44th Meeting of the AWI Scientific Advisory Board (SAB)
11th and 12th of October 2023 in Bremerhaven

Agenda Item 2:
Annex 3 Strategy for North Sea long-term ecological research (LTER) and associated long-term observatories and data sets

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Summary

Helgoland and Sylt Roads time series have provided data on physical, chemical and biological parameters for more than six decades, and hence provide invaluable information on long-term change in the North Sea. The Helgoland and Sylt Roads data have been integral to the publication of over 850 scientific articles, which have substantially advanced our understanding of human impacts on coastal systems, and of plankton ecology in general. In addition, these time series have been used by a suite of national and international agencies, and are integrated into many national and international reports. Helgoland and Sylt Roads time series are essential to achieve the goals of coastal research at AWI. To ensure that the necessary data to achieve these goals are available, we have developed four strategic priorities: 1. Understand the whole system and close the gap to the microbial loop; 2. Scale up: linking Helgoland and Sylt Roads single-point measurements to the whole North Sea; 3. Understand the synergistic effects of multiple stressors; and 4. Support Blue Economy and multi-use initiatives in the North Sea. In this document, we elucidate these strategic priorities and develop an action plan to reach our goals. This strategy will safeguard, improve and expand the data and further facilitate the increased use of the time series.

1. Mission

Marine ecological time series represent an essential base for local, regional and global research, particularly in times of change. With the Helgoland Roads (HR) and Sylt Roads (SR) time series, we provide the infrastructure to obtain high quality data with unrivaled temporal resolution. Our goals are to document change processes, to enable a functional understanding of exchange and interaction processes between and within marine and coastal systems, and to improve the data basis required for the assessment of change in ecosystem services. In order reach these goals, the continued development of the time series, in terms of data collection and technology, quality control and curation, as well as in data archival, accessibility and usage is of utmost importance. In this document, we assess the status quo of the HR and SR long-term series, and identify strategies to protect, improve, expand and increase the use of the time series.

2. Introduction

> *"Some of most valuable scientific discoveries and some of the most beautiful and iconic illustrations in environmental sciences were only possible thanks to the data obtained by long-term systematic observations – the so called Time Series - of natural events and conditions."*
> (O'Brien et al. 2017, What are Marine Ecological Time Series telling us about the ocean. A status report., IOC-UNESCO)

Time series measurements of the sea, with the aim of understanding marine ecosystems, have been a mainstay of German marine research since its start in the 19th century (Machoczek 2013). In 1962, our colleagues at the Biologische Anstalt Helgoland (BAH) realised that ongoing eutrophication of the German Bight might pose a threat to ecosystem functioning, and consequently augmented the original parameters of temperature and salinity measured at the "Kabeltonne" station at HR (54.188330N; 7.900000E). From then on, work-daily measurements of nutrient concentrations, Secchi depth, and phytoplankton abundances complemented the time series. Later, the increases in nutrients in the whole North Sea (Wiltshire *et al.* 2010; Van Beusekom *et al.* 2019) resulted in the initiation of a similar monitoring in the Wadden Sea, SR (55.030000N; 8.460000E). In 1975, zooplankton monitoring was added to the LTER routine at both stations (Greve *et al.* 2004; Martens & van Beusekom 2008).

3. Expertise

At AWI, we have recognized the value of time series in general (Franke & Gutow 2004; O'Brien *et al.* 2017) and of the interdisciplinary Helgoland Roads (HR) and Sylt Roads (SR) time series in particular, with over 800 categories of plankton monitored work-daily, together with the nutrients and physical conditions. Until the beginning of this century, HR and SR were not formally quality-controlled. Formal quality control of the data and analyses started in 2001, first for the ongoing samplings, followed by checks for the older data. This enabled us to upload over 1100 data sets into the open access international data repository PANGAEA[1]. A summary of the important variables measured at both sites is in the Appendix, Table A1. The data of the HR and SR time-series have been fundamental to many scientific projects within the past decade, both internally and externally. Furthermore, the data collected and collated for the HR and SR time series are integrated into many national and international reports (e.g. BSH 2002; Brockmann *et al.* 2007; O'Brien *et al.* 2013; Landesamt für Landwirtschaft 2014; Gonzalez-Pola *et al.* 2022), and have been used by a whole suite of national and international agencies to comply with national and international legislation (OSPAR, ICES, SCOR, Framework directives).

The HR and SR data were integral to the publication of over 850 scientific articles (Scopus search 22.08.2023, search string: All fields ("Helgoland Roads" OR "Sylt Roads")), including keystone articles such as one of the first papers on warming in the North Sea (Wiltshire & Manly 2004). Indeed, the impact of human activities is particularly strong in coastal regions such as the North Sea, which is a warming hotspot (Wiltshire & Manly 2004; Wiltshire *et al.* 2010; Amorim *et al.* 2023). Over the past decades, warming of the coastal North Sea has been accompanied by changes in dissolved nutrient concentrations (Wiltshire *et al.* 2010; Meunier *et al.* 2018; Van Beusekom *et al.* 2019). Together this has led to changes in the functioning of the ecosystem, such as the timing of the spring bloom (Wiltshire *et al.* 2008) and shifts in phenology of phytoplankton (Scharfe & Wiltshire 2019) and zooplankton (Schlueter *et al.* 2010; Marques *et al.* 2023). Furthermore, stoichiometric and food web alterations were observed (Boersma *et al.* 2015; Meunier *et al.* 2018; Käse *et al.* 2021), as well as influx and enrichment of neobiota (Franke & Gutow 2004; Reise *et al.* 2006; Hamer *et al.* 2011). Our work has also enabled us to substantially advance the field of plankton ecology by studying the drivers of

species succession, biodiversity, and coexistence (Teeling *et al.* 2012; Klindworth *et al.* 2014; Wiltshire *et al.* 2015; Teeling *et al.* 2016; Sarker & Wiltshire 2017; Chafee *et al.* 2018; Sarker *et al.* 2018). First attempts were made to integrate the time series with other international time

