50-100 k€) to work on new research foci. This process was successfully executed during phase II of the Cluster with 148 supported projects and 19 investment projects from 73 so called minimproposal calls for innovative high risk project ideas.

2.2.1 R1 OUR COMMON FUTURE OCEAN

Martin Visbeck, Tom Duscher, Martin Quaas, Ulrike Kronfeld-Goharani, Barbara Neumann, Jörn Schmidt, Konrad Ott

Scope

Our Common Future Ocean brought researchers together from the disciplines of ethics, economics, arts, political and social sciences, law and natural marine sciences to develop a concept of ocean sustainability. The conceptual approach is complemented by analytical, societal and scientific discourse on ocean sustainability and by experimentally eliciting sustainability views held by society. The sustainability concept is applied to a range of specific ocean issues including CO_2 storage in the ocean and the use of ocean resources.

Sustainability has been a key notion in the societal and scientific discourse about the relationship between humanity and nature at least since the Brundtland report ‘Our Common Future’ (WCED 1987). Sustainability is widely agreed to be a general and abstract objective and implementing changes has remained limited. A major challenge is what sustainability means in a concrete decision-making context. The Brundtland report considers sustainability to be an aspect of future development (‘sustainable development’). However, future development of the ocean will always remain uncertain and foreseeable only to a limited extent because of stochastic events and our limited knowledge about ocean dynamics. Whether the actual development path will satisfy sustainability requirements, such as the maintenance of specific ecosystem services, can only be verified ex post. However, one can assess certain development scenarios. Thus, pure outcome-based concepts of sustainability, as suggested by the Brundtland report are not applicable because of the uncertainty. Furthermore, a sustainability concept can only be of practical relevance if it is shared by a large part of society. To this end, it is necessary to increase public and cultural awareness about the effects of ocean change and to consider the normative views on sustainability held by society. Against this background, the central question was: How can sustainability of the uncertain future ocean be conceptualized so that it can be widely agreed upon and result in responsible decision-making? The concept of sustainability was advanced by combining philosophical (ethical), cultural, economic, political, and legal considerations.

Scientific achievements

The interdisciplinary research group has been actively involved in the development and implementation progress of SDG 14 on oceans in the United Nation's 2030 Agenda for Sustainable Development. It has advanced the conceptual progress on sustainability, and has been broadly engaged with politicians and the society. Researchers in the disciplines of ethics, economics, arts, political and social sciences, law and natural marine sciences including graduates and postdocs worked together in this research focus.

The Ocean and Sustainable Development

Coastal and marine areas are subject to growing socio-economic and environmental pressures which include climate-change related effects such as sea level rise that are critical for human development and provide livelihoods in many parts of the world (e.g. Visbeck et al. 2014). Establishing a shared understanding of what sustainable development entails is crucial for guiding governance and decision-making (Fig. 7). We combined social ecological assessments, expert elicitation, interdisciplinary discourse analysis and transdisciplinary approaches to link this work to the global political sustainability agenda. Beginning when the United Nation's 2030 Agenda for Sustainable Development (United Nations, 2015) was negotiated between member states with the involvement of non-State actors and representatives from academia, Kiel's work has contributed to expert deliberations requested by the United Nations (UN) and, together with the research topic R2 on Ocean Governance, provided science-based input to the scientific (Visbeck et al. 2014) and political discourse including the UN's policy agenda. The adopted sustainability agenda of the UN takes note of the urgent need to conserve, protect and manage coastal systems and marine systems by dedicating one of its 17 sustainable development goals (SDGs) to oceans, seas and marine resources including coastal areas (SDG 14).

Yet, various aspects that are relevant for putting the aspirational 2030 Agenda into practice and

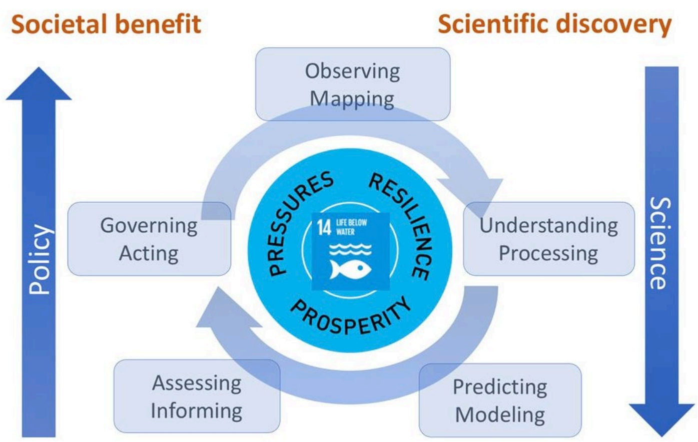

Figure 7: Increased need for ocean information to meet societal needs. Meeting a growing range of societal demands and achieving Sustainable Development Goal 14 (Conserve and sustainably use the oceans, seas, and marine resources) from the 2030 Agenda for Sustainable Development can only be fully realized if all elements of the ocean value chain are resourced adequately and more integrated science agendas are advanced. ©UNITED NATIONS. All rights reserved (from Ocean science research is key for a sustainable future. Visbeck, 2018).

successfully achieving SDG 14 have not been fully developed and are possibly still open to debate. These include defining sustainable development in the context of the challenges facing coastal and marine areas, factoring in trade-off and co-benefits between different development goals in the implementation of the 2030 Agenda and SDG 14, and monitoring progress made through suitable concepts and frameworks. By identifying challenges emerging for the human-ocean system and the actual implementation of the “integrated and indivisible” 2030 Agenda (United Nations 2015), we co-authored a first assessment of interlinkage of SDG 14 with other goals and targets (Schmidt et al. 2017) as part of a study commissioned by the International Council for Science. This study examined how SDG 14 might interact with other SDGs, employing a seven-point rating scale developed by (Nilsson et al. 2016) and identifying policy options to mitigate possible negative interactions and maximizing positive outcomes. The study confirmed not only that the ocean and its resources have a central role in the Earth system and for humanity, but also that ocean conservation and sustainable use of marine resources can only be achieved when policies and measures are aligned between the 17 goals and 169 targets of the 2030 Agenda. For example, tackling ocean pollution (target 14.1 under SDG 14) requires appropriate action on sustainable consumption and production (SDG 12) or food provisioning from land and sea (SDG 2) (Fig. 8). The results also point to the inadequacy of the current governance system for ocean and coasts with its split sectoral and spatial responsibilities between economic and environmental sectors and between land and sea, especially when arguing for a “strong sustainability” approach (Neumann et al. 2017). So in summary, we advocate thinking about the ocean in its fullest dimension in the 2030 Agenda, which includes SDG 14 but is much wider in scope.

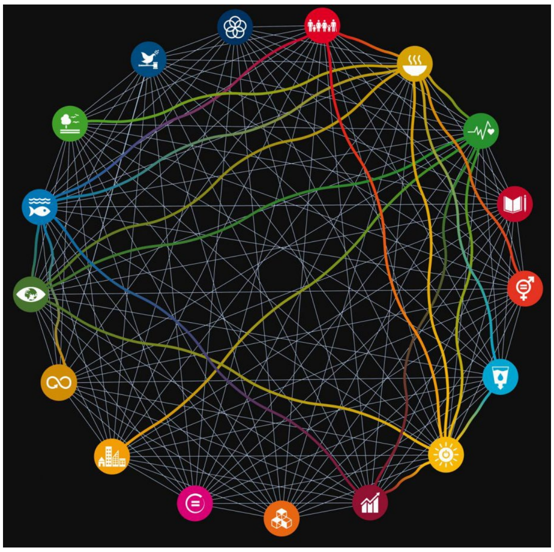

Figure 8: Ocean scientists from Kiel and the Institute for Advanced Sustainability Studies IASS Potsdam, delivered a detailed analysis of four United Nations Sustainable Development Goals (SDGs) for the international report of the International Council of Scientific Unions (ICSU), 2017: A Guide to SDG Interactions: from Science to Implementation. Foto/Copyright: ICSU, Paris

Furthermore, monitoring progress to achieve the SDG goals and targets, including those for the ocean, coasts and marine resources is essential to ensure that humanity operates within a safe and just space and in accordance with shared visions of sustainability. Here, it is vital to set the proper indicators and benchmarks for monitoring progress and it is also critical to decide what kind of monitoring framework and what conceptual understanding of sustainability is applied when weighing and balancing the measures.

Assessment of ocean sustainability concept

The concept of sustainability has become the worldwide dominating leitmotif for shaping international environmental and developmental relationships. However, the definitional ambiguity and the variety of possibilities for characterizing the term have led to a situation in which the concept is used in a multitude of contexts. To develop a common ground to understand what sustainability means, the discourse on ocean affairs with a special emphasis on the articulation of the concept of sustainability was explored. It could be illustrated that the concept provides a framework not only for the conservation of nature but for tackling growing societal challenges such as ensuring food security, energy supply, health and human well-being, whilst simultaneously responding to climate change, marine pollution and the destruction of marine and coastal habitats but needs a more defined concept to not being adjusted randomly (Kronfeld-Goharani, 2015).

A new normative framework termed “strong sustainability” has been developed (Ott 2019; Fig. 9). The amount of “natural capital” – any property of the system that contributes to human welfare – needs to remain constant in any environmental system for achieving sustainable development. Animals, plants and clean water are obvious examples, but pleasing landscapes or relaxing surroundings would also count. Studies show that maintaining this natural requirement may require to invest in damaged environments in order to get them back to their original condition. Hence, decisions on strong sustainability often/naturally call for qualitative judgements. For example, it might be appropriate to devote special effort in restoring rare environments because of their contribution to natural diversity. It rejects the strictly economic calculations involved in the ecosystem services approach, which sets monetary values on green assets and takes account of intergenerational equity by trying to leave adequate natural capital for future generations.

Ott and Neumann are researching how this concept relates to SDG 14 and the sustainable use of oceans, seas, marine resources and coastal areas mentioned in two targets within SDG 14, i.e., target 14.2 and target 14.5. They argue that the SDG process might be regarded as an opportunity to address ocean and coastal challenges on a range of scales. But this requires a clear summary of the underlying approaches, principles, and objectives. The two targets analysed by Neumann et al. (2017) presuppose and promote a “strong sustainability” concept. According to this study, most of the SDGs refer to humanitarian aspirations. However, there are reasons to ground SDG 14 in a concept of sustainability that does not allow for ongoing substitution of natural capital, but provides for restoration, rehabilitation, and conservation. Realising the coastal targets set out under SDG 14 through policies and actions based on strong sustainability brings about challenges and pitfalls. For example, target 14.5 prescribes the conservation of “at least 10 per cent of coastal and marine areas” but does not specify how to implement these conservation areas, i.e. which habitats or species require conservation, or where these areas ought to be located.

Engaging in the Stakeholder Dialogue on the Ocean and Society

Research is producing three types of solutions to today’s issues in science and human development. Firstly, is to generate “ocean literacy,” the ability to understand the ocean and factor it into social thinking (Visbeck, 2018). The research group from “Our Common Future Ocean“ has been active in public outreach and engaging with the scientific community, politic actors and the public.

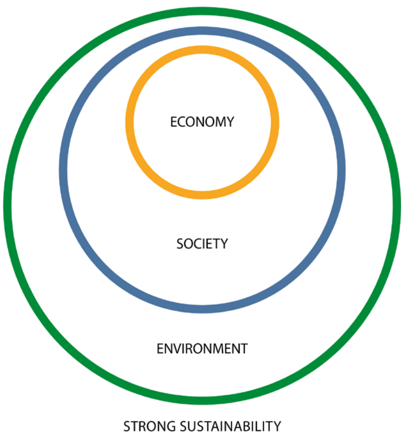

Figure 9: Strong sustainability focuses on protection and restoration of critical natural capital. This concept has deep roots in history, and is related to Rawl’s theory of justice via the fair saving principle. The resources of the ocean that contribute to human welfare need to remain constant in any environmental system for achieving sustainable development (Ott 2019).

In 2015, the group organized an international symposium on ocean sustainability within the framework of the cluster's semester topic. More than 140 scientists from 22 countries and different disciplines, representatives of politics, society, non-governmental organizations (NGOs), as well as young researchers met at the Ocean Sustainability Science Symposium in Kiel to discuss the sustainable protection and the responsible use of the ocean and its coasts. The group also organized a weekly lecture series "The Changing Ocean: Challenges of the Future" for Kiel's public, which covers various aspects of ocean sustainability.

Resulting from the semester topic, a World Ocean Review on „Sustainable Use of our Oceans – Making Ideas Work" (WOR IV) was published. Together with an NGO, the group coordinated the publication of the Ocean Atlas with an emphasis on how we use and change the ocean (Fig. 10). It was published within the context of the Ocean Conference in New York in 2017, hold by the United Nations to Support the Implementation of SDG 14. Both aim to inform political decision makers, multipliers in education, students, and the interested public, about marine science and are part of the cluster's strategy for general ocean literacy. The group also co-organized a side event on ocean sustainability during the Ocean Conference in New York in May 2017. Over five years, the group co-organized together with the Institute for Advanced Sustainability Studies IASS Potsdam, various political conferences on ocean governance issues enhancing the dialogue between scientists and politicians. Kiel researchers have proposed solutions, which are intended for consideration and implementation. They will help societies and in particular coastal communities to become more sustainable, resilient and even prosperous. They also encourage people to become more aware of climate issues.

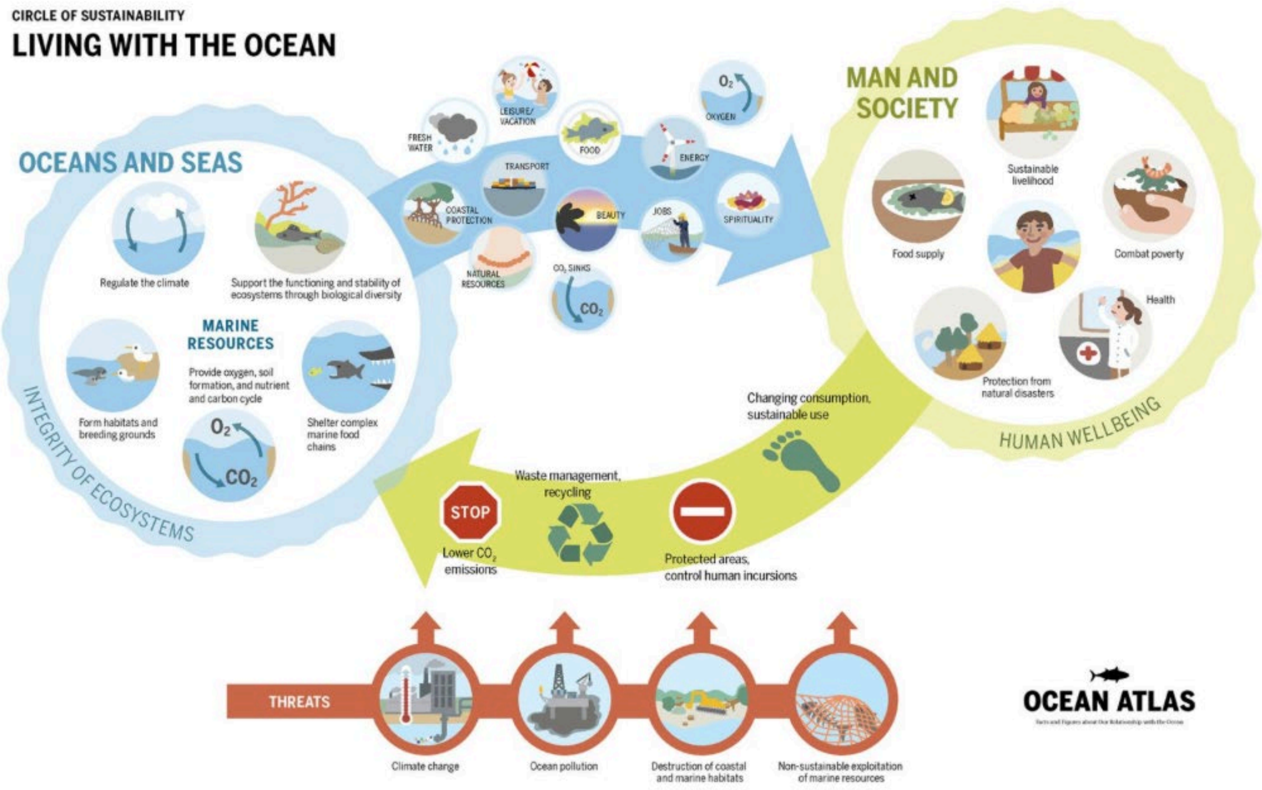

Figure 10: Human-ocean interactions highlighting ocean ecosystem services and their threads (taken from Ocean Atlas, 2017).

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2.2.2 R2 OCEAN GOVERNANCE

Nele Matz-Lück, Kerstin von der Decken (neé Odendahl), Martin Quaas, Jörn Schmidt

Scope

Ocean Governance brought researchers together from the disciplines of law, economics, political sciences, philosophy, geography and natural marine sciences to evaluate existing and propose new approaches to governing our use of the ocean towards sustainability, maintaining the ocean's essential functions and ecosystem services while balancing anthropogenic uses such as transportation, fisheries, resource extraction, and renewable energy generation.

Existing approaches to governing the oceans in a comprehensive manner have largely failed. While some issues such as international shipping are relatively well regulated, governance approaches remain piecemeal and suffer from significant shortcomings on either the level of regulation or implementation. One example is the issue of overfishing in coastal waters as well as the high seas. According to FAO (2011), the state of the world's marine fish stocks is worse than ever: Almost a third of all stocks are overexploited or depleted, imposing a threat to marine biodiversity and the functioning of marine ecosystems. New problems, such as CO_2 storage in the ocean or climate engineering, are also not sufficiently handled by existing frameworks and thus require completely new governance approaches. Furthermore, all these international issues lack a clear assignment of responsibility to authorities, institutions with strong mandates, or persons. Different players impact the ocean, including States, international organizations, private businesses and individual citizens. A major challenge is the growing interconnectedness of differing societies in the world and the issues that States and civil societies have to deal with. Therefore, regulation at different levels (international treaties, EU law, national law, 'soft law' such as codes of good practice, contracts between private parties or with the State, or discussion processes) must be coordinated.

We focused on different approaches of governing the ocean towards sustainability from the perspective of assigning responsibility for the sustainable use of the oceans to specific entities. Central questions included: 1) how responsibility and liability for damages to the marine environment can be established and implemented, 2) how rules and regulations must be established or adapted to govern sovereign rights in exclusive economic zones (EEZs). In the course of research over the years another focus was placed on the question of how to establish governance mechanisms for areas beyond national jurisdiction, i.e. the high seas and the deep seabed.

Scientific achievements

The governance of the ocean is highly segmented and even on a global level, many institutions are engaged in activities that can be labelled ocean governance (Fig. 11). Scientists from Kiel have been addressing issues related to ocean governance from different perspectives and with different research foci, including fisheries, seabed resources and biodiversity beyond national jurisdiction (BBNJ). The work specifically looked into environmental liability (Matz-Lück and van Doorn, 2017), the impact of regional conventions (here OSPAR) on biodiversity protection in areas beyond national jurisdiction (Matz-Lück and Fuchs, 2014), fisheries as common heritage of humankind (van Doorn et al. in prep), and on balancing different ocean uses (Matz-Lück, forthcoming). Due to the high demand in the national and international policy domain on these issues, Kiel scientists have also been contributing to many workshops on ocean governance, which led to several reports and

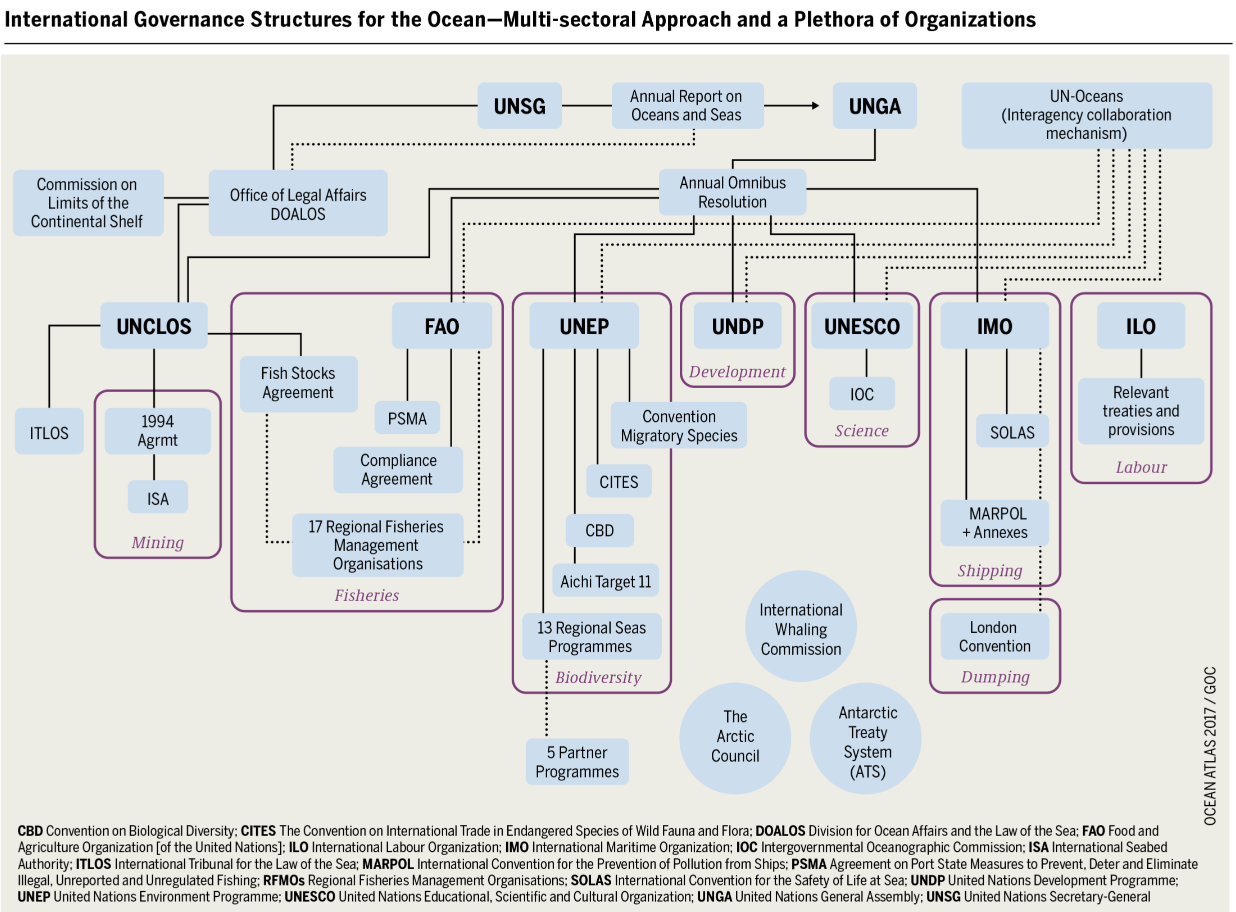

Figure 11: Global Ocean Governance (with permission from the Ocean Atlas 2017).

Governance approaches to fisheries

The 1982 United Nations Convention on the Law of the Sea (UNCLOS) has divided the ocean into exclusive economic zones (EEZs), in which coastal States have the exclusive right to harvest fish stocks, and high seas, where such an exclusive right does not exist. Experience has shown that multi-lateral fisheries management in the high seas is particularly difficult. There is a lively debate on how to achieve sustainability in high seas fisheries with some proposing to fully close the high seas to fisheries. We propose to govern the ocean's high-seas fisheries under the Common Heritage of Humankind, as it applies to the deep seabed under UNCLOS. Drawing on the characteristics of Common Heritage of Humankind, as laid out in UNCLOS, we develop a conceptual framework how such an approach could be operationalized.

A quintessential characteristic of common heritage is that benefits that arise from its exploitation should be shared among humankind. Contrary to the freedom of the high seas, access to a common heritage is restricted. Humankind consequently needs to regulate the access and benefit sharing. In economic terms, the benefit to be shared is the return on the natural capital value of the high-seas fish stocks. It is given by the economic surplus that arises if the stocks are built up to the MSY population sizes. Here, we suggest adopting the idea to grant individual licenses for harvesting the total allowable catch (TAC) that is determined according to the MSY principle.

In his PhD project, Erik van Doorn evaluated different models of fisheries governance: From sovereign rights over the EEZ to open access regimes for the high seas based upon the freedom of the high seas which includes the freedom of fishing. For fisheries on the high seas he placed particular focus on governance models based upon a common interest and common responsibility. In this respect, he discussed the regime established for the ocean floor as a potential model. The ocean floor beyond national jurisdiction and its mineral resources are legally the common heritage of humankind. Current negotiations concerning a new legal instrument for biological diversity beyond national jurisdiction might extend the application of this principle into the water column, the high seas. What the common heritage distinguishes most from the centuries-old freedom of the seas is its obligation to share benefits, not only among human beings currently but also with future generations. This makes the notion of a common heritage of humankind like the Anglo-Saxon idea of a public trust. The high seas as a trust with humankind as a trustor and an organization like the International Seabed Authority as a trustee might stimulate new thinking about ocean governance. With his research on the common heritage and benefit-sharing with current and future generations as elements of governance, Erik van Doorn included environmental ethics into legal considerations and concluded his PhD as an interdisciplinary work with Nele Matz-Lück and Konrad Ott as supervisors from the fields of law and philosophy respectively.

Fisheries Policy

Fisheries management often fails because one of the main management measures, the (TAC) is set too high, both from a biological as well as from an economic point of view. The reason for this inefficiency lies in the political negotiations, e.g. in the European Council, among the fisheries or agricultural ministers. To study why these decision-makers choose higher TAC, a model has been developed to analyse the annual TAC negotiations. This model captures the heterogeneity of the ministers, coming from different political backgrounds as well as different situations in their countries with respect to fisheries (jobs, income and relevance for the country). The model shows that it is often optimal for the less patient decision makers to set inefficiently high TAC. Long-term management plans with rules on how to set the TACs in relation to the yearly advice and decoupling the decision from short term thinking will help in solving this problem and lead to a more sustainable fishery management (Hoffmann and Quaas, 2016).

Future Ocean Spatial Planning

The different maritime zones of the ocean are being used for a variety of different uses; e.g. transportation, recreation, resource extraction, fisheries, and renewable energy generation. While potentially competing uses increase in intensity and variety, ocean space remains the same. The level of regulation differs with regard to the sovereign rights allocated to coastal States. The UN Convention on the Law of the Sea acknowledges different legitimate ocean use by establishing rights and obligations in the field of navigation, resource exploitation, fisheries and others. Yet, it addresses competing uses on a case-by-case basis and does not provide for planning tools. Marine spatial planning is a governance process that allows for a structured planning approach to address different ocean uses in a maritime area. This includes a coastal State's EEZ, which is particularly prone to different uses due to exclusive sovereign rights over marine resources on the one hand and certain freedoms for all States such as navigation or the laying of pipelines and cables on the other hand. Marine spatial planning is a multi-disciplinary and multi-stakeholder process. It is designed to allow for a procedure to define uses, involve stakeholders, plan the implementation for a specific area and monitor the results with a view to revise, if necessary. In 2013, an international interdisciplinary workshop was held in Kiel to discuss spatial ocean planning as a governance instrument. Marine spatial planning has since remained on the agenda of Kiel researchers, e.g. in the context of increased shipping in the Arctic. The research collaboration with the Ocean Frontiers Institute in Halifax, Canada, includes research by Nele Matz-Lück concerning marine spatial planning in the EU context as a potential model for the Canadian territorial waters and EEZ to accommodate shipping with other uses.

