Research Programme 2024 – 2033

Perspectives of Coastal Seas

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1. Introduction

1.1 What is the overall objective?

Coastal seas play a pivotal role in our planet's ecological balance and human well-being. These dynamic environments are home to diverse marine ecosystems, supporting a wide array of marine species and providing paramount ecosystem services as well as essential habitats for various organisms. Additionally, coastal seas significantly impact regional and global climate patterns, acting as heat and carbon sinks as well as influencing weather phenomena. However, coastal seas face mounting challenges like pollution, habitat degradation, and rising sea levels due to climate change. Effective research is essential to understand, protect, and manage these vital marine ecosystems for the benefit of both nature and humanity. In support of the societal transformation towards sustainability and resilience, fundamental knowledge, innovative methodologies and science-based scenarios are needed. These are the driving principles behind our mission to provide "**Perspectives of Coastal Seas"**.

We therefore strive to understand,

- which processes under which framework conditions keep the "coastal sea system" in balance (Research Area 1),
- which natural fluctuations the coastal seas are subject to, and whether, against this background, changes due to anthropogenic use and climate change can be identified (Research Area 2).

Moreover, facing an alarming acceleration of changes, with the Baltic Sea being one of the fastest warming marine areas on Earth, we recognize the urgent need to speed up and intensify our efforts by making our tools more efficient and powerful. Therefore, we also aim

- to establish new integrative approaches for a holistic ecosystem assessment, through improved instrumentation and analytics and optimal data re-use, including the use of artificial intelligence, and up-to-date modelling approaches (Research Area 3).

1.2 Where do we come from?

1.2.1 Events and changes influencing the course of the previous research programme

The research programme 2013 – 2023 "**Understanding Coastal Seas**" followed a well-structured system approach, in which relevant processes over appropriate time and spatial scales were addressed in an integrated way. However, shortly after the launching of the programme an unpredictable natural phenomenon occurred that shaped our work, when in December 2014, **a large Major Baltic Inflow (MBI)** emerged. It happened to be the largest inflow within the then last 60 years and the third largest since observations began in 1880. [1] The impact of this event on a range of variables was therefore a major focus in the following years. It was alarming to see that the oxygen transported to the bottom waters in the deep basins was consumed again within six months [2]. One of the results of the associated research activities was that small-scale intrusions into and below the redoxcline exceed the effect of MBIs by an order of magnitude, thus, the role of the MBIs for the oxygen supply seemed to be overestimated [3], [4]. The importance of **medium-intensity inflow events (MIEs)**, moreover, was also confirmed by geochemical studies on sediment cores from the Landsort Deep showing that the oxygenation of the bottom waters of the Landsort Deep is triggered not only by MBIs but also by the more frequent MIEs [5].

In 2012, a **working group on geomicrobiology**, had been newly established strengthening microbiological research at the IOW. This group had a special interest in metabolic pathways and elemental fluxes in microorganisms and microbial communities. Special emphasis is put on the questions how microorganisms gain their energy demands in these ecosystems and how this influences the elemental fluxes.

With the founding of the **environmental microbiology working group,** also in 2012, a new emphasis was set on the connection between microbiology and societally relevant topics. Examples are the more frequent occurrence of pathogenic Vibrio strains in the summerly Baltic Sea due to global warming or the colonization of microplastic particles with pathogenic microorganisms.

In the course of the research programme, methods of molecular biological analyses gained in importance. This had two consequences on our infrastructure: first, it became evident that **expertise in bioinformatics** had to be available permanently at the IOW; and second, the increasing research need in analysing metagenomes or metatranscriptomes called for the development of specific sampling methods that fix water directly in the environment, and by this instantaneously conserve the gene expression profile in situ. The **development of such an Autonomous Flow Injection Sampler, in short AFIS**, which went along with the establishment of the environmental microbiology group, paved the way to new scientific approaches like the monitoring of microbial activities and functions in the environment through the analysis of gene abundance and expression.

Establishing **a new working group on regional climate modelling** in 2015, enabled the IOW to investigate, how the climate of the Baltic Sea and its ecosystems might develop under the influence of Global Change. To this purpose, a coupled atmosphere – ocean model with a novel coupling technique was developed as a basis for an IOW regional climate model. In conjunction with our further enhanced biogeochemical ERGOM model, we now have the tools to compute projections on the degree of eutrophication, on salinity or temperature development, both for the past 8.000 years and the future 100 years.

Since 2020, an Emmy Noether Junior Research Group has been established at IOW to study **interactions between marine fungi and phytoplankton**. The effects of parasitic fungi on matter cycles and ecosystem function are poorly known or quantified. The Emmy Noether Junior Research Group will investigate the functional and quantitative role of parasitic fungi on phytoplankton productivity and cycling in brackish and seawater.

1.2.2 Selected highlights of the previous research programme

It is a core objective of the IOW to achieve research insights that are relevant for the Baltic Sea scale and beyond. The following section exemplifies achievements of the previous research programme period through selected highlights and their major references.

Taking the Black Sea, with its permanent stratification, large oxygen-free water masses and extensive zones of toxic hydrogen sulphide (H_2S), as an excellent natural laboratory to study **survival strategies of specialised organisms** in such an environment, we could demonstrate how bacteria are able to grow there. For the first time it could be shown that a bacterium frequently occurring near the “dead zone” specifically uses manganese (IV) oxide to **gain metabolic energy from H_2S** converting it into non-toxic sulphate [6].

We were also able to show that conspicuous phosphorus anomalies in the Black Sea can be attributed to the fascinating abilities of certain large bacteria. Until then, the scientific community had not been able to explain these anomalies. We showed that so-called **magnetotactic bacteria**, which are capable of accumulating polyphosphate and can migrate in a directed manner within the water column thanks to their magnetic properties, are the main cause of phosphate displacements. In this way, they help to control the phosphate content in surface water [7].

In the Baltic Sea, we found out by a combination of high-resolution profiling, molecular techniques and process rate measurements that **archaea** (Thaumarchaeota) alone are responsible for nitrification in the suboxic zone, not bacteria! And we could provide experimental evidence that the tolerance of ammonia-oxidizing archaea to sulfidic conditions is one probable reason for their dominance in periodically euxinic systems worldwide [8].

The **estuarine circulation** is one of the driving physical processes within coastal seas. During the previous research programme we made substantial progress in elucidating its role in sediment dynamics. This led to respective modelling approaches, which we successfully applied, for instance, in projecting the distribution of microplastics along the coastline of the Baltic Sea or from the estuary of a representative river to the open Baltic [9], [10].

Since 2003, the IOW is running a programme of **high-resolution measurements of pCO_2 (since 2009 also methane)** in the surface water of the Baltic Sea by means of a Voluntarily Operating Ship (VOS), the Finnish cargo ferry FINNMAID. This programme, which has been continued through the whole duration of the previous research programme and will be going on as a German contribution to the international ICOS programme, created a valuable backbone for several studies on carbon dioxide and methane cycles in the Baltic Sea. Thus, we demonstrated that high-resolution data of CO_2 in surface waters **reveal very precisely any temporal or spatial changes in primary production by phytoplankton** [11]. We were able to show that this method is much more reliable and sensitive than traditional methods – both to describe small-scale processes quantitatively and to recognize long-term trends early-on [8]. We also showed that **ocean acidification in the Baltic Sea was buffered by increasing alkalinity** over the 1995-2015 period, highlighting the complexity of this process in coastal seas [12].

Investigating **processes of the methane cycle in a combined gaschemical, microbiological and physical approach** became one of the IOW characteristics during the last decade. For example, we determined for the very first time the efficiency, with which methane-oxidising bacteria from the seafloor can travel with gas bubbles from submarine methane seeps into the open water column and influence biogeochemical processes there. This transport process can be of importance for the removal of the greenhouse gas methane in the marine environment and thus for global climate developments. Furthermore, we identified a CH_4 enrichment below the thermocline in shallow waters. By means of community and food-specific grazing experiments, we found out that zooplankton, potentially associated with methanogenic archaea, contributes to this enrichment depending on its community composition as well as food quality and diet-consumer relationships [13], [14] [15] [16].

Using **stable isotopes of nitrogen and carbon** to decipher the pathways and processes within the respective matter cycles has been one of the cornerstones of the IOW biogeochemistry work since its very beginning in the early 1990s. During the last decade a focus was set on the nutrient transformations in coastal waters and the regulation of N losses. Comprehensive studies resulted in unique inventories of the main elementary components of dissolved organic substances in the estuaries of the Baltic Sea including the analyses of their genesis [17], [18], [19].