[1] https://doi.org/10.1594/PANGAEA.864951, https://doi.org/10.1594/PANGAEA.931217, https://doi.org/10.1594/PANGAEA.886050, https://doi.org/10.1594/PANGAEA.927019, https://doi.org/10.1594/PANGAEA.940529)

series to investigate regional differences nutrient conditions as a result of differential inflow of large rivers and the resulting phytoplankton growth (van Beusekom *et al.* 2009).

In all our endeavours, we have used the HR and SR data to describe, statistically evaluate, and model ongoing changes occurring in North Sea. Currently, Helgoland Roads is sampled five times a week (work-daily) for water chemistry and phytoplankton and three times a week for zooplankton. The sampling frequency at Sylt is slightly lower with two times weekly for all variables (see Appendix, Table A1 for detailed information). To upscale the spatial information, HR and SR are complemented with monthly ship transects in the German bight analysing physical and chemical parameters in surface and bottom water at 23 stations (Figure A1, Table A1). The analyses allow the formulation of hypotheses on the functioning of the ecosystems, which are subsequently tested in experimental setups. Results from these experiments allow predictions of what we expect to happen or have happened *in situ*, allowing the ground-truthing of experimental results (Shama 2017; Moreno *et al.* 2022). The experimental approaches include a scaled suite of different in vitro experimental setups, ranging from multiple incubator blocks with single organism assays, through laboratory aquaria, flow-through systems in constant temperature rooms, to large-scale mesocosms, both on land and *in situ*. We apply many different methods ranging from complex molecular biological and genetic assessment through pigment analyses, remote sensing, and conventional microscope analyses (Armonies *et al.* 2018; Osswald *et al.* 2019; Garin-Fernandez *et al.* 2020).

Below, we discuss the scientific areas of interest related and connected to long-term ecological research, which clearly transcend the current period of programme-oriented funding, and identified six scientific strategic priorities related to LTER research, which will be pursued as a part of the long-term scientific strategy. To achieve these strategic goals, we identified a list of action points related to these, ranging from modernizing methods to improving data accessibility.

4. Strategic research priorities (SRP) for the coming decade

As indicated above, the LTER data serve as a baseline, and inspiration for hypotheses about the state of the North Sea, as well as testbed for our scientific work with regard to prediction of changes. As such, HR and SR are important tools to achieve the research goals formulated

in the long-term strategy of coastal research, and those of our current research programme in the immediate future. Specific goals, related the LTER work are:

1. To understand the long-term responses and interactions of the North Sea and adjacent Wadden Sea to anthropogenic and natural changes, both affected by regional drivers (riverine inputs, coastal armouring and construction) as well as by global drivers (temperature change, acidification) (e.g., Wiltshire et al 2010, van Beusekom et al. 2019).

2. To find more complete and effective ways of assessing and monitoring biodiversity in difficult offshore environments, including microorganisms, for example, using molecular, optical or other methods (Banos et al. 2020), and identify ways to combine different approaches in an effective way.
3. To understand the synergistic effects of multiple stressors ranging from, e.g., underwater noise, shifts in nutrients, and temperature on key species and marine systems (Laspoumaderes et al. 2022; Leiva et al. 2022), which would allow the assessment of those drivers that alone or in combination affect the ecosystem most, and the identification of those pressures, where mitigation measures would be most promising.
4. To reliably model food webs in relation with changing physical environments (Horn et al. 2021). Here, we have begun to apply our highly flexible new FESOM-C hydrographic models to understand, for example, the effects and extent of sea level rise on intertidal habitats (e.g., seagrass) and hydrographic current shifts related to sediment transport and species dispersion in a warmer environment (Fofonova et al. 2021; Galvez et al. 2021).
5. To integrate knowledge and information on restoration options of coastal seas and investigate their potential in carbon storage (Pogoda et al. 2020).
6. To provide advice and information on management and mitigation in the Blue economy and multi-use framework of the North Sea (Schupp et al., 2019; Krause et al., 2022).
To ensure that we can provide the necessary data and information to address the research goals, we have developed four strategic priorities (SRP) below that we will continue to develop in the coming years.

SRP 1: Understand the whole system and close the gap to the microbial loop

In recent years, much of the work on the LTER has focused on key species and their role in habitat stability and species function (Sarker *et al.* 2018; Scharfe & Wiltshire 2019; Käse *et al.* 2020). Single species studies then culminated in biodiversity assessments in association with environmental variability on seasonal to decadal scales from micro-organisms to larger species, with a special focus on neobiota (Lackschewitz *et al.* 2014; Teeling *et al.* 2016; Bowler *et al.* 2017; Cornelius & Buschbaum 2020; Reise *et al.* 2023). Especially, the establishment of the HIFMB will continue to increase this venue of functional biodiversity research, including the assessment of indicators and methods to address system biodiversity. For both HR and SR time series, we still have blind spots that we aim to close in the coming years.
Currently, the HR and SR time series include data on environmental parameters, phyto- and zooplankton abundances in high taxonomic resolution and frequency, enabling us to address questions particularly related to global change. However, some of the organisms which are expected to benefit from global change, may not be sufficiently well covered by the HR and SR time series. For instance, several studies suggest that the microbial loop may gain in