Environmental liability

Liability is considered one approach to steer behaviour related to activities with a potentially harmful effect on the marine environment. While national law applies to activities under the jurisdiction of coastal states, e.g. oil exploration, many high-risk activities are undertaken in areas beyond national jurisdiction. In such case liability must be assigned to states either directly or via their jurisdictional link to private entities such as vessels or companies. Different models of liability under international and national law are being implemented and discussed for future uses such as deep-seabed mining. To establish liability as a governance tool, the potential damage, the assessment of risks and economic consequences must be evaluated. From a legal perspective Nele Matz-Lück

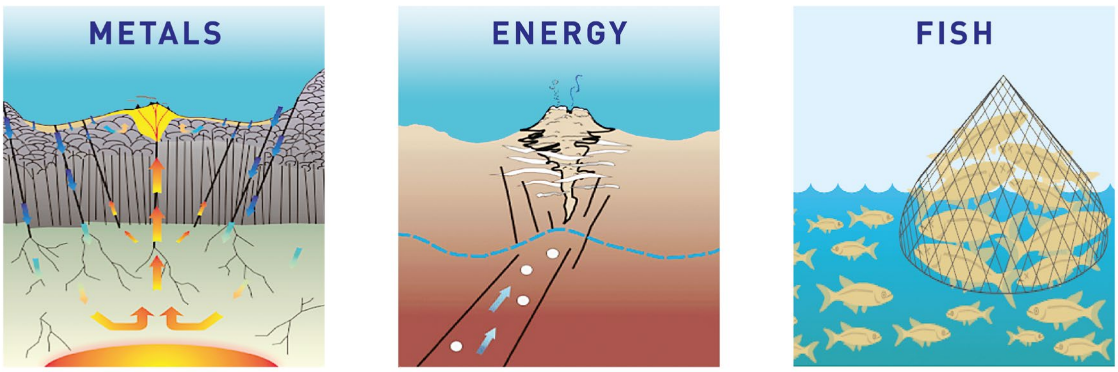

Figure 12: The Ocean holds living and non-living resources of importance for human living.

and Erik van Doorn have systematically assessed standards of due diligence as exemplified by decisions by international courts and tribunals that lead to the responsibility of States concerning harmful activities by private entities. The assessment assigns an important role to international dispute settlement bodies to shape and dynamically develop international law. The issue continues to be topical with regard to commercial mining of deep-seabed resources which has not yet begun but for which rules and regulations are developed by international institutions such as the International Seabed Authority as well as with regard to a new legally binding instrument on biological diversity in areas beyond national jurisdiction. Kiel researchers from different disciplines have actively engaged in exchanges of views concerning such instrument inter alia during workshops held at the IASS to discuss with decision-makers and other scientists about the input to negotiations on the international level.

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2.2.3 R3 OCEAN RESOURCES

Till Requate, Lars Rüpke, Jörn Schmidt

Scope

Ocean Resources brought researchers together from biology, geology, economics and law to investigate the potential of living and seafloor resources and new avenues of better management and governance of ocean resources.

For millennia, human beings have taken advantage of the ocean in multiple ways. The oceans serve as transport media, provide food and other resources, and serve as a sink for human waste. For several decades the oceans have also served as a source of fossil fuels, with gas hydrate exploitation as one of the most recent developments. A severe problem with living ocean resources is their overuse. Due to ill-defined property rights and missing or insufficient rules and regulations, ocean resources and services are being used in an unsustainable way. Exploitation of common property resources under open access has led to over harvesting and severe stock depletion of major seafood species. This kind of overuse calls for national or international coordination and agreements on limiting economic activities to sustainable levels and for associated management rules. This research proposal has therefore two main objectives: To explore the functioning and potentials of ocean resources on the one hand, and to develop improved management and governance rules, on the other.

With respect to the resources, this report focuses on geological resources such as deep-sea ore deposits and methane hydrate accumulations, and biological resources such as fish and other living resources (Fig. 12). The aim of this research area was (i) to better understand the formation and global distribution of geological seafloor resources and to evaluate the risks and benefits of their exploitation, (ii) to better understand the relationship between fishing practices and other human impacts on the genetic diversity and health of fish (and other seafood) stocks, and (iii) to define operational management rules and targets in the presence of common property and ill-defined property rights. Against this background, the central question is: How can ocean resources be exploited in a sustainable or low impact manner by an appropriate balance between ocean use and ocean protection?

Scientific achievements

Geological, economic, and environmental assessment of marine minerals

The global ocean is hosting vast amounts of geological resources that might prove economically viable to extract. In an integrative study, Petersen et al. (2016) assessed their abundance, distribution and national versus international jurisdiction. Manganese nodules that are found in old, stable regions of the ocean floor, especially in the Pacific, and typically in water depths of 3000-6000 m are the best-known example. They are likely to occur in economically viable amounts across more than 50 million square kilometres of the deep ocean. Most of these areas lie beyond areas of national jurisdiction, the so-called Exclusive Economic Zones (EEZ), of any nation. The greatest concentrations of metal-rich nodules occur in the Clarion-Clipperton Zone (CCZ) of the eastern Pacific Ocean, which extends from the west coast of Mexico to Hawaii. While they consist largely of iron and manganese compounds, these nodules are referred to as “polymetallic” as they host other elements of economic interest such as nickel, copper, cobalt, lithium, and the so-called rare earth elements. In addition, the mining of cobalt-rich manganese crusts that form on the flanks of old volcanic seamounts also seems viable. The most promising region for this kind of deposit lies in the western Pacific. Like the nodules, these crusts contain mainly iron and manganese. But they hold large quantities of cobalt, tellurium and yttrium that far exceed land-based reserves.

A third kind of geological resource is volcanogenic massive sulphide (VMS) deposits that form in the neighbourhood of “black smokers” hot subsea vents in volcanically active regions of the ocean floor. These deposits are rich in copper, zinc, and in some cases gold and silver. Some occurrences contain other valuable elements such as selenium and cadmium but may also contain abundant toxic metals such as mercury or arsenic. It is much harder to assess the commercial potential of black smoker deposits. Unlike manganese nodules and crusts, their deposits are three-dimensional, and information on their depth and therefore their size is often lacking. The biggest deposits of this kind host a few million tons of ore, which is small compared to land-based deposits. Further studies suggest that we may be underestimating the scale of these deposits. One group has examined the basic science of so-called “hydrothermal” zones in the ocean (groundbreaking publications, Hasenclever et al. (2014)). They find that hydrothermal flow observations are best explained by a hybrid hydrothermal flow model in which the entire crust is cooled by a combination of shallow on-axis and deep across-axis flow. Their calculations show that the amounts of metal that could be mobilised by hydrothermal flow are far greater than current estimates based on the deposits we know of today.

These integrative studies reconfirm the notion that the overall resource potential of deep-sea minerals is immense. But the question whether deep-sea resources will play a significant role in providing raw materials in the future cannot be answered at present, due to the lack of information on their distribution and metal content. It is important, however, to provide basic geological information as a basis for political, economic and societal discussions on the prospects for deep-sea mining. The possibility of deep-sea mining implies that exploratory work needs to be carried out in vast areas of the global ocean floor that have never been investigated in detail. This research will need to be complemented by improved frameworks for assessing the societal and environmental impact of marine resource exploitation. The benefits of this new technology depend on the trade-off between the market value of these resources and the risks of their exploitation. At present it is impossible to assess this trade-off. We lack fundamental knowledge of the implications for the deep-sea ecosystems. So, we cannot envisage how the value of a marine mineral deposit compares to the environmental risks of mining it. It is also important to realise that many geological resources exist close to the shoreline in submerged areas of the continental shelf (Hannington et al. 2017), which opens the possibility that mining these deposits from land may be feasible. This approach could reduce the environmental risk to seafloor ecosystems while helping to meet global resource demands. In the light of such large uncertainties with regard to the ocean's metal endowment and the risks associated with marine metal exploitation, it is becoming increasingly clear that ongoing international research activities must be accounted for in international regulations to protect the ocean realm from future mining impacts (Boetius et al. 2018).

Gashydrates and their role in the Earth System

Vast amounts of methane are locked up in marine sediments as solid gas hydrates, where water pressures are high (>~400 m), temperatures are low (<~10°C), and the gas flux is sufficiently high for hydrates to form. This has sparked interest in gas hydrates as a future energy resource. Yet, methane is also a greenhouse gas implying a potential feedback between changing environmental conditions at the seafloor and methane emissions from dissociating hydrate reservoirs. In a series of papers, we have assessed the global abundance of hydrate trapped in marine sediments and what the fate of those hydrates might be under global warming. Kretschmer et al. have shown that over 1.1 trillion tonnes of methane are trapped in hydrate form impacts (Boetius et al. 2018). However, predictions for ocean bottom temperatures over the next century are reassuring. They imply that less than 500 million tonnes of methane will be released, which is in sufficiently deep water to prevent emissions into the atmosphere. This limited impact of warming seafloor temperatures on marine hydrates over the next century is in accordance with a study on methane emissions offshore Svalbard. Berndt et al. (2014) find that currently observed methane vents have been active for at least 3000 years implying a natural rather than an anthropogenic trigger. The economics of hydrate exploitation has been investigated in Döpke et al. 2014.

Sustainable exploitation of seafood resources

The world’s fish stocks are increasingly under pressure, not only due to climate change effects, but also due to socio-economic development, leading to a worldwide increased demand for fish. Currently, many of the world fisheries are in a bad shape, causing both ecological and socio-economic problems. One major reason is failing fisheries management, allowing for too generous catch opportunities, while disregarding socio-ecological-economic feedback dynamics.

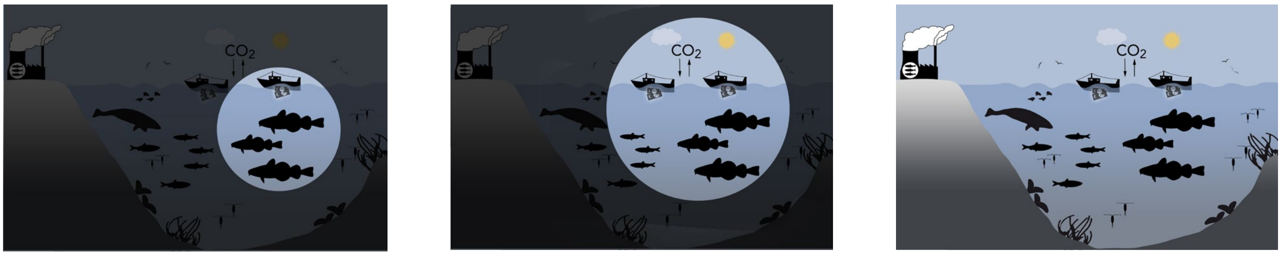

Figure 13: Widening the scope of ecological economy to solve imminent conservation problems & to achieve sustainable fisheries management: from a focused stock perspective to ecosystems and globalmarkets.

Researchers in Kiel went beyond traditional concerns with overfishing and ecosystem stability, working in interdisciplinary teams, which include biologists and fisheries experts, economists, physical oceanographers and even lawyers with knowledge of international maritime agreements. They have shown that economic factors might have a bigger influence on the future of fishing than climate change or ocean acidification. The experts agree that to achieve sustainable fisheries, it is necessary to consider the full picture (Fig. 13).
The experts have shown that the expected growth in aquaculture will not satisfy the world's demand for fish (Quaas et al. 2016). Instead, improvements in fishing technology will make fishing more productive and add to pressure on fish stocks. At the same time, population growth and increasing incomes will lead to increasing demand for fish probably driving some important stocks to extinction if management is not improved.

In several respects, our team of experts proved that interdisciplinary research leads to useful insights about the natural world and the way mankind uses it. E.g., they looked at fishing as a form of borrowing from the ocean and draw policy conclusions from the "interest rate" we pay on this loan (Fig. 14). A catch reduction today is an investment in future fish stocks, and these returns can be large. Recent catch limits for North Sea herring have shown that it is feasible for the fishing industry to realise these returns through temporary reductions in fish catches. The experts have looked in detail at data for 13 species of fish caught off Europe, from Ireland to the Baltic, and have worked out the shadow interest rate which these lost fish imply for commercial fishing (Quaas et al. 2012). It turns out to range from 220 per cent a year for saithe caught in the North Sea to 16 per cent for Norway pout. These big numbers are another way of saying that reduced fish catches, despite being politically controversial, could return significant profits to the fishing industry in just a few years.

In another joint contribution by biologists and economists is a new approach on fisheries management. The team studies optimal fishery management in an age-structured, bio-economic model where several age classes can be harvested independently. They show that the optimal amount of catch differs with age classes, and they derive conditions under which it is optimal to harvest only one age class. Their main policy implication is that optimal age-structured harvesting can be implemented by a single total allowable catch (TAC) and tradable harvesting quotas, where the latter are specified in terms of the number of fish harvested rather than in terms of biomass. In this case, the usually applied gear restrictions (such as mesh-size prescriptions) turn out to be obsolete. The experts apply their model to the Eastern Baltic cod fishery. Many other disciplinary and interdisciplinary papers have been published by the experts. For a highly cited assessment from a biological, economic, and legal perspective (Khalilian et al. 2010; Highlight 2: Sustainable Fisheries).

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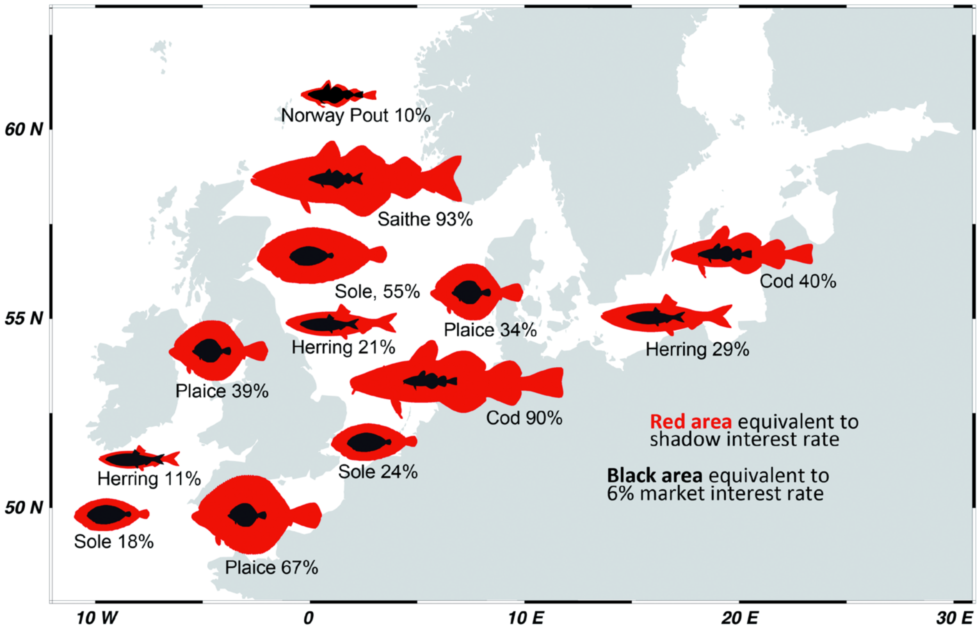

Figure 14: Shadow interest rate for 13 species. The higher the percentage, the more overfished the stock. More investments benefit both the fishing industry and the fish stock.

2.2.4 R4 OCEAN INNOVATION

Stanislav Gorb, Ruth Schmitz-Streit, Denise Tasdemir, Carsten Schulz

Scope

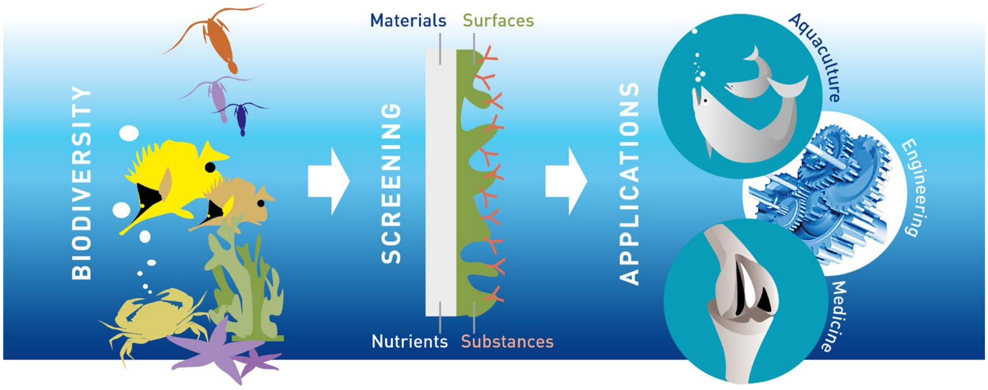

Figure 15: Ocean Innovation studied chemical, structural, and physical principles of certain functions in marine organisms for developing biomimetic materials, medical products, and dietary additives.

Ocean Innovation brought researchers together from biology, medicine, and materials science to identify chemical, structural, and physical principles that act or could potentially be implemented in form of specific biomimetic materials, surface microstructure, coatings for medical products and dietary additives. The diversity of marine life forms harbors an invaluable resource of biological substances, materials, and principles that may potentially be exploited for medical and technological applications (Fig. 15).

The resource comprises a wide range of molecular structures from small diffusible molecules with signaling, antibiotic, and other functions to large biopolymers, materials from bioceramics to hydrogels, and surfaces from adhesive to anti-fouling ones. Despite the theoretical wealth of these principles, only very few marine bioactive substances, materials, surfaces, and/or their biomimetics have found their way into application. Recent technological advances (e.g. automated diving and sampling units, NMR spectroscopy, advances in imaging techniques and high-throughput genomics) have enabled a streamlined discovery process that may allow for a rationale target prioritization scheme. It is evident that a broad-scale drug screening and particularly the subsequent development program across many indications cannot be realized in an academic environment, yet the unique resources and the expertise available within the Cluster was an excellent starting point to follow up with a competitive translational approach focused on specific innovations that can be reached from research on marine organisms. Against this background, the central question was: How can ocean biological substances and material be used to support technological innovations for a range of applications benefitting human society?

Scientific achievements

Biomimetics of materials and surfaces studies of biological surfaces

This research includes approaches of several disciplines: zoology, morphology, biomechanics, physics and materials science. Using a wide variety of methods, including CLSM, Cryo-SEM, micro CT, AFM and force measurement systems from nano to macro range, high speed video tracking and 3D printing, we studied mechanical/physical phenomena in biological and artificial biologically inspired systems. The research was mainly focused on biological surfaces specialized in enhancing or reducing frictional/adhesive forces. Such surfaces are composed of highly specialized materials and bear surface structures optimized for a particular function. Some of these systems also employ secretory substances, modulating forces in the contact area. We studied underlying principles of underwater adhesion, such as material properties of the adhesives and their interactions with various substrates for further implications in development of reliable artificial surfaces preventing adhesion and in turn preventing biofouling in an environmentally friendly way.

Adhesives used by barnacles can stick to almost any surface underwater. The reason is the complex chemical composition of these adhesives. The aim of our research was therefore to develop a surface as universal as possible, which, based on physical principles, prevents the organisms from adhering. For the development of the new micro structured surface with antifouling properties, the wettability of the barnacle cement, meaning the ability of the secretory substances to wet surfaces underwater and to spread this "cement" throughout the surface, was analysed. We succeeded in understanding the physical process of wettability of barnacles and developed strategy to fight it by introducing an appropriate surface microstructure (Petersen et al. 2019). This specific surface geometry prevents a strong adhesive bond between barnacles or mussels by preventing wetting of the newly developed surface. In a first practical test, parts of the hull of four sailing yachts of the Kiel Yacht Club were covered with the new material and tested for one season. The tests have proven: No barnacles or other macro-foulers, such as mussels, could be found on the new coating. The material also showed other positive characteristics. While barnacles on hard materials such as metal or acrylic glass break off bluntly during removal and leave their adhesive layer behind, they could detach from new surface without leaving any residue. With our findings we have taken a major step forward in the further development of new materials that can make a significant contribution to the reduction of biofouling. In addition to the technological relevance, our work also makes a fundamental contribution to the biomechanics of adhesion of marine organisms, since biomechanical aspects of underwater adhesion still remained a mystery to scientists.

Additionally, such subtopics as denitrification of Formanifera (Prof. Tal Dagan), marine carbonate materials (Prof. Anton Eisenhauser), functional morphology of Strombidae and Pteropoda (Prof. Ulf Riebesell), and biomineralization (Prof. Frank Melzner) were in the focus of this research.

Antibacterial substances and marine drugs

The unique nature of the marine environment means that it harbors a vast and exclusive biodiversity and thus contains molecules that are unique and unknown on land. Those molecules are a rich source for identifying compounds which can be used in industry to improve productiveness as well as in medicine to relieve pain or fight diseases. So far, only a minute proportion of such substances are discovered and ultimately the process of getting a known substance to an effective and safe compound is long. This research focus aimed to discover and characterize new marine bioactive compounds to ensure that the best-identified compounds are best used to meet human needs for medicine, food and other essentials.

Successful examples include two compounds termed nucleosides, chemical relatives of RNA and DNA, which are derived from a sponge, found in the Caribbean Sea (Li et al. 2018). These marine metabolites are currently developed for application as drugs against diseases, from Herpes simplex to HIV and cancer. Other marine products include an analgesic, 1,000 times more powerful than morphine. This small peptide is derived from a snail which uses this metabolite to paralyze fish prey. A further research study exploited the switch on chemical pathways of competitive organisms, e.g. different marine fungi that produce compounds that have a role in attack or defense (Silber et al. 2016). Here, several toxins and antimicrobials were identified and might serve as starting point for producing novel, biotechnologically relevant compounds.

Further research aimed to discover new pharmacologically active marine natural products (MNPs) for development into medicines. MNPs belong to the class of secondary metabolites, i.e. they are complex molecules produced by the organism, and/or its associated microbiome, to enable its interactions with other organisms in its ecosystem, including use as chemical weapons, or to provide UV protection. Such molecules designed for a function and validated by Nature for millions of years evolution to work *in vivo* have high potential to become drugs. Approx. 10 drugs originating from marine organisms or microbes are currently used in clinics and many are undergoing clinical trials for use against cancer, pain and neurodegenerative diseases. MNP drug discovery research has mostly relied on random selection and screening of marine organisms. In this topic, instead, a) we adopted a chemical ecology driven approach for selection and work-up, as ecological relevance underlies the pharmacological activities of MNPs, b) studied the whole holobiont, i.e. the macroorganism and its associated microbiome. This unique multidisciplinary approach integrates chemical ecology, marine biotechnology, metabolomics, mass spectrometry based chemical imaging, microbiology, marine natural product chemistry and bioactivity for accelerated discovery of new, bioactive molecules.

Biological surfaces are crucial sites for chemical interactions and prone to rapid colonization by bacteria to form biofilm and fouling. Surfaces also represent hotspots for discovery. We identified for the first time the full surface metabolome of the seegrass *Zostera marina*. The surface extract, as well as its individual chemical components inhibited the growth or the settlement of epiphytic yeasts. DESI-Imaging mass spectrometry (DESI-IMS) uncovered spatial localization of the compounds on the leaf surface and indicated the link with their spatial distribution and their ecological function for the first time. In a follow up study, the mycobiome of the phyllosphere (leaf) and the rhizosphere (roots) of *Zostera marina* was cultured and analysed for chemical, ecological and pharmacological activity profiles. Many fungi showed strong anti-quorum sensing, antibiofilm and antibacterial activity, including those highly pathogenic human Gram-negative bacteria.

One group also analysed the surface biofilm of the brown seaweed *Fucus vesiculosus* for its microbiome (epibiome) in conjunction with its metabolome. Surface metabolome was very different than the whole algal metabolome. For the first time in the literature, we identified a number of bacterial and fungal metabolites with reported antimicrobial, cytotoxic/anticancer or other bioactivities from the surface of the seaweed, while DESI-IMS mapped their specific localization on different parts of the seaweed surface or in cross sections. In the next step, >100 fungi were isolated from the surface and inner tissues of the *Fucus vesiculosus* holobiont and cultured by innovative methods. Most extracts showed antitumoral activity or toxicity. Many new, diverse molecules that have been isolated from the seagrasses and seaweeds as well as their microbiome are currently undergoing in-depth bioactivity studies and assessment of their medical potential in our lab.

A further aspect of this research was the identification of novel, naturally occurring, and marine biofilm inhibiting compounds. Microbial biofilms are formed on almost any surface and when formed on engineered surfaces or in a medical context, the presence of the biofilm is detrimental, because they cause material degradation, fouling, contamination, or infections. The best approach is to stop biofilms during their formation. Since bacterial cell-cell communication, so-called Quorum sensing (QS), appears to be a key player in regulation of virulence and the formation of biofilms, interference with QS systems, known as Quorum quenching (QQ), has developed into an innovative strategy for future antimicrobial applications. The construction and establishment of a reporter screen to identify such QQ activities from bacterial isolates as well as marine eukaryotes and metagenomic libraries led to the identification of several promising QQ enzymes (Weiland-Bräuer et al. 2015). For instance, the communication-disrupting protein QQ-2 was identified and can prevent many different types of bacterial biofilms and in particular clinical, infectious *Klebsiella* biofilms when immobilized to a surface (Weiland-Bräuer et al. 2016). Moreover, the two QQ enzymes QQ-5 and QQ-7 were discovered, which interfere with the morphogenesis of the infectious yeast *Candida albicans* by inhibiting the yeast-to-hyphae transition, ultimately leading to impaired biofilm formation (Weiland-Bräuer et al. 20119A). Finally, even QQ activities in a marine, multicellular organism were shown, where the moon jellyfish *Aurelia aurita* was identified*,* here the host-derived QQ-activities control bacterial colonization to maintain a healthy homeostasis (Weiland-Bräuer et al. 2019B). Ultimately, all these examples disclose the enormous potential of QQ activities for the future development of compounds to fight the growth of disease-bearing biofilms.

In summary, the vast amount of already identified marine, bioactive compounds together with the rich source oceans harboring so far undiscovered compounds discloses the enormous potential to not only find and characterize bioactive, useful compounds, but particularly bring the most promising ones into application to fight the problems and diseases of tomorrow.

Nutritive Substances

This research topic focuses on nutritive substances with high biological activity for metabolism of highly unsaturated n-3 fatty acids. These substances are essential for the nutrition of terrestrial and aquatic vertebrates as they affect their growth and health. Especially in the aquatic food chain, their supply is limited by primary producing aquatic organisms, mainly photo-autotrophic algae. The use of fish oil, rich in n-3 fatty acids, as a feed ingredient has become a limiting factor in aquaculture production. The limited availability concomitant with the high demand excessively increased its price. As a result, vegetable oils are increasingly used as a substitute for fish oil in fish nutrition, which leads to a reduction in the product quality of fish due to their lower contents of long-chain polyunsaturated fatty acids (LC-PUFA).

