Polar Biology (2019) 42:1631–1645
https://doi.org/10.1007/s00300-019-02553-w

ORIGINAL PAPER

Pechora Sea ecosystems: current state and future challenges

Alexey Sukhotin[1,2] · Stanislav Denisenko[1] · Kirill Galaktionov[1,2]

Received: 16 June 2019 / Revised: 17 July 2019 / Accepted: 5 August 2019 / Published online: 19 August 2019

Abstract

The south-eastern part of the Barents Sea, conventionally called the Pechora Sea, is among the most peculiar regions of the European Arctic. It is a shallow shelf area that is directly influenced by modified Atlantic and Arctic waters, as well as by freshwater runoff from the Pechora River. Due to its unique environmental features and habitats, the Pechora Sea is regarded as one of the most important areas of the Barents Sea. Rich planktonic and benthic communities, including extensive mussel beds, support large stocks of fish, seals, and walruses, and enormous gatherings of benthos feeding waterfowl. In recent years, economic activities, such as oil and gas production, shipping of crude oil through marine terminals, and ship traffic along the Northern Sea Route, have dramatically increased in the Pechora Sea. These anthropogenic pressures, as well as the observed and predicted natural environmental changes, will most likely affect the sea's pelagic and benthic ecosystems. Therefore, information on the current state of the Pechora Sea ecosystems is urgently needed to provide baseline reference data, against which possible future shifts can be determined. The research presented in this special issue provides such data on the most important elements of the Pechora Sea ecosystems and adjacent areas and demonstrates the interconnection between these ecosystem components and key environmental factors. Considering the already recorded and potential changes in this region, the observed trends and processes in marine biota can be applied to other low Arctic seas and serve for modelling and predictions of future ecosystem shifts.

Keywords Arctic · Pechora Sea · Ecosystems · Pollution · Climate change

Introduction

Pechora Sea is the local name given to the relatively small area in the most south-eastern corner of the Barents Sea, with western boundaries between Kolguev Island and the mainland and between Kolguev Island and Novaya Zemlya (Fig. 1). The Pechora Sea is convenient for considering the complex biological and hydrometeorological processes in that part of the Barents Sea, where its hydrographic regime is determined mostly by the influence of the Pechora River. The approximate inner dimensions of the Pechora Sea are 300×180 km, and its total area is 89,574 km^2 (Potanin and Lagutin 1984). In addition to the large islands Kolguev and Vaygach, the area includes numerous smaller islands and sand bars. The Pechora Sea is regarded as one of the most peculiar regions of the Barents Sea, as it receives almost 80% of all terrestrial inflow to the Barents Sea, is located on the border of the adjacent Kara Sea, and is an important part of the Northern Sea Route.

The Pechora Sea is relatively shallow with predominant depths of less than 50 m and maximum depths of 210 m at its western border. The Pechora Sea has an embayed coastline, with the Pechora Bay and Khaypudyr Bay being the largest. Two straits in the south-eastern part of the sea, the Kara Gate and the Yugorsky Shar, connect it to the adjacent Kara Sea. The width of the Kara Gate is about 50 km, and its maximum depth is 70 m, while the Yugorsky Shar is about 10 km wide and 15–20 m deep.

Unlike other areas of the Barents Sea, no large-scale commercial fishing takes place in the Pechora Sea. The absence of notable economic activity in the past led to the lack of extensive research on the area. Therefore, its marine biota was largely understudied until the end of the 1990s

This article belongs to the special issue on the"Ecology of the Pechora Sea", coordinated by Alexey A. Sukhotin.

✉ Alexey Sukhotin
Alexey.Sukhotin@zin.ru

[1] Zoological Institute of Russian Academy of Sciences, Saint Petersburg, Russia

[2] Saint Petersburg State University, Saint Petersburg, Russia

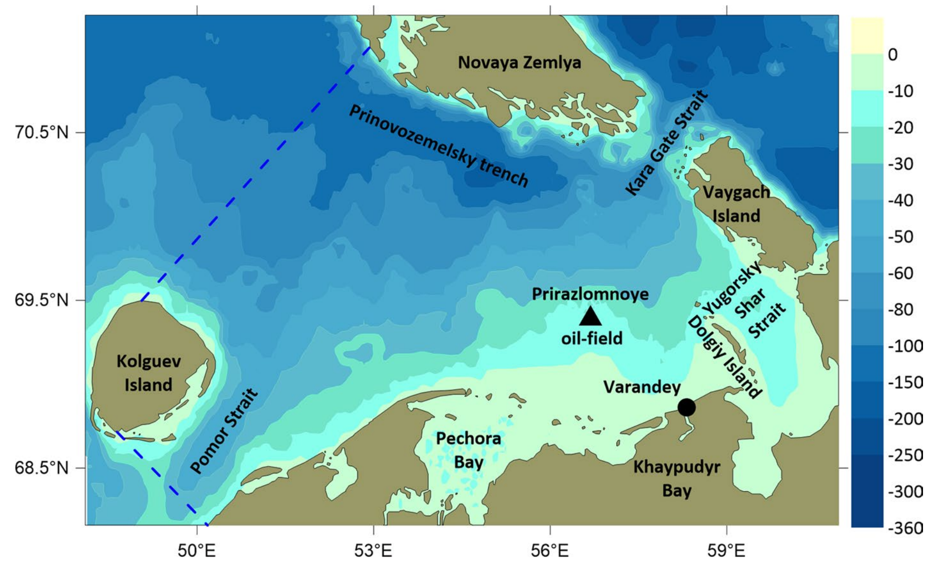

Fig. 1 The boundaries of the Pechora Sea (according to Potanin and Lagutin 1984), its bathymetry (m, colour scale), and main geographical features. (Color figure online)

(Denisenko 2013). Systematic observations were initiated in the 1970s due to the development of a project to transfer the flow of several northern rivers, including the Pechora River, into the Caspian Sea Basin (Matishov and Denisenko 1996). The project caused a wide discussion on ecological consequences and was stopped in 1986, but it triggered a series of oceanographic studies in the Pechora River estuary. Major research activity in the Pechora Sea started in the early 1990s, when offshore oil and gas deposits were explored. The first offshore oil field in the Pechora Sea, Prirazlomnoye field, was prepared for operation; the platform Prirazlomnaya began commercially producing oil in December 2013. Moreover, construction projects for terminals for oil and gas transportation from Western Siberia to Europe started on the Pechora Sea coast. This activity led to a rise in scientific interest in this area and facilitated research on it as well. Extensive study of the area became especially urgent in 1994–1995, following a massive oil spill from an oil pipeline within the Pechora River basin that threatened large-scale pollution of the Barents Sea. This ecological disaster attracted attention from international environmental organisations. Numerous national and international expeditions were organised (e.g. by the Murmansk Marine Biological Institute of Kola Science Center of Russian Academy of Sciences, N.M. Knipovich Polar Research Institute of Marine Fisheries and Oceanography, Zoological Institute of Russian Academy of Sciences, P.P. Shirshov Institute of Oceanology of Russian Academy of Sciences, Arctic and Antarctic Research Institute, and others), and a large body of data was accumulated. In recent years, economic activities, such as oil and gas production, the shipping of crude oil through marine terminals in Varandey and on Kolguev Island, ship traffic along the Northern Sea Route and in the Pechora River, and tourism, have dramatically increased in the Pechora Sea. These anthropogenic factors, as well as observed and predicted natural environmental changes, such as air and water temperature rise, increased precipitation and terrestrial runoff, increased storm event frequency, loss of sea ice and ice-related habitats, and penetration of invasive species, will most likely profoundly affect the pelagic and benthic ecosystems of the Pechora Sea. Therefore, information on the current state of the Pechora Sea ecosystems is urgently needed to provide background reference data, against which possible future shifts can be determined.

An archipelago of small islands, sand bars in the mouth of the Pechora River and the adjacent sea area, belong to the Nenetsky State Nature Reserve. Vaygach Island recently received wildlife sanctuary status, and plans are to establish several additional terrestrial and marine regions (e.g. the southern coasts of Kolguev Island and Khaypudyr Bay) as protected areas (Shavykin and Ilyin 2010; Boltunov et al. 2014). These areas provide habitats for the Pechora Sea population of the Atlantic walrus (Born et al. 1995; Boltunov et al. 2010; Semenova et al. 2019), serve as nesting and feeding grounds for numerous waterfowl, and provide stopovers for birds migrating along the East Atlantic flyway (Anufriev 2006; Krasnov et al. 2006; Nikolaeva et al. 2006). Due to its environmental features and habitats, the Pechora Sea is regarded as one of the most important areas of the Barents Sea (Larsen et al. 2003).

The present special issue of Polar Biology is dedicated to providing a description of the past and current state of important elements of the Pechora Sea ecosystems in relation to environmental conditions. In order to place the research findings presented in this issue into a broader environmental context and to facilitate comparisons with other marine Arctic ecosystems, a brief description of the key oceanographic features of the Pechora Sea is provided first.

Short oceanographic description of the Pechora Sea

In the Pechora Sea, coastal zones with water depths of less than 15 m are formed by well-sorted sands mixed with small pebbles. The more northern areas with depths from 20 to 50 m are occupied by a silty-sandy admixture of pebbles, while sandy muds characterise the central areas with depths from 50 to 120 m. Soft aleuritic and pelitic deposits are typical for the Prinovozemelsky Trench west of the Novaya Zemlya archipelago and for the Pomor Strait between Kolguev Island and the mainland (Klenova 1960).

