

RESEARCH AGENDA 2020



Helmholtz Centre for Ocean Research Kiel

PREFACE

This document, written by GEOMAR scientists, is a forward-looking perspective on GEOMAR's marine scientific research for the next decade. It is based on numerous discussions and debates that have helped to shape our future scientific profile.

The role of the oceans in climate change, the climate impact on marine ecosystems, living and nonliving marine resources, plate tectonic processes and geological hazards were identified as overarching research themes for the coming years. Over the past four years, the Institute has increased its staff to about 750 and has a total annual budget of about 60 M Euros, of which about 50% comes from third-party research funding. Together with the University of Kiel, GEOMAR scientists have been successful in acquiring two large-scale, long-term Collaborative Research Centres (SFBs) that are funded by the German Research Foundation (DFG). These Research Centers investigate the subduction factory and the sensitivity of oxygen-related processes in the tropical oceans. Additionally, GEOMAR and the University of Kiel were awarded the excellence cluster "The Future Ocean" in 2007, which we hope will continue until 2017. Finally, the Institute has successfully bridged the gap between basic and applied science in a number of specific research areas relevant to industry.

Building on this foundation, GEOMAR is well positioned to meet the scientific challenges of the future. This science plan outlines GEOMAR's research agenda until 2020, recognizing that research is not steady and predictable, but a highly dynamic process that will provide us with many new strategic insights along the way.



A handwritten signature in white ink on a blue background. The signature is stylized, with a large 'H' and 'M' and a long horizontal line extending to the right.

Peter Herzig,
Director GEOMAR
Kiel, January 1, 2012



FROM THE DEEP SEA TO THE ATMOSPHERE

RESEARCH AGENDA 2020

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1 GEOMAR AT A GLANCE

The GEOMAR | Helmholtz Centre for Ocean Research Kiel investigates the world oceans, from the seafloor to the atmosphere covering the entire oceanographic research spectrum. The primary mission of the Institute is “fundamental research” as stated in the Institute’s constitution. However, GEOMAR strives to link fundamental knowledge to applied issues concerning future use of marine resources, and interactions with the marine environment.

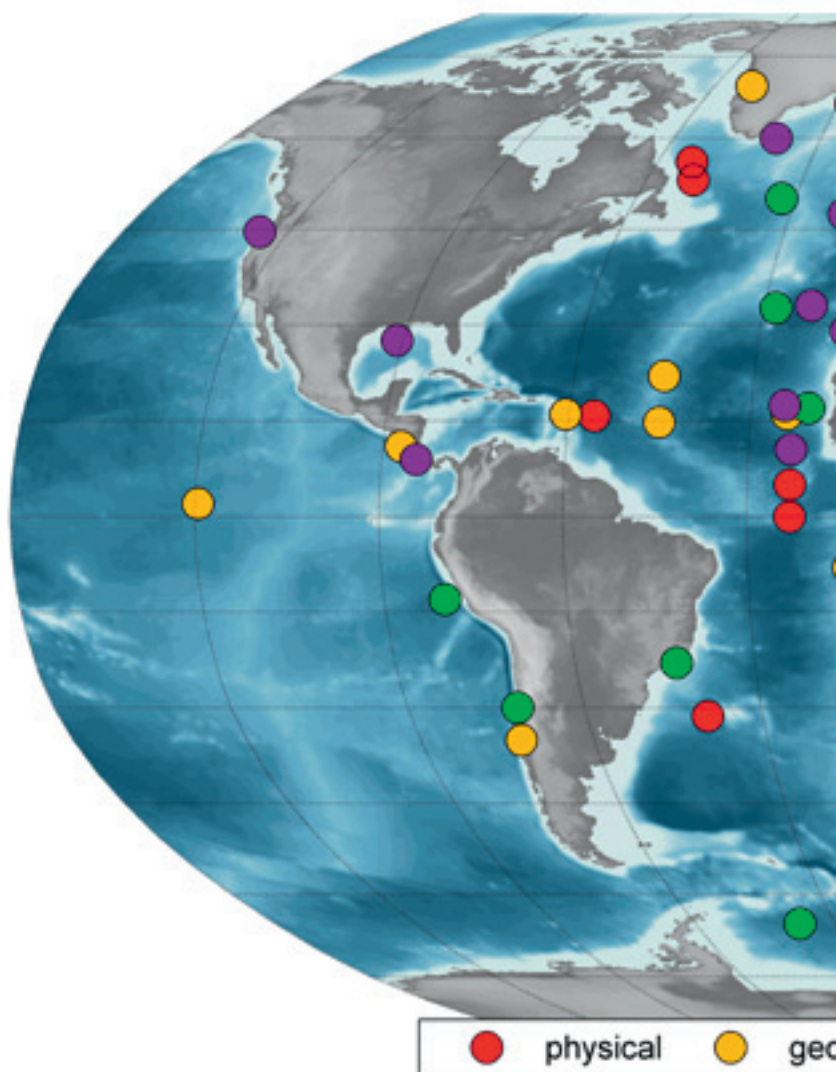
Research in the Institute is conducted within Research Divisions that study Ocean Circulation and Climate Dynamics, Marine Biogeochemistry, Marine Ecology and the Dynamics of the Ocean Floor. This broad research base addresses four common challenges found in marine science:

Mission Statement

... to investigate the physical, chemical, biological, and geological processes in the oceans and their interaction with the seafloor and the atmosphere ...

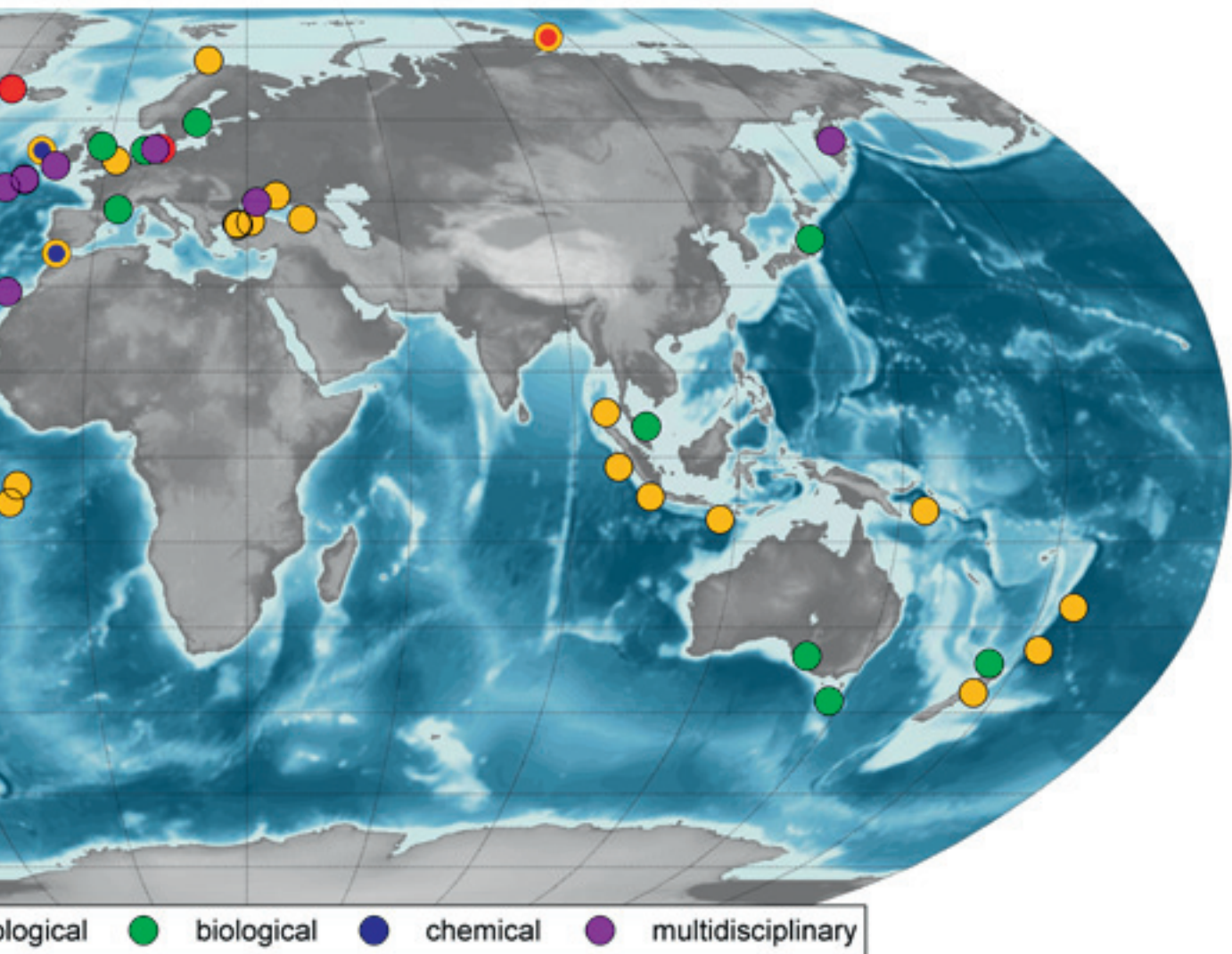
■ **Understanding.** The oceans cover more than 70% of the Earth’s surface. They are difficult to study, remain largely unexplored, and are poorly understood. Increasing the knowledge of the oceans, understanding their basic functions and complex interactions is the focus of the Institute’s research agenda.

■ **Observing.** Documenting the oceans’ behaviour and gaining awareness of marine-related risks is dependent on the development and deployment of advanced observational technologies. All the Research Divisions have active research programs aimed at improving this fundamental ability.



■ **Resources.** The oceans represent the largest source of both living (e.g. food, bioactive components) and non-living (e.g. energy, minerals) resources on the planet. In addition, humans profit from the oceans through a wide range of environmental services (e.g. tourism, recreation, transportation, storage of CO₂). The Institute strives to develop areas of applied research at the interface between science and industry. A solid balance between economic use and ecological protection of the oceans is the underlying goal of these activities. Responsible use of the oceans is consistent with the fundamental research mission and expertise of the Institute.

■ **Risks.** The Earth is changing rapidly and the oceans and their ecosystems are intimately involved in, and affected by, this change. Human populations are increasingly vulnerable to



risks associated with the oceans and the ocean crust (e.g. climate change, earthquakes, tsunamis, volcanoes, submarine slides, major storms). The Institute strives to transfer knowledge gained from fundamental research to applications of immediate relevance to human society.

The Institute conducts research in all the world's ocean basins. This global profile, with a strong but not exclusive focus on the open oceans, gives GEOMAR a central collaborative role within the German marine science community. **With its scientific impact, size, infrastructure and research agenda, the Institute is the leading, national "blue ocean" oceanographic centre in Germany.** GEOMAR has a particularly strong, synergistic relationship with the University of Kiel and also cooperates with other key national Universities.

Interactions with national research centres and universities are coordinated within the *Konsortium Deutsche Meeresforschung*, of which GEOMAR is a founding member.

On an European level, the Institute has developed strong links with the National Oceanography Centre in Southampton, UK, and IFREMER in Brest, France. Internationally, GEOMAR works with major oceanographic institutions in the USA, Canada, Japan, Korea, India, China and Russia, both directly as well as in the framework of alliances and coordinating bodies such as the "Partnership for the Observation of the Global Oceans" or POGO.

... from the deep sea
to the atmosphere ...

2 MAIN RESEARCH THEMES

2.1 ROLE OF THE OCEAN IN CLIMATE CHANGE

General

The oceans play a central role in global change processes. Major aspects of climate change are associated with the ocean's heat transport, heat capacity, and the global water cycle. However, oceanic storage, transformation, transport and exchange of radiatively and chemically active gases and particles also exert an influence on climate through their impact on atmospheric radiation transfer. Past climate change has had demonstrable influences on the isotopic and chemical composition of seawater, which permits these signals to be investigated as potential recorders of change. Since exchanges of heat and substances between the ocean, land and the atmosphere operate on time scales ranging from seasons to millennia, they are amongst the most important factors for shaping future global climate change.

Understanding of Past, Present and Future Overturning Circulation Changes

Climate variations during key periods in the past have been closely linked with changes in ocean circulation. Of special significance are changes in the Atlantic Meridional Overturning Circulation (MOC), the "lower limb" involving formation and circulation of deep waters. In the North Atlantic, the "upper limb" of the MOC transports vast amounts of heat towards the high northern latitudes and is partly responsible for the mild climates of central and northern Europe. The MOC exhibits a highly non-linear behaviour, which may in part explain its large variability in the past. In contrast, the present warm period, the Holocene, features relatively weak MOC variability. A major goal of GEOMAR is to improve understanding of these differences in variability between different modes of the past MOC and their driving factors on glacial-interglacial, and on shorter millennial to decadal time scales. This also requires continued observation in the key regions of North Atlantic Deep Water formation and transport. There are three principal areas of expertise: (1) the conception, development and experimental testing of new proxies for past ocean geochemical conditions and climate-based, state-of-the-art analytical technology; (2) the continued application of modern ocean observing techniques and participation in global ocean observing systems and process studies; and (3) the application of state-

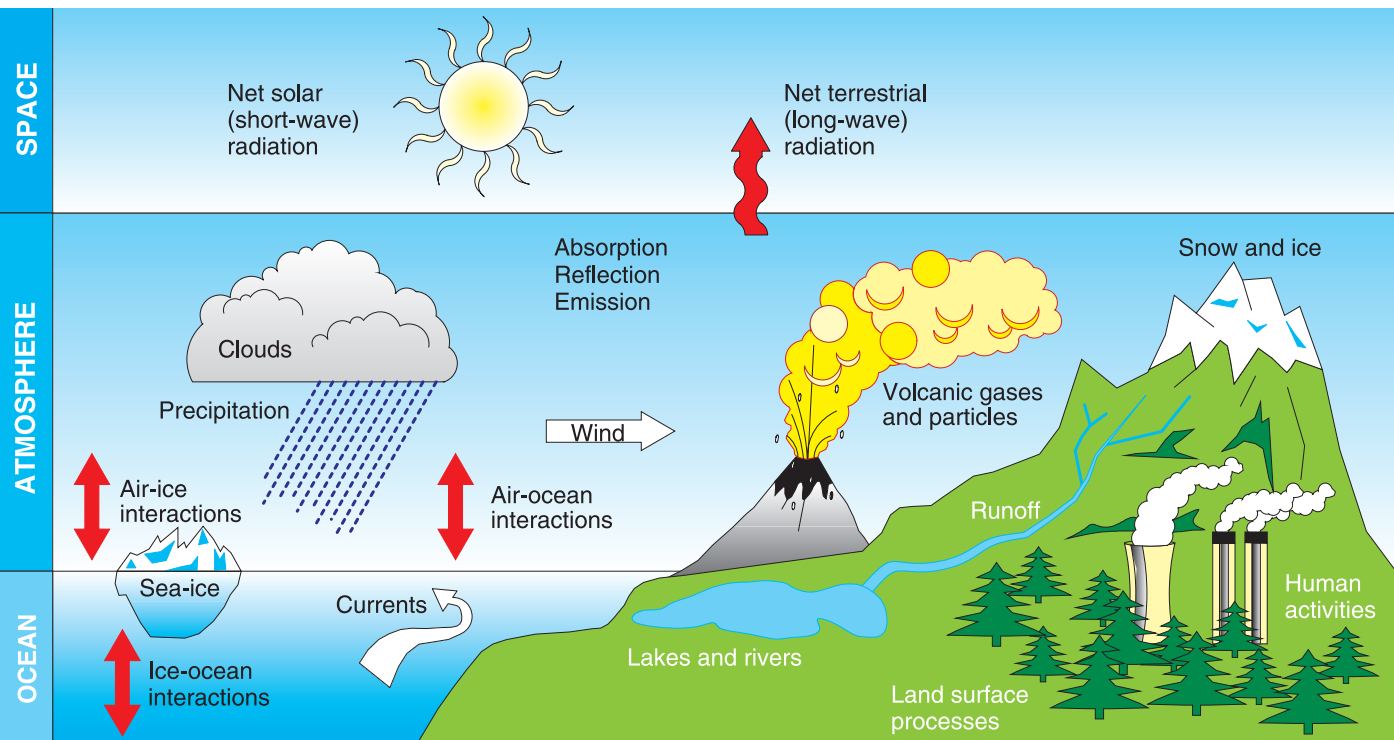
of-the-art climate and ocean circulation modelling. The regional focus will be on the North Atlantic sector, however, global connections will become increasingly important on decadal and longer time scales.

Changes in the Tropics

The tropical oceans are regions with the strongest seasonal to multi-decadal coupled climate variability. For instance, decadal-scale variations in Atlantic hurricane activity, as well as variations in Sahelian rainfall, correlate well with changes in Atlantic sea surface temperature (SST). Shifts in upper ocean stratification and circulation influence SST variability, showing the important role the ocean plays in forcing these fluctuations. Our aim is to understand the mechanisms underlying this variability and to quantify the contribution of oceanic circulation, specifically the MOC and shallow tropical circulations. This may help to develop a decadal forecast capability in the next years. The relevant expertise (theory, modelling, and observation) exists at GEOMAR. Furthermore, the nature of the physical interactions of the ocean with the atmosphere and their influence on biogeochemical cycles and atmosphere-ocean material exchanges will be studied.

A major goal of GEOMAR over the next ten years will be to observe and understand processes operating in the tropical oceans. Physical and radiative air-sea feedbacks such as SST/cloud feedbacks will be studied, and these will be coupled to biogeochemical studies of the effect of changing surface forcing (e.g. light, wind, dust input or precipitation) on biological productivity and the related sea-to-air flux of trace gases, including CO₂, N₂O, and gases involved in ozone destruction.

In order to get more insight into these problems, measurements of large-scale transport and water mass changes will be conducted and a hierarchy of numerical models developed. Furthermore, some key ocean processes that control the large-scale ocean circulation need to be better understood. These include water mass transformation, mixing and upwelling processes, and ocean eddies. Measurements of fine structures and process modelling will help to understand these small-scale processes and their interactions with the large-scale dynamics. In order to address long-term changes in biogeochemical properties, GEOMAR will establish long-term observing systems as well as improved logistical capabilities in the tropical Atlantic Ocean. A strategic goal is to establish a long-term fixed-point observing station in the tropics suitable for conducting biogeochemical experimental work (Cape Verde Islands). This should be coupled to observations of physical and biogeochemical parameters on regional scales that can be made using state-of-the-art autonomous platforms (e.g. gliders).



The information gained from the new station in the tropics as well as from other sources will be applied to improve our understanding of a range of key interdisciplinary and climate-related issues such as:

- Tropical atmosphere-ocean interaction related to heat/water/gases/rainfall/dust/productivity/clouds.
- Climate-biogeochemical interactions with tropical oxygen minimum zones.
- High resolution reconstruction (centennial to subannual) of climatic and oceanic parameters from suitable archives (e.g. corals).
- Understanding and predicting tropical climate variability on time scales from seasons to decades.
- Responses to anthropogenic climate change.

Present and Past Arctic Oceanography and Climate

The Arctic will remain an area of process-oriented collaborative research at GEOMAR. The Arctic has responded sensitively to climatic changes on different time scales in the past and its marine and continental records provide a wealth of detailed information on these responses. On the other hand, the Arctic Ocean and its surrounding landmasses also actively control climate, for example through processes such as the ice-albedo feedback.

Future research will aim towards a better understanding of arctic shelf environments, which have undergone significant changes during the last few decades. GEOMAR will continue to play a key role in coordinating cross-disciplinary programs, both nationally and internationally, to substantially improve our understanding of the mechanisms controlling sensitive shelf environments. This includes the study of virtually unexplored territories of sub-sea permafrost that are vulnerable to warming. Given that huge amounts of organic carbon and gas hydrates are stored in the upper permafrost layer, thawing could release large amounts of greenhouse gases into the atmosphere, further amplifying global warming. A continuing focus of GEOMAR's research will be the palaeo-oceanographic and climatic reconstruction of the Arctic Ocean and its surrounding landmasses, which includes investigations of short-term variability over the past centuries, as well as long-term changes over the past 60 million years.