The aim of this project was therefore to understand LC-PUFA biosynthesis in fish and evaluate different approaches to enhance the endogenous biosynthesis of LC-PUFA in order to increase the levels of eicosapentaenoic acid (20:5n-3, EPA) and docosahexaenoic acid (22:6n-3, DHA) in fish (Torno et al. 2019).

We evaluated potential effects of various isoflavones (e.g. daidzein, biochanin A, formononetin, equol and genistein) as potent ligands for transcription factors centrally involved in the LC-PUFA biosynthesis. An additional approach to increase the LC-PUFA biosynthesis in fish was to identify substrate specific bioconversion of (18: 3n-3, ALA) and stearidonic acid (18:4n-3, SDA) to EPA and DHA and involved regulation processes (Fickler et al. 2019).

In summary, this work showed that the endogenous biosynthesis of LC-PUFA in e.g. rainbow trout can be increased by a specific dietary fatty acid composition as well as by bioactive substances or the combination of both. However, the effect of isoflavones seems to be dependent on the dose administered and the fatty acid composition of the feed. In contrast, dietary SDA is able to effect the EPA and DHA biosynthesis more effectively confirming that desaturation of ALA limits further LC-PUFA metabolism.

Our gained results gave fundamental insights in the FA metabolism of aquatic vertebrates. Furthermore, we were able to present potential alternative fish feeding strategies to overcome fish oil shortage in aquaculture while maintaining high fish product quality.

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2.2.5 R5 OCEAN SINKS

Andreas Oschlies, Ulf Riebesell, Katrin Rehdanz, Klaus Wallmann

Scope

Ocean Sinks brought researchers together from economics, law, mathematics, biogeochemistry, geosciences, and marine biology to assess the potential and limitations of marine carbon sequestration techniques.

The global ocean is the major natural sink for carbon, nutrients and other biologically active substances. Most of the anthropogenic CO_2 will ultimately be removed from the atmosphere and transferred into the oceans to be stored as dissolved inorganic carbon in seawater and particulate organic and inorganic carbon in marine sediments. The uptake rate of atmospheric CO_2 is determined by the efficiency of the physical and biological marine carbon pumps transferring CO_2 to the ocean's interior. Climate engineering (CE) approaches have been proposed to stimulate these natural CO_2 pumps. They aim at exploiting the vast nutrient inventory of the oceans to sequester additional CO_2 in the form of marine biomass or intend to employ the buffering capacity of seawater to neutralize CO_2. Geological formations below the seabed have already been used to dispose CO_2 recovered from offshore natural gas production for more than a decade and a large

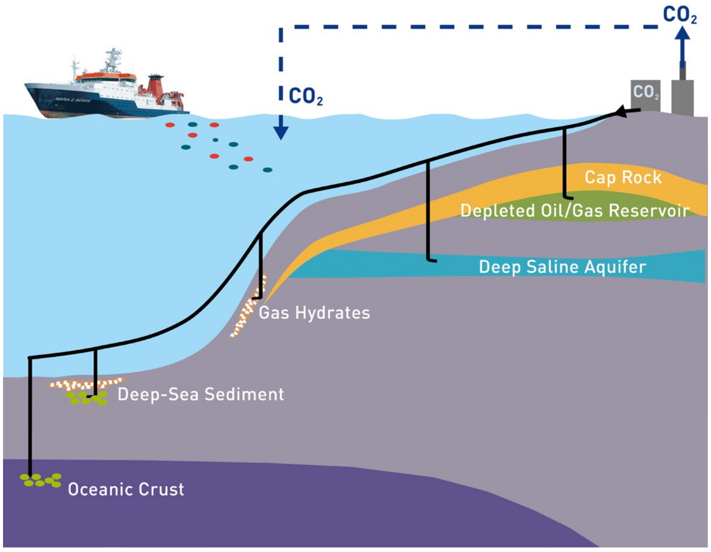

Figure 16: Ocean Sinks studied marine carbon capture and storage (CCS) and climate engineering (CE) options. CO_2 is either removed at the source (e.g. coal-fired plants) and stored in geological formations below seabed (CCS) or sequestered from the atmosphere by manipulating the natural marine system (CE).

number of new storage sites below the seabed will be opened in the near future to accommodate CO_2 from coal-fired plants. Marine CE options and sub-seabed CO_2 storage may help to mitigate future climate change but could also amplify ongoing ocean acidification and oxygen loss in the ocean with potentially grave and harmful consequences for marine ecosystems. By combining perspectives of disciplines relevant to the subject, the research topic Ocean Sinks aims for an unbiased assessment of these marine carbon sequestration techniques (MCST) (Fig. 16).

Scientific achievements

Impact of sub-seabed CO_2 storage on marine ecosystems

Geological formations situated below the seabed are used to store CO_2 at industrial scale (1 M t yr^{-1}) since the pilot project Sleipner located in the Norwegian sector of the North Sea was launched by Statoil (Equinor) in 1996. Seed funding provided by the Future Ocean was employed to set up the first EU project assessing the safety and environmental impacts of CO_2 storage below the seabed (https://www.eco2-project.eu/). Over its funding period (2011-2015), this project identified abandoned wells and natural seeps as major pathways of leakage. At these sites, natural gas (methane) ascending from geological reservoirs is released into ambient bottom waters and ultimately into the atmosphere. CO_2 leakage would occur if these reservoirs were used for CO_2 storage.

Additional funding was provided by the Future Ocean to study the leakage potential of abandoned wells. Methane gas emissions were quantified at three leaky wells situated within the vicinity of the Sleipner storage formation (Vielstädte et al. 2015). The methane leakage rates were substantial (1-19 t yr^{-1}) and the isotope analysis revealed that most of the gas was formed by microbial degradation processes. Seismic data identified gas pockets located 0.5-1 km below the seabed as the mostly likely source of the emitted gas. The North Sea harbors more than 10,000 abandoned wells that were drilled by the oil and gas industry to explore the subsurface and produce hydrocarbons. Our ongoing work shows that about 10-40 % of these wells were drilled through gas pockets and are therefore emitting methane gas into the marine environment. Our emission data and seismic observations indicate that methane release through these wells is by far the largest source of methane to the North Sea and exceeds all-natural sources by at least one order of magnitude (Vielstädte et al. 2017).

We conducted a field experiment to explore the environmental effects that would occur if CO_2 is stored below leaky wells and released into overlying bottom waters. Using a lander system deployed at the seabed above the Sleipner storage formation, we emitted CO_2 gas at a rate (31 t yr^{-1}) comparable to the previously determined methane emission rates. Our field observations and numerical models revealed that the emitted CO_2 was rapidly dissolved in ambient bottom water within 2 m above the ground. The CO_2 dissolution induced a drop in bottom water pH which significantly affected benthic biota over an area of about 50 m^2 (Vielstädte et al. 2019). Beyond this area, the pH change was smaller than the natural pH variability because rapid tidal currents induced an efficient dispersion of the emitted CO_2. The scale of the CO_2 footprint was confirmed by a follow-up experiment conduct by the STEMM-CCS project in summer 2019 (https://www.stemm-ccs.eu/). Based on our results, we conclude that CO_2 storage below the seabed may lead to emissions that affect local benthic ecosystem in the immediate vicinity of leaky wells. However, our data also suggest that most of the stored CO_2 (>99 %) would remain in the subsurface such that the beneficial climate effects of CO_2 capture and storage outweigh the local harmful effect induced by leakage.

Assessing ocean-based carbon dioxide removal

Artificial ocean alkalization (AOA) has been proposed as carbon dioxide removal (CDR) method that aims to reduce surface seawater pCO_2 and thereby enhance oceanic carbon uptake. Model simulations of AOA (Keller et al. 2014; Feng et al. 2016, 2017) have found AOA to have, theoretically, a high carbon sequestration potential, and explored how it might affect ocean carbonate chemistry. Studies with Earth system models showed that in high CO_2 emission scenarios, the terrestrial biosphere loses carbon, via climate-carbon cycle feedbacks, as atmospheric CO_2 and temperatures decrease in response to increasing oceanic CO_2 uptake (Keller et al. 2014). Furthermore, the mean state of the ocean carbonate chemistry determines the magnitude of the Earth system response to AOA. There appears to be little cessation effect as CO_2 taken up by the ocean as a result of AOA remains in the ocean upon AOA termination. Enhancement of the biological pump as a means of atmospheric CDR has centered on macro- and micro-nutrient ocean fertilization. Keller et al. (2014) found that as in many earlier studies, there is limited potential for iron fertilization to draw down CO_2. Moreover, they showed that when iron is added during a high CO_2 emission scenario, fertilization-induced atmospheric CO_2 drawdown is initially opposed by a net loss of carbon from the terrestrial biosphere, via climate-carbon cycle feedbacks, as atmospheric CO_2 and temperatures decrease. This phenomenon lasts until it is countered by a decreasing sequestration efficacy (i.e., fertilization becomes less effective at enhancing oceanic carbon uptake) and increased terrestrial uptake as a result of CO_2 fertilization. They also show that in the fertilized region there is a decline in pH and an increase in pCO_2. Carbon cycling is also affected in other regions of the ocean because of reduced nutrient availability following enhanced biological production. Furthermore, if ocean iron fertilization is terminated, carbon may remain in the ocean for a few decades (Keller et al. 2014), but after 100 years up to a third of it could be potentially returned the atmosphere.

The group investigated artificial ocean upwelling as a biological pump enhancement. Many of the impacts are the same as for ocean fertilization since it is the goal of this method to fertilize upper ocean biology with upwelled nutrients. However, upwelling also directly affects the carbon cycle since in most places the deep water that is pumped up contains more CO_2 than the surface ocean, part of which may outgas into the atmosphere if the additional C is not consumed by phytoplankton. Deeper waters are also cooler than the surface ocean, and when pumped up have a cooling effect. In model simulations, this has been shown to increase terrestrial carbon uptake via reduced heterotrophic respiration at lower temperatures, i.e., there is no terrestrial loss of C as with other ocean-based CDR methods depicted (Keller et al. 2014). Indeed, in model studies, artificial upwelling sequesters most (80% on centennial timescales) of the carbon drawn down from the atmosphere on land (Keller et al. 2014), and may therefore not be viewed primarily as ocean method. When artificial upwelling is stopped, the sequestered carbon is returned to the atmosphere within a few decades, and re-adjustment of the planetary energy budget leads to global mean temperatures even higher than in a world that had never experienced artificial upwelling (Keller et al. 2014). A comprehensive assessment of potentials and Earth system feedbacks of both terrestrial and marine carbon dioxide removal (CDR) methods is provided by Keller et al. (2018) and their possible roles in optimal and cost-efficient climate strategies are analysed by Rickels et al. (2018), and their possible contribution to reaching the Paris climate goals is estimated by Lawrence et al. (2018).

New nitrogen production in diazotrophic cyanobacteria and the effect on community carbon sequestration

Stimulation of phytoplankton community productivity through the increase in fixed nitrogen in the system from nitrogen fixing (diazotrophic) organisms could present a possible biological carbon sink, alter dissolved organic matter (DOM) production and remineralisation as well as potentially change microbial loop efficiency.

In temperature and pCO_2 manipulation experiments, Paul et al. (2016, 2018 → 7.1) found no conclusive evidence that ocean acidification had measurable effects on new N inputs. This was despite a significant negative effect of elevated CO_2 on abundances of diazotrophic filamentous cyanobacteria (*Nodularia spumigena*) detected during an indoor mesocosm study (Paul et al. 2018). While increased CO_2 resulted in higher sustained particulate matter concentrations under persistent low N availability (Paul et al. 2015), it appears unlikely to be attributable to increased diazotrophic N inputs (Paul et al. 2016). Instead, higher suspended particulate and dissolved organic carbon concentrations in the water column under elevated CO_2 was driven by a shift in the plankton composition to dominance of small non-diazotrophic phytoplankton (<2 µm). These CO_2 - related differences in the water column could not be traced into the sinking particle flux within the study period.

Selected publications

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2.2.6 R6 DANGEROUS OCEAN

Jan Behrmann, Karl Stattegger, Sebastian Krastel-Gudegast, Athanasios Vafeidis

Scope

Dangerous Ocean brought researchers together from geosciences, coastal engineering, economics, and law to investigate oceanic and coastal geohazards and their socio-economic consequences. We primarily focused on large events (e.g., plate boundary earthquakes and associated tsunamis, large landslides, sudden relative sea level rise, floods and storms) in order to evaluate their impacts on the coastal zone and to develop adaptation strategies for coastal geohazards, based on the analyses of ongoing, recent and past events. Recent experience teaches mankind that oceanic geohazards, such as plate boundary earthquakes, volcanic eruptions, coastal and submarine landslides, and resulting tsunamis can reach dimensions that exceed the probable and the expected, as would be defined by conventional hazard and risk analysis. This new class of threats (e.g. the 2011 Sendai event in Japan) results from a chain of superimposed disasters and can produce an immediate impact on the intricately linked global community and economy.

They affect large populations and sensitive industrial installations on coasts and offshore that are already confronted with problems of rising sea level, rapid coastline retreat, delta subsidence, sediment trapping in upstream river systems, and severe storms.

The group envisioned an integrated and multidisciplinary research approach covering the continen-

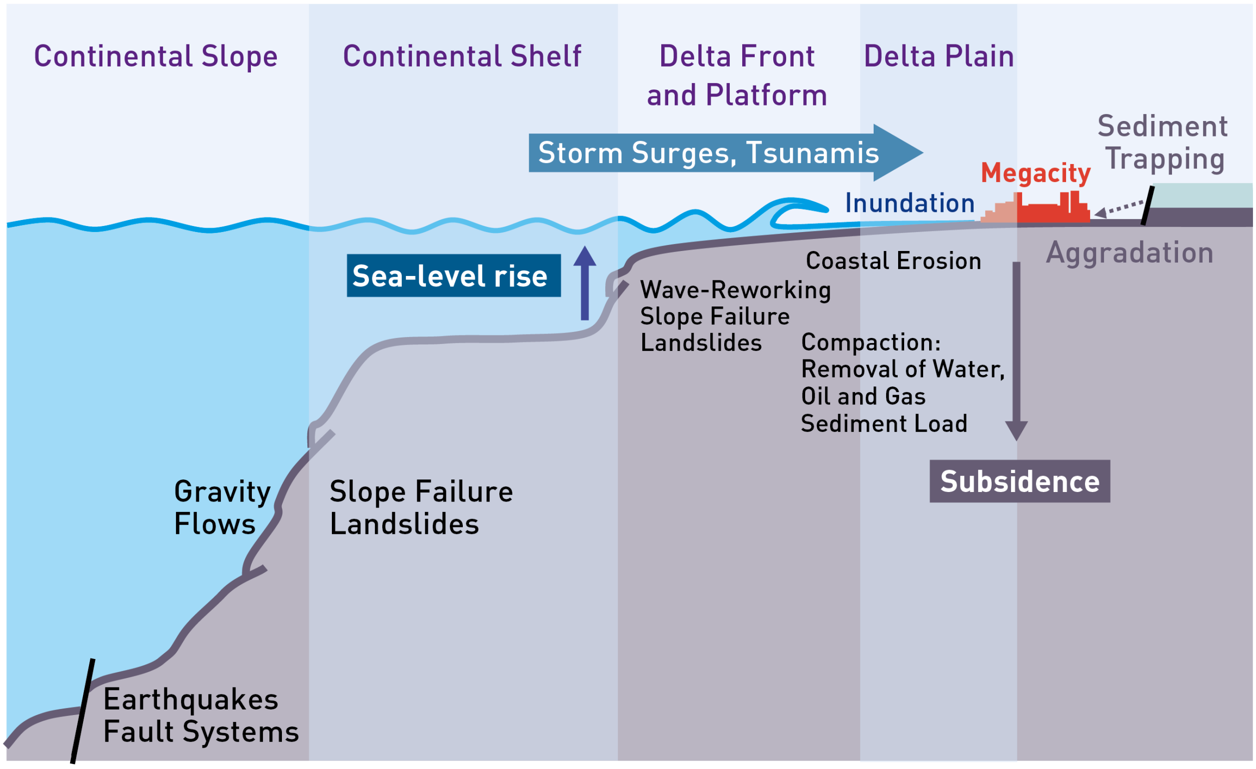

Figure 17: Sea-coast continuum and associated geohazards.

tal slope, the shelf, and coastal areas in order to investigate the entire chain from the physical state of the seafloor to consequences on the coast (Fig. 17). Against this background, the central question is: How can we cope with ocean hazards and prepare for coastal change?

Scientific achievements

Sea Level Rise, Coastal Risks and response to Coastal Hazards

We have contributed to the further development of integrated modelling frameworks and databases for assessing the future impacts of sea level rise and associated hazards and for evaluating the effectiveness of different adaptation options. Our work included the further development and downscaling of the Dynamic and Interactive Vulnerability Assessment (DIVA) modelling framework and supporting databases and the development and application of global models for assessing impacts of sea level rise. Importantly, in this process we also considered the degree to which socioeconomic development defines impacts. Specific work included a global assessment of future sea level rise impacts under different physical, socioeconomic and adaptation scenarios, a global exposure analysis of land and population to sea level rise under different physical and socioeconomic scenarios (Neumann et al. 2015), a global assessment of coastal wetland response to sea level rise and a Mediterranean-wide assessment of impacts of sea level rise on UNESCO World Heritage Sites (Reimann et al. 2018). Further work in this context included regional and local studies of vulnerability, exposure and risk assessment, including development and downscaling of scenarios of future population distribution, drivers of household level adaptation and a novel understanding of how extreme water levels affect the characteristics of coastal flooding (Santamaria-Aguilar, 2017). The above work has been used to support policy decisions on responses to accelerated sea level rise and is currently used as the basis for the development of future adaptation pathways, for a variety of locations and scales.

Investigations at the seafloor to assess the state of preseismic loading on selected fault systems in earthquake- prone regions

The group led and contributed to studies of great past and recent plate boundary earthquakes, among others the 1960 and 2010 Southern Chile, the 2011 Tohoku events, and the past and upcoming seismotectonic activity along the Northern Chile forearc. Central was the question whether the possibility of plate boundary rupture all the way to the deep sea trench in all areas is a new quality of earthquake-induced geohazard in need of a new assessment to improve safeguarding of global trade (raw material export from Pacific South America) and complex infrastructures like nuclear power stations (e.g. 2011 Fukushima, Japan) and risk mitigation. In addition, our work comprised groundbreaking studies of the instability of large volcanic edifices and sediment piles deposited on entire continental margin segments. Instability can be seismically triggered, relate to magmatic effects, or result from long-term changes in the physical properties of the sediment itself (Kurzawski et al. (2016).

Seafloor monitoring and multi-hazard impact assessment tools

Supported by the structures and a close cooperation of groups within the Cluster working on natural hazards, the group developed and implemented a holistic approach for an integrative workflow from hazard identification to impact assessment. The group focused on Southern Italy and especially Europe’s largest volcano, Mt Etna. The region was struck by several tsunamis in the past and is known for its seismic activity and a large-scale instability at Mt Etna’s edifice. In the first phase, high-resolution 2D/3D seismic data was conducted, which showed for the first time the direct linkage between on- and offshore gravitational sliding of Mt Etna (Gross et al. 2016). Furthermore, this instability manifests in several mass transport deposits, which was traced in the shallow subsurface. To test the hypothesis of a coupled volcano edifice and continental margin instability, this insight to deploy a seafloor geodesy network for in-situ displacement measurements at a strike-slip fault line was used, which was proposed by Gross et al. (2016) to act as the southern boundary of Mt Etna's sliding flank. This system consisted of five acoustic transponders deployed at the seafloor on the hanging- and footwall of the strike-slip fault system. The seafloor network was the first to monitor an offshore strike-slip event in subcentimeter resolution, therewith proving the feasibility of the emerging acoustic direct-path ranging method to monitor volcanic flank instability (Urlaub et al. 2018). To better understand the impact of natural hazards in the working area, the group started to develop an integrative platform for the impact assessment of hazard scenarios (www.oceanriskapp.com*).* This platform uses the GoogleEarthEngine™ to compile real-time calculated impact maps by using the given scenarios and a dedicated Landsat 8 based land-use classification. The platform is still in the beta stage and will be the basis for future projects.

Giant landslides: Preconditioning factors and consequences

Giant landslides were investigated in different settings; the Grand Bank Landslide occurred on 18 November 1929 south of Newfoundland and triggered a tsunami that was recorded across the Atlantic Ocean. New seismic reflection shows a thick rotational slump that occurred in addition to shallow translational sliding. Only the combined effect of slumping and transitional sliding allowed modelling the observed tsunami. The landslide mass quickly disintegrated in a large turbidity current. The calculated average bulk sediment concentration of the flow was 2.7–5.4% by volume. Flow concentrations has never been measured directly nor convincingly estimated in large submarine flows. It is orders of magnitude higher than directly measured smaller-volume flows in river deltas and submarine canyons (Stevenson et al. 2018). The NW-African continental margin is well known for the occurrence of large-scale but infrequent submarine landslides. The most prominent similarity between all investigated landslides is the existence of widespread glide planes. Integrating ODP drilling with high-resolution seismic reflection data point to a thin diatom ooze unit (<5 m) capped by clay as weak layer. Diatom ooze layers are common on many continental margins and may explain submarine mega-slides at low gradient continental slopes globally. Changes in global climate affect the abundance of diatoms and thus formation of diatom oozes, thereby preconditioning the sediments for failure. However, the actual timing of failure is independent of environmental changes. The relation between gas hydrates and landslide occurrence was investigated in the Arctic Ocean. A strong spatial correlation between submarine slope failures and the occurrence of gas hydrates has been attributed to dissociation of hydrates due to bottom water warming or sea level drop. New modelling approaches show that build-up of overpressure at the base of the gas hydrate stability zone results in hydro-fracturing forming pipe structures as pathways for overpressured fluids. Where these pipe structures reach shallow permeable beds, this overpressure transfers laterally and destabilizes the slope. This process is independent of environmental change and water depth (Elger et al. 2018).

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2.2.7 R7 OCEAN INTERFACES

Gernot Friedrichs, Friedrich Temps, Ulf Riebesell, Tina Treude

Scope

Ocean Interfaces brought together researchers from biology, chemistry, geochemistry, geology, physical oceanography, and mathematics to investigate the accumulation, transformation and transport of climate-relevant substances at and across the diverse ocean interfaces – figuratively speaking to study the 'breathing of the oceans through their skins'. Including pilot studies on interface-mediated microplastics processing were conducted.

The ocean interacts with the atmosphere and lithosphere through continuous exchange of matter and energy. Understanding exchange processes across the ocean interfaces is key to unraveling complex interplays such as climate system feedbacks. The relevant processes are determined by a combination of physical, chemical, and biological impacts acting on a variety of scales in time and space (Fig. 18). Accumulation of organic and inorganic substances, including microplastics, both in the wider boundary layers and in the microlayers directly at the interface, together with intense biological activity, lead to unique heterogeneous physico-chemical and biological properties deviating greatly from bulk seawater conditions. Further modifications of ocean interfaces, e.g., through photochemical and microbial transformations, contribute to forming an environment in which transfer processes can both be augmented and diminished. By combining state-of-the-art molecular, microbiological and biogeochemical analytical techniques, laser spectroscopy, indoor and field mesocosm experimentation, in-situ measurements and numerical modeling, the research topic R7 on ocean Interfaces addressed the central research question: How do micro-scale processes at ocean interfaces affect fluxes and transformation of matter?

The group investigated formation, retention, and emission processes of climate-relevant substances in the shallow sub-seafloor, such as for CH_4. The biological imprints on extracellular organic matter and interface properties was targeted by investigating the accumulation of organic substances and their intense microbial transformation in the surface ocean boundary layer. The group set an emphasis on the specific role of the ocean microlayer for air-sea gas exchange by investigating chemical aspects of the ocean as a major source and sink for radiatively and chemically active atmospheric trace gases.

Scientific achievements

Research in Ocean Interfaces mostly addressed basic research questions related to Ocean System Understanding. Not striving for a complete presentation of past and ongoing Ocean Interfaces research, the following four thematic blocks only target the main fields of pursued interdisciplinary research activities. In all cases, close collaboration of scientists from different disciplines turned out to be highly valuable and effective in paving the way to new research directions and outcomes. The collaboration and networking was further strengthened by hosting the semester topic "Ocean Interfaces – From Nanoscales to Global Impact" in 2015, comprising the co-organization of the SOLAS Open Science Conference in Kiel, two very successful international workshops on the "Application and Perspectives of Cavity Enhanced Optical Detection Techniques in Ocean Sciences" and "The Ocean Surface Microlayer and Biogeochemical Feedbacks in the Earth System" which was a dedicated session on Ocean Interfaces at the EGU conference in 2011 and a high-level lecture series.

Oceanic methane production and emissions

Methane production, consumption and release from anoxic sediments, gas hydrates and seeps has been a very active field of cluster research (e.g., Maltby et al. 2016). A detailed assessment of biogeochemical and physical controls of methane cycling is necessary to better constrain carbon inventories and to address the role of oceanic methane emissions into the atmosphere. Having a global warming potential of about 30, methane emissions induce a strong feedback for enhanced global warming.

The anaerobic benthic methane filter controls the source strength of methane escaping into the overlying water column. Moreover, methane in the free water column is subject to aerobic methanotroph oxidation (MOx). Luckily, this biological MOx filter often prevents methane to be released into the atmosphere. In the past, the supply of nutrients and the local water chemistry were thought to control methanotroph communities and hence the overall methane emission budget. However,

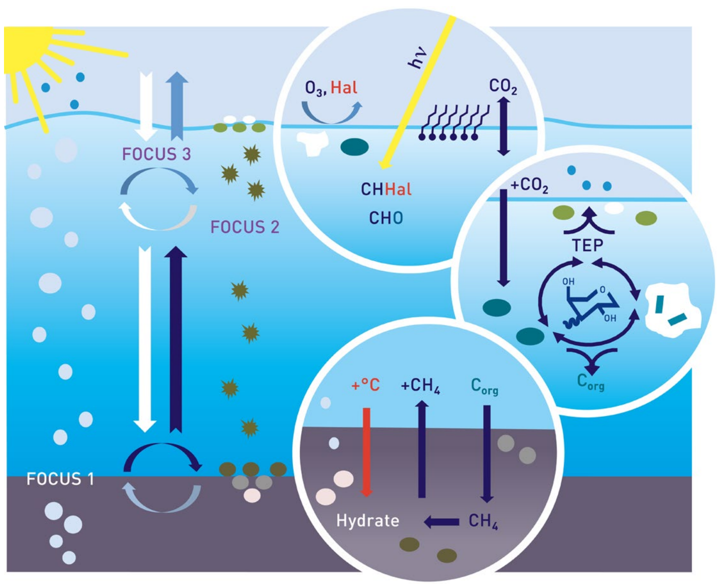

Figure 18: Micro-scale transformation processes determine the exchange of climate relevant substances at lithosphere-ocean-atmosphere interfaces.

combined experimental and modelling study of Steinle et al. (2015), based on field measurements performed at the Svalbard methane seep, showed that physical water mass properties and ocean currents strongly affect oceanic emissions. The shift from an offshore to a nearshore position of the current rapidly and severely reduced methanotrophic activity in the water column. Globally, fluctuating currents are common at many methane seep systems. Similarly, for microbially produced methane in anoxic sediments of coastal waters that may account for more than 75% of global oceanic methane emissions, the efficiency of the MOx filter is influenced by a combination of diverse environmental controls as well. Time-series studies performed at the seasonally stratified and hypoxic Boknis Eck (Baltic Sea) time-series station near Kiel turned out to be key in revealing seasonal variability, which is dominated by oxygen availability and hydrographic dynamics. Clearly, recent cluster research has proven both the complex interactions that control oceanic methane cycling and the need for combined experimental and modelling studies to accurately assess the source strength of oceanic methane emissions for future climate predictions. Ongoing research continues along these lines.

