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WHITE SEA ECOSYSTEMS

Review Paper

Long-term monitoring studies as a powerful tool in marine ecosystem research

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Abstract Global environmental challenges, such as climatic shifts, ocean acidification, and anthropogenic pressures urgently require detailed knowledge on functioning of the marine biota in order to create realistic models that predict future changes in populations, communities, and ecosystems. The long-term monitoring observations remain one of the best and sometimes the only way of acquiring knowledge on the complex seasonal and multiannual processes taking place in marine realms. This volume focuses on the long-term studies conducted for the past several decades in the White Sea, a relatively small marine basin located in sub-Arctic and Arctic zone in the northwest of Russia. It has a peculiar hydrologic structure: the upper water layers which experience strong seasonal temperature fluctuations and are inhabited by boreal organisms almost do not mix with the deeper waters which have negative temperatures the year round and are occupied by the Arctic species complex. The White Sea has a long-standing history of extensive environmental monitoring spanning all levels of the ecosystem. The goal of this special issue is to present the key findings of these studies to international research community and to identify environmental and biological processes that are involved in the ecosystem change of this important sub-Arctic marine basin.

Keywords Long-term data series · Monitoring · White Sea · Ecosystems · Marine biological stations

Long-term data series and monitoring of marine environment and ecosystems

Marine environments have been continuously changing since the beginning of the Earth. The driving forces, mechanisms, and the rates of these changes varied over time, and currently we are witnessing one of the most rapid environmental changes in the geological record caused (at least partly) by the human activity. Detecting these changes and identifying their rates can only be achieved via series of successive observations and/or comparisons against references. Environmental change can often be recorded with acceptable resolution through indirect proxies such as analyses of structure and composition of ice (Royer et al., 1983) and sediment (Jennings et al., 2001; Field et al., 2006) cores, growth archives of living organisms such as trees, corals, algae, shells of bivalve mollusks (Becker & Kromer, 1993; Corrége, 2006; Hallmann et al., 2008; Giry et al., 2010;

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Halfar et al., 2011; Butler et al., 2012) as well as through direct instrumental measurements. The changes in the functional aspects of populations and communities (such as structure, abundance, species richness, and diversity) generally cannot be resolved from the paleontologic record, especially over the intermediate time frames that are relevant to the current global change, and can only be identified through a series of direct observations—the monitoring. Data series obtained through the monitoring allow to reveal *long-term trends and tendencies* that may reflect climatic changes or anthropogenic influences and to separate these trends from the noise of highly variable natural data affected by regular cycles and/or spontaneous fluctuations. The ecosystem monitoring is also essential for identifying the regular *natural oscillations* due to the normal environmental (e.g., seasonal) changes or biotic shifts such as the predator and prey dynamics, host–parasite interactions, inter- and intraspecific competition, and recruitment fluctuations. In addition, *cycles* of development of natural populations (e.g., mussel beds), irregular (spontaneous) rises and falls of species abundance, *anomalies*, and *rare events* can also be detected only through the monitoring. The long-term data form a basis for understanding of the present state of the ecosystems, as well as the global and local climatic trends, effects of the introduction and expansion of invasive species, and anthropogenic influences such as pollution, eutrophication, and disturbance. Therefore, monitoring studies of marine ecosystems are of fundamental importance especially in the context of the current concerns about the long-term changes in marine ecosystems related to anthropogenic pressures, global climate change, and ocean acidification (Franke et al., 2004; Navarette et al., 2010; Giani et al., 2012). The problems, approaches, and outcomes of long-term monitoring studies in marine realms have been discussed at the recent meetings “The Importance of the Long-Term Monitoring of the Environment” held by Sherkin Island Marine Station (Ireland) on September 14–19, 2003 (Solbé, 2005), the 44th European Marine Biology Symposium held in the University of Liverpool in September 2009 (Marine Ecology, 2011, vol. 32, suppl. 1) and in special reviews (e.g., Ducklow et al., 2009; Katsanevakis et al., 2012).