Future Greenhouse Warming: Assessment and Scenarios

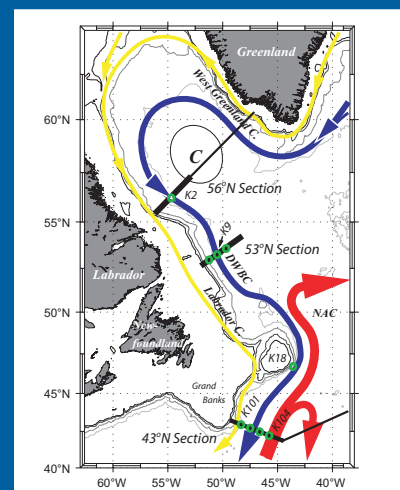
Greenhouse warming is one of the most significant challenges facing mankind. Future climate change will strongly depend on the response of the ocean to anthropogenic forcing. The ocean greatly reduces the level of global warming as a result of CO_2 uptake (Ocean-Atmosphere-Exchange, chapter 3.2). Regional expressions of global warming and their impacts, such as changes in the frequency and magnitude of weather extremes, depend on many factors including changes in ocean circulation. Carbon uptake will be influenced not only by inorganic processes, but also by the response of marine life to ocean warming, circulation changes, and ocean acidification. In order to study the role of the ocean in climate change, its uptake of anthropogenic CO_2

and its response to global warming, we are participating in the development and implementation of a global ocean observing system (GOOS). The data can also be used to initialize global climate models and test ocean, climate and carbon-cycle models that are used in scenario integrations to estimate the consequences of greenhouse warming. These include physical aspects such as sea level rise and changes in ocean circulation, as well as chemical aspects such as the increase in seawater CO_2 concentration and associated acidification.

Certain feedback processes need to be considered in this context. Important physical feedback involves the ice-albedo feedback, the water vapour feedback, and the cloud feedback. Carbon uptake by the ocean may be strongly reduced by global warming, circulation changes, and ocean acidification. Furthermore, ocean warming may lead to a destabilisation of gas hydrates, which would amplify global warming considerably should gases such as methane escape into the atmosphere. Our goal is to quantify the risk of such a destabilisation by a joint assessment using our observational and modelling capabilities.

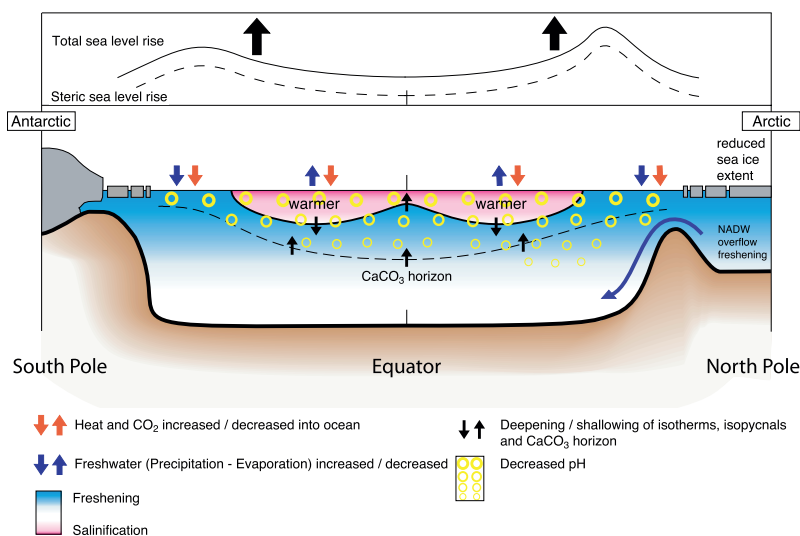
Meridional Overturning Circulation, Greenhouse Gases and Climate

The term “Meridional Overturning Circulation” (MOC) refers to an ocean-wide circulation pattern through which warm surface waters are transported from the tropics to high latitude oceans, cooled and then transported into the deep ocean basins. The circulation pattern is closed by the upwelling and mixing of deep waters into the surface layers. This circulation plays a critical role for the Earth’s climate: in the North Atlantic Ocean, the “upper limb” of the MOC, commonly referred to as the “Gulf Stream”, transports warm waters to northern latitudes and therefore is partly responsible for the mild climates of central and northern Europe. The circulation pattern is also significant for the sequestration and transport of greenhouse gases, for example for the removal of anthropogenic carbon from the atmosphere or the release of the greenhouse gas N_2O to the atmosphere from sub-surface ocean.



Why Study the Tropical Oceans?

The tropical oceans play a major role for both climate and ocean biogeochemistry. The climate role is well-recognised, with tropical oceans being the loci for major modes of climate variability such as the El Niño Southern Oscillation and the African and Indian monsoons that affect vast human populations. The climate role arises from massive atmosphere–ocean exchange of heat and water which takes place in the tropics. A direct effect of tropical climate on ocean biogeochemistry is mediated via the transport of dust from arid regions on land to the tropical oceans. This dust delivers key nutrients to otherwise nutrient-starved biological communities. Shallow overturning circulations associated with tropical atmosphere–ocean exchanges and wind patterns drive localised but intense upwelling of nutrients and dissolved carbon from the deep ocean. This controls both the magnitude of biological productivity and the sea-to-air flux of CO₂ and other radiatively active gases. Finally, interactions between tropical climate, ocean circulation and biogeochemistry control the distribution of sub-surface oxygen and especially the location and intensity of the ocean's oxygen minimum zones, which are located predominantly in the tropics. Biogeochemical processes within these zones determine the fate of major nutrients (nitrogen, phosphorus) for the world's oceans.



Past Geochemical Change in the Oceans

In addition to studies of past climate change, GEOMAR will investigate the direct and indirect response of oceanic geochemistry to climate forcing. Novel methods based on analyses of stable isotope compositions (B, Mg, Si, Ca, Sr) will be developed to allow reconstruction of changes in ocean pH, temperature, pCO₂, as well as nutrient budgets both during the Quaternary and throughout the Phanerozoic. To achieve detailed and reliable reconstructions, the new isotopic tools will be calibrated through a set of programs for measurements of modern seawater and suitable archives. These archives include foraminifera, corals, molluscs, diatoms or even fish otoliths. The signal formation processes for these archives will be the subject of coordinated investigations between biologists and geochemists. Detailed time series will then be recovered from these archives and will be subjected to palaeo-modelling efforts that apply a whole suite of models with different complexities.



2.2 HUMAN IMPACT ON MARINE ECOSYSTEMS



Why study Biological Invasion?

Higher temperatures, more CO₂ in the oceans due to global change and eutrophication place individual organisms and entire marine ecosystems under pressure, which decreases their resistance. As a result, native organisms may become less competitive and more susceptible to invasions by alien species. During the last decades, global shipping has further promoted invasions. Aliens may be benign, but often represent a threat not only to marine ecosystems, but also to human interests. The sea-walnut (*Mnemiopsis leidyi*) is one example of a dangerous invasive species. In October 2006, the American comb jelly-fish was discovered by GEOMAR researchers in the Baltic Sea. It is known for its extraordinary appetite and it therefore reduces zooplankton, the food resource of juvenile fish. In addition, fish eggs and larvae are eaten by *Mnemiopsis*. If the recruitment of fish stocks is endangered, local fisheries will also be endangered.



The present and future state of the ocean's ecosystems and biogeochemical cycles is not exempt from the increasing impact of human activities on our planet. Predicting future developments, assessing associated risks and preventive strategies require an in-depth understanding of the sensitivity of marine ecosystems and biogeochemical cycles to global warming, it is also important to consider ocean acidification, oxygen depletion in intermediate and deep waters, changes in surface ocean mixing and nutrient supply, anthropogenic transfer of invasive species, regional and global species extinctions, and increased exploitation of biological resources.

Multiple environmental stressors do not operate in isolation from one another. Therefore, understanding the combined impact of multiple stressors is a major challenge for future research.

Ocean change not only influences the most sensitive species (e.g. calcifying species impacted by acidification), but also those species which interact with them as predators, prey, competitors, epibionts, etc.. Thus, the response of one species to an environmental stressor might cause additional pressure or, on the contrary, provide an opportunity for another species to succeed in the ecosystem. The combined result of direct and indirect responses can lead to changes in the transfer of matter and energy in marine ecosystems and biogeochemical cycling. Aggregated system level responses are typically:

- Changes in biological productivity
- Changes in the efficiency of energy and matter transfer to higher trophic levels
- Changes in the ocean's biological pump
- Changes in air-sea exchange of climatically relevant gases

These responses are integral components of feedback processes linking ocean biology to the climate system. Throughout Earth's history, the

ocean has played a crucial role in modulating atmospheric carbon dioxide through a variety of physical, chemical, and biological processes. The same processes will be involved in the ocean's response to anthropogenic perturbations of the global carbon cycle.

The transfer of effects through the ecosystem may be dampened or amplified, depending on the prevalence of negative or positive feedback loops. Accordingly, system response to changing environmental conditions can be gradual or catastrophic ("multiple stability", "regime shifts"). Negatively affected ecosystems can have a completely altered physiognomy compared to the undisturbed system, for example, overgrowth of coral reefs by algae, replacement of perennial macrophytes or domination of higher trophic levels by jellyfish instead of fish. The immediate consequences include the loss of habitats, nursery and feeding grounds for dependent species, which ultimately leads to the risk of extinction. Biogeochemical ecosystem functions such as storage and transformation of carbon and nutrients can also be altered by such structural changes thereby reducing the buffering capacity against environmental impacts.

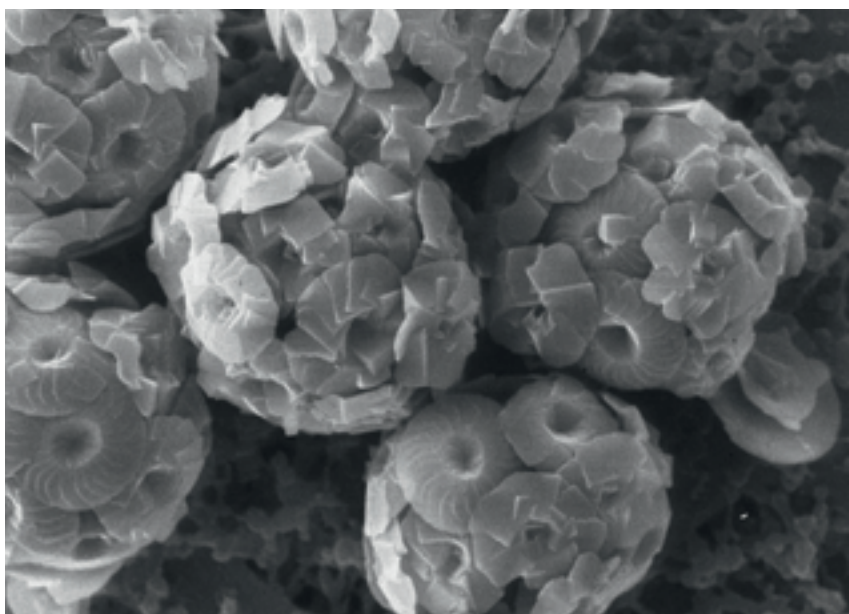
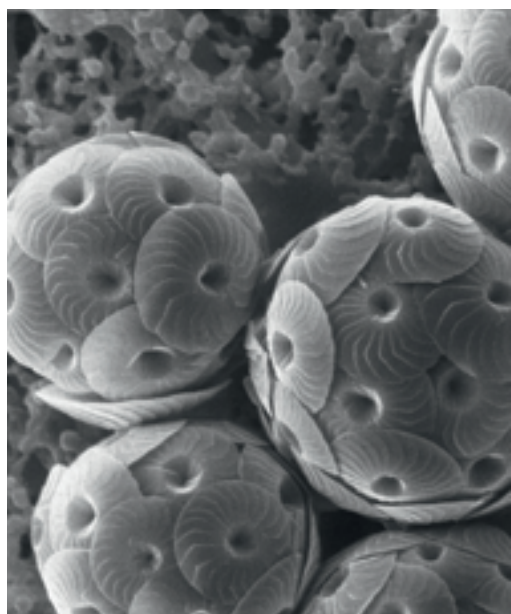
At the species level, the highest risks involve the demise of sessile species forming physical structure (corals, macrophytes) and outbreaks of harmful species. Such outbreaks include blooms of toxic or otherwise damaging algae and mass developments of jellyfish. Both can strongly impair ecosystems, commercially valuable species and environments important for marine economic branches such as coastal tourism and fisheries. Poorly understood outbreaks of harmful organisms follow highly stochastic patterns and have increased in frequency during the last decades.

Palaeo-oceanographic records offer valuable insight into the state of marine ecosystems in periods of elevated temperatures, lowered pH, and depleted oxygen in deep/intermediate waters. However, there are limits to interpretive extrapolations from the past to the near future. While previous environmental changes might have been larger in magnitude, they probably occurred much slower than those of today. The velocity of change is a critical issue, both in terms of the physico-chemical buffering of the Earth system and for biological response time and with respect to environmental change. For instance, rising atmospheric CO₂ leads to drastic ocean acidification only if it occurs on time scales shorter than deep ocean turnover and dissolution of calcium carbonates in ocean sediments. In this sense, the ongoing CO₂ perturbation caused by the burning of fossil fuels is probably a unique event in Earth's history, implying that an appropriate palaeo-analogue for the projected human-induced ocean acidification probably does not exist.

Biological communities may adapt to change through replacement of species performing similar functions but having different environmental

optima. Species may adapt by changing genotypes or evolving new genotypes ("microevolution"). However, community and species level adaptation requires time and might be too slow to keep pace with human-induced global change. Traditional ecology has supported a very pessimistic view concerning adaptation. It is based on a distinct separation between the ecological and the evolutionary time scale and works on the assumption of fixed species reaction norms. However, there is increasing evidence that the time scale of microevolution overlaps with the ecological time scale, thus making micro-evolutionary adaptation a potentially important mechanism for successful survival of current environmental change rates and a top priority of future research in global change biology.

Single-point mutation at the DNA level can lead to drastic variation in the function and resistance of an organism subjected to strong selective pressure caused by, for example, toxins. This has been recorded in many organisms, including clams exposed to dinoflagellate toxins. Such point mutations will be rapidly fixed by populations exposed to specific stressors and thus make microevolution important in the face of global change. The advent of marine genomics, the study of whole genomes of marine organisms allows us to look at adaptive diversification of closely related organisms at the molecular genetic level for the first time. The rapidly growing database of genomes from marine organisms also opens the possibility of extending our knowledge of microbial consortia by incorporating metagenomic approaches in ecological studies (chapter 3.5 molecular biological analyses).



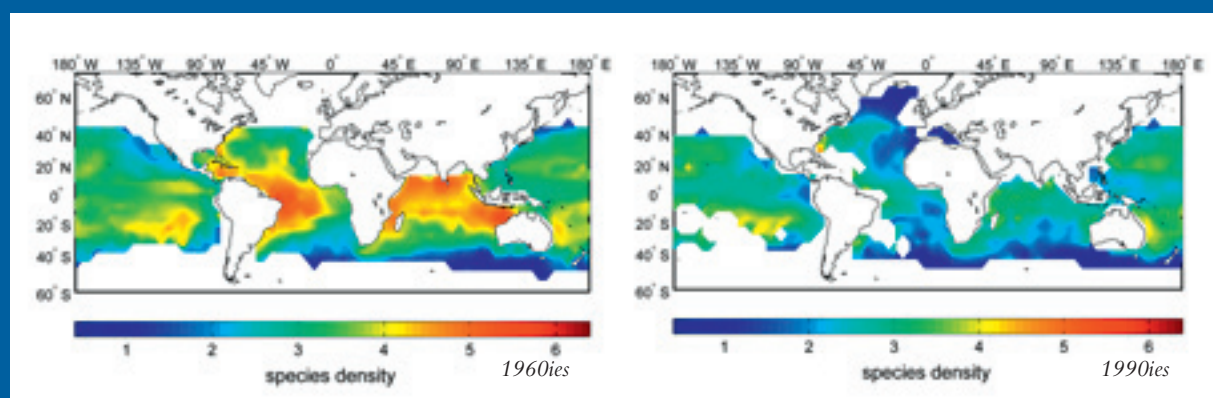
Ocean Acidification: the other CO₂ Problem.

The world ocean has taken up nearly half of the fossil fuel CO₂ emitted into the atmosphere since pre-industrial times. As CO₂ emissions continue, the ocean will remain the predominant natural sink, ultimately sequestering 90% of man-made CO₂. What proves to be a blessing with regard to climate change may soon turn out to become a curse for marine life. If anthropogenic CO₂ emissions continue to rise at current rates, before the end of this century upper ocean pH will decrease to levels lower than have been experienced for tens of millions of years. Recent studies show adverse effects of ocean acidification on a variety of marine life forms, in particular calcifying organisms, such as certain phytoplankton species (e.g. coccolithophores), molluscs, and corals. Little is presently known about possible effects at the community to ecosystem level or possible synergistic effects from other environmental changes, such as global warming. Also unknown is the extent to which marine organisms are capable of adapting to ocean acidification.

2.3 LIVING AND NON-LIVING MARINE RESOURCES

Sustainability in Fisheries

The examination of the mechanisms of living marine resource exploitation indicates that a fundamental change in the socio-economic, institutional, and ecological settings is needed to accomplish a turnaround to sustainability. Since the majority of bio-economic models draw on single-species models and do not reflect dynamic ecosystem interactions or the stochastic nature of processes related to the specific life strategy of marine organisms, the aim of future research at GEOMAR is to develop coupled bio-economic models. These models adequately take into account the complexity and the uncertainty of developing marine ecosystems.



The word “resources” implies exploitation by humans. The resources available for exploitation in the world’s oceans can be divided into living (of relevance, for example, as food, sources of useful bioactive molecules and environmental services) and non-living (including raw materials such as metals, energy and the storage of anthropogenic CO₂ in marine sediments). The research challenges for the future lie in finding new resources, elucidating how these resources were formed (non-living) or how they function (living), and in developing environmentally sound and sustainable ways to exploit these resources. Exploring marine resources and analyzing the impact of resource utilization on marine ecosystems and environments involve different research approaches for living and non-living resources. Nevertheless, the effects of resource utilization are likely to have implications on both living and non-living components and an accurate assessment of the consequences will require close cooperation from scientists studying both aspects.

Ecosystems Services and Aquaculture

Marine ecosystems are highly adapted to specific or variable abiotic conditions and characterized by complex food web interactions. These communities and food web structures are substantially influenced by non-linear anthropogenic impacts such as fishing, oil and gas exploration, waste dumping, and natural as well as anthropogenic climate change effects. Selective reduction of the upper trophic levels of marine food webs through intensive fishing has resulted in substantial impacts on individual populations and species, on the biodiversity and the function of marine ecosystems, and on the potential for their exploitation. Anthropogenic environmental changes (e.g. in habitat structure, nutri-

ent levels, toxic substances) also directly affect the lower part of the food web and the energy transfer from primary to fish production. One of the central goals of future research into living marine resources at GEOMAR will be to provide the scientific basis for new forms of ocean management. The new approach will incorporate multiple factors including changes in ecosystem structure, for population dynamics and food web interactions, for the stochastic nature of many processes and natural as well as anthropogenic-driven climate trends in order to ensure sustainability in resource utilization.

As many marine food resources are currently at or beyond maximum sustainable yields, a major contribution towards the ever-growing demand for seafood is expected from marine aquaculture. Nevertheless, habitat destruction related to open culture systems and the dependence of aquaculture on wild caught food sources often limit the benefits of this technique for natural marine ecosystems. Future research at GEOMAR will focus on technical and biological optimization of closed-system aquaculture and the interaction of mariculture production with ocean fisheries in order to evaluate associated benefits and risks.

Genetic Resources and Products from Microorganisms

The genetic composition and diversity of many marine ecosystems remain uncharacterized and unexplored. The advent of environmental genomics opens the door to the characterization of these untapped living resources and may lead to the discovery of new genes. The results from genetic investigations can be used not only in the development of new medications, but also in other biotechnologies such as the advancement of molecular biology, clean fuel industry and the discovery of new enzymes for use in household products such as detergents.