Linking microbial transformation of organic matter with surface microlayer effects

The ocean surface microlayer (SML), the uppermost <1 mm thick layer of the water column with distinct physical, chemical, and biological properties, provides the ultimate interface where heat, momentum, and mass exchange between the ocean and the atmosphere takes place. Despite the huge extent of the ocean's surface, relatively little attention has been paid to the SML. SML composition and abundance modulate its effect on air-sea gas transfer and are closely linked to the biogeochemical processes taking place in the underlying surface water. Cluster research aimed to improve our molecular-level understanding of SML effects by field and laboratory studies combining comprehensive biogeochemical analysis of microlayer samples on the one hand and laser spectroscopy to address physico-chemical properties of the so-called nanolayer on the other hand. The latter was accomplished by sum-frequency generation spectroscopy (SFG), a new surface-sensitive method to investigate surfactant abundance (Laß et al. 2013) and chemical reactivity toward interface-selective oxidation processes. In the framework of the SOPRAN Aelotron wind wave channel study, it was also possible could establish a strong correlation between the amount of surfactants and γ-aminobutyric acid (a marker for microbial decomposition of organic matter), suggesting that microbial cycling of amino acids can indeed control SML properties. How the chemical and biological composition of the SML varies over the annual cycle was investigated through time series observations from Boknis Eck. Other studies investigated microbial nitrogen fixation, the strength of carbon uptake, and several dedicated mesocosm experiments have been conducted to assess the effect of acidification and warming on biological-driven surface layer processes (e.g., Boxhammer et al. 2018). Actually, mesocosm field experiments at increased CO_2 level revealed an enhanced enzymatic hydrolysis of organic matter and increased availability of gel particles as substrate, supporting up to 28% higher bacterial abundance and thus strengthening the role of the microbial loop in the surface ocean. Indications were also found that acidification effects on the abundance and activity of microorganisms during phytoplankton blooms, resulting in changes in the composition and dynamics of organic matter in the SML. The results point to a potential coupling between anthropogenic CO_2 emissions and the properties of the SML.

Much more work needs to be done to fully assess the diverse roles of the surface microlayer in the global and regional systems. As an outcome of the "Microlayer" workshop, the perspectives paper "The Ocean's vital skin: Toward an Integrated Understanding of the Sea Surface Microlayer" by

Engel et al. (2017) summarizes cluster research and identifies gaps in our current knowledge of the SML and summarizes future research priorities. Interdisciplinary expertise and collaboration are needed to bridge between ocean and atmospheric sciences. Stimulated by the outcome of the same workshop and lead by the Marandino research group, two research cruises (Baltic Sea Gas Exchange, BalticGasEx) took place in 2018, aiming at quantifying the influence of surfactants and of the SML on air-sea fluxes of trace gases and to relate their abundance with organic compounds in the water column.

Optical Detection Schemes for Quantitative Trace Gas Monitoring

Understanding biogeochemical cycles in the context of global change requires us to quantify the oceanic pathways and ocean-atmosphere exchange of climate relevant gases such as CO_2, CH_4, and N_2O. Recent years have seen an enormous upturn in the use of optical laser-based trace gas analysis in marine applications. In particular, cavity enhanced absorption schemes offer precise, accurate, and fast measurement capabilities for trace gas detection on small temporal and spatial scales. Early cluster research pioneered the use of such spectrometers for continuous isotopic detection of CO_2 aboard research vessels (Becker et al. 2012). Meanwhile, a 3-year time series of underway surface δ13C(CO_2) data was obtained with an autonomous isotopic cavity ringdown analyzer installed on a voluntary observing ship sailing the North Atlantic between the UK and Canada Such unique data sets help to better understand controls of the surface ocean carbon system and, in particular, the role of the North Atlantic as a natural CO_2 sink. Another natural system, in this case linked to the nitrogen cycle and to stratospheric ozone depletion, is the greenhouse gas nitrous oxide (N_2O). Taking advantage of the high spatial and temporal resolution of an off-axis integrated cavity output spectrometer (OA-ICOS), Arévalo-Martínez et al. (2015) have measured N_2O concentrations in the large upwelling ecosystem off the coast of Peru and detected a massive release of N_2O to the atmosphere, considerably higher than previously known. Only the improved measurement capabilities made possible such studies. They also feed into the much-needed databases like the Surface Ocean CO2 Atlas SOCAT or the MarinE MethanE and NiTrous Oxide database MEMENTO that provide the basis for global trace gas emission assessments.

Optical trace gas analysis is not limited to the afore mentioned, more regularly measured major greenhouse gases. For example, in a joint effort of many cluster scientists, a prototype OA-ICOS analyzer was used to investigate oceanic emissions of carbonyl sulfide (OCS) to the atmosphere. Whereas tropical emissions have been proposed to close a gap in the atmospheric budget of OCS, the reported measurements and box model calculations point to a minor role of direct and even additional indirect oceanic contributions. Future technical developments are expected to drive this lively research field. Therefore, in order to keep track with the fast-technical developments of laser trace gas analysis, the cluster funded a versatile mid-infrared laser system. It has been used for the development of optical detection schemes for volatile halocarbons to complement conventional gas chromatography data analysis. Furthermore, the general problem of cross sensitivity (i.e., two different trace gases absorb at the same wavelength), which was mentioned as a main limitation of optical trace gas analysis during the “Cavity Enhanced Optical Detection” workshop, is currently addressed by testing the potential of a new method of Selective Optical Saturation Spectroscopy for Two-Species-One-Wavelength Detection. A corresponding patent has been filed.

Microplastics

Marine plastics ranging in size from macroparticles to nanoparticles have been recognized as a worldwide environmental and ecological threat because they are distributed by ocean currents and accumulate at the diverse ocean interfaces. To this end, several pilot studies have been conducted in the framework of ocean interfaces to address important research questions related to microplastics distribution, aggregation, sedimentation, and breakdown through degradation by microorganisms. For example, in a recent project, which gained tremendous public attention, Tanhua and Gutekunst were able to track the distribution of microplastics by making use of measurements on yachts participating in the Volvo Ocean Race 2017/2018. Although found in even the most remote areas, the concentration of microplastics in the surface layer of the oceans is considerably lower than expected, given the ongoing replenishment of microplastics and the tendency of many plastic types to float. Michels et al. (2019) addressed this mismatch by studying the interactions of microplastics with marine biogenic particles. Rapid aggregation of biofilm-covered particles followed by sedimentation takes place and may explain their fast removal from the surface and accumulation in marine sediments. In another study, light was shed on the further fate of plastics in Baltic Sea sediments. It was found that biodegradable plastic bags were much more strongly colonized by microbial communities than polyethylene bags, however, neither type of bag showed any sign of biodegradation during the 100-day study. Stimulated by the outcome of such studies, and recognizing many interdisciplinary links between physical and life sciences with the humanities, research on marine plastics will be continued by exploiting new funding lines.

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2.2.8 R8 EVOLVING OCEAN

Thorsten Reusch, Philipp Rosenstiel

Scope

Evolving Ocean brought researchers together from biogeochemistry, marine ecology, genomics, and biomedical research to evaluate the rapid evolutionary change of populations, species and communities in the context of their biogeochemical environments.

Life originated in the sea, and the oceans harbor the greatest phylogenetic diversity of life, which in turn drives biogeochemical cycles and ecosystem services (R3: Ocean Resources). At the same time, marine ecosystems are increasingly exposed to multiple stressors such as warming, ocean acidification, deoxygenation, eutrophication, and species invasions (Fig. 19). Thus far, global change research has focused on the short-term physiological and ecological consequences of anthropogenic disturbance, while the potential of populations and communities to adapt rapidly to global change has rarely been considered, a major gap for future ocean scenarios and biogeochemical models. Evidence is rapidly accumulating that eco-evolutionary feedbacks determine biotic interactions and hence the functioning of ecosystems over time scales like present-day anthropogenic disturbances (Hoffmann and Sgro 2011). At the same time, the fundamental molecular genetic principles of many traits that underlie important ecosystem functions can now be analyzed in many marine species that are not genetic models, owing to rapid progress in genomic and transcriptomic techniques. For an in-depth analysis of historical and contemporary trait evolution, two trait complexes with great expertise in Kiel were selected that are increasingly compromised by global change: (i) biomineralization – the formation of mineralized shells, scales, skeletons and epidermal structures, and (ii) the diversity of life cycles and life spans. Against this background, the central question was whether and how rapid evolutionary change of populations, species and communities would affect ecosystem and biogeochemical processes.

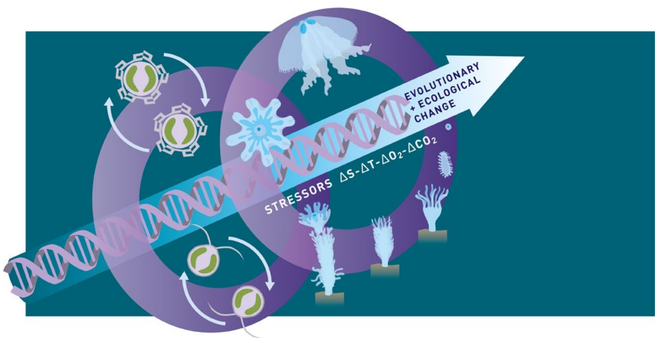

Figure 19: Environmental changes such as deoxygenation, acidification and warming drive the evolution of life cycles and life span, and may result in ecological and evolutionary regime shifts.

Scientific achievements

Multiple stressor impact on benthic communities – the Kiel Outdoor Benthocosms (KOB)

Kiel marine research takes place on all possible scales, from the laboratory bench to the semi-closed mesocosms and on to the open ocean. In order to address the complex combinations and fluctuations of stressors predicted for the future ocean, the Kiel Outdoor Benthocosms (KOB) were designed, an array of twelve water tanks connected to the Baltic on the Kiel seafront. As a major improvement over earlier set-ups with near constant conditions, these allow Kiel scientists to simulate future conditions while respecting natural fluctuations. If climate modelling or extrapolations from time series suggest changing salinity, carbon dioxide concentration, hypoxia or the availability of nutrients, those conditions can be simulated here for multispecies communities. It is also possible to examine extreme events. The tanks contain over 100 sensors to track and control environmental variables. This approach is generating more realistic insights into the ecological consequences of global change. One important finding concerns the seasonal variation of global change impact. In a warmer sea, organisms may grow more in winter if resources are available, increasing their resilience for surviving the heat stress of summer. In contrast, high metabolism in a warmer winter may be stressful when resources such as light are lacking. Better or worse winter performance may affect the rate and timing of spring reproduction. Shifting environmental conditions affect different plants and animals in different ways. For example, ecologically important and long-lived seaweeds suffer more from temperature stress in summer than do the short-lived filamentous algae which compete with them. These algae, in turn, are kept under control by small crabs which graze on them. But if the water temperature exceeds 21°C, these crabs disappear. Thus, warmer conditions can lead to a complete takeover by new species of small algae, with different and less valuable ecological functions.

The future of marine biological calcification

If seawater becomes more acidic, in turn, many marine calcifying species pay higher energy costs to maintain the formation of shells, scales or skeletons. One prominent model organism featured in Kiel are mussels, in particular the blue mussel *Mytilus edulis* that is also increasingly used in marine extractive aquaculture. When occurring in a biological benthic community, processes are complex, since biological activity in a natural community causes acidity to vary throughout the day, and mussels are expert at calcifying their shells at the best time. This typically happens during the hours of daylight, when acidity is at its lowest. Kiel scientists started to recognize natural fluctuations on different scales, including the seasons and their effects on calcification. This was motivated by the findings that warming may benefit species during the winter months, making them more able to resist heat stress in summer. To overcome this bias, Kiel scientists conduct large-scale, year-round mesocosm experiments in different areas of the world. The researchers are also investigating hypoxia, reduced levels of dissolved oxygen in ocean water. This is a natural phenomenon in enclosed bays or seas but is less familiar in the open ocean. Ocean warming combined with nutrient enrichment favors the development of large masses of algae. When the light, nutrients and other resources they need to grow start to decline, these masses of algae die off, and their microbial degradation may lead to hypoxic conditions which create dead zones in deeper waters. If this lifeless water wells up in shallow areas, there can be economic as well as ecological harm. Another complication is the general resource availability to calcifying species. It is, for instance, puzzling why in the Kiel Fjord, where average pCO_2 already today exceeds 750 ppm, mussels happily thrive and calcify. The key to understand this is evolutionary ecophysiology. It could show that juvenile mussels when building their first shells are able to decrease the proton concentration at the site of calcification strongly, but only if they are in well-fed conditions (Ramesh et al. 2017). This ability, however, may break down if baseline acidification levels continue to increase, which will likely bring up natural pCO_2 levels to >2,000ppm under upwelling of corrosive deeper and oxygen deficient water.

Evolving Phytoplankton Communities

Kiel researchers have led efforts to solve one of the biggest enigmas related to marine global change research, namely whether or not oceanic species feature sufficient genetic diversity to cope with rapid climate change, which was tested in marine phytoplankton species, the base of the ocean's food web. These species lend themselves for long-term experiments, as they divide on a scale of days, thus are hypothetically able to adapt rapidly in evolutionary terms. Indeed, within a period of three months, diatoms in the mesocosm experiment can adapt the way they use their genes to cope with increased ocean acidity. This is known as "genotypic sorting or selection" of their genetic diversity to adapt to changed conditions. This adaptability was subject of several projects conducted within the cluster Future Ocean on marine life and its ability to adapt to high levels of stress. As well as temperature, it is monitoring stresses such as increased salinity and acidity to see how rapidly species and whole ecosystems can adapt. Kiel scientists looked at the ability of the world's "most important calcifying organism," the coccolithophore *Emiliania huxleyi,* to respond with rapid adaptive evolution to ocean acidification. Most research in this area has been short-term, but this project involved several experiments, the longest of which lasted for four and a half years and almost 2,000 generations. It revealed that experimental populations exposed to higher levels of carbon dioxide initially grew more slowly than those experiencing current levels, but that they could fully restore their initial growth rates after long-term evolution (Lohbeck et al. 2012). However, after four years, all the cultures exposed to extra carbon dioxide had reduced coccolith (scale) growth. To make the story even more complex, long-term adaptation reduced the capacity for coccolithophores to produce calcite, but only under elevated CO_2 levels, while cultures when brought back to present day CO_2 levels calcified as much as present day isolates. The authors therefore have a mixed message: while growth rates are restored by adaptive evolution, calcification is switched off under high concentrations of CO_2. On a more positive note, another series of experiments revealed even faster adaptation to warming, which played out independently of simultaneous adaptation to acidification. To bridge the gap between long-term laboratory experimentation and more realistic field conditions, Kiel researchers have worked with colleagues from the UK, the US, Finland and Sweden on mesocosm experiments which show that marine microbes are surprisingly robust when it comes to coping with climate change (Scheinin et al. 2015). By exposing a natural plankton community to higher or lower levels of carbon dioxide, the marine diatom *Skeletonema marinoi* showed a positive selection response within three months, driving the mean population fitness to better utilize enhanced ocean pCO_2. Over that short period, this important species could evolve in response to carbon dioxide enrichment to the point where its population growth rate increased by 30 per cent (Schlüter et al. 2014). Another recent study synthesized experimental evolution in the laboratory with a near natural test in natural phytoplankton communities and found that adaptation to elevated CO_2 levels coincided with markedly divergent abilities to outcompete other phytoplankton species (Bach et al. 2018), highlighting that future research should combine community ecology with phytoplankton experimental evolution. Kiel research will also emphasize the genetic and epigenetic basis to such responses to climate change.

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2.2.9 R9 OCEAN CONTROLS

Christian Berndt, Birgit Schneider

Scope

Ocean Controls brought researchers together from geophysics, biogeochemistry, paleoceanography, and climate modeling to investigate the role of the ocean in past climate and environmental change and identify key processes and potential tipping points that could control future global warming (Fig. 20).

The group studied examples of past climate warming and environmental change in order to investigate the main patterns of ocean feedbacks on climate by concentrating on changes in three-dimensional (3D) ocean circulation, ocean carbon cycle, gas hydrate dynamics, and the influence of geological greenhouse gas emissions. The approaches put an emphasis on the combination of earth system modeling with new and improved high-resolution proxies of past environmental conditions under different forcing mechanisms of climate warming. The warm(ing) climate studies cover a large range from the deep times of the Cretaceous (e.g. Blöhdorn PhD thesis 2013; Steinig PhD thesis 2019) over the Pliocene (Song et al. 2017; Leduc et al. 2014; Khelifi et al. 2014; Zhang et al.

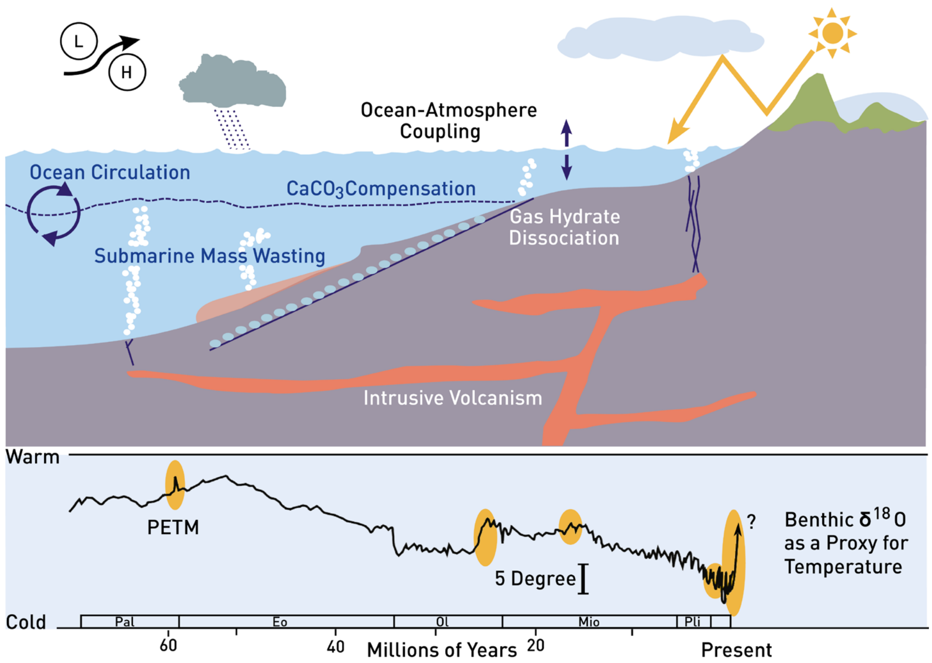

Figure 20: Earth system processes involved in past climate warming.

2012; Krebs-Kanzow et al. 2011), the Eemian and the Holocene (e.g. Schneider et al. 2010; Salau et al. 2012; Khon et al. 2012; Xu et al. 2015; Segschneider et al. 2018; Repschläger et al. 2015 a,b; Zinke et al. 2014) into the future. For the comparison with paleo data new data sets were assembled (e.g. Leduc et al. 2010) and generated (e.g. Poggemann et al. 2018; Wang et al. 2013; Reissig et al. 2019). Especially the mechanisms of individual forcing factors driving the changes in mean climate and its variability have been investigated in detail (e.g. Khon et al. 2014, 2018).

Scientific achievements

One of the core activities of R9 Ocean Controls was the consequent application of the state-of-the-art IPCC-type coupled climate model KCM (Kiel Climate Model) to past climate conditions. Whilst in the pre-Cluster time, climate modeling and climate reconstruction were mostly carried out separately or in parallel, our aim was the direct combination of both. Model-proxy comparison turned out less straightforward than initially thought, since new large proxy assemblages showed that with regard to reconstructed sea surface temperature (SST), there were diverging trends (e.g. during the Holocene and the Eemian) between two very well established paleo proxies (e.g. Mg/Ca and Uk'37; Leduc et al. 2010; Schneider et al. 2010), both of which were usually interpreted as representative of annual mean sea surface conditions. This gave us the opportunity not only to work on model improvement, which nevertheless was done in terms of bias correction (Song et al. 2018) and an improvement of the realization of climate variability (Bayr et al. 2019), but also to re-think the signals captured in the proxy records. Our first proposition that proxies either based on phytoplankton or on zooplankton may capture different seasonal signals has received considerable international attention. Although the idea was not entirely new, our robust demonstration of diverging trends, explained with support from the climate model must have been very convincing, so that the idea is now commonly used in the interpretation of paleo records. In addition, better knowledge on potential seasonal signals in paleo proxies allows reconstruction of past changes in mean climate and helps to quantify trends in climate variability such as the seasonal cycle and even beyond, for example interannual variability (e.g. El Niño/Southern Oscillation). This was also well received by the international community and a Paleo Modeling Intercomparison Project (PMIP) working group on past climate variability was established with the Future Ocean contribution.

Among others, the group also carried out model simulations following standard PMIP protocols for certain time periods in the past (Holocene, Eemian), so that a direct benchmarking of these results with those from other large climate modeling centers in the world was possible. The KCM has thus received international attention and was involved in and contributed results to a larger number of community papers (e.g. Emile-Geay et al. 2015, Bakker et al. 2013; Lunt et al. 2013). Here the group also contributed to the investigation of a newly emerging topic on the link between climate and the development of human societies in the past, which requires tight links between climate modelers and social scientists (e.g. Jennings et al. 2015).

The combination of the Kiel coupled climate model (KCM) with an ocean biogeochemical model (PISCES) allowed us to investigate not only the physical aspects of climate and ocean circulation, but also biogeochemical properties of water masses (carbon, nutrients, oxygen, productivity). The goup's latest achievement is a continuous transient non-accelerated simulation from the early Holocene over present and into the future of both climate and ocean biogeochemical cycles (Segschneider et al. 2018). This kind of simulation with seamless transition between several climate

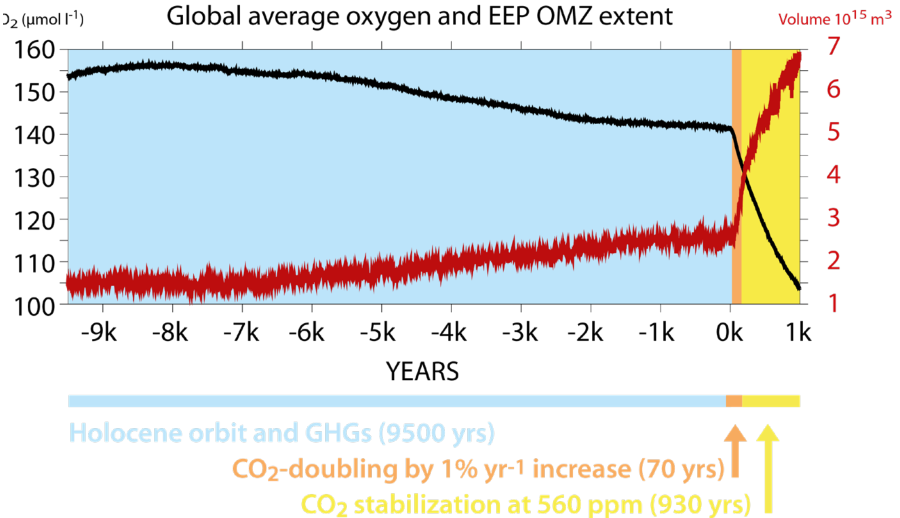

Figure 21: Global average oxygen and EEP OMZ extent

forcing periods (orbital, CO_2) is unprecedented, since usually different time periods (past, present, future) are started from different initial states (spinups). The realization of this simulation required about 35,000 CPU hours on the NEC SX-ACE High Performance Computing System at Kiel University, which is equals to about one-year (real) run time. Its output fills about 60 TB of disk space.

One of the major results of this simulation is that the currently observed expansion and intensification of the oxygen minimum zone (OMZ) in the Eastern Equatorial Pacific (EEP) was already ongoing since about the mid-Holocene, however, the process has greatly accelerated under anthropogenic forcing and it is projected to continue over a long time (millennia) even after stabilization of atmospheric CO_2 concentrations (Figure 21).

In order to study questions of ocean acidification and climate warming in past, present and potential future climates, new research teams have formed, covering a large palette of established and new pH and other proxies. For example, Pteropod shells were used as indicators for variations in temperature and pH (Postdoc project N. Keul). The application of Mg-Isotopes, Ca^{2+}-Channels, Ca^{2+}-ATPases and Boron Isotopes as pH indicators were refined, whereby the latter works were also substantially supported by an investment into the instrumentation of the science support platform. From a more ecological aspect, two studies were carried out to investigate changing habitats of calcareous calcareous plankton in a greenhouse world (PhD project A. Harbers) and dissolution effects on planktonic foraminifera as controlled by bottom water saturation state (Postdoc project M. Regenberg). A particular focus on proxies for the quantification of surface ocean warming was laid in two studies using Sr/Ca ratios measured on corals (Sagar et al. 2016; von Reumont et al. 2016).

More methodologically, large efforts were put into proxy development. In a study by Storz et al. 2013, oxygen isotopes in combination with Sr/Ca ratios in marine corals were applied as indicators for climate variability in the NW Indian Ocean. The potentially confounding impact of coral growth and high SST variability on coral paleothermometry was investigated by Grove et al. 2013. Although Mg/Ca ratios from foraminifera are already well established as indicators for ocean temperature variability, calibrations are still not optimal and a refinement was provided by Cappelli et al. 2015. Improvements on the technical aspects of proxy measurements were made regarding sample preparation for LA-ICP-MS measurements (Garbe-Schönberg and Mueller 2014). A large scale interlaboratory calibration study for element rations measured on corals (e.g. Sr/Ca) was led by Kiel scientists (Hathorne et al. 2013).

Future predictions on the functioning of the climate-sensitive tropical Western Hemisphere Warmpool rely on the understanding of its dynamics during climate change, e.g. during the last transition into a warm climate. Rapid and high-amplitude variations in ocean temperature and salinity, and nutrient inventory recorded by proxy data point to extreme oceanographic changes at different depth levels. At intermediate depths, deglacial warming and nutrient enrichment point to considerable changes in the Southern Ocean and the rapid northward transfer of the chemical signature via Antarctic Intermediate Water (Poggemann et al. 2017; 2018). Extensive warming at subsurface level reflect the southward expansion of the Subtropical Gyre and the intensified expansion of Salinity Maximum Water during AMOC perturbations (Reissig et al. 2019).