We established the method of analysing **compound-specific nitrogen isotopes in amino acids** (CSIA-AA for short) and are today one of the few laboratories in the world applying this method. It allows to see how much essential nutrients are being produced for a food web. An example of our findings supported by this method is the recognition that much of amino acids is still produced in cyanobacteria carpets even when the bacteria already largely stopped their activity after the climax of the bloom. This inevitably must have consequences for the food web. With a global increase of cyanobacteria blooms such an excessive supply of nutrients before winter is a relevant parameter for the seasonal growth cycle of zooplankton – but also for fish-stocks [20], [21].

The **state of the food web** is also an important information regularly monitored by the Helsinki Commission (HELCOM). On the basis of our long-term data series we developed a new indicator for changes in the food web: the ratio of diatoms to dinoflagellates in the spring bloom composition – the so-called dia/dino index. It describes, which of the two groups dominated the yearly spring bloom. This in turn has effects on the organisms preying them: If diatoms dominate the spring bloom, more parts of the food web take profit than if dinoflagellates are the major group. So, this simple relation provides authorities like the HELCOM with a good measure to describe the state of the food web [22].

With our profound expertise in **zoobenthology**, we not only monitored the state of protected habitats like sand banks and reefs within the German EEZ, the latter being represented by boulder fields on moraine ridges. We also showed that it is possible to predict, which contribution the effects of climate change and eutrophication will have on the distribution of important zoobenthic key species in the Baltic Sea [23], [24].

We have succeeded for the first time in reconstructing the history of blue-green algae blooms in the central Baltic Sea over the last 160 years by using **biomarkers** and a well-dated sediment core. This way, we extended the period, for which information on the frequency of blooms was previously available, well into the past. No clear evidence of a causal link between cyanobacteria abundance and eutrophication of the Baltic Sea was apparent, but we found evidence of a link with increased summer surface water temperatures [25]. One of our well-dated sediment cores from the Gotland Deep has even been nominated for the **"Golden Spike"** – the Global Boundary Stratotype Section and Point (GSSP) – of the **Anthropocene**. With detailed analyses on geochemical markers typical for human-made impact, we demonstrated to be able to pinpoint the onset of this proposed new geological epoch [26].

Under the umbrella of the **Coupled Model Intercomparison Project 5 (CMIP5)** climate and environmental projections for the Baltic Sea were created. On this basis we examined the combined influence of plausible climate change and overfertilization scenarios on the coupled physical-biogeochemical system of the Baltic Sea. Based on the then largest existing ensemble of simulations and a new method that can quantitatively describe uncertainties in the projections, we could show that natural variability is a larger source of uncertainty than previously thought [27].

Research demands on natural climate variability led to first investigations of teleconnections. They showed that in order to understand changes in Baltic Sea climate and its impact on the ecosystem it is important to consider also low-frequency large scale natural modes of variability such as the **Atlantic Multidecadal Variability**. Most recently, we could demonstrate its impact on the Baltic Sea surface water winter temperatures as well as on its salinity [28, 29].

With the release of two reports on the development of the Baltic Sea under the influence of Global Change (Baltic Earth Assessment of Climate Change for the Baltic Sea - **BACCII** in 2015 and Baltic Earth Assessment Report - **BEAR** in 2023) the Baltic Earth community under the coordination of IOW scientists provided respective comprehensive state-of-the-art-reports similar to the IPCC reports. The most recent report, which actually consisted of a series of sub-reports, was also published as a climate change fact sheet for stakeholders by the international scientific network Baltic Earth and the Helsinki Commission (HELCOM) [30].

Pollution of the Baltic Sea with all kinds of contaminants, such as polychlorinated biphenyls and polycyclic aromatic hydrocarbons, but also herbicides, pesticides, compounds from pharmaceuticals or personal care products is one of the main issues threatening its ecosystems. Milestones of the previous programme related to the pollution topic included comprehensive surveys on the distribution of polycyclic aromatic hydrocarbons (PAHs) and the development of the first method that allows to detect glyphosate in saltwater [31], [32]

Soon after the launch of our research programme the issue of non-decomposing, i.e. accumulating **microplastics** in the environment became a major concern within the marine science community. At the IOW, the question whether these ubiquitous particles might be a vehicle for pathogenic microorganisms has been at the forefront of related research. This was combined with methodical efforts, as analysing tiny fractions of a material that is present in nearly all working materials or clothes proved to be a great challenge. Developing working standards, was thus an important achievement of IOW, which made the respective research in general more efficient. Today, thanks to IOW´s research, we know that the biofilms covering the particles are not a favourite habitat for pathogens [33], [34]. However, further damages caused by microplastics are still under debate. Data from a long-term mooring within the Madeira Basin operated by the IOW over the last decades have shown for the very first time the temporal evolution of microplastic pollution in the North Atlantic Ocean at 2000 m water depth [35].

1.3 Where do we want to go?

1.3.1 What is new: Major changes in the orientation of our work

IOW has a long tradition in interdisciplinary coastal and marginal sea research and in the development of innovative technologies and methods. It is very well networked internationally, operates central infrastructures for marine research as well as (governmental regulatory) monitoring, and makes significant contributions to the transfer to society. Building on this tradition and these strengths, we want to develop and implement an integrated research agenda, increase international visibility in research and transfer, and use advances in digitization to enable new scientific insights. Our vision is to provide **Perspectives of Coastal Seas** as a whole and - through scientific knowledge, innovative methods and dialogue with society - to contribute to solving regional and global challenges.

Our new research programme is structured along three research areas (see Figure 1), addressing open questions in "**Key Processes across Scales**" (Research Area 1), **"Coastal Seas in Transition – Present, Past and Future Perspectives"** (Research Area 2) and **"Emerging Technologies"** (Research Area 3). An important new step compared to the previous programme is its additional orientation towards the **shallow water area** between the coastline and a water depth of about 10-20 m. This interface will experience a certain concentration of research over the next decade and will require new approaches and technologies. A strategic expansion of the institute´s budget has created the necessary preconditions for this. After decades of operating autonomous measurement stations and long-term observations at different positions in the Baltic Sea with water depths >15 m, we are now also venturing into this shallow water region, which has so far eluded continuous observation due to its high dynamics. This transition zone between land and ocean is characterised by complex interactions, short timescales and strong heterogeneity. New methods, both in the investigation of fundamental processes, their metrological recording and their integration into models, are necessary. This also includes participatory approaches such as citizen science or real-world laboratories. Analysing these near-shore processes and learning how these "**Shallow water processes and Transitions to the Baltic Scale**" (**STB**) affect the entire Baltic Sea is a central new task that tackles all three Research Areas.

With the launch of the new programme, we will also establish **a new organisational unit "Marine Observations" (OBS),** which will bring together all the scientific and technical staff involved in developing the measurement strategies and technological equipment needed for coastal ocean observation. This includes the newly recruited technicians and engineers responsible for innovative shallow water technologies as well as the working group that has built our reputation for oceanographic observation systems: engineers and technicians responsible for autonomous measurement stations such as the MARNET stations and sophisticated seagoing sampling and measuring equipment, previously organized as a working group under the umbrella of the department Physical Oceanography. This will be complemented by a (re-)development of capacities for the use and interpretation of multi-spectral remote sensing data on multi-spatial-temporal scales within the IOW as well as with other partners. The new OBS unit will be headed by an experienced scientist who will be appointed jointly with the University of Rostock to a professorship dedicated to "Marine Observations".

An overall goal of IOW is to create a coherent and multi-dimensional representation of the real and virtual (marine) environment. This requires an integration of different observation systems, models and intelligent data analysis in high resolution and quasi real time, combined with intuitive interfaces. Recognizing the wide range of opportunities that smart data handling offers in terms of generating new research results or identifying gaps in our understanding, we will integrate new aspects of **data science** to our research programme, including the application of artificial intelligence. Our final goal is the full exploitation of the collected data and the provision of science-based scenarios and perspectives, empowering knowledge-based decision making in an interactive environment, known as "**Digital Twin** of the Baltic Sea". To strengthen a **dialogue-oriented transfer**, we will extend our communication and participation platforms. This will also include the involvement of citizens and stakeholders in the creation, realisation and evaluation along the scientific process.