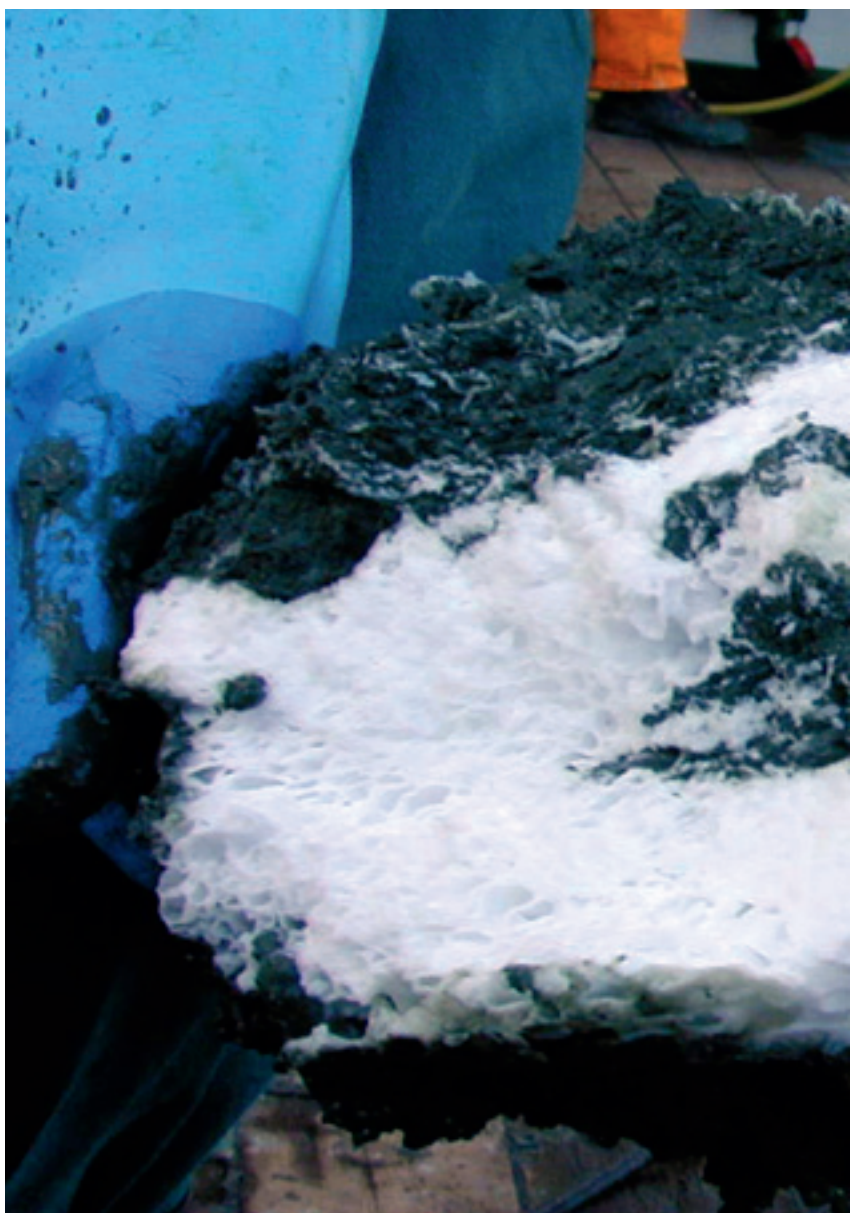
The use of microorganisms in biotechnological processes does not harm the ocean environment, because only negligible amounts of material are needed and once cultivated in the laboratory, no further natural resources are extracted. Basic studies to explore the potential of marine bacteria and fungi in biotechnological processes are of increasing importance in marine research and will be a major focus in the field of marine microbiology. Marine bacteria and fungi represent a rich source of natural products for potential treatment of human diseases (e.g. infections, cancer, inflammations).

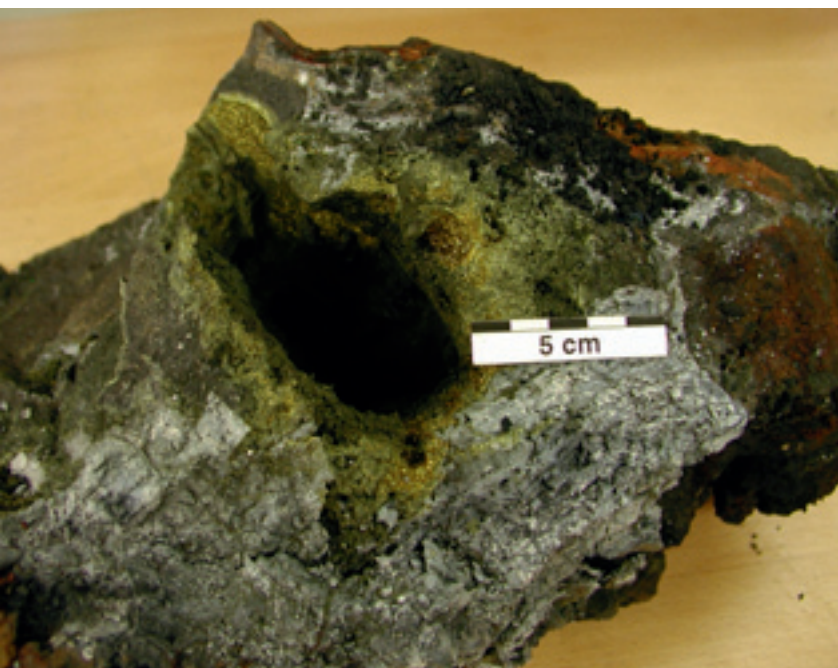
Marine Minerals

Hydrothermal systems on the ocean floor are a potential resource of base (copper, zinc, lead) and precious metals (gold, silver) but can also introduce large amounts of potentially toxic elements such as mercury, arsenic, antimony, and lead into the marine environment. Economic considerations are likely to make underwater metal mining profitable within this decade. However, the processes leading to the formation of marine metal resources, which occur both at and below the seafloor, are still poorly understood even on the qualitative level. Specifically, investigations of these systems in terms of the third dimension, the thermodynamics of metal precipitation, the metamorphic and metasomatic processes occurring at depth, and the sub-surface topology of fluid flow are necessary in order to understand resource formation, element enrichment processes and the fluxes of elements into the oceans. Exploitation of these resources may, however, result in conflicts with marine conservation efforts. In the fields of marine minerals mining and marine environmental protection, GEOMAR will continue to play a leading role in providing scientific advice on national and international level. The goal is to attain a sustainable balance of economic use and environmental protection for our oceans.

Marine Gas Hydrates

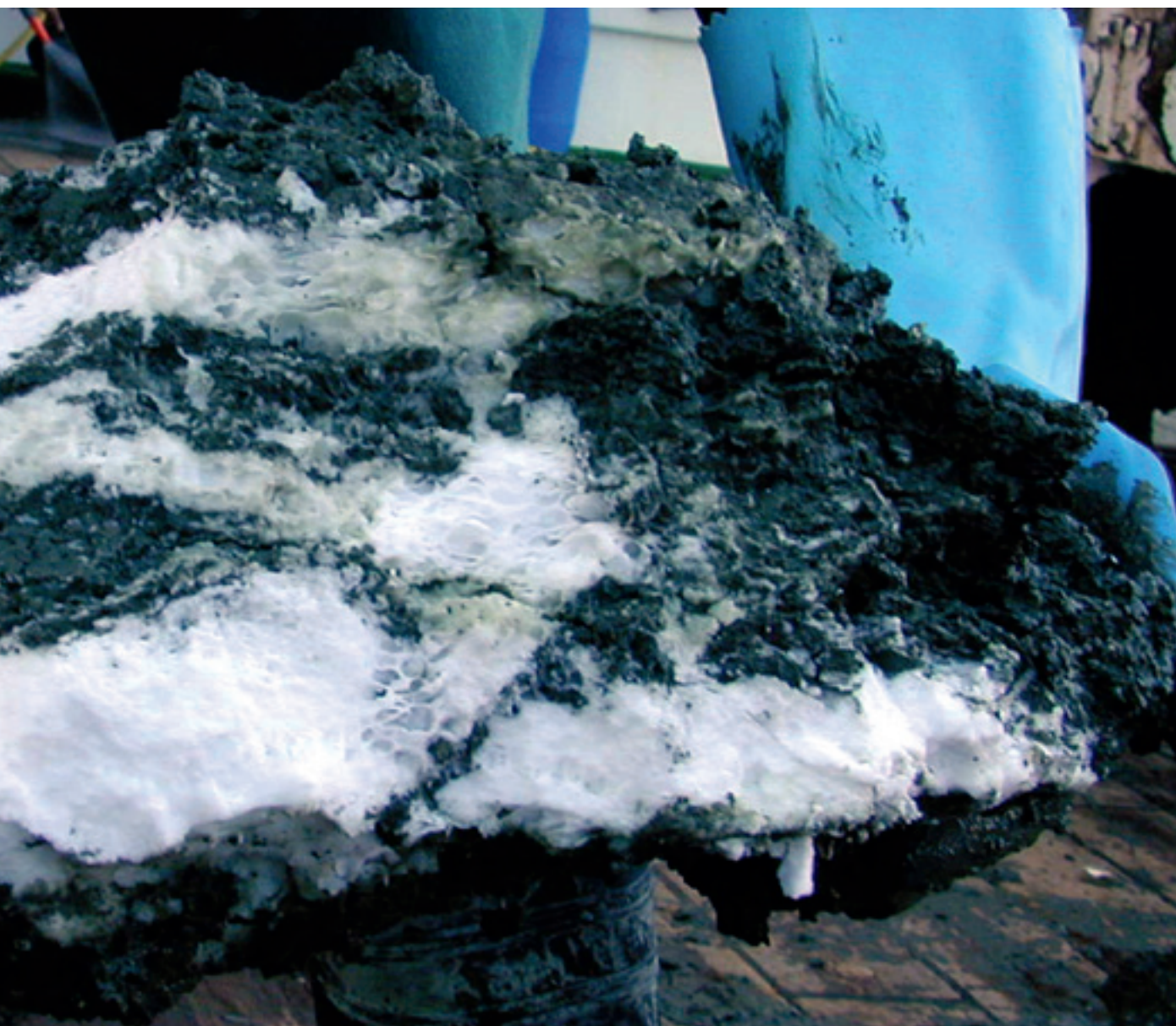
Methane hydrates in marine sediments will probably be exploited in the near future and could serve as a major energy resource in the coming decades. The deposits may contain more carbon than all known oil and gas sources combined. Laboratory experiments and thermodynamic modelling show that methane gas can be liberated from sedimentary hydrates by the injection of liquid CO_2 . CO_2 occurs either as a dense liquid or solid hydrate under the high pressure and low temperature conditions prevailing below the seafloor. Both of these CO_2 phases are immobile, so that seabed storage can be regarded as the safest option for CO_2 sequestration on the planet. Hence, methane production from natural gas hydrates through CO_2 injection is an economically and ecologically promising approach. The technology of hydrate exploitation and CO_2 injection in marine sediments is still in its infancy and needs to be further developed (chapter 5.6). Moreover, the long-term fate of CO_2 in sediments as well as the potential of CO_2 -leakage and its effects on marine ecosystems still need to be evaluated.





Marine Mineral Resources: El Dorados on the Seafloor?

Although the location and shape of some mineral seafloor deposits is already known, their sub-surface extent, which ultimately determines whether the resources are exploitable, remains in most cases a mystery. This situation can be changed with future developments in three areas: improvements in the resolution of remote-sensing technologies; development of suitable remotely-controlled drilling capabilities; and refinement of modelling tools.



2.4 PLATE TECTONIC PROCESSES AND GEOLOGICAL HAZARDS

Scientists at GEOMAR study a wide range of processes affecting the oceanic lithosphere in the following plate tectonic settings: 1) divergent margins, 2) convergent margins, 3) rifted (passive) margins, and 4) intraplate regions. All four settings represent critical stages in the life-cycle of ocean basins. Ocean basins are created by the breakup of continents and development of passive continental margins. After breakup, oceanic lithosphere is formed at mid-ocean ridges and back-arc spreading centres. The oceanic crust is subsequently modified by low- and high-temperature interactions with the overlying seawater, the addition of intraplate magmas, the deposition of marine sediments, and tectonic processes occurring at or near transform and convergent plate margins. When oceanic lithosphere is subducted at convergent margins, the dehydration of the subducted plate causes arc volcanism that creates and modifies the continental crust and transfers climate-relevant volatiles into the atmosphere. Passive continental margins and subduction zones are the Earth's principal sites of sediment accumulation, with fluid exchange processes in these areas being of global importance. Passive continental margins and subduction zones host vast geological resources, such as oil, gas and gas hydrates. Because subduction zones have high seismicity, they pose a major threat to humankind in the form of earthquakes. Since the sediments at passive and active continental margins are often mechanically unstable, submarine mass wasting in these areas, triggered for example by earthquakes or gas hydrate decomposition, is a major geological hazard that may cause tsunamis. Coastal communities and offshore oil and gas pro-

duction platforms are threatened by tsunamis. The dynamics of the ocean floor, and the investigation of geological resources and hazards will guide future geosciences research at GEOMAR.

Rifted (passive) Margins and Continental Breakup: the Birth of the Oceans

We investigate the structure of rifted margins to understand the tectonics of rifting, the processes by which crustal separation occurs, and the nature of the transition to true seafloor spreading. Key questions to be worked on in the future include what is/are the 1) major mechanism(s) of continental breakup (e.g. ridge propagation into continents, subduction roll-back on the margins of supercontinents, major igneous events

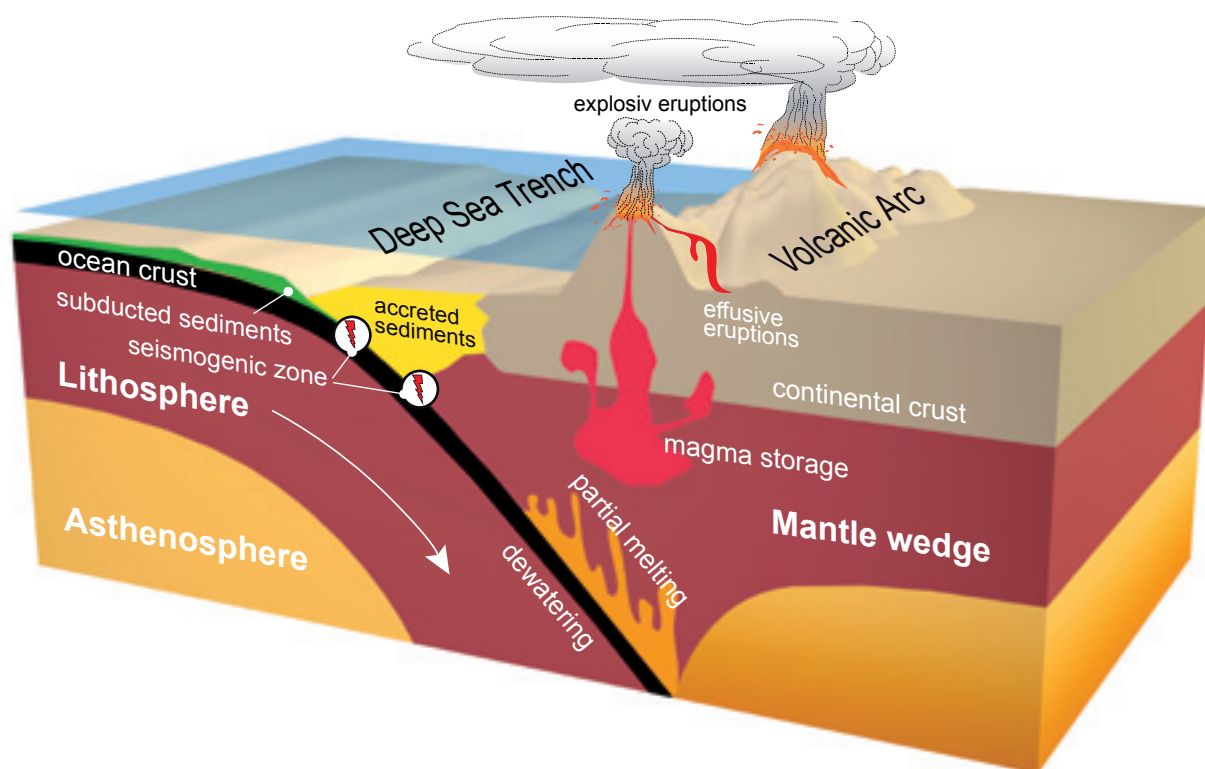


forming Large Igneous Provinces (LIPs)), 2) controls on magmatism and on the interaction of mantle melts with continental crust and seawater (and effects on its chemistry) before and during breakup, 3) chemical and biological variations at hydrothermal vents and polymetallic sulfide deposits in areas of recently rifted continental crust, and 4) effects of the opening and closing of marine gateways on ocean circulation.

Formation and Evolution of the Ocean Floor and the Ocean Basins

The ocean basins grow by continued plate divergence at oceanic spreading centres. We will continue to investigate the genesis of the ocean floor, i.e. the processes by which the plates split and move apart, allowing mantle to upwell and partially melt, as well as the mechanisms by which the resulting melt or magma rises, intrudes and erupts to form oceanic crust. Hydrothermal and low-temperature interactions

between magmatic crust and overlying sediments and seawater have a major effect on the composition of seawater and the formation of ore deposits. Interaction between seawater and the oceanic lithosphere (crust and mantle peridotite) will remain a major area of research. Other important new areas of investigation include 1) study of lower-crustal rocks on ultra-slow-spreading ridges to acquire insights into mantle melting beneath these ridges, 2) estimation of the bulk composition of magmatic crust (lavas, dikes and gabbros), and 3) determination of segment-scale (tectonic) processes along the Mid-Atlantic Ridge. The study of unique life forms at hydrothermal vents (black smokers) will continue to be a research focus, further linking biologists and geologists.



Geological Hazards at Subduction Zones

Subduction zones are among the most dynamic tectonic environments on Earth. This example from the Central American Deep-Sea Trench shows the deformation zone geometry between the actively converging Pacific and Caribbean Plates. The seismogenic zone is the area where devastating earthquakes originate as a result of catastrophic ruptures on the plate boundary. Further westward, there is a broad zone of distributed deformation without major earthquakes. Here, large amounts of fluid released by the subducted rocks are transported upward and discharged at the seafloor. The rugged topography at the lower Caribbean slope is caused by active deformation and submarine landslides. Near the deep-sea trench the Caribbean Plate acts like a bulldozer, forming a wedge of accreted sediments that is continually scraped off from the Pacific Plate. Both earthquakes and submarine landslides are major geological events that can trigger tsunamis of potential hazard to coastal areas.

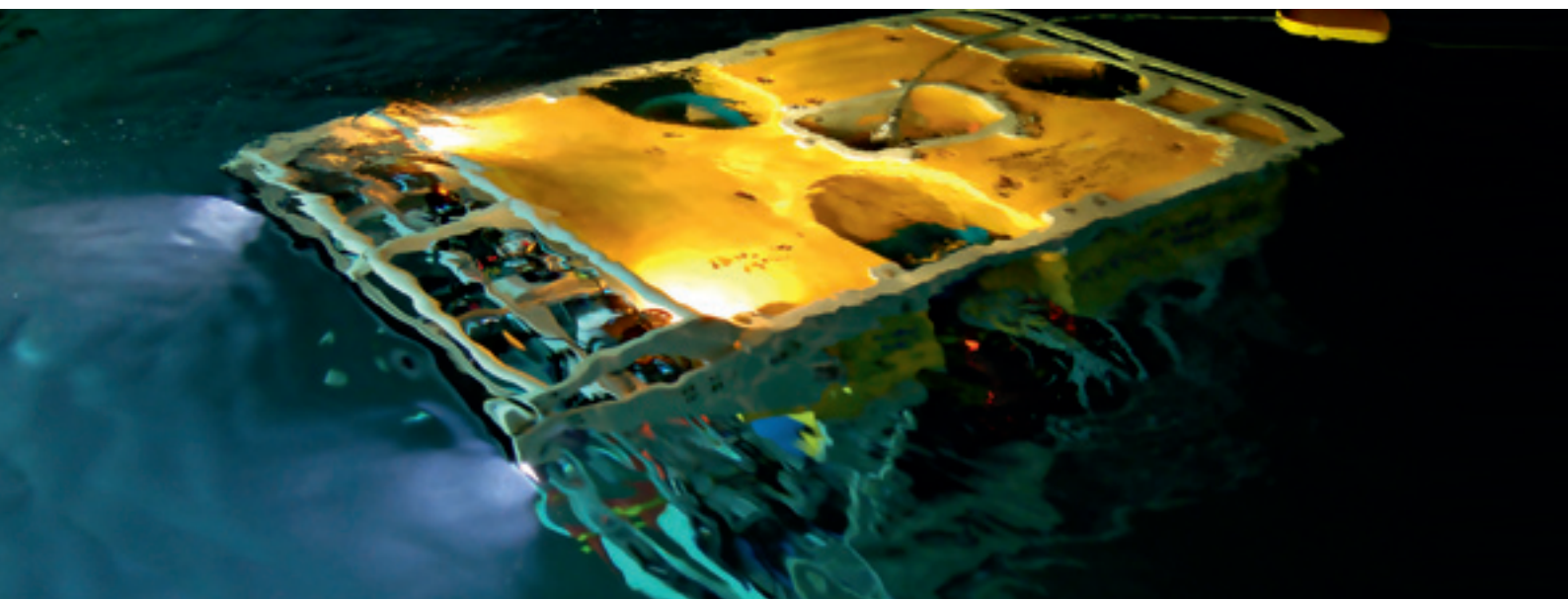
Intraplate 'Hotspot' Volcanism: Sampling the Upper and Lower Mantle?