As mentioned above, gas hydrate emissions are known to be related to climate warming and may have triggered larger climate excursions in the past as e.g. the Paleocene Eocene Thermal Maximum (PETM). Several research teams conducted several studies to investigate gas hydrate dynamics (Dumke et al. 2014, 2016; Vielstädte et al. 2015). In a highly interdisciplinary study, climate modelers together with geoscientists and biologists quantified the effect of Arctic ocean warming on gas hydrate stability, using a combination of ocean circulation and climate models with thermodynamic considerations of gas hydrate stability in ocean sediments. This study revealed important insights into the amount and rates of gas hydrate release implications on considerations of potential climatic consequences.

Finally, work carried out under the umbrella of research topic R9 Ocean Controls is also tightly linked to societally relevant questions of ocean resources. For example, long-term model integrations of climate and biogeochemical cycling provide estimates of ocean primary productivity. Since this is at the base of the food chain, variations in primary productivity are expected to influence higher trophic levels and finally fishery yields. In the Aquamaps project, model results are systematically used to project potential future ocean fish stocks (aquamaps.org).

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2.2.10 R10 OCEAN OBSERVATIONS

Wilhelm Hasselbring, Martin Visbeck, Arne Körtzinger

Scope

Ocean Observations brought researchers together from chemical and physical oceanography, informatics, geochemistry, geology, law and economics to develop and promote elements needed to enhance global and regional sustained ocean observations – figuratively speaking for 'taking the ocean's pulse.'

The current provision of routine and sustained global, regional and local information on the marine environment is not sufficient to meet society's needs for describing, understanding and forecasting natural marine variability from days to decades, marine responses to climate change (e.g., ocean warming, acidification, and deoxygenation) and other human impacts (loss of biodiversity, pollution), sustainable management of living marine resources (fish stocks) and marine protection. In order to fulfill society's mandate for ocean observations (e.g. SDG 14, OceanObs'19), (i) advanced concepts and routines have to be developed, tested and implemented to ensure sensors efficiently deliver the required information via simulated ocean models and (ii) the systematic design of global, regional and local ocean observation systems. Scientific, technical, legal, and economic constraints still need to be addressed (Fig. 22). Against this background, the central question is: How can ocean observations be improved?

Scientific achievements

Data and information are the key to using and managing the oceans wisely, and to keeping them healthy for the future. To help do this, data are gathered by a range of global observation networks, where they are processed, stored and analysed by specialists. There is global agreement on the importance of ocean data. In the 2016 Tsukuba Declaration on the future of science, technology and innovation, the G7 industrialized nations have recognized the good environmental status of the oceans as crucial for economic development. The Declaration detailed data priorities for the oceans, many of which are being pursued by researchers in Kiel. They are deeply involved in

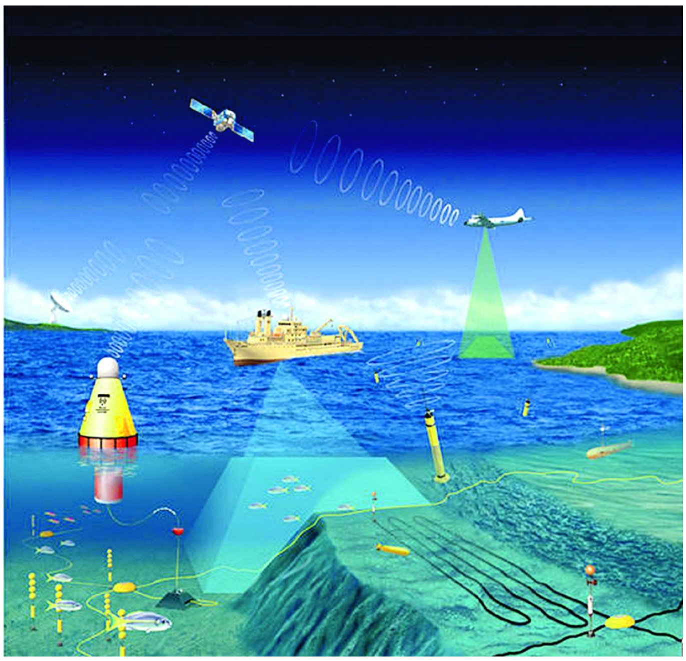

Figure 22: Illustration of some of the key elements of a multidisciplinary and multifunctional global ocean observations network. Source: Integrated Ocean Observing System: http://www.ioos.gov

the collection, analysis, open publishing and sharing of ocean data, much of it gathered through interoperable observation systems.

Autonomous sensor platforms

The ARGO programme has involved the creation of a global array of nearly 3,900 free-drifting profiling floats that measure the temperature and salinity of the upper 2,000 m of the ocean and is perhaps one of the greatest success stories in physical oceanography. Chemical oceanographers pioneered oxygen measurements from Argo floats and are involved in the development of the Biogeochemical Argo Group, which is pushing for a fully-fledged biogeochemical Argo programme. Argo working groups, including the one in Kiel, have developed and successfully deployed the next generation of these marine observation robots, which are equipped with biogeochemical sensors measuring oxygen, pH, nitrate, chlorophyll and suspended particles in the water column. A global array of these multidisciplinary floats will greatly enhance our ocean database and our knowledge of ocean behaviour. It will allow us to map these parameters on a global scale in real time and detect even slight environmental change early on.

Other autonomous sensor platforms, which are also employed and further extended by Kiel researchers, include Voluntary Observing Ships (VOS). These are usually merchant ships which sail stable routes across the ocean. They are equipped with sophisticated analytical instruments that measure CO_2, oxygen, chlorophyll, and other parameters continuously along the same routes throughout the year. The use of novel autonomous instruments has been explored by the group in order to extend the range of measurable parameters (e.g, alkalinity, stable carbon isotopes). Kiel scientists are also active in more static forms of data gathering.

Seabed ocean observatory

MoLab (modular deep-seep laboratory), a seabed ocean observatory which can be left in place for months at a time to gather data from sites of scientific interest, was developed to fill the need for a fixed ocean observing system. It was first used in 2012 off the North coast of Norway, to investigate the region’s cold-water coral reefs 300 m below the sea surface. With the MoLab different detectors can be placed at different locations across several kilometres of the sea floor, allowing a complete picture of the region to be built up. These subsystems communicate with each other by sound, so no cables need be laid on the seafloor. In the Norwegian experiment, MoLab was used to measure currents, tides, temperatures, salinity, nutrients and oxygen consumption, and the reef was observed continuously by MoLab’s cameras. In this experiment, high resolution time series data and photographs from MoLab were analysed with machine learning techniques to determine the polyp activity patterns of cold-water corals. The results showed that activity on the reef was governed by the strong tidal currents that prevail in that location. The coral was able to adapt to the large-scale patterns of water movement to optimize nutrient uptake.

Time series sites

Baltic Sea researchers take a long-term view. They have maintained the Boknis Eck station since the late 1950s. Monthly sampling there began on 30 April 1957, making Boknis Eck one of the world’s oldest time series sites for marine data still in operation. In December 2016, a cabled underwater observatory was deployed close to the site. It sits in 14.5 m water depth and its sensors generate continuous in-situ data that are available in real time. It complements the established monthly sampling at Boknis Eck and allows short-term trends and events in the western Baltic Sea to be detected.

Another major example is the Cape Verde Ocean Observatory (CVOO), which was set up by GEOMAR researchers as a new time-series station in the tropical North-East Atlantic in 2006. The site is maintained until today and modern research facilities (Ocean Science Centre Mindelo), academic teaching programmes (Master Research Program “Climate Change and Marine Sciences”, Universidade de Cabo Verde and GEOMAR) as well as a multi-facetted research agenda has developed around CVOO since then. Plans exist to develop this into an international Marine Science & Education Hub.

CO_2 in Oceans

Chemical oceanographers at GEOMAR have been concerned with CO_2 for a long time and research its movement between the ocean and the atmosphere. High-quality CO_2 measurements have been performed now for nearly 15 years from merchant vessels crossing the North Atlantic routinely between Europe and North America, thereby continuously covering the subpolar North Atlantic, which is one of the most important areas in which carbon dioxide enters the ocean and is stored. The work does not stop, however, with the data generation. A major focus has therefore been placed on aggregating the flows of data into a consistent global data product, showing the potential for big data to revolutionize our understanding of the oceans. This led to the creation of SOCAT, the Surface Ocean CO_2 Atlas (Bakker et al. 2016). This massive global database unites updated, quality-controlled values for the carbon dioxide concentration of global surface oceans and coastal seas from a wide range of sources. Version 2019 of SOCAT has been released in June 2019 and contains 25.7 million quality-controlled surface ocean fCO_2 (fugacity of CO_2) observations from 1957 to 2019 for the global oceans and coastal seas. SOCAT has made an impressive 1.5 to 2 million observations per year for the last decade. Each data point comes with a quality flag, allowing users to gauge the reliability of data from different sensors and platforms. SOCAT is used for a wide range of important scientific investigations, particularly on the ocean sink for atmospheric CO_2 and its long-term variation. The long and ever-growing list of publications employing the SOCAT data is vivid evidence of the utility of such data products, which are produced in an international community spirit. It is noteworthy that the SOCAT data are an important input to the annually released global carbon budget (LeQuéré et al. 2016), a key element in the compilation of the well-known Special Reports on Climate Change by the Intergovernmental Panel on Climate Change (IPCC).

Oxygen Minimum Zones

The growing availability of data on the oceans has allowed Kiel researchers to find out about previously unknown dead zones of the Atlantic (Fiedler et al. 2016), working with colleagues in the Cape Verde Islands and elsewhere. An interdisciplinary group of chemical, physical and biological oceanographers discovered these oxygen-poor dead zones at the Cape Verde Ocean Observatory (CVOO) in the eastern tropical North Atlantic. They used data on dissolved oxygen in the oceans obtained from subsea gliders, moored measuring devices, research vessels, and the Argo floats mentioned above. This novel dataset reveals that dead zones are common in the tropical Eastern Atlantic. They occur within eddies, swirling water bodies of more than 100 km in diameter. The lowest oxygen concentrations are typically found just below the surface, from 50 to 150 m depth, with consequences for the marine fauna.

It seems that these low-oxygen zones form because the swirling motion and the unique physical processes associated with this particular eddy type, isolates them from the rest of the ocean, while high levels of biological activity depress their oxygen content (Karstensen et al. 2017). These results are important because we already know that climate change is likely to reduce the amount of oxygen in the oceans, and oxygen is important for almost all marine life. In light of projected ocean deoxygenation, oxygen loss events like these eddies are already showing how microbial communities and ecosystem structures will be altered in the future. There could be significant impacts on primary productivity and on biogeochemical processes in oceanic water bodies. This could also have severe consequences for nations such as Cape Verde and the rest of West Africa, where national economies are heavily dependent upon fisheries. Ocean deoxygenation is therefore one of the science topics addressed at the new long-term Cape Verde Ocean Observatory (CVOO).

Ocean Monitoring

Sensors are improving rapidly, while Argo and other initiatives allow us to monitor large parts of the ocean on a regular basis. The new parameters measured by the BioGeoChemical Argo are likely to lead to a major breakthrough in marine biogeochemistry (Roemmich et al. 2019). However, knowledge gaps still remain. Few observatories target the deep sea – and even these are mostly temporary. The zone below 2,000 m is well explored only in small patches of specific interest, for instance where commercial exploration for oil or other minerals has taken place or where there are geological or ecological features. Most of the deep sea between the seafloor and the upper two km of water remains largely unexplored. This problem is now being addressed. One approach is the improvement and extension of the existing ocean observation network and technologies (Roemmich et al. 2019). New infrastructure installed at the Ocean Science Centre Mindelo (OSCM) in the Cape Verde Islands provides a modern, multifunctional platform for deep ocean assessment. Its development follows what we term the 3-Spheres-Approach. This addresses the sphere of international marine research, the sphere of regionally motivated research driven by socio-economic needs, and the sphere of capacity building in the West African region. Coherent and concerted activity in all three of these spheres is one of the foremost tasks for marine science in Kiel.

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2.2.11 R11 PREDICTED OCEAN

Claus Böning, Arne Biastoch, Malte Braack

Scope

Predicted Ocean brought together researchers from ocean circulation, climate and carbon cycle modeling with modern methods in numerical mathematics and optimization theory to elucidate the mechanisms governing prospective changes in regional ocean dynamics and biogeochemistry over the next 50 to 100 years.

The evolution of the state of the ocean on decadal time scales is influenced by both natural modes of variability and anthropogenic trends and involves spatial patterns, which are far from uniform (Fig. 23). A leading factor governing regional ocean changes is the response of ocean circulation to atmospheric forcing variability and trends: the associated ocean transport anomalies strongly influence the geographical patterns of oceanic processes such as carbon uptake, acidification, near-bottom warming and å. Local rates of sea level change during the last decades, for instance, significantly differed from the global mean rise due to circulation related swings in the warm upper ocean waters. Future changes in nutrient supply and associated biological productivity as well as in oceanic carbon uptake and associated acidification will be significantly impacted on a regional scale by the changes in the 3-D circulation, for instance, the up- and down-welling patterns in the southern ocean and in the tropics, or the deep wintertime convection in the subarctic Atlantic. A common denominator of future ocean changes at the regional scale is an overarching influence of ocean dynamics: understanding the behavior of ocean circulation and its effect on biogeochemical fluxes in response to changing atmospheric conditions represents a prerequisite for developing capabilities in projecting the future evolution of societally relevant properties at the regional scale, such as the occurrence of species and fishing opportunities.

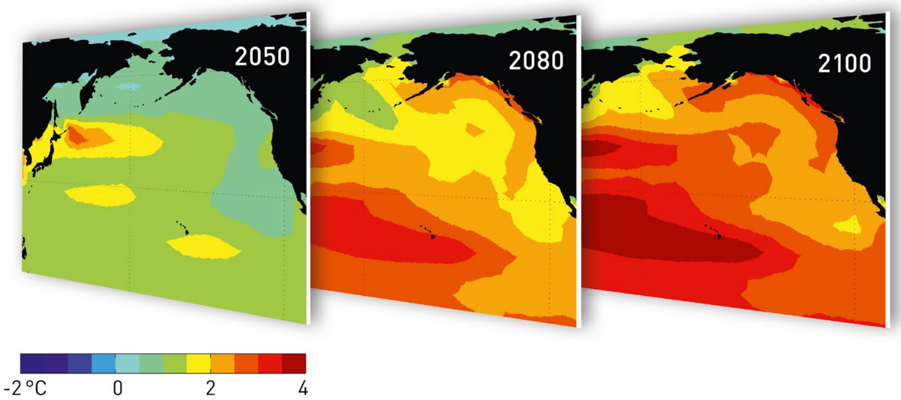

Figure 23: Future evolution of sea surface temperature as projected by the Kiel Climate Model in a $2xCO_2$ ensemble simulation.

Against this background, a central goal of this group's research activities was directed at the understanding of mechanisms and the development novel methodologies needed to advance ocean predictions on regional scales.

Scientific achievements

Greenland loses ice

A major interest of Kiel research has been on the ongoing or imminent changes in the subpolar North Atlantic. This includes one of the most discussed aspects of human-induced climate change, the possible destruction of Greenland's immense glaciers and its effect on the ocean current systems that govern the Atlantic meridional overturning circulation (AMOC). Working with colleagues from the UK, Kiel researchers have modelled the impact on the ocean circulation of the growing mass loss from the ice sheets of Greenland, which has been observed since the 1990s (Böning et al. 2016). With a growing flux of fresh water pouring into the northern Atlantic, oceanographers have become concerned that a concentration in the surface waters of the Labrador Sea could weaken the deep wintertime convection processes which are central to the transformation of the warm, northward flowing upper-layer waters to the cold, southward return flow at depth. Some bleak forecasts suggest that this effect could slow the AMOC and therefore the Gulf Stream's journey from the Gulf of Mexico to the North-East Atlantic, and thereby reduce winter temperatures in continental Europe. The Kiel modelling program helped to assess the impact of these increased flows of fresh water, using a novel global ocean circulation model with a grid spacing fine enough to capture the small-scale, eddying transport processes in the subpolar North Atlantic. This modelling suggests that so far, the invasion of meltwater from the ice sheets of West Greenland has had only a limited effect in the Labrador Sea. The effect so far does not exceed the region's natural variability, which involved episodes of natural freshwater anomalies associated with pulses of enhanced outflows of sea ice from the Arctic Ocean (i.e., the so-called "great salinity anomalies"). In contrast to these short-term freshening events, the meltwater from Greenland is progressively accumulating, however. The model results suggest that during the next decade the freshening of the Labrador Sea may be reaching a magnitude where it could leave first imprints in the convection patterns and, in consequence, the regional current systems. In case of a continuation of the actual, observed increasing trend in the melting rate, the freshening of the Labrador Sea could begin to have a significant impact on the strength of the AMOC around 2040. Theoretical work has been carried out in enhancing numerical schemes for the modeling and simulation of ice shelves and glaciers, namely the p-Stokes equations: Ahlkrona and Braack (et al. 2019) developed and analyzed finite element schemes for a more robust simulation on highly anisotropic meshes. This is important to better resolve the anisotropic features of ice sheets in future climate models including the coupling to ice melting.

Agulhas Influence

Kiel modelers are also unravelling the complex flows of water and heat at the other end of the Atlantic. Here warm, salty water is carried from the Indian Ocean to the Atlantic by the so-called Agulhas leakage, an extension of the Agulhas Current in the Indian Ocean around the southern tip of Africa. The water that Agulhas leakage brings to the Atlantic could not be more different from the cold, pure meltwater of Greenland. But it too could be an indicator of human-made climate change. GEOMAR's high-resolution ocean and climate models shed some light on the recent and possible future evolution, in a large international collaboration effort (Biastoch et al. 2015). They find that the previously disregarded Agulhas leakage is “a crucial component of the climate system” and that “ongoing increases in leakage under anthropogenic warming could strengthen the Atlantic Overturning Circulation.” While Kiel research on ice loss in Greenland suggests that this vital feature of global ocean circulation is threatened by the arrival of large volumes of cold water in the Arctic, it also indicates that injecting warm, salty water to the South would add to its strength. This research is not all about the ocean. The Agulhas leakage is also influenced by prevailing winds. Current models suggest that the westerly winds observed in the region will move south under conditions of global warming. If so, they change Agulhas leakage and the amount of warm and salty Indian Ocean water entering the Atlantic from the south. The researchers say that it is already possible to observe a trend towards increasing Agulhas leakage consistent with the observed increasing intensity of the westerly winds over the past three decades. It is “projected to continue over the 21st century” as a result of anthropogenic climate change.

Migration path of juvenile turtles

Data about the ocean is not gathered only from buoys, aircraft, ships and satellites. New technology means that we can learn about the ocean from the movement of ever-smaller animals. “Nanotags”, for example, were attached to new-born loggerhead turtles in Boa Vista, one of the Cape Verde islands, in collaboration with colleagues from Cape Verde and London. The newly hatched turtles are only a few centimetres in size, and it has not been feasible before now to attach such tracking devices to them. This work has shown that the turtles, which hurry into the sea as soon as they hatch, can cover 15 km of ocean during their first few hours of independent life. They use sea currents to travel at up to 60m per minute. It seems that bigger turtles swim more than smaller ones, and that the turtles’ behaviour is adapted to local ocean conditions. Many turtle species such as the loggerhead are endangered or threatened. So, this research helps design the right strategy for their conservation. Up to now, there is little knowledge of their early life. This research has shown that once they are at sea, the loggerhead turtles’ movement is determined largely by ocean currents. Boa Vista is close to near-shore currents, and the turtles there have less far to swim to reach them than turtles in Florida, also a major population centre for these animals. This means that the Cape Verde turtles can become inactive at night at an earlier age, allowing them to be less obvious to predators (Scott et al. 2014). In a new and highly innovative study in Gabon, behavioural studies of hatchling turtles were being combined with in-situ observations of ocean currents. These in-situ observations, collected using novel turtle inspired surface oceanic drifters, enable us to accurately assess the swimming behaviours of hatchlings whilst improving our understanding of upper surface processes. Hatchling turtles actually experience, and have evolved to respond, to very fine scale ocean variability, which models are too coarse to resolve. In-situ studies of this nature on young turtles can provide valuable new high-resolution ocean current data to test the robustness of ocean models.

The future of the ocean biota

Global coupled biogeochemical ocean models are now routinely applied to predict the ocean biota's response to climate change, as well as its impact on future climate. Besides circulation, the equations and constants that describe the interaction between organisms and their environment can play an important role for these mutual interactions. However, in contrast to physical processes, the description of biological processes is mainly based on empirical observations, which are associated with a considerable range of uncertainty and a high level of simplification. Within Future Ocean, significant progress has been made with regard to the identification of the sources and degree of uncertainty and their impact on global model fit to present day observations (Schartau et al. 2017). Tools have been designed that facilitate global model simulation and optimization, or allow for automatic model calibration against different components of societal relevance (e.g. oxygen minimum zones (Sauerland et al. 2019). Together with individual model studies that targeted specific processes such as calcification and the carbon cycle, the marine nitrogen cycle, or the representation of ecosystem diversity in global models, these methodological innovations have begun to considerably identify and narrow uncertainties in global models (and their future predictions), and to flesh out the potentially important feedback mechanisms between ocean biota and the earth system.

Modelling of sustainable fishing strategies

The behavior of a fishing fleet and its impact onto the biomass of fish can be described by a nonlinear parabolic diffusion–reaction equation. Looking for an optimal fishing strategy leads to a nonconvex optimal control problem with a bilinear control action. Braack and Quaas present such an optimal control formulation (Braack et al. 2018) and prove its well-posedness and derive first- and second-order optimality conditions. These results provide a basis for tailored finite element discretization as well as for Newton type optimization algorithms. Numerical test problems show typical features as so-called No-Take-Zones and maximal fishing quota (total allowable catches) as parts of an optimal fishing strategy.

Selected publications

Park, T., Park, W. und Latif, M. (2016) Correcting North Atlantic Sea Surface Salinity Biases in the Kiel Climate Model: Influences on Ocean Circulation and Atlantic Multidecadal Variability. Climate Dynamics, 47 (7). pp. 2543-2560. DOI 10.1007/s00382-016-2982.

Böning, C. W., Behrens, E., Biastoch, A., Getzlaff, K. und Bamber, J. L. (2016) Emerging impact of Greenland meltwater on deepwater formation in the North Atlantic Ocean Nature Geoscience, 9 (7). pp. 523-527. DOI 10.1038/ngeo2740.

Scott, R., Biastoch, A., Roder, C., Stiebens, V. und Eizaguirre, C. (2014) Nano-tags for neonates and ocean-mediated swimming behaviours linked to rapid dispersal of hatchling sea turtles Proceedings of the Royal Society B-Biological Sciences, 281 (1796). p. 20141209. DOI 10.1098/rspb.2014.1209.

Biastoch, A., Durgadoo, J. V., Morrison, A. K., van Sebille, E., Weijer, W. und Griffies, S. M. (2015) Atlantic multi-decadal oscillation covaries with Agulhas leakage. Nature Communications, 6 (10082). DOI 10.1038/ncomms10082.

Ahlkrona, J., Braack, M. (2019) Equal-order stabilized finite element approximation of the p-Stokes equations on anisotropic Cartesian meshes, Comput. Meth. Applied Math, 2019, DOI: https://doi.org/10.1515/cmam-2018-0260

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Schartau, M., Wallhead, P., Hemmings, J., Löptien, U., Kriest, I., Krishna, S., Ward, B. A., Slawig, T. and Oschlies, A. (2017) Reviews and syntheses: Parameter identification in marine planktonic ecosystem modelling Biogeosciences (BG), 14 (6). pp. 1647-1701. DOI 10.5194/bg-14-1647-2017.

Sauerland, V., Kriest, I., Oschlies, A., & Srivastav, A. (2019). Multiobjective calibration of a global biogeochemical ocean model against nutrients, oxygen, and oxygen minimum zones. Journal of Advances in Modeling Earth Systems, 11. https://doi.org/10.1029/ 2018MS001510

3 PEOPLE

More than 200 scientists from seven faculties at Kiel University, the GEOMAR Helmholtz Centre for Ocean Research Kiel, the Kiel Institute for the World Economy (IfW), and the Muthesius University of Fine Arts and Design, participated in the Cluster. One of the major strategic objectives of the Cluster was to create a tenure track option from junior professor (W1) or associate professor without tenure (W2) to a tenured associate professor (W2) level at the Kiel University. The Cluster established 13 interdisciplinary research areas where young, high-potential scientists were recruited to lead Junior Research Groups (JRG). All positions were advertised as (W1/W2) competitive tenure-track. The recruiting process included a full-page advertisement in *Nature* and several other online job market outlets one month after the formal start of the Cluster funding. Two months later we hosted about 75 young scientists from around the world for a week-long visit in Kiel. During the morning sessions they gave their scientific presentation, and in the afternoon the commissions met with their respective applicants. Social events hosted each evening by the participating institutions of the Cluster, rounded off the experience, since then dubbed the ‘Kiel Week’ in the German Cluster community. Successful candidates were offered a 5-6 year-long W1/W2 contract and in addition each JRG leader was given a start-up fund of 800 k€ to be used at their discretion. Dual career options were available and used in two cases. Almost all offers were made within 6 months after the advertisement, and within 18 months after the Cluster start, 13 JRG leader positions were filled. Although our target was to hire 50 % female scientists, only 26 % of the candidates invited to ‘Kiel Week’ were women. However, the short list of candidates contained 36 % women, and those offered a tenure-track position included 44 % women. Unfortunately, only 31 % of those accepting this offer were females. The initial Cluster proposal stated that up to nine tenure positions could be made available. After an in-depth comparative review process in spring 2011, the final decision on tenure for all candidates was made and nine permanent W2 positions were awarded in the faculties of Mathematics & Natural Sciences, Law, Business, Economics & Social Sciences, Engineering, and Medicine (see Appendix B, Table 11). One JRG leader left Kiel early and two candidates were offered a permanent research position after their contracts expired. Subsequently one tenure track W2 professor position in Law of the Sea was re-advertised to replace the departed one. Moreover, more social scientists were successfully incorporated to the Cluster, and a new W3 professorship in environmental ethics was established and became the founding director of the Gustav Radbruch Centre for Environmental Ethics in 2011.

In addition, tenure for a high-profile female professorship had been secured to be awarded in 2015/16. In addition to the nine Cluster professorships, eleven other professorships in marine science-related fields were filled recently. Most of them became vacant because of retirement or departures to other positions. However, three new positions became available to strengthen the CAU Marine Science research focus. The research environment of the Cluster further provided the framework for the university to also successfully compete against highly attractive offers from other universities and non-university research institutions to retain key professorships.

For phase II of the Cluster, an increased emphasis was placed on postdoctoral scientists, young investigators and scientific support personnel in general. A strategic goal of the Cluster was to strengthen Kiel Marine Science at all levels, including the research scientist level. Several of the specific measures are described below as part of the IMAP network. The CAU offered the equivalent of six research scientist positions (E13/E14 equivalents) to providing partial tenure to advanced research scientists and in addition to providing four permanent positions for different science support measures in the newly established head office, a central unit within the administration of Kiel University. Furthermore, the university successfully negotiated the implementation of two new fixed-term professorships in marine social science and political science with the State of Schleswig-Holstein in 2017 in order to further expand the expertise in strategically important research fields.