Carrying out the monitoring studies is a thankless job. It is time and effort consuming and does not provide immediate scientific gratification. Usually, the data produced by the monitoring become valuable only when accumulated over a long period of time (sometimes decades). Duration of monitoring is determined by the biological question and the system under study, but generally, the longer the data series the more valuable it is. Often the initial data cannot be published, and the meaningful publishable results appear only after several years of intensive work. A hypothesis-driven approach can rarely be applied in such long-term studies which often begin with a limited amount of the baseline data on which testable hypotheses can be based. Moreover, the original hypotheses applied when the monitoring was planned, may completely change in the course of the study, and the features that were initially considered marginal may emerge as the dominant and most important drivers in the population, community, and ecosystem dynamics. Often monitorings that last over decades are started by one person or team and are continued by different people, so the ideas and interests change as is a common practice at biological stations. In nature reserves or national parks, the data may routinely be collected by technical staff, students, or volunteers rather than professional scientists, and the scientists’ roles come later, at the stage of the data analysis and interpretation. Therefore, a discovery-oriented approach is typical for the long-term monitoring studies. Biological and environmental monitoring is often carried out at special observatory sites such as marine labs, biological stations, nature reserves, or national parks due to the convenient position and accessibility of material all year round, availability of some basic research funding, and of the permanent expert staff and/or regular workforce including scholars, students, and volunteers. The student involvement also allows to tie in the monitoring with education, which does not require immediate scientific output and peer reviewed publications.

Financial support of the long-term monitoring is a special problem. Due to a significant effort and delayed outcome, such studies are financed reluctantly and should be planned in advance. The prevalent system of scientific funding through short-term (often 2–5 years) grants is not appropriate for the long-term monitoring studies, as it does not provide sufficient time to collect the critical mass of the data or allows for continuity. Obviously, the monitoring needs special long-term funding such as provided by the National Science Foundation Long-Term Ecological Research (LTER) programs in the United States and similar programs (e.g., Baltic Monitoring Program of the Helsinki Commission (HELCOM) in Europe).

While many environmental parameters can nowadays be monitored by automatic buoys, remote stations, satellite sensors, and data loggers, the studies of marine biota (microorganisms, plankton, benthos, parasites, fish, mammals, and birds) remain labor intensive and require work of highly trained experts. Many of the monitoring programs that have been running since mid-twentieth century were stopped in 1970s–1980s due to the reduction of governmental funding (Duarte et al., 1992; Franke et al., 2004). The few lucky survivors encompass the biological studies that last for many decades including (but not limited to) a 150+-years ecosystem monitoring of the local environment and biota around Helgoland Island in the North Sea (Franke et al., 2004; see also a special issue in Helgol Mar Res 2004, vol. 58), the 80+-years-long observations on the plankton in the North Atlantic performed by The Sir Alister Hardy Foundation for Ocean Science (SAHFOS), based in Plymouth, UK (http://www.sahfos.ac.uk), the over 60-years long multidisciplinary observations on the marine environment and resources off the Californian coast (The California Cooperative Fisheries Investigations Program CalCOFI, Ohman & Venrick, 2003), the long-term (>50 years) monitoring of hydrologic and biological parameters in the Baltic Sea (for review see: Feistel et al., 2008), started by Institute for Oceanography (now Leibniz Institute for Baltic Sea Research), Warnemünde and the 55 years-long studies of hydrology and zooplankton communities in the White Sea, NW Russia (Berger et al., 2003) covered in the present special issue (Usov et al., 2013).

The present topical set of papers in Hydrobiologia is dedicated to various biological monitoring studies that have been carried out in the White Sea for the last 50 years. In order to place the findings of the long-term research presented in this issue into the broader environmental context and to facilitate the comparisons with other marine sub-Arctic and Arctic ecosystems, a brief description of the key oceanographic features of the White Sea is provided below.