Intraplate volcanism on the ocean floor occurs in several forms: Hotspot volcanism as represented by chains of volcanoes which become older in the direction of plate motion, single isolated volcanoes (off-ridge seamounts), clusters of volcanoes without obvious age progression with respect to plate motion, and oceanic volcanic plateaus and other Large Igneous Provinces (LIPs), which can have diameters in excess of 2,000 km. The eruption of LIPs causes long-lasting global climatic changes with devastating environmental impact (e.g. all Phanerozoic mass extinctions occurred contemporaneous with LIP events). Intraplate volcanism is believed to be primarily related to mantle plumes rising from deep within the Earth and therefore may play an important role in the material and heat transfer from the lower mantle to the Earth's surface. Important questions that will be addressed at GEOMAR include 1) the origin of intraplate volcanism, in particular alternatives to the mantle plume hypothesis such as lithospheric detachment, 2) the age and composition of LIPs (e.g. Hikurangi, Manihiki, Ontong Java, Caribbean) and their effect on the chemistry of

seawater and life forms within past oceans, 3) interaction between mantle plumes and mid-ocean ridges in time and space (Iceland, Galapagos, Ascension) and 4) the link between the shape, composition and age of seamounts and their associated ecosystems.

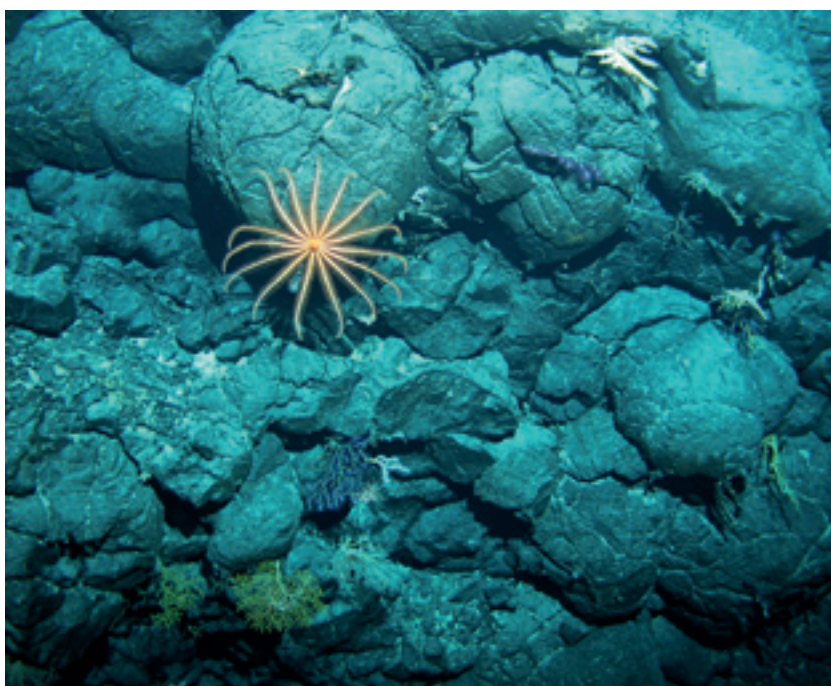
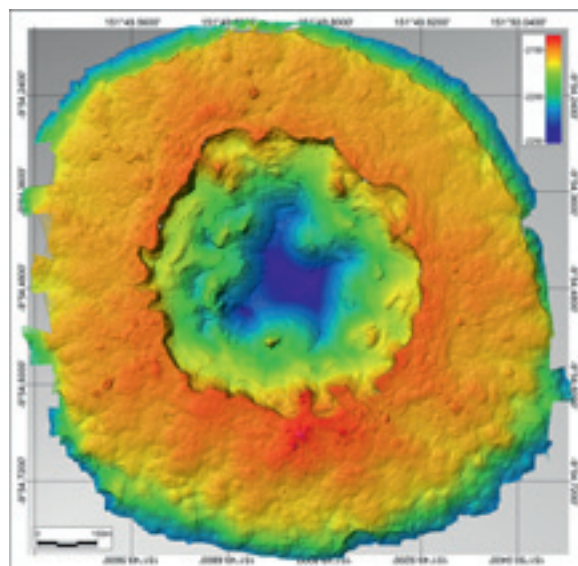
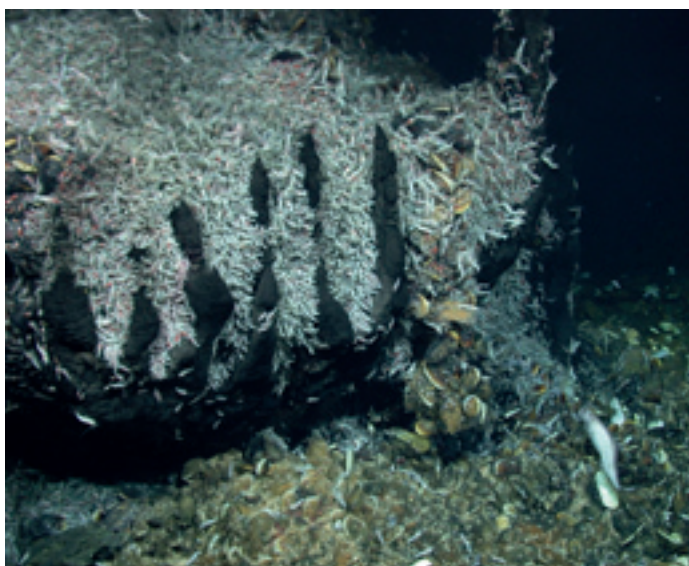
Convergent Margins: The Subduction Factory

At the "subduction factory", continental crust is generated through the processes of accretion and fluid-induced melting of the subcrustal mantle, expressed as arc volcanism. However, continental crust is also partly destroyed in these zones through subduction erosion. Climate-influencing fluids and volatiles are transferred upwards from the subducting plate and mantle wedge, through the forearc and the volcanic arc and are released into the hydrosphere and atmosphere. Convergent margins are also the sites of the highly explosive volcanic eruptions, permanent volcanic degassing and earthquakes and tsunamis, which are among the most dangerous and destructive geological hazards facing highly populated coastal areas. Important areas of ongoing and future research include 1) the origin of earthquakes in subduction zones, 2) the volatile and fluid cycles through subduction zones, 3) biological activity related to forearc fluid venting, 4) spatial and temporal variations in the composition and structure of subduction zones, and 5) the link between material input (e.g. subducting slab), and the fluid output in the forearc, and magmatic output in the volcanic arc (e.g. volatile and other material fluxes through the subduction system).



Undersea Volcanoes – Oases of the Deep Sea

Seamounts are undersea volcanoes, reaching heights of up to 4,000 m above the seafloor. With their wealth of marine life, seamounts represent biological oases for life forms that could not survive in the open ocean. Furthermore, they act as stepping-stones for migrating fish and other marine organisms. The composition of biological habitats change through the life-time of a seamount, from the initial volcanic growth stage producing unstable undersea mountains with uneven surfaces, to the waning stage that may result in a smoother rock morphology. During formation of the seamount, the geochemical composition of the volcanic rock can change, affecting its suitability as a habitat or a biological oasis. Seamounts also can act as pathways, allowing seawater to enter the underlying oceanic crust or crustal fluids to enter the water column. Impermeable sediments that usually lie between older oceanic crust and the water column prevent direct crust-seawater fluid exchange. Venting of crustal fluids at seamounts can provide important nutrients for submarine life.



3 RESEARCH STRUCTURE

3.1 OCEAN CIRCULATION AND CLIMATE DYNAMICS (RESEARCH DIVISION 1)

Through air-sea exchange, redistribution and storage of heat, freshwater and radiatively active trace gases, the ocean is an integral part of the climate system. With its intricate, three-dimensional pattern of circulation, the ocean is a key factor in shaping climate, both present and past. The dynamics and changes of ocean circulation and its interaction with the atmosphere play an active part in climate variability on interannual, decadal and longer time scales. The role of the ocean is thus of prime importance for understanding past climates and for predicting future climates under natural and anthropogenic forced conditions.

Research in the Division includes

■ **Advancing our understanding of the physical processes and phenomena** in the ocean and the atmosphere which are critical to the large-scale mean and variability of the ocean-atmosphere system.

■ **Deciphering modern and past global changes** in ocean circulation and climate by quantifying current variations in key aspects of the ocean-atmosphere system and exploring marine climate archives. In addition, water mass properties, marine organisms, and seafloor sediments provide unique data sets for the evaluation of the present and past state of our planet.

■ **Developing and applying numerical models** that incorporate process dynamics in order to allow realistic simulations of ocean variability and its interaction with the atmosphere and the ocean biogeochemistry, a prerequisite for assessing past changes on different time scales. These modelling results can be applied to explore the predictability of climate variability and anthropogenic change.

A particular strength of the Division is a combined expertise in large-scale and process-oriented modelling, observational tools and sea-going capabilities to address the dynamics governing the present day system. These strengths, coupled with palaeo-oceanographic expertise allow the Division to improve its understanding of past climate scenarios.

Accordingly, GEOMAR's strategy is to examine the forcing mechanisms of present and past large-scale circulation variability including processes of ocean-atmosphere interaction. The research program of the respective disciplines is well integrated with international programs related to future and past global change and variability.

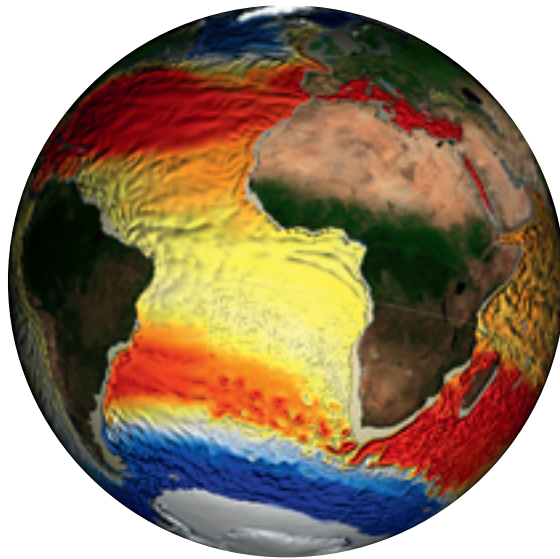
Modern Climate and Future Climate Change

Research Division 1 (RD 1) studies climate variability and future climate change through theoretical, observational, and modelling work. A new challenge is the decadal-scale variability that is reflected, for instance, in decadal modulations of hurricane activity or Sahelian rainfall. It is also visible in European climate indices, such as surface air temperature. In RD 1, we would like to understand the dynamics of these decadal-scale variations and their predictability.

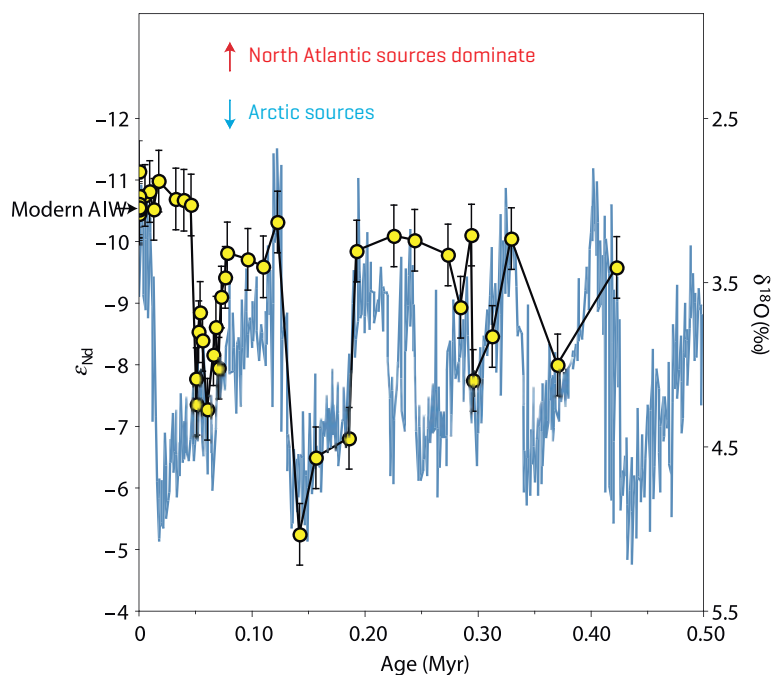
A phenomenon of prime importance for the climate of north-western Europe is the oceanic poleward heat transport associated with the Atlantic Meridional Overturning Circulation (MOC) and its variability. A key process of this circulation, which is also relevant to decadal variability, is the formation of deep water in the sub-polar North Atlantic with concomitant large heat loss to the atmosphere in winter. This contributes to the poleward heat transport from low to high latitudes. The temperature conversion of northward flowing upper-layer waters of the Gulf Stream and its extension, the North Atlantic Current, to the cold waters flowing southward between 1,000 and 4,000 m depth, is believed to be one of the key controls of the large-scale overturning circulation in the ocean. In the Atlantic Sector these ocean currents are responsible for carrying heat far into the Nordic Seas. Through the ensuing, deep reaching mixing of these waters in winter, a significant share of anthropogenic trace gases such as CO₂ and CFCs are sequestered. However, various processes that are presumably critical for the system are still poorly understood and represented in models. One example is the inflow to the MOC from the south, in particular the Agulhas region around South Africa. Through a vigorous mix of variable and strong currents warm and saline are transported from the Indian Ocean to the South Atlantic, eventually findings its way to the North Atlantic. Surface warming and/or increased freshwater influx in response to greenhouse warming may weaken the circulation. As a consequence, there is a cooling tendency over north-western Europe that may counteract greenhouse warming.

Due to the fact that the tropical Atlantic and the MOC intimately interact, this region is a focus area for RD 1. As salinity anomalies in the tropical Atlantic are transported polewards by the mean circulation, they affect the density pattern in the sub-polar Atlantic, the area of the ocean which mainly drives the MOC. The interannual to decadal variability in the tropical Atlantic is very complex because, unlike the tropical Pacific, not one single phenomenon dominates. Both, remote forcing of the tropical Atlantic by the tropical Pacific and local mechanisms have been proposed. The El Niño/Southern Oscillation (ENSO)

Numerical simulation of the Agulhas current: a key process of the global thermohaline circulation (figure shows modelled temperature at 450 m depth in a high-resolution model nested in a global ocean/sea-ice model)



Variability of Arctic Intermediate Water (AIW) Formation



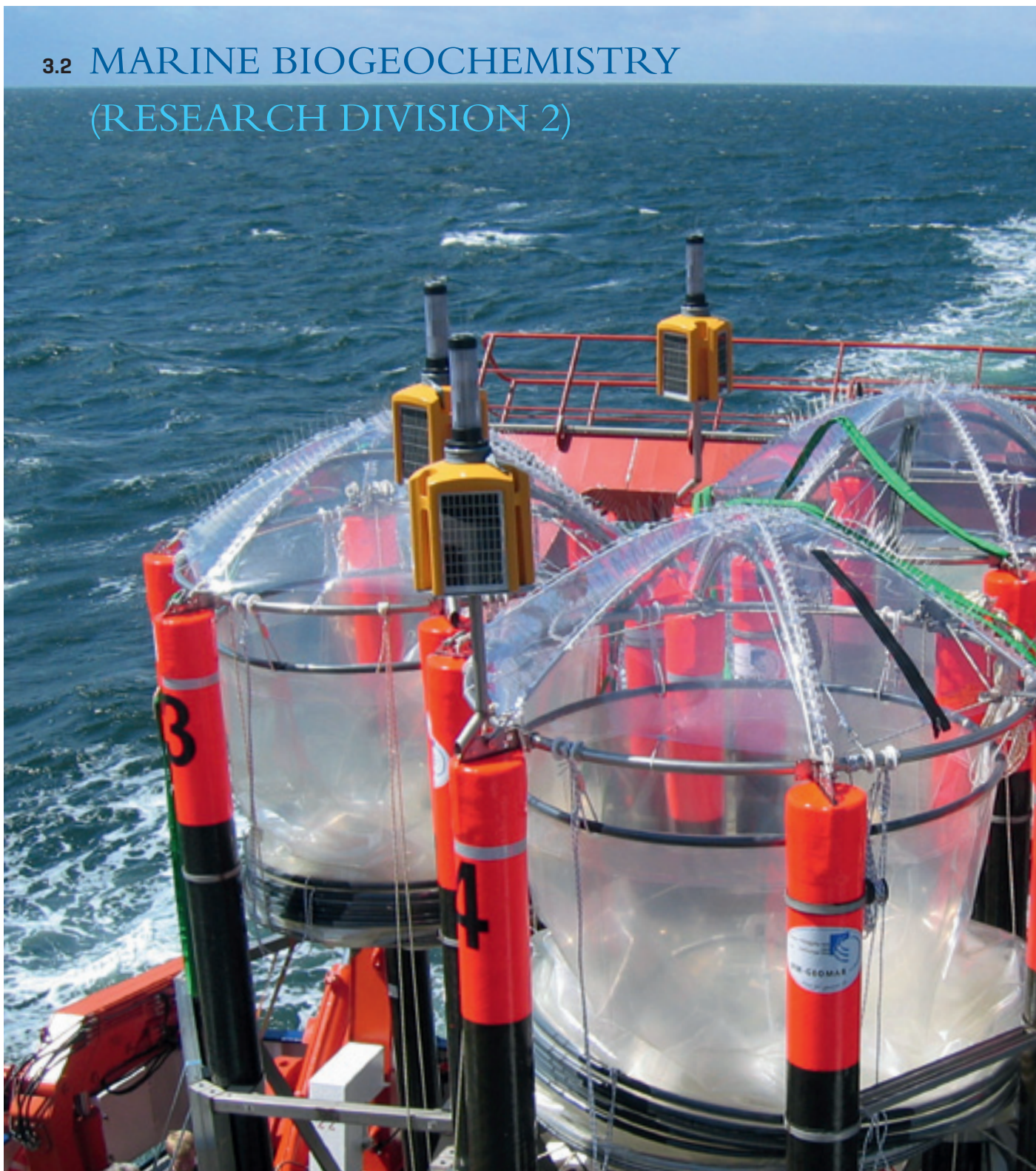
phenomenon in the equatorial Pacific, for instance, affects the circulation in the tropical Atlantic by way of an atmospheric bridge. Locally, the variability associated with the shallow subtropical cells is important in generating interannual to decadal fluctuations.

Other research areas of interest include the dynamics of the Southern Oceans Circumpolar Current and its interaction with the mesoscale eddy field, tropical circulations in the Pacific and Indian Ocean, past climate changes in the Arctic and dynamics of ENSO.

Past Ocean Circulation and Climate

Local and global climate and ocean circulation have been subject to major natural changes on time scales ranging from millions of years to decades. The reconstruction of this variability and its forcing mechanisms is crucial as a baseline for understanding man-made changes. Research efforts focus on the development and application of geochemical (in collaboration with RD 2) and palaeontological proxy indicators for the reconstruction of the palaeo-environment. A particular focus for the next 15 years will be the development of more quantitative proxy indicators for past ocean circulation and biogeochemical cycling based on trace elements and their isotopes. For this purpose research on present day seawater will be combined with work on various archives for precise proxy calibrations. The parameters reconstructed on the basis of these proxies range from past ocean temperatures and salinities, oxygenation, water mass mixing, and weathering inputs to bioproductivity, nutrient levels and their utilisation at highest temporal resolution. A whole suite of different archives are used, such as foraminifera or diatoms recovered from marine sediments, corals or ferromanganese crusts. Regional foci are the Arctic Ocean environment and tropical climate variability, as well as geobiological coupling at continental margins (e.g. deep-sea corals and carbonate mounds). Within RD 1, the palaeo-data are interpreted by making use of an increased understanding of present-day climate and of ocean circulation. In the future, efforts in modelling past climate variability with a hierarchy of climate models will be enhanced.

3.2 MARINE BIOGEOCHEMISTRY (RESEARCH DIVISION 2)



Work in Research Division 2 (RD 2) focuses on chemical interactions between sediment, oceanic, and atmospheric reservoirs and the organisms (including humans) which mediate marine biogeochemical processes. Major emphasis is on the highly dynamic interfaces between the atmosphere and the ocean at the surface, and between the sediment layer and the water column on the seafloor. Particular attention is paid to elements and compounds that are highly mobile and radiatively active. A closely related theme is the development of chemical, biological and isotopic diagnostic tools (proxies and tracers) that are suited to investigation of current and past oceanic conditions. An emerging research area concerns the future biogeochemical state of the oceans in a high-CO₂ environment, for example, for the benchmark 1,000 ppm CO₂-content of the atmosphere.

