Leibniz Institute for Baltic Sea Research Warnemünde

Research Programme 13.2.2013

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CONTENT

1. Mission and Structure

1.1. IOW research mission

It is the IOW´s mission to conduct interdisciplinary marine research in coastal seas with the aim of an in-depth understanding of the functions of such large marine ecosystems. The main target area of the IOW is the Baltic Sea, where joint focal activities are harboured. However, key processes are investigated beyond these boundaries, wherever appropriate to gain general insights in coastal seas ecosystem functions.

The overall objective is to differentiate between natural variability and anthropogenically triggered changes. To reach this goal, the research focuses on observation and modelling of ecosystem changes and their underlying processes. With this knowledge, sediments and their proxy content are analysed in order to decipher the variability of former system states. Describing the present status of the ecosystem states and deciphering their developments in the past, is the IOW´s basis to simulate future scenarios for ecosystem development.

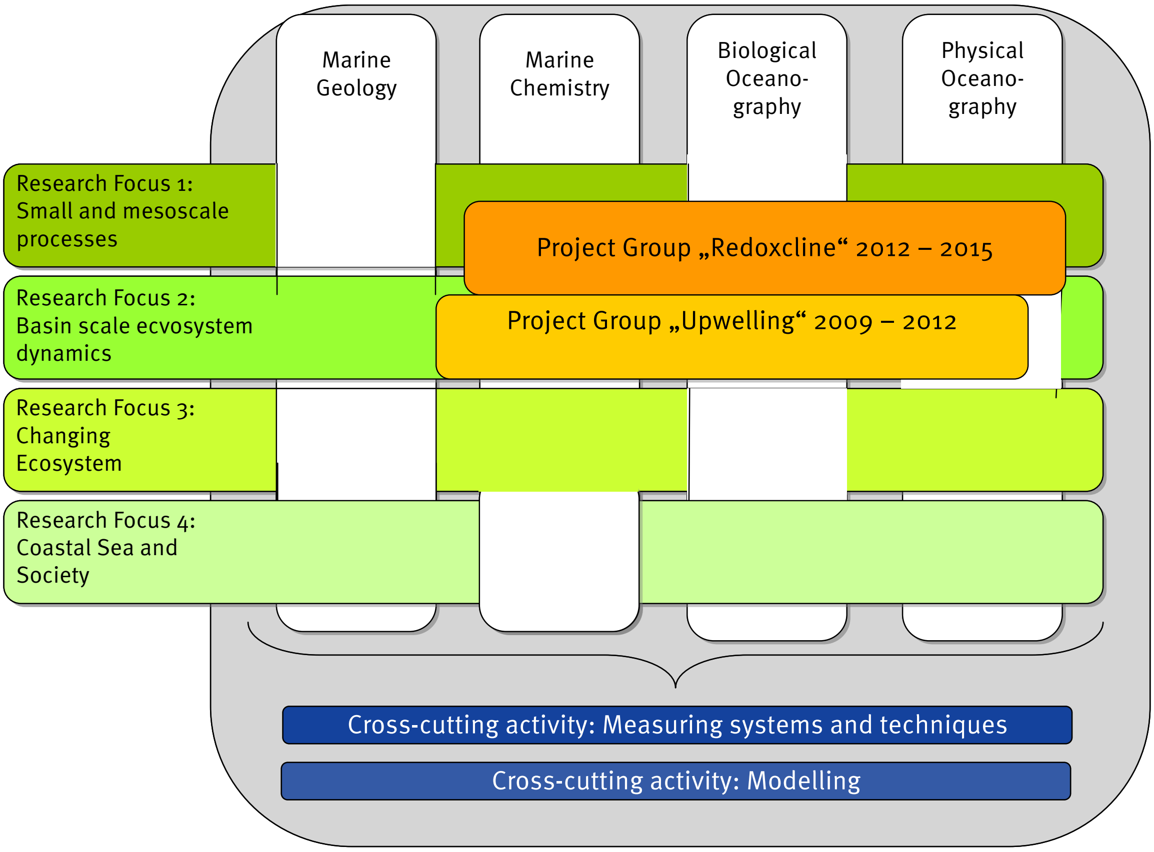

Fig 1: Matrix structure of the IOW research.
The disciplinary competence is sophisticated in the four scientific sections (vertical columns). Members of all sections support the interdisciplinary research carried out within four research foci (horizontal rows). Specific scientific questions are addressed in special research groups (orange boxes). The cross-cutting activities support all IOW research.

1.2 IOW structure

The institute is structured into four departments according to the main disciplines in marine research: physical oceanography, marine chemistry, biological oceanography and marine geology (Fig. 1). Within the departments, disciplinary expertise is fostered and further developed, especially in relation to academic teaching and methodological tools.

These scientific departments are supported by central units like the instrumentation group, a precision engineering workshop, the analytical group, the IT group and a library. They guarantee that high-level research at IOW can be conducted with the most appropriate and advanced technological tools and methods and offer easy access to published research results and data. A public relation and knowledge transfer group takes care for outreach products to the society.

Scientific departments and central units closely co-operate in order to constantly adjust the purchase and operation of infrastructure to the scientific needs.

1.3 The position of the IOW Research Programme in the institutional structure

All departments work jointly on the 10 years **IOW Research Programme (2013 – 2023)**, which is structured in four main research foci and two cross-cutting activities (Fig. 1 and 2). The objectives of the programme and the research questions that form the basis of its different parts have been identified by IOW scientists as urgent and relevant. Implementation of the ambitious research programme relies on projects funded by third parties in addition to the institute's basic financial resources. Close interdisciplinary cooperation is essential to the complex challenges of this long-term research programme. Thus, implementation of the programme is realised by intertwining its research foci with the disciplinary expertise of the departments, in the form of a matrix structure (Fig.1) with project groups dedicated to key questions in which capacities are focused for a limited duration of three to five years.

2. Research Programme of the IOW

2.1 Transition from the previous to the new research programme

The previous research programme (2002 – 2012) concentrated on themes and processes relevant to the structure and function of marine systems with a special emphasis on the Baltic Sea. The sustainability of marine ecosystems is a rapidly emerging field, and one in which we wish to concentrate future efforts. Based on long-term measurements, it is now apparent that regime shifts are typical for the Baltic Sea. This knowledge has come to replace the former view of a system undulating around a mean steady state. The much deeper insight into the mechanisms causing such shifts led us to adjust our research concept, by instituting a system approach in which relevant processes over appropriate time and spatial scales are addressed in an integrated way. Several examples from recent findings can be cited: (a) The identification of microbial communities in oxygen minimum zones and the role of biodiversity in the dynamics of the redoxclines are best evaluated at **scales of minutes and centimetres**. (b) Ocean filaments and eddy formation at upwelling fronts, as observed by ship-borne observations and in high-resolution modelling, persist **at sub-basin scales**, with typical physical and biogeochemical signatures, even if their sea surface temperature signals are no longer detectable by satellite SST images. **At the basin scale**, observations of halocline dynamics on a high-resolution cross-section through the Baltic Sea were successfully recorded by means of a towed ScanFish. **Another basin-scale observation** with ongoing importance is the exchange of CO2 and other gases with the atmosphere, measured by means of automated sampling established on ships of opportunity. (c) The concept of distinguishing external forcing and internal change in **a changing marine system on geological, centennial and decadal scales in the past and into the future**, as outlined in Research Focus 3, agrees with this new approach. In summary, we propose adjusting the new research programme along spatial and temporal scales. Information gained from these research foci that become relevant for society in general will be synthesised (d) in a new fourth research focus **"Coastal Sea and Society"**.

By concentrating on the relevant scales and with the aim of further promoting an interdisciplinary system approach, the **new research foci** will be: **"Small- and Mesoscale Processes"** (Research Focus 1) and **"Ecosystem Functioning"** (Research Focus 2). Research Focus 3: **"System Changes"** remains dedicated to long-term measurements, retrieving sedimentary records and projecting future ecosystem scenarios through the construction of models. A substantial strengthening of the former cross-cutting activity **"Coastal Sea and Society"** will lead to a new Research Focus 4 with the same title (Fig. 2).

The new programme will address important scientific challenges for the years to come and will contribute to solution-orientated research for sustainability. It will promote effective interdisciplinary collaborations to assure timely information and involvement of policy-makers, funders, academics, and other sectors of civil society in co-designing and co-producing research agendas and knowledge. We will increase capacity-building in science, technology and innovation and will engage in the education of a new generation of scientists. Thus, the IOW research programme addresses the emerging issues of the international Future Earth Initiative.