The major part of the sedimentation material is introduced into the Pechora Sea due to the scouring of glacial ridges and the coastal erosion of ancient glacial deposits. Dispersing of terrigenous and organic material by ice, as well as the removal of fine fractions of bottom sediment rich in organic matter from the Pechora River, also plays an important role in the formation of the sediment structure.

Concentrations of total organic carbon in the sediments of the Pechora Sea range from 0.1 to 2.0% (Loring et al. 1995). The sediments in the Prinovozemelsky Trench are richest in organic matter, because there is practically no erosion of the surface layer (liquid brown silt). In the southern shallow part of the Pechora Sea, where active water movement occurs due to the interaction of constant tidal and wind-driven currents, the sediments are poor in organic matter, with total organic carbon content less than 0.1%.

Ice conditions in the Pechora Sea are more severe than in the western parts of the Barents Sea. Several sites of ice formation appear in the sea in autumn and winter: in the extreme south-east from October to December and in the central part from January to March. Ice melting in the Pechora Sea is also patchy: it is well expressed in June and July, when intense melting takes place in the Pechora and Khaypudyr bays and in the central part of the sea. The ice budget in the Pechora Sea is negative: the volume of inflowing ice from the Kara Sea is about 4.6 km^3 (area 4200 km^2), while the volume of that carried out to the Kara Sea is about 21.4 km^3 (26,700 km^2). Thus, the drift of ice into the Kara Sea indicates the advection of surface water through the Kara Gates strait.

Judging by the velocities and directions of currents, calculated according to the ice drift, water circulation in the Pechora Sea is subject to significant changes. There is a general shift from west to east with average current velocity of 0.05–0.10 m s^{-1}. The Pechora Sea is poorly influenced by the Gulf Stream system, which is the main factor in the formation of water masses in the Barents Sea basin as a whole. Also, the unchanged Atlantic waters barely reach the sea, neither in the surface layer, which is occupied by the desalinated Pechora River runoff waters, nor in the bottom layer, which is too shallow for intermediate Atlantic water masses.

The Pechora Sea is rather shallow; therefore, during the most active interaction between ocean and atmosphere, that is, in the autumn–winter period, the entire water column from surface to bottom is homogeneous. With the onset of spring, the water column begins to stratify, revealing differences in the water masses, the formations of which are associated with the advection of the Kolguevo-Pechorskoye Current, the Pechora River inflow, and the melting of the floating ice cover of the Pechora Sea.

Figure 2 shows the multiyear average isotherms in the water column and near-bottom layer for the ice-free period from July to October. A gradual increase of 10° in surface water temperature is observed from May to August; the temperature declines from September to November. The most striking feature of seasonal temperature change in the Pechora Sea water column is the one-month delay in reaching the summer maximal temperature in the deep.

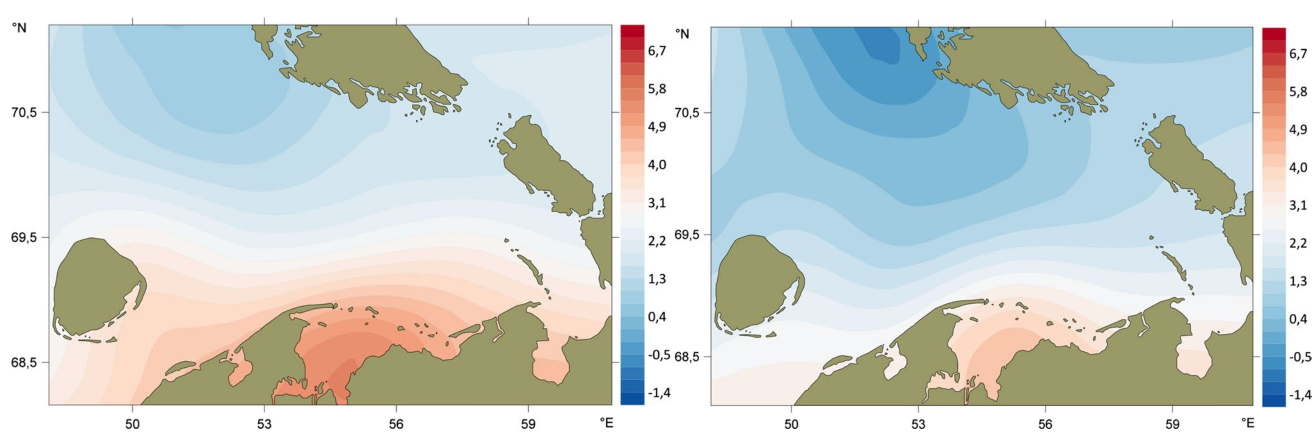

Fig. 2 Multiyear average isotherms in the water column (left) and near-bottom (right) layer (°C, colour scale) during the ice-free period (mapped based on Potanin and Lagutin 1984). (Color figure online)

Our measurements of the sea water temperature at a 3 m depth for 3.5 years (2010–2013) performed using the Onset® HOBO® data logger located in Lyamchina Bay of the Vaygach Island (69°49.82′N, 59°25.58′E) showed that the period of negative temperatures lasts for seven months (from November to May), while the highest temperatures (8–10 °C, on average) are observed in July and August (see Fig. 3). Recordings also show that in four consecutive summers, the maximal temperatures consistently increased, rising from 10.2 °C in 2010 to 16.8 °C in 2013.

Long-term processes in the Pechora Sea, in contrast to those in the western regions of the Barents Sea (the century-old Kola meridian section) (Boitsov et al. 2012; Matishov et al. 2012) have received little attention from researchers. Constant observations were conducted only at meteorological stations. In the whole Barents Sea, the 2000–2009 decade was the warmest in the period 1900–2009, in terms of both air and water temperatures (Boitsov et al. 2012). In the Pechora Sea, the lowest sea surface and bottom temperatures in summer occurring in August–September were recorded in 1982 and 1979, respectively (Antziferov and Guzenko 2002). The highest summer temperatures were observed beginning in 2005 and in the years following (Boitsov et al. 2012; our observations).

The Pechora Sea is unique because it is the only region in the Barents Sea where freshwater plays a major role in the hydrological regime. In other areas, the freshwater budget is supported solely by precipitation and floating ice melt.

Beginning in June of each year, the variation of water characteristics of the Pechora Sea is influenced by two processes: flood runoff and ice melting. The annual discharge of the Pechora River is, on average, 131.4 km^3. The Pechora Bay is shallow, with a 32 km^3 volume. Thus, the annual flow of the Pechora River is four times the volume of the bay. The freshening effect of the Pechora River is amplified by input from numerous smaller rivers and streams. According to the average seasonal and long-term dynamics of the terrestrial runoff, the amount of freshwater entering the Pechora Sea differs within three distinct periods: 2–5.2 km^3 per month December through April; 20–50 km^3 per month May through July; and 7–14 km^3 per month August through November. The effect of freshwater runoff extends to a depth of 20 m, while below 25 m true marine waters are situated. The greatest desalination occurs during the flood period, when waters with a salinity of 26–28 reach the southern tip of Novaya Zemlya.

From November to May, the water column is characterised by homohalinity. From June to October, freshwater inflows from the south into the surface layer simultaneous to the onset of saline water flowing from the north into the bottom layer. High stratification of the water column is typical in this period.

The waters of the Pechora Sea are well aerated from the surface to the bottom. In the lower part of the surface layer, at a depth of 20–30 m, maximal concentrations of dissolved oxygen are observed due to the large supply of nutrient salts utilised by phytoplankton, which comprise the main source of dissolved oxygen in the short spring–summer period of the year. During the rest of the year, the extent of oxygen saturation from the atmosphere depends on the water

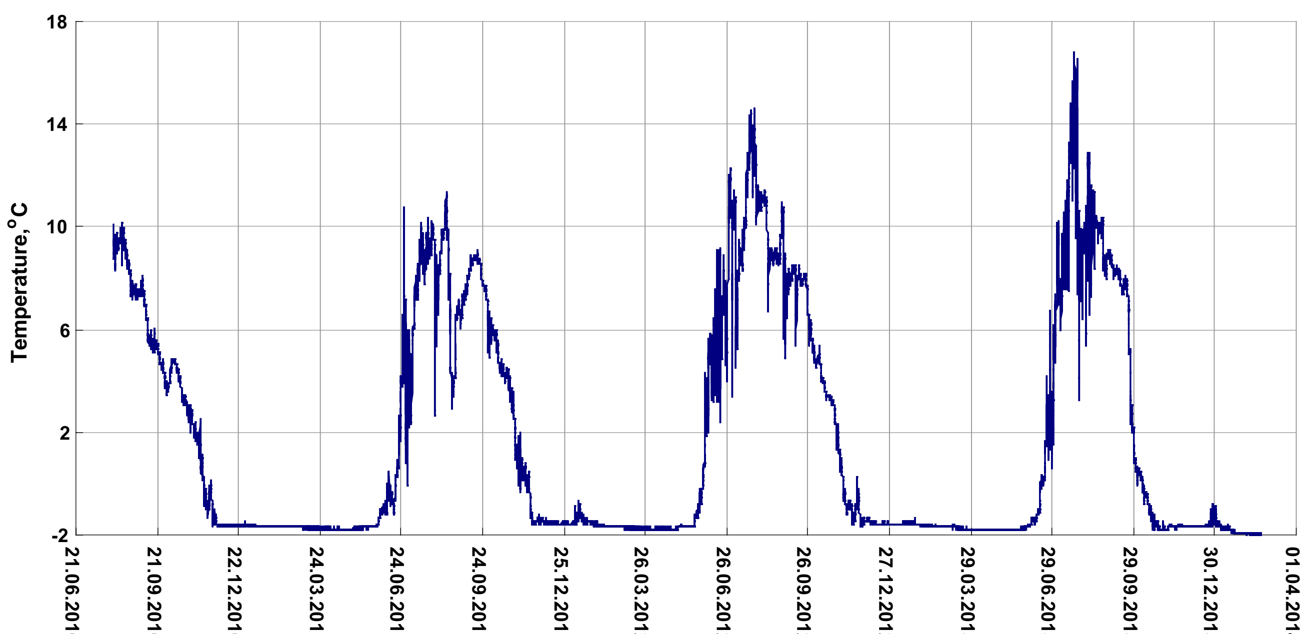

Fig. 3 Temperature recordings at 3 m depth in Lyamchina Bay (Vaygach Island, Pechora Sea)

