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ORIGINAL ARTICLE

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Ecological long-term research at Helgoland (German Bight, North Sea): retrospect and prospect—an introduction

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Abstract This paper summarizes and evaluates ecological long-term observations at the island of Helgoland (German Bight, North Sea). It is an introduction to a series of seven contributions to an issue of Helgoland Marine Research (vol. 58, no. 4) dealing with observations on the physico-chemical environment and the local biota (pelagic bacteria, phytoplankton, zooplankton, macroalgae, macrozoobenthos). More than 150 years of research at Helgoland (at the Biologische Anstalt Helgoland, BAH, since 1892), and particularly the Helgoland Roads time-series which started in 1962, has provided a multitude of data which represents a valuable basis for analysing past changes, evaluating the present status and predicting future changes in ecosystem parameters. Predicting the consequences of the recent rapid ecological change on regional and global scales requires increased efforts of focus on long-term ecological observations. Future efforts in this field will rely on the application of innovative advanced technology and on the concerted activities of a large number of institutions which only collectively can establish the large-scale patterns of temporal and spatial change in ecosystem functions.

Keywords Long-term observations · Ecological change · Helgoland · North Sea

The beginnings

With the epochal work of Charles Darwin, it became evident that life had originated in the sea and had evolved there through many millions of years before it started to conquer terrestrial and freshwater habitats on our planet. This revolutionary discovery, as well as the need for a more intense but rational exploitation of marine resources for a growing human population, created an increasing interest in scientific studies of marine life. The bloom of marine biological sciences during the second half of the nineteenth century was intimately connected with the successful activities of "Biological Stations" which, by that time, had been founded all along European coasts.

In the German Bight, about 60 km off the estuaries of the rivers Elbe and Weser, one location had attracted the interest of German and other naturalists since the 1830s: the small rocky island of "Heligoland", under British administration since 1810. From a German geographical point of view, this island was the ideal place to establish a permanent biological station. With a high diversity of marine life and many different easily accessible inter- and subtidal habitats, this location stood out over other potential locations in the south-eastern part of the North Sea which is dominated by sandy and muddy bottoms. Furthermore, remarkable biological discoveries, which were made by German naturalists during their visits to Helgoland from the 1830s to the 1880s (Florey 1995), had proved the island's excellent suitability as a place for marine research.

Johannes Müller (1801–1858; Fig. 1) was the leading German nineteenth-century authority in the fields of physiology and zoology. During several stays on Helgoland between 1845 and 1854, he discovered an astonishing diversity of previously largely unknown small organisms, among them the pelagic larval stages of many benthic species, which drift freely in the water column. Müller (1846) was not the first to use fine-mesh nets for collecting minute aquatic organisms which were subsequently observed under the microscope, but he improved the method and systematically used nets which were pulled along behind a boat. In this way he opened a new and exciting field of research to biological sciences (Florey 1995; Zissler 1995). Due to Müller's (1846)

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Fig. 1 Johannes Müller (1801–1858), pioneer of plankton research at Helgoland

pioneering activities on Helgoland, this island may justly be considered the "cradle of plankton research" (Bückmann 1959). Müller (1846) coined the term "Auftrieb" (floating stuff) for the community of suspended drifting organisms: this was replaced about 40 years later by the term "plankton" (Hensen 1887: "I thereby mean everything that drifts in the water column, whether shallow or deep, living or dead", translated from the German).

Johannes Müller, as well as his pupil Ernst Haeckel (1834–1919; research stays on Helgoland in 1854 and 1865), studied plankton communities from a qualitative aspect (systematics, morphology, developmental biology) and apparently were not aware of (or not interested in) the important role which these small organisms play in the cycling of nutrients within the marine environment. It was Viktor Hensen (1835–1924), a professor of medical physiology at Kiel University and a frequent guest on Helgoland, who introduced quantitative methods to plankton research. Hensen was an exponent of applied marine biology, particularly interested in the economic aspects of sea fisheries. Inspired by trends in agricultural sciences at that time, he revealed plankton organisms as the "Urnahrung" (basic food) of the oceans, and emphasized the need for a quantitative estimation of the primary (and secondary) production and its dependence on physico-chemical and biological parameters (Hensen 1887). Hensen was a founder member of the "Kommission zur wissenschaftlichen Untersuchung der deutschen Meere in Kiel" (since 1900 "Deutsche wissenschaftliche Kommission für Meeresforschung", DWK). In 1872, the Kiel commission established a network of observation stations, including Helgoland, where regular observations were made on weather, properties of the water and plankton (Mills 1989). Accordingly, 1872 may be considered the starting point of regular pelagic observations at Helgoland.