prominence as a result of global change (Caron & Hutchins 2013; Aberle *et al.* 2015; López-Abbate 2021). However, to date, we sample the players in the microbial loop with insufficient resolution. This is on the one hand due to sampling issues, leading to an inefficient observational capacity of some unicellular plankton size classes (microzooplankton such as ciliates), and on the other hand caused by the fact that we lack resources to address small unicellular eukaryotes, as well as bacteria, archaea and viruses, which cannot be observed using traditional taxonomical approaches. This means that not only the monitoring of biodiversity is incomplete in terms of species, but also that important data are missing to understand the ecosystem. Hence, it is highly relevant to improve the monitoring of prokaryotic and eukaryotic microbes on Sylt and Helgoland. For instance, Next Generation Sequencing (NGS) approaches unveiled that, algal substrate availability provides ecological niches for specialized bacterial populations (Teeling *et al.* 2012). Furthermore, we observed that short-term bacterial successions associated with phytoplankton spring and summer blooms are indirectly affected by temperature (Lucas *et al.* 2015), and that small-sized eukaryotic microbes have distinctive blooming patterns (Käse *et al.* 2020). While these studies highlight the importance and complexity of the microbial loop, and the potential of NGS techniques to unravel hidden diversity, most cover a period of weeks to a few years only. Consequently, long-term temporal dynamics of pico- and nanoplankton is not sufficiently covered to identify changes in community composition and biodiversity resulting from global change. As a first step, we joined the bioarchive initiative within the project CREATE (DAM project) and are taking weekly samples for subsequent DNA extraction and sequencing at HR and SR (see below Action 3). Also, we have participated in international sampling programs such as coastal Tara, the Earth Microbiome Project (Thompson *et al.* 2017), and the ocean sampling day (Kopf *et al.* 2015). Ultimately, we envisage that we sample all meso- and micro- biota in the ecosystem efficiently and quantitatively, and we will have developed ways to combine the different methods in such a way that it will allow proper estimates of the functional and taxonomical biodiversity of the North Sea, as well as the computation of flows of energy and nutrients through the system.

SRP 2: Scaling up: linkage of HR and SR single site measurements to the whole North Sea

The Wadden Sea and German Bight exhibit complicated hydrography due to the interplay between coastal currents, riverine input, tidal and wind forces, as well as complex topography (Kuznetsov *et al.* 2020). As a result, multiple regions with different players are present, relying on habitats with different abiotic and biotic conditions. Hence, since HR and SR time series are single point observatories, albeit with a very high temporal resolution, their representativeness for the broader area is limited. Ultimately, our aim is to understand and predict processes in the complete North Sea. Thus, given the large regional and temporal differences, a robust description must be based on a larger set of long-term data sets. Apart from the monthly AWI-transects described above, riverine observations (e.g. from the FGG Elbe, or from Rijkswaterstaat, NL) and coastal observations (e.g. by the BSH or by the federal fisheries agencies) in combination with surveys from the continuous plankton recorder (CPR), and state environmental agencies, may be used.

In order to achieve the goal of wider geographic coverage, we follow a multi-pronged approach. We aim to extend our observational capacity using for example the ferry box systems on our research ships and passenger ships of opportunity. We have intensified and modified the number of parameters that are collected on the monthly cruises (Figure A1), and are in close contact with other national and international institutions sampling other parts of the North Sea. We also envisage extending this observational power by remote sensing or other optical methods that will allow a higher spatial coverage of the North Sea. We aim to integrate the different data sets using modelling approaches, such as the newly developed coastal model FESOM-C. We are currently concentrating on near coastal processes, for example on the effects and extent of sea level rise on intertidal habitats (e.g. seagrass) and hydrographic current shifts related to sediment transport and species dispersion in a warmer environment (Fofonova et al. 2021; Galvez et al. 2021). Although we have recently shown that for example temperature measurements at HR and SR are representative for the whole North Sea (Amorim *et al.* 2023), this is likely to be very different for the interaction between temperature and species distributions (Sprong *et al.* 2020).

SRP 3: Understand the synergistic effects of multiple stressors

The change processes described for the North Sea are induced by factors that do not act separately or linearly, but that produce complex non-linear impacts. Hence, in recent years a substantial amount of work has dealt with the interactive actions of multiple stressors, both with the explicit aim to tease apart the effects of single stressors, and their interactions, as well as using them in climate change scenarios to predict reactions of complex communities to the whole suite of changes currently occurring and predicted to continue. We will proceed using the time series to analyse the interrelationships between ecosystem change and environmental parameters. Currently, we are focussing on the effects of trends, heatwaves and decadal climate shifts (Di Pane *et al.* 2022; Gimenez *et al.* 2022; Amorim *et al.* 2023). Further, the role of (de-)eutrophication and its effects on plankton communities, species compliments, and food quality (Meunier *et al.* 2016; Laspoumaderes *et al.* 2022), in the context of warming environment is a very promising venue for further research to be intensified. We aim to include new potential stressors, which have thus far not been part of the long-term series, such as underwater noise (Laspoumaderes et al. 2022; Leiva et al. 2022). Ultimately, this should yield hierarchal models of which drivers or stressors, alone or in concert with others, are the most important ones affecting the ecosystem. This knowledge will allow us to advise policy makers and the public as to which mitigation measures are particularly promising.