Short oceanographic description of the White Sea

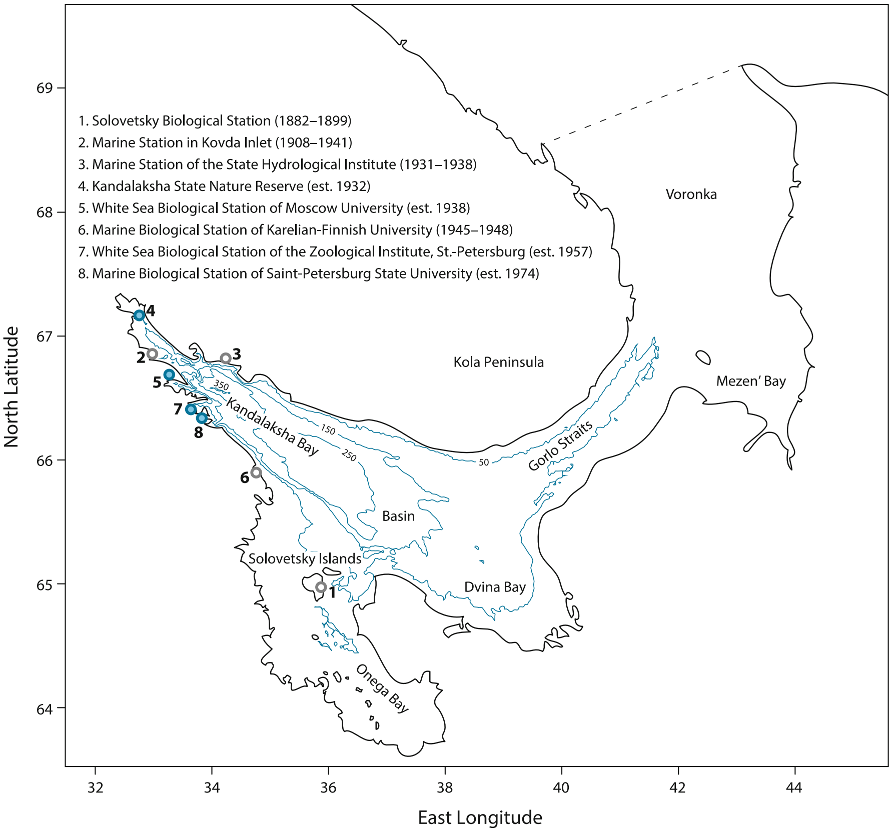
The White Sea is a part of the Arctic Ocean. The geographic boundary between the White Sea and the adjacent Barents Sea passes along the line from the Cape Svyatoy Nos to the Cape Kanin Nos (Fig. 1). The White Sea is subdivided into three large oceanographically distinct parts—Voronka, Gorlo Straits, Basin, and four bays—Kandalaksha, Onega, Dvina, and Mezen' Bays. The sea area is about 90,000 km^2, the volume is 5,400 km^3 (Babkov & Golikov, 1984).

The White Sea is located in the marginal continental depression at the periphery of the Baltic Shield. The relief of the sea has shaped in the Neogene (Koshechkin, 1976) and has complicated topography. The White Sea is quite shallow, with an average depth of 67 m (Babkov & Golikov, 1984). The deepest part is the Basin with the predominant depths of 200–300 m, although the maximal depth (343 m) is found in the Kandalaksha Bay. Mezen', Onega, and Dvina Bays are relatively shallow (with the maximum depths of 20, 60, and 100 m, respectively). Bottom sediments of the White Sea are highly diverse represented by boulder beds, pebble–gravel, sand, aleurite, and pelite components. Sandy fractions predominate in the areas with intensive currents while in the deep and stagnant places, the fluviatile mud is typical.

The main hydrological feature of the White Sea is sharp thermal stratification with the surface waters well heated in summer and the year-round negative temperatures below 60–70 m of depth (Derjugin, 1928; Babkov & Golikov, 1984). Therefore, the White Sea can be viewed as a two-layer basin with a boreal zone in the surface waters and the Arctic zone in the depths. The only exceptions are the regions with active hydrodynamics displaying vertical homothermy, such as Gorlo Straits and Onega Bay.

The average annual temperature for the whole water column varies between −1.2°C in winter and 4.2°C in summer (Filatov et al., 2006). The average temperature of the surface waters in different parts of the sea is 3–4°C. Summer heating raises the surface temperature to 18–19°C in most of the sea area, while in the northern parts, (Voronka) the temperature usually does not exceed 6–8°C. In the areas with intensive turbulence (i.e., in the Gorlo Straits and Onega Bay), a small difference is normally recorded between the surface and bottom temperatures. In the Basin and the bays, where vertical temperature stratification is observed, summer heating along with the wind-induced mixing penetrates to the depths of less than 15–20 m. Below this level, the water temperature drastically drops attaining negative values beneath 60 m. The lowest temperatures (about −1.7°C)

Fig. 1 The map of the White Sea. *Circles* indicate existing (*filled circles*) and former (*open circles*) biological stations. The *dashed line* denoted a formal boundary between the White and the Barents seas



are found in the bottom depressions (Berger, 1995). The warmest months are July and August after which the surface waters slowly cool down. Temperature starts to equalize throughout the water column, and by the middle of winter, homothermy sets in. For about half a year, the sea is covered with ice, although in its central part, the ice fields do not form. The average thickness of ice cover is between 45 and 80 cm (Filatov et al., 2006). The ice cover forms in late November–December and breaks up usually in mid-May (Babkov & Golikov, 1984).