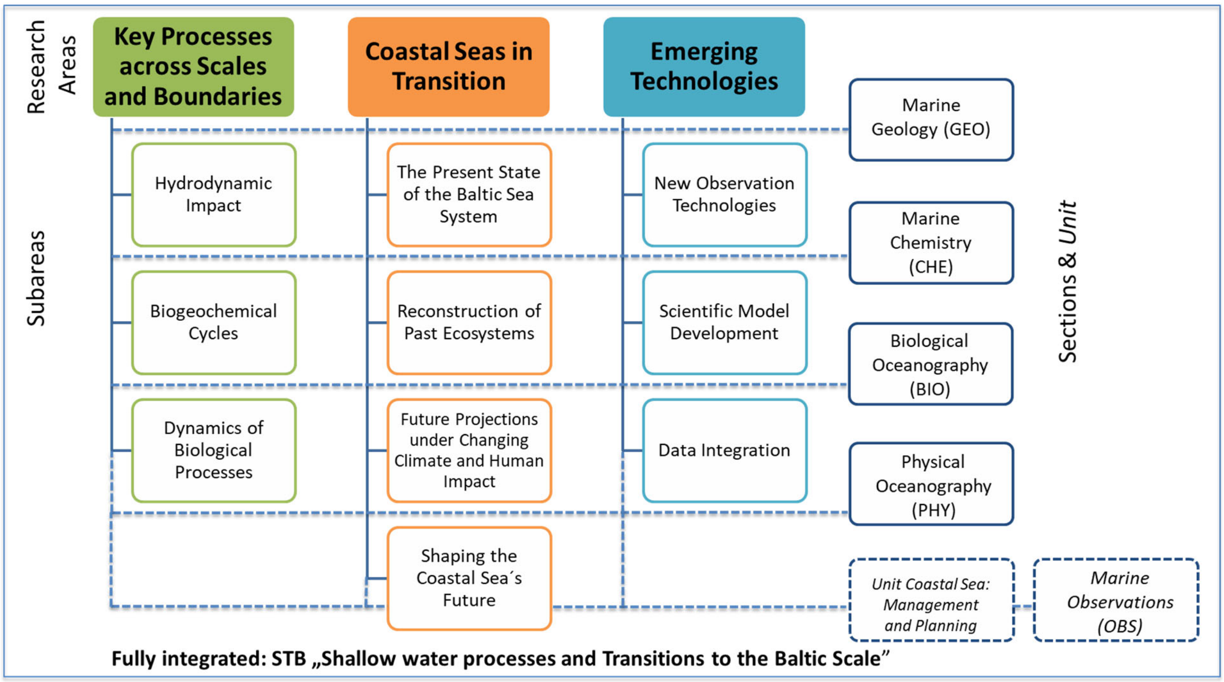

Fig. 1: Structure of the new IOW research programme „Perspectives of Coastal Seas" 2024-2033.

The overall structure of the IOW 10-year Research Programme will follow the well-established **matrix approach**, where all sections and the new organisational unit OBS contribute to the three Research Areas (see organigram). As a new tool to address specific topics in an agile way and on shorter timescales, we are introducing the so-called **Baltic Challenges**. They bundle research activities within the three research areas that are suitable for making progress on specific emerging topics of interest for the Baltic Sea. These are described in more detail in the Implementation section 3 of this document.

1.3.2 What does our research require?

Infrastructure: Traditionally, a tripartite approach has been used to systematically study the functioning and variability of coastal seas: observations, experiments and models. In the future, the massive growth and ongoing diversification of the resulting data will require a fourth approach: specialised data processing that requires sustainable research data management capable of handling data from heterogeneous sources as well as from high-performance computing facilities. Our infrastructure needs to be tailored to this approach. In the following, some of our most important infrastructural assets or needs are indicated.

Access to research vessels is one of the most obvious prerequisites for successful marine research. Since 2012, the **research vessel Elisabeth Mann Borgese** has been available to the IOW which will be not only maintained but further developed as a modern topic-adaptive oceanographic infrastructure. Successful implementation of our research programme will only be possible through the continued provision of this and other research vessels. The IOW therefore looks forward to the renewal of the German research fleet.

The analysis of seawater and sediment for abiotic and biotic constituents requires a wide range of laboratories, measuring instruments and microscopes of various types. Maintaining them, adapting them to the latest developments and operating them properly requires not only the necessary financial resources, but above all well-trained specialist staff.

Since late 2011 we also operate a **CAMECA NanoSIMS** 50L - a secondary ion mass spectrometer (SIMS) performing with a lateral resolution down to 50 Nanometres (Nano). With this instrument up to seven elements and/or isotopes can be analysed and quantified in, e.g., the subcellular level or inorganic particles. An example is the quantification of the uptake of isotopic labelled nutrients on the single cell level. Thus, e.g., C-, N- und S-nutrient cycling can be connected to the organisms performing these processes in lab cultures and natural habitats.

Numerical models for the Baltic Sea region are becoming increasingly complex with higher spatial resolution in order to map the Earth system ever more reliably. Therefore, supercomputers are necessary for the calculations with these models. The IOW regularly acquires computing time from the federally and state-funded National High Performance Computing Alliance (NHR) and provides a member of the Scientific Board. After completion of such time-limited compute projects, the model data are stored and further analysed at IOW. Apart from modelling applications, the NHR infrastructure is also increasingly required to process the large amounts of data generated by other disciplines at IOW, such as bioinformatics.

To enable novel insights in remote areas, we will establish new capacities for the development of new methodologies and rapid interpretation of available multi-spectral remote sensing data on multi-spatial-temporal scales supported by a network of regional and international partners.

Sustainable data management is essential to ensure data FAIRness in all disciplines at IOW. The existing infrastructure for **data management**, maintained by IT specialists, needs to be extended and improved to adapt to the increasing volume and heterogeneity of scientific data. Specifically, tools will be built to simplify the enrichment of research data with metadata, including provenance information, from the beginning to the end of the scientific process, thereby avoiding redundancies in data dissemination, increasing traceability and reproducibility, and ensuring findability and reusability. Storage solutions, (semi-)automated workflows and adaptive data pipelines will be provided to enable user-friendly access to heterogeneous data and metadata in all stages of processing (from raw to validated data and final data products) for timely analysis in interdisciplinary investigations with a specific focus on continuous data generation.

To put our results into practise, be it in business, politics or the public in general, we foster a professional knowledge transfer, which is responsible for identifying and addressing potential users, translating scientific findings into a user-specific language as well as fostering the dialogue with society. In order to transfer our technological or methodological developments to potential enterprises, we provide expertise in securing intellectual property rights or in marketing instruments. This will be complemented by open-science, open-technology outreach, capacity building, transfer via personnel and providing an environment that supports entrepreneurship.

Co-operations: All major disciplines of marine research are represented at IOW. In some specific cases, this enables an interdisciplinary in-house approach, in particular related to our core topics. In general, we depend on additional expertise and are aiming at cooperative solutions. National and international collaborations in research networks are therefore an important prerequisite for the success of our research programme. As a member of the **German Marine Research Alliance** (DAM) and the **Konsortium Deutsche Meeresforschung** (KDM) we are in close exchange with nearly all German marine research institutions. The experiences of fruitful cooperation with colleagues from Baltic Sea countries that we gained under the umbrella of the BONUS projects, have strengthened our Baltic Sea network and will be further extended, for example in the Baltic Operational Oceanographic System (BOOS).

Besides, as Earth System scientists, we depend on the cooperation with experts from the adjacent Earth compartments like atmospheric scientists, meteorologists, limnologists, geographers, sociologists or economists. The international **Baltic Earth** network is our strategic backbone to include all these necessary expertise in our research work.

On a Pan-European scale beyond the Baltic Sea region, we actively contribute to EuroMarine, JPI-Oceans, the European Marine Board and other organisations. International collaborations from pole-to-pole and on both sides of the Atlantic Ocean complement our profile, guided by the principle of knowledge gain and transfer from coastal and marginal seas with relevant similarities to the Baltic Sea.

It is one of our goals to conduct dialogue-orientated transdisciplinary research with stakeholders. This needs stable and active networks constantly fostered and expanded as needed. Our main stakeholders are ministries and agencies at a national and state level that are responsible for adopting or controlling environmental regulations. On the international level, the **Helsinki Commission** (HELCOM) is our main partner in this respect.

Third-party funding: The topics identified in our new research programme cannot be addressed without additional third-party funding. It will therefore be necessary to adapt our research plans to the thematic funding programmes of the federal government and the EU as well as to the structural programmes of the DFG and the Leibniz Association within the framework of the goals we have set ourselves. Additionally, we are committed to actively support the federal government, the EU and the Leibniz Association in implementing their research policy programmes.