SRP 4: Support the Blue Economy and multi-use framework for the North Sea

The North Sea is packed with use. As evinced by the marine spatial planning maps of the BSH there is not one single area in the North Sea that has not been designated for specific use. On top of this, the German government plans to have 75 GW of wind power established in the North Sea by 2045. Together with the other pressures for space, for example, the establishment of MPAs, the production of hydrogen and food will increase the competition for space tremendously. With our long-term ecological time series, we can provide multiple services to aid the development and the assessment of the environmental impact of the infrastructure. First, we can provide the long-term base line of parameters of interest, even if these are changing with the environmental drivers, before the disturbance. Second, we can provide the data after the structures are placed. This includes the monitoring of organisms that are either used for marine aquaculture in a multi-use environment, and might increase or decrease also outside the aquaculture devices, or those organisms that have been restocked or restored in the North Sea such as lobster and oyster, larvae of which would be found in our

plankton surveys. Also, changes in nutrient concentrations in the water column could indicate changes in the pelagic system as a result of the disturbance. Further, using the combination of the results from our first three priorities, we should be able to identify areas, where change processes are particularly prominent or absent, and use this information in the spatial planning process to either designate or avoid a certain area for a specific use. Thus, we can provide advice and information on management and mitigation in the Blue economy and multi-use framework of the North Sea (Schupp et al., 2019; Krause et al., 2022). Ultimately, we envisage that our LTER data will be used in a more comprehensive way in environmental assessments and in decision making processes. Examples of such partnerships can be the activities on sediment dumping sites in the North Sea (Stormer *et al.* 2013), and the water quality assessments of coastal waters (Ndah *et al.* 2022)

5. HR´s and SR´s role in the national and international research landscape

The past, ongoing, and planned future research activities are anchored in national and international collaborations. Our closest national collaborative partners are Helmholtz Centre HEREON, Max-Planck Institute for Marine Microbiology (MPI-MM), Senckenberg – Leibniz Institution for Biodiversity and Earth System Research, the Federal Maritime and Hydrographic Agency (BSH), the Federal Agency for Nature Conservation (BfN), the Johan Heinrich von Thünen Institute (vTI), the State Office for Environment (LFU), and the state office for Agriculture and sustainable Rural Development (LLnL) of the State of Schleswig-Holstein, the NLWKN in Niedersachsen, as well as multiple universities (Bremen, Kiel, Oldenburg, München). As to European Alliances, especially the trilateral Wadden Sea research agenda with Denmark and the Netherlands is important. Unfortunately, sampling strategies are still insufficiently aligned, but there are initiatives underway to streamline and coordinate those. This will be especially important in the framework of the planned research in the Wadden Sea, funded through the joint initiative of BMBF and NWO. Internationally, we are, among many others, very well connected to the Sir Alister Hardy Foundation for Ocean Science (SAHFOS-UK), the National Oceanic and Atmospheric Administration (NOAA), and the University of Venice. Our long-term data are core data for a variety of national and international commissions and stakeholders e.g. BLANO (Bund/Länder-Arbeitsgemeinschaft Nord- und Ostsee), ICES, OSPAR and SCOR. They are well represented in European and International LTER databanks[2]. We provide experts and LTER data for many national and international working groups, such as several national groups (e.g., BLANO-working groups, LTER-Germany, KDM Observatory group, DAM Mission Coastal futures, EuNäp group), and international commissions (e.g., ICES working groups[3]

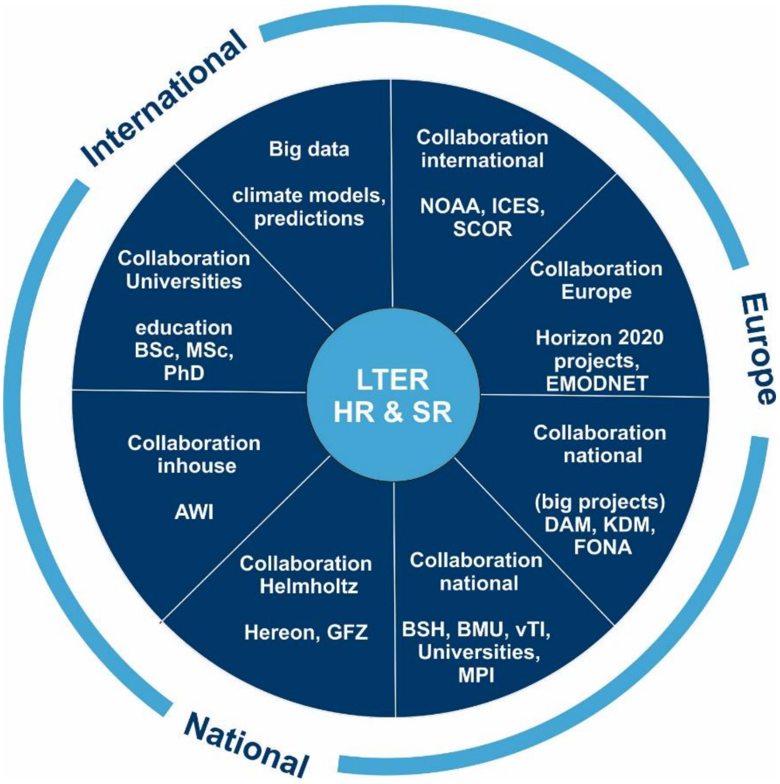

Figure 1. National, European and international stakeholders of HR and SR

[2] https://www.st.nmfs.noaa.gov/copepod/time-series/de-30201/;
3 https://ocean.ices.dk/core/iroc

(WGPME, WGZE, WGOH), SCOR-UNESCO Phytoplankton, and LTER Europe, UN-Ocean assessment groups, IPCC working groups, WMO).