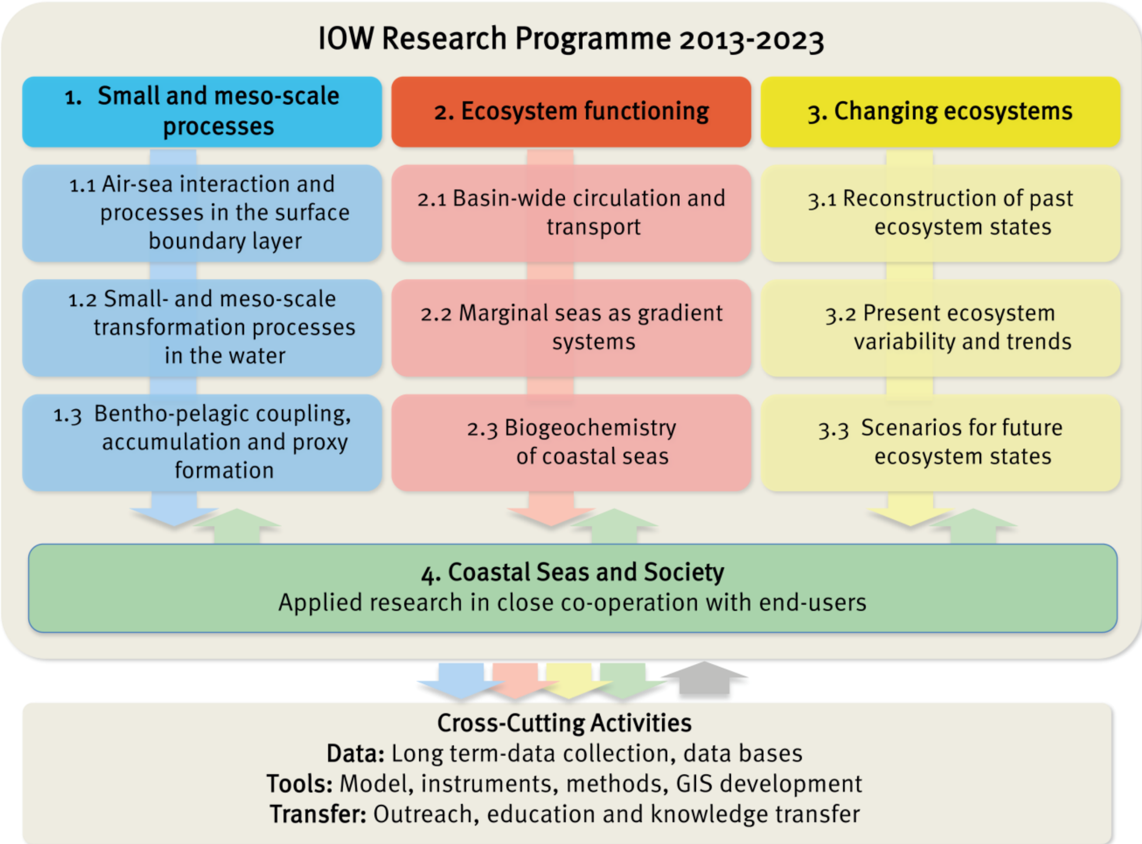

Fig. 2: Structure of the IOW research programme 2013-2023, see text for details.

2.2. Components of the IOW research programme 2013-2023

2.2.1 Research Focus 1: Small- and meso-scale processes

The Research Focus 1 (RF1) Small- and Meso-Scale Processes identifies and quantifies processes in different compartments of the ecosystem and examines the regulation by biotic and abiotic factors in interdisciplinary field studies and laboratory experiments as well as in numerical process modelling. Important research topics are the exchange of matter between sea surface layer and atmosphere, effects of system stoichiometry on food web structure and dynamics in the surface mixed layer, biogeochemical element transformations at the pelagic and benthic redoxclines and bentho-pelagic coupling at the sediment-water interface. The three major functional strata of RF1 research are the surface mixed layer including the air-sea interface (RF1.1), the subsurface layers including pelagic redox gradients (RF1.2), and the benthic boundary layer including the upper sediment layers and associated benthic compositional gradients (RF1.3). Over the course of the research programme, RF1 aims at an integration of those studies into an assessment of the coupled functioning between these important sub-systems.

The quantitative and mechanistic understanding of processes impacting different ecosystem compartments is fundamental for the implementation in any model framework, as well as for a sound assessment of its sensitivity to past and future environmental changes. RF1 addresses the smallest interactions of ecosystem components that, however, set the initial conditions and limits for large-scale developments. The research focus concentrates on processes and their coupling in three major functional marine strata: the surface boundary layer including the air-water interface, the stratified inner layers including the pelagic redoxcline, and the benthic regime including the bottom boundary layer, the water-sediment interface, and the upper sediment layers. The integrated assessment of functioning and coupling of processes from the atmosphere to the sediment thus provides the base for further transfer of scientific findings on system-relevant mechanisms onto the basin scale and into decadal and even longer time axes.

Over the course of the last research programme of the IOW a large quantity of process studies on smaller scales have been conducted. Progress in this direction was closely coupled to advances in available instrumentation and methodological approaches. So, Physical Oceanography expanded research on small-scale turbulence using microstructure profilers and acoustic devices, Biological Oceanography established molecular techniques for analysing the structure and function of microorganisms, Marine Geology improved techniques for single particle elemental and micro-textural analysis, and Marine Chemistry increased sampling resolution at the marine microlayers and attained improved flux estimates. Also numerical modelling tools at IOW have been refined, in terms of better process- and numerical resolution (due to increase of computational resources). The quest for smaller scales and resolution of complex structures and processes was facilitated by substantial project funding, led to new scientific insights and yielded highly acknowledged publications in the respective fields. In the new research programme we intend to cross-link these disciplinary efforts to scale-adapted sub-system approaches. A joint study of surface microlayer biology and the linkage to the dynamics of halogenated organic volatiles is in progress. Research has started on the coupling between biogeochemical redoxcline processes and small-scale physical forcing, e.g., to examine the impact of lateral intrusions on microbial activity, element speciation and mineral formation. Studies are in progress dealing with the basic actors of the nitrogen cycle, which particularly in the Baltic gradient affects large functional and structural parts of the ecosystem.

An important planed task on the way towards integrated studies is to follow the pathway of minuscule tracers and proxies for external changes from their input or formation at the boundaries of the ecosystem to the final deposition areas and to record their modification in every subsystem. New Nano-SIMS and improved FEM-capabilities together with existing high-precision analytical facilities will once again secure technical state-of-the-art assistance throughout the new programme, and support the scientific orientation towards smaller scales.

General aim of the research focus is the continuous description of coupled marine process-chains between atmosphere and sediment in our marginal sea and the definition of quantitative relations between system relevant processes as well as its regulation by abiotic and biotic forces. Progress in this knowledge will continuously be translated into model advancement, which will lead to an up scaling of the quantitative performance of the basic building blocks of the ecosystem to the level on the next temporal-spatial scale. Modelling will also be an important guide for the identification of crucial small-scale processes still calling for better empirical parameterization.

Execution and classification of experiments interact with the evaluation of environmental data collected over several decades at the IOW. Long-term data sets from various stations of the Baltic Sea provide the opportunity to allocate the results of process studies to the proper environmental situations. Likewise, the analysis of shifts in the long-term development of environmental variables often induces studies on the basic processes, sustaining or modifying these variables.

RF1.1 Air-sea interaction and processes in the surface boundary layers

The surface boundary layer is directly affected by external forcing, both naturally and anthropogenically (as investigated in RF3), including the annual cycle of temperature, wind forcing, irradiation, ice cover as well as loading of chemical compounds and nutrients via run off from land and through the atmosphere causing for example a high variability of the plankton community (e.g. shift in species composition). Airborne fluxes considerably contribute to the external supply of nitrogen for primary production and of different hazardous substances (important information for RF4) in many marginal seas. Conversely, the production and release of environmentally important volatiles in the Baltic are controlled by upper water column processes. As environmental changes have a strong impact on the pelagic food web structure and its ecosystem functions, the effect of these external drivers on the diversity, community structure and quantitative performance of pelagic and benthic communities is a major objective within RF 1.1 as well.

The advances in scientific knowledge from the former research programme which in particular relate to the physical background for nutrient transport, the qualitative and quantitative description of the nitrogen transformations in the photic zone, the close examination of the role of the immediate surface layer for gas transfer and new insights into functional aspects of food web interactions lead to the future challenges for this focus:

- Improvement of the description of physical, chemical and biological processes controlling matter transfer between atmosphere, land, marginal sea and biota of the boundary layer.
- Determination of important processes in the surface microlayer such as the role of the microbial community in regulation and generation of gases, and their role for the ecosystem function of the mixed layer
- Determination and quantification of the fluxes of environmentally important volatiles, including the elucidation of the role of planktonic organisms for the production and consumption
- Determination of the control mechanisms of the C/N/P stoichiometry for primary production and mineralization, with special emphasis on the mechanisms that generate and sustain cyanobacteria blooms
- Quantification of the role of DOM for cycling of organic matter along the natural salinity gradient of the Baltic Sea
- Assessment of the interaction between environmental forces and the structure, species composition and performance of pelagic food webs and the resulting quantitative flow of matter
- Investigating the response and adaptation of planktonic key organisms to environmental changes (e.g., warming, acidification, deoxygenation etc.)

The challenges of this research focus will be met by multidisciplinary approaches and application of new experimental strategies. Synoptic and spatially resolving integrated biogeochemical and physical ship-based observations of the meso-scale, submeso-scale and small scale structures of the near-surface region will be executed to understand the impact of near-surface physics on primary production and biogeochemical turnover. C/N/P ratios during primary production over the course of the production period will be scrutinized using new sampling strategies, including the use of commercial voluntary observatory ships. High-resolution coupled physical biogeochemical models to quantify the mechanisms

controlling the primary production will reproduce these eddy-resolving simulations and refined changing stoichiometric relations.
A suite of experimental approaches will serve assessments of the biological contribution to production and consumption of volatiles and the resulting sea-air fluxes on different scales.
The function of DOM (DON, DOP) in coastal ecosystems will be investigated regarding its sources, concentrations, distribution, composition and its utilization by organisms
Advancement of numerical models will resolve e.g. developmental stages of zooplankton in close combination with modern, higher resolving new acoustic and optical *in situ* observational techniques.
All of these future tasks need a strong integration of disciplinary approaches and a consideration of driving forces and final products of the observed processes. This facilitates the transition of acquired knowledge to the successive research foci.