An important hydrological feature of the White Sea is a plentiful runoff of numerous rivers (Severnaya Dvina, Onega, Mezen', Vyg, Kem', Kuloy and many others). Severnaya Dvina accounts for 65% of the total annual terrestrial runoff into the White Sea, which is about 230–240 km^3 (Babkov & Golikov, 1984). Approximately 50% of freshwater runoff comes into the sea during spring flood period (May–June). As a result, the surface water salinity normally does not exceed 24–26 ppt over most of the White Sea, while below 50 m of depth, it increases to 29.5–30 ppt. The horizontal gradient of salinity is even stronger. Salinity increases from the innermost parts of the bays (13–17 ppt) toward the boundary with the Barents Sea (32 ppt). Substantial seasonal fluctuations in salinity are typical for the White Sea. During the period of snow and ice melting, freshwater spreads under the ice making the top 1–2 m of the surface waters almost fresh (Lukanin & Babkov, 1985). This gradient rapidly dissipates due to wind mixing after the ice cover breaks up. In autumn, the surface salinity slowly starts to increase reaching its maximum in winter.

The average velocity of the constant anticyclonic circulation current does not exceed 10–15 cm s^{-1}. More significant are the semi-diurnal tidal currents with the velocities reaching 2.6 m s^{-1} in the Gorlo Straits and 1.0 m s^{-1} in the Onega Bay. Under the influence of tidal currents, the water enters Voronka and Gorlo from the Barents Sea causing significant tidal amplitude (up to 9 m in the innermost part of the Mezen' Bay). In the Basin and other bays, the tidal amplitude decreases to 2–2.5 m (Babkov, 1998).

Water exchange with the Barents Sea also plays an important role in the general water balance of the sea. The full saline and cold Barents Sea waters after passing Gorlo Straits sink to the deep filling the sea basin and supplying the pseudobathyal organisms with oxygen (Timonov, 1947).

The White Sea waters are well aerated. Dissolved oxygen levels vary in the range 6–9 mg O_2 L^{-1} depending on temperature and photosynthesis rates. Oxygen saturation levels are about 95–130% within the photic zone decreasing to 75–80% below 100 m (Sapozhnikov et al., 2012). In isolated and stagnant bights, a reduction of oxygen concentration in water or even anoxic conditions accompanied by hydrogen sulfide formation in sediments may occur.

The average concentration of nitrate, the major nitrogen-containing nutrient in the White Sea, is close to 60 mg m^{-3}. During the spring phytoplankton bloom, the nitrate levels in the photic zone drop to nearly zero (Sapozhnikov et al., 2012). By autumn, the levels of nitrates recover due to recycling processes and inflow from the deeper water layers and the river runoff. The average concentration of phosphates in the White Sea is about 15–20 mg m^{-3}, declining in summer after the phytoplankton bloom and recovering by autumn. Dissolved silica levels in the near bottom waters are 450 mg m^{-3} and do not considerably vary over the whole area of the White Sea. In the surface layers, it varies between 300 and 2,000 mg m^{-3} in different regions of the sea. Dissolved silica concentrations also fluctuate depending on the phytoplankton activity (Maximova, 1991, 2004). The main limiting factor for the primary production in the White Sea is the rapid depletion of nitrates during spring phytoplankton blooms (Fedorov et al., 1995; Ilyash et al., 2003; Sapozhnikov et al., 2012). In summer, dissolved silica and phosphates may be limiting despite their faster regeneration (Sapozhnikov, 1994; Sapozhnikov et al., 2012). Chlorophyll *a*, as a proxy for the photosynthetic activity, shows rather uneven distribution over the White Sea (Bobrov et al., 1995; Sapozhnikov et al., 2012). In the inner parts of the bays and in the anticyclonic circulation in the central area of the sea, chlorophyll *a* concentrations in the photic layer reach 1.5 mg m^{-3}. Somewhat higher chlorophyll *a* levels (up to 3–4 mg m^{-3}) are registered in the surface waters close to the Solovetsky archipelago (Modrasova & Ventzel', 1994; Bobrov et al., 1995). The lowest values of <0.5 mg m^{-3} are recorded in the northern parts of the Basin and in Gorlo Straits.