Well-trained staff: Most of the leading scientists at the IOW are simultaneously professors at the University of Rostock or, in the case of the geosciences, at the University of Greifswald. They contribute with their expertise to the **training of students** (bachelor, master, PhD) and supervise them on their way to academic degrees. Through this close cooperation between the IOW and the two state universities in Mecklenburg Western Pomerania, we provide the students with access to additional methods, equipment and infrastructure, and support the universities in an excellent training programme. Moreover, the direct contact with students allows us to directly advertise vacancies and recruit future employees.

In some areas of the institute, we also offer training in non-scientific professions: we provide apprenticeships for chemical-technical assistants, for administrative assistants or for industrial mechanics. If our staff capacities allows it, we will strive to expand the range of these training programmes in the future.

2. Our Research Agenda in the three Research Areas

2.1 Research Area 1: Key Processes across Scales and Boundaries

It takes both, precise observations and profound knowledge of processes, on a broad variety of scales to comprehend and project the functioning of marine systems like the Baltic Sea. Building upon the achievements of decades of process studies and observations, we identified the main challenges to work on for the next decade. These are the **processes at interfaces** and **cross-scale processes** providing foundations for perspectives of coastal seas. Both require the expertise of several disciplines and a joint research approach. For details see Box 1.

- **Processes at interfaces**

Interfaces and boundary layers such as the air-sea interface, the redoxcline, the bottom-boundary layer, the ice-ocean interface and the land-sea interface are of particular relevance for biogeochemical and physical transformations and transports. IOW's multidisciplinary approach offers the best opportunities for elucidating these processes. In-situ and remote-sensing observations and sampling devices will allow for measurements highly resolved in time and space to quantify processes in these high-gradient intermittent regions. The next generation of modelling systems will combine traditional ocean models with subsystem models that include representations of benthic processes, atmospheric dynamics, surface waves, sea ice, floating ice shelves, groundwater exchange, and others. A very special case regarding interfaces is the highly dynamic shallow water region in the land-sea border area. The investigation of processes at and near the interfaces connecting these subsystems will therefore constitute an important focus of the new research programme.

- **Cross-scale processes**

An important characteristic of the previous research program was a clear separation of research on small-scale processes and basin-scale dynamics, respectively. However, it has become increasingly necessary to directly and simultaneously investigate the entire continuum from small-scale to basin-scale processes. This is supported by the recent progress in nested numerical modelling systems and multi-scale field observations. A central topic of the new research program will therefore be the investigation of cross-scale interactions, and the associated feedback between physical, biological, and biogeochemical processes, which can span from micrometre to kilometre scales. Shallow water areas and the role of the coastal zone for the functioning of the whole system will now be fully integrated for a better representation of the land-sea-continuum.

Box 1: Research area (RA) 1 emphasises on joint topics, requiring concerted multidisciplinary efforts.

In general, we identified knowledge gaps in various basic research topics indispensable for a holistic understanding and projection of marine systems, including water mass transformation & hydrodynamics (2.1.1), biogeochemical cycles (2.1.2) and the dynamics of biological processes (2.1.3). They comprise the main drivers of the entire ecosystem dynamics. Progress in each of these areas, based on our own expertise and/or in cooperation with others, is our goal for the next decade. A detailed overview of the specific research questions addressed in this research area is given in Table 1.

2.1.1 Hydrodynamic Impact

Small-scale physical processes and mixing: Overturning circulation in the Baltic Sea and many other marine systems and estuaries, **water-mass transformations**, and biogeochemical budgets are affected by small-scale processes. Recent research has highlighted especially the relevance of **submesoscale processes** with scales of order 0.1-10 km for the transport of matter and the transformation of energy. Building upon new observation technologies and numerical models able to resolve these motions, we will study their impact on **surface-layer dynamics**, **air-sea interactions**, and the **lateral exchange of fluids** between the interior and the (surface and bottom) boundary layers. Through interdisciplinary collaboration, we will investigate how these processes affect overall ecosystem functioning in the Baltic Sea and other selected systems. We will identify **mixing hotspots**, and study how small-scale lateral intrusions affect biogeochemical turnover especially inside redoxclines. **Upwelling processes** are the most efficient drivers for the transport of saline and nutrient-enriched bottom waters to the euphotic zone. However, upwelling in the Baltic is transient and not fixed to distinct locations. Thus, data for a quantification of vertical transport are still sparse and require further investigation.

There are two special regimes in marine systems where our knowledge on physical processes needs to be boosted within the next decade: the shallow coastal waters as highly energetic hotspots of element and energy turnover, and the various interfaces and boundary layers where either different compartments of the Earth system or waters with different properties meet and interact.

Shallow water hydrodynamics: This energetic area with pronounced biogeochemical and physical gradients (e.g., due to freshwater runoff, coastal embayments, and groundwater exchange) is subject to strong mixing due to the combined effects of wind-driven turbulence, surface-wave effects, and bottom-generated turbulence. However, there is not only one type of coastal zone, but a diverse landscape of bays, fjords, and estuaries with varying water residence times. There, we will investigate the efficiency of exchange, the role of topographic differences, and the impact of freshwater sources (e.g., river plumes).

Surface layer dynamics: Among the physical processes, those acting on small-scales determine how transport, water mass properties and circulation patterns respond to changes in external forcing, such as climate change. But even in most current physical-geochemical models, many of these small-scale processes are not yet represented. This is of special concern with regard to surface layer dynamics. Various small-scale physical processes that we are just beginning to adequately resolve strongly impact on both, air-sea exchange and biological and biogeochemical processes in the surface-layer. To successfully make progress related to the RA1 stepping stone “Processes at interfaces” will require more insights into the physical processes driving the element cycles across interfaces and boundary layers.

2.1.2 Biogeochemical cycles

Triggers and regulating processes of the major element cycles: Closing the **budget for relevant elements** and their metabolic processes has been and will remain a major challenge for understanding the functioning of coastal seas. New approaches combining spatially and temporally highly resolved observational data offer new opportunities for reaching such an understanding (see RA3). The development of a new method for an integrated assessment of cyanobacterial **N_2 fixation** will help to overcome the uncertainties in quantifying the N2-input via this pathway. We will further address the variability of C/N/P ratios in different phases of the productive period and during mineralization processes in the water column, with direct implications of the latter on oxygen budgets and H_2S occurrence. This work is mandatory for a proper description of the underlying processes in the biogeochemical models. Due to their implications for the global climate, **greenhouse gases** and their pathways of production and consumption will remain on our agenda.

The microbial control of the element cycles: We will investigate the so far still unknown microbially-mediated element transformations with the aim of identifying the key players, environmental controls and thresholds regulating their performance and functioning. Besides, previously poorly known parasitic and saprophytic interactions such as those between phytoplankton and fungi are coming into focus as important drivers of biogeochemical pathways.

The role of shallow coastal waters: Research studies of recent years revealed evidence that the coastal areas separating the land side with its nutrient discharges from the open sea have the potential to reduce the nutrient flux by acting as a so-called coastal filter. The retention, transformation and loss of material and compounds in the near-shore zone are currently far from understood in a systematic way and are major obstacles for budget closure. From a physical perspective, we will focus on the interaction of large-scale motions of the open waters with small-scale near-shore processes to understand their impact on the efficiency of the coastal filter. The C-, the P- and the N-cycles can be strongly affected by the ever-changing variations in near-shore sediments, ranging from complete removal of nitrate and phosphate to the release of intermediate N-compounds to even enhanced N- and P-loads, controlled by the activity of the bacterial communities. Organic carbon derived from land or produced in the shallow coast might be transformed before further transfer to the basins, or can be mineralized in the shallow zone, leading to currently poorly constrained emissions of methane and carbon dioxide. In parallel with research on biogeochemical processes in shallow coastal waters, their changes along the continuum between the shallow coast and deep basins will be an important topic in the coming years, especially with regard to how sediment fluxes and benthic-pelagic coupling change along this transect.

2.1.3 Dynamics of biological processes

Biodiversity: The Baltic Sea, with its rapidly changing salinity, large areas of anoxic bottom water and intensive anthropogenic use, is characterised in large parts of its biosphere by a low biodiversity, both naturally and due to the anthropogenic pressure. Changing environmental conditions might aggravate the situation. To recognize the effect on the different levels of biodiversity (genetic, community, functional, habitat) and to analyse consequences for the ecosystem is therefore an ongoing research target. In order to better assess responses of benthic and pelagic organisms to changing environmental conditions, mechanisms of **adaptation** will be investigated for key species. Information on the genetic structure and diversity of their populations will be generated and trait spaces will be characterized experimentally along environmental gradients. Advances in (meta-)genomics and experimental phenotyping now make it possible to link qualitative data on genetic diversity with quantitative data on functional diversity. Thus, both information can be integrated into numerical models investigating ecosystem effects of adaptive responses.