3.1 PROMOTION OF EARLY CAREER RESEARCHERS

3.1.1 DOCTORAL EDUCATION – INTEGRATED SCHOOL OF OCEAN SCIENCES (ISOS)

The doctoral programme "Integrated School of Ocean Sciences" (ISOS) focused on interdisciplinary education outside of curricular courses. It offered supplementary training, a framework of supervision, mentoring and mobility for doctoral candidates (Fig. 24). The ISOS programme was designed to support doctoral candidates and their supervisors alike and they participated on a voluntary basis in the ISOS doctoral programme based on a transparent system of incentives and obligations. Candidates were from all natural science disciplines, law, economics, ethics and many other subjects. They sharpened their scientific profile and were challenged to think beyond their discipline and to equip themselves for life after a doctorate. The programme took a holistic view of research-based education, involving partners from academia, industry, politics and NGOs, and bringing in ad hoc expertise where required. An active alumni network provided input to the programme, especially in supporting career perspectives beyond the doctorate

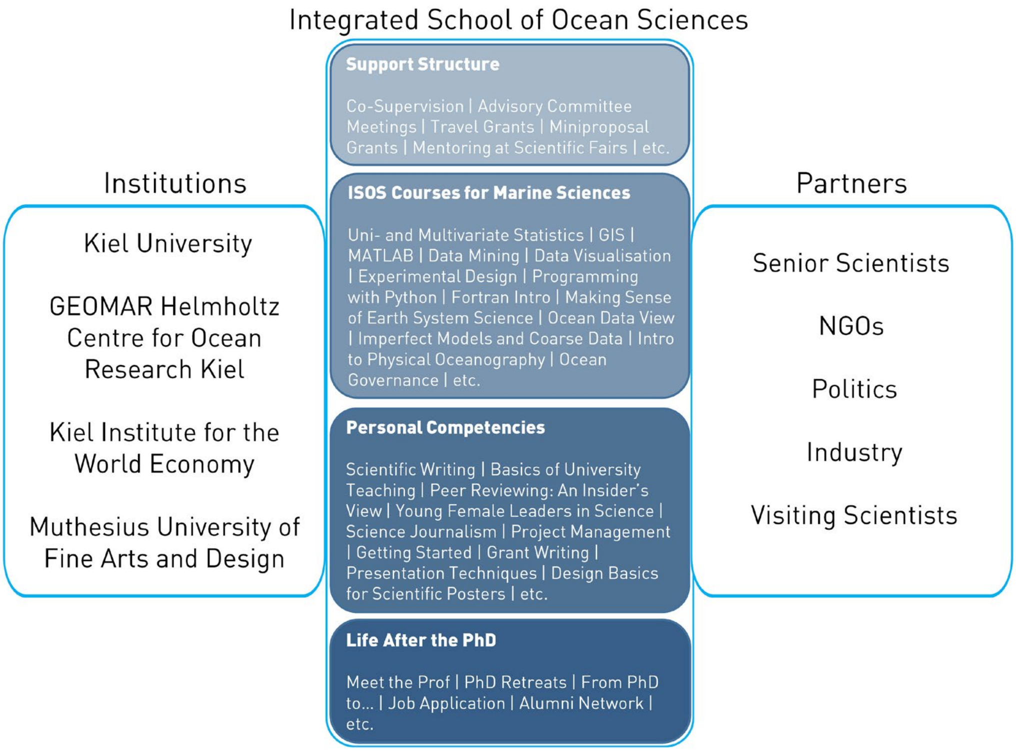

Figure 24: The foundation for the ISOS programme is a close cooperation between four research institutions in Kiel and partners from in and outside the academic system.

Over both Cluster funding periods (2006-2019) the number of participants increased continuously reaching an average number of 160 doctoral candidates and reaching a peak of more than 180 in 2018. Doctoral candidates were supervised by at least two supervisors in a multidisciplinary environment (Fig. 25). During both funding periods, ISOS offered more than 370 courses, which were attended by more than 3300 participants in total: 230 courses were offered on scientific skills (e.g. Data Management, scientific methods, programming skills, multidisciplinary topics) and 148 transferable skill courses (e.g. scientific writing, personal competences, communication skills). ISOS involved 107 cluster scientists to lecture more than 150 courses.
Various events challenged doctoral candidates to think beyond their discipline and to deal with the theory of science. These events involved the multidisciplinary lecture secies “BIG questions” (more than 100 lectures over both funding periods) and the Doing Science series (seven events in the second funding period: e.g. Research integrity, panel discussions, Doing Science Seminars).

Topics of the different events were "Science-Diverse ways of Life?", “Research Integrity: Black or White?” and "Research Impact" to name just a few.

In eigth ISOS Retreats doctoral candidates got together with their peers and discussed topics like "Science Communication", "Prepared for Social Responsibility?" or "Life after the Doctorate". Doctoral candidates are encouraged to think beyond the doctorate, to be enthused and inspired by role models and to network outside their own academic field. Several events addressed this career topic in both cluster phases: 23 “Meet the Prof”/”Meet the Expert” events were organized between 2011 and 2019 where young researchers could meet – personally and informally – with top-level international scientists and experts. In eight Career Evenings networking with professionals from in- and outside academia was enabled and during the second funding period II “Meet the Alumni” and nine “From Doctorate to…” introduced success stories from in- and outside academia by ISOS Alumni.

Besides career events ISOS offered the opportunities to start own research projects within the funding line "Miniproposals" or to make optimal use of visiting a scientific or commercial fair by the mentoring programme "Science Fair Mentoring". In total, 14 Miniproposal were granted (2006-2019). This financial support enables doctoral candidates to apply for own funding by initiating and developing an own research project. Going through the application process and conduct the re-

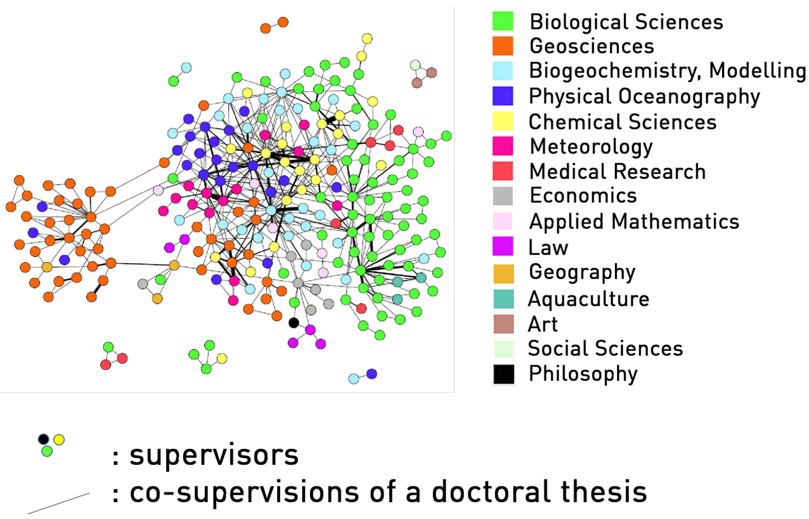

Figure 25: Multidisciplinary co-supervision is a requirement for integrated doctoral research and ensures best-practice institutional support.

search was of high value for all candidates and gave them the opportunity to network with international colleagues.

Also, the "Science Fair Mentoring" fostered the career development of ISOS candidates. Mentees were matched with a Mentor who fits their interests and requirements and shared his/her experience, gave insights and introduced the mentee to colleagues. Between 2006 and 2019 ISOS supported seven candidates to attend scientific and commercial fairs, which was a fruitful experience for all candidates with respect to career development and building their own network. ISOS candidates were also entitled to apply for financial support to participate in conferences, workshops or summer schools. Between 2006 and 2019 ISOS granted 281 travel supports.

Attracting young talent

Attracting talented and innovative young scientists to the integrated research environment of marine sciences in Kiel played an important role in bringing in fresh ideas, encouraging innovative research at an early career phase and creating and extending the unique cross-disciplinary research environment. Twice, in 2012 and 2014, the cluster of excellence “The Future Ocean” set out to recruit a cohort of early career scientists by not defining projects but issuing an open call for doctoral proposals with a particular focus on the interdisciplinary profile of marine sciences in Kiel. Applicants were asked to match their proposal to one research area within the framework of “The Future Ocean” and contact possible supervisors. Over 200 young scientists from around the world responded, proposing to unite, among others, law with fisheries, art with ocean sustainability and ocean modeling with biogeochemistry. After a first review round, short-listed proposals were then presented at a large symposium giving the applicants the possibility to introduce their research idea.

The two proposal rounds resulted in 19 young researchers being given the opportunity to implement their research idea in the marine science environment in Kiel, constituting to a new generation of excellent marine researchers. Accepted proposals were fully funded for a three-year period.
Each year from 2009 on, ISOS advertised doctoral research topics from cluster scientists primarily for China Scholarship Council Stipend (CSC) applicants but also at conferences (AGU/ASLO/EGU) and online. Since 2009 38 CSC Stipend holders have been attracted and supervised in the Cluster. Further, since 2008 16 DAAD Stipend holders have become ISOS candidates.

3.1.2 INTEGRATED MARINE POSTDOC NETWORK (IMAP)

The support of postdoctoral researchers had been identified as a strategic goal for the second funding phase of the Cluster. In 2012, the Cluster established the Integrated Marine Postdoc Network (IMAP) to support young researchers in networking and career development. Operational for more than six years, it is now a network of 130 postdoctoral researchers currently working in marine sciences in Kiel and almost 100 alumni who continue their careers within the global academic community or in the non-academic labor market. IMAP supported all researchers on temporary contracts who were admitted to the Cluster as Associate Members, referred to as IMAP members, in their development until they reached either a junior professorship or a permanent position as a senior research scientist or left Kiel to continue their careers elsewhere. IMAP members work at the Cluster’s partner institutions - at Kiel University, the GEOMAR Helmholtz Centre for Ocean Research Kiel, the Kiel Institute for the World Economy and the Leibniz Institute for Mathematics and

Science Education. Many members of the IMAP community have come to Kiel from other marine science institutions around the world, creating an excellent opportunity to facilitate international networking. Some of them were recruited and supported to contribute to the Cluster's research topics or selected as fellows by the Alexander von Humboldt Foundation, but in their majority, they were supported by non-Cluster related funds.

IMAP members work in the full range of subjects encountered in "The Future Ocean", from the natural, social and life sciences to computing, economics, law and philosophy and were therefore essential assets to the Cluster's research. They produced core scientific results, supported educational activities, provided technical expertise to Master and PhD students and sometimes even co-ordinated research projects. In addition to being a valuable basis for developing all the competences a researcher needs, the support provided by the network allowed postdocs to expand their portfolios into new fields and take on additional tasks in line with the Cluster's overall mission. These included engagement in politics and dialogue with stakeholders, as well as the management of larger-scale projects and cooperation with industry. These broader challenges called for additional professional skills, and the Cluster provided opportunities to develop them through training, coaching and mentoring.

IMAP caters to early postdocs and research scientists on non-permanent positions, which are currently also included under the term postdoc, but have different levels of experience and naturally different needs for support. Specifically, career development measures for the early career phase and some level of financial security and independence for scientists at later stages of their career were developed. The early postdoc phase of up to 6 years after completing the doctorate concentrates mainly on personal scientific career development. The academic career path after the postdoc phase can either lead to a high-level academic career with junior and full professorship, or on a track with a focus on either research or teaching eventually leading to a senior scientist position, which was often tenured in Germany and formed the so-called 'Mittelbau' (mid-level structure). The number of these latter permanent positions has decreased dramatically in recent years in Germany because a change of the employment law turned the rigid, inflexible tenure system into a system of uncertain and insecure career perspectives.

In taking up the specific need for more financial security and possibilities for planning on longer time frames, "The Future Ocean" offered postdocs a range of project-based research opportunities lasting between two and five years. As principal investigators for these projects, postdoctoral researchers had the opportunity to gain independence and develop their individual research profiles. The Cluster, however, also explored possibilities for novel career paths below the professorship level, e.g. a performance-based stepwise shift from a fully non-permanent postdoc position over a partially permanent Junior Research Scientist position to a perma-

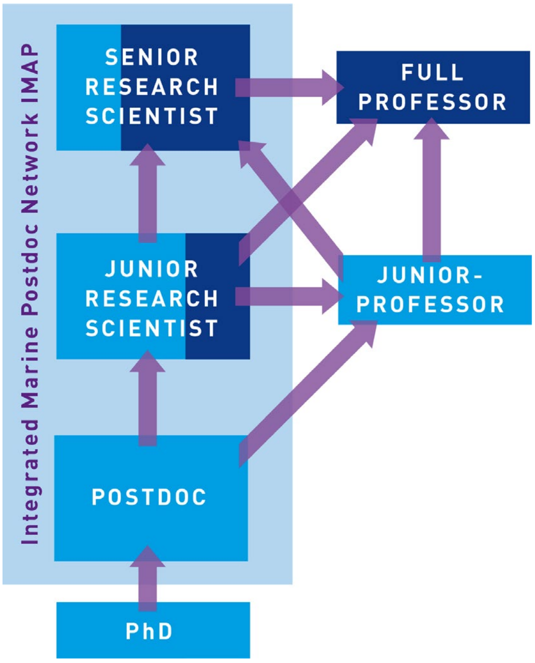

Figure 26: Diagram of possible career paths; light blue depicts temporary positions, dark blue permanent positions or tenure.

nent Senior Research Scientist position (Fig. 26) or permanent researcher positions assigned to interdisciplinary teams and financed through third-party funds.

Junior Research Group Leaders

After the very successful hire of nine junior research group leaders as full professors during Cluster phase I, The Future Ocean was prepared to provide supplemental funding for externally funded junior research group leaders, such as (Helmholtz junior research groups, DFG Emmy Noether fellows, ERC starting grants etc.). These funds were granted as part of the flexible research funds allocation process based on a short and efficient application process. The last tenure track W2 position international law was filled in 2011 (Prof. Dr. Nele Matz-Lück), and given a moderate level of start-up funding equivalent to one postdoc position.

The ISOS graduate school and IMAP network are an integral part of marine sciences and consequently will be continued beyond the second Cluster funding phase. ISOS is also part of the CAU wide graduate center and the ISOS director (Dr. Avan Antia) was tenured at the end of the Cluster phase II. Most recently the IMAP coordinator (Dr. habil. Gesche Braker) was promoted to Director of Postdoc Center of Kiel University. Both ISOS and IMAP are examples how the Cluster spawned CAU wide programmes.

3.1.3 ALUMNI

Both ISOS and IMAP maintain connections with their alumni. They receive commitment and full support from the scientific community, the institutions involved and external partners. Data from these programmes (Fig. 27) allow dynamic responses to be made to participants' needs, as well as to opportunities that may arise such as international exchanges, new career opportunities, and funding options. During the second phase the number of ISOS and IMAP alumni has grown. Some 300 alumni are continuing their careers at research institutions in Germany and abroad, or hold leadership positions in the non-academic sector, further enhancing the Cluster's network. Many former ISOS and IMAP members stay in touch with marine science in Kiel and support the Cluster as role models for future careers, as external reviewers or as members of conference steering committees.

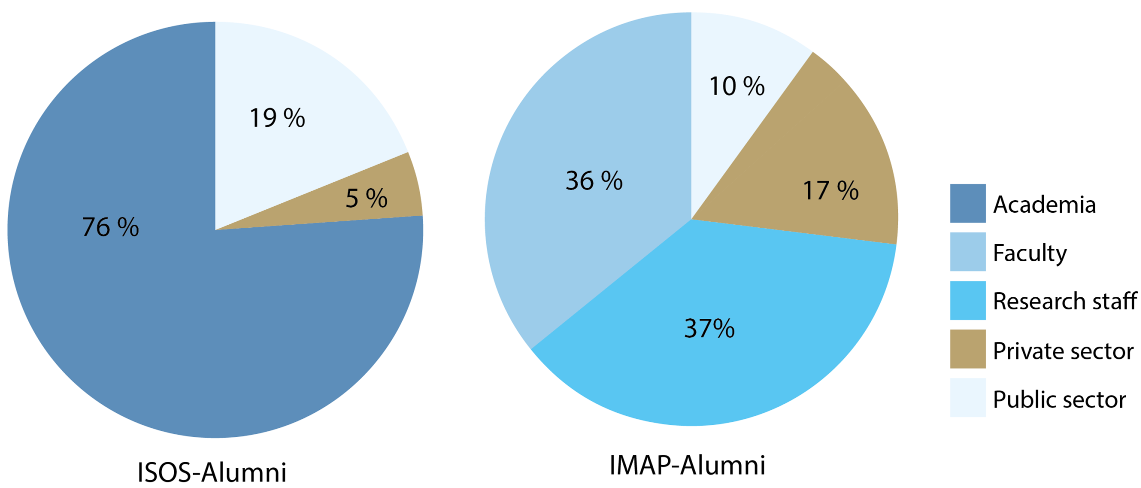

Figure 27: Monitoring the careers of ISOS and IMAP-Alumni allows continuous adaptation of the programmes tot he members' needs.

3.2 PROMOTION OF GENDER EQUALITY

The Cluster established a tradition of dedication to achieving equal opportunity targets from its inception, with constant improvements throughout both phases. Moreover, it has set pioneering milestones that have had an enduring effect on the representation of female scientists in marine science at Kiel University and its partner institutions. A continuing commitment to quantitative gender targets of 50% for junior research group leaders and postdoctoral research positions has led to a significant increase in the number of female professors and researchers in a number of faculties at Kiel University (the Faculty of Mathematics and Natural Sciences, the Faculty of Business, Economics and Social Sciences, and the Faculty of Law), thereby helping to meet the gender targets set by the university and the departments participating in the Cluster. The progress made can be clearly seen from the increased number of female PIs (6% in 2006, 40% in 2017; Fig. 28) and full members of the Cluster "Future Ocean" (10% in 2006, 19% in 2017). These achievements are largely a result of the influence of the university's Gender Equality Commissioner who is endowed with voting rights in the Cluster's executive board and who instigated, in close cooperation with the executive committee, full integration of equal opportunity targets into all recruitment processes, as well as providing strategic advice. Thus, decisions are taken within the Cluster to improve fairness and sensitivity with regard to gender and diversity.

A special measure for gender-equal staff recruitment in the area of early career researchers is the "Postdoc Call", which has been carried out several times in recent years in the cluster Future Ocean. This international recruitment measure for postdoc scientists is based on previously clearly-defined content quality criteria of the projects, an open, transparent, multi-stage selection process with the participation of many expert Cluster members and equality experts, gender competence training for the decision-makers, and an anonymised final selection by the Board. This complex procedure reduces implicit gender bias in the evaluation of scientific performance, so that as a result of the previously-set and consistently-communicated goal, gender parity could be achieved in selection. A university-wide rollout of this measure is planned in the near future.

A Gender Equality Coordinator was also established to act as an interface between the Cluster and the Central Office for Gender Equality, Diversity and Family at Kiel University, and to organize workshops on, e.g., gender awareness, career development, and leadership competencies in cooperation with ISOS and IMAP. It has been the coordinator's responsibility to conduct the "via:mento_ocean" programme, which is a cluster-specific mentoring programme for female postdoctoral researchers from all disciplines within the Cluster aimed at assisting female postdoctoral researchers to successfully continue their careers in academia or other leadership positions (Fig. 29). The career steps following the mentoring programme will be monitored. The programme includes individual counselling and coaching, networking activities, and seminar invitations of prominent female role models in science and is offered in English in order to cater equally to domestic and international researchers.

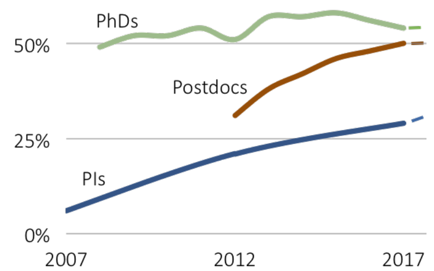

Figure 28: Percentage of women at different career stages in Future Ocean

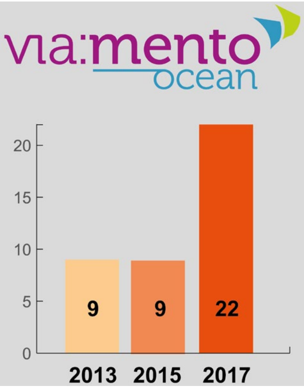

Figure 29: An increasing number of female scientists participate in the monitoring program for female scientists.

via:mento_ocean was highlighted in the DFG toolbox of instruments as an innovative model example of an outstanding equality measure. Continuous recording of gender-specific data, which is published transparently on the Cluster's webpage, is an important aspect of gender equality monitoring and awareness raising within the Cluster.

There is close cooperation between Kiel University and its partner institutions with regard to equal opportunity, in particular in the case of joint appointments, programmes for the advancement of female early career researchers, the professionalization and networking of gender equality commissioners and especially with the "Women's Executive Board" at GEOMAR.

As an institution of learning, the Cluster took part in research and development projects with respect to equal opportunity in its own structures and processes, e.g., in the Kiel (GEOMAR) led EU-H2020 funded project "Baltic Gender". Innovative indicators (e.g. gender of the chief scientist on research cruises) and recommendations developed within this project will also be taken into account in KMS. Two gender equality measures of the Cluster (postdoc-call, via:mento_ocean) have been evaluated in detail in the framework of the EU project "Baltic Gender", and selected as "Best Practice" examples. They have been published as such and recommended for imitation in other national and international institutions. With regard to family-friendliness, the Cluster has provided a number of services (e.g., childcare facilities, childcare during conferences and workshops, and a Family Commissioner) that are available to all members, as well as continuing to supply funding for cluster-financed positions while scientists (both male and female) are on parental leave.

4 STRUCTURES

4.1 ORGANIZATION AND MANAGEMENT OF THE CLUSTER

Organization

The research activities of the Cluster involved seven of the eight CAU faculties (Mathematics and Natural Sciences; Law; Faculty of Engineering; Faculty of Medicine; Business, Economics and Social Sciences; Agricultural and Nutritional Science; Arts and Humanities) and several divisions of the research institutions GEOMAR and IfW, and the MKH. Thus, rather than forming a separate research unit within a particular faculty, the Cluster office and its supporting functions have been implemented within the CAU administration as part of the research and planning division. All Cluster members reside in their respective faculties and research institutions. Since 2009, the CAU has identified four research priority areas (Kiel Marine Science; Kiel Life Science; Kiel Nano Science; and Societal, Environmental and Cultural Change). The cluster of excellecnce “The Future Ocean” is the flagship activity under the Kiel Marine Science (KMS) research priority area.

Management

The Cluster developed an operational framework, which has been approved by the General Member Assembly in 2008. The Cluster framework defined the decision making process, advisory mechanisms, and several core groups (Fig. 30): (i) the General Member Assembly elected the Cluster’s speaker, vice speaker and members of the Executive Committee. It also voted on new full and associate membership applications. The General Member Assembly meets at least once a year. (ii) The Cluster Council is the assembly of the principal investigators, Cluster JRG leaders, and consists currently of 55 members. It advised the Executive Committee on research-related matters, overall budget allocations and met at least twice a year. (iii) The Executive Committee comprised of a number of representatives from the various Cluster research and science support topics and participating institutions, including platforms, graduate school, junior research groups, postdoc network, and PhD students. The Executive Committee met monthly and made all operational, management and funding decisions of the Cluster. (iv) The External Scientific Advisory Board (SAB) comprised of 15 national and international experts. The SAB met in Kiel once a year and provided guidance and advice to the Cluster. The Cluster Council installed several topical advisory panels on a need basis. These were concerned with data management, quality management, gender, graduate education, public outreach, and knowledge transfer.

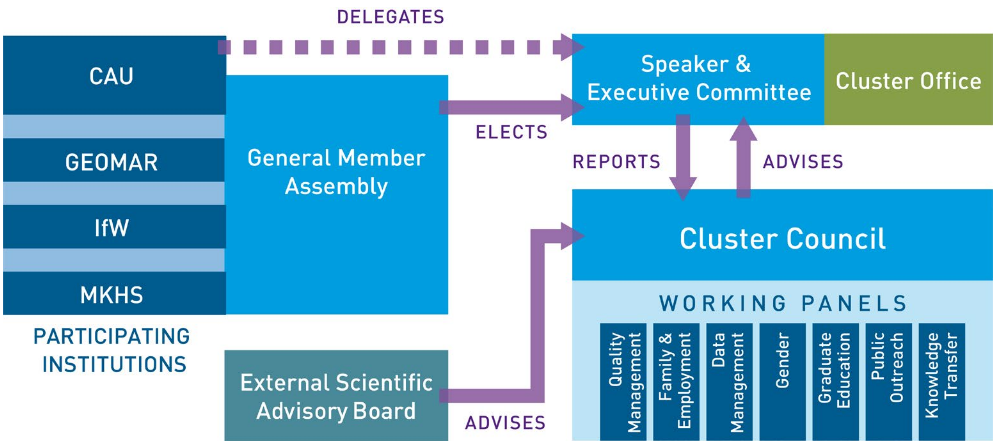

Figure 30: Future Ocean governance and management structures.

As of phase I the Cluster established a Cluster Office to ensure effective cooperation and communication between the participating institutions, executes administrative actions and science support activities. Since 2017 the Cluster has been managed through the Kiel University's "Kiel Marine Science" (KMS) centre, supported by the KMS Office in the Service Centre for Research, IT and Structural Development. The KMS Office ensures effective cluster management, as well as cooperation and communication between participating institutions, the Cluster members and its internal advisory panels and all relevant governing bodies within the university. It handles day-to-day operations and implements the operational framework that defines decision-making and advisory procedures.

Public outreach and engagement

The Cluster has an excellent track record in ocean science communication. We have invested in ocean exhibits as well as print, digital, and social media and benefit from access to communication design and interior design experts at the Muthesius University. Recent highlights of the Clusters outreach activities include: (1) The “Future Ocean Dialogue”, a roving modular exhibition, which was presented internationally in Brazil in the context of the German-Brazilian Year (2014), and had been displayed in Cape Verde (2017 and 2019), addressing the general public, schools and young scientists. (2) Press releases, annual reports, bi-monthly newsletters for Kiel based researchers, international cooperation partners and alumni. (3) A deep website which also serves as interactive ocean knowledge platform, e.g. deep-links ocean knowledge on plastics, a special site for the research report of “The Future Ocean” (https://hr.futureocean.org/) or tailored information for visitors of the exhibition Future Ocean Dialogue. (4) A massive open online course (MOOC) on Ocean Sustainability. (5) The widely recognized World Ocean Review periodical (in German and English), with a worldwide distribution in excess of 150,000 and more than 485.000 page impressions on www.worldocenreview.com, the new Ocean Atlas (published within the context of the Ocean Conference by the United Nations in New York in 2017). Both of the publications are produced with NGOs and aim to inform political decision makers, multipliers in education, students, and the interested public, about marine science and are part of the cluster’s strategy for general ocean literacy.
The cluster concept envisaged enhanced communication, outreach and knowledge exchange activities for specific target groups (e.g. for the general public, political decision makers and stakeholders in the private or public sectors) through thematic assessments, policy briefings or newly designed visual communications media. We successfully implemented innovative formats in Kiel, such as serious games for education and stakeholder engagement (e.g. the fisheries management game “ecoOcean”, a marine spatial planning game for the Arctic) or new visualizations (e.g. interactive digital posters), produced jointly by natural scientists and artists from the Muthesius University and publically honored by the German “Red Dot Award” for communication design. We established and broadened our existing online communications, including our successful “oceanblogs” blog portal, in order to improve our outreach to cross-disciplinary and public audiences.