Although the idea of establishing a permanent German biological station on the island of Helgoland dates back to at least 1876 (Werner 1993), it was not until after the island had again become German (1890) that this long-cherished wish of many German naturalists came true: In 1892, the "Königlich Biologische Anstalt auf Helgoland" was founded as an institution of the Prussian Ministry of Culture. In 1894 a new journal ("Wissenschaftliche Meeresuntersuchungen", Fig. 2) appeared, co-edited by the Kiel commission and the Biologische Anstalt Helgoland (BAH), which was the predecessor of the current journal "Helgoland Marine Research". It started with a contribution from the first director of the BAH, Friedrich Heincke (1852–1929), who specified the "mission" of the newly founded station. "Regular, periodical observations" of parameters and processes relevant to either pure or applied (particularly fishery) biology were explicitly mentioned, thus establishing the institution's characteristic status as a place of research with a high measure of continuity; special emphasis was given to the study of plankton as the "Urproduktion" in the sea (Heincke 1894).

With the foundation of a permanent research institution on Helgoland, a period of intensive hydrographic and biological investigation of the German Bight, North Sea, was launched, interrupted only by evacuation of the island in the wake of World Wars 1 and 2. Plankton, commercially important animals (i.e. various species of fish, oysters and lobsters), the macroalgae of the hard-bottoms around the island, and the benthic invertebrates of hard and soft bottoms were the focal points of continued qualitative and quantitative studies. Unlike

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1894.

Fig. 2 Title page of the first volume (1894) of "Wissenschaftliche Meeresuntersuchungen", the predecessor of the current journal "Helgoland Marine Research" today, when long-term studies basically aim at the detection of *trends* in physico-chemical and biological parameters, long-term studies up to the mid-twentieth century were carried out to record and understand *periodical phenomena* such as long-term fluctuations in fish populations.

At the end of World War 2, the facilities of the BAH, along with the village of Helgoland, were completely destroyed. Only in 1959 could the BAH resume its regular activities on the island. Meanwhile, applied fisheries biology, which until then had been a prominent field of activity at the BAH, had found a new home at the "Bundesforschungsanstalt für Fischerei" in Hamburg (founded in 1952), and the BAH was free to focus on basic research in marine biology.

The Helgoland Roads data series

Under the directorship (1962–1984) of Otto Kinne, the BAH assumed a new and modern image. A programme on North Sea ecosystem research was initiated in 1963, defining two major objectives: (1) the determination of the ecological dynamics of the German Bight (North Sea), with special reference to the trophic ("food web") interconnections; and (2) the causal analysis of these dynamic processes in laboratory experiments (Hagmeier 1998).

A series of regular measurements and water sampling (on every workday) was started at Helgoland Roads (54°11.3'N, 07°54.0'E; station "Kabeltonne", Figs. 3, 4). Both physico-chemical parameters (temperature, salinity, Secchi-depth, and concentrations of dissolved inorganic nutrients such as phosphate, nitrate, nitrite, ammonium, silicate) and biological parameters (qualitative and quantitative data on phytoplankton, micro-organisms and, since 1974, particular groups of zooplankton) were analysed. Additionally, monthly transect cruises were made along a number of fixed routes in the German Bight, sampling the water column and the sea bottom. In was not until 1976, however, that a large modern laboratory for experimental ecology could be put into service on Helgoland. It provided, and still provides, ample facilities to maintain or culture even sensitive marine organisms, and to conduct mesocosm experiments on the performances and interspecific interactions (trophic, competitive, etc.) of ecologically relevant species (key species).