Food webs: Global Change conditions affect the phenology of the production cycle known to cause mismatches in food web interactions with unclear consequences for the trophic transfer. Additionally, warming will foster heterotrophic processes at the base of the pelagic food web. This can lead to a trophic lengthening of the whole food web by raising the trophic position of all following trophic levels. Mass and energy losses for higher trophic levels and a collapse of top carnivores might be the consequence. A new method based on the analysis of nitrogen stable isotopes in amino acids enables the identification of the trophic position based on single field samples, allowing for **relating functional changes directly to environmental stressors**.

Response to transient events: In the shallow coastal waters, which react very fast to hot periods and are strongly affected by storm events, increasingly fluctuating conditions are expected due to climate change. We will investigate how such short-term disturbances, especially marine heat waves, affect the biota. Research on the processes on the cellular and gene level, which are behind the responses, are included. Moreover, we will investigate whether the shallow coastal waters might contribute to the diversity and functional stability of marine systems via coastal seed banks.

Table 1: Overview of research area 1 "Key Processes across Scales and Boundaries"		
2.1.1 Hydro-dynamic Impact	Physical small-scale processes and mixing	• Which are the mixing hot spots in the Baltic Sea and other estuarine and marine systems, and what is their system-wide relevance for the overturning circulation and basin-wide biogeochemical transformations? • Which biogeochemical cascades are driven by episodic or persistent coastal upwelling? • How do small-scale lateral intrusions affect water-mass transformations and redoxcline processes? • Which deep-water lateral stirring processes determine the exchange of fluids between the interior and the bottom boundary layer? • What are the dynamics of river plumes of non-tidal systems, how do they affect the coastal filter?
	Shallow water hydro-dynamics	• How do transport and transformation processes in the shallow water regions influence the general land-ocean interaction and how does this impact the open sea? (STB) • How do surface waves contribute to vertical mixing, to lateral exchange between the coastal zone and the open waters, and to benthic-pelagic coupling? (STB)
	Surface layer dynamics	• What is the role of submesoscale processes for surface-layer dynamics, ecosystem functioning, and air-sea exchange in coastal systems? • How do surface-wave effects and diurnal warm layers impact on surface-layer processes and atmosphere-ocean feedback mechanisms?(STB) • Ocean-Ice interactions: How do basal melt processes under glacial or sea ice control the matter budgets and structure of the mixed layer below? • Air-sea interactions: Which specific surface-layer and interface processes alter energy and material fluxes (including, e.g., greenhouse gases) at the air-sea interface?
2.1.2 Biogeo-chemical cycles	Triggers and regulating processes of the major element cycles	• Nutrients: How do variable C/N/P ratios affect production and mineralization rates and elemental budgets? • Greenhouse gases: What are the pathways of greenhouse gas production and consumption and how do they react to environmental changes? • What is the impact of the bentho-pelagic interface on the greenhouse gas production and consumption and how is it affected by physical forces? • Oxygen: What are the biogeochemical and physical processes shaping the state of oxygen deficiency zones? • What is the importance of halocline and pelagic redoxcline interface processes for the transfer of energy and transfer/transformation of important biogeochemical components?
	Microbial control	• Can metatranscriptomic approaches improve our understanding of microbially mediated biogeochemical transformations? • Are there hitherto neglected microbially mediated element transformations and unknown key organisms? • How do so far understudied groups of organisms (e.g. fungi, meiofauna) influence the element cycling?
	The role of shallow coastal water within the matter cycles	• How does the coastal filter function and how is material modified in the near coastal zone (STB)? • Sediment-water: What is the functional role of sediment heterogeneity in shallow coastal waters? By which processes do sedimentary fluxes and the benthic-pelagic coupling change in the continuum from the shallow coast to the deep basins? • How can processes controlling the major biogeochemical cycles from the near coast to the open sea be properly described?
2.1.3 Dynamics of biological processes	Biodiversity	• How is biodiversity at different levels (genetic, community, function, habitat) affected by changing environmental conditions and what are the ecosystem consequences, specifically in shallow coastal waters? • What are the functional consequences of changing diversity patterns along the North-Sea –Baltic Sea salinity gradient? • Can coastal seed banks contribute to diversity and functional stability of marine systems under pressure?
	Food webs	• How do altered phenologies affect structure and function of pelagic and benthic food webs? • Can we quantify and assess the importance of individual organic compound classes (such as amino acids, polysaccharides) for the quality of nutrition and stability of food webs? • Does trophic lengthening affect pelagic and benthic food webs differently? • How do poorly known microbial interactions such as those between phytoplankton and fungi work and how are they regulated?
	Response to transient events	• What are the cellular and gene level processes behind the responses of marine organisms to environmental fluctuations? • How do short term disturbances such as heat waves affect pelagic biota at different levels of organization, specifically in shallow water?

2.2 Research Area 2: Coastal Seas in Transition: Present, Past & Future Perspectives

Our coastal seas are no static systems. The Baltic Sea, for example, has - since the last glaciation - been subject to natural fluctuations as response to variations in basin geometry and climate over the course of decades, centuries and millennia. Only by recognising this natural variability and all its implications, we can identify the human-made changes of the Late Holocene and particularly the Anthropocene, which superimpose the natural background. With joint forces, we will work on two overarching topics, which thematically require the application of various IOW disciplines. These are the expansion of our long-term observation programme and modelling activities to hotspot areas of climate change response: the Northern Baltic and the shallow water regions, and the reconstruction of past ecosystem conditions to inform the future. For details see Box 2.

- **Expanding our long-term observation programme and modelling activities in the Baltic Sea to hotspot areas of climate change response: the Northern Baltic and the shallow water regions**

The long-term observation programme is one of the centrepieces of our research: on 5 cruises per year important environmental parameters are recorded at different water depths on a fixed network of stations that extends into the central Gotland Basin. The resulting data show the variability of these parameters on a yearly scale as well as trends on the decadal scale. This programme enabled the recognition of the rapid warming of the Baltic Sea surface waters and suggested recently accelerated oxygen consumption rates despite overall decreasing nutrient inputs, to name just two examples of the outcome. It is an essential backbone for our hydrodynamic and ecosystem modelling work as well as for many different applied projects investigating the impact of anthropogenic activities and climate change. For the coming years, we want to expand our joint activities on observations and modelling into two regions: the northern Baltic Sea, undergoing drastic changes due to the reduction in seasonal ice cover, and the shallow water areas, which will be particularly vulnerable to extreme events like heat waves, or storm flood.

- **Reconstructing past ecosystem conditions to inform the future**

To achieve high quality climate and environmental reconstructions at as highly resolved as seasonal time-scales and to couple these results with model simulations for interglacial periods such as the Holocene, we need a collaborative effort among sedimentologists, geochemists, paleoceanographers, biologists, and modelers. The linkage of proxy-based estimations with monitoring observations and hindcast simulations together with a precise depositional chronology will enable us to recognize the timing and rate at which climate and ecosystem shifts occurred in the past. It will permit synchronizing local sediment records with regional and global records in order to evaluate the dynamics, mechanisms, and patterns involved in climate and environmental changes on a hemispheric and even planetary scale. To this end, it will be essential to include the North Atlantic, the key region of climate variability in northern Europe, to understand the link between the different North Atlantic variability patterns (AMV, NAO, AMOC) and the Baltic Sea region in the past and the future.

Box 2: Research area (RA) 2 emphasises on topics, requiring concerted multidisciplinary efforts.

In general, we identified research needs in four subtopics. The first three of them are: The **present state of the Baltic Sea** system (2.2.1), the **reconstruction of past ecosystem conditions (2.2.2)** and f**uture projections under changing climate & human impact (2.2.3).** With the onset of the Anthropocene, any Earth system research has to include humankind as an important factor of influence. Beside the multitude of negative impacts leading to the triple planetary crisis of climate change, pollution and biodiversity loss, humankind is also an actor when it comes to mitigation and restoration measures. These aspects are highlighted under the fourth subtopic **Shaping the coastal sea´s future (2.2.4)**. A detailed overview of the specific research questions addressed in this research area is given in Table 2.