The research of RD 2 presently addresses the following major themes.

Upper Ocean Biology and Ocean-Atmosphere Exchange

Ocean-atmosphere exchange of gases and particles underlies rapid feedback mechanisms associated with anthropogenic global environmental change. Under this theme, research is focused on ocean surface layer biological and chemical processes. One project area concerns the production and exchange of gases that play a key role in controlling the composition, chemistry and radiative balance of the atmosphere (e.g. carbon dioxide, N_2O , halocarbons). A second project area concerns the physical and chemical processes that control the growth of key phytoplankton and micro-organisms (e.g. nitrogen fixers). The latter includes consideration of trace metal cycling, aerosol deposition, and volcanic input in controlling surface ocean productivity. A third focus concerns the effects of elevated CO_2 levels and the resulting ocean acidification on upper ocean biota and ecosystems, as well as carbon cycling.

The overall topic is addressed with a broad mix of advanced methodologies, including molecular biology studies, high-sensitivity chemical analyses, deliberate manipulations in the framework of mesocosm experiments, in-situ observing systems such as the volunteer observing ships and ocean observatories, as well as advanced biogeochemical modelling (see below). Much of the work under this topic is performed in the context of the international research program "Surface Ocean - Lower Atmosphere Study" (SOLAS).

Ocean Interior Cycling and Transport

This topic is aimed at understanding and quantifying basin- to global-scale processes which control the distribution of biologically-cycled elements including anthropogenic CO_2 within the ocean's interior, including interactions with the sedimentary reservoir. One major perspective is consideration of the ocean floor as a highly dynamic boundary and biogeochemical filter that injects and sequesters oceanic materials on varying time scales, thereby modulating element cycling. A specific focus on cold seeps and processes associated with gas hydrates is included within this perspective. Additional research issues concern characterization of anthropogenic CO_2 distributions in the ocean interior and the associated sub-surface acidification effects, the effects of low oxygen levels on remineralization and microbial nutrient cycling within the mesopelagic layer and near-surface sediments, and the influence of biomineralization on the trace element and isotope composition of ocean water.

Under this topic, the Research Division is integrating expertise in early diagenesis, the methane cycle, sediment-water exchange and modelling of reaction-transport processes with expertise in water-column chemistry, biology and oceanography. In addition to field work using advanced observing techniques such as benthic landers and autonomous profiling floats, this topic employs advanced isotope geochemical analyses and laboratory studies, including use of custom pressure-laboratories. Experimental and field studies are linked closely to local and global biogeochemical modelling approaches (see below).

Geobiochemistry and Palaeo-Environment

Many factors can act as master controls of long-term environmental change: Waxing and waning of global reefs, opening and closing of ocean passages, release and sequestration of methane hydrate, acceleration and deceleration of lithospheric plate motion, changes in cosmic radiation, as well as the influence of anthropogenic CO_2 release and human induced climate change. Marine biogeochemical processes play a central role in determining such changes, either via direct forcing (e.g. evolution- or tectonic-related processes) or through providing feedbacks for external forcing. Under this topic, we seek to apply the combined expertise of our Division's personnel to the understanding of biogeochemical controls of global environmental change on different time scales. Three approaches will be applied: (1) in-situ measurements of exchange and transformation processes; (2) development of proxies and chemical indicators for these processes that are applicable to various time scales; (3) biogeochemical modelling on a range of time scales, including consideration of future changes. The first two approaches utilize expertise in deep-sea instrumentation, high-precision dating, proxy and isotopic analyses, and early diagenesis. The third approach involves the development of models that incorporate data on biogeochemical cycling deduced from field studies and palaeo-archives. This may involve assessments of the evolution of specific biochemical metabolisms via genetic analyses as well as the effects of plate tectonics on oceanic conditions such as weathering, sea level and plate accretion.

Marine Biogeochemical Modelling

Chemically-, biologically- and geologically-driven transformation of material in the ocean, as well as exchanges with the seafloor and the atmosphere, takes place in a dynamic fluid environment. Reactants, products, as well as organisms and their enzymes, are all strongly affected by circulation and mixing processes as well as changes in the temperature and salinity of seawater. In order to understand and predict biogeochemical transformations in the ocean, the influence of the physical environment must be understood and accounted for explicitly. The Research Division develops and applies state-of-the-art coupled circulation-biogeochemical numerical models. One of the goals for the future is to develop a comprehensive model that can address complex oxidation-reduction reactions that affect oceanic oxygen, nutrients, metals and carbon dioxide, including exchanges with the atmosphere and the seafloor.

3.3 MARINE ECOLOGY (RESEARCH DIVISION 3)

Research Division 3 (RD 3) addresses the processes and mechanisms that govern the interactions between marine organisms, the interactions between organisms and their physico-chemical environment, and the sensitivity of marine ecosystems to anthropogenic and natural change. It is necessary to address these questions using a full scale of hierarchical levels from genes to individuals and populations or entire communities and ecosystems.

The Research Division studies the following overarching themes:

Ecological Genetics: From Genes to Ecological Performance

The role of different microbial genotypes in biogeochemically relevant transformations will be studied in a variety of marine ecosystems with emphasis on deep-sea hot vents, phototrophic bacterial communities in the coastal zone, microbial aspects of the nitrogen cycle with focus on N_2O formation and transformation, and on bacteria involved in associations with marine invertebrates and algae.

The genetic studies of multicellular organisms are currently devoted to identifying self-sustaining stock components and the effect of fisheries on the genetic complexity of natural populations. Fish genetic studies also consider aspects of speciation and biogeography. An expansion of ecological genetics to the analysis of microevolutionary adaptation to global change is planned for the near future.

Global Change Ecology: Marine Ecosystems in a Changing Climate

We anticipate that climate change and its hydrographic consequences will lead not only to shifts in the geographic distribution of species, but also to changes of seasonal growth, activity, and recruitment patterns. Because of species-specific sensitivities, these shifts will not be simultaneous between all species interacting within an area possibly resulting in a temporal or spatial mismatch between food demand by predators and food supply by prey. This may lead to some major restructuring of regional ecosystems, potentially dampened by physiological or genetic adaptation within species or replacements between functionally equivalent species. The research will be based on single-species laboratory

studies, multi-species mesocosm and field experiments, as well as on retrospective analysis of long-term data series and modelling. By simulating the shifting of climatic zones, the performance and invasibility of translocated communities and species can be assessed. The isotope signals in the shells of geologically old bivalve species are calibrated to serve as proxies for the reconstruction of palaeo-climate (temperature, CO_2). Depending on the availability of an appropriate experimental infrastructure, the impact of enhanced CO_2 -concentrations on marine ecosystems will also be studied.

Trophic Ecology: Feeding in the Sea and Food from the Sea

Food web studies form an ongoing research focus of RD 3 and include laboratory research on single-species, food requirements and selectivity, mesocosm experiments, field research, stable isotope analyses (particularly ^{15}N) and genetic finger-printing of gut contents to elucidate trophic relationships. Main research questions for the near future encompass the identification of trophic levels of copepods (herbivores versus microzooplankton-feeders) and their dependence on environmental conditions, the trophic role of gelatinous zooplankton, and the role of *Homo sapiens* as the top-predator in many marine ecosystems, including the potential top-down transmission of fishing effects in the food web.



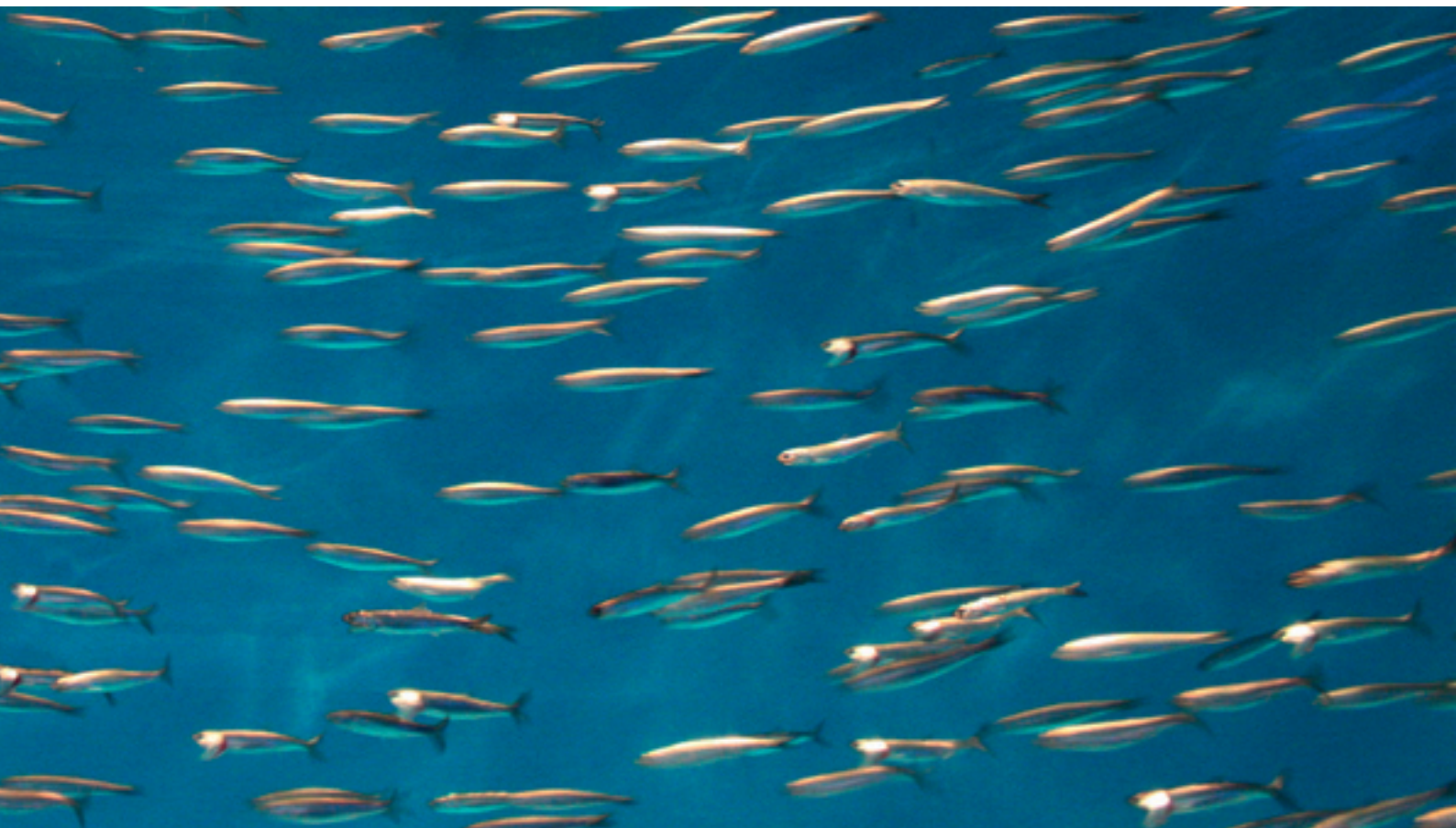
A further aspect is how prey can control its consumers by inducible defences and preventive signalling among menaced individuals.

Chemical Ecology: Chemical Interactions in the Sea - Chemicals from the Sea

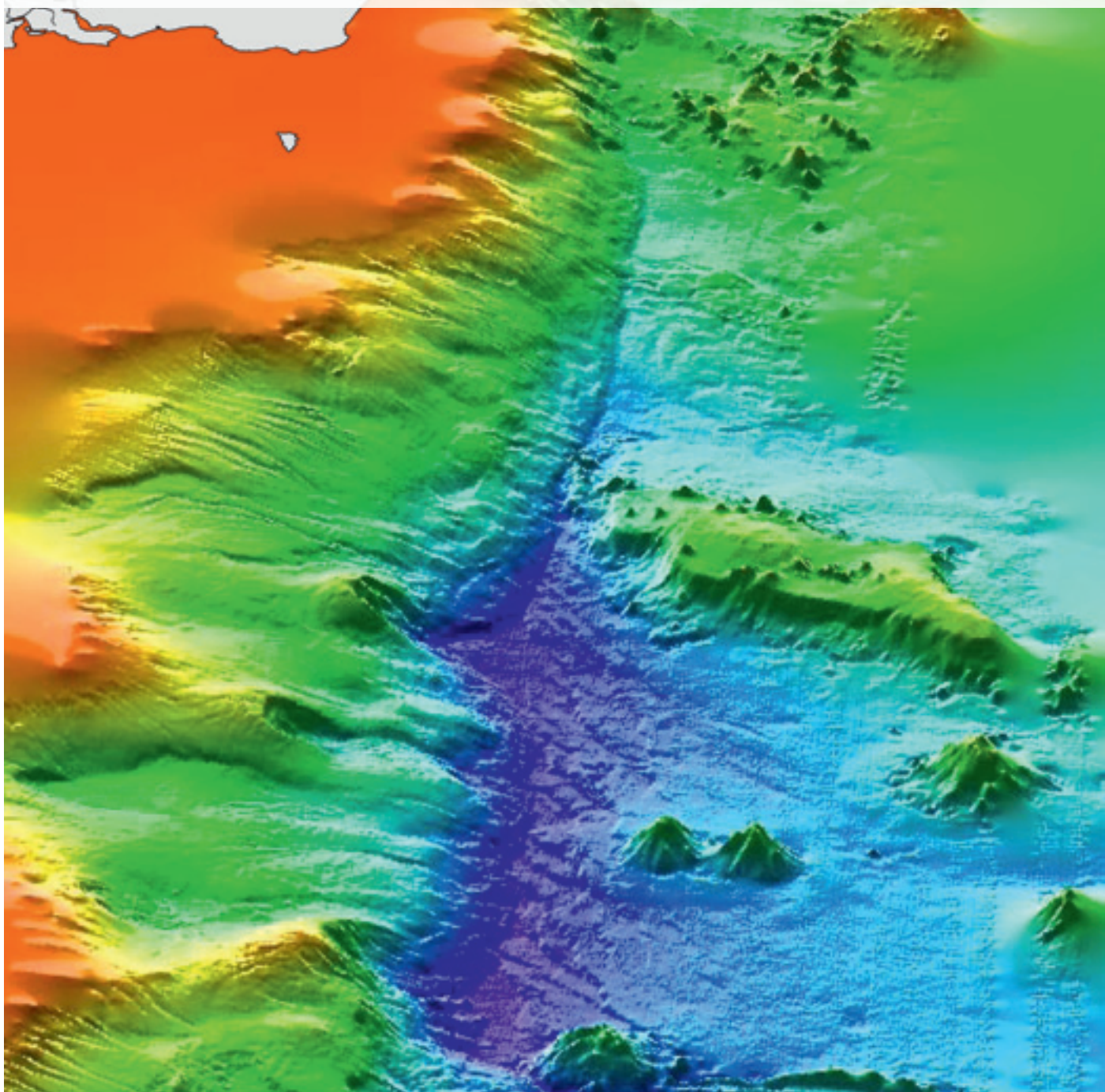
The analysis of chemical interactions within marine communities is relatively new compared to the study of feeding relationships. Chemical interactions include the production of defence substances against predators and fouling organisms, the production and recognition of signal substances, and the responses to these substances. Major current topics include the chemical regulation of macroalgae-herbivore interactions and sponge-microbial interactions. The latter is part of a national research project and has led to a spin-off company for the commercial use of natural substances for potential medical applications. Key research questions will address the role of micro-organisms in the chemical defence of marine invertebrates (host-symbiont interactions). These include the investigation of patterns and regulation of chemical anti-fouling and anti-predator defences and the effects of climate stress on chemical defence mechanisms.

Biodiversity Research: Marine Biodiversity - Patterns, Causes and Functions

While species extinction is proceeding at a rate unprecedented in history, basic patterns of biodiversity are still not explained satisfactorily and the ecosystem function of biodiversity has become one of the most active research areas in world-wide ecology. The scope of studies is expanding from species richness over functional diversity in food webs to genetic diversity at the intraspecific level. Field studies on biodiversity will focus on deep-sea microbial diversity, seamounts as regional hot spots of marine biodiversity, and the relationship between local and regional biodiversity. Experimental studies will analyse the role of environmental variability and disturbance in maintaining biodiversity and in the role of biodiversity in buffering ecosystem function against environmental impacts and invasion events.



3.4 DYNAMICS OF THE OCEAN FLOOR (RESEARCH DIVISION 4)



Research Division 4 (RD 4) focuses on studies of the seafloor and the margins of ocean basins.

The central research themes concern the processes that shape the ocean basins, and the impact of these processes on the environment, e.g. climate and natural hazards. These research themes are pursued in three main geotectonic settings: di-vergent margins (where oceanic lithosphere is created), convergent margins (where oceanic lithosphere is destroyed and continental crust is created and recycled), and intraplate regions (where the lithosphere is modified).

Spreading Centres: Formation of the Ocean Floor and the Ocean Basins

The ocean basins are formed by the breakup of continents and by continued plate divergence at oceanic spreading centres (“ridges”). Our focus is on processes that build the ocean floor. These are the processes by which the plates split and move apart, allowing mantle to upwell and partially melt, and the means by which the resulting magmas rise, intrude and erupt to form the oceanic crust. Hydrothermal and low temperature interactions between magmatic crust and seawater play a key role in the exosphere’s large-scale hydrologic cycle, and influence the deposition of mineral resources.

Convergent Margins: The Subduction Factory

At convergent margins, the subduction of an oceanic plate beneath another plate, in some cases the edge of a continent, results in a complex system of mass transfer, volatile exchange and chemical transformation between and within the down-going and over-riding plates. At the “subduction factory”, continental crust is generated through processes of accretion and fluid-induced melting of the subcrustal mantle, expressed as arc volcanism. It is, however, also partly destroyed through subduction erosion. Climate-influencing fluids and volatiles are transferred from the subducting plate and mantle wedge through the forearc and the volcanic arc into the hydrosphere and atmosphere. Convergent margins are also the sites of the most destructive earthquakes, large-scale mass wasting which can trigger deadly tsunamis, highly explosive volcanic eruptions, and permanent volcanic degassing, all of which continuously impact human society.

Intraplate Tectonic-Magmatic Activity: Modifying the Plate

Intraplate volcanism on the ocean floor occurs in several forms: hotspot volcanism as represented by chains of volcanoes and volcanic ridges which become older in the direction of plate motion, single isolated volcanoes (off-ridge seamounts), clusters of volcanoes without obvious age progression with respect to plate motion and oceanic volcanic plateaus often referred to as Large Igneous Provinces (LIPs). Intraplate tectonism occurs in association with this volcanism and on isolated features such as fracture zones within the oceanic plate. Intraplate processes have large-scale causes and effects: The eruption of LIPs causes long-lasting global climatic changes with devastating environmental impacts (e.g. all Phanerozoic mass extinctions occurred contemporaneously with LIP events). Intraplate volcanism is believed to be primarily related to mantle plumes rising from deep within the Earth and therefore plays an important role in the material and heat transfer from the lower mantle to the Earth’s surface. Intraplate tectonic and magmatic activity controls material exchange between the lithosphere and the hydrosphere in the largest crustal unit on Earth.

The Research Division (RD) also studies the evolution of the seafloor from the time of its formation at divergent plate margins to its destruction at convergent plate margins and is working on a proposal for a Graduate College that would also include RD 2, RD 3 and members of the Geoscience Institute at the University of Kiel. Furthermore, the Research Division established two junior research groups that investigate seafloor resources and geohazards within the Future Ocean Cluster of Excellence, with strong links to RD 2 and the Geoscience, Geophysics and Mathematics Departments at the University of Kiel.