Fig. 4 Max Gillbricht, one of the initiators and responsible persons of the Helgoland Roads time-series (photograph: BAH archive). The "Kabeltonne", where daily measurements and samplings have been carried out since 1962, was taken out of the water and exposed to view in front of the BAH aquarium in 1990

Fig. 3 Station "Kabeltonne" on Helgoland Roads (54°11.3'N, 07°54.0'E) between the main island of Helgoland (in the background) and the "Düne" (photograph: P. Mangelsdorf)

Initiated by BAH director Otto Kinne, the ongoing series of "European Marine Biology Symposia" (EMBS) started in 1966 on Helgoland. The main topics of the first symposium ("Experimental ecology—its significance as a marine biological tool" and "The food web in the sea") clearly reflected the new BAH research programme.

When the Helgoland Roads data series was started in 1962, its initiators probably had no idea that this enterprise should result in one of the most important marine data sets of the world, unique with respect to the length of the time-series, the sampling frequency and the number of parameters measured. The series has now been running continuously for more than 40 years. In the 1970s and 1980s the time- and money-consuming long-term observations were often considered old-fashioned, became politically inopportune in many countries and had to be interrupted when government funding was withdrawn. Due to the foresight of Max Gillbricht and Wolfgang Hickel, the driving forces behind the Helgoland Roads data series, this series did not suffer the same fate.

The first two decades of sampling coincided with an economical boom period when man's consciousness of, and sensitivity to, the impact of its activities on natural ecosystems was still in its infancy. The data (analysed with the help of the Institut für Meereskunde, Hamburg) revealed the ecological dynamics of the German Bight to be much more complex and variable than originally expected. Nevertheless, the character of the series made it possible to extract a number of steady changes (trends) in ecosystem parameters from the noise of high natural variability. These trends apparently reflected an increasing human influence on shallow, coastal North Sea waters which thus could be studied in this way. The anthropogenic impact was evident, particularly in the form of eutrophication, i.e. in a strong increase in dissolved nutrients (introduced with river runoffs and via the atmosphere) and, although less obvious, probably in quantitative and qualitative changes in the phytoplankton (e.g. Radach and Berg 1986; Gillbricht 1988; Radach and Bohle-Carbonell 1990; Hickel et al. 1992, 1993). Contrary to original expectations, there was no simple causal relationship between phytoplankton stocks and eutrophication. This was also true for the heterotrophic dinoflagellate *Noctiluca scintillans*, a conspicuous component of the plankton in the German Bight, which has been monitored continuously at Helgoland for more than 30 years. The extremely high year-to-year variability has not as yet allowed the extraction of trends (Uhlig and Sahling 1995). During the 1980s, due to a high pelagic loading of particulate and dissolved organic matter, biologically threatening oxygen deficiencies could be recorded repeatedly in the bottom waters around Helgoland (e.g. Hickel et al. 1989). The Helgoland data have also revealed the positive results of legislative measures leading to the reduction of the input of phosphate, nitrate and particulate organic matter into the German Bight: the concentrations of phosphate and nitrate have been decreasing since 1982 and 1991, respectively, and periods of marked oxygen deficiencies in bottom waters have not been recorded in this area for nearly 15 years.

Long-term measurements relating to water pollution in the German Bight, i.e. the accumulation of anthropogenic toxic substances such as heavy metals and halogenated hydrocarbons, have been largely under the jurisdiction of the Deutsches Hydrographisches Institut [DHI; renamed in 1990 to Bundesamt für Seeschiffahrt und Hydrographie (BSH)], and thus were not part of the Helgoland time-series. Rather, research at the BAH concentrated on case studies of the toxic impacts of pollutants on fish, fish larvae and marine invertebrates (e.g. Westernhagen et al. 1979, 1989; Cameron et al.1992; Lange et al. 1998).

Microbiological parameters were a permanent element of the Helgoland Roads data series from the outset. It was only in the 1960s that the importance of microbial functions and loops in the marine pelagic food web were recognized, followed by the development of continually new methods and hypotheses. This is well reflected in the history of the Helgoland bacterial long-term series, with new methods constantly being introduced every few years, partly substituting the older ones (Gerdts et al. 2004). In the 1970s, there was an increasing concern that oil pollution might become a chronic ecological problem in the North Sea. In order to monitor this development, regular measurements of the abundance of oil-degrading bacteria were initiated (Gunkel 1973; Gerdts et al. 2004).