2.2.1 The present state of the Baltic Sea system

Variability on a decadal scale: Coastal ecosystems are subjects to trends and variability. The IOW and its predecessors have run a **long-term observation programme** with five cruises per year on a fixed station network since the 1950s. It covers all parameters necessary to assess the state of eutrophication, deoxygenation and pollution. In addition, a monitoring programme implemented by a Ship-Of-

Opportunity Programme (SOOP) provides data of high temporal resolution from the Baltic Sea surface waters related to primary production.This programme, which was established two decades ago, is now embedded in the European Research Infrastructure ICOS. It is known that climate change and an increasing human pressure will have an impact on the coastal seas, however, it is still only partially known in which way this is or will be expressed. The data of our long-term observation programme are an indispensable tool for identifying patterns, trends or shifts and the main backbone for additional studies on specific aspects of the consequences of anthropogenic pressure. In the future, we will include the hotspot areas of climate change responses in the Baltic Sea into our observation programme. These are the northern part of the Baltic with its decreasing seasonal ice cover and the shallow coastal areas prone to heat waves and storm surges. Future challenges will also address new methodological approaches in terms of an improved **spatiotemporal resolution**, and of **new observation strategies for shallow water conditions**.

Anthropogenic stressors: The Baltic Sea, surrounded by highly industrialized countries, experiences a broad variety of anthropogenic stressors. Identifying the impact of each of these disturbances is desirable to enable mitigation measures, but needs specific experimental or modelling set-ups to gain significant results. Besides, **emerging contaminants** - mainly organic compounds such as pharmaceuticals and personal care products, hormones, pesticides, flame retardants, all released into the environment without existing regulations - will require the development of new analytical methods.

Impact of environmental regulations: Several areas in the Baltic Sea are under protection by European and national law. To assess how the reduction of human impact has affected the development of these areas is an ongoing tasks of the institute. In the **marine protected areas** of the German waters, we observe the environmental state and investigate the **integrity of the seafloor** and the **functional diversity** of the benthic communities.

2.2.2 Reconstruction of past ecosystems

Proxy development and validation: High-quality paleoenvironmental reconstructions for gradient systems like the Baltic Sea need well-calibrated and validated inorganic and organic proxies. We will apply three different approaches. First, the modern situation in the water column and surface sediments provides proxies on a daily, monthly and up to annually timescale. Second, proxy data from well-dated sediments can be linked to instrumental records from the last 60 years at a pluriannual to multi-decadal scale. And third, hindcast simulations will help to validate proxy data beyond instrumental observations. **Redox-sensitive trace metals** are applied to reconstruct redox settings in the past. **Lipid biomarkers and organic proxies** provide insights to past temperature, salinity, pH, redox conditions, as well as plankton biomass. A combined approach of biomarkers with **ancient DNA** represents a new, complementary approach to estimate biodiversity and its biomass in the past.

Stratigraphy and synchronization: A precise chronology is a prerequisite to estimate the timing and rate at which climate and ecosystem shifts occurred in the past. It permits synchronizing local sediment records with regional and global records in order to evaluate the dynamics, mechanisms, and patterns involved in climate and environmental changes on a planetary scale. We aim to develop new time markers to improve the event stratigraphy applied to date sub-recent sediments and work on the identification of basin-wide events based on inorganic and organic proxies and regional biostratigraphy. The application of the cosmogenic radionuclide ^{10}Be and volcanic ash layers in order to both date Baltic Sea sediment records and synchronize them with other records not only on a basin-, but also on a hemispheric scale is an ongoing task. A further development of the seismic stratigraphy will also help to identify late Pleistocene and Holocene marine, limnic, fluvial and terrestrial regimes in the Baltic Sea history.

Disentangling forced and unforced variability: Internal variability on various time scales plays an important role for the Baltic Sea ecosystem. We need to identify relevant time scales that drive this internal variability by conducting model simulation runs for periods spanning approximately the last 8.000 years. Both, global and regional, fully coupled ocean-atmosphere models, such as the IOW-ESM model, will be used to enhance the understanding of low-frequency variability in the Baltic Sea region and its origin in the North Atlantic region. Since internal variability significantly impacts single model realizations, large ensemble simulations are needed to improve both the signal-to-noise ratio and the analysis of low-frequency variability. Ultimately, the results of these centennial to multi-millennial climate simulations can be evaluated and validated using proxy records from sediment cores. The better we understand internal variability, the easier it is to separate the signal of external forcing such as the glacial isostatic adjustment and changes in solar irradiance, aerosols or greenhouse gas emissions from these unforced variations.

2.2.3 Future projections under changing climate and human impact

Teleconnections in future climates: Past research has shown that important drivers of climatic and environmental change in the Baltic Sea region are located far removed from the Baltic Sea region. One example is the North Atlantic, which is a major source of atmospheric heat and moisture supply for the Baltic Sea and which modulates the European climate and the Baltic freshwater budget on multi-decadal to multi-centennial time scales. In order to take these influences into account, the spatial scales that we were previously focused on need to be extended to include the North Atlantic and Arctic Sea. This way, we aim to identify the main modes of natural climate variability in the Baltic Sea region and how they may change in the future in response to climate warming. Taking the hypothesized potential collapse of the Atlantic Meridional Circulation as an example, we will investigate the impact of such changes on the Baltic Sea climate.

Projections of future extreme events: With respect to climatic extremes, advanced algorithms will be applied to detect marine heat waves in high-resolution climate model data sets and observations and to relate them to meteorological forcing and internal oceanic processes. For instance, storms will be analysed in global and regional ensemble data in both Lagrangian and Eulerian frameworks. A common problem associated with climate extremes is the lack of sufficiently long time series to robustly diagnose the statistics of extremes. Therefore, newly available model simulations covering the last few millennia will be analysed to better understand the likelihood and magnitude of future climatic and environmental extremes in scenario simulations. Furthermore, in collaboration with social and economic scientists changes in natural hazards will be investigated.

Multiple anthropogenic stressors: Ecosystems of coastal seas in populated areas are affected by climate change and various human impacts such as eutrophication. We will apply our regional climate model system, which includes marine biogeochemistry components, to investigate the combined impact of multiple stressors on the future Baltic Sea ecosystem to support marine management with plausible scenarios. For instance, for the problem of eutrophication it is important to explore the role of the coastal filter under changing climate and changing nutrient inputs. An ultra-high resolution set-up for limited regions along the coastal zone will be used to explicitly resolve dynamical modes that are missing or highly parameterized in traditional ocean climate models. For instance, complex sediment models developed at IOW will be implemented to better account for processes controlling the coastal filter. The findings will allow the development of parameterizations of the coastal filter and to perform future projections with coarser climate models for the entire Baltic Sea.

2.2.4 Shaping the coastal sea´s future

As a response to increasing pressure on our coastal seas, new and comprehensive environmental policies were adopted and their implementation is ongoing. To meet target values in climate and environmental politics requires a scientific support of societal transformation processes. Against this backdrop challenges for applied research are increasing in number, complexity and spatial coverage. Addressing them requires sophisticated methods, models and expertise as well as interdisciplinary approaches and a holistic ecosystem understanding.

Inter- and transdisciplinarity for a sustainable use of the seas: Moving from findings to recommendations for action requires an interdisciplinary dialogue between the natural sciences and the social and economic sciences, as well as transdisciplinary exchange between researchers and representatives of agencies and authorities. We want to extend these approaches towards sustainability research that helps to reduce and prevent unsustainable use of marine resources.

Adapting our tools: There are two main requirements of policy and society that we have to address in the coming years. First, we have to further develop our tools for describing the environmental state of the Baltic Sea in order to increase their reliability and make them sufficiently operational. Second, we need to adapt our planning approaches, management tools and models to react to the increasing and diversifying needs of the society in relation to marine space, offering new pathways for interactions and transdisciplinarity.

Developing and testing of restoration measures: Restoring a good environmental status of coastal and marine ecosystems will become an increasingly important topic for the years to come as will any ocean-related measure to reach the climate targets of the 2015 Paris agreement. Measures for remediation, mitigation, prevention including ecotechnologies are needed, but have to be tested and their potential positive, but also negative, impact has to be investigated. Holistic assessment frameworks to address environmental risks and benefits, participation and burden sharing as well as the analysis of actors and decision making bodies need to be developed in a transdisciplinary way for the best possible governance of the Baltic in the decades to come.