Further research foci are:

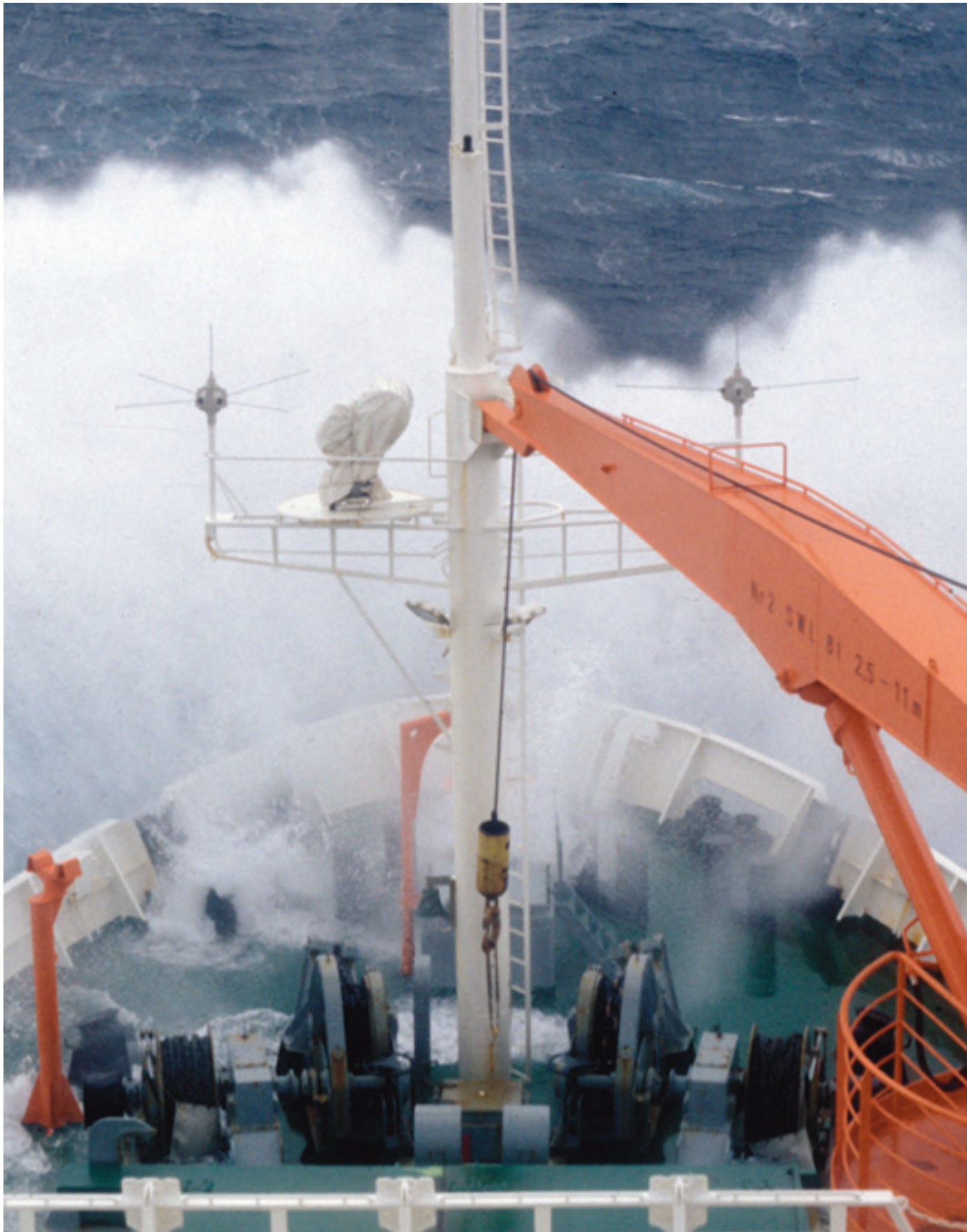
Margin Stability and Gas Hydrates

Gas hydrates are mainly found along the continental margins. Hydrates may be a future resource and potentially relevant for rapid climate change. However, accurate estimates of hydrate volume are lacking. Hydrates also play an important but complex role in the (de-) stabilisation of continental slopes. RD 4’s research focuses on the identification, quantification and distribution of hydrates at the continental margins, their effect on the shear strength (i.e. stability) of slope sediments and the causes and consequences of hydrate dissociation.

Geological Hazards

Geological hazards associated with oceanic intraplate volcanism and subduction include large-scale landslides, destructive earthquakes, highly explosive volcanic eruptions, and high-impact tsunamis. Hazard assessment requires a fundamental understanding of the trigger mechanisms for such events. RD 4 investigates earthquake activity during subduction, the stability of volcanic edifices and continental slopes (where seamount subduction and gas hydrates play essential roles), and past frequency and physical processes of volcanic eruptions. All of these can be key factors in tsunami generation.

3.5 RESEARCH INFRASTRUCTURE



Large sea-going equipment and laboratory infrastructure are essential for research in marine sciences. GEOMAR makes use of a full array of cutting-edge tools and instruments in marine science and technology. These include research vessels, two deep-sea ROVs and AUV technologies, a manned submersible, advanced observing technologies such as gliders, trace element and isotope facilities, molecular biological analyses, culture rooms, a core and sample depository and advanced computing capabilities.

Research Vessels

Research vessels of different types and sizes are vital for present and future research at GEOMAR, since they provide the necessary platforms for a wide range of science programs that investigate both coastal and ocean environments. GEOMAR operates four fully-equipped research ships of different classes. The ocean-class R/V POSEIDON has been operating since 1976 in the North Atlantic and adjacent seas. The regional class R/V ALKOR has been in service since 1990 in the Baltic and North Seas. For student education and training, GEOMAR also operates two smaller ships, the research cutter LITTORINA, which has been used since 1976 in the western Baltic and is operated in cooperation with the University of Kiel, and the barge POLARFUCHS, which is used for local research and the testing of new technology.

GEOMAR scientists can also submit proposals for access to four large ocean-class German research vessels R/V SONNE, R/V METEOR, R/V MARIA S MERIAN and R/V POLARSTERN on a competitive basis.

Technology and Logistic Centre

Since 2006 one of GEOMAR's central units has been the Technology and Logistic Centre (TLZ), which operates a fleet of deep sea vehicles and all of the centre's ocean-going equipment, many of which are unique in German oceanographic research. Of particular importance are the manned submersible "JAGO" with a 400m diving depth, the "Kiel 6000" work class ROV (6000m), the "Phoca" work class ROV (3000m), the "Abyss" AUV (6000m), a mobile multi-disciplinary deep-sea observatory ("MoLab"), five deep sea lander systems, nine

floating open ocean mesocosms, various smaller ocean observatories, a broad spectrum (4-400kHz) of acoustic sources and receivers including a 3D towed streamer system, deep towed acoustic and electro-magnetic systems, a large TV-operated grab (6000m), towed ocean bottom observation systems, oceanographic mooring systems, deep sea probes, and nine ocean gliders. About 45 engineers, technicians and mechanics are employed in the TLZ which also supports five apprenticeships in precision mechanics and electronics. The TLZ includes workshops for metal, wood, and synthetic materials as well as for electronics. It is responsible for the design and construction of new instruments and set-ups for experiments in direct cooperation with the scientists, as well as for the maintenance of instruments and vehicles and their adaptation to specific operational requirements and conditions. The TLZ is equipped with heavy lifting gear, test tanks (up to 1000bar), a CTD calibration laboratory, and other specialized installations. It cooperates closely with local SMEs specializing in marine technology. With the deep sea vehicles listed above, some of which are unique in German and European ocean research, GEOMAR is well equipped to address the great scientific challenges of future ocean research, and is internationally competitive.

GEOMAR also makes this research infrastructure available to other German and European institutions. The development of deep sea technology offers great potential for innovation and for technology transfer to industry and society. The technological infrastructure and expertise of the TLZ therefore provides an outstanding contribution to the nation's facilities for oceanographic and deep sea technology, and to the perception of German oceanographic research in the scientific, industrial, political, and general communities.





Trace Element and Isotope Analytical Facilities

Precise measurement of the composition of trace elements and their isotopes is the basis for research in almost all fields of modern marine science. The continued development of analytical methods to address existing and new problems in marine science, as well as a continued drive for improvement in precision, accuracy, spatial and temporal resolution and sample-throughput of existing methods, is a focus of research in this field. At GEOMAR, a wide array of stable, radiogenic and radioactive isotope systems (e.g. O, C, N, Mg, Si, Ca, Fe, Sr, Nd, Pb, Hf, U, Th, Ra and Ar), as well as trace elements, are analyzed to obtain information about chemical speciation, bioavailability, sources, sinks, transport and redox processes within the ocean, and for age determination of various fluids and sedimentary, metamorphic and igneous rocks. For example, trace elements and their isotopes as measured in suitable marine archives, in relation to measurements in the present day water-column and sediment, can provide proxy information for past oceanic conditions, including seawater temperature, salinity, pH, and ocean circulation. They can also provide information concerning the origin, age, and evolution of the seafloor, including chemical exchanges between the seafloor and seawater.

The analytical facilities at GEOMAR are equipped with the latest generation of instruments, including state of the art mass spectrometers, voltameters, and flow-injection systems, all of which allow the development and application of new techniques for tackling cutting-edge scientific problems in marine sciences. For accurate and precise determination of

element concentrations and isotope ratios, the mass spectrometer facilities of GEOMAR are equipped with two multi-collector ionization coupled plasma mass spectrometers (MC-ICP-MS) and two thermal ionization mass spectrometers. These enable the determination of the isotopic composition of almost all elements of the periodic table. Several state of the art gas mass spectrometers for stable isotope measurements of carbonates, and a laser Ar–Ar mass spectrometer for age dating of single crystals and other particles are also available. Additional instruments for determining major and trace element contents in sedimentary pore fluids, seawater, sediments and igneous rocks complement the analytical spectrum. Sea-going analytical systems include voltametric systems for trace metal speciation analysis and flow-injection chemiluminescence, and spectrofluorometric systems for determination of iron and other bio-elements at ambient open ocean levels. For almost all of these analytical systems, it is essential to avoid contamination during preparation and analysis of samples which requires modern, ultra-clean laboratories, the largest of which was finalised in 2009. In addition, GEOMAR maintains a sea-going containerized clean room for collection and ship-board analyses of open-ocean seawater samples.

Recent analytical developments include high spatial resolution and precise measurement of trace elements and their isotopes on small samples by a laser ablation system coupled with either MC-ICP-MS or an ICP-MS instrument. This allows the measurement of selected trace elements and their isotopes within solid samples without any chemical preparation. A recently installed state-of-the-art electron microprobe allows in-situ high resolution “mapping” of major and selected trace elements in solid samples. In order to maintain the high standard of the existing facilities and to keep up with new requirements and demands, the installation of two modern mass spectrometers and a new electron microprobe system is planned for the near future. Furthermore, a new trace metal sampling CTD rosette system, enabling contamination-free seawater sampling in the full water column is envisaged for 2012.



Molecular Biological Analyses

Molecular biology and, more recently, genomics are revolutionizing all fields of life sciences. Marine science is no exception in this regard. For example, many major discoveries concerning the role of marine microbial communities have been made by combining molecular methods with more traditional approaches. In general, molecular methods provide ideal tools to characterize taxonomic units, such as populations, and species in space and time. Thereby, they can be implemented in defining biodiversity and in tracing the pathways of evolution. Selective forces, such as ocean warming or human fishing activity, have been shown to cause adaptive genetic changes and often also a loss in genetic diversity.

Understanding evolutionary responses of marine organisms to a changing environment and human influence is central to the prediction of future scenarios and for development of management options such as implementation of protective measures or the establishment of marine protected areas. Molecular approaches are a fundamental basis for modern research in these areas.

Basic molecular techniques are well established at GEOMAR at the central molecular laboratory. The laboratory has a permit to conduct genetic work at the S1 level (lowest safety level), and is well equipped for techniques such as DNA and protein gel electrophoresis, PCR, qPCR and DNA cloning.

In addition to gel electrophoresis equipment, camera systems, and three standard thermocyclers, the laboratory hosts an ABI Prism 7,000 instrument for qPCR (gene expression and Taqman assays for identification of microbial groups), two -80°C freezers, a Nanodrop system for the accurate quantification of nucleic acid concentrations, a spectrophotometric 96-well plate reader and a chemiluminescent system for immunodetection of proteins on western blots. Recombinant DNA work at the S2 level in the context of environmental metagenomic studies will also be possible in the near future.

Concomitant with these developments and increased applications are collaborations in the field of bioinformatics (or computational biology) which will enable exploitation of rapidly growing information contained in the genomes and metagenomes of marine organisms.

Culture Rooms

Experimental ecology is being studied by substantial parts of Research Divisions 2 and 3 and relies heavily on a technically sophisticated infrastructure which enables a controlled, manipulative and replicated investigation of the interactions between organisms and their abiotic and biotic environments. Practical research in marine sciences usually relies on three complimentary pillars: field work in the oceans, laboratory investigations, and culture room experiments which simulate small sections of the real world in a controlled manner.

In the framework of the Excellence Cluster “Future Ocean”, the culture rooms at GEOMAR will play an even more prominent role. They will be used as a laboratory tool to investigate the reactions of individual organisms, populations, communities and interspecies interactions to a changing environment. Variables which can be manipulated include light, temperature, salinity, pH, CO_2 , stratification, and nutrients. To realistically simulate possible future climate scenarios, these variables must be manipulated in different combinations. Together with other ongoing research, the new foci can be implemented in a moderately large set of culture rooms which cover different ranges of temperature between 4°C and 25°C . The larger rooms are equipped with filtered running Baltic Sea water ($90\text{ m}^3/\text{d}$). Proposed construction of the new institutional facilities on the east shore include plans for extending and modernizing the culture room. Changes will include a facility with an effective temperature range of -2°C to 30°C and must be supplied with open circuit Baltic water (filtered and unfiltered, total supply: $100\text{ m}^3/\text{d}$), closed circuit artificial seawater, temperature-controlled fresh water, gas supply (air, CO_2 , O_2), and adjustable light. Computer-control, alarm systems and webcam facilities are also important additions. Rooms (20 m^2) for storage, laboratory facilities and a workshop are proposed. One full technician is required for maintenance and service.

Lithothek

More than 17 kilometres of sediment core and approximately 100,000 rock samples were recovered during GEOMAR expeditions. Half of every core recovered is kept as an “archive half”, normally only available for viewing. Work half-cores are used for sampling and further analysis as well as automated non-destructive geophysical measurements (i.e. “core logging”), including many of those which provide essential data for reconstructing the Earth’s climatic history, such as high-resolution magnetic susceptibility, natural gamma spectroscopy, and UV/VIS/IR spectrophotometry. Currently, 400–500 m of sediment core are added to the core repository annually.

Information Centre

The Information Centre of GEOMAR consists of the Data and Computing Centre and the Library.

The Data and Computing Centre is responsible for all information and communications technologies. It focuses on the central administration of an extensive server park running EDP services that include “supercomputing”, office applications, networking, the network security of approximately 400 work stations, the connection to the LAN of the University of

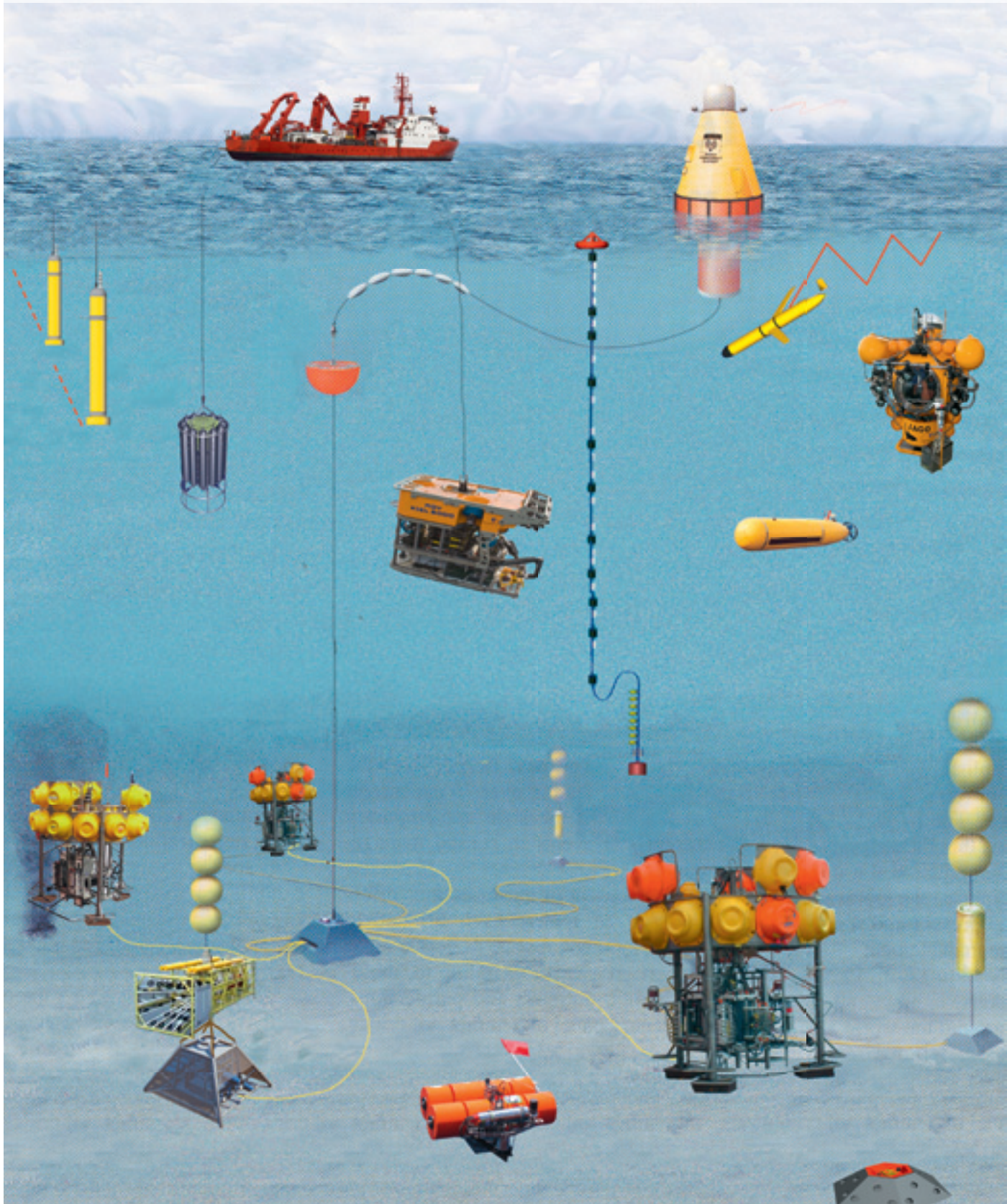
Kiel and the Internet, as well as data management and web presence. The hardware consists of computers of all sizes, from high-end computers to PCs. Central computing and file servers are mainly used for extensive data analysis and processing. GEOMAR collects several gigabytes of observational data and accumulates terabytes of modelling results annually. Currently, the central back-up and storage system (HSM-Hierarchical Storage Management System) is licensed for 70 terabytes with 20 terabytes of online disk space and 50 terabytes of magnetic tapes. This system, together with the computing servers, are part of a high performance SAN (Storage Area Network). With increasing user requirements of disk space, the storage capacity can be enlarged by an additional 160 terabytes. The HSM-System allows for a permanent usage of several terabytes of on-line disk space for analysis and visualisation of model output and comprehensive observational data. It also allows the storage of large data sets (model, video, satellite data, etc.) for later use. High-performance computing facilities are provided by the University of Kiel through a NEC SX8 vector computer (5 nodes, 20 terabytes disk space, tape library). To satisfy the growing needs in computing power due to the increasing complexity and higher resolution of numerical models the power of the NEC SX8 will be increased.

The library is one of the largest and oldest marine science libraries in Germany and as such internationally recognized. The library hosts a comprehensive collection of books on subjects related to various fields of ocean sciences, a collection of about 130,000 media items, and nearly 800 open serial titles. The GEOMAR library is a member of several national and international library associations and cooperates closely with the Library of the University of Kiel. Via a z39.50 interface, it is able to participate in the “Linking Libraries Project”, which aims at resource sharing among marine and aquatic science libraries worldwide.





4.1 IN-SITU OCEAN OBSERVATIONS



Marine sciences in the 21. century must meet a growing demand for qualitative and quantitative ocean observation. In-situ observation is needed to continuously track global ocean properties as outlined by the international concepts formulated in GOOS (Global Ocean Observing System) and at the regional and local scale. Increased understanding of the marine system prompts new questions regarding, for example, the interaction between marine sub-systems such as the seafloor and the water column, oceanographic circulation and the ecosystems. These elements and processes must then be considered in interaction with marine chemistry. Of growing interest is the time evolution of crucial processes on interannual to multi-decadal time scales.

Dramatic advances in sensor and communication technologies have opened up exciting new possibilities for marine sciences. Ship-based surveys can be extended in scope by launching AUVs (Autonomous Underwater Vehicles) such as the GEOMAR's AUV "ABYSS", which can be programmed to map the seafloor and environmental conditions in the deep ocean down to 6000m at high resolution independently of a research vessel. Highly energy-efficient gliders (propeller-driven miniature submarines) operate in the water column to collect oceanographic data.