RF1.2 Processes in subsurface layers and pelagic redox gradients

The subsurface layers, which constitute the largest water masses in the sea, exchange mass and energy with both surface and bottom layers. Particle flux constitutes the fastest connection between surface layer production and deep water/sediment biogeochemistry. Therefore this process was monitored as a mirror of both current surface layer system functioning and as a driver for future development of deep water/sediment environments over the last decade. Analysis of both quality and quantity of settling particles allowed a detailed view on the functioning of the pelagic system in the central Baltic. Particle degradation and deposition processes are influenced by physico-chemical conditions in the water column, in the Baltic Sea particularly by the availability of oxygen. Therefore the different sub-systems of the Baltic Sea, with different mixing and oxygen conditions, can be viewed as models for a wide variety of coastal seas.
The central Baltic Sea can be used as a model system for the study of the impact of oxygen-deficient (hypoxic) conditions within a water column on overall biogeochemical cycles. Although we know the main oxidation and reduction reactions, which are important within the redoxcline, we need a better understanding of how the redox reactions are linked and expressed in terms of rates of transformation. The redoxcline is a site of intense particle (trans-) formation such as authigenic Mn/Fe-minerals, which may interact with dissolved species in the aqueous phase but also with sinking organic material produced in the surface layer. From studies over the last years there is evidence that these processes impact the fluxes of nutrients such as phosphate and trace elements. However, the magnitude of these processes, the most important element transformations, and the contribution of abiotic and biotic factors still contain a number of fundamental open questions that remain to be investigated.
Research within the last decade enabled the identification of a set of prokaryotic key players, which control element transformations in redoxclines of the Baltic Sea, but are also globally distributed in marine oxygen-deficient systems. One of these microorganisms, which links the nitrogen and sulphur cycles, could be established as a model organism. Combined genomic and physiological analysis demonstrated its adaptations to this habitat and an extremely versatile metabolism. With the potential to control accordant transformations those key players are ideal tools for a better system understanding and future modelling. New insights on the redoxcline microbial food web have recently been achieved. They allow to show how trophic interactions (e.g., with protists and viruses)

change along the redox gradient. The metabolic network, created by the different prokaryotic key players, and its impact on overall redoxcline biogeochemistry, however, still needs to be resolved.

Pelagic redoxclines have traditionally been viewed as gradually evolving, vertically layered systems of constituents with continuous “turbulent diffusion” and particle sinking as the main vertical transport mechanisms. From observations over the last years there is increasing evidence, that this one-dimensional picture is strongly modified by the occurrence of intermittent lateral transport processes. Intermittent turbulent mixing across these gradients induces specific and indicative microbial activities and adaptations, resulting in a strong modification of the biogeochemical transformation processes and rates. As a consequence of the findings from the past studies, the challenges for this focus are:

- Assessing the impact of hypoxic conditions on overall particle flux and decomposition
- Studying the link between microbial community structure and biogeochemical transformations in marine chemoclines by performing comparative analysis of Baltic Sea chemoclines with other redox-gradient-driven marine systems
- Elucidating the indicator/proxy potential of prokaryotic key organisms for distinct transformation states
- Combining and improving novel technologies for sampling and data assessment in high spatial and temporal resolution in order to deduce the impact of intermittent turbulent mixing across redoxclines for subsequent biological reactions
- Linking 1D biogeochemical water column models with ecosystem and turbulence models for better understanding of the complexity of pelagic redoxclines and their impact on overall nutrient cycles
- Investigating the impact of environmental changes (e.g., temperature, pH, CO_2) on organism activities, populations and community structure, food web interactions and overall biologically mediated energy and matter fluxes

This will be accomplished by experimental investigations with communities of different complexity, from isolated microbial key players to *in situ* assemblages for assessing principal microbial activities related to biogeochemical transformations. It will imply multidisciplinary approaches to integrate geochemical, biological and physical processes at pelagic redoxclines in the Baltic Sea and other marginal and coastal oxygen-deficient marine systems. It will build on new methodological approaches like *in situ* profiling instrumentation, tools for cell-specific analysis such as NanoSims, cell sorting and whole genome amplification and further development and application of methods (e.g. stable isotope techniques) to link functions and identity of microorganisms as well as on “omics”-approaches for assessing the genetic potential and the realised activities of important prokaryotes. To promote interdisciplinary research on redoxcline biogeochemistry, a IOW project group has been established.

RF1.3 Benthic-pelagic coupling, accumulation and proxy formation

Nutrient and carbon dioxide availability and the removal of excess material in the sea is strongly dependent on the balance between recycling and burial of organic matter in the sediments, which is influenced by physical forcing at the sediment surface, the activity of benthic organisms and the corresponding transport processes across the benthic boundary layer. The coupling between diversity of benthic organisms from macrofauna to bacteria and functional properties of sediments is a focal theme in this task. Moreover, the study of the processes responsible for the formation of temporal geochemical tracers, as well as conserved sediment properties (so-called 'proxies') is essential for ecosystem reconstruction. Strong feedback mechanisms between redox state and sedimentary functioning call for a robust and detailed understanding of diagenesis, and of the physical bases, the biological impacts, and the chemical consequences of exchange processes. Hereby, the biogeochemistry of diagenesis is linked to the water column processes and vice versa. Sedimentary authigenic minerals carry geochemical and micro-textural information about biogeochemical processes and, for instance, water column redox-states, as well as further diagenetic modifications that have to be analyzed in detail.

Research in the last decade has shown the importance of the dynamic fluff layer that is impacted by environmental changes and large-scale boundary conditions (e.g., climate change, anthropogenic impacts). This thin boundary layer initializes the formation of sediments and controls the relative fraction and further transformation of material that may be preserved forming the later sedimentary record. The dynamic properties of the thin boundary layer are controlled by currents, shear stress and small-scale turbulence, and set the preconditions for transport, settling and re-suspension of mobile material at the sediment surface. To establish links between water column processes and buried matter requires a process-oriented knowledge about the quantitative balance between material fluxes from the water column and the re-flux back to the bottom waters across the sediment-water interface. Activity and mutual control of macrozoobenthos and sediment bacteria are key processes controlling these fluxes. At sites of subterranean ground water discharge (SGD), fresh and recycled coastal waters bearing nutrients, carbon species and metals may impact the material balance of the ecosystem and creates a further, so far quantitatively under-investigated process of benthic-pelagic coupling.

Building on this previous knowledge, future challenges for this focus are:

- Exploring and quantifying the control of element fluxes across the sediment-water interface as a function of sedimentary and corresponding geochemical, biological, and physical characteristics
- Establishment of relationships between benthic biodiversity and –abundance and mass transfer between sediment and water column
- Development, evaluation, and calibration of processes creating geochemical sedimentary proxies for selected important pelagic and benthic processes and system boundary conditions
- Calibration and application of geochemical proxies in other modern and fossil coastal and marginal sea ecosystems
- Quantifying the role of subterranean groundwater discharge for benthic-pelagic biogeochemical element budgets in the coastal zone
- Assessment of the impact of turbulent processes in the bottom boundary layer on particle transport, and on water and element exchange between sediment and bottom waters.

Our research will investigate the functional services of the relevant types of (surface) sediments of the Baltic Sea on different spatial and temporal scales. The results can be directly transferred within RF2 to a basin wide assessment. Results will be related to natural and anthropogenic external and internal drivers (e.g. climate change, eutrophication, pollution) e.g. as required for RF4. In close co-operation with RF 3 we will estimate the material fractions that take part in short-term (re-)cycling compared to a long-term burial and the characterization of bonding-types of, e.g. nutrients and anthropogenic substances. Results from modern investigations will be related via proxy-target relationships to modern and fossil Baltic Sea-type systems to gain information about temporal changes to allow and calibrate predictions for future ecosystem

2.3.2 Research Focus 2: Basin-Scale Ecosystem Dynamics

This research focus aims at the identification and quantification of fundamental process interactions on a basin scale, which determine the function and dynamics of the entire ecosystem, studied by observations, experiments and regional-scale ecosystem modelling[1] in high process and numerical resolution.

The large-scale function and dynamics of ecosystems is governed by the integrated effects and interactions of processes as they are individually investigated in RF 1, resulting in one functional system such as the present ecosystem of the Baltic Sea. This requires a scientific approach, which is integrating physical and biogeochemical processes within a spatial (system-wide) context.

Over the past decade several efforts were initiated at IOW to extend single point observations to two- or three-dimensional basin scale assessments. Successful attempts were conducted in projects that recorded continuously CO_2, O_2, nutrient and chlorophyll surface concentrations on ships of opportunity, thereby facilitating the quantitative estimation of primary production and, indirectly, nitrogen fixation on a large spatial scale. Maps of geological and biological surface sediment properties meanwhile cover a large part of the south–western Baltic and are about to be extended to maps of functional characteristics. Seasonal surveys of microbial diversity throughout the whole Baltic gradient allowed coupling the decomposition capacities for introduced loads to biodiversity patterns and the chemical environment in the distinct basins. As an example for (sub-)meso-scale variability as a driver for basin dynamics IOW has studied upwelling filaments in the Central Baltic Sea as a phosphate source to the euphotic zone in summer, which has been identified as a crucial parameter for the development of cyanobacterial blooms. These successful research efforts are by far not completed and will be further pursued and extended in the coming years.