temperature. Similar to what is found in the Barents Sea as a whole, the deficiency of dissolved oxygen in the waters of the Pechora Sea does not exceed 20%, with the exception of the estuaries, where in the bottom waters the relative oxygen content may drop to 30% due to biochemical decomposition of organic matter.

Vast terrestrial runoff somewhat increases the turbidity of the Pechora Sea waters; total annual suspended matter discharge is 8.5–10^6 tons. Corrected for the volume of the sea, the amount is about 2 g m^{-3}, which is two times more than in the White Sea and 65 times more than in the Barents Sea in general (Shevchenko et al. 2003).

Elements of the Pechora Sea ecosystems

Phytoplankton

Until the 1990s, the Pechora Sea was the least studied area of the Barents Sea with regard to phytoplankton (Vasyutina 1991). Since then, however, several marine expeditions have been carried out in this region, which resulted in various publications on phytoplankton diversity, distribution, seasonal cycle, and primary production in the Pechora Sea (Makarevich 1996; Druzhkov and Makarevich 1999; Pautova 2001, 2003; Makarevich et al. 2014).

The major components of phytoplankton communities are diatoms (117 species, approximately 58% of the total species number) and dinoflagellates (67 species, 34%) (Druzhkov and Makarevich 1999). *Chaetoceros* spp. (28 species) and *Protoperidinium* spp. (26 species) are the most diverse genera. Other groups of plankton algae comprise about 8% of the total species number (Pautova 2003). Among diatoms and dinoflagellates, 40.8% of the species belong to the Arctic-boreal group, 33.1% are cosmopolitan, 17.4% are boreal forms, and the others are of unknown biogeographic affiliation (Druzhkov and Makarevich 1999).

Lag phase in phytoplankton is observed December through February, when communities are represented mostly by mixotrophic and heterotrophic flagellates. Cryophilic algae start to vegetate in March, reaching maximal density of 500,000 cells L^{-1} and biomasses of greater than 2000 µg L^{-1} in April, while chlorophyll *a* concentration reaches 6 µg L^{-1} (Pautova 2003; Vedernikov et al. 2003; Makarevich et al. 2012). Primary production during spring bloom may be as high as 210–420 mgC m^{-3} day^{-1} (Kuznetsov and Druzhkov 1997). Spring bloom ends in June, when the Arctic-boreal species complex is replaced by cosmopolitan diatoms. In summer, after consuming nutrients, algal density may decline to 200,000–300,000 cells L^{-1} and biomass to 200 µg L^{-1}; at this time of year it is dominated by picoplankton and diatoms (mainly by species of the genera *Nitzschia* and *Skeletonema*) and by large dinoflagellates. In summer, phytoplankton mostly accumulate in the upper 30 m water layer with maximal abundances close to the surface and to the pycnocline. Primary production during the summer in most parts of the Pechora Sea falls to 5–90 mgC m^{-3} day^{-1}, while in the Pechora Bay, where nutrients are constantly delivered by the Pechora River, production of algal communities may persist at the higher level (Vedernikov et al. 2003). Autumn starts in October, when phytoplankton biomass declines to 2–50 µg L^{-1} with a correspondent drop in primary production.

Zooplankton

The first extensive studies of zooplankton in the Pechora Sea were undertaken in the late 1950s (Zelikman 1961, 1966), when 72 holoplanktonic species were identified. Later expeditions found 33–57 taxa of zooplankton, including larvae of the benthic species (Timofeev and Shirokolobova 1996; Musaeva and Suntsov 2001; Usov et al. 2019).

Zooplankton communities in the Pechora Sea are relatively diverse, containing oceanic and neritic species in similar proportions (Musaeva and Suntsov 2001). During the ice-free period, average biomass varies between 30 and 300 mg m^{-3}, reaching values of greater than 500 mg m^{-3} (Timofeev and Shirokolobova 1996; Troshkov and Gnetneva 2000). Copepods dominate zooplankton in summer and autumn, while in some months Hydrozoa and larvae of bottom animals are observed in high densities, accounting for up to 50% of total zooplankton abundance (Musaeva and Suntsov 2003; Usov et al. 2019).

Benthos

In general, the Pechora Sea is characterised by poorly developed littoral and sublittoral vegetation due to two factors: (1) the predominance of mobile bottom sediments, and (2) long-term ice cover and its destructive effect on coastal communities during melting and ice formation. Greater diversity is observed in the areas adjacent to the straits between the Barents and Kara seas.

According to available data (Malavenda et al. 2017), the bottom macroalgae of the Pechora Sea are represented by 64 species: 9 Chlorophyta, 18 Phaeophyta, and 37 Rhodophyta. Marine vegetation is formed mainly by brown and red algae, and the communities are dominated by perennial forms, although green algae are rare.

In the southern part of the Pechora Sea, algal communities, predominantly red algae *Ptilota gunneri* and noted bushes of *Chorda filum* and *Chaetopteris plumosa,* are formed on silt-sandy sediments with an admixture of shell sand poor in species. Fucouids and laminarians are absent (Metelskiy 2014).

The seaweed *Fucus vesiculosus* forms belts on hard bottoms from the lower littoral horizon to a depth of 3–5 m, although they are very sparse. At a depth of 3–5 to 10–15 m, belts of *Saccharina latissima* and *Laminaria digitata* are observed, which sometimes form fairly dense thickets. Deeper down, they are replaced by red algae, dominated by *Phyllophora interrupta*, *Odonthalia dentata*, *Phycodris rubens,* and *Ptilota plumosa*, which extend to a depth of about 20 m. In general, this vertical zonation is typical for the high boreal areas of the North Atlantic.

The first quantitative data on zoobenthos of the south-eastern Barents Sea were obtained in the 1924–1926 R/V *Persey* expedition (Zenkevich 1927; Brotskaya and Zenkevich 1939; Filatova 1957). In 1958–1959, the Murmansk Marine Biological Institute organised the second benthic survey to the Pechora Sea; however, only data on species composition and quantitative representation of some systematic groups of benthos were published (Galkin 1964; Khodkina 1964; Streltsov 1966). In 1970, the Polar Research Institute for Fisheries and Oceanography (PINRO, Murmansk) performed a third survey in the Pechora Sea, the results of which were published several years later (Antipova 1973). This publication presents information on the distribution of zoobenthos and structure of benthic communities. The most complete dataset on the structural and spatial organisation of zoobenthos in the Pechora Sea was obtained during a benthic survey carried out 1991 through 1995 by the Murmansk Marine Biological Institute in cooperation with the Marine Arctic Geological Expedition (Murmansk, Russia), Akvaplan-niva (Tromsø, Norway), and Finnish Institute of Marine Research (Helsinki, Finland) (Denisenko et al. 2003).

Within the macrozoobenthos sampled during several cruises from 1991 to 1995, a total of 712 taxa were recorded, 505 of which were identified to species level, comprising about 24% of the total number of species encountered in the whole Barents Sea (Sirenko 2001). Polychaetes were represented by 176 taxa (127 identified to species level), molluscs by 139 taxa (101 to species level), crustaceans by 157 taxa (129 to species level), bryozoans by 83 taxa (71 to species level), echinoderms by 27 taxa (22 to species level), and cnidarians by 40 taxa (29 to species level). The remaining systematic groups, such as foraminifera, sponges, nematodes, sipunculids, and tunicates, were identified mostly to species level but tentatively.

The number of taxa of zoobenthos at each station correlated closely with the sediment type and bottom relief. The lowest number (15–18 taxa) was observed in the deepest part of the Prinovozemelsky Trench at the depth of 189–210 m on fine sediments with a high water content. In the shallow areas of the central and southern parts of the Pechora Sea with sandy bottoms, the number of taxa was comparatively high (50–65). Near the Pechora Bay mouth in the zones with a strong influence of freshwater, the number of species drastically decreased (20).