Precise sampling at the seafloor is possible with deep diving, manned submersibles such as GEOMAR's JAGO or tethered unmanned remotely operated vehicles such as the ROVs "Kiel 6000" and "PHOCA". Controlled in-situ manipulations are now possible within small benthic chambers attached to seafloor lander systems. Floating mesocosms can be used to study the ocean's response to changes in environmental conditions, such as increased CO₂ and reduced O₂ levels. Tagging of water bodies by drifting floats or harmless chemical substances allow the study of dispersion and mixing in the ocean on sub-basin spatial scales.

To document the evolving ocean, efforts are under way to establish long-term multi-disciplinary ocean observing systems that contribute to an understanding of the processes at one location. These systems will be part of the global network called OceanSITES and thereby contribute to an understanding of the overall picture. The classical equipment are either bottom-mounted sensors such as seismic recorders and

temperature, pressure and inverted echo sounders or moored systems in which a vertical array of instruments such as current meters, temperature and salinity sensors are deployed. In some regions, it is now possible to connect observing systems to seafloor communication cables. Alternatively, there are several new options of transmitting data back to shore which range from infrequently launched data shuttles to subsurface winch systems that allow for daily communication, and a permanent small surface expression with satellite data transmission.

Finally, drifting profiling floats within the international ARGO consortium today sample the upper global ocean on a weekly basis. This network has the potential to grow in scope from measuring not only temperature and salinity, but also dissolved oxygen and other parameters. In coastal and shelf regions, the network needs to be augmented by gliders that can be recovered and have the ability of limited navigation. Both systems provide options for full ocean depth sampling.

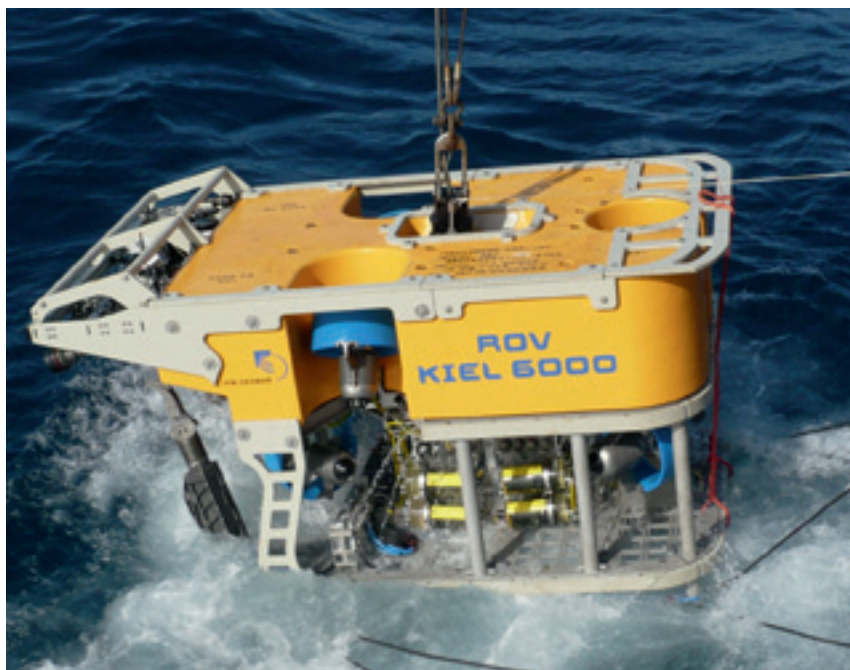
In summary, GEOMAR, together with its national and international partners, is one of the world's leading marine science institutions in pursuing a wide range of cutting-edge observing technologies. These exciting technologies advance our understanding of the global marine environment from the deep seafloor, the deep and upper oceans, to the atmosphere. Our efforts are integrated in international frameworks under the international GEO-Program (Group on Earth Observations), which supports the implementation of GCOS (Global Climate Observing System) with its marine part GOOS. On a European level, GMES (Global Monitoring for Environment and Security) is a strong partner in GEO.



**High-priority developments
at GEOMAR include:**

Remotely Operated Vehicles (ROVs)

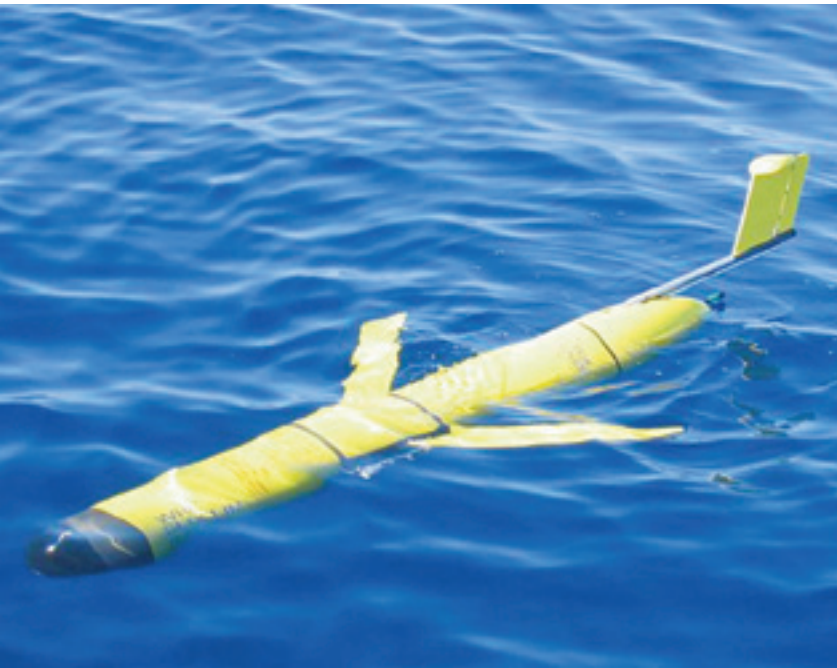
GEOMAR operates two work class deep-sea ROVs, which have a depth rating of 6000 m (“KIEL 6000”) and 3000 m (“PHOCA”). They have highly efficient electric propulsion systems, hydraulic systems, five and seven function manipulator arms, high-definition cameras, high bandwidth telemetry systems, and a modular design in terms of their scientific payloads and electronics, making them one of the most advanced and diversified deep-sea vehicle fleets of its kind for scientific research. The scientific modules and pay loads that are emplaced on the sea floor by the ROVs are being continuously developed and assembled at the TLZ. The KIEL 6000 and PHOCA ROVs are vital to our deep sea research activities. They are also used for installation and maintenance of ocean observatories, such as GEOMAR’s “MoLab” mobile observatory and other observatories that are planned for the Arctic (Fram Strait) and the tropics (Cape Verde).



AUV (Autonomous Underwater Vehicle)

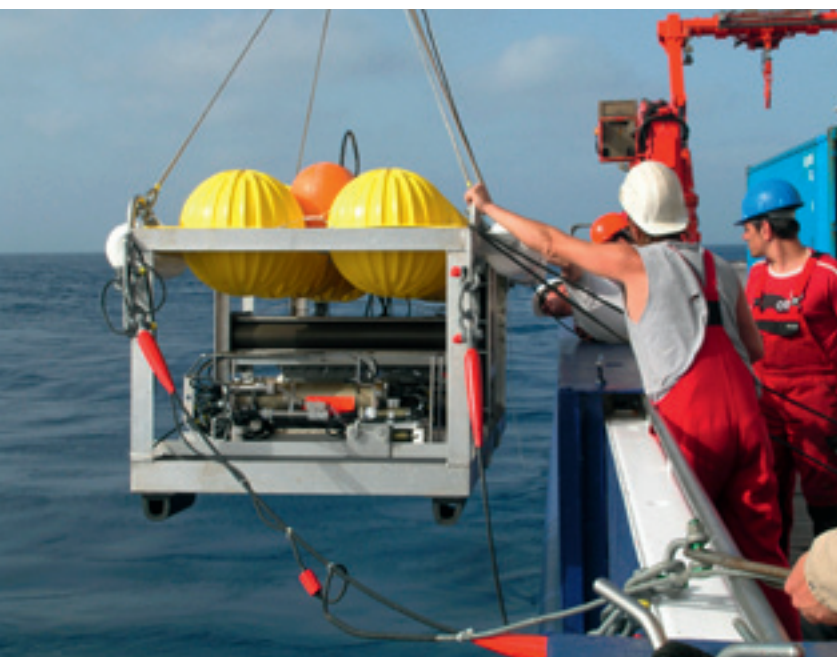
GEOMAR operates an AUV (“ABYSS”) for deep-sea applications (6000 m rated). Its basic configuration consists of swath bathymetric, side-scan and sediment penetrating sonar, optical backscatter sensor, navigation units and communications equipment. It allows measurements of both the seafloor and the water column at a higher spatial and temporal resolution than ship-mounted systems. It can be adapted with specialized sensors according to scientific needs.





Glider Swarm

A small number of autonomous low-power ocean gliders are operated by GEOMAR. Gliders sample the upper ocean (up to 1000 m depth) with low power electronic sensors. They rise to the surface 4 to 8 times per day, where they communicate their data via satellite phone and receive instructions for the next dive. In the future, we plan to deploy a small fleet of 5-10 gliders to enable four dimensional observations within key ocean regions. The observations will improve our understanding of temporal and spatial interactions within mesoscale eddy regimes, upwelling zones and the exchange between the mixed-layer and the ocean's interior.



Tracer Injection System

The GEOMAR Ocean Tracer Injection System (OTIS) allows for injection of a non-toxic chemical tracer into the ocean and to subsequently survey the dispersed patch with a chemical detection system. The dispersion of the tracer patch is documented by discrete water samples that are analyzed using a gas chromatograph. Open-ocean injections of 100 kg tracer release 510 moles that can be traced for several years until the concentration drops below 10-14 mol/kg. Tracking vertical and horizontal dispersion allows the determination of precise ocean mixing and stirring rates that are crucial for the improvement of ocean models. Future experiments are planned to study questions that pertain to large-scale climate, biogeochemical interactions, and the exchanges between benthic and pelagic systems.



Multi-disciplinary Long-term Observatories

GEOMAR has a long-standing tradition of research using cutting edge observation systems. Bottom landers for long-term benthic observations, seafloor mounted seismographs, and full ocean depth mooring systems are some of the key technologies that are under constant development. Modular multidisciplinary observatories with the ability to survey larger areas over longer time scales are seen as the next step in ocean observation, which is why we have developed the “MoLab” mobile modular multidisciplinary laboratory or observatory for benthic boundary layer research down to a depth of 6000 m. The MoLab observatory can conduct synchronous measurements of different oceanographic parameters, which will enable us, for the very first time, to investigate interconnected processes on various scales using a truly 4-D approach. The comprehensive data sets will be used as a basis for various types of numerical models to improve our understanding of processes operating both on the seafloor and within the water column. We plan to develop additional advanced, modular, long-term multidisciplinary ocean observing systems. Since one of the main concerns in such systems is the power supply, the use of low-energy sensors and data systems is being explored, together with alternative fuel cell technologies. If available, a local network of seafloor cables can provide real time communication. Low bandwidth surface telemetry from full ocean depth moorings, profiling winch systems, and infrequent autonomous data transmission are some of the options. GEOMAR has formed a strategic partnership with the Cape Verde Islands to jointly operate a multidisciplinary open ocean observatory in the tropical Atlantic. Other sites include the high Arctic (Fram Strait), and locations of international collaborations such as the EMSO and OceanSITES networks.



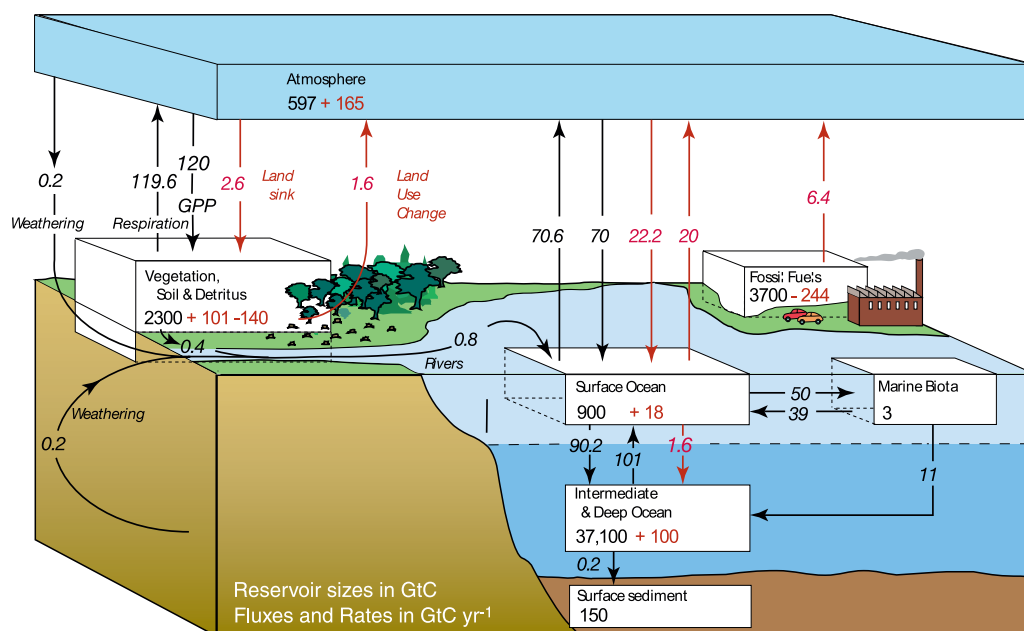
Off-shore Mesocosm Facility

A total of six free-floating mesocosm systems for off-shore deployment have been developed by the Technology and Logistics Centre of GEOMAR. The facility is used for manipulative experiments to simulate marine environmental changes, such as ocean acidification and redox-related shifts in nutrient stoichiometry in natural pelagic communities. Each of the six (later nine) mesocosm units comprises a floating device which supports a flexible bag that encloses 50–80 m³ of seawater. The facility includes basic instrumentation such as an automated CTD profiler, sensors for light intensity, pH and oxygen concentration, and depth-integrating water samplers. The mesocosms are fully containerized to facilitate ship transportation. Off-shore mesocosm experiments are conducted as part of the SOPRAN (Surface Ocean Processes in the Anthropocene) project and will be an integral part of national and international programs on ocean acidification.

Voluntary Ship Observations

Energy and material exchange between the ocean and the atmosphere plays a crucial role in the physical (heat), chemical (CO₂), and biological (primary production) development of our climate system. GEOMAR has developed a multi-disciplinary, ship-based, autonomous measurement system that monitors all relevant atmospheric forcings and associated biological and chemical responses. In combination with satellite data, feedbacks to the atmosphere are also investigated. This system has been mounted to voluntary observing ships with the aim to establish a network of in-situ and remote sensing observations on a long-term time scale.

4.2 CLIMATE AND OCEAN SYSTEM MODELLING AND SYNTHESIS



The scientific impact of numerical climate and ocean modelling has grown dramatically over the last few decades. In addition to contributing to our fundamental understanding of climate and ocean dynamics by extending theory beyond the limits of analytical methods, modern numerical modelling systems have now reached a degree of realism that enables valuable planning of cruises and field experiments, as well as providing an essential information base for decision makers.

Scientific interest in climate and ocean modelling arises to a large extent from our need to better understand, quantify, and eventually predict the ocean's role in the global energy, water, and carbon cycles, and to provide projections of the future climate. Cycles of related elements, such as nitrogen, phosphorus or iron, can act as limiting nutrients for phytoplankton growth, as well as oxygen, which controls a number of redox processes involved in the cycling of these elements. Other aspects include the prediction of decadal climate variability, the impact of ocean acidification, harmful algal blooms, a quantitative understanding of oceanic food webs and the possible impact of marine sulphur and halogen emissions on atmospheric chemistry and the radiation budget.

In order to account for the relevant feedbacks that act in the climate system and involve physical, biogeochemical and, in the anthropogenic, socio-economical processes, climate and ocean system models will require multi-disciplinary approaches. While physical model components are now considered to be relatively mature, ecological and biogeochemical components are still at an early empirical stage, that must be superseded by more mechanistic models before reliable extrapolation to new climatic environments can be made. This new generation of coupled Earth system models will also be applied with respect to changes in past ocean circulation in order to understand key periods of past climates on different time scales, ranging from a million years (e.g. the Cretaceous green house) to

centennial time scales (e.g. abrupt climate changes during the last glacial period).

The use of ocean and climate models to examine current and past climate events is an important avenue of research in order to gain confidence in their application to future climate change projections. By combining information from spatially and temporally isolated data points with a mathematical description of the laws of nature, of postulates or of hypothetical concepts, models yield an internally consistent description of the ocean and its evolution over time. Alternate models and observations can, on the one hand, enhance data analysis and interpretation and on the other hand, help to identify model shortcomings and guide model improvement.

Diverse numerical model requirements are associated with the vast range of space and time scales in applications ranging from studies of individual processes to simulations of long-term global changes. GEOMAR modelling efforts are aimed at establishing a common model environment (the "Kiel Climate Modelling System") that comprises a flexible hierarchy of model components of various complexities. The development of individual model components is linked to various national and international activities and model consortia. These provide important frameworks for critical assessments of model behaviour, for example, in the context of coordinated model intercomparison efforts.

Other areas of future modelling challenges include:

High Resolution Nested Models

High priority developments at GEOMAR include coupled climate–ocean–biogeochemistry models that account for feedback processes governing past and future climate development over centennial to millennial time scales. The main emphasis is on the improved representation of critical marine physical and biological processes that require much higher resolution of the ocean component than presently achieved in climate modelling. An important element of the model system in this context is the provision of “nesting” capabilities that permit a targeting of specific resolution needs to key oceanic processes and areas.

Parameterisations of Unresolved Physical Processes

An ongoing task is the development of improved representation of small-scale physical processes which cannot be resolved in the next generation of global models, even though they govern the long-term evolution of the ocean–atmosphere system in numerical simulations. Research efforts in this respect build on the tradition of a strong interaction between observational scientists and modelling groups at GEOMAR. In particular, joint research programs between the

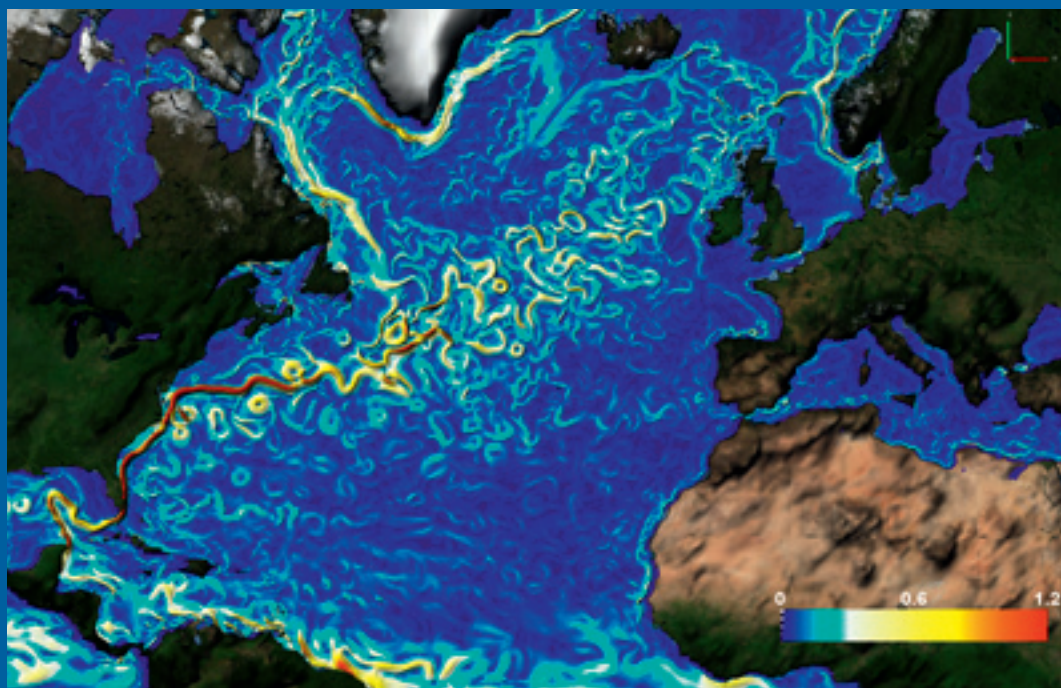
two approaches target turbulent mixing processes within the ocean surface and bottom boundary layers, as well as exchanges at the sediment–water interface. A second aspect is lateral dispersion and mixing due to mesoscale eddies in the ocean. Typically, ocean models can not resolve the mesoscale, and hence parameterisations are required.

Data Assimilation and Model Guided Sampling

Increasing capabilities of robotic sampling systems such as drifters, gliders and AUVs allow an intense observation of ocean parts in a semi-automatic fashion. In order to maximize the information gain, the observed data must be assimilated into regional ocean models in real time, to allow for the sampling capabilities to be guided to regions of largest uncertainty. New modelling capabilities are needed which can optimally integrate operational forecast products from national and international centres with research mode data assimilation to guide autonomous sampling systems.