We increased our involvement of laypeople by means of four citizen science projects: Plankton ID uses volunteers to identify species in automatically-taken photographs. Another project, conducted in collaboration with schools in Germany and Chile, looked at the widespread problem of plastic litter around the coasts. A third asked lay scientists who do Scuba diving to submit photographs of fish, while the fourth requested pictures of the coast to map the occurrence of certain types of landscape feature (www.coastwards.org). Each of these produces unique scientific data and valuable results for the Cluster scientists.

Citizen science projects were first successfully initiated with the support of scientists at the ocean:lab of the Kieler Forschungswerkstatt (Kiel Science Factory). The Kieler Forschungswerkstatt ocean:lab offers school programs, which bring real science to schools and school curricula, and to promote young academics in science. The Kids University, a successful activity for pupils, celebrated its ten-year anniversary at Kiel University in 2017. It attracts about 2500 young visitors from grades 8 to 12 for lectures on marine topics each year. Within the first phase so called "Expedition Boxes" for the topics plastics, climate change, marine chemistry, plankton and benthos were designed to be borrowed from teachers and intending to integrate research-related experiments into the classroom.

Knowledge Transfer

The Cluster engaged in knowledge transfer via a structured approach ranging from the scientific publication of key results, participation in scientific assessments, providing knowledge about marine issues to stakeholders and politics, transfer to application of technological options, and a range of public outreach activities for society at large.

The structured program encompasses knowledge exchange formats that connect its researchers with experts from both the private and the public sectors in order to make accessible knowledge for fact-based decision-making, as well as for future innovation and the development of new technologies. Activities will include issue-based assessment and publications, targeted presentations, exhibitions, and policy briefings. The Kiel-based Kieler Marktplatz program brings together academic research and industry on a regular basis to discuss current state of knowledge and develop joint projects. These activities were supplemented through the Maritime Technology Platform program (MaTeP) that provided a forum to enhance knowledge transfer and the cooperation with European stakeholders from private and public sectors including co-funding for seed projects.

In phase II the Cluster provided both information and support to global research initiatives (e.g. the “Future Earth” initiative, the SCOR, and the IOC), intergovernmental panels, and activities that relate to policy briefings for the UN's 2030 Agenda and SDG 14, EU Integrated maritime policy and other related policies.

Internationalization

The Future Ocean Cluster set up an internationalization strategy, which is mainly based on four distinct activities: institutional partnerships, support for research mobility, an active marketing initiative for Kiel as an excellent research location at conferences, and workshops and proactively maintaining contact with former employees and visitors through an alumni network.

Kiel’s ocean research involves three forms of international collaboration through institutional partnerships. The most important partners are major North American universities, Columbia University in the US and Dalhousie University in Canada. Their partnerships with Kiel work at all levels, from collaboration between PhD students to senior scientists proposing and running substantial research projects cooperatively. A slightly different type of joint working is seen in Kiel’s cooperation with Ocean University of China and Zhejiang University in Hangzhou, China: In 2011, the Center for Sino-German Cooperation in Marine Sciences (SGMS) was founded jointly by the Ocean University of China (OUC) in Qingdao, Kiel University (CAU) and other partners. The SGMS strives to expand cooperation between both countries in the areas of higher education, research and development. Main activities of the SGMS include summer schools and symposia. Kiel also collaborates closely with the marine science excellence cluster LabexMer in Brest, France, which includes the research institute Ifremer and the Université de Bretagne Occidentale, and with the University of Bergen in Norway, including the Bjerknes Center for Climate Research. Kiel's work with these leading institutions involves special partnerships and programmes as well as collaborative working on specific projects. The third type of cooperation is exemplified by Kiel's work with its colleagues at the Instituto Nacionale de Desenvolvimento das Pescas (INDP) in Cape Verde. Kiel marine scientists are involved in joint learning and capacity-building in marine science and related areas with their Cape Verde colleagues. Kiel marine scientists are also helping to build research capacity in South-East Asia. The Future Ocean Cluster is home to one of a dozen UNESCO chairs in Germany, in the field of integrated marine science.

The Future Ocean has supported science mobility by offering travel grants to Cluster members for individual research collaboration and to attend conferences. This measure also enables members to attend conferences beyond their core expertise, offering them a glimpse into other research disciplines, helping them decide whether closer involvement might enhance their own research. The Cluster also organizes and finances joint conferences and workshops with international partners to create opportunities for international collaboration for our scientists.

The Future Ocean has actively promoted its marine research, open positions, funding opportunities, summer schools and workshops, as well as open calls to co-host research proposals at international conferences, exhibitions and workshops. For this purpose it teams up with federal initiatives like Research in Germany, German funding agencies like the DAAD (the German academic exchange network), DFG (Deutsche Forschungsgemeinschaft), AvH (the Alexander von Humboldt Foundation) and with other Clusters of Excellence and research institutes by sharing conference booths and hosting events together). Since 2013 the cluster has been developing a research alumni network, and has organized workshops and conferences with alumni participation (Tab. 4). The goal of this network is to engage former co-workers and friends who know the research environment in Kiel well and are happy to spread the word about the advantages and opportunities.

Table 4: Hosted and organized joint workshops and conferences.

Year/Location	Hosted and organized joint workshops and conferences
2011/Hamburg, 2012/New York, 2013/Lisbon	Conference series organized with the Earth Insitute of Columbia University in cooperation with the Dräger Foundation on "Sustainable Oceans: Reconciling Economic Use and Protection"
2012/Kiel	joint workshops with Dalhousie University
2012/New York	joint workshops with Earth Institute and LDEO at Columbia University
2013/Kiel	Workshop on Capacity Building with Venugopalan Ittekkot (Capacity Building expert, Marum/ZMT)
2014/Brest	Joint workshops and conference with LabexMer on "How to Do Interdisciplinary Marine Research"
2015/Kiel	International Workshop on Ocean Governance and Capacity Building during the Ocean Sustainability Science Symposium

Year/Location	Hosted and organized joint workshops and conferences
2015/New York	Kiel Marine Sciences International Research Alumni Conference with the Earth Insitute (supported by a grant from the Humboldt Foundation)
2016-17/Kiel	Four Kiel Marine Science International Research Alumni Workshops (supported by a grant from the DAAD Alumni Program)
2017/Kiel	International Research Alumni Conference (supported by a grant from the DAAD Alumni Program)
2018/Halifax	Kiel Marine Sciences International Research Alumni Conference on Transdisciplinary Marine Science with Ocean Frontiers of Dalhousie University (supported by a grant from the Humboldt Foundation)

Infrastructure and Data Management

The Cluster provided significant science support infrastructure to Kiel Marine Sciences. The concept of research-specific, but shared research platforms, as implemented in phase I of the Cluster was extended to all priority research areas at the CAU. Several of these infrastructures are shared between more than one CAU research priority areas and respective partner institutions. For the Cluster, both shared research infrastructures and scientific data management efforts continued.

We see data management as means of enabling a full realization of the value of research data by facilitating their accessibility, utilization, and multiple re-use. Internationally open and collaborative data exchange is becoming standard for marine research in general. GEOMAR and Kiel University have established a joint Kiel Data Management Infrastructure (KDMI) to make the most of their institutional capabilities and resources for this task. Kiel University has been contributing to the technical infrastructure of the KDMI since 2009, as well as to its personnel. Expanding beyond the field of marine research, Kiel University has established a network of discipline-specific data managers in its four priority research areas and invested in joint data management facilities that are continually improved in order to meet data management requirements, both within and across disciplines. Since 2011 an expert panel from Kiel University and its partner institutions in Kiel has served as a discussion and steering group for research data management (RDM) projects and activities. This group develops recommendations and policies for joint activities, aiming to create a data-driven environment to deal with the scientific challenges that arise from sampling, data creation, documentation, and analysis, through to publication, re-use, and the provision of open access regardless of the affiliation of researchers or the location of the laboratory facilities within Kiel. In 2015 Kiel University (which was one of the first universities in Germany) published a general research data policy and GEOMAR research units started setting up procedures for handling research data under this policy. The KDMI encompasses the Ocean Science Information System (OSIS) as a central information hub for collaboration and data exchange. The OSIS connects research activities such as expeditions, experiments and simulations, to publications, as well as tracking the storage locations for any resulting data and data versioning. Expanding the OSIS network through links to discipline repositories, wikis, versioning tools, image annotation tools, or digital notebooks, enables comprehensive documentation capabilities. International interoperability within the global marine science community has been implemented through the use of persistent identifiers (PIDs) and recommendations from organizations such as the Research Data Alliance or the Ocean Data Interoperability Platform.

4.2 RELATIONSHIP BETWEEN THE CLUSTER, THE HOST UNIVERSITY AND THE PARTICIPATING PARTNERS

The Cluster is a joint activity by four participating institutions: Kiel University (CAU), the GEOMAR Helmholtz Centre for Ocean Research Kiel, the Kiel Institute for the World Economy (IfW) and the Muthesius University of Fine Arts and Design (MKH).

The Cluster is hosted by the CAU, however the Cluster Executive Committee has representation from each of the four participating institutions. Once a year, a high level meeting between the Presidents and Directors of the participating institutions took place to discuss the Cluster's progress, concerns and future ambitions.

The CAU and GEOMAR are the two largest partners and have developed a legal and financial framework for all Cluster matters, including provisions for overhead allocations. They have provided arrangements for shared infrastructure, such as in the areas of high end scientific computing, analytical capabilities, and access to local research vessels and library services. For all of its partners, the Cluster has created the unique opportunity of integrating basic research in marine natural and environmental sciences with fundamental research in applied mathematics, chemistry, biology, life sciences, and combining those with the legal, economic, social, political and ethical dimension. Finally, the Cluster supports a wide range of outreach and knowledge transfer activities and benefits tremendously from the input provided by communication experts. The participating institutes are very satisfied with the results of the Cluster's cross-institution collaboration from the first funding phase and continued in the second phase. Consequently, the CAU has defined Kiel Marine Sciences (KMS) as one of its four research priority areas.

In 2011, the first steps towards the establishment of a research alliance of interdisciplinary marine sciences were taken. The alliance continued to grow during the Cluster phase II with two more institutions joining in: the Leibniz Information Centre for Economics (ZBW) and the The Leibniz Institute for Science and Mathematics Education (IPN). It currently involves a partnership of now six institutions led by the KMS research centre at Kiel University. The alliance is embedded in the larger framwork of the Schleswig-Holstein Alliance for Excellent Research, which is a cooperation of two leading research universities and eleven non-university research institutions in Schleswig-Holstein. Together to support interdisciplinary and transdisciplinary research as well as building a dual-career-track network, fostering mutually accessible research platforms and dedicating think-tanks to issues in politics, commerce and society.

4.3 SUSTAINABILITY

The projects funded through the Excellence Initiative catalysed research in the priority areas through structural units and decision-making processes within the university as a whole. In 2012 the Kiel Marine Science Centre for Interdisciplinary Marine Science (KMS) was established as a cross-faculty institution to coordinate the university's main area of research in marine science. The KMS head office (with four tenured members of staff) is embedded in the "Research, IT and Strategic Innovation" Service Centre, a subordinate department of the President's University Board. Moreover, the speaker is a member of the University's Standing Committee (Wissenschaftskommission), which consists of the University Board, the Deans of the eight faculties, and the speakers for the four priority research areas, of which KMS is one. The KMS centre is therefore an integral component of the central administration and a stakeholder within the academic self-government (akademische Selbstverwaltung). In addition to the establishment of KMS the “Future Ocean“ cluster provided a hub and a role model for many cross-cutting activities at the University, most notably in the fields of education and reliable early career support. Education formats for schoolchildren, initially developed within the “Future Ocean“ cluster, formed the nucleus for the foundation of the school laboratory Kieler Forschungswerkstatt, which now offers a broad range of activities, including training for teachers. At the academic level, the ISOS and IMAP programs, initiated under the “Future Ocean“ cluster, have not only provided a template for advanced support of graduates and early stage researchers, but also initiated the foundation of the Graduate Centre at the University. A major impact of the “Future Ocean” cluster on Kiel University has been the successful implementation of tenure-track appointments for professorships as a new career path, which was a direct result of the establishment of tenured junior professorships during the first phase of the cluster.

During the last seven years, the Kiel University has made tremendous efforts (for what is only a medium-sized university), to attract and retain distinguished researchers in marine science and to strengthen research in this priority area across all eight faculties. Following the first phase of the “Future Ocean” cluster, eight assistant professors were tenured in the faculties of Mathematics & Natural Sciences (G. Friedrichs, B. Schneider, T. Slawig, and A. Vafeidis), Law (N. Matz-Lück), Business, Economics & Social Sciences (M. Quaas and K. Rehdanz) and Medicine (P. Rosenstiel). Kiel University also established four new additional marine-oriented professorships in the faculties of Mathematics & Natural Sciences (S. Krastel and T. Dagan), the Faculty of Philosophy (K. Ott), and the Faculty of Agricultural and Nutritional Sciences (C. Schulz). The University further identified, on the basis of a strategic process, areas in which it lacked expertise and successfully applied for two new fixed-term professorships funded through structural and development funds from State of Schleswig-Holstein (2017), these being in social science (S. Klepp) and marine political science (A. Mondré) and will establish a new full professorship Political Economy of Marine and Coastal Resource Management in 2019. The University further competed successfully with highly attractive offers from other universities and nonuniversity research institutions to retain key professorships (R. Schmitz-Streit (2016), K. Rehdanz (2016), W. Hasselbring (2015), M. Quaas (2015), A. Scherp (2015), R. Schneider (2012)). Finally, the University tenured six academic mid-level faculty positions to strengthen cornerstone professorships and the quality of teaching. Marine science also benefit greatly from joint appointments with non-university partner institutions. GEOMAR also tenured two assistant professorships from the initial phase of the “Future Ocean“ cluster (L. Rüpke, T. Treude, now at UCLA – University of California, USA).

5 OVERVIEW OF THE CLUSTER'S RECOURCES

5.1 RESOURCES

5.1.1 STAFF

Table 5: Staff

	Number of persons **funded by the Cluster ***			Number of persons **funded by other sources***		
Academic staff	**f**	**m**	**total**	**f**	**m**	**total**
Professors (W2-W3)	2	6	8	27	119	146
Professors (W1)	3	4	7	0	0	0
(Junior) group leaders	0	0	0	4	1	5
Postdocs (including temporary substitute positions for clinicians)	55	70	125	95	129	224
Doctoral researchers	38	35	73	47	34	81
Research associates/other academic staff	4	1	5	6	3	9
Guest researchers	0	0	0	7	11	18
Non-academic staff	26	10	36	9	5	14

* Individuals are counted in both funding categories when their position funding changed over the project period (2006-2019).

5.1.2 INFRASTRUCTURE

Table 6: Major infrastructure measures since the Cluster's set-up

Infrastructure measure	Year of purchase	Costs (€K)	Funded by
Gas Chromatograph Agilent 6890N	2006	179	CAU
NewWave Laser-Ablation System	2006	280	CAU
Spectrometer 600 MHZ NMR	2006	278	CAU
ICR-Mass Spectrometer	2006	689	CAU
Mass Spectrometer	2006	400	CAU
Electron MicroscopeTecnai	2006	870	CAU
Transfection-Robot	2006	179	CAU
Next Generation Sequenzer Solid (ABI)	2006	522	CAU
High Throughput Pipetting Instrument & Upgrades	2006/07	617	CAU
CAP DNA Analyzer	2007	206	CAU
Avatech XRF Core Scanner	2007	280	CAU
Vector. Network Analyzer	2007	345	CAU
FS -Laser System	2007	354	CAU
Periphery for Spectrometer 600 MHZ NMR	2008	171	CAU
Periphery for Electron MicroscopeTecnai	2008	179	CAU
Reflected Light Microscope LSM 700	2008	164	CAU
X-ray Diffraction Instrument	2008	400	CAU
X-ray Micro-Tomography System Skyscan	2008	286	CAU
Storage Virtualization	2008	150	CAU
Disk Storage	2008	152	CAU
Spectrometer System EPR	2009	186	CAU
Femtosecond Spectrometer	2009	461	CAU
Laboratory Press 1000 t	2009	175	CAU
Laser-Microdissection Workplace	2009	265	CAU
Computer-Cluster	2009/10	205	CAU
Laser-Scanning Microscope FV1000	2010	400	CAU
Dye Laser	2011	173	CAU

Infrastructure measure	Year of purchase	Costs (€K)	Funded by
Micro-X-Ray-Computer Tomography System	2012	254	CAU
Fluorescence Microscope	2012	178	CAU
IR-OPO-Laser	2012	223	CAU
High-Content Imaging System	2013	326	CAU
ICP-Sector Field Mass Spectrometer	2013	390	CAU
Lab Instrumentation (Microbiology)	2013	160	CAU
Storage Virtualization	2013	236	CAU
Lab Instrumentation (Triaxial Pressure Device)	2014	264	CAU
Streamer	2015	380	CAU
Gas Isotope Mass Spectrometer	2015	450	CAU
Seismic Array	2016	237	CAU
Coastal Research Vessel "Egidora"	2017	1039	CAU
Lab Instumentation (Botany)	2018	375	CAU
Rock Eval Analysator	2018	249	CAU
Confocal Laserscanning Microscope	2018	700	CAU
Virtualized Datacenter	2018	488	CAU
Server & Storage Infrastructure	2018	245	CAU
9 Gliders	2006-10	700	Participating Institutions
Submersible JAGO	2006	1800	Participating Institutions
JEOL JXA -8200 Microprobe / EMS	2006	631	Participating Institutions
HS M-System (V440, L500, SA M-FS)	2006	170	Participating Institutions
Upgrade Baruna Jaya 4	2006	495	Participating Institutions
Nu Plasma HR MC-ICP-MS	2007	647	Participating Institutions
AX IOM System: Accessories /Laser	2007	178	Participating Institutions
Fermentation Equipment 63206	2007	170	Participating Institutions
2 Tracer Injection Sied	2007	174	Participating Institutions
TV-Grab	2007	693	Participating Institutions
Mass Spectrometer MAT 253	2008	415	Participating Institutions
HPLC-System Hitachi + micrOTOF	2008	320	Participating Institutions

Infrastructure measure	Year of purchase	Costs (€K)	Funded by
AttoM HR-ICP-MS	2008	265	Participating Institutions
T-Connector for Streamer Systems	2008	189	Participating Institutions
Hydrophonknoten	2008	237	Participating Institutions
Pressure Pipes	2008	165	Participating Institutions
GeoLasPro Laser-Ablation System	2009	243	Participating Institutions
Avance III Spectrometer	2009	964	Participating Institutions
HATLA PA Mobile Winch	2009	176	Participating Institutions
LADCP System	2010	201	Participating Institutions
Master Lander Modul (LML)	2010	254	Participating Institutions
Anchorage Module (VKM) (MOLA B)	2010	166	Participating Institutions
Video Setting Frame (VAR)	2010	207	Participating Institutions
ROV: Deep Sea Robot Kiel6000	2010	3596	Participating Institutions
Launch and Recovery System/LA RS	2010	239	Participating Institutions
Deep Sea Winch (ROV)	2010	1012	Participating Institutions
Submersible JAGO	2010	496	Participating Institutions
Mesocosm System	2011	173	Participating Institutions
NMR Small Pressure Chamber	2011	567	Participating Institutions
Sediment Echo Sounder SES 2000	2011	202	Participating Institutions
Medium Size Work-Class ROV PHOCA	2011	1189	Participating Institutions
GEOSEA system incl. Wave Glider	2013	2248	Participating Institutions
Triton "TIMS" (mass spectrometry)	2014	542	Participating Institutions
Deep-sea crawler "VIATOR"	2014	270	Participating Institutions
Q-Exactive "ESI-MS" (mass spectrometry)	2015	300	Participating Institutions
"MC-ICP-MS" NEPTUNE (mass spectrometry)	2015	630	Participating Institutions
"N-GMS" HELIX equipment	2015	435	Participating Institutions
"HR-ICP-MS" ELEMENT XR equipment	2015	281	Participating Institutions
UHPLC system (high performance liquid chromatog-raphy)	2015	405	Participating Institutions
NEPTUNE (mass spectrometry)	2016	389	Participating Institutions
Wave Glider "SV3 LR-1000"	2016	210	Participating Institutions

Infrastructure measure	Year of purchase	Costs (€K)	Funded by
Ceel Sorting Unit "Astrios"	2017	449	Participating Institutions
Wave Glider Liquid Robotics	2017	243	Participating Institutions
AUV "Aegir" (Autonomous Underwater Vehicle)	2017	210	Participating Institutions
Lander MOSES	2017	183	Participating Institutions
Glider "G3 Slocum"	2018	227	Participating Institutions
LWL- Telemetry	2018	156	Participating Institutions
Arena2 - Visualization Laboratory	2018	298	Participating Institutions
AUV "Girona 500" (Autonomous Underwater Vehicle)	2019	724	Participating Institutions

Table 7: Major research equipment provided by the Cluster's set-up

Infrastructure measure	Year of purchase	Amount [€k]
Major research equipment (exceeding €150,000 per item)		
Bio-Interaction Analysis-Instrument Biacore X100	2007	168
Capillary Sequenzer 3730-XL (Applera)	2007	343
2 Isotope Mass Spectrometers: Finnigan MAT 253 1 Carboprep and 1 GC with IRMS Interface	2007	857
Confocal Laser-Scanning Microscope Leica TCS SP5 AO BS	2007	399
CETA C Technologies Beam Delivery	2007	150
SX -8 System (Addition vector computer)	2007	370
Qiagen Robot BR 8000	2008	150
AGILENT Quadrupole ICP-MS	2008	176
193 nm Excimer Laser Ablation	2008	253
2-D Streamer	2008	319
IR-OPO-Laser für IR Lasersystem	2013	223,3
Total [€k]		**3408,3**

5.2 EXPENDITURES

Table 8: Cluster expenditures

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Sum
	in €k												
Professors (W2-W3)	11	113	676	740	644	629	786	270	270	246	217	126	**4728**
Professors (W1)*	-	-	-	-	-	-	-	-	-	-	-	-	**-**
Post-doc & doctoral researchers	-	752	1874	2801	2998	1891	2292	3586	3573	2890	3169	3220	**33237**
Other staff	5	292	678	597	729	782	564	446	508	514	510	486	**6663**
Sum (staff)	**16**	**1157**	**3228**	**4138**	**4371**	**3302**	**3642**	**4302**	**4351**	**3650**	**3896**	**3832**	**44627**
Research equipment [2)]	198	5608	681	336	94	54	753	783	1116	276	481	422	**11264**
Other costs [3)]	242	706	1634	1400	1389	749	664	900	857	1098	1503	1062	**13521**
Total [€k]	**456**	**7471**	**5543**	**5874**	**5854**	**4105**	**5059**	**5985**	**6324**	**5024**	**5880**	**5316**	**69412**

[1)] Including fellowships

[2)] > €10,000 per item

[3)] Including minor research equipment (< €10,000 per item)

6 COMMENTS TO THE DFG

No comments.

7 APPENDIX A (Non-Confidential)

7.1 100 MOST IMPORTANT PUBLICATIONS OF THE CLUSTER

Arevalo-Martínez D. L., Kock A., Löscher C., Schmitz R. A., Bange H. W. (2015): Massive nitrous oxide emissions from the tropical South Pacific Ocean. Nature Geoscience 8, 530-533. DOI: 10.1038/ngeo2469.

Bach, L. T., Lohbeck, K. T., Reusch, T. B. H. and Riebesell, U. (2018) Rapid evolution of highly variable competitive abilities in a key phytoplankton species. Nature Ecology & Evolution, 2 pp. 611-613. DOI:10.1038/s41559-018-0474-x.

Baumgärtner, S., Quaas, M.F. (2010) What is sustainability economics? Ecol. Econ. 69, 445 – 450. http://dx.doi.org/10.1016/j.ecolecon.2009.11.019.

Beal, L. M., De Ruijter, W. P. M., Biastoch, A., Zahn, R., Cronin, M., Hermes, J., Lutjeharms, J., Quartly, G., Tozuka, T., Baker-Yeboah, S., Bornman, T., Cipollini, P., Dijkstra, H., Hall, I., Park, W., Peeters, F., Penven, P., Ridderinkhof, H. und Zinke, J. and SCOR/ WCRP/IAPSOWorking Group 136 (2011) On the role of the Agulhas system in ocean circulation and climate. Nature, 472 (7344). pp. 429-436. DOI 10.1038/nature09983.

Becker M., Andersen N., Fiedler B., Fietzek P., Körtzinger A., Steinhoff T., Friedrichs G. (2012): Using cavity ringdown spectroscopy for continuous monitoring of $\delta^{13}C$ (CO_2) and fCO_2 in the surface ocean. Limnology and Oceanography: Methods 10, 752-766. DOI: 10.4319/lom.2012.10.752.

Bergen, B., Endres, S., Engel, A., Zark, M., Dittmar, T., Sommer, U. und Jürgens, K. (2016): Acidification and warming affect prominent bacteria in two seasonal phytoplankton bloom mesocosms. Environmental Microbiology 18, 4579-4595. DOI: 10.1111/1462-2920.13549.

Berndt, C., Feseker, T., Treude, T., Krastel, S., Liebetrau, V., Niemann, H., Bertics, V. J., Dumke, I., Dünnbier, K., Ferre, B., Graves, C., Gross, F., Hissmann, K., Hühnerbach, V., Krause, S., Lieser, K., Schauer, J. und Steinle, L. (2014) Temporal Constraints on Hydrate-Controlled Methane Seepage off Svalbard. Science, 343 (6168). pp. 284-287. DOI 10.1126/science.1246298.

Biastoch, A., Treude, T., Rüpke, L. H., Riebesell, U., Roth, C., Burwicz, E. B., Park, W., Latif, M., Böning, C. W., Madec, G. und Wallmann, K. (2011) Rising Arctic Ocean temperatures cause gas hydrate destabilization and ocean acidification. Geophysical Research Letters, 38 (8). L08602. DOI 10.1029/2011GL047222.

Biastoch, A., Durgadoo, J. V., Morrison, A. K., van Sebille, E., Weijer, W. und Griffies, S. M. (2015) Atlantic multi-decadal oscillation covaries with Agulhas leakage. Nature Communications, 6 (10082). DOI 10.1038/ncomms10082.

Biastoch, A., Treude, T., Rüpke, L.H., Riebesell, U., Roth, C., Burwicz, E.B., Park, W., Latif, M., Böning, C.W., Madec, G., Wallmann, K. (2011) Rising Arctic Ocean temperatures cause gas hydrate destabilization and ocean acidification. Geophys. Res. Lett. 38, L08602, https://doi.org/10.1029/2011GL047222DOI: 10.1029/2011GL047222.

Boetius A. and Haeckel M. (2018) Mind the seafloor, Science, Vol. 359, Issue 6371, pp. 34-36. DOI 10.1126/science.aap7301.

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7.2 ADDITIONAL ACHIEVEMENTS

Awards

Briski, E. 2014-2019 Alexander von Humboldt Stiftung; Sofja Kovalevskaja-Preis
Do Ponto-Caspian species have inherent advantages over Northern European or Great Lake-St. Lawrence River species in colonizing new areas?