Flora and fauna of the White Sea are formed by boreal, boreal–arctic, and arctic organisms. The species composition is relatively diverse although somewhat depleted in comparison to that of the adjacent Barents Sea (Derjugin, 1928; Zenkevich, 1963; Berger, 1995, 2012; Berger et al., 2001). The great role in studying the biota of the White Sea has always been played by marine biological stations.

Biological stations at the White Sea

Marine biological stations in Russia have long-standing history. The Zoological Station at the Black Sea was the first European marine biological station opened in 1871 in Sevastopol. On the Pacific coast of Russia, the Marine Station in Avacha Bay at Kamchatka operated for a short period in 1931–1936, and the currently active marine biological station Vostok (that belongs to the Institute of Marine Biology named after A.V. Zhirmunsky of Far East Department of Russian Academy of Sciences) was founded in 1970 in the Vostok Bay of the Sea of Japan. In the Russian North, the Murman Marine Biological Station in the village Dal'nie Zelentsy (Kola Peninsula, Barents Sea) has been operating from 1937 till 1989, when moved to Murmansk. At the White Sea, the biological research has 250 years-long history since the pioneering works by academician Ivan Lepekhin, who has organized and headed multi-disciplinary scientific expedition (1762–1767) on the exploration of the Russian North including the White Sea. However, extensive studies have only started in 1882, when a biological station has been launched by the Saint-Petersburg Naturalist Society on the Solovetsky Island in the Onega Bay of the White Sea (Fig. 1). The Station neighbored the famous Solovetsky Monastery—the Orthodox Christian citadel of the fifteenth century. The prominent biologists of the late 1800s, such as Nikolay Vagner, Christophor Gobi, Herman Klüge, Nikolay Knipovich, Konstantin Merezhkovsky, Konstantin Sent-Iler and many others worked at the Solovetsky Biological Station. The station existed for only 17 years and was closed in 1899 by the request of Synod. Despite its relatively short existence, this station played an extremely important role in establishing zoological research not only at the

White Sea but in Russia in general. The obvious advantages of stationary marine studies compared to the short-term marine expeditions regarding the possibility of seasonal observations and keeping animals in the labs that allowed more detailed morphological and physiological exploring were recognized by the researchers at the Solovetsky Station. After its closing, several stations at the White Sea were founded, such as the Marine Station of Tartu (former Yurjev) University in Kovda Inlet (1908–1941), organized by Konstantin Sent-Iler, the Marine Station of the State Hydrological Institute (1931–1938) launched by Konstantin Derjugin, Marine Biological Station of Karelian-Finnish University (1945–1948) founded and headed by Sergey Gerd in a village Gridino (Fig. 1). In 1932, Kandalaksha State Nature Reserve was organized in the Northern part of the Kandalaksha Bay of the White Sea. It is worthy of note that almost all marine stations were and are located in the Kandalaksha Bay of the White Sea (Fig. 1). Most likely, the reason for this is the convenience of transportation between the stations and major cities, such as Saint-Petersburg, Moscow, Petrozavodsk, and Murmansk. In the early twentieth century, the railroad from St. Petersburg to Murmansk was built and put into operation. This line approaches the shores of the White Sea most closely along the south-western coast of the Kandalaksha Bay. A long time maintaining of biological stations at the coast became possible due to the proximity of the railroad and a highway.