6. Actions

The continuity of HR and SR time-series is essential for addressing the science priorities identified above. In order to assess the strengths and weaknesses of HR and SR systematically, and to define a development strategy for the coming years, we conducted a S-W-O-T (strengths, weaknesses, opportunities and threats) analysis. This analysis produced the following results:

- **Strength - Comprehensiveness:** The breadth and detail of information available, including physico-chemical and biological parameters, in the HR and SR time series for long-term and marine ecosystem analyses are unique in the world.
- **Weakness - Comparability:** One of the biggest challenges in long-term time series analysis is the comparability of different data sets, taking into account differences in sampling effort (temporal and spatial) and various methods used, as well as the challenges that come with changing equipment, people and taxonomy, and the inclusion and integration of newer and more modern methods.
- **Opportunities - New technology:** The implementation of new aspects and technologies offer great potential for the development of the time-series. For instance, adopting optical and molecular techniques would provide unique information on microbial diversity and therefore provide a more complete picture of plankton biodiversity. We have started with focusing on microbial diversity through third party funding, which will then have to be secured in a next phase of implementation. Also, in the context of the SOOP project a we are currently developing easy access automatic measuring devices, which have the potential to become more widely used in the future.
- **Threats - Continuity:** Long-term series require long-term commitment, both in terms of financial support as well as taxonomical and technical expertise. Ascertaining the maintenance of expertise is a constant challenge, especially given the limited number of people involved in the day-to-day running of the time series (see chapter 7 also for a comparison with other time series). Currently, the financial support is guaranteed through the integration of HR and SR-associated operations and the necessary personnel into the large-scale research infrastructure as a long-term and strategic fundament for research.

Based on this S-W-O-T analysis and our existing expertise, we identified a set of action points that need to be tackled for the LTER work at AWI. The timeline of each action point, ranging from today – 10 years, is indicated in years, respectively.

Action 1: Harmonization of LTOs HR and SR

Harmonization of time series by aligning different variants of processes, by capturing their commonality and variability, at the same time ascertaining the seamless continuation of the time series (today - 10 years).

Comparability between time-series is essential, primarily between the SR and HR time series, which have a different history and provenience but also between other time series in the same area (Continuous Plankton Recorder[4], The Scottish Coastal Observatory in Stonehaven[5], NIOZ long-term ecological time series[6] and others). Streamlining allows more comprehensive inference of what has happened and is continuing to happen in the North Sea as a whole (Corona *et al.* in press). In general, one of the biggest challenges in long-term time series analysis is the comparability of different data sets, taking into account differences in sampling effort (temporal and spatial) and various methods used. Even within institutions, differential protocols are in place, and we will continue to align these, with the important caveat, that

comparability within time series is a large constraint. Since changing protocols in an existing time series would lead to continuity issues within one time series the possibilities of harmonization are limited to newly implemented aspects and variants of processes. Standard Operational Procedures (SOPs) were drafted for most of the current sample collection activities, as part of the data management plan (Action 5).

Action 2: Increase the resolution of measurements in time and space

HR and SR are high intensity low spatial resolution time series, as they are sampled at one point only. Increasing spatial information is vital. This will be done by a combination of intense cooperation’s with other time series (# chapter 2 SP 4 and chapter 3), and high-resolution modelling (2 - 10 years).

Habitats in coastal oceans are defined by their biotic and abiotic properties and are subject to high spatial and temporal variability. HR and SR stations provide information with high temporal resolution for a spatially limited area. The high variability of habitat characteristics places high demands on monitoring programmes to identify relevant time and space scales, not to forget that the relevance is also depending on the parameter investigated and the respective research field and question. We want to promote an interdisciplinary and multi-scale approach for analysing LTER data by offering insights into both abiotic and biotic conditions across various temporal scales. We will assist scientists from diverse disciplines in accessing relevant information. To increase the representativeness of the LTER data we will combine it with other

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4 https://www.cprsurvey.org/
5 https://www.gov.scot/collections/marine-scotland-science/
6 https://www.nioz.nl/en/expertise/wadden-delta-research-centre/data-tools/long-term-ecological-time-series

available time series (see also chapter 4 SP 2 and chapter 5) and coastal ocean modelling results available and produced at, e.g., AWI (FESOM-C model), IOW (GETM model), HEREON (SCHISM model), and CAU (DELFT3D model).

Action 3: Implementation of novel technologies

The HR and SR time-series were started 50-60 years ago, with state-of-the-art measuring and analyses techniques available at the time. One of the greater challenges is the extension of our observational power, while at the same time ensuring continuity of the data. New observational systems are continuously tested, and will be included in the set of LTER parameters, once they are deemed appropriate. These include molecular and optical techniques (2 - 10 years).

Autonomous devices have the potential to significantly improve the data collection when it comes to permanent or recurring measurement tasks or the collection of samples. Thus, we will continue to develop and deploy autonomously operating devices, such as e.g. new autonomous filtration devices, optical devices and ferry boxes. Currently we have a ferry box system operating on the passenger ship MS Helgoland recording twice a day temperature, salinity, oxygen, and chlorophyll a along the transect between Helgoland and Cuxhaven. Furthermore, an Oceanic Standard Measurement Box (OSMB) is currently under development. It will be based on the open-source measurement system architecture and will enable autonomous, strong quality-assured measurement operations.