The abundance of total macrofauna varied between 384 and 6732 ind. m^{-2}. The highest values were recorded in the south-eastern Pechora Sea at the depth interval of 25–50 m, on sand and partly clay sediments (Denisenko 2006). Areas with a relatively low abundance were found just outside the Pechora Bay (with depths less than 20 m), in the central areas close to Novaya Zemlya, between Kolguev Island and the mainland, on erosion bottoms with sandy and partly sandy-mud sediments, and in areas characterised by high current velocities. In almost all cases, zoobenthos abundance was dominated by polychaetes.

Total biomass varied between 1.5 and 536 g m^{-2} (Denisenko 2006). Particularly high biomass values were recorded in the north-western part at depths of approximately 100 m (greater than 500 g wet wt m^{-2}) and in the south-western part (greater than 400 g wet wt m^{-2}). On shallow sandy erosion bottoms close to the Pechora Bay, biomasses were very low. Benthic biomass was overwhelmingly dominated by molluscs, with polychaetes as the second largest group. The highest biomass of molluscs was recorded in the north-western part between Kolguev Island and Novaya Zemlya (Denisenko 2006).

Among bivalve molluscs, *Astarte borealis*, *Ciliatocardium ciliatum*, *Serripes groenlandicus*, *Macoma calcarea*, *Astarte montagui*, and some others dominate by biomass. The contribution of gastropod molluscs is comparatively low, with the highest biomass found north east of Kolguev Island and in the north-western area.

The biomass of polychaetes is considerably low compared to that of molluscs. The highest concentration of worms was found in the Novaya Zemlya Depression, where they dominated in local biomass. Polychaetes also formed high biomass in the north-western area, with *Spiochaetopterus typicus*, *Maldane sarsi*, *Nothria hyperborea,* and *Myriochele oculata* being the most abundant species.

In the north-western part of the sea and also close to the Kara Gate region, echinoderms form a significant fraction of benthic biomass (Denisenko 2006). A similar biomass distribution pattern recorded for echinoderms is also seen in crustaceans, although the latter are less abundant. In the low-biomass southern part of the area, bryozoan populations play an important role in benthic communities.

In terms of feeding mode, zoobenthos in the Pechora Sea is dominated by filter feeders, mainly represented by bivalve molluscs of the families Astartidae, Cardiidae, and Myidae, and other groups, such as bryozoans and tunicates. On mixed sediments with hard material, mobile and immobile filter feeders (e.g. *Ciliatocardium ciliatum*, *Serripes groenlandicus*, *Pelonaia corrugata*, and *Alcyonidum disciforme*) are the main species. The role of detritivorous species is also significant, but less than that of filter feeders, both in quantitative representation and in occupied bottom area. Detrivores (e.g. *Spiochaetopterus typicus*, *Ctenodiscus crispatus*, *Macoma calcarea*, and *Maldane sarsi*) dominate in areas where intensive accumulation of organic material occurs.

Fishes

A wide range of environmental conditions and pronounced ecological gradients in mouth areas of Arctic rivers, including those in the Pechora Sea, allow different species and age groups of fish to find optimal habitats for feeding. This makes Arctic estuaries a home for a unique ichthyocomplex that includes freshwater, marine, and anadromous species. The Salmonidae family is among the most diverse groups in the Pechora Sea ichthyofauna, represented by 10 species (Karamushko et al. 1996; Semushin et al. 2019). Some of these species, such as Atlantic salmon (*Salmo salar*), Arctic char (*Salvelinus alpinus*), and Pink salmon (*Oncorhynchus gorbuscha*), are long-distance migrants, breeding in the rivers of the Pechora Sea (mainly in the Pechora River) and spending a major part of their life cycle in the adjacent marine basins. Pink salmon has been repeatedly introduced into the White and Barents seas from the Pacific since the late 1950s and currently forms stable populations in the rivers of the Barents and White seas (Chernitskiy 1995). Atlantic salmon, one of the most important fishery species in the region, was intensively harvested throughout the twentieth century, which caused a significant reduction in this fish population by the beginning of the millennium (Martynov 2007). In the 1920s and 1940s, the average annual total catch of Atlantic salmon in the Pechora River stabilised at about 300 tons, which enabled maintenance of the optimal level of harvestable stock. In the 1950s, the average annual catch over the decade increased to 500 tons, which was promoted by the introduction of improved fishing gear and an increase in the size of fishing grounds. This apparently undermined the Pechora population of Atlantic salmon (Martynov 2007). The optimal average annual number of spawning migrants of the Pechora salmon was estimated to have been 100,000 fish from the 1950s through the 1980s (Martynov 2007). The current population size in the Pechora basin is at least an order of a magnitude lower than the optimal level.

The estuarine complex of semi-anadromous fish of the Pechora Sea is formed mainly by representatives of the Coregoninae subfamily, such as sardine cisco (*Coregonus sardinella*), whitefish (*C. lavaretus* sensu lato), muksun (*C. muksun*), Arctic cisco (*C. autumnalis*), and nelma (*Stenodus nelma*) (Novoselov et al. 2012; Boltunov et al. 2014). The populations of these commercially important species have declined dramatically since the 1980s (Novoselov et al. 2012).

The Pechora Sea is characterised by significant ice cover in the winter–spring period and, unlike the western areas of the Barents Sea, is less affected by the warm North Atlantic Current. Accordingly, Arctic and Arctic-boreal species play the greatest role (about 40% of all species) in the Pechora Sea fish communities (Karamushko et al. 1996; Semushin et al. 2019). The most numerous and commercially important are navaga (*Eleginus nawaga*), Polar cod (*Boreogadus saida*), and Pacific herring (*Clupea pallassi*). Polar cod is a pelagic cold-water species, typical for areas with a stable, seasonal ice cover. Usually it inhabits waters with relatively low salinity (from 25–30 to 10–15 and lower) and negative or close to zero temperatures (Karamushko et al. 1996). In the Pechora Sea, Polar cod form dense shoals and spawn from late December to late March, with a peak in January–February in coastal areas from the Kanin Peninsula to Vaygach Island. They feed mostly on common zooplankton and phytoplankton species and, to a lesser degree, on small bottom crustaceans, fish eggs, shrimps, and fish fry. Being the main consumer of plankton and serving as food objects for many fish, marine birds, and mammals, Polar cod play an extremely important role in the Pechora Sea food chain (Borkin 2012). Navaga are widespread throughout the entire Pechora Sea coast and are present in commercial quantities near Kolguev Island and in the Pechora Bay. Navaga live in shallow depths, prefer low temperatures, and form large accumulations; navaga spawn in December and January under ice at depths of about 10 m in places with a strong current and stony or sandy sediment. Navaga has been a typical species for the Pechora Sea coastal fishery since the 1930s. Winter-spawning navaga, Arctic flounder (*Liopsetta glacialis*), and Pacific rainbow smelt (*Osmerus mordax*) are objects for traditional winter fishing in coastal areas (Kobelev 2001). Every October to March, in different parts of the Pechora Sea coast from the Kanin Peninsula to the Yugorsky Peninsula, up to 500 local fishers are engaged in fishing. From 1965 to 2000, the average annual catch of navaga was 1470 tons, in contrast with the average of 130 tons of Arctic flounder and 60 tons of Pacific rainbow smelt (Kobelev 2001).

Mammals

Specific conditions of the Pechora Sea formed a special fauna of marine mammals, the composition and diversity of which differ significantly in the warm and cold seasons. In the waters and coasts of the Pechora Sea, 15–19 species of marine mammals can be observed in different seasons (Kondakov 1996; Larsen et al. 2003). Some species, such as the White (Beluga) whale *Delphinapterus leucas*, the Atlantic walrus *Odobenus rosmarus rosmarus*, the Bearded *Erignathus barbatus*, Ringed *Phoca hispida,* and Harp *Pagophilus groenlandicus* seal, and the Polar bear *Ursus maritimus*, permanently inhabit the Pechora Sea, while others (most of which are cetaceans, such as the Minke whale *Balaenoptera* *acutorostrata*, the Sei whale *B. borealis*, the Killer whale *Orcinus orca*, and the Harbour porpoise *Phocoena phocoena*) spend only part of the annual cycle there. Most of these species are listed in the Red Data Book of Russia and International Union for Conservation of Nature (IUCN) Red List of endangered species (Karpovich et al. 1984).

The White whale *Delphinapterus leucas*, the most common cetacean species in the Pechora Sea, are frequently observed near Kolguev and Vaygach islands, along the mainland coastline, and off the west coast of Novaya Zemlya. It is generally believed that White whales are more numerous and occur in relatively equal numbers in the Pechora Sea in the summer and autumn, while in the period of ice cover they are less abundant (Matishov and Ognetov 2006; Kovacs et al. 2009). According to another opinion (Kondakov 1996), the Barents Sea serves as a wintering area not only for the local population of *Delphinapterus leucas*, but also for those inhabiting the adjacent White and Kara seas. In summer, most of them migrate to the Kara and White seas and to the ice edge in the north. White whales feed mostly on fish (Arctic cod, herring, capelin, navaga, and Arctic char) and crustaceans. Although White whales were regularly harvested in the twentieth century and are still considered a commercial species, it is unknown if they are hunted in the Pechora Sea. Unregistered random harvesting of single individuals for the needs of the local population may occur (Boltunov et al. 2014).