Presently, three marine biological stations operate in the White Sea, all of which are located on the Karelian coast of the Kandalaksha Bay (Fig. 1). The oldest one is the White Sea Biological Station of the Lomonosov Moscow State University. It was organized in 1938 for educational and research purposes and from 1951 till 1987 was led by Nikolay Pertsov who has become the station's namesake in 1995. The Marine Biological Station of the Saint-Petersburg State University has been established in 1974 on the Sredniy Island in the estuary of the river Keret'. Both university stations carry out marine field courses for the students as well as research projects. The third marine station—the White Sea Biological Station "Kartesh" (WSBS) belongs to the Zoological Institute of Russian Academy of Sciences and performs fundamental and applied research of marine biota. It was founded in 1949 and initially based in Petrozavodsk (Southern Karelia), far from the sea. The Station owned two small research vessels, and the studies were carried out only in summer until 1957 when the Station has been moved to the coast of the White Sea near cape Kartesh in the Chupa Inlet (66°20.230′N; 33°38.972′E). This opened a new period in the history of the WSBS and in fundamental research of the White Sea ecosystems. Construction of the living quarters and laboratory buildings, dormitories, workshops, piers and other infrastructure allowed all-the-year-round observations, sampling, and experimentation. Regular seasonal and long-term monitoring studies also became possible. Observations of the marine pelagic and benthic communities in a freezing sea with a 6-months-long ice cover made these studies rare and very valuable among the similar ones. Sampling of the zooplankton and measurements of the temperature and salinity near the WSBS in July 19, 1957 became a starting point for a unique monitoring of the pelagic ecosystem, which continues until this day. Thus, summer 1957 is considered the birthday of the WSBS. Since then, the Station has developed in a modern marine laboratory of international importance. Two research vessels ensure research trips and studies not only in the White Sea but also in the adjacent Barents Sea. The WSBS is also a member of the international networks including the Network of Excellence: Marine Biodiversity and Ecosystem Functioning (MarBEF) and The European Network of Marine Research Institutes and Stations (MARS).

Ongoing biological monitoring studies in the White Sea

The three currently existing marine stations and the Kandalaksha State Nature Reserve perform scientific and educational activities including the monitoring studies of the White Sea environment and biota. It is our great pleasure to introduce this special issue of Hydrobiologia, which presents the results of the long-term studies conducted at the White Sea on the ecosystems, communities, and populations, makes a considerable wealth of unique long-term data series available to international research community and serves to identify some key environmental and biological processes involved in the long-term ecosystem change of this important sub-Arctic marine basin. The findings reported in this special issue reveal a broad range of biological phenomena and processes that can be detected only through the long-term regular studies. Thus, the multiyear monitoring showed that besides the weak trend of long-term warming of the surface (<70 m) waters of the White Sea, the onset of hydrological summer in the upper water layers has shifted about 20 days earlier in the last 50 years. The "cold-water" zooplankton species appeared to be affected by these changes to a greater extent than the "warm-water" ones (Usov et al., 2013). Rare extreme events such as abnormally cold or warm years and/or ice scouring of the soft sediments in the intertidal zone are followed by a relatively fast recovery of the pelagic and benthic communities (Naumov, 2013; Usov et al., 2013). In contrast, it takes years for subtidal benthic communities to recover from the impacts of the organic enrichment from the mussel aquaculture (Ivanov et al., 2013). Similarly, the anthropogenic disturbance of marine birds determines the long-term trends in populations of the parasites that spend part of their life cycles in intertidal communities (Levakin et al., 2013). Many populations and benthic assemblages have shown temporal instability of population structure, abundance, species composition and other key characteristics. This instability is manifested as intrinsic cyclic oscillations or random fluctuations depending on interspecific (Khalaman, 2013; Khaitov, 2013) and intraspecific (Gerasimova & Maximovich, 2013; Khaitov, 2013) interactions, resource depletion (Kozminsky, 2013), sediment changes (Skazina et al., 2013; Yakovis et al., 2013), parasite influence (Granovitch & Maximovich, 2013), or random events (Khalaman, 2013; Marfenin et al., 2013). Important methodological approaches and methods have been developed such as the assessment of the temporal variability of spatial patterns in benthic assemblages (Varfolomeeva & Naumov, 2013) and extraction and validation of the long-term trends in organism's abundance through Singular Spectrum Analysis (Levakin et al., 2013). Also, the *difference of oligomixness* index has been introduced (Naumov, 2013) as a statistical measure of stability of communities. Overall, the research presented in this special issue demonstrates the long-term changes in marine ecosystems and their potential underlying mechanisms that are of general biological importance and may be applicable to other sub-Arctic and Arctic marine environments. Besides that, these studies demonstrate links between the environmental or biotic trends in the ecosystems and can serve to provide the background reference data against which the possible future shifts have to be determined.

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