Prokaryotic and eukaryotic microbes and their long-term community changes are much more elusive, compared to larger phyto- and zooplankton, mainly due to their size and often uniform morphology, which makes visual identification challenging, if not impossible. Hence, we aim to complement the HR and SR long-term ecological time-series using modern next-generation sequencing technology including prokaryotic and eukaryotic microbial communities. We have experience the molecular analysis of bacteria (Gerdts *et al.* 2013), viruses (Garin-Fernandez *et al.* 2020), fungi (Banos *et al.* 2020), microalgae (Käse *et al.* 2021) and zooplankton (Laakmann *et al.* 2013; Laakmann *et al.* 2016). We now aim to incorporate those analyses into the time series. Therefore, as a first step, we joined the bioarchive initiative within the project CREATE and are taking additional samples for subsequent DNA extraction and sequencing. We also cooperated with external partners on other identification methods such as using protein fingerprints. The implementation of next-generation sequencing offer great potential for the development of HR and SR. To sustainably implement molecular tools in the time-series we need to diversify our funding sources and expertise, potentially by closer cooperation's with external partners.

Action 4: Full digitalization of Sylt and Helgoland Roads data flows

Full digitization of Sylt and Helgoland Roads data flows, which includes all aspects starting at data acquisition, suitable O2A workflow entrances and data assessment and processing for LTER Data, plus metadata registration to make the data FAIR (2 - 3 years).

Digitalization of all processes involved in LTER at HR and SR is one of the main ongoing challenges in our work and includes everything from sample collection to data archival and retrieval. Much of the data collection at HR and SR is carried out by hand. The digitalization will increase efficiency and precision of data collection. For all parameters, a quality control strategy has to be established and implemented including quality flagging of data. An entry point for the LTER data into the O2A workflow[7] will be established, and tools will be evaluated as candidates for digital data acquisition and processing, e.g. a Mobile Event Log App for field sampling. Data collections will be published and updated on a yearly basis via Pangaea and the data infrastructure platform of the Research Area "Earth and Environment"[8].

Action 5: Create data management plan

The creation of a dynamic Data Management Plan (DMP) for HR and SR long-term time series will increase the transparency as well as the integrity of HR and SR LTER data (1 - 2 years).

Data and processes in the context of their collection must be documented in a subject-specific manner and supplemented with metadata. Clarity regarding the provenance of the data must be ensured by describing the data transformations. Data management plans ensure the documentation of these processes and the description of the data. The DMP will clarify how and what data will be created, processed, and documented. It will identify the means of data archiving and publication regarding costs as well as access conditions for the scientific community and the public. Dynamic DMPs for HR and SR will be developed with support from GFBio[9].

Action 6: Increase data accessibility

Given the fact that the HR and SR time series are unique in the world, with their combination of length and intensity of sampling, they have been widely used by scientists, managers and policy makers alike. However, even though usage has increased considerably, there is still a need to make accessibility of the data easier, more user-friendly and especially as more traceable (2 - 5 years).

It is planned that all LTO data at AWI will be assessed, archived, managed, and made useful for all according to the Research Data Guideline and Research Data Directive of AWI and the

[7] https://dashboard.awi.de/data-xxl/#
[8] https://marine-data.de
[9] https://www.gfbio.org/plan/

FAIR principles in the framework of the joint data infrastructure management of Research Field Earth and Environment supported by HGF and BMBF. We work on the creation of user-friendly

BOX A: HR and SR Dashboard's and Data Products

To make information about and the knowledge resulting from the HR and SR LTER time series findable and accessible for the scientific community and other interested stakeholder groups meaningful and reproducible data products were compiled for parameters of the HR and SR time series. The resulting data products are presented on two AWI dashboards (Helgoland Roads Dashboard *https://dashboard.awi.de/?dashboard=34404*; Sylt Roads Dashboard *https://dashboard.awi.de/?dashboard=38606*), where information about the time series, near-realtime data and the data products are consolidated.

Data products from the LTER sites have to meet the needs of the users. Especially the (governmental and state) stakeholders rely on the data from the HR and SR time series, and products that can be used directly. We are in close contact with many stakeholders, and will establish formal procedures to interact with them to continuously update our portfolio of products according to the needs of the users.

Not only the scientific and political community should be aware and using the LTER data of SR and HR, it is also important that the general public can use the information. We will develop a storyline around the HR and SR dashboards and create graphic and media output for the broad public.

data collections of data sets with similar nature with clear event labels to differentiate LTER data sets from associated satellite projects. FAIR, plausibility checked and flagged data will be made open access available on PANGAEA. LTER data sets will be made open access after two years moratorium after publication in PANGAEA and on the portal of the German Marine Alliance (via the FB EuU data platform[10])

Action 7: Increase visibility of LTER at HR and SR

Good visibility, acceptance and use of the LTER is highly dependent on the presentation of the LTER in websites, data archives, data products and the proper linkage of those with others, and an easy to access system for harvesting data. We will extend this for the HR and SR considerably and implement those features (today - 2 years).

Visibility, communication, and education have always been essential aspects of the work conducted at the marine stations Helgoland and Sylt, and LTER activities. Recently, much has

10 https://marine-data.de

been done to make information about and the knowledge resulting from the HR and SR LTER more visible (Box A).

Action 8: Extend collaboration and networking within LTER

One LTER is an asset, many together are a treasure. We envision extending the existing cooperation's with other LTER-sites, to jointly analyse, present and make available the data of the different long-term observation series. Furthermore, a partnership within EMBRC structures is currently being surveyed (today - 10 years).

We will continue to cooperate and provide expertise and LTER data for international commissions and stakeholders as well as national and international working groups (see chapter 3). To extend the existing cooperation's with other LTER-sites, we participated in a joined proposal submitted to EuroMarine to create the Marine Biodiversity Observation Network for Europe (MBON)[11], with partners from Nord university, VLIZ, IRB, SDU, UHEL, IFREMER, GEOMAR, NUIG, UniP, GELIFES, NTNU, CIIMAR, CCMAR, MARE, CSIC, and UCA.