Among pinnipeds, the Ringed seal *Phoca hispida* comprises the largest population of year-round residents in the Pechora Sea. This species is relatively sedentary and does not undertake distant migrations, but makes local migrations depending on food availability and ice regime in the winter period. Winter distribution coincides with the boundaries of the ice cover. The seals live at this time both on land-ice and on drifting ice. The Pechora Sea is considered the main breeding area of the Ringed seal in the Barents Sea (Kondakov 1996; Boltunov et al. 2014). The breeding season of this species extends from the end of winter until late spring. Most of the seals in the coastal areas of the Pechora Sea are whelping from mid- or late-March to mid-April, and sometimes later (Kondakov 1996). The absence of significant tidal fluctuations in sea level in the area creates favourable conditions for the successful reproduction of the seals on fast ice. In recent decades, the area and thickness of the fast ice in the Pechora Sea have significantly decreased in comparison to the average multiyear data (Boltunov et al. 2014; for the Barents Sea see Laidre et al. 2015), which creates a potential threat of breeding habitat reduction or loss for this species. In summer with ice melt, the Ringed seals distribute along the coastline, mainly in a 10-km wide zone from the shores, concentrating in small bays and estuaries (Boltunov et al. 2014). The Ringed seal is a commercial species, and the annual allowable catch for the south-eastern part of the Barents Sea is 500 individuals (Boltunov et al. 2014). Despite the significant stock of these seals, the only hunting conducted is by the local population for dog food.

The Atlantic walrus *Odobenus rosmarus rosmarus* is currently one of the most intensively studied marine mammals in the Pechora Sea. Until the 1820s, walruses were one of the main target species hunted in the area. Unregulated and unscrupulous harvesting raised a concern about the very existence of this subspecies in the Russian Arctic. Intensive ship harvesting of walruses was conducted in the western part of the Kara Sea and in the Barents Sea near Novaya Zemlya from 1929 to 1935 and was then stopped due to unprofitability. The permanent ban on walrus hunting in the Pechora Sea was introduced only in 1956 (Kondakov 1996). Currently, this species is highly protected: it is listed in the Red Data Book of the Russian Federation and considered Near Threatened by IUCN. Until the end of the twentieth century, walrus stock in the Pechora Sea was estimated at several hundred individuals (Kondakov 1996), but since the beginning of the 2000s, a significant increase in population abundance and restoration of coastal haul-outs has been observed (Semenova et al. 2015; Anufriev et al. 2017). Recent aerial surveys documented a population of approximately 4000 individuals in the ice-free period (Chernook et al. 2012). Until the 2010s, scientific data on the ecological features, behaviours, and population structure of walruses in the Pechora Sea were virtually absent. In 2009, the Council for Marine Mammals and World Wildlife Fund established an expert advisory group on the conservation and study of the walrus of the south-eastern Barents Sea and adjacent waters. In the last decade, considerable efforts have been made to study this species, including aerial surveys and photography, satellite monitoring, satellite tracking, and DNA sampling, for example. The result of these efforts was a number of monographs, brochures, and journal papers, such as Semenova et al. (2015, 2019), Anufriev et al. (2017), and Boltunov et al. (2019).

Birds

The Pechora Sea is particularly important for waterfowl. Hundreds of thousands of sea ducks nesting in the coastal tundra between the Kanin Peninsula and Central Taimyr molt and stop here during migrations along the East Atlantic flyway to wintering sites in the White, Baltic, North, and Norwegian seas and the western regions of the Barents Sea (Anker-Nilssen et al. 2001; Krasnov et al. 2002, 2004). In the 1990s, ornithological surveys of the coastal areas of the south-eastern Barents Sea identified the largest non-breeding flocks of sea ducks in northern Europe. They consisted of mostly two species, the King Eider (*Somateria spectabilis*) and Common Scoter (*Melanitta nigra*), which create large gatherings in shallow waters (Krasnov et al.

2002, 2019). During autumn migrations, other species, such as the Long-tailed Duck (*Clangula hyemalis*), Velvet Scoter (*Melanitta fusca*), and Steller's Eider (*Polysticta stelleri*), stay there, although in smaller numbers. Calculations based on aerial surveys showed that, at the beginning of October in the south-eastern Pechora Sea, from 0.6 to 4.5 million individuals could simultaneously be present (Krasnov and Shavykin 2005). The Common Eider (*Somateria mollissima*) nests in the narrow coastal zone of the Pechora Sea, as do geese (*Anser fabalis, Anser albifrons,* and *Branta leucopsis*) and swans (*Cygnus bewickii* and *Cygnus cygnus*), which are especially numerous at Novaya Zemlya and Vaygach Island (Krasnov et al. 2002; Anufriev and Punantsev 2019).

The attractiveness of the Pechora Sea for waterfowl is associated with a relatively high biomass of benthic invertebrates, the major food for sea ducks, and their availability due to the shallowness of the area. The diet of birds includes gastropod and bivalve molluscs and polychaetes. However, blue mussels *Mytilus edulis* play a special role. In some coastal areas along Vaygach, Kolguev, and Dolgiy islands, in the Yugorsky Shar straits, and in the Khaypudyr Bay, these molluscs form settlements characterised by a relatively high aggregation (Sukhotin et al. 2008; Denisenko et al. 2019b). In 2007, mussel biomass in aggregations reached 4 kg m^{-2} (Sukhotin et al. 2008); they are more readily available than single benthic organisms for ducks. This explains the predominance of mussels in the Eider's diet (Gavrilo and Strøm 2005; Krasnov et al. 2009, 2014).

In the Pechora Sea, mussels are characterised by slow growth (Sukhotin et al. 2007); successful recruitment does not occur every year (Sukhotin et al. 2008). Their populations on sandy and pebbly bottoms common to this sea are strongly influenced by environmental factors. In recent decades, wind activity has increased due to warming and general climate changes in the Pechora Sea area (Semushin et al. 2019). This factor, and, possibly, activity of the Atlantic walrus, the number of which has increased (Semenova et al. 2019), have resulted in the redistribution of bottom sediments that caused a decrease in the biomass of benthic filter feeders, including mussels (Denisenko et al. 2019b). Storm activity can also affect mussel populations directly. Indeed, their sharp degradation in the area near Dolgiy Island occurred as a result of summer storms in 2010 (our observations). Mussels were cast ashore, where their shells were lying in heaps in a storm belt. This undermined the forage base of King Eiders and led to the redistribution of their flocks in the Pechora Sea. In 2016 and 2017, these birds were recorded at the mouth of Khaypudyr Bay and were not observed in the places of their usual large gatherings near the Dolgiy Island, where mussel populations are just beginning to recover (Denisenko et al. 2019b; Krasnov et al. 2019; KG & SD, personal observations).

Parasites

High local concentrations of waterfowl in the shallow waters and coastal areas of the Pechora Sea create favourable conditions for the transmission of parasites, for which birds serve as final hosts, while marine invertebrates and fish serve as intermediate hosts. Large-scale parasitological studies in the Pechora Sea were undertaken in the 1980s by the Murmansk Marine Biological Institute (Galaktionov 1986; Galaktionov and Marasaev 1986). Large sites of infection of benthic mollusks by larvae of trematodes of waterfowl were identified in shallow waters and coastal areas of the islands in the course of these surveys. Reported levels of infection of molluscs exceeded those known for the rest of the Barents and White seas (Galaktionov and Marasaev 1990). Comparison of these data with the aerial surveys of waterfowl (Krasnov et al. 2002, 2004) showed a clear confinement of the sites of infection of molluscs to the gatherings of birds (Galaktionov 2016) (Fig. 4).

The edge of the distribution range of some boreal-Arctic species of invertebrates and fish (Atlantic cod *Gadus morhua*, three-spined stickleback *Gasterosteus aculeatus*, and blue mussels *Mytilus edulis*) lies in the Pechora Sea. From the parasitological point of view, of particular interest is the subtropical-boreal littoral mollusc *Littorina saxatilis*, the marginal populations of which are confined to the western coast of the Dolgiy, Vaygach, and Novaya Zemlya islands. In boreal waters, 26 species of trematodes are associated through their life cycles with this mollusc, using it as the first intermediate host (Galaktionov 2017). In the Pechora Sea populations, this number is reduced to six.

Warming of the Arctic in recent years, distinctly pronounced in the Pechora Sea (e.g. Semushin et al. 2019), cannot but affect the composition of the parasite fauna and their transmission (Hoberg et al. 2013; Galaktionov 2017). Prolongation of the warm season favourable for transmission (i.e. expanding the seasonal "transmission window") can lead to an increase in the infection of host animals. Penetration of boreal invertebrates and fish into the Arctic makes possible the transmission of parasites typical to temperate seas. Expansion to the north of the ranges of a number of birds, which has already been observed (Ganter et al. 2013), will lead to the concomitant introduction of their parasites, some of which could find favourable conditions in the transformed arctic ecosystems. The change in birds' migration routes in the Arctic and the expansion of intermediate host invertebrates in coastal Siberian seas can contribute to the transArctic parasite fauna exchange between the North Atlantic and North Pacific.

These are only the most obvious of possible consequences. Monitoring studies are required to detect changes in the parasitological situation, and the Pechora Sea seems to be a convenient testing ground for their implementation.