Table 2: Overview of research area 2 "Coastal Seas in Transition - Present, Past & Future Perspectives"		
2.2.1 Present ecosystem variability, trends and threats	Decadal Variability	• Which recent trends can be detected in the Baltic Sea system and what are the causes? • What do these trends tell us about the state of the environment?
	Anthropo-genic stressors	• What are the critical biogeochemical parameters to delineate the impact of the diverse anthropogenic stressors on the ecosystems? • How do legacy loads of pollutants develop and can we find smart solutions to monitor them? • What are the contaminants of the future and how can they be detected?
	Impact of environ-mental regulation	• How can the success of implemented environmental regulations be measured? • What is the state of the Baltic Sea Natura 2000 regions in the German EEZ?
2.2.2 Recon-struction of past ecosystem states	Long-term natural variability	• What new proxy development and application is needed to advance the understanding of major paleoclimatic and paleoenvironmental changes in the Baltic Sea? • Were climate modes (e.g. AMO, NAO/AO) and external forcing (solar variability) playing a dominant role in the past climate of the Baltic Sea?
	Strate-graphy & synchron-ization	• What new stratigraphic tools can help improve the chronology of the sediments from the different Baltic Sea sub-basins? • How can such new stratigraphic constraints contribute to regional and hemispheric synchronization of our local paleoenvironmental records?
	Disen-tangling forced and unforced variability	• What are the impacts of the various external drivers (glacial isostatic adjustment, solar variability, volcanic eruptions, and greenhouse gas emissions) compared to internal climate variability as revealed by proxy- and model-based estimations?
2.2.3 Future project-tions under changing climate and human impact	Telecon-nections	• What are the main large-scale modes of natural climate variability and processes of the Earth system affecting the climate and environment of the Baltic Sea region and how do they change in response to climate warming?
	Extreme events	• How will the likelihood and magnitude of environmental extremes be affected by changing climate? • How will these changes and extremes impact the functioning of shallow coastal waters and their feedbacks to the Baltic scale?
	Multiple anthropo-genic stressors	• How do various anthropogenic drivers impact the future Baltic Sea applying a multiple stressor approach?
2.2.4 Shaping the coastal sea's future	Inter- and transdis-ciplinarity for a sustain-able use of the seas	• How can we foster transdisciplinary research to develop a sustainability science and reduce and avoid unsustainable anthropogenic impacts on the sea? • How should interdisciplinary approaches in cooperation with social sciences and economics, especially the Ecosystem Service assessment methods, be designed to allow a better detection of unsustainable practices in seas
	Tool adaptation	• Are existing tools, approaches and methods defined for describing the Baltic environmental state sufficiently reliable and operational to meet the present and future policy and societal demands today and in the future? • In which way can planning approaches, management tools and models for the marine space be adjusted to the intensifying and diversifying needs of the society?
	Develop-ing and testing of restoring measures	• Which remediation, mitigation and prevention measures together with eco-technologies and alike approaches can help in restoring a good environmental status of coastal and marine ecosystems in an ecologically sound, sustainable and cost-efficient way?

2.3 Research Area 3: Emerging Technologies Enabling Advanced Marine Science

Innovative technologies are capable of not only facilitating science, but also accelerating and improving it, representing a science field on their own. New opportunities to link different data sets, the significantly growing computational resources, innovative molecular biological approaches or the use of machine learning or artificial intelligence to analyse huge amounts of data, demonstrate that research in methodology and technology will in the future create an enormous benefit for environmental science. The IOW will support this strategy of embracing the potential of innovative technologies to foster science and support the societal transformation towards sustainability with the new research area "Emerging Technologies Enabling Advanced Marine Science". Two overarching topics will be targeted in a combined effort of several disciplines. These are (1) to develop and improve robust autonomous measuring and sampling devices for the highly dynamic near-shore area and (2) to build up a Digital Twin of the Baltic Sea. For more details see Box 3.

- **Robust autonomous measuring and sampling systems for the highly dynamic near-shore area**
  Measurement and sampling requirements are diverse, ranging from a traditional CTD setup to geochemical variables, autonomous phytoplankton detection, sampling methods for molecular biological analyses or sediment acoustics. The dynamic shallow coastal area, a new regional focus of our research, requires specific technological advances to capture the temporal and spatial variability with adaptive and autonomously operating systems.

- **A Digital Twin of the Baltic Sea**
  The increasing volume and complexity of scientific data calls for new strategies and approaches for data acquisition, processing, storage, analysis, and re-use. Integrating the abundance of observational information with coupled numerical models, together with advanced model and visualization techniques, will provide unprecedented realism in future simulations. With such a "Digital Twin of the Baltic Sea" we will investigate the response of the system to various influences and provide a means of interaction with societal actors.

Box 3: Research area (RA) 3 emphasises on topics requiring concerted multidisciplinary efforts.

In general, we will follow three research lines: **New observation technologies (2.3.1)**, **scientific model development (2.3.2)** and **data integration (2.3.3)**. Research in this area is envisaged to be tightly accompanied by the adaptation and further development of our infrastructure to create the significant push forward, which is needed to fully exploit the new opportunities and meet the challenges of the future. To differentiate between the scientific and the infrastructural approaches in the following sub-chapters, the description of the infrastructural approaches are written in italic letters. A detailed plan of the specific research questions addressed is given in Table 3.

2.3.1 New observation technologies

Despite significant advances in observational technologies in recent decades, our ability to measure relevant ecosystem parameters to assess processes and budgets remains limited. To make progress in this respect, **adaptive strategies** ensuring measurement campaigns at the right place at the right time are just as important as the development and improvement of measurement technologies and methods that work reliably even in difficult environments. In addition, the **identification of new parameters**, such as genes and their expression, that can be used to describe the characteristics of the systems in an integrative way, have to be moved forward. Therefore, we will focus not only on the development of novel sensing technology, improved sampling methods and new analytical techniques, expanding the observation parameter space and **optimizing observation frequency, resolution, and spatial coverage**, but also on the development of the best strategy to eliminate the most severe blind spots in our observation programmes. Smart combination of data streams from different European research infrastructures (ICOS, Euro-ARGO, Copernicus) with tailored data from individual projects will be a crucial component of this effort. In particular, for the dynamic shallow water coastal zone, technological advances are needed to capture its temporal and spatial variability. The deployment of equipment based on novel technologies in parallel to the traditional devices also requires an adaptation of the infrastructure: Data processing procedures and calibration routines that ensure observation quality and address measurement uncertainties in a transparent and reproducible way will be automated for a wide array of parameters. Furthermore, suitable integration mechanisms for data from heterogeneous sources will be designed.

2.3.2 Scientific model development

To improve the representation of the earth system complexity in Baltic Sea models, we will focus on building an efficient **multi-model coupled system**. It will consistently describe ocean processes and their interactions, such as in coupled atmosphere-ocean-land-hydrology models or in multi-scale coupled physical-biogeochemical numerical models of shallow-water regions. Especially the development of the latter will address the challenge of designing a model system, where a high-resolution coastal zone interacts with the lower-resolution model of the open sea. For instance, our model system will be equipped with new methods of regional model grid refinement using advanced methods for nesting (e.g. AGRIF). This functionality will enable the required resolution of coastal dynamics and its interaction with the large-scale models, where these processes are missing or parameterized. Furthermore, **new multivariate statistical modelling approaches** for the prediction of ecosystem communities and functions in both benthic and pelagic environments are needed, which account for the strong spatio-temporal heterogeneity of the available data and appropriately consider the interdependence of observations. Innovative numerical, statistical or artificial intelligence methods are also needed for a better integration between empirical research and ecosystem modelling. This will require an **infrastructure for software and data management** that facilitates a combined use of observations and model data. It will improve our future or scenario projections by boosting physical process understanding and accelerating ecosystem model development. Conversely, model results will be used to identify observational gaps, to adapt/optimize observation strategies and thereby maximize our ecosystem knowledge.

2.3.3 Data integration

Over the past decade, the amount and diversity of scientific data being produced in all disciplines of IOW's research increased significantly. This trend is expected to continue with the development of new observation technologies and modelling approaches, allowing for data science applications that leverage data sets available at IOW and elsewhere at various spatial and temporal scales within a joint analytical framework across disciplinary boundaries. We will focus on the **adaptation and implementation of targeted and exploratory data science applications**, like machine learning and artificial intelligence and on the development of approaches for the re-use (i.e. discovery and integration) of heterogeneous data sets in this context. These approaches will exploit such data resources for the purpose of pattern recognition to provoke innovative research questions (and solutions) that only become apparent due to the available data volume. This includes also the development of decision support tools. A key element for the success of such research endeavours is a **common information infrastructure for the FAIR management of scientific data**. Building on the current research data infrastructure (comprising databases for oceanographic and benthic data, a metadata catalogue across heterogeneous data sources, as well as GIS, DOI, and THREDDS servers), future developments will address the challenges related to (i) the integration of data generated by novel technologies, including 'omics methods, into existing and new data structures and scientific procedures, (ii) data quality assurance including provenance information and (iii) the ability to find and re-use existing data, which requires intelligent storage strategies as well as richly described contextual parameters and metadata.