A new focus: climate change, biological globalization, biodiversity

In the 1990s, long-term studies developed a new focus, away from the phenomena of eutrophication and pollution, towards ecological changes in the wake of potential climate changes, as well as the unintended introduction of more and more species by man to areas which had been inaccessible to them before (biological globalization). The long-term records from the Helgoland area offer excellent material to answer questions such as: are the waters of the German Bight really getting warmer? And if so, are there already any substantial warming-related changes in the abundances of species, their seasonal distributions, the species spectrum and finally the basic construction of local food-webs?

Apparently, we are witnessing a period of rising global average temperatures, whatever the exact reason for this phenomenon may be, and this is also reflected in North Sea waters which have become warmer and more marine (i.e. less continentally influenced). Severe winters with the formation of sea ice off Helgoland (Fig. 5) occurred about every 10 years up to the 1940s, but have occurred only once (1963) in the past 60 years. Average water temperature at Helgoland has risen by 1.13°C for the 40 years since 1962, and over the same period of time average salinity has risen by 1.0 PSU (Wiltshire and Manley 2004). A number of biotic changes have been recorded, all potentially related to climate change: A rigorous analysis of the Helgoland phytoplankton series showed that there has been a warming-related shift in the spring diatom bloom over the past 40 years (Wiltshire and Manley 2004). As the phytoplankton succession is the main driving factor for ecosystem seasonality in marine temperate zones, changes in the timing of

Fig. 5 Sea ice formation off Helgoland in the 1920s (photograph: P. Krüß, archive of O. Goemann) and 1963 (photograph: G. Sahling)

phytoplankton blooms will inevitably affect the performances of other members of both the pelagic and benthic food webs.

Long-term research at Helgoland has documented the disappearance of native species. However, over the period of the past 15 years, in the Helgoland area there have also been an increasing number of regular records of species previously absent or only occasionally found. Most of them are oceanic or warm water species which, as potential indicators of a warming trend, seem to be about to extent their range from Atlantic waters into the North Sea (e.g. Greve et al. 1996; Franke et al. 1999; Franke and Gutow 2004). On the other hand, the continued existence of populations which are at their southern distributional limit at Helgoland seems to be threatened. Some species of macroalgae and invertebrates have been introduced intentionally or unintentionally by man and have successfully established themselves as permanent members of the local ecosystem (Bartsch and Tittley 2004; Franke and Gutow 2004). The most recent example is the Pacific oyster (*Crassostrea gigas*), which was first recorded at Helgoland in 2003. At least some of the new non-indigenous species have altered (or are about to alter) local habitats, biodiversity and ecosystem functions. In a warmer North Sea, there would also be an increased risk that toxic flagellates from subtropical or tropical areas could establish themselves as seasonally dominant elements in the pelagic environment.

Prospect

Moderate climate zones are characterized by a high year-to-year variability of ecological parameters. Due to ecological complexity, only long-term observations of ecological phenomena spanning several decades allow the extraction, against the background noise of natural variability, of periodic changes on long timescales as well as the differentiation of true long-term trends. Extreme, episodic events represent another category of ecological phenomena which can be detected and evaluated only by long-term studies. Nevertheless, it is not that long ago that long-term routine observations (monitoring) in ecology met with a rather negative reception as boring, simple in methodology and unscientific. This narrow view shifted in the1990s when global temperature change became accepted as a fact and when it became clear that a warming trend would have profound impacts on ecosystem functions and human life in the near future.

The purpose and significance of long-term routine observations, however, are not limited to mere monitoring of changes relevant to ecosystems. The data from such series represent a basis for modelling ecosystem functions as well as for asking important and meaningful questions on ecological phenomena which can then be analysed experimentally. The accuracy of predictive ecological models and of hypotheses developed from laboratory studies can then, in turn, be tested by data from ongoing ecological time-series. Ecological long-term research has recently become widely recognized as essential for predicting ecological responses to human activities, developing environmental policies and managing resources.