7. LTER HR & SR as part of the large-scale infrastructure

Research at the AWI is financed and organized within the framework of programme-oriented funding (PoF) of the Helmholtz Association. The large-scale research infrastructures operated by the Helmholtz Centres enable and support the programme research as well as offer dedicated usage time for researchers outside Helmholtz. With the start of the fourth period of PoF in 2021, the marine stations Helgoland and Sylt, and their long-term time series, became such a large-scale research infrastructure. Operation of these research infrastructures is of great significance to the national and international community and must fulfil the following conditions:

- External use (= outside Helmholtz) must make up significantly more than 50 percent of all use
- Users/projects must be selected in a transparent procedure by an external committee (e.g. User Advisory Board)
- Operating costs (full cost basis) must be in the order of / higher than €6 million annually

National and international users can request usage time at the marine stations Helgoland and Sylt and including services (e.g. LTER data, research vessels, etc.) via a webportal. In order to track the output resulting from the research conducted at the marine stations grant numbers have been invented in 2023 and assigned for each request. User are obliged to cite the given

11 https://marinebon.org/mbon-europe/

grant number as well as the DOI of the description of the infrastructure in JLRSF (Alfred-Wegener-Institut Helmholtz-Zentrum für Polar-und Meeresforschung, 2023).

8. Immediate and concrete needs

To continue HR and SR, fulfil our scientific Strategic Priorities and user requirements in the future we identified S-W-O-T and necessary actions. To ensure the feasibility of the actions identified in the previous section, HR and SR will need the appropriate resources.

- The research vessel Aade was built in 1974 and has been in operation ever since. For some years now, the number of ship days lost due to technical defects has been increasing. Hence, to ensure the continuity of LTER at HR, the need for a new research vessel is urgent. The design of this new vessel is currently being developed, tendering for construction should be pushed forward.
- Ascertaining the maintenance of sufficient taxonomical and technical expertise is a constant threat, especially given the limited umber of people involved in the day-to-day running of the time series (Table 1). Other time series operate with higher numbers of staff. For example, the Institute for Baltic Sea Research (IOW) operates their physico-chemical and biological time series with approximately double the staff than HR, with a comparable number of parameters and samples. The CPR survey operates with around 16 people for taxonomic analysis alone. Furthermore, specific expertise is needed for the different time series (e.g. chemistry, phytoplankton taxonomy, zooplankton taxonomy) and additional expertise will be needed for the implementation of new aspects (e.g. molecular methods). Ideally, additional resources are availble for new personnel with overlapping contracts to ensure training and knowledge transfer.

Table 1: Overview of personnel involved in the day-to-day running of HR and SR.

LTER	Position	Task	FTE
HR	Scientist	Management of the team, labs, and programmes	1
HR	Technician	Measurement and analysis of physico-chemical parameters	1
HR	Technician	Taxonomical analysis of phytoplankton	1
HR	Technician	Taxonomical analysis of zooplankton	1
SR	Scientist	Management of the labs, and programmes	0,5
SR	Technician	Measurement and analysis of physico-chemical parameters	1
SR	Technician	Taxonomical analysis of phytoplankton	1

- To ensure the success of long-term collaborations, institutional commitment to monitoring is needed, e.g. by signing Memoranda of Understanding specific to LTER with key partners such as MPI-MM and BSH.
- The implementation of new aspects and technologies offer great potential for the development of the time-series. Albeit very promising, some approaches are costly. We need to diversify our funding sources to sustainably implement new aspects, potentially by closer cooperation's with the federal and state agencies.

9. Closing remarks

If we are to deal with the challenges that face us now and in the future, we need to understand the past, and know how our environment is changing. The Helgoland and Sylt Roads time series are the ideal instrument for this understanding, and with these unique time series we keep the finger at the pulse of our ever changing North Sea. Hence, HR and SR are important tools to achieve the research goals formulated in the long-term strategy of coastal research, and those of our current research programme in the immediate future.
Already in the last century, the first director of the Biologische Anstalt Helgoland, F. Heincke, asserted that long-term data provide a trove of information for the understanding of trophic dynamics and food webs in a rapidly changing environment. This is as true today as it was 100 hundred years ago.

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11. List of abbreviations

AI	Artificial Intelligence
ARGE	Arbeitsgemeinschaft
BfN	Bundesamt für Naturschutz (Federal Office for Nature Conservation)
BSH	Bundesamt für Seeschifffahrt und Hydrographie (Federal Maritime and Hydrographic Agency of Germany)
BLANO	Bund/Länder-Arbeitsgemeinschaft Nord- und Ostsee
BMBF	Bundesministerium für Bildung und Forschung (Federal Ministry for Education and Research)
DAM	Deutsche Allianz Meeresforschung (German Marine Research Alliance)
DMP	Data Management Plan
CAU	Christian-Albrechts Universität zu kiel (Kiel University)
CPR	Continous Plancton Recorder
CREATE	Concepts for reducing the impacts of anthropogenic pressures and uses on marine ecosystems and biodiversity
DOI	Digital Object Identifier
EuNäP	Facharbeitsgruppe Eutrophierung, Nährstoffe und Plankton
FAIR	Findable, Accessible, Interoperable, Reusabl
GFBIo	German Federation for Biological Data
HEREON	Helmholtz-Zentrum Hereon
HIFMB	Helmholtz Institute for Functional Marine Biodiversity
HGF	Hermann von Helmholtz-Gemeinschaft Deutscher Forschungszentren (Helmholtz Association)
HR	Helgoland Roads
ICES	International Council for the Exploration of the Sea
IPCC	Intergovernmental Panel on Climate Change
JLSRF	Journal of Large-Scale Research Facilities
KDM	Konsortium Deutsche Meeresforschung (Geman Marine Research Alliance)
SAHFOS-UK	Sir Alister Hardy Foundation for Ocean Science
LTER	Long Term Ecological Research
LTO	Long Term Observatory
LFU	Landesamt für Umwelt (State Office for Environment)
LLnL	Landesamt für Landwirtschaft und nachhaltige Landentwicklung (State office for Agriculture and sustainable Rural Development)
MPI-MM	Max Planck Institute for Marine Microbiology