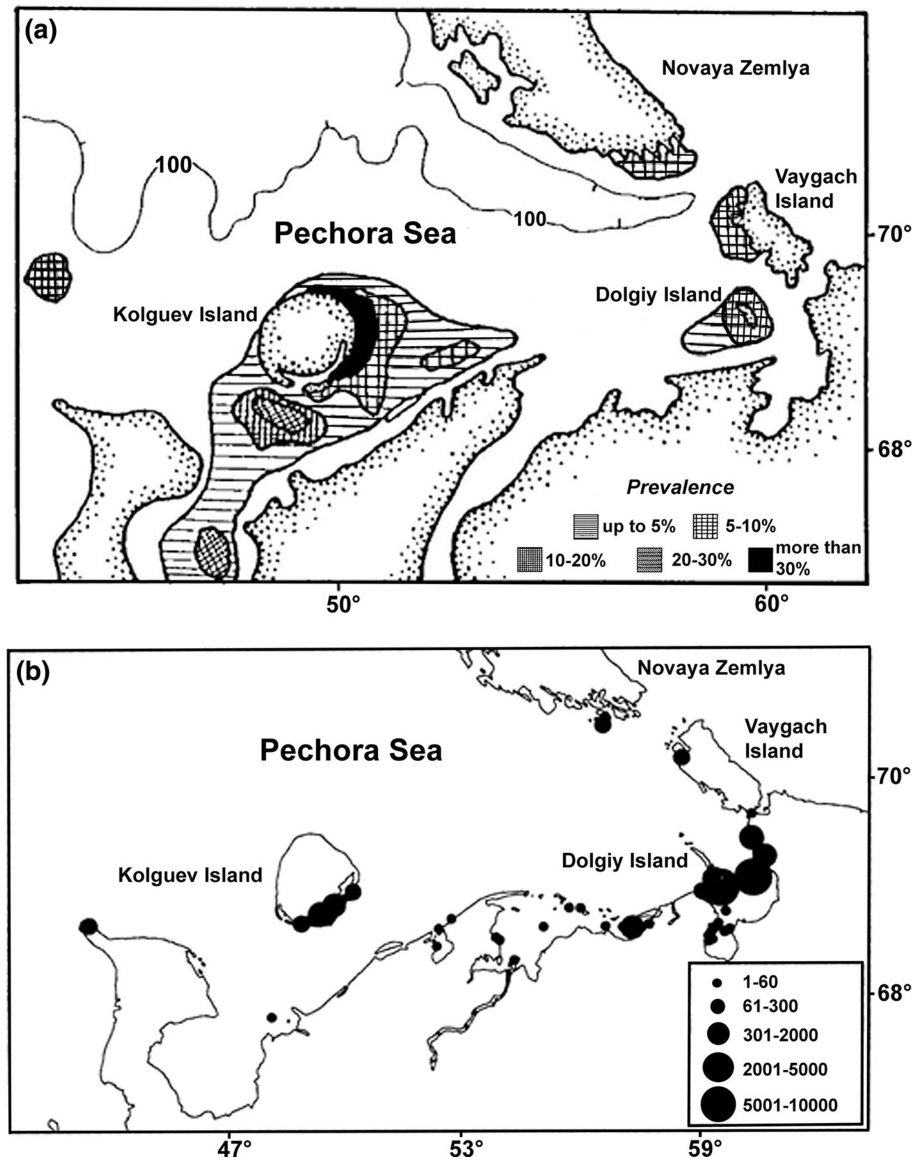

Fig. 4 Distribution patterns of **a** the prevalence by trematode larvae in benthic molluscs of the Pechora Sea according to surveys in 1983–1985 (Galaktionov 1996) and **b** the abundance of ducks in the same regions, according to aerial observations in August 1998 (Krasnov et al. 2002) (modified from Galaktionov 2016)

This is determined by the boundary position of the Pechora Sea between the European and Siberian Arctic seas and the favourable conditions for the transmission of parasites as noted. Therefore, the Pechora Sea region is the first place where one can expect parasitological manifestations of a changing climate.

Anthropogenic pollution

Anthropogenic pollution is one of the major threats expected to the Pechora Sea. The main potential sources of contamination are long-distance atmospheric and water transfer, including the Pechora River outflow, offshore oil and gas production, and marine transport (shipping, tourist, and military vessels), nuclear waste disposal, possible wreck of nuclear powered vessels, and nuclear experiments.

Nevertheless, to date, the Pechora Sea is still characterised by low anthropogenic impact and has negligible background contamination, which was recorded only at a local level (Mitskevich and Telitsina 2002; Samokhina 2009; Novikov and Draganov 2018).

Pollution containing petroleum hydrocarbons, organochlorine pesticides, synthetic surfactants, and phenols is considered the most dangerous for marine ecosystems (AMAP 2017). The content of organochlorine pesticides, synthetic surfactants, and phenols in the waters of the Pechora Sea is relatively small (Yearbook 1988–1993; Dauvalter 2002). The average concentration of organochlorine pesticides remains almost constant at about 1 ng L^{-1}, while the maximal concentration varies in different years from 1 to 2 ng

L^{-1}. The content of surfactants is between 0 and 0.08 mg L^{-1}, i.e. significantly lower than the permissible level of pollution. The concentration of phenols remains, on average, about 0.001 mg L^{-1}, which is within the maximum allowable for fishery reservoirs. Persistent organic pollutants accumulate in the species at higher levels of marine trophic chains (Boltunov et al. 2019).

Oil derivatives, including polycyclic aromatic hydrocarbons (PAHs), represent a significant threat to the Pechora Sea ecosystems, as oil and gas condensate production and transport have developed rapidly in the area, leading to an increased probability of spills. The number of hydrocarbons in the sediments of the Pechora Sea is currently below the background for the Barents Sea (Romankevich et al. 1982), varying within the very narrow limits of 0.002–0.003% (Loring et al. 1995; Danilov et al. 2004). It has been shown that the geochemical background of organic matter in the Pechora Sea sediments corresponds to the general patterns of their distribution in the Barents Sea region as a whole and has a predominantly terrigenous genesis. The composition of hydrocarbons is determined primarily by geochemical processes and does not have an anthropogenic origin (Danilov et al. 2004). The intensity of water pollution with oil film in the Pechora Sea does not exceed two points (Yearbook... 1988–1991) and represents the lowest level in the Barents Sea in general (Dahle et al. 2006). A special study on the vulnerability of different components of the Barents Sea (including the Pechora Sea) ecosystems to oil contamination was undertaken in 2006–2007 (Shavykin and Ilyin 2010). As a result, seasonal maps of the integrative sensitivity of all Barents Sea regions were created. The assessment of the vulnerability of marine biota to oil spills was based on meaningful criteria for the impact of oil on the main components of ecosystems. Unfortunately, in assessing the vulnerability of marine communities, biodiversity indicators were not considered. Coefficients of the vulnerability of phytoplankton, zooplankton, ichthyoplankton, zoobenthos, fish, marine mammals, and birds were calculated based on the analysis of the effects of oil products on these groups of organisms living in the Barents Sea or in other seas under similar conditions. The ichthyoplankton (fish eggs and larvae) and marine birds were characterised as having the greatest vulnerability to oil pollution (provisional coefficient of vulnerability $W = 6.3$). Marine mammals that have a high degree of protection from the external environment and complicated behaviour that allows them to avoid contaminated sites or forage in large areas were determined to be the least vulnerable (provisional coefficients of vulnerability $W = 1$). The degree of vulnerability of phytoplankton, zooplankton, zoobenthos, and fish in the Barents Sea is intermediate.

Studies on trace metal distribution and concentration in sediments, water, and marine organisms showed that the Pechora Sea is relatively clean compared to the western areas of the Barents Sea and other European seas (Loring et al. 1995; Regoli et al. 1998; Novikov and Draganov 2018). Thus, concentrations of Cd, Cr, Cu, Hg, Ni, Pb, V, and Zn in sediments were at or near natural levels, varying according to natural sediment composition (Loring et al. 1995). Trace metals were identified in soft tissues of bivalve molluscs *Limecola* (*Macoma*) *balthica* and *Mytilus edulis*. The levels of As, Cd, Cr, Cu, Fe, Mn, Pb, and Zn found in bivalve molluscs in the southern part of the Pechora Sea were typical of those found in unpolluted or low polluted environments (Savinov and Savinova 1996; Regoli et al. 1998). Concentration of lead was somewhat higher in *Limecola* (*Macoma*) *balthica* and *M. edulis* from Khaypudyr Bay (8 and 17 mg g^{-1} dry tissue, respectively), although it still was below the threshold level values (MAFF 1992). An elevated concentration of As, exceeding background levels, was detected in sediments in the north-eastern part of the Pechora Sea (Chernaya Bay of Novaya Zemlya) (Loring et al. 1995). This enrichment could be accounted for by deposition of As-rich radioactive particulate material dispersed by underwater nuclear explosions in Chernaya Bay in the 1950s. Consistent with this, high concentrations of radionuclides ($^{239,240}Pu$, ^{137}Cs, and ^{60}Co) were detected in the sediments and in marine benthic organisms, such as brown algae, bivalve molluscs, and polychaetes (Smith et al. 2000).