Table 3: Overview of research area 3 “Emerging Technologies enabling advanced Marine Science”

2.3.1 New ob-servation techno-logies	Holistic ecosystem observa-tion systems	• How can holistic ecosystem observation be achieved by automated and high-throughput measurement systems, such as genetic in-situ methods, multi-spectral remote sensing on different platforms, in-situ mass spectrometry, as well as coupled in-situ and ex-situ approaches?
	Bridging to spatial and temporal hetero-geneities	• How can automated measurement devices be integrated with traditional sampling approaches to adequately assess spatial and temporal heterogeneity in gradient systems and across interfaces?
	New concepts for adaptive measure-ments	• Which adaptive sampling concepts need to be designed and integrated in observation systems to provide high-resolution data on short-term disturbances, such as blooms, extreme weather events or anthropogenically induced pulses, while keeping long deployment presence?
2.3.2 Scientific model develop-ment	Optimizing the coupling of different models	• What is the optimal model system required for the variety of applications in Baltic Sea research, that offers a flexible and modular coupling of the different models in use, based on latest coupling and nesting technologies? • How can we implement an energy-consistent flux exchange between models on different grids in this generic coupled system?
	Improving the repre-sentation of important processes	• To which extent can refined numerical schemes improve the representation of the important hydrodynamic and biogeochemical processes in our models?
	Develop-ment of new statistical models	• How can new statistical modelling approaches allow a prediction of ecosystem communities and functions, both benthic and pelagic?
2.3.3 Data integration	Optimal utilization of existing data pools	• How can data from heterogeneous sources be integrated to extend the spatial and temporal scope of ongoing research activities? For instance, can existing disjoint observations be integrated with the more structured time-series data collected within the STB to provide additional insights into long-term changes in a broader geographic context? • Which data science applications need to be developed or can be adapted from other disciplines (e.g. informatics, linguistics) for the identification of patterns in large and heterogeneous ecological data sets that can be used for hypothesis validation as well as hypothesis generation?

3. Implementation

A scientific work within our research programme will be promoted by five elements: (3.1) implementation plans; (3.2) annual progress seminars within the research areas; (3.3) the definition of responsibilities, actors and supporters; (3.4) financial incentives; and finally (3.5) cross-cutting working groups on Baltic Challenges.

3.1 Implementation plans

Implementation plans, showing all running projects as well as submitted and planned project proposals for a period of 3 years allow recognizing topical or financial gaps, synergetic and complimentary research efforts and, thus, can serve as a steering tool. Generating these 3-year-plans lies in the responsibility of the director and the science management unit. The basis of these plans will rely on the respective data from our internal research information system KLAUSI, complemented by information out of the research areas related to envisaged project proposals. The running period of three years also allows for responding to emerging topics or challenges in a timely way. The IOW´s internal Scientific Council will be asked to comment on these plans. Implementation plans related to this programme will cover the periods 2024 – 2026; 2026 – 2028; 2028 – 2030; 2030 – 2033 with a one-year overlap each.

3.2 Annual progress seminars

All scientists involved in a respective research area will gather at least once per year to exchange scientific progress, results and ideas for new proposals. These meetings of the research areas will be open to all IOW members. These annual events also serve to discuss and adjust implementation plans. We plan to organize these seminars as a concise conference-like event of 2 to 3 days covering all research areas. External cooperation partners can participate upon invitation.

3.3 Definition of responsibilities, actors and supporters

The scientists of the IOW assign their activities and the third-party funds granted to them to specific research areas. Double assignments are permissible. The scientists of the research areas elect two to three persons from among themselves as spokespersons, who report once per year to the Scientific Council, the Scientific Advisory Board, the Steering Committee of the Institute and the Director on the progress in the research areas. They are asked to promote collaboration within the areas and to invite all related scientists to the annual progress seminars with the support of the Science Management Unit. All scientists assigned to specific research areas are expected to present their work at these meetings.

3.4 Financial incentives

From a centrally managed account, funds can be used to promote the research programme: This includes **funding of up to 20 TEUR to finance a student assistant or covering the costs of special services or visits** may be granted on the basis of a justification why this would help academically to overcome obstacles or enable a third-party application. This can be applied at any time, provided financial availability. The decision on the approval of these funds lies in the hands of the director based on a recommendation of the IOW steering committee.

The necessary **funds for a PhD-group of 3 persons for 3 -4 years** can be jointly applied by at least three scientists from different departments who have the right to supervise PhD students. The topic of the group should be dedicated to one of the stepping stones defined in the research areas or comprise a cross-research area topic, preferably from the Baltic Challenges. Applications should be submitted when the process of developing implementation plans begins. The decision on the approval of these funds is in the hands of the IOW´s steering committee on the basis of a comparative review by members of the IOW´s external Scientific Advisory Board and after consultation of the internal Scientific Council.

3.5 Baltic Challenges

With the Baltic Challenges, a new tool is introduced to our research programme (see Figure 2). A Baltic Challenge should be about a major environmental problem of the Baltic Sea that is also of global importance. They offer an agile element in the long-term research plan and are initiated for typically 3-4 years. Selection and evaluation of Baltic Challenges will involve feedback from the IOW Scientific Advisory Board. Among the emerging topics we focus on those environmental issues that require working in a multi-layered way among the different research approaches of the three research areas.

Baltic Challenges are designed to be adaptable to upcoming topics of interests and will be run in a flexible, self-organized structure. Objectives, structures and approaches are up to the participants´ agreement and scientific demands, with exception of the initiation, an annual thematic day to review achievements and strategy, and its termination. Involvement of the scientific management will support knowledge transfer and alignment with the overall IOW research plan. Baltic Challenges are fully eligible to the financial incentives described under 3.4.

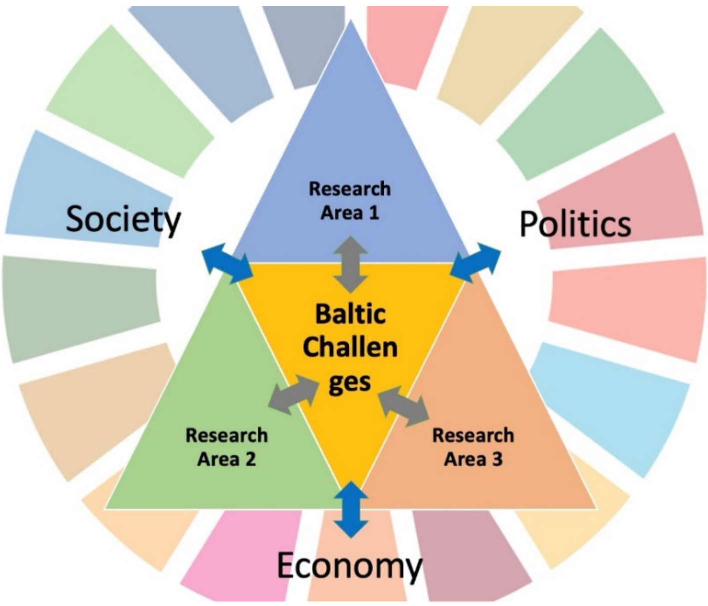

Fig. 2: Concept of the „Baltic Challenges“,requiring a collaborative effort of two to three research areas to address specific emerging challenges of the Baltic Sea.

In order to achieve their aim, Baltic Challenges identify all relevant research activities conducted at the IOW, which might contribute to solve issues connected with these challenges, gathering the respective scientists at least once per year in order to identify interfaces between different research approaches. Working out new research proposals and other ways of funding, as well as identifying potential guest scientists, which might help to accelerate progress is key to realising defined objectives.

Ideally, “Baltic Challenges” are established if the related topics are tackled with different approaches in all 3 research areas of the new programme. To keep the procedure focussed and manageable, we aim to deal with 2 – 3 topics maximum for a period of 3 to 4 years. Candidates for such “Baltic Challenges” are dedicated to issues like eutrophication, expanding oxygen minimum zones, pollution, biodiversity loss, or extreme events.

APPENDIX

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