MBON	Marine Biodiversity Observation Network
MURSYS	Meeres-Umwelt-Report-System
NOAA	National Oceanic and Atmospheric Administration
O2A	Data flow from Observations to Analysis & Archives
OSPAR	Oslo and Paris Conventions Commission
PoF	Programme-oriented-Funding
SCOR	Scientific Committee on Oceanic Research
SR	Sylt Roads
SWOT	strengths, weaknesses, opportunities, threats
vTI	Johan Heinrich von Thünen Institute
WGPME	ICES Working Group on Phytoplankton and Microbial Ecology
WGZE	ICES Working Group on Zooplankton Ecology
WGOH	ICES Working Group on Oceanic Hydrography
WMO	World Meteorological Organization

12. Appendix

Table A1: List of parameters and their temporal resolution measured at HR, SR and transects in the German bight (total 23 stations).

Station	Parameter	Temporal resolution
HR	Temperature	work-daily
HR	Salinity	work-daily
HR	SECCHI depth	work-daily
HR	Nitrate	work-daily
HR	Nitrite	work-daily
HR	Ammonium	work-daily
HR	Phosphate	work-daily
HR	Silicate	work-daily
HR	Chlorophyll a (BBE)	work-daily
HR	Chlorophyll a (HPLC)	twice weekly
HR	pH	work-daily
HR	Oxygen	work-daily
HR	Phytoplankton quantitative	work-daily
HR	Microplankton semi-quantitive	weekly
HR	Mesozooplankton quantitative	thrice weekly
SR	Salinity	twice weekly
SR	Temperature	twice weekly
SR	pH	twice weekly
SR	Chlorophyll a (HPLC)	twice weekly
SR	Phosphate	twice weekly
SR	Silicate	twice weekly
SR	Ammonium	twice weekly
SR	Nitrite	twice weekly
SR	Nitrate	twice weekly
SR	Nitrogen, organic, dissolved	twice weekly
SR	Phosphate, organic, dissolved	twice weekly
SR	Suspended matter	twice weekly
SR	Microplankton semi-quantitive	weekly
SR	Gelatinous zooplankton abundance at Sylt Roads	weekly
SR	Meroplankton	thrice weekly
SR	Mesozooplankton quantitative	weekly
SR	Phytoplankton quantitative	twice weekly
SR	Fish monitoring	monthly
SR	Macroplankton	weekly
SR	Macrozoobenthos	yearly
Helgoland transects Eider, Elbe, P8	Temperature	monthly
Helgoland transects Eider, Elbe, P8	Salinity	monthly
Helgoland transects Eider, Elbe, P8	SECCHI depth	monthly
Helgoland transects Eider, Elbe, P8	Nitrate	monthly
Helgoland transects Eider, Elbe, P8	Nitrite	monthly
Helgoland transects Eider, Elbe, P8	Ammonium	monthly
Helgoland transects Eider, Elbe, P8	Phosphate	monthly
Helgoland transects Eider, Elbe, P8	Silicate	monthly
Helgoland transects Eider, Elbe, P8	Chlorophyll a (HPLC)	monthly
Helgoland transects Eider, Elbe, P8	pH	monthly
Helgoland transects Eider, Elbe, P8	Oxygen	monthly

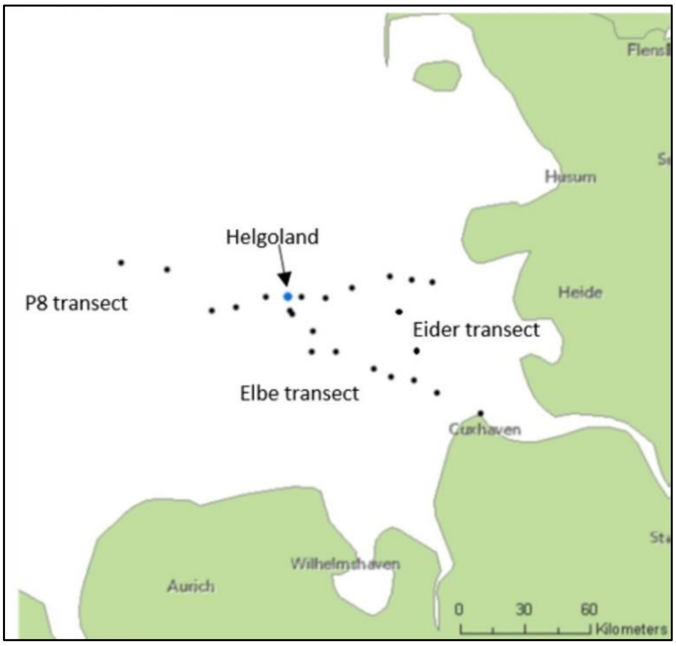

Figure A1: Map showing the spatial resolution of Helgoland Roads associated monthly ship tracks in the German bight (total 23 stations).