The aim for the next decade is to generate consistent multi-parameter observational data sets, with a high spatial (horizontally and vertically) resolution including biodiversity patterns and process rates along the different gradients to feed into IOW's numerical models and to provide synoptic impressions of the ecosystem state. Long-term observations are essential to evaluate the relative importance of certain ecosystem states. As a brace for these large scale approaches, basin-wide ecosystem modelling, as it has been developed and successfully applied at IOW during the last two decades, has the necessary integrative capacity. The vision for the next decade is to construct a process-based quantitative understanding of biogeochemical matter fluxes (transport and transformation) in marginal sea ecosystems. The semi-enclosed Baltic Sea with its sequence of basins and sills, its

[1] Ecosystem modelling is understood here as an application of a coupled physical-biogeochemical model.

different abiotic gradients and the practical absence of tides provides an ideal natural laboratory to study basin-wide process networks in marginal seas. With its subsystems, it offers enough spatial variability to allow exploration of a large range of ecosystem characteristics (e.g., oxic-anoxic, mixed-stratified, eutrophic-oligotrophic). An in-depth knowledge of the dynamics in the ecosystem of the Baltic Sea also helps to understand other marginal sea ecosystems such as the North Sea, the Black Sea or the Benguela upwelling system. It also provides a system understanding, which is sufficiently consistent to allow for reconstructions of past (RF3.1) and projections of possible future (RF3.3) ecosystem states as well as to study ecosystem variability on multi-decadal time scales (RF3.2).

Research Focus 2 explores the marginal seas as a whole, regarding transport and mixing of matter (RF2.1), spatial variability in functional biodiversity along gradients (RF2.2) and their role as reactors for rapid and complex biogeochemical cycling (RF2.3). The scientific scope of RF2 is to disentangle the complex network of processes that shape the marginal sea ecosystems. Ultimately, the goal of these efforts is to approach closed budgets for heat, momentum, and the cycling of key elements, which can give us the confidence that we have identified and quantified all major processes, which determine the fate of matter passing from land through the costal environment and into the open ocean. To reach this goal, RF2 strongly relies on basin-wide *in-situ* observations and experiments, ecosystem regional-scale multi-decadal ecosystem modelling, and the state of the art parameterization of all key processes (promoted within RF1).

RF2.1 Basin-scale circulation and transports

The lateral link between sources and sinks of matter within a marginal sea and its subsystems and the driver for mass exchange with the ocean is basin scale advective and turbulent transport. Regional differences of coast-to-basin and basin-to-basin exchanges and the resulting biogeochemical transformations create the regional differences in distribution patterns of dissolved and particulate substances. The assessment of transport rates and distribution patterns forms the base of any basin-wide elemental budget. The practically non-tidal Baltic Sea is a perfect site for unbiased analysis of density-driven (e.g., estuarine circulation regimes) and wind-driven (e.g. upwelling regimes) dynamics. Due to the relatively small size of the basins, direct exchange of open waters with the coast plays a significant role for the ecosystem functioning. Three prototypes of lateral exchange regimes will be focus of IOW's research during the next decade:

Estuarine circulation regimes: These systems are characterised by a variable overturning circulation driven by net inflow of dense bottom water and outflow of less dense surface waters. The circulation is closed by a suite of mixing processes, which have substantial effects on transport of solutes and particulate matter. During the last decade, IOW has quantified a number of these processes (e.g., entrainment in the Western Baltic Sea, mixing by inertial oscillations and boundary mixing in stratified basins), by means of dedicated field campaigns and advanced numerical modelling. It is now timely to integrate these processes into a system-wide context to explain the overturning circulation in marginal sea systems, again with the Baltic Sea as prototype, but also for fjords, lagoons, coastal areas, tidal and non-tidal estuaries and the Wadden Sea (for which IOW has identified estuarine circulation as one major sediment transport mechanism).

Upwelling regimes: Coastal upwelling leads to significant horizontal and vertical transports near the coast, and thus plays a crucial role in the nutrient and carbon cycles of marginal sea ecosystems. Due to the highly variable winds, upwelling events in the Baltic Sea are episodic and allow direct observations of the developing and diminishing upwelling and the role of coastally trapped waves. One essential question under investigation is the role of upwelling for driving cyanobacteria blooms in the Central Baltic Sea by supply of phosphorus. In addition, the role of wind stress curl driven upwelling and dynamically driven upwelling at bathymetric gradients is yet a widely unexplored topic for the Baltic Sea. IOW has gathered vast experience (in terms of observations and numerical modelling) with the Baltic Sea coastal upwelling as well as with the persistently forced upwelling in the Benguela region and the seasonal upwelling in the South China Sea. There, the vertical transport of nutrients into the euphotic zone is very efficient and provides an ideal place for studies of plankton succession and formation of oxygen minimum zones due to decomposition of organic matter.

Land-sea flux regimes: Matter fluxes from land are mediated by river and ground water flows. Relevant transformation processes occur in large rates within estuaries, lagoons, river plumes and groundwater seeps before marine waters are reached. Essential for the functioning of marginal sea ecosystems is the fate of riverine inorganic nutrients and organic matter, their rates and locations of uptake, mineralisation and decay and which compounds are finally transported into the coastal ocean. For the southern Baltic Sea, scientific progress made over the last decade suggests that most riverine N-compounds are lost or remain close to the coast and that coastal biogeochemical processes cause a major removal of reactive nitrogen. This is supported by numerical model studies which have investigated the fate of marked riverine nutrient loads of Baltic Rivers by tracking the pathways, an approach which is based on reliable knowledge of hydrodynamics and biogeochemistry (RF2.3), and benthic and pelagic food web structures (RF1.1, RF1.3).

The challenges for this focus are:

- Process-based advective and diffusive closure of circulation in the Baltic Sea and other estuarine circulation regimes including transports of solutes and particulate matter.
- Understanding and quantifying the dynamics and properties of coastal upwelling, the related coastal currents, fronts, coastally trapped waves and the role of the spatial structures of wind patterns.
- Investigating the impact of upwelling on plankton communities, particularly cyanobacteria blooms.
- Description of the dynamics determining residence times and transformation rates within estuaries, lagoons, and river plumes.

During the next decade, the closure of the basin-wide estuarine circulation by diapycnal mixing and the resulting advective and turbulent transport pathways will be investigated by field surveys with increasing spatial and temporal resolution and coverage (including tracer release experiments) combined with numerical modelling. A major research effort will be on the contribution of the episodic and partially reversible upwelling events to nutrient transport into the euphotic zone, and how this is quantitatively related to direct diapycnal mixing by small- and mesoscale turbulence. It will further be investigated (e.g., by means of stable isotope signals in sediments and isotope budgets) on which time scales compounds travel through estuaries and along the coast and to which extent they are transported normal to the coast due to e.g. mesoscale processes, as solutes or particulate matter.

RF2.2: Functional biodiversity in the gradients of marginal seas

As transition areas between land and ocean the marginal and shelf seas offer extreme gradients in environmental conditions due to the large variability in physical, chemical and biological properties on small spatial scales. These gradients strongly impact the biodiversity in water and sediment and determine their function as efficient reactors for land derived material and their prominent role in the regulation of land-ocean fluxes. The consequences of changing species composition for qualitative and quantitative properties of ecosystem processes within the gradients and the resulting changes in ecosystem services are only rudimentary explored, in spite of the general importance for riparian societies.

Over the last decade the research conducted by the IOW showed Baltic Sea gradients to be reflected in structural and functional heterogeneity of organisms that in turn will affect elemental balances and system stoichiometry (see RF1.1, RF2.3). First attempts to map these functional properties in response to changing species composition of both higher organisms and the microbial communities in sediment and water, have been initiated. Our interdisciplinary approach of coupling biodiversity and biogeochemical research is expected to contribute important insights into the field of marine functional biodiversity research. It will allow us to interpret the similarities and differences in ecosystem functioning in regions of pronounced differences in diversity along the steep environmental gradients of the Baltic Sea as well as in other marginal seas. The question, how these subsystems react on naturally introduced riverine and terrestrial organic material refers to basic functions of a coastal sea as modulator between land and ocean. The potential of the ecosystem to buffer nutrient loadings and to detoxify organic pollutants is a topic of high social relevance (RF4). Due to the paleo-environmental changes from a freshwater to a brackish-marine Baltic Sea ecosystem (RF3), distinct vertical biogeochemical gradients are also developed within the sediment-pore water system, creating an active transport shuttle of dissolved components from the sediment to the bottom waters and vice versa. This benthic-pelagic coupling depends sensitively on climate change and anthropogenic input of matter. Therefore, the general capacity of a marginal sea for decomposition, transformation and accumulation of introduced matter requires an in-depth analysis of the functional properties of key organisms and communities and of abiotic structural components, which are to a large part already a component of long-term observations carried out by the IOW (e.g., hydrography, water chemistry, distribution of plankton and macro-benthos, sediment properties). Based on this, RF2.2 is aiming to gain an in-depth insight into the interaction between biodiversity and structural components, and resulting ecosystem function along the gradients of the Baltic Sea. The major challenges for this focus are therefore,