Current research on the Pechora Sea ecosystems

We are pleased to introduce this special issue of Polar Biology, which presents the results of numerous studies on the Pechora Sea ecosystems, communities, and populations, makes a considerable wealth of unique data available to the international scientific community, and identifies some environmental and biological processes that determine ongoing and potential changes in the ecosystems of this important low Arctic marine area. The findings reported in this special issue reveal a broad range of biological phenomena and processes occurring at many ecosystem levels and make it possible to project potential future shifts in communities and populations. The study by Gerasimova et al. (2019) shows that the distribution and abundance of the two common bivalve mollusc species *Serripes groenlandicus* and *Macoma calcarea* have not changed over the last 20 years. The density and growth rates of these species depend primarily on the type of sediment and hydrodynamic conditions of the habitats; therefore, their populations are not expected to be directly affected by climatic changes observed in the Pechora Sea. Studies by Usov et al. (2019) and Denisenko et al. (2019a) demonstrate spatial distribution of zooplankton and benthic communities along environmental gradients, such as salinity and turbidity clines caused by a massive terrestrial freshwater runoff. Benthos was only slightly disturbed by spring freshwater discharge, mostly through intensified ice scouring, while zooplanktonic communities were expectedly more labile, showing higher diversity and reduced abundance in more turbid and less saline waters. The observed regularities contribute to understanding changes in coastal biota under conditions of increased precipitation and associated freshening predicted in most scenarios of climate change in the Arctic region. The other key environmental factor in recent climate change is temperature. A slow but obvious long-term temperature increase observed in the Pechora Sea led to shifts in composition of fish communities (Semushin et al. 2019). Three-decade observations of ichthyofauna revealed an increase of species diversity and contrasting trends on proportion of the Arctic species in catches. Increased spring temperatures and prolonged frost-free periods in recent years influenced the avifauna on the islands of the Pechora Sea (Anufriev and Punantsev 2019). The abundance of waterfowl showed a stable increase, while a strong competition between geese species has been recorded. Marine birds and fish serve as final hosts of parasitic flatworm trematodes, commonly found in the Arctic ecosystems. Peculiarities of and factors influencing transmission of six trematodes species have been studied in the Pechora Sea since the 1980s (Galaktionov et al. 2019). The abundance and distribution of the final hosts of parasites, rather than environmental spatial and temporal gradients, determine the transmission success of trematodes. The comprehensive study by Galaktionov et al. (2019) makes possible meaningful predictions of parasite distribution in the Arctic under future climate scenarios. Temperature rise and increased storm events might cause changes in the structure of benthic communities in the Pechora Sea, leading to partial replacement of filter feeders by subsurface deposit feeders (Denisenko et al. 2019b). However, another important factor could be the foraging activity of the Atlantic walrus (*Odobenus rosmarus rosmarus*), the Pechora Sea population of which has significantly increased since the last century (Semenova et al. 2019). Although the Atlantic walrus is a highly protected species in the Russian Arctic, it could be sensitive to increased economic activity in the Pechora Sea. The unique data on the activity around haul-outs and short- and long-distance migrations of walruses in the area (Semenova et al. 2019) are important for taking appropriate measures to further protect this species. The paper by Boltunov et al. (2019) presents the first data on accumulation of persistent organic pollutants in tissues of walruses of the Pechora Sea population. The authors found an enormous individual variability of persistent organic pollutant concentrations, which can indicate significant differences in the food preferences of walruses.

Overall, the research presented in this special issue provides data on the past and current state of the most important elements of the ecosystems of the Pechora Sea and adjacent areas and demonstrates the interconnection between different components of marine ecosystems and environmental factors. Taking into account the already recorded and potential future environmental changes in this productive region, the trends and processes in marine biota revealed can be applied to other low Arctic areas and serve for modelling and predictions of future shifts in ecosystems.

Acknowledgements Some of the presented data have been collected in several expeditions to the Pechora Sea on board of research vessels "Pomor" and "Professor Vladimir Kuznetsov". The excellent work of crews of these ships is greatly acknowledged. While working on this manuscript the authors have been supported by research projects of the Zoological Institute of Russian Academy of Sciences AAAA-A19-119022690122-5, AAAA-A19-119020690109-2, AAAA-A17-117030310207-3, and by the Russian Foundation for Basic Research grant # 18-05-60157. We thank the Editor-in-Chief of Polar Biology and all the reviewers for their help in preparing this special issue.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

AMAP (2017) Chemicals of emerging Arctic concern. Summary for Policy-makers. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. https://www.amap.no

Anker-Nilssen T, Bakken V, Strøm H, Golovkin AN, Bianki VV, Tatarinkova IP (eds) (2001) The Status of marine birds breeding in the Barents Sea Region. Norsk Polarinst, Rapport, p 113

Antipova TV (1973) Distribution and abundance of benthos in the southeastern part of the Barents Sea in 1970. Proc Polar Res Inst Mar Fish Oceanogr 33:24–33 **(in Russian)**

Antziferov MYu, Guzenko VV (2002) Distribution of mean multiyear hydrometeorological characteristics in the eastern part of the Barents Sea in August and September for the period 1972–2001. Polar Research Institute of Marine Fisheries and Oceanography, Murmansk **(in Russian)**

Anufriev VV (2006) Avifauna of islands of the Pechora Sea. Vestn Pomor Univ (Bull Pomor Univ) 1(9):70–79 **(in Russian)**

Anufriev VV, Punantsev EA (2019) Changes in the summer bird communities with an emphasis on waterfowl on Dolgy Island during 2004–2017. Polar Biol. https://doi.org/10.1007/s00300-019-02545-w

Anufriev VV, Glotov AS, Zolotoi SA (2017) Atlantic walrus monitoring in the Nenetsky State Nature Reserve. Trans Karelian Res Cent Russ Acad Sci 4:15–25 **(in Russian)**

Boitsov VD, Karsakov AL, Trofimov AG (2012) Atlantic water temperature and climate in the Barents Sea, 2000–2009. ICES J Mar Sci 69:833–840. https://doi.org/10.1093/icesjms/fss075

Boltunov AN, Belikov SE, Gorbunov YA, Menis DT, Semenova VS (2010) The Atlantic walrus in the southeastern Barents Sea and adjacent areas: review of present-day status. WWF-Russia and Marine Mammal Council, Russia **(in Russian)**. https://wwf.ru/upload/iblock/7c7/walrus_review.pdf

Boltunov AN, Dubinin MYu, Yezhov AE, Larionov MV, Novoselov AP, Pukhova MA, Frolova EA (2014) Areas of limited anthropogenic activity: the Pechora Sea. Oil and gas industry. World Wildlife Fund (WWF), Murmansk **(in Russian)**. https://wwf.ru/upload/iblock/ef4/pechorsea_cover.orig.jpg

Boltunov A, Semenova V, Samsonov D, Boltunov N, Nikiforov V (2019) Persistent organic pollutants in the Pechora Sea walruses. Polar Biol. https://doi.org/10.1007/s00300-019-02457-9

Borkin IV (2012) The Polar cod in nutrition of guillemots and Northern fulmar—the most abundant piscivorous seabirds in the Barents Sea. Vestn Krasn Gos Agrar Univ (Bull Krasn State Agrar Univ) 10:76–81 **(in Russian)**

Born EW, Gjertz I, Reeves RR (1995) Population assessment of Atlantic walrus. Norsk Polarinstituttt, Meddelelser, p 138

Brotskaya VA, Zenkevich LA (1939) Quantitative recording of bottom fauna of the Barents Sea. Proc Russ Res Inst Fish Oceanogr 4:3–150 **(in Russian)**

Chernitskiy AG (1995) Pink salmon. In: Berger VJA (ed) White Sea: biological resources and problems of their rational exploitation. Part II. Zoological Institute of Russian Academy of Sciences, Saint-Petersburg, pp 84–88 **(in Russian)**

Chernook VI, Lydersen C, Glazov DM, Trukhanova IS, Kovacs KM (2012) Aerial survey of Atlantic walruses (*Odobenus rosmarus rosmarus*) in the Pechora Sea, August 2011. In: Boltunov AN (ed) Marine mammals of the holarctic. Collection of Scientific Papers, Moscow, pp 722–725

Dahle S, Savinov V, Petrova V, Klungsøyr J, Savinova T, Batova G, Kursheva A (2006) Polycyclic aromatic hydrocarbons (PAHs) in Norwegian and Russian Arctic marine sediments: concentrations, geographical distribution and sources. Nor J Geol 86:41–50

Danilov AI, Mironov EU, Spichkin VA (eds) (2004) Variability of environmental conditions in the shelf zone of the Barents and Kara Seas. Arctic and Antarctic Research Institute, Saint Petersburg **(in Russian)**

Dauvalter V (2002) Persistent organic pollutants in sediments of the Pechora river system: the preliminary results of investigation in frame of SPICE Project. Second AMAP international symposium on environmental pollution of the Arctic. Extended Abstracts. Rovaniemi, Finland. October 1–4, 2002. P-P15. AMAP website: www.amap.no

Denisenko SG (2006) Long-term changes of zoobenthos in the Pechora Sea. News Russ Geogr Soc 138:37–48 **(in Russian)**

Denisenko SG (2013) Biodiversity and bioresouces of macrozoobenthos in the Barents Sea: structure and long-term changes. Nauka, Saint-Petersburg **(in Russian)**

Denisenko NV, Rachor E, Denisenko SG (2003) Benthic fauna of the southern Kara Sea. In: R Stein, K Fahl, DK Fütterer, EM Galimov, OV Stepanets (eds). Siberian River run-off in the Kara Sea: characterization, quantification variability and environmental significance. Proceedings in Marine Science, vol 6, pp 213–236