Evolutionary Ecosystem Models

Much of the current effort towards improving ecosystem model realism is devoted to refining the representation of ecosystem structure in terms of species resolution. This is achieved at the expense of a massive increase in the number of model parameters that are exceedingly difficult to constrain. A new alternative is the development of evolutionary-based modelling strategies to describe marine ecosystems. In contrast to resolving individual species, each with prescribed and fixed properties, evolutionary models consider species populations as the smallest entity, each population having a continuous property spectrum. Environmental conditions and trophic interactions determine the growth of populations and at the same



High resolution ocean/sea-ice models simulate the variability of the North Atlantic circulation (figure shows a snapshot of surface speed in a 1/12 global model)

time select for optimal properties, thus leading to shifts in property spectra. This approach requires robust and efficient representations of property spectra and may include phenotypic or genotypic approaches. Successful development of evolutionary ecosystem models builds on a close collaboration between theoretical and experimental groups, both well-established at GEOMAR.

Benthic-Pelagic Coupling

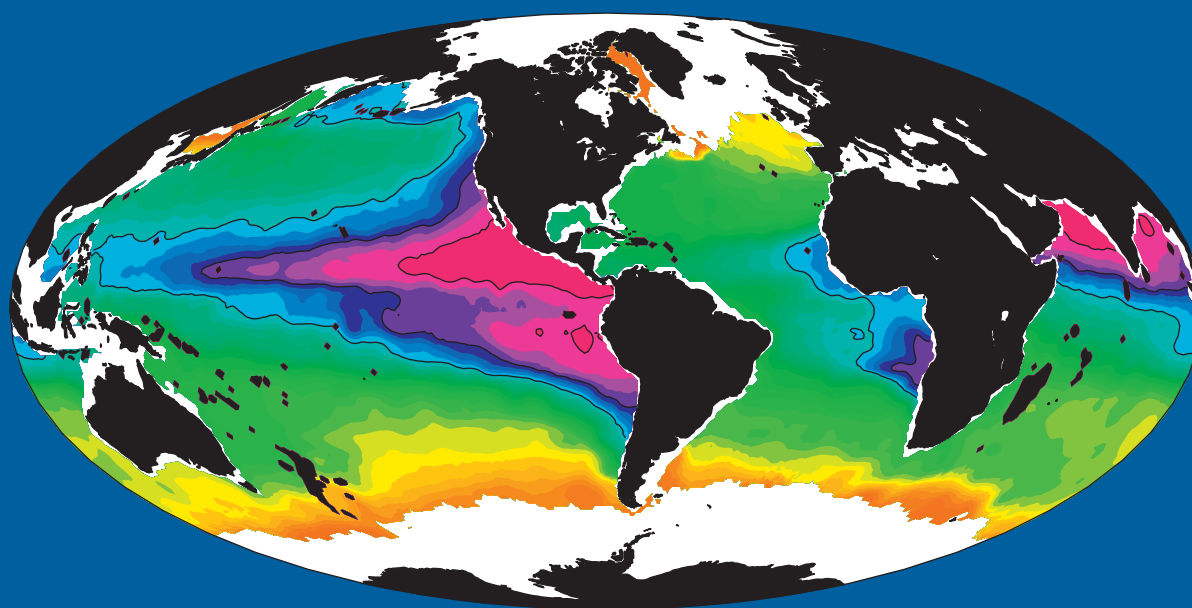
Benthic biogeochemical reactions are driven by the vertical flux of pelagic organic matter to the seafloor and are further influenced by, and feed back to, bottom water concentrations of dissolved nutrients and oxygen. These reactions ultimately control biogeochemical processes in the water column and thereby affect climate-biogeochemistry feedbacks in the Earth system. Because of the different transport processes involved, response times to changes at the sediment-water interface are typically orders of magnitude larger for the sediment than for the water column. Spinning up the coupled system over the long benthic time scales is computationally expensive, and efficient coupling algorithms are required to include dynamic sediment modules in state-of-the-art high-resolution climate models.

Reactive Fluid Flow Through the Sea Floor

Earth sciences have progressed from descriptive to quantitative studies of geological processes. At GEOMAR, computational methods are becoming increasingly important as quantitative research tools that allow a combination of different data sets as well as the testing of new ideas and concepts.

Examples of this include numerical studies of deep-sea hydrothermal systems and of melt migration patterns at rifted continental margins. The discovery of hydrothermal systems at mid-ocean ridges in the late 1970s was one of the most exciting developments in the marine sciences, because of its importance for different fields of geosciences. Hydrothermal systems efficiently mine heat from the young ocean floor, host unique ecosystems in extreme environmental conditions, and are associated with commercially interesting high-quality ore deposits on the seafloor. However, much of our knowledge of hydrothermal systems originates from surficial observations of vent sites. The patterns of deep hydrothermal flow inside the oceanic crust are inaccessible to direct observation. The next generation of reactive transport models, which are currently being developed at GEOMAR, will be important tools for better understanding and elucidating the details of hydrothermal flow through the crust.

Similarly, the geological processes that lead to continental rifting and the opening of new ocean basins are closely linked to melt migration through the Earth's lithosphere. It has recently become apparent that continental rifting cannot be adequately understood without accounting for feedbacks between deformation, melt/fluid migration, and metamorphic reactions. Improved numerical models will be the key for integrated studies of continental rifting and for a better understanding of the geological processes responsible for the formation of new ocean basins.



Dissolved oxygen concentrations on the 26.9 isopycnal (at a depth of about 300m). Pink areas denoting low oxygen waters are located predominantly in the tropical ocean.

5 TRANSFER TO APPLICATION



The primary mission of GEOMAR is “fundamental research”. The ultimate purpose of basic research is to provide a sound and objective basis of information for the non-scientific recipient and for society in general. Moreover, the Institute strives to link fundamental knowledge to applied issues concerning human use of the ocean (resources).

5.1 Transfer of Knowledge

Scientists at GEOMAR provide leadership to international scientific programs such as World Climate Research Program (WCRP), International Geosphere-Biosphere Program (IGBP), and Integrated Ocean Drilling Program (IODP). Furthermore, they have acted as authors on the latest report of the Intergovernmental Panel on Climate Change (IPCC), published the World Ocean Review, a current state analysis of the oceans, and are actively involved in providing guidance to various state and federal governments or to the European Commission. Expert advice from GEOMAR scientists is frequently sought from companies who work in the marine sector, and other governmental and private decision makers. GEOMAR scientists cooperate with public schools to acquaint pupils and teachers with marine research. Finally, GEOMAR scientists work closely with the media (TV, radio, newspapers and journals) to convey the excitement of marine research and share the latest discoveries with the public at large.

5.2 Marine Protected Areas

Recognition of increasing human pressure on marine ecosystems has created the political will to establish Marine Protected Areas (MPAs) in many countries. There is growing concern about ecosystems of the open ocean and large marine ecosystems that extend beyond exclusive economic zones or that are shared by several nations. These deep-sea habitats are threatened by largely unregulated human activities. In addition to the need for a legal basis for establishing and operating MPAs in international waters, a further problem is the lack of scientific knowledge required to design and effectively operate MPAs.

National and international policy makers frequently point to the need for science programs to accompany marine related policies including OSPAR (North Sea), HELCOM (Baltic), the European Policy on maritime affairs, the UNESCO “Mauritius Strategy” and others. However, application of scientific data for Marine Protected Areas is still in its infancy. One may well question the purpose of MPAs if neither the area itself, nor the definition of harmful versus tolerable activity or the ability to assess effectiveness is based on sound scientific information.

Scientists at GEOMAR already contribute significantly to marine protection and management policies. However, this role can be expanded by providing basic science information for the establishment and management of MPAs in areas and ecosystems that are the focus of our research activities.

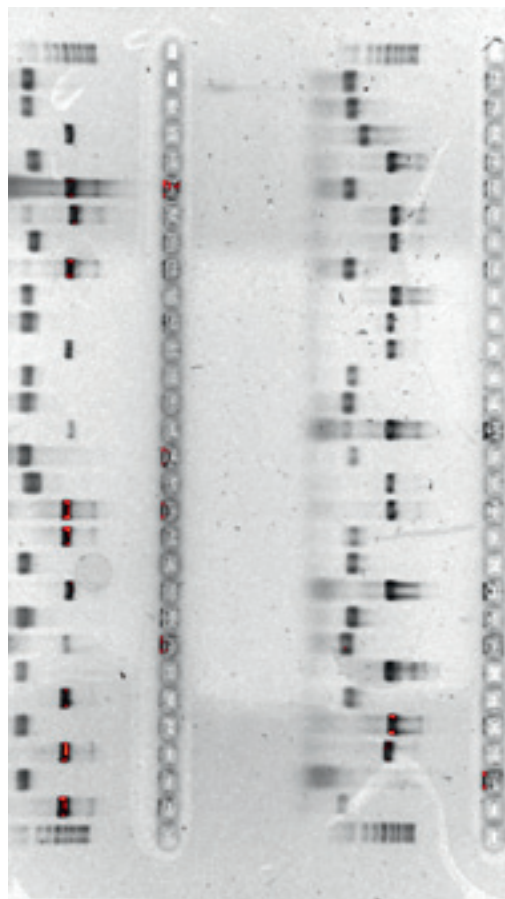
5.3 Marine Natural Products

Research on new natural products is a major focus of the Marine Microbiology Research Department. The “Center for Marine Substances Research” is a platform for the investigation of natural products from marine microorganisms and bioactive components. The major goals include studies of the role of natural products in biological interactions between marine organisms, within marine ecosystems and their transfer to applications. Natural products from marine bacteria and marine fungi are a particular focus with respect to applications in medicine. Major research topics include the biology of actinomycetes, the biosynthesis of secondary metabolites and their regulation, the systematics of marine fungi, and aspects of quorum sensing and molecular communication, particularly in interaction with the formation of secondary metabolites. The target is clearly oriented towards applied aspects in order to identify and develop new substances for the treatment of human diseases. The most important applications are infectious diseases by bacteria (including multiresistent forms), fungi, and viruses, as well as cancer, neurological, and inflammatory diseases. Experimental work includes all steps starting from the ecosystem to the purified chemical substance and the conduction of pre-clinical studies. Alliances in the field of the Blue Biotechnology in Schleswig-Holstein were formed to ensure rapid transfer of scientific results into commercial products.



5.4 Marine Genetic Resources

Marine bioprospecting is a future area of growth. The ocean represents 90% of the Earth's biosphere and hosts living organisms that have adapted to some of the most extreme conditions of light, temperature, pressure, and nutrients observed on Earth. Given the remoteness of many oceanic regions, it is not surprising that the marine biota and their genetic diversity remain largely unexplored even today. Microbes, in particular, are a promising source of material for biotechnology applications, including the discovery of new proteins, polymers, carbon-neutral biofuels, drugs, and enzymatic processes. Certain enzymes may even be capable of providing improved, cleaner industrial processes, increase environmental sustainability, and decrease environmental pollution. Although only 1% of marine microbes are culturable, the advent of marine genomics and metagenomics allows the exploration and exploitation of marine genetic resources without the need to cultivate the living organisms in the laboratory. The exploitation of marine genetic resources will be undertaken in such a way as to preserve their sustainability.





5.5 Marine Aquaculture

Marine finfish and crustacean aquaculture in its present form is far from representing a substantial relief for overexploited natural resources. The dependency of aquafeeds on fish meal and fish oil, eutrophication caused by massive nutrient export from open aquaculture systems and interactions of domesticated aquaculture escapees with wild populations, further impair the condition of wild stocks. Ongoing research on the substitution of fish meal in shrimp diets, the development and improvement of integrated and land-based systems, as well as the identification of reliable indicators and models for site selection of fish and shellfish farms and monitoring of their environmental impact, directly address these topics and contribute to the optimization of culture systems. However, due to environmental problems with open cage farming in marine environments, research and development activities increasingly focus on closed or near-closed systems.

As a further step towards combining expertise and strengthening the research competence in this promising area of research, the “Center for Marine Aquaculture” has been established in Schleswig-Holstein. This alliance consists of several research and development partners including GEOMAR with the overall aim of improving the efficiency of recirculating aquaculture systems. International cooperations and the involvement of further partners facilitate the transfer of the scientific results to application.



5.6 Marine Gas Hydrates and CO₂ Sequestration

Coal-based power plants are major CO₂ emitters and growing contributors to the CO₂ problem, since developing countries like China and India are depending on coal as a major energy resource. New technologies are currently being developed to capture CO₂ from these plants and sequester the CO₂ in deep saline aquifers and other geological structures, both on-shore and on the continental shelf. In these geological settings, CO₂ occurs as a buoyant and mobile supercritical fluid, whereas solid hydrates and high density liquids would be the major CO₂ phases within marine sediments deposited on the continental slope and rise. Since solids and dense fluids are less mobile and buoyant than supercritical fluids, deeper marine repositories offer opportunities for more secure deposition of fossil-fuel CO₂. Thus far, these deep sedimentary options have not been explored in detail by the industry. Ongoing research shows, however, that methane gas could, in principle, be produced from natural methane (gas) hydrates through the injection of liquid CO₂ into slope sediments. This expertise is directly related to studying the potential for deep-ocean CO₂ sequestration technology.

5.7 Marine Mineral Resources

Hydrothermal systems on the ocean floor produce mineral resources of potential economic interest for base (copper, zinc, lead), precious (gold, silver) as well as other technical metals such as selenium, gallium and indium. These minerals have recently attracted the international mining industry. Published analyses show concentrations of economic metals that are often much higher than those found in ores from massive sulfide deposits mined on land. The high concentrations of gold and silver in some of these deposits have, at current high metal prices, received special attention.

Future research will focus on two areas driven by applied research requirements: exploration and resource estimation. Finding old, inactive hydrothermal sites for commercial purposes will entail the development of geophysical remote sensing techniques, most probably for deployment on autonomous vehicles. Such techniques will eventually find direct transfer to application. Once located, estimating the size and internal structure of the mineral deposits is a pre-requisite to establishing their economic significance. They are, however, complex three-dimensional bodies whose size and internal enrichment structure can only be determined by a combination of field mapping and drilling. Sampling of the sub-seafloor with lander-type seafloor drill rigs or ROV-based drills is therefore of utmost importance. Our work on developing reliable technologies in order to produce quantitative resource estimates will take place hand-in-hand with the international marine mining industry.



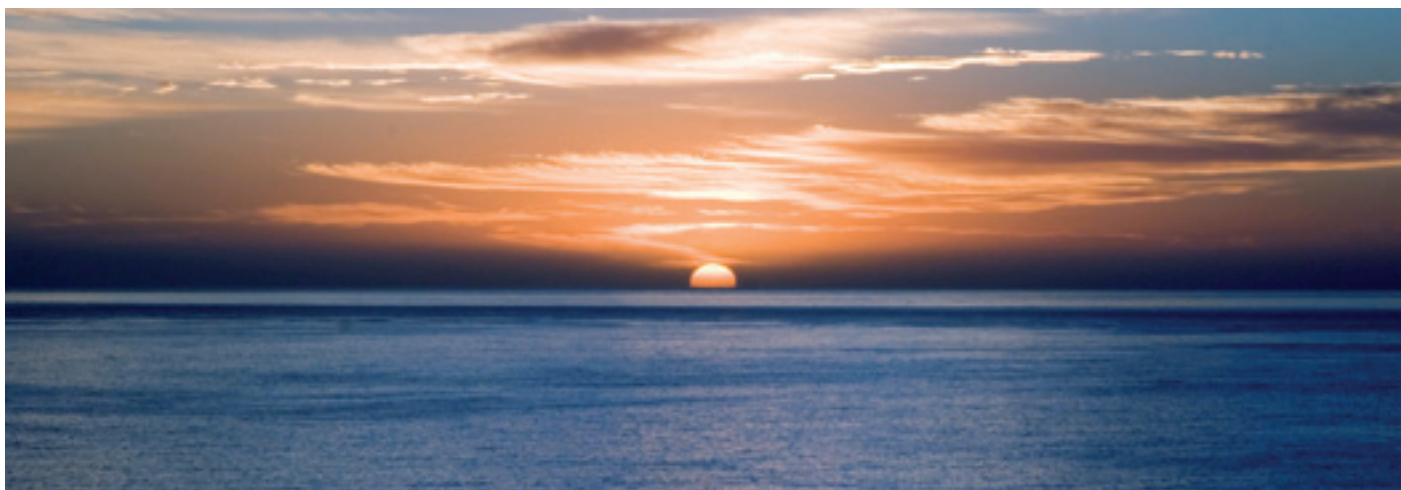
5.8 Measurement Technologies and Observing Systems

GEOMAR will develop, modify and implement modern off-shore technologies in both fundamental and applied science. We therefore seek a close collaboration with industrial partners and government agencies. Our activities include the development of instrumentation and technical infrastructure in collaboration with local and national industrial partners, the merging of existing technological components to develop new applications, and a close collaboration with companies possessing various technical expertise. These projects are of mutual benefit to both the scientific and private industrial parties.

At GEOMAR scientific programs will be developed to maturity in order to transfer the results to government agencies for further operational use. The international ARGO program may serve as an example in which an initial phase was driven by the science community. The program provides significant data to address questions related to climate dynamics and demonstrates a high technological maturity in terms of instrumentation, data distribution, and quality control. Moreover, ARGO serves as a future-oriented platform where new sensors and applications will be developed.



6 HORIZONS



“With the establishment of this truly multidisciplinary Cluster of Excellence, Kiel is now nationally and internationally recognized as an outstanding centre for education and research in marine sciences. We will address both on-going and future changes within the oceans as well as their interaction with society in terms of resources, services and risks.”

Peter Herzig, Director GEOMAR



Strategic Alliances

Strong national and international networks are a prerequisite for progress and advancement in marine sciences. GEOMAR actively builds strategic alliances that encompass a range of disciplines, organisations, and nations.

GEOMAR launched a number of large-scale initiatives together with the University of Kiel and other leading academic institutions, thereby creating a cutting-edge centre for ocean studies in Kiel with an internationally outstanding and unique profile.

■ **Locally:** In cooperation with GEOMAR, the excellence cluster “The Future Ocean” has significantly enhanced the profile of the University of Kiel and has elevated marine sciences to one of its core areas of expertise.

■ **Regionally:** GEOMAR and the Kiel Institute for the World Economy founded the Kiel Earth Institute in order to facilitate research and provide expert advice on issues at the interface of environment – society – economy.

■ **Nationally:** On the national level, scientists from GEOMAR are regularly selected as members of the DFG’s Senate Commission on Oceanography which plans and coordinates the activities of the German Research Foundation (DFG) in the area of marine research.

The Institute is also a founding member of the German Marine Research Consortium (KDM; Konsortium Deutsche Meeresforschung) and its Director, Peter Herzig, was KDM’s first chairperson. Today KDM has 15 member institutions and is the national association of academic and research institutions working in the field of marine sciences. Its goals include fostering collaboration and the development of joint research programs, intensifying cooperation and coordinated use of infrastructure and large equipment, as well as public relations. KDM acts as a voice for German marine research and is also active in the broader European community and at an international level.

■ **Internationally:** For the advancement of marine sciences, the three leading marine research institutes of Europe, namely Ifremer, France, National Oceanography Centre, Southampton, UK and the GEOMAR | Helmholtz Centre for Ocean Research Kiel have founded the G3 Group of European Marine Science institutions and are committed to a program to actively promote the marine science agenda and develop the European research area.



Spreading the Message to Future Generations

Marine sciences are not conducted in an ivory tower but are shaped in response to societal needs. Marine sciences play a leading role in two prime global challenges of the 21. century, namely climate change and natural resource limitations. Scientists at the GEOMAR play an active role in implementing structural changes towards a knowledge-based society. By communicating the relevance of marine research, the institute addresses important stake holders; such as policy makers, industry representatives, the younger generation and the general public.

Societal and economic relevance: GEOMAR's marine research offers objective and independent information and helps to find solutions for complex and often controversial objectives.

Promotion of young researchers: GEOMAR's cutting-edge research and high-quality, advanced education go hand in hand. In view of ongoing demographic changes, international study programs, career development strategies and perspectives for employment are part of the Institute's agenda to attract the brightest international students and young researchers.

Building a knowledge-based society: Children are our future. This simple message holds true not only for the next generation of marine scientists but for society as a whole. Joint activities and projects for school children and teachers contribute to this prime objective of the Lisbon Strategy. Exhibits and events for the general public provide information about ongoing research and demonstrate the societal impact of marine sciences.

www.geomar.de



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