- To map the biodiversity of yet underrepresented groups of organisms (e.g., microorganisms) along the gradients of the Baltic and other marginal seas
- To assess functional traits of hitherto understudied pelagic and benthic key organisms and communities and their adaptive capacities along environmental gradients
- To assess changes in distinct ecosystem functions such as decomposition and accumulation of anthropogenically derived substances in response to changing di-

versity of both higher organisms and the microbial community in sediment and water.
- Understanding present day basin scale biodiversity-driven processes and their imprint e.g. in marine sediments in order to facilitate the interpretation of paleo-signatures, which may allow a more reliable prediction of future scenarios

Over the next decade our research will concentrate on an extended mapping of organism groups and species throughout the complete Baltic salinity gradient between the Kattegat and the Bothnian Bay. This has been partly performed for phytoplankton, zooplankton and benthic organisms within long-term observation (monitoring) programs, and recently for pelagic bacteria, whereas the diversity of benthic bacteria remains to be studied. Likewise, bacteria, which interact positively (symbiontic) or negatively (pathogenic) with eukaryotic micro- and macro-organisms have so far received little attention. Studies on the natural biodiversity gradients will be combined with multi-trophic manipulation experiments and biogeochemical studies (performed in RF2.3) to assign functional properties to biological communities along the Baltic gradient and to predict the consequences of species losses. Products of this effort will be maps of structural properties (sediments, habitats, key organisms, biomass) that in combination with biogeochemical fluxes can be translated into maps containing functional information (C, N, P-flux, trace gas emissions, accumulation rates, decomposition rates). This way, service functions of marginal seas can be evaluated on a regional as well as on a comprehensive scale and therefore our approach not only advances marine basic research but also gains insight in the socio-economic relevance.

RF2.3: Biogeochemistry of coastal seas

A feature of global importance is the capacity of marginal seas to modify materials introduced from land or the atmosphere, to accumulate some of them and export others to the ocean or atmosphere. The stoichiometry of production, export and retention is extremely dependent on the redox state of the seas. The combination of regional biogeochemical essays with export balances for relevant elements (C, N, P, S, O, Fe) is a challenging aim of this thematic focus. One of the important understudied processes is the formation and cycling of environmentally relevant volatiles. Land and atmosphere-derived organic and inorganic pollutants can be chemically altered and the tracking of compounds through the ecosystem and food web as well as the evaluation of their risk potential is a particular challenging scientific task. All of these biogeochemical transformations are strongly linked to the ionic strength (i.e. salinity); thus, to RF2.1. and RF2.2.

Element cycling in marginal sea ecosystems: Concentrations and ratios of the major biologically relevant elements are more variable in coastal seas than in the open ocean. External as well as internal forcing can strongly alter the stoichiometry of the nutrient pools and in newly produced organic material. In the Baltic, the inputs of nutrients from land and atmosphere have been anthropogenically increased in the past decades with N:P ratios being usually far above the 16:1 ratio. Different coastal turnover and sequestration processes for N and P, lead to low N/P ratios in the central Baltic, which have been documented by long-term observations but are not yet been fully understood. Moreover, nitrogen fixing organisms exhibit very high N:P ratios and significantly contribute to primary production in the open Baltic in summer. Especially the mass development of cyanobacteria, a typical feature of the Baltic, is strongly related to the availability of P. In order to understand the relationship between bacterial blooms and P cycling we will evaluate so far understudied P pools such as DOP, intracellular polyphosphate and particular phosphate (e.g. Fe-bound). Moreover, the role of P-turnover and transformation at the redoxcline and in sediments needs to be studied. In contrast to the P cycle the Baltic nitrogen cycle has been intensively investigated. To close current gaps in our knowledge we will extend investigations to pools of N, which have been receiving less attention such as dissolved organic nitrogen and nitric oxide. These studies will be extended from the basins into permeable sediments in the near shore zones, which require an adaptation of methods. A mechanistic understanding of the cycling of key elements calls for a detailed description of C, N, P, S and O-bearing species and knowledge of the fractionation of element concentrations and corresponding stoichiometries during the biogeochemical transformation processes. To reach this important goal, the cycling of further elements has to be addressed simultaneously like trace intermediate components, redox-sensitive trace elements, and in particular stable isotopes (S, O, C, N, Me). RF2.3 thus relies on a wide range of process descriptions, and provides the integrated view needed to design important future process parameterization studies within RF 1.

Environmentally relevant volatiles formation and cycling: Cycling of climatically or environmentally important volatiles differs between marine and fresh water systems, and is highly influenced by climate change or eutrophication. Marginal seas are thus expected to transform trace gases in various ways and on short timescales. Moreover they may be important areas to predict future changes in their aquatic source strength. The reactions involved in the cycles of compounds with highest relevance like CH_4, N_2O, VHOCs, or Hg(0) are strongly redox sensitive. A comprehensive investigation of relevant key processes and controls (as part of RF1), combined with the detailed understanding of the hydrographical and biogeochemical boundary conditions offers a unique opportunity for the description of trace gas transformation and budgets. Relevant processes partly match those studied in other research foci like N_2O production by denitrification or nitrification. The wide range of conditions within the salt and redox gradients (see RF2.1 and RF2.2) offers the unique opportunity to relate the functioning of marine trace gas cycling worldwide.

Organic and Inorganic pollutants: The ever-increasing number of new and evidentially or potentially dangerous organic or inorganic substances (i.e. pollutants) and their tracking in the marine environment is a challenging disciplinary task in Marine Chemistry. Far more complex, however, is the judgement of the effect of these substances in the ecosystem (ecotoxicology). It requires identification of the stressors on individuals caused by these pollutants, for which new and advanced biochemical, microbiological, and genomic methods have to be applied. It also needs to constrain the dependency of these stressors on other physical or biogeochemical parameters. Only the embedding of these investigations in the physical and biogeochemical description of the ecosystem as a whole will allow to assess and to predict cause/effect relations between pollutants and ecosystem response.

The challenges for this focus are:

- Implementation of organic and inorganic carbon as independent variables in the different model environments based on a reliable experimental data base
- Implementation of variable C/N/P stoichiometries for major element transformation processes (primary production, respiration, denitrification etc.) on a basin-wide scale

- Basin-scale determination of phosphate uptake and turnover rates
- Parameterization of the production and decay of CH_4, N_2O, and other environmentally important volatiles based on other key variables
- Understanding the effect of new hazardous substances and pollutants by a comprehensive understanding of their fate and effects during transition from shore to sea and through different trophic levels

The vision for the next decade is to quantify relevant biogeochemical processes to an extent that allows an extrapolation of their significance for large scale transformation of matter within coastal and marginal sea ecosystems. In close collaboration with RF2.2 we are intensifying the study of known processes by including the turnover of understudied pools and initiate the investigation of processes, which have so fare received little or no attention. With a strong focus on stoichiometry we try to identify the interactions between different element cycles. In order to predict the consequences of changes in the environment we seek to identify the relevant parameters, which influence the quality and the quantity of the biogeochemical fluxes.

2.2.3 Research Focus 3: Changing Ecosystems

Unravelling causes for past and present trends of ecosystem changes as a basis for scenario development for possible future ecosystem states by acquisition, analysis and interpretation of sedimentary archives (RF3.1), acquisition and analysis of long-term *in-situ* data (RF3.2), and multi-decadal coupled three-dimensional ecosystem modelling (RF3.3).

A multitude of external factors and internal processes active on various time scales are shaping the environmental state and functioning of coastal and marginal sea ecosystems. Like in the Baltic Sea, long-term environmental trends initiated with the Glacial Period (eustatic sea level rise, regional glacio-isostatic rebound, hemisphere-wide Holocene climate changes) up to inter-annual to multi-decadal meteorological processes reaching the basin and its catchment from the wider North Atlantic region are prescribing the actual state of the ecosystem. Various human-induced pressures on this system (land use, eutrophication, transportation, construction) gained importance during the more recent history but their relative impacts on the natural developments are not fully understood. This understanding, however, is crucial for a successful and sustainable management of the future Baltic Sea (as worked upon in RF4).

The long-term measurements of hydrographic, hydrochemical, and hydrobiological data in the Baltic Sea form the basis for a regular assessment of the ecosystem state and the data series are meanwhile long enough to resolve temporal fluctuations up to about 30 years. These observations revealed that the Baltic Sea underwent several regime shifts during the past decades. Significant progress has been made in reconstructing the functioning of the Baltic Sea ecosystem for the last 1000 years by combining multi-proxy sediment studies, observational data, and sound ecosystem modelling approaches. The strong relations between temperature and oxygen concentrations in the deep water of the Baltic Sea have been confirmed on the example of the Little Ice Age (LIA). Recent progress in the development of the ecosystem model of the Baltic Sea (ERGOM) and the availability of supercomputing power made simulations of periods longer than 100 years a routine commodity. One of the outcomes of this improved set of tools and infrastructure was that the relationship between winterly weather conditions and the strong probability of strong cyanobacteria blooms has been shown. Together with partners from other Baltic Sea riparian countries ensemble simulations on the impact of Climate Change led to the main conclusions that a future Baltic Sea will be warmer, less saline, and less oxygenated.

In the future a significant effort will be devoted to the extension of the long-term observational records through the permanent acquisition of new physical, chemical, and biological data in the Baltic Sea. This will be crucial for defining reference conditions of the ecosystem and assessing ongoing changes (RF3.2). In order to reveal the elasticity and the full bandwidth of changes in an ecosystem, instrumental data will be merged with detailed paleoenvironmental reconstructions reaching back far beyond the observational period (RF3.1). Together with the knowledge gained in RF1 on fundamental small- and meso-scale processes and RF2 on basin-scale ecosystem dynamics a more integral view on ecosystem functioning will be achieved by assimilating these data into progressively complex numerical ecosystem models with the capacity to develop scenarios of future ecosystem trends and allowing also for cause-effect studies to elucidate the relationship between drivers and the response of the ecosystem (RF3.3).