Denisenko NV, Denisenko SG, Lehtonen KK (2019a) Distribution of macrozoobenthos in an Arctic estuary (Pechora Bay, SE Barents Sea) during the spring flood period. Polar Biol. https://doi.org/10.1007/s00300-018-02452-6

Denisenko SG, Denisenko NV, Chaban EM, Gagaev SYu, Petryashov VV, Zhuravleva NE, Sukhotin AA (2019b) The current status of the macrozoobenthos around the Atlantic walrus haul-outs in the Pechora Sea (SE Barents Sea). Polar Biol. https://doi.org/10.1007/s00300-018-02455-3

Druzhkov NV, Makarevich PR (1999) Comparison of the phytoplankton assemblages of the south-eastern Barents Sea and South-Western Kara Sea: phytogeographical status of the regions. Bot Mar 42:103–115. https://doi.org/10.1515/BOT.1999.013

Filatova ZA (1957) General overview of the fauna of bivalve mollusks of the northern seas in the USSR. Proc Inst Oceanol RAS 20:3–59 **(in Russian)**

Galaktionov KV (1986) Metacercariae of family Microphallidae Travassos, 1920 from benthic molluscs of the south-eastern part of the Barents Sea. Parazitologiya 20(5):389–396 **(in Russian)**

Galaktionov KV (1996) Life cycles and distribution of seabird helminths in the Arctic and sub-Arctic regions. Bull Scand Soc Parasitol 6(2):31–49

Galaktionov KV (2016) Transmission of parasites in the coastal waters of the Arctic seas and possible effect of climate change. Biol Bull 43(9):1129–1147. https://doi.org/10.1134/S1062359016110054

Galaktionov KV (2017) Patterns and processes influencing helminth parasites of Arctic coastal communities during climate change. J Helminthol 91:387–408. https://doi.org/10.1017/S0022149X17000232

Galaktionov KV, Marasaev SF (1986) Ecological analysis of trematode fauna in benthic mollusks from the southeastern Barents Sea. Parazitologiya 20(6):455–460 **(in Russian)**

Galaktionov KV, Marasaev SF (1990) Distribution of trematode infection foci in the Barents Sea. In: Matishov GG (ed) Ekologiya i biologicheskaya produktivnost' Barentseva morya (Ecology and biological productivity of the Barents Sea). Nauka, Moscow, pp 37–47 **(in Russian)**

Galaktionov KV, Nikolaev KE, Aristov DA, Levakin IA, Kozminsky EV (2019) Parasites on the edge: patterns of trematode transmission in the Arctic intertidal at the Pechora Sea (South-Eastern Barents Sea). Polar Biol. https://doi.org/10.1007/s00300-018-2413-3

Galkin Y (1964) Long-term changes in the distribution of bivalve mollusks in the southern part of the Barents Sea. In: New studies of Plankton and Benthos of the Barents Sea. Proceedings of Murmansk Marine Biolgical Institute, vol 6, no 10, pp 22–40 **(in Russian)**

Ganter B, Gaston AJ, Anker-Nilssen T et al (2013) Birds. In: Meltofte H, Josefson AB, Payer D (eds) Arctic biodiversity assessment: status and trends in Arctic biodiversity. The conservation of Arctic flora and fauna (CAFF). Arctic Council, Akureyri, pp 142–181

Gavrilo MV, Strøm H (2005) Ration of king eiders (*Somateria spectabilis*), molting in the Pechora Sea. In: Gavrilo MV (ed) Anseriformes of the N Eurasia. Proceedings of the 3rd international symposium, Saint Petersburg, pp 72–73 **(in Russian)**

Gerasimova AV, Filippova NA, Lisitsyna KN, Filippov AA, Nikishina DV, Maximovich NV (2019) Distribution and growth of bivalve molluscs *Serripes groenlandicus* (Mohr) and *Macoma calcarea* (Gmelin) in the Pechora Sea. Polar Biol. https://doi.org/10.1007/s00300-019-02550-z

Hoberg EP, Kutz SJ, Cook J, Galaktionov KV, Haukisalmi V, Henttonen H, Laaksonen S, Makarikov A, Marcogliese DJ (2013) Parasites in terrestrial, freshwater and marine systems. In: Meltofte H, Josefson AB, Payer D (eds) Arctic biodiversity assessment: status and trends in Arctic biodiversity. The conservation of Arctic flora and fauna (CAFF). Arctic Council, Akureyri, pp 420–449

Karamushko LI, Chernitzkiy AG, Karamushko OV (1996) Ichthyofauna. In: Matishov GG (ed) Ecosystems, biological resources and anthropogenic pollution of the Pechora Sea. KNC RAN Publ, Apatity, pp 72–79 **(in Russian)**

Karpovich VN, Bragin AB, Khokhlov AM (1984) The current state of rare and endangered animals in the Murmansk region. In: Filippova LN (ed) Problems of nature protection in the White Sea basin. Murmansk Publishers, Murmansk, pp 51–63 **(in Russian)**

Khodkina IV (1964) Echinoderms of the southern Barents Sea. In: Zelikman EA (ed) New studies of Plankton and Benthos of the Barents Sea. Proceedings of Murmansk Marine Biolgical Institute, vol 6, no 10, pp 41–75 **(in Russian)**

Klenova MV (1960) Geology of the Barents Sea. Academy of Sciences of the USSR, Moscow **(in Russian)**

Kobelev EA (2001) Biological basis of commercial use of fish stocks in the southeastern Barents Sea: on the example of navaga, Arctic flounder and smelt. PhD Dissertation, Moscow **(in Russian)**

Kondakov AA (1996) Marine mammals. In: Matishov GG (ed) Ecosystems, biological resources and anthropogenic pollution of the Pechora Sea. KNC RAN Publ, Apatity, pp 89–98 **(in Russian)**

Kovacs KM, Haug T, Lydersen C (2009) Marine mammals of the Barents Sea. Chapter 18. In: Sakshaug E, Johnsen G, Kovacs K (eds) Ecosystem Barents Sea. Tapir Academic Press, Tronheim, pp 453–496

Krasnov Y, Goryaev Y, Shavykin AA, Nikolaeva NG, Gavrilo MV, Chernook VI (2002) Atlas of the Pechora Sea birds: distribution, abundance, dynamics, problems of protection. Publishing Company of the Kola Branch of the Russian Academy of Sciences, Apatity **(in Russian)**

Krasnov YuV, Gavrilo MV, Chernook VI (2004) Distribution of birds over the Pechora Sea: data of aerial surveys. Zool Zhurnal 83:449–458 **(in Russian)**

Krasnov Yu, Gavrilo M, Nikolaeva N, Goryaev Yu, Strøm H (2006) East-Atlantic flyway populations of seaducks in the Barents Sea region. In: Boere GC, Galbraith CA, Stroud DA (eds) Waterbirds around the world. The Stationery Office, Edinburgh, pp 512–513

Krasnov YuV, Shavykin AA (2005) The practice of monitoring seabirds in the Barents Sea. Challenges and Prospects. In: Matishov GG (ed) Moderninformation and biological technologies in the development of resources of the shelf seas. Nauka, Moscow, pp 141–156 (**in Russian**)

Krasnov YuV, Shklyarevich GA, Goryaev YuI (2009) Feeding by moulting king eiders in the shallow waters of the southeastern part of the Pechora Sea. Casarca 12:68–75 **(in Russian)**

Krasnov YuV, Shklyarevich GA, Sukhotin AA (2014) Feeding habits of common eiders *Somateria mollissima* on the western coast of Vaygach island. Dokl Biol Sci 459:341–343. https://doi.org/10.1134/S0012496614060015

Krasnov YuV, Ezhov AV, Galaktionov KV, Shavykin AA (2019) Numbers and seasonal distribution of the western population of the king eider (*Somateria spectabilis*): monitoring setup in the northern seas of Russia. Zool Zhurnal

Kuznetsov LL, Druzhkov NV (1997) Exploration of the pelagial of the Arctic seas in the winter-spring period (Research experience on the ships of the icebreaker fleet along the Northern Sea Route). Okeanologia 37(6):946–948 **(in Russian)**

Laidre KL, Stern H, Kovacs KM, Lowry L, Moore SE, Regehr EV, Ferguson SH, Wiig Ø, Boveng P, Angliss RP, Born EW, Litovka D, Quakenbush L, Lydersen C, Vongraven D, Ugarte F (2015) Arctic marine mammal population status, sea ice habitat loss, and conservation recommendations for the 21st century. Conserv Biol 29:724–737. https://doi.org/10.1111/cobi.12474

Larsen T, Nagoda D, Andersen JR (eds) (2003) A biodiversity assessment of the Barents Sea Ecoregion. Contribution of the St. Petersburg Biodiversity workshop 12–13 May 2001 participants. WWF Barents Sea Ecoregion Programme, Oslo

Loring DH, Næs K, Dahle S, Matishov GG, Ilyin G (1995) Arsenic, trace metals, and organic micro contamination in sediments from the Pechora Sea, Russia. Mar Geol 2:153–167

MAFF (1992) Monitoring and surveillance of non-radioactive contaminants in the aquatic environment and activities regulating the disposal of wastes in the sea. Aquatic Monitoring Report 30, Lowestoft, UK