The main objectives of the Alexander von Humboldt Sofja Kovalevskaja Award study is to determine if Ponto-Caspian species have inherent advantages over Northern European or Great Lakes' species in colonizing new areas and if they are capable to spread from brackish estuaries of Northern Europe to marine environments of the North and Baltic Seas.

Dagan, T. 2012-2018 ERC-Starting Grant (European Research Council)
EVOLATERAL (The mechanisms for lateral gene transfer in nature as reflected in prokaryote genomes)

The ERC-Starting Grant EVOLATERAL aims to quantify the contribution of lateral gene transfer mechanisms to bacterial genome evolution.

Gutekunst, K. 2017-2022 BMBF-Research Award (Forschungspreis: „Maximierung der Wasserstoffproduktion in Cyanobakterien in vivo")

The Grant supports a study with the aim to maximize the hydrogen production of a cyanobacterium that uses electrons from the photosynthetic electron transfer chain to reduce protons to hydrogen. Hydrogen is a promising energy carrier, as it can react in fuel cells with oxygen to pure water yielding a high amount of energy.

Hoving, H-J. 2017-2022 Emmy Noether grant: The role of pelagic foodfalls in subsidizing deep-sea bottom communities in a changing ocean

The Emmy Noether Research group Deep Sea Biology of H.-J. Hoving studies the role of large organisms such as squid & large gelatinous plankton for the biological carbon pump, how this subsidizes life at the ocean floor & how this may change in a warmer and less oxygenated ocean.

Klepp, S. 2012-2017 Fellow of the German Young Academy of Scientists (Die Junge Akademie), now Alumna

The fellowship provides interdisciplinary & socially relevant spaces for outstanding young academics to work in interdisciplinary research groups and at the intersection of academia and society.

Marandino, C. 2012-2016 Helmholtz Young Investigator Group (Helmholtz Association)
Trace gas air-sea exchange using eddy correlation

Within the Helmholtz Young Investigator Group TRASE-EC, rare open ocean direct flux measurement systems were successfully developed. These systems can measure a range of climate active trace gas air-sea fluxes, including those of carbon dioxide and dimethylsulphide.

Oschlies, A. 2011 Georg Wüst Prize – To Honor Outstanding Ocean Researchers

Andreas Oschlies received the Georg Wüst Prize for his outstanding contributions to oceanic research, addressing the oceanic carbon uptake and its climate sensitivity by means of physical, biogeochemical and ecological modelling.

Riebesell, U. 2012-2019 Gottfried Wilhelm Leibniz Prize of the German Research Foundation

U. Riebesell was awarded for his research on ocean change, one of the most wide-reaching side effects & consequences of anthropogenic climate change & in particular his ground breaking work on ocean acidification.

Riebesell, U. 2017-2021 ERC-Advanced Grant (European Research Council, HORIZON 2020)
"Ocean artificial upwelling" (Ocean artUp)

Ocean artUp aims to study the feasibility, effectiveness, associated risks and potential side effects of artificial upwelling in increasing ocean productivity, raising fish production, and enhancing oceanic CO_2 sequestration.

Roth, O. 2017-2022 ERC-Starting Grant "Male pregnancy – unravelling the coevolution of parental investment and immune defence" (MALEPREG)

The ERC Starting Grant MALEPREG investigates how rearrangements of the immune system and shifts in microbiota coevolved with the unique male pregnancy in pipefishes and seahorses. It sheds light on a particular adaptation to life in the ocean and strengthens the Cluster´s effort towards animal health and infectious disease ecology.

Schmidt, J.	2018 – 2021 UNESCO Chair in Integrated Marine Sciences		

Jörn Schmidt, a fisheries biologist at Kiel University now shares the UNESCO Chair for Integrated Marine Sciences with Arne Körtzinger (GEOMAR) following an appointment by the UNESCO. Therefore, Kiel retains one of only twelve UNESCO Chair in Germany. The UNESCO awards these chairs to strengthen international relationships and promote young scientists in emerging and developing countries. Dr Jörn Schmidt addresses issues such as socio-ecological systems and concepts of sustainability of the ocean, fisheries management and science communication. He has worked intensively in several West African countries, specifically in Senegal, Cape Verde and Nigeria and South America, especially in Brazil and Peru.

Scholz, F.	2016-2021	Emmy Noether Grant ICONOX - Iron cycling in continental margin sediments and the nutrient and oxygen balance of the ocean

The ICONOX research group conducts sea-going research, laboratory experiments and numerical modelling to evaluate a novel concept of how changes in sedimentary iron burial and release modulate the ocean's nutrient and oxygen balance at present and through geologic time.

Tegtmeier, S.	2015-2020	Emmy Noether Grant AVeSH - A New Threat to the Stratospheric Ozone Layer from Anthropogenic Very Short-lived Halocarbons

The interdisciplinary research proposal will enable the answer to the emerging question if anthropogenic activities in marine and oceanic environments will pose a new threat to the stratospheric ozone layer recovery.

Visbeck, M.	2015	Elected fellow of the American Geophysical Union (AGU)

Martin Visbeck has been elected as AGU fellow "for outstanding contributions to ocean circulation and mixing and the role of the oceans in climate."

Visbeck, M.	2018	EPG member of UN Decade of Ocean Science for Sustainable Development

Martin Visbeck was selected to joint the 18 member high level Executive Planning Group for the UN Decade of Ocean Science for Sustainable Development (2021-2030)

Visbeck, M.	2019	Henry Stommel Medal (AMS) and AMS (American Meteorological Society) Fellow

Martin Visbeck was awarded the Henry Stommel Research Medal "For outstanding contributions to understanding ocean circulation and mixing, and the role of the oceans in climate" and was elected Fellow of the AMS.

Visbeck, M.	2019	President of The Oceanography Society (TOS)

The Oceanography Society (TOS) was founded in 1988 to advance oceanographic research, technology, and education, and to disseminate knowledge of oceanography and its application through research and education. TOS promotes the broad understanding of oceanography, facilitates consensus building across all the disciplines of the field, and informs the public about ocean research, innovative technology, and educational opportunities throughout the spectrum of oceanographic inquiry.

Distinguished Functions / Leading positions in Committees

Behrmann, J. 2015-2018 ECORD (European Consortium for Ocean Research Drilling) Science Support & Advisory Committee

ESSAC is the Science Committee of ECORD and responsible for the scientific planning and coordination of ECORD's contribution to and participation in IODP (Integrated Ocean Drilling Program). 2016-2017 the ESSAC Office was managed by Jan Behrmann at GEOMAR and he was the Vice-Chair from January to December 2018.

Engel, A. 2012-2017 Member, Scientific Steering Committee of SOLAS (Surface Ocean Lower Atmosphere Study)

Based on her expertise on biological-physical interactions & feedbacks between the ocean and atmosphere and research on their role in the regulation of climate and global change, A. Engel has been appointed as a scientific advisor for SOLAS theme 2 'Air-sea interface and fluxes of mass and energy', since 2017 leader of implementation team theme 2.

Hasselbring, W. Since 2013 Scientific head of the User Group "Software architecture and Software Development"

At Softwareforen Leipzig, launched in 2008 as a spin-off of the University of Leipzig, W. Hasselbring is the technical director of the User Group "Software Architecture and Software Development" in advanced education.

Hentschel-Humeida, U. 2017(2019) Vice-Chair of the Gordon Research Conference "Animal-Microbe Symbioses"

The expertise of Ute Hentschel-Humeida on understanding the physiology, metabolism and molecular mechanisms of interaction between marine animals and their microbial habitants resulted in her nomination to act as Vice-chair in 2017 and Chair in 2019 of a prestigious Gordon Research Conference (USA) with about 170 international attendees from the life sciences.

Klepp, S. Since 2017 Member of the Rat für Migration (RfM, German council for migration)

Silja Klepp was invited as a member of the German Council for Migration (RfM) because of her expertise on environmental migration within the European Borders. The Council is a nationwide association of about 150 scientists from various disciplines with research foci on issues of global migration and integration. Its central task is to critically support political decisions and public debates on migration, integration and asylum.

Körtzinger, A. 2018-2021 UNESCO Chair in Integrated Marine Sciences

The UNESCO awards these chairs to strengthen international relationships and promote young scientists in emerging and developing countries. The Chair interacts with the Executive Secretary of IOC-UNESCO on the planning of the UN Decade of Ocean Science for Sustainable Development (2021-2030). Arne Körtzinger is the Head of the OSCM and CVOO – major infrastructures in support international marine research for young scientists from Cape Verde and the West African region. The focus of research and education is on global change on the marine realm.

Kopp, H. Since 2019 President German Geophysical Society (DGG)

Heidrun Kopp was elected as the first female president of the DGG based on her scientific reputation and engagement in the research of ocean floor dynamics and associated geological hazards. The DGG has more than 1.200 members in over 30 countries. It represents the German geophysical community at national and international levels, with a formative impact on industry and political stakeholders and geoscience education.

Matz-Lück, N. Since 2018 Chair of the Board of Directors of the International Foundation for the Law of the Sea

The International Foundation for the Law of the Sea, in close cooperation with the International Tribunal for the Law of the Sea, regularly organizes events to bring together scientific expertise and perspectives by practitioners on ocean matters. As the Chair of the Board Nele Matz-Lück is responsible for strategic decision-making and cooperation with other institutions.

Ott, K. 2000-2008 Member of the German Advisory Council on the Environment (SRU)

During eight years of membership in the German Advisory Council on the Environment (SRU) as expert on environmental ethics, Konrad Ott intensified his research on sustainability theories focusing on marine issues leading to a “SRU Special Report Marine Environment – Protection for the North and Baltic Seas".

Oschlies, A. Since 2016 Founding member of the UNECSO/IOC Global Ocean Oxygen Network (GO_2NE)

With his expertise on integrated research on ocean carbon uptake Andreas Oschlies acted as the German founding member of the international Global Ocean Oxygen Network GO_2NE, a working group established by UNESCO’s Intergovernmental Oceanographic Commission (IOC) in 2016. It is committed to providing a global and multidisciplinary view of recent deoxygenation, with a focus on understanding its multiple aspects and impacts. This scientific network offers advice to policy makers to counter this concerning trend and to preserve marine resources in the presence of deoxygenation.

Peters, I. 2015-2017 Member of the Expert Group on Next Generation Altmetrics initiated by the European Commission

The Expert Group on Altmetrics has outlined how to advance a next-generation metrics in the context of Open Science and has advised policies on the Open Science Agenda: fostering Open Science, removing barriers to Open Science, developing research infrastructures and embed Open Science in society. The Cluster can exploit this work for measuring the success of open science and transdisciplinary activities.

Peters, I. Since 2017 Mentor in Open Science Fellowship Program (Wikimedia e.V.)

The Open Science Fellows Program is a joint project of Wikimedia Deutschland, the Stifterverband, and the Volkswagen Foundation. It is aimed at doctoral students, post-docs, and junior professors who want to promote their research in an open manner.

Quaas, M. 2014-2016 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), expert and CLA

IPBES is the intergovernmental body which assesses the state of biodiversity and of the ecosystem services it provides to society. Martin Quaas has been asked to join their expert panel. The preliminary guide on diverse conceptualizations of values of nature has been an influential input to all thematic assessments of IPBES.

Rehdanz, K. 2014 – 2016 Member of Science Steering Committee of IMBER

In the last few years the Future Earth IMBER (Integrated Marine Biosphere Research) project developed new areas of relevant research, focussing ever more on the integration of marine and human systems.

Reusch, T. since 2015 Member of German Academy of Sciences (Leopoldina); committee on environmental issues ("Wissenschaftliche Kommission Umwelt")

Schmitz-Streit, R. 2015 Chair of the Gordon Research Conference “Archaea”

Prestigious conference with a long history and a strong reputation for high-quality and cutting edge research in the field of archaea including numerous marine archaea.

Schmitz-Streit, R. Since 2017 President of the Association for General and Applied Microbiology (VAAM – Vereinigung für Allgemeine und Angewandte Mikrobiologie)

VAAM is representing all microbiologists in Germany (marine, applied and soil microbiologists) thus impacting statements, advices for German microbiologists and education in microbiology, including marine microbiology involved in dialogs with stakeholders and industry.

Schneider, R.	since 2017	Member European Marine Board

The European Marine Board (EMB) is a unique strategic pan-European forum for ocean research and technology. Aims are to share knowledge, identify common priorities, scientific challenges and opportunities through analysis and studies, develop common positions and provide high-level recommendations for European and national research funders and policymakers as well as the scientific community. It connects to stakeholders from the marine and maritime communities, European research networks, as well as from policy and the private sector.

Schneider, R.	Since 2006	Executive Director, IMAGES, The Marine Past Global Change Program (PAGES), Core Project of IGPB/Future Earth

Leader of an international organization planning and executing drilling of marine sediments as archives for climate change and documentation of marine hazards.

Visbeck, M.	Since 2012	Member, Leadership Council of the SDSN (Sustainable Development Solutions Network) International and Germany.

The UN Sustainable Development Solutions Network (SDSN) has been operating since 2012 under the auspices of the UN Secretary-General. SDSN mobilizes global scientific and technological expertise to promote practical solutions for sustainable development, including the implementation of the Sustainable Development Goals (SDGs) and the Paris Climate Agreement. SDSN aims to accelerate joint learning and promote integrated approaches that address the interconnected economic, social, and environmental challenges confronting the world. SDSN works closely with United Nations agencies, multilateral financing institutions, the private sector, and civil society. The German Sustainable Development Solutions Network (SDSN Germany) was founded in April 2014 by leading German knowledge centres. The network pools knowledge, experience and capacities of German academic, corporate and civil society organizations in order to contribute to the sustainable development of Germany as well as to German efforts for sustainable development across the globe. The Ocean Massive Open Online Course has been published in cooperation with the SDG-Academy an SDSN-platform.

Visbeck, M.	2013 - 2018	Chair of the German Future Earth and WCRP committee (Deutschen Komitees für Nachhaltigkeitsforschung in Future Earth)

The German Committee Future Earth acts as the national representative for international relationships, developments and activities within the international research programs Future Earth and WCRP. On a national level, the DKN Future Earth provides support for interdisciplinary and integrated research and for the identification of relevant research topics within a national as well as international context. In this regard, the DKN Future Earth encourages the collaboration between natural and social sciences, the humanities and engineering to advance research activities that help shape the pathways for a global sustainable society, to find a systematic approach for problems and to generate societal relevant knowledge. Moreover, the German Committee Future Earth partners with SDSN Germany and IASS to supports the newly established ‘Science Platform Sustainability 2030’ of Germany. The Platform provides scientific advice to the German government in support of the German sustainability strategy.

Transfer

Duscher, T.	2014	Red Dot: Best of the Best Award for Communication Design for „Next Generation Scientific Poster" (interactive poster about tsunamis), Design Centre North Rhine-Westphalia, Germany

The Red Dot: Best of the Best Award is recognition of the highest design quality. The interactive poster is a new format of visualisation of scientific context for communicating science. This is a statement of an international jury that the Excellence Cluster „The Future Ocean" does not only carry out excellent research, but also excellent design and communication for marine research (Scientific input by Cluster PI: **Krastel, S.**).

Hasselbring, W.	Since 2013	Member of the executive board of DiWiSH e.V. with more than 200 IT companies as members.

DiWiSH e.V. (Digital Economy Association Schleswig-Holstein) is the regional network of the digital economy in Schleswig-Holstein.

Scientific input by various Cluster PIs	2010, 2013, 2014, 2015, 2017, 2019	World Ocean Review Series

The development of a series about integrated research for public outreach published by maribus; first public outreach publication of its kind for a broader community of readers from the public interested marine science. The scientific content is provided by "The Future Ocean" Cluster researchers and recently also by researchers from the German Marine Research Consortium (KDM).

Samuel-Fitwi, B.	2014	Spin-off: AquaCube: create your own fish farm

The team from AquaCubes Systems (ACS) offers a new, innovative fish production plant for anyone. The compact modules are called AquaCubes and contain all the technical innovations required – from the hatchery onwards – that are easy to use. With the fish produced in AquaCubes, there are no plant protection products as feed additives, no chemicals and no extraneous water for the preservation of frozen fish products.

Patent

Wallmann, K. (jointly with M. Haeckel)	2011	Method for producing natural gas from hydrocarbon hydrates while simultaneously storing carbon dioxide in geological formations. DE 102009007453.8, NZ 593290, BG EP2394021, BR PI1007791-0, CA 2,754,356, CN 201080003778.8, CY EP2394021, DK EP2394021, EP 2394021, FR EP2394021, GE 12347/01, GR EP2394021, IN 5948/DELNP/2011, JP 2011546589, KR 1020117014773, NO EP2394021

A technical approach in geo-engineering for the production of natural gas from hydrocarbon hydrates with simultaneous storage of carbon dioxide in geologic formations.

Fischer, M., Friedrichs, G., Wahl, M.	2011	Großflächiger Biofilmsensor / Large-area biofilm sensor. Patent: DE 102011101934.4 (granted 2017)

Optical biofilm sensor for determining biological properties of biofilm on settlement substrate, has set of photoconductive glass fibers arranged under substrate and around light source, where light source is arranged in sensor head.

7.3 PIs AND OTHER PARTICIPATING RESEARCHERS

Table 8: Principal Investigators (2012-2019)

	Title, first name, surname	Institute	researcharea(s)
1*	Prof. Dr. C. Berndt	GEOMAR	Dynamics of the Ocean Floor
2	Prof. Dr. M. Bleich	CAU	Physiology
3	Prof. Dr. C. Böning	GEOMAR	Ocean Circulation & Climate Dynamics
4	Prof. Dr. T. Bosch	CAU	Zoology
5*	Prof. Dr. M. Braack	CAU	Mathematics
6*	Prof. Dr. S. Gorb	CAU	Zoology
7*	Prof. Dr. W. Hasselbring	CAU	Software Engineering
8	Prof. Dr. K. Hoernle	GEOMAR	Marine Geology
9	Prof. Dr. G. Klepper	IfW	Environmental Policy Instruments
10	Prof. Dr. A. Körtzinger	GEOMAR	Marine Biogeochemistry
11	Prof. Dr. M. Latif	GEOMAR	Ocean Circulation & Climate Dynamics
12*	Prof. Dr. K. von der Decken (Odendahl)	CAU	International Law
13*	Dr. S. Peterson	IfW	Environmental and Resource Economics
14	Prof. Dr. T. Requate	CAU	Resource Economics
15*	Prof. Dr. T. Reusch	GEOMAR	Marine Ecology
16	Prof. Dr. U. Riebesell	GEOMAR	Marine Biogeochemistry
17	Prof. Dr. R. Schmitz-Streit	CAU	Molecular Biology
18	Prof. Dr. R. Schneider	CAU	Geosciences & Paleoceanography
19*	Prof. Dipl.- Ing. M. Schulz	MKHS	Spatial Strategies & Interior Design
20	Prof. Dr. U. Sommer	GEOMAR	Marine ecology
21	Prof. Dr. A. Srivastav	CAU	Applied Mathematics & Computer science
22	Prof. Dr. K. Stattegger	CAU	Coastal Geology
23	Prof. Dr. F. Temps	CAU	Physical Chemistry
24	Prof. Dr. M. Visbeck	GEOMAR	Ocean Circulation & Climate dynamics
25	Prof. Dr. K. Wallmann	GEOMAR	Marine Biogeochemistry
J1*	Prof. Dr. G. Friedrichs	CAU	Physical Chemistry
J2*	Prof. Dr. S. Krastel	GEOMAR	Marine Geology
J3*	Prof. Dr. F. Melzner	GEOMAR	Marine Ecology
J4*#	Prof. Dr. M. Quaas	CAU	Resource Economics
J5*	Prof. Dr. K. Rehdanz	IfW	Environmental & Resource economics
J6*	Prof. Dr. P. Rosenstiel	CAU	Clinical Molecular Biology
J7*	Prof. Dr. L. Rüpke	GEOMAR	Marine Geology
J8*	Prof. Dr. B. Schneider	CAU	Biochemical Modeling
J9*	Prof. Dr. K. Schrottke	CAU	Coastal Geography
J10*	Prof. Dr. T. Slawig	CAU	Applied Mathematics & Computer science
J11*#	Prof. Dr. T. Treude	GEOMAR	Marine Biogeochemistry
J12*	Prof. Dr. A. Vafeides	CAU	Coastal Geography

* new PIs compared to the initial proposal submitted in 2006,
# PI left universities/participating institution

Further participating scientists are listed in the chapter 8 Appendix B (confidential).

7.4 PARTICIPATING INSTITUTIONS AND COOPERATION PARTNERS

Table 9: Detailed list of the participating institutions and the most important cooperation partners

Institutes of the host university/universities	Location
Center for Molecular Biosciences	Am Botanischen Garten 9, 24098 Kiel
Clinic for Dermatology, Venerology and Allergology	Rosalind-Franklin-Straße 7, 24105 Kiel
Clinic for Nephrology and Hypertonic Diseases	Universitätsklinikum Schleswig-Holstein, Arnold-Heller-Straße 3, Haus 6, 24105 Kiel
Department of Computer Science	Christian-Albrechts-Platz 4, 24118 Kiel
Department of Economics	Olshausenstr. 40, 24098 Kiel
Division of Research and Technology Transfer	Koboldstraße 2-4, 24118 Kiel
Institute of Biochemistry and Molecular Biology	Am Botanischen Garten 9, 24098 Kiel
Institute of Botany	Am Botanischen Garten 5, 24118 Kiel
Institute of Clinical Molecular Biology	Rosalind-Franklin-Straße 12, 24105 Kiel
Institute of Crop Science and Plant Breeding	Am Botanischen Garten 1-9, 24118 Kiel
Institute of Electrical Engineering and Information Technology	Kaiserstraße 2, 24143 Kiel
Institute of General Microbiology	Am Botanischen Garten 1-9, 24118 Kiel
Institute of Geography	Ludewig-Meyn-Str. 14, 24118 Kiel
Institute of Geosciences	Ludewig-Meyn-Straße 10, 24118 Kiel Otto-Hahn-Platz 1, 24118 Kiel
Institute of Human Nutrition and Food Science	Düsternbrooker Weg 17, 24098 Kiel
Institute of Inorganic Chemistry	Max-Eyth-Str. 2, 24118 Kiel
Institute of Materials Science	Kaiserstraße 2, 24143 Kiel
Institute of Medical Informatics and Statistics	Brunswiker Straße 10, 24105 Kiel
Institute of Philosophy	Leibnizstr. 6, 24118 Kiel
Institute of Physical Chemistry	Max-Eyth-Straße 1, 24118 Kiel
Institute of Physiology	Hermann-Rodewald-Straße 5, 24118 Kiel
Institute of Plant Nutrition and Soil Sciences	Hermann-Rodewald-Straße 2, 24118 Kiel
Institute of Polar Ecology	Olshausenstrasse 75, 24118 Kiel
Institute of Prehistoric and Protohistoric Archeology	Johanna-Mestorf-Straße 2-6, 24118 Kiel
Institute of Social Sciences	Westring 400, 24118 Kiel

Institute of Toxicology and Pharmacology for Natural Scientists	Brunswiker Straße 10, 24105 Kiel
Institute of Zoology	Am Botanischen Garten 1-9, 24118 Kiel
Interdisciplinary Center for Numerical Simulation	Christian-Albrechts-Platz 4, 24098 Kiel
Leibniz-Laboratory for Radiometric Dating and Isotope Research	Max-Eyth-Str. 11-13, 24118 Kiel
Research and Technology Center West Coast	Hafentörn 1, 25761 Büsum
Walther-Schücking-Institute for International Law	Westring 400, 24118 Kiel
Institutes of the participating universities [1)]	**Location**
MKH - Centre for Media	Legienstr. 35, 24103 Kiel
MKH - Spatial Strategies	Legienstr. 35, 24103 Kiel
Non-university institutions [1)] (if applicable)	Location
GEOMAR - Ocean Circulation and Climate Dynamics	Düsternbrooker Weg 20, 24105 Kiel
GEOMAR - Marine Biogeochemistry	Wischhofstraße 1-3, 24148 Kiel
GEOMAR - Marine Ecology	Düsternbrooker Weg 20, 24105 Kiel
GEOMAR - Dynamics of the Ocean Floor	Wischhofstraße 1-3, 24148 Kiel
Most important cooperation partners [2)]	**Location**
LabexMER, Cluster of Excellence, c/o University of Brest	Plouzané, France
National Oceanography Centre	Southampton, United Kingdom
The Bjerknes Centre for Climate Research (BCCR), Universitetet i Bergen	Bergen, Norway
Earth Institute/Lamont-Doherty Earth Obervatory, c/o Columbia University	New York, USA
Ocean Frontiers Institute, c/o Dalhousie University	Halifax, Canada
Ocean University of China (OUC)	Qingdao, China
The First Institute of Oceanography(FIO) at the State Oceanic Administration(SOA)	Qingdao, China
The Institute of Oceanology, Chinese Academy of Sciences (IOCAS)	Qingdao, China

1) Institutions that were funded by the Cluster.

2) Institutions that were not funded by the Cluster but contributed their own resources to the Cluster (e.g. research partners, industrial cooperation partners, or other service providers, museums, cultural institutions, applications partners, etc.)

7.5 DOCTORAL RESEARCHERS

Table 10: Doctoral researchers – completed and ongoing theses

	Doctoral theses completed within the Cluster [1)]	Thereof: (partially [≥ 50 %]) financed by the Cluster	Ongoing doctoral theses after expiry of Cluster's funding
Total (number)	254	36	150
Thereof: Female researchers (%)	53,5	55,6	54,0
Origin [2)]	**Number**		
Africa	7	2	3
Central America	0	0	2
East Asia	18	0	25
Eastern Europe	6	1	2
Europe	195	31	103
New Zealand	1	1	1
North America	3	0	2
South America	7	0	3
South Asia	8	1	5
South East Asia	3	0	2
Western Asia	6	0	2
	Percent		
Africa	2,8	0,06	2,0
Central America	0,0	0,00	1,3
East Asia	7,1	0,00	16,7
Eastern Europe	2,4	0,03	1,3
Europe	76,8	0,86	68,7
New Zealand	0,4	0,03	0,7
North America	1,2	0,00	1,3
South America	2,8	0,00	2,0
South Asia	3,1	0,03	3,3
South East Asia	1,2	0,00	1,3
Western Asia	2,4	0,00	1,3

1) Completed during the Cluster's total funding duration; completion is defined as the date of the final doctoral exam, e.g. "Disputatio" or "Rigorosum".

2) Refers to the location of the last position held prior to joining the Cluster.

TIB / GEPRIS

The authors hereby

☒ agree
☐do not agree

to having their final report (sections 1–6, Appendix A) be made accessible to the general public via **TIB (Leibniz Information Centre for Science and Technology University Library)**.

The authors hereby

☒ agree
☐do not agree

to having the summary and the list of the Cluster’s most important publications be made accessible to the general public via **GEPRIS**, the DFG’s online project database (http://gepris.dfg.de/en).

Host university:
Kiel University
Christian-Albrechts-Universität zu Kiel (CAU)
Christian-Albrechts-Platz 4
24118 Kiel
Germany

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