RF3.1: Reconstruction of past ecosystem states

The only way to describe the full range of variability of a coastal and marginal sea ecosystem beyond the period of instrumental observations and to assess how it would function under different climate conditions, is to study its past states and variability. This is possible by interpreting the environmental information recorded in sedimentary archives and by using these typically more localized results for developing conceptual models and to validate and support numerical ecosystem models.

Besides reconstructions of past environmental changes in coastal areas and studies on coastal-basin interactions in the Baltic Sea and other selected coastal and marginal sea systems, one major research focus was and will be on the dynamics of anoxia. For the Baltic Sea, by way as example, the extension of anoxic areas is one important measure of the status of the ecosystem. The redox stage in the different sub-basins of the Baltic Sea has frequently changed between oxic and anoxic. Large scale external (e.g., climate, eustatic sea-level) and regional (isostatic rebound, land-use) factors as well as manifold internal feedback mechanisms in the system control the dynamics of anoxia.

In the frame of former projects it has been successfully demonstrated that large temperature changes impacted on the Baltic Sea´s ecosystem during the past 1000 years. Ecosystem modelling studies have been performed to confirm the hypothesis that a colder climate, like the Little Ice Age, supports higher oxygen concentrations in the deep water, but similar investigations are lacking for other designated time periods of different climate regimes. Anoxia, as observed today in the deeper basins, seems to have also occurred especially during warm periods of the ancient Baltic Sea´s history. Henceforth, a key-question to be addressed is the status of the Baltic Sea during past natural warm periods.

Progress has been made also on the reconstruction of the dynamics of saline water inflow and concomitant changes in surface water salinities in the Baltic proper. However, the links between surface and deep water changes and anoxia remain under discussion. There is little known about past precipitation/river runoff changes into the Baltic, and also about surface water salinity changes in areas outside the central Baltic. Thus, reconstructions on past freshwater budgets are lacking although they are critical for the status of the Baltic

Sea. A link to the climatic development in the wider north Atlantic is not clearly established yet but there is likely a strong influence of the North Atlantic Oscillation and Atlantic Multi-decadal Oscillation on the Baltic Sea´s ecosystem.

Effects of regional factors such as the significant water volume decrease of ~47% during the last 8000 years due to differential isostatic rebound in the Baltic Sea basin are not studied yet. The same applies for changing land-use during the last millennia. Significantly different paleoceanographic conditions are assumed for the early Baltic Sea with a diverging development of the northern and central basins in the later course of the Holocene. Moreover, previous studies have identified significant fine-grained lateral sediment transport from the western and northern Baltic into the Baltic proper that is not solely related to the isostatic uplift. This pathway of matter fluxes to the deep basins has to be studied in detail, as it is highly relevant to the development of anoxia. Since it is not clear which basins or basin parts served and presently act as accumulation, erosional or as “transport” areas for sediments, the calculation of accumulation/burial rates of various sedimentary components is severely hampered. Owing to the difficulty of direct observation, indirect methods can be applied to simulate lateral matter transport. A detailed sediment-acoustic mapping combined with paleoenvironmental reconstructions and modelling will enable to extract basin-wide flux rates and accumulation of matter for particularly defined past states of the ecosystem.

The challenges for this focus are:

- Synchronizing well-dated sediment sequences from different sub-basins of the Baltic Sea in order to investigate the large-scale sedimentation history on geological time-scales and to extract basin-wide flux rates and accumulation of matter.
- Reconstructing spatial-temporal developments of anoxia and related surface and deep water properties in the Baltic Sea and other comparable marginal sea systems by mapping short and long sediment cores taken along basin wide transects and applying decisive paleoceanographic proxies.
- Combining sediment proxy and ecosystem modelling studies to (i) elucidate cause-effect relationships of the changing Baltic Sea environment, (ii) identify external forcing factors, (iii) disentangle external forcing and internal feedbacks, and (iv) discriminate anthropogenic from natural pressures affecting the ecosystem.

A major task for the next decade will be to achieve the best possible chronostratigraphy for Baltic Sea sediments for linking the very diverse sedimentary archives along the successive sill-separated sub-basins, which store up to seasonal-scale environmental information. Detailed spatial and temporal mapping of sediment cores across the individual anoxic basins will reveal spatial-temporal fluctuations of the anoxic areas and associated changes in accumulation rates and patterns that will allow us to understand long-term driving mechanisms and the significance of the oxygen-depleted areas for the ecosystem. Beyond proxy formation processes and calibration (topic in RF1), another major prerequisite for conclusive high-resolution multi-proxy reconstructions of ecosystem changes is linking key sedimentary archives of adequate temporal resolution with the, in the Baltic Sea particularly extended, long-time observations and instrumental time series. Forced by climate reconstructions and proxy results, model-based ecosystem simulations will ultimately be used for an integral view on past ecosystem states for key periods representative of natural distinct environmental states of the system without e.g. substantial anthropogenic influences.

RF3.2 Present ecosystem variability and trends

Coastal ecosystems, especially under human pressure, are never in a steady state, but are subject to trends and variability. These need to be investigated to understand the variability (bandwidth of marginal sea ecosystem states) and to predict regime shifts due to changed external forcing. Long-term data from moorings, ship cruises, and remote sensing together with short sediment cores in combination with multi-decadal ecosystem hindcast models allow for reliable ocean state estimates for the past decades. Only the combination of these methods can eventually lead to explain regime shifts in response to changes in the external forcing.

Inter-annual variations of key parameters exceed the multi-decadal signals by orders of magnitudes. Therefore, only continuous and homogenous long term observation records combined with consistent model estimates will reveal systematic and random changes of the highly sensitive Baltic Sea system on the decadal and centennial scale providing the basis to understand their causes and consequences. IOW has carried out such observations and measurements and substantially contributed to the HELCOM database. As a major trend in the Baltic Sea, eutrophication leads to phenomena such as aggravated algal blooms, turbid water, oxygen depletion and lifeless sea bottoms (RF1, RF2). Artificial structures like bridges and offshore wind parks may e.g. influence the matter transport and thus the ventilation of the stratified basins of the Baltic Sea.

Long-term changes in species composition contribute to biodiversity changes (RF2) and are receiving increased awareness. Some of the invading species are hard to identify and often the transport vectors cannot be traced. An outburst of these species can cause significant ecological change and potentially economic damage. However, not only invading species are of interest, but also those subject to extinction. Sound knowledge on biodiversity changes supports measures for natural conservation and environmental protection (RF4).

Results from research on ecosystem trends are of high scientific interest and arouse political relevance. Thus, research results are highly wanted by political and economic stakeholders and contributed recently to the Water Framework Directive, the Marine Strategy Framework Directive, and the HELCOM's Baltic Sea Action Plan. New scientific results provide measures to control the success of those political regulations.(RF4).

The challenges for this focus are:

- Improving the spatio-temporal resolution of long-term observations to meet future demands via e.g. automated data acquisition and support from numerical models, without losing consistency with already existing data sets.
- Include critical biogeochemical parameters in automated long-term observations.
- Construct ocean state estimates based on long-term data using process-based ecosystem models to allow for long-term budgets of environmentally relevant parameters including their trends and variability.

To overcome the spatial and temporal under-sampling, a combined approach of ship based measurements and usage of automatic platforms will be used. Our multi-platform data acquisition will be 1) continuously improved as new techniques emerge, 2) extended to new platforms and parameters and 3) supported by model results of verified consistency with established data. The observational data will be augmented by high-resolution paleoenvironmental reconstructions from short sediment cores at representative positions. The same state-of-the-art numerical model systems, which are further developed within RF1 and RF2 (see also cross-cutting activity "Model development"), will be combined with the long-term data to give optimal ocean state estimates of past decades.

RF3.3 Scenarios for future ecosystem states

Only numerical models which have been validated against long-term data and which in turn have proven to represent all relevant key processes are able to provide sound scenarios for future ecosystem states for marginal seas under natural and anthropogenic pressures. To obtain the range for possible future ecosystem states, ensembles of dynamic downscaling from global via regional to marginal sea scales are necessary. This is a major computational task.

Against the background of the pronounced variability at different temporal and spatial scales, the challenge emerges to identify trends, which are caused by external drivers. Most important drivers for the Baltic Sea ecosystem are eutrophication, climate change, and utilization of the marine environment for different purposes. One aim is to identify those trends sufficiently early as a basis to assess possibilities of adaptation and mitigation and to provide a scientific basis for decision support (RF4).

Mathematical models are indispensable tools for a description of the complex interactions between physical, biogeochemical, biological, and geodynamic components. Together with scenarios of future trends of economic development, e.g. provided by the IPCC, and coupling with land use scenarios, possible impacts on the marine ecosystem can be evaluated. The aim is to provide scenarios of future development with the aid of mathematical models that encompass: i) physical dynamics, ii) nutrient and oxygen concentrations, and biogeochemical fluxes, iii) the carbon cycle, iv) bentho-pelagic coupling including sediments and pore water phase, and v) links to higher trophic levels like zooplankton, jellyfish and shellfish.

Owing the high interannual and decadal variability of the Baltic Sea (RF3.2), transient ensemble simulations will be used to assess the possible range of uncertainty and updates will be provided in response of updated global scenarios.