More than 150 years of research in the Helgoland area has produced a treasury of data which represents an excellent basis for analysing past changes (retrospective studies), evaluating the current status of the ecosystem, and predicting future changes in ecosystem parameters. One of the most important problems with long-term series is to ensure the quality and comparability of data collected over long periods of time by a changing staff and with different techniques (see Wiltshire and Dürselen 2004). Nevertheless, the demand for continuity should not exclude the design and establishment of advanced technology, which allows for a more efficient documentation of ongoing changes on relevant temporal and spatial scales. Sensors, buoys and stationary ferry-boxes, which transmit the measured values telemetrically to terrestrial stations (Fig. 6), can perform automatic measurements of nutrients and physical parameters with a much higher frequency than traditional techniques. Furthermore, measuring instruments on ferries and occasional ships, as well as networks of buoys, can produce data sets with a previously unequalled high spatial resolution. Flow cytometry facilitates the study of pelagic samples in the laboratory; methods of remote sensing and the Geographical Information System (GIS) allow for more rapid analyses of the status of benthic ecosystems.

The administrative history of the BAH has been a very complex one; in 1998 the institution finally became part of the Foundation Alfred Wegener Institute for

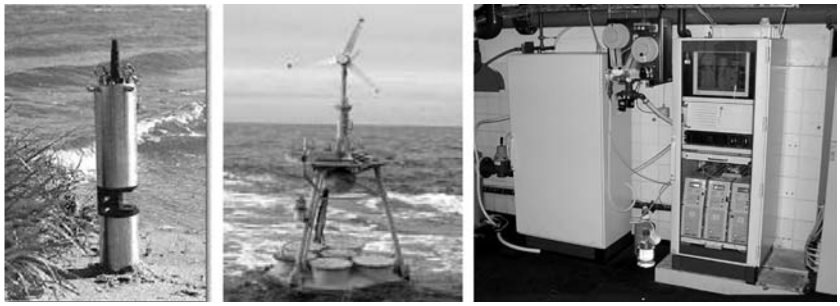

Fig. 6 Automatic measuring techniques to extend the Helgoland Roads long-term series; from *left* to *right*: sensors, buoys and stationary ferrybox unit

Polar and Marine Research (AWI), Bremerhaven, Germany. As specified by the new research programme (Coastal Dynamics and Causes of Change), developed with the cooperation of AWI and the GKSS Forschungszentrum Geesthacht, the documentation of ecological changes at Helgoland will continue to be an integral part of the institute's activities. Long-term research at Helgoland is now closely linked with that performed at other places in the German Bight (e.g. at the island of Sylt) and by other institutions participating in this programme (internal networking). Furthermore, the BAH is well embedded in an external network of institutions performing long-term ecological research. The BAH was a founder member when, in 1996, the European Network of Marine Research Stations (MARS) was established, now with 56 participating stations covering most of Europe's coasts from Svalbard in the north to the Canary Islands, and from the Azores to Israel. Because of its off-shore location, its representative array of habitat types and the advanced state of data availability from long time-series, Helgoland has been chosen as one of the "flagship sites" of long-term concerted research in marine biodiversity, and this provides a good platform for continued and extended long-term monitoring.

Following this introductory paper, the current issue of Helgoland Marine Research (vol. 58, no. 4) presents a series of seven publications summarizing long-term studies at Helgoland on bacteria (Gerdts et al. 2004), phytoplankton (Hoppenrath 2004; Wiltshire and Dürselen 2004; Wiltshire and Manley 2004), zooplankton (Greve et al. 2004), macroalgae communities (Bartsch and Tittley 2004) and the macro-zoobenthos (Franke and Gutow 2004). Additional papers on related topics will appear in irregular succession.

The statement of the first director of the BAH, Friedrich Heincke, is more valid than ever: "Das Meer ist groß, und man kann ihm mit kleinen Mitteln nicht beikommen" (The sea is huge and getting to its roots requires huge efforts). The establishment of large-scale spatial and temporal patterns of change is essential for a proper understanding of ecosystem functions. Future efforts in this field will be distinguished by the application of advanced technology for more efficient observations and measurements on adequate temporal and spatial scales, and by concerted research activities with a high measure of continuity and staying power at a large number of reference sites.

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