Progress has been made in scenario simulations for a future Baltic Sea under different pressures. Transient simulations for the next 100 years with a three-dimensional ecosystem model of the Baltic Sea have become routine.

A major focus is put on cause-effect studies to elucidate the relationship between drivers and the response of the ecosystem. A sound understanding of the quantitative importance of the involved processes, as investigated in RF1 and RF2, will be developed. For instance the water mass transformation, with an exchange time scale of 30 years, was identified as such a key component.

IOW's specific approach is here to apply the same ecosystem modelling system components which have been applied for the process studies in RF1 and which have been used to reproduce the dynamics for various marginal sea ecosystems in RF2. With this it is ensured that relevant processes and their impact on the ecosystem are properly resolved also in climate projections.

The challenges for this focus are:

- Testing of possible future scenarios for different IPCC scenarios (including effects of sea level rise, global warming, changed air-sea fluxes) by developing and applying a regional earth system model.
- Carrying out sensitivity experiments for consequences of direct human impact (e.g. changes in nutrient inputs or fishery, extensive offshore constructions)
- Combined studies of climate change and changed direct human intervention.
- Gaining sufficient knowledge of the mechanisms driving the Baltic Sea ecosystem to be able to evaluate the impact of external changes on the marine ecosystem.

Research will be focused on designing and improving a regional earth system model for the Baltic Sea and its catchment that is adjusted to the relevant time and space scales and is based upon long-term and process data sets at IOW and worldwide. In the models state-of-the-art improvements of process description, model resolution, and model complexity will be implemented, to allow for most reliable projections and sensitivity experiments. Ensembles of simulations for up-to-date IPCC scenarios combined with scenarios of changed direct human interventions (e.g., decreased or increased eutrophication) will be performed.

2.2.4 Research Focus 4: Coastal Seas and Society

This new research focus comprises applied research in close co-operation with end-users. It emerged from an increasing demand. The spatial focus is on coasts, water body and sediments of the Baltic Sea. Interactions with river basins are taken into account where necessary. In 'Coastal Seas and Society' a synergy is sought which feeds competence and knowledge of basic IOW research (as provided by RF1, RF2, and RF3) into the solution of applied problems and at the same time comprehends environmental problems as large-scale experiments that induce basic reaction patterns of stressed ecosystems. For example, the observation of system reactions on anthropogenic interventions provides data for the basic assessment of ecosystem flexibility and resilience. Therefore this new RF will also intensely feed back to the basic research agenda of IOW.

Already in the past, IOW carried out applied research and provided expertise for authorities and specific national and international end-users (e.g. HELCOM, UNEP-ICARM, UNESCO-IOC). The effort yielded numerous products specifically directed towards this patronage and various stakeholders. However, this work was largely carried out within limited projects, where a special expertise was required or was a subsequent use of research results. During the last decade the number and scale of human interventions as well as of uses and conflicts in coastal seas increased and became more complex. As a response to increasing pressure on our coastal seas, new and comprehensive environmental policies were adopted and will be implemented during the next decade. Global and regional transformation processes that strongly influence our seas overlay these developments. Against this background challenges for applied research are increasing in number, complexity and spatial coverage. They ask for sophisticated methods, models and expertise as well as interdisciplinary approaches and a holistic ecosystem understanding.

Major tasks of RF4 within IOW are (a) to support the extension and improvement of our model systems (flexibility, spatial coverage, resolution and new sub-modules) to increase their predictive capacity and to enable more accurate tailor-made information for practice; (b) to support the development of databases and geo-information systems, which serve as a safe storage for data, allow analysis and provide information on state and spatial distribution of marine ecosystem parameters for applications in science, planning and policy implementation and (c) intensified communication and co-operation with end-users of our research as well as improved transfer of our research results and translation into information that serves the demand of authorities and policy. These tasks will be supported by the German branch of EUCC - International, EUCC - Die Küsten Union Deutschland e.V., located at IOW.

Objective is to provide tools, expertise, assessments, implementation support and model based projections for authorities and specific national and international end-users. A major support is provided by the series of long-term data, which for several decades are recorded by IOW in coastal and basin subsystems of the Baltic Sea. Within RF 4 they serve as a general comparative matrix for the assessment of local and short-term system changes. Research is driven by curiosity as well as societal and political challenges and ensures a synergy between and mutual benefits of scientific progress and practice. Thematic flexibility, a fast response to new challenges, the exploration of new research themes as well as a high degree of external funding is characteristic for this activity. Further main features are multidisciplinary and close co-operations with social, economic, planning and engineering sciences as well as with non-governmental organizations and private enterprises, taking care not to compete with the latter. “Coastal seas and society” supports the dissemination of scientific knowledge and helps to increase the public awareness about marine and coastal problems. To improve the scientific exchange and developments we seek a strategic partnership with major applied research institutes in the Baltic.

RF4.1 Anthropogenic uses and interventions in coastal and marine systems

Anthropogenic uses (e.g. tourism, energy production, extraction of minerals, maritime transport, and aquaculture), constructions and interventions (e.g. bridges and tunnels, off-shore wind farms, gas pipelines and cable routes, coastal protection measures, channel deepening) have various impacts on coastal and marine ecosystems and interfere with natural processes and variability.

In the past, selected impact assessment studies on e.g. planned off-shore wind farms, the Fehmarn Belt link or mussel cultivation allowed to fill gaps in our datasets, to carry out detailed studies on zoo- and phytoplankton as well as a mapping of benthic communities, to refine and extend our models and supported the development of innovative methods. They improved our knowledge about the Baltic Sea ecosystem and gave an impression how interventions might affect processes on different temporal and spatial scales. They answered questions, like to what extend pillars of bridges and wind farms affect water inflow, mixing and a decreasing density of the oxygen carrying salt water. The results were of importance e.g. for the spatial structure, density and design of these constructions.

The challenges for this focus are:

- Providing impact assessment studies for new constructions like offshore wind, aquaculture farms and new coastal protection measures
- Assessing impact of increasing vessel traffic with larger ships on the ecosystem
- Estimating effects of larger ships that require a deepening of channels and harbour entrances as well as frequent dredging and dumping with multiple consequences on water bodies and sediments.
- Other challenges not foreseeable today might emerge.

Research is required to be able to assess the consequences of these interventions and to support a sustainable Marine Spatial Planning.

Objectives are to understand how the ecosystem and its processes are influenced by anthropogenic measures and interventions, to give advice how to manage the ecosystem as well as to maintain major ecosystem services.

RF 4.2: Implementation of marine and coastal policy

National and international environmental policy is an important challenge for science. Relevant examples are European directives like Water Framework Directive, Bathing Water Directive, Habitats Directive, Framework Directive on Integrated Coastal Zone Management and Maritime Spatial Planning, the Strategy on Sustainable Use of Natural Resources, and HELCOM recommendations. Most recent examples are the European Marine Strategy Framework Directive (MSFD) and its implementation to reach a good environmental status in the Baltic Sea as well as the HELCOM Baltic Sea Action Plan (BSAP).

The development of a marine strategy for the Baltic Sea was a topic of major concern during the last years. There was a strong involvement of IOW scientists in preparing an initial assessment of the current environmental status of the German part of the Baltic Sea, in preparing a determination of a good environmental status as well as establishing environmental targets and associated indicators. The implementation of the EU Habitat Directive (Natura 2000) also was an important issue. Location, characteristics and typical features of predominant habitats have been investigated and indices to assess their status have been developed. Another important example of past research is the assessment of water quality objectives according to the EU Water Framework Directive.

The implementation of the Marine Strategy Framework Directive will be the major challenge during the next decade, because it serves as an umbrella for the European marine and coastal policy. The descriptors and associated indicators for a good environmental status of marine ecosystems in the MSFD already indicate gaps in our knowledge and outline future research needs. The following descriptors are most important for our future research: biological diversity, marine food webs, eutrophication, sea floor integrity, alteration of hydrographical conditions, contaminants and marine litter. While for most descriptors data, expertise and models are available, marine macro and micro litter still requires a lot of basic interdisciplinary research: quantifications, monitoring, method developments as well as transport, source and contaminant analysis are required.

The implementation of the Baltic Sea Action Plan as a part of the MSFD and the evaluation of eutrophication abatement measures will remain important issues. Nutrient load reductions in river basins often are not sufficient to reach a good status in coastal waters. New supporting measures in coastal seas have to be tested with respect to effectiveness and cost-efficiency. New management approaches have to be developed. Ecosystem services, as another relevant topic, shall be addressed in future. A transfer of valuation methods, their introduction into ecosystem models and spatial monetary assessments for Baltic Sea regions are pending tasks.

The Baltic Sea Region is a forerunner in the implementation of Marine Spatial Planning (MSP). This, however, revealed the currently weak knowledge foundation of MSP and a new need for the availability of further scientific data, tools and advice. Pressing questions focus on cumulative impacts, cross-border impacts, spatial relations and patterns as well as spatial typologies. Interdisciplinary research and transnational co-operation is needed to create suitable knowledge.

The aim within RF 4.2 is to provide a sound scientific basis for the implementation of those polices in co-operation with major authorities. Among others, indicators will be developed and tested to measure the state of ecosystems and a successful implementation of environmental policy.

RF 4.3: Regional Change – impacts, response and adaptation

Climate change, increasing pressure by human activities on coasts and seas, as well as land-use changes in river basins, directly and indirectly affect coastal and marine waters and thus marginal seas.

In the past, model simulations were carried out to analyse the consequences of Climate Change on the Baltic ecosystem and how Climate Change affects the implementation of the Baltic Sea Action Plan. It turned out that Climate Change has only limited consequences on water quality. Socio-economic and agricultural changes, like the increased growth of energy plants in the river basin, are of higher importance. However, Climate Change alters important parameters like salinity and temperature. First studies on consequences of regional changes on micro-organisms, jellyfish, mussel cultivation, the shipworm, and beach management have been carried out.

The challenges of this research focus derive from Climate Change and socio-economic transformation processes around and in the Baltic. They are on-going and require new assessments as well as the development of adaption measures and strategies. Special emphasis lies on integrated applications of river basin and marine ecosystem models. Climate Change, for example, might create new problems with micro-organisms. New human-pathogenic species enter our waters and others (e.g. vibrions) benefit from changing conditions. Interdisciplinary research, method developments and new management tools are required to deal with these potential problems. Improved tools like geographic information systems and flexible models help us to meet the challenges. Applications with improved models shall include economic evaluations and address topics like changes of ecosystem services as well as the cost-effectiveness of measures.

Objective is to provide projections of future changes and their consequences on marine ecosystems by means of “state-of-the-art” models as well as to provide the scientific basis for adaptation measures to be implemented by authorities and administrations.

2.2.5. Cross-cutting activities

As the backbone of the IOW research programme, both, ocean observation and modelling can be identified. Beside the important work of securing the operability of sophisticated equipment in these fields, there is a constant need of a further development of new technological solutions to match the scientific needs. Respective activities serve all research foci of this programme and are therefore designed as cross-cutting activities.

2.2.5.1 Innovative Instrumentation

Innovative instrumentation and new methods are required to reach the major objectives of the research programme. For the understanding of key ecosystem processes, continuous observations of physical, biological and chemical variables are necessary in the ocean, spanning scales of space and time over many orders of magnitude from sub-second to decadal and sub-mm to basin wide. Measurements are carried out employing a variety of observational tools from satellite observation systems to in situ instrumentation. The continuous development of new scientific instrumentation, methods and algorithms is driven by the exact definition of the observational and analytical requirements in a constant bi-lateral exchange between developer and science user.

As the development from a first concept to fully functional instrumentation or established method is a long lasting process, we aim to optimize the mechanisms to match scientists' observational needs to technologists' solutions potentially meeting these requirements. The IOW's emphasis on instrumentation and method development is application of new technologies in the most useful and often very specific manner rather than development from scratch. IOW will develop, integrate and optimise the techniques and components necessary for new instrumentation and methods in close collaboration with technologists, academic and industrial partners, ascertaining the transfer of newly developed techniques and components to a wider user range. Where appropriate new developments will be guided into patent applications. The involvement of the science user in every step of the instrumentation development process is indispensable.

One objective already identified is the automated high resolution online monitoring of microbial communities and activities. To reach this goal, new, and especially molecular tools are needed that can be applied to ship-based detection and sampling systems as well as to autonomous ocean observation platforms.

In consequence, this set of observational and methodological tools will provide new knowledge on structures and functions that will help answering fundamental questions on processes and their spatial and temporal distributions, regulations and development.

The new instruments and methods will create a wealth of data that will be effectively linked to the improved IOW data management infrastructure; this will allow easy access for interpretation of the collected data in ways that were not anticipated at the time of collection.

The challenges for this crosscutting activity are:

- Developing optimal design processes for new scientific instrumentation
- Optimize the interplay between user requirements and application of new technology in scientific sampling instrumentation
- Providing functional instrumentation to operational scientists and thus supporting them to meet the research goals

- Support the transfer of new technologies
- Enable the transformation from a 'mechanistic' to a functional ecosystem assessment
- Quality assurance of measurements of new parameters employing uncertainty analyses and new calibration facilities
- Establishing innovative technical options for data transmission from measuring platforms to the data archives.

2.2.5.2 Model development

The quantification of budgets and fluxes of matter in marginal seas as well as the study of ecosystem susceptibility to change requires the availability of suitable coupled physical-biogeochemical model systems. For this purpose, IOW hosts a numerical model environment consisting of various components coupled together interactively. Backbones of this model environment are hydrodynamic community models for coastal and marginal sea scales. Turbulence, biogeochemical, zooplankton and fish, surface wave, and sediment and many other modules are coupled to the hydrodynamic modules. One major aim is the model development in the next decade to increase the modularity of the system in a way that modules can be easily exchanged, for example if a new type of hydrodynamic or biogeochemical model is needed. All applied modules are open source, and it is the intension to make all IOW model developments available to the public through the World Wide Web. This is not only a community service, but does also provide an additional model quality control.

Two levels of model development are distinguished: 1. Extension of existing modules towards inclusion of additional processes or refined parameterisations and 2. Numerical or infrastructure developments. The former is taking place in close collaboration with field researchers within the framework of the three research foci where the respective work is described. Such model development is generally not requiring substantial changes in the model numeric or infrastructure. Developments on the latter level however become necessary for a number of tasks.

Processes and parameterisations

Physical modelling: New developments of turbulence closure models and its integration into numerical modules is a main task for IOW model development. These new developments, which are necessary to investigate ocean mixing and transport phenomena in greater detail, are the interaction between waves currents and turbulence, both for surface and for internal waves (see RF1.1). Due to increased model resolution, meso-scale and submeso-scale processes impacting on transports and small-scale mixing need to be parameterised in different ways as before. The same is valid for lateral intrusions which state-of-the art-models are able to resolve partially. Furthermore, with steadily increasing computer resources, resolution of non-hydrostatic processes will more and more be feasible, with consequences for the validity of various parameterisations of small-scale mixing and internal wave dynamics. The activities will specifically support activities within RF2.1 (Basin-scale mixing and transports), which in turn will strengthen the predictive capacity of the model system when applied within RF3.

Biogeochemical modelling: The biogeochemical models developed at IOW represent the matter cycles relevant for the ecosystem of the Baltic Sea. Various modules with higher functional resolution exists such as modules for stage-resolving zooplankton, stage and species resolving fish dynamics, and redox processes including bacterial dynamics. One of the great challenges is the end-to-end modelling which combines all involved trophic levels into one consistent model system (RF2.2) allowing for investigations of bottom-up and top-down trophic relations within one model system. The coupling of existing vertically resolving benthic modules and its further development will enable us to investigate the essential processes involved in benthic-pelagic coupling and its role for marginal sea ecosystems in much greater detail (RF1.3).

Numerical and infrastructure developments

Marginal seas such as the Baltic Sea are typically characterised by significant stratification and are interacting with steep topography in many ways: density-driven inflows propagate over long distances through basins and over sills, effective vertical mixing is caused by a combination of lateral transport and mixing at the sloping bottom rather than direct vertical mixing and lateral intrusions from inflows, and boundary mixing propagates far into the stratified bulk of the basins. Nevertheless, mixing time scales may be long in such marginal seas, typical being on multi-decadal time scales. As no hydrodynamic model is resolving all these processes in a sufficient way, IOW aims to develop numerical methods with higher resolution and decreased numerical dissipation and mixing.

Model infrastructure development will be necessary to allow for more flexible combination of modules (connected by flexible links, e.g. pelagic hydrodynamics with pelagic biogeochemistry) and models (coupled together via model couplers, e.g. pelagic hydrodynamics with surface wave model). Other crucial fields of development are tools for adaptations and refinements of model bathymetries and other external forcing data such as river loads and atmospheric forcing. Strategically, we seek for further intensifying collaboration with national and international partners to jointly work on further developing and exchanging state-of-the-art modules and models.

Challenges for this cross-cutting activity are:

- To develop parameterisations for consistent energy cascade down from the mesoscale via the submeso scale to the small scale.
- To refine turbulence closure models for better representation of internal wave impact on mixing.
- To develop new and refined ecosystem process descriptions for increased model predictivity.
- To integrate IOW's numerical modelling system into a flexible modular framework for complex marginal sea ecosystem simulations.
- To couple additional external modules such as for surface waves and benthic early diagenesis to the modelling system.
- To refine numerical schemes for higher accuracy allowing for better resolution of dynamics at interfaces and better reproduction of inflow processes.

3. Abbreviations:

BSAP:	Baltic Sea Action Plan
BSH:	Bundesamt für Seeschifffahrt und Hydrographie ; Federal Maritime and Hydrographic Agency
C/N/P:	Ratios of carbon to nitrogen to phosphorus
DFG:	Deutsche Forschungsgemeinschaft; German Researcg Foundation

DIN: dissolved inorganic nitrogen
DOM: dissolved organic matter
DON: dissolved organic nitrogen
DOP: dissolved organic phosphate
ERGOM: Ecological Regional Ocean Model
EUCC-D: The Coastal Union Germany
Fe: Iron
IOW: Leibniz Institute for Baltic Sea Research
IPCC: International panel on climate change
LIA: Little Ice Age
MSFD: Marine Strategy Framework Directive
MSP: Marine spatial planning
NanoSIMS: Nano secondary ion mass spectrometry
O: Oxygen
RF: Research Focus
S: Sulphur
SST: Sea Surface Temperature
UNEP-ICARM: Integrated Coastal Area and River Basin Management of the United Nations Environment Programme
UNESCO-IOC: United Nations Educational, Scientific and Cultural Organization - Intergovernmental Oceanographic Commission
VHOC: volatile halogenated hydrocarbons
VOS: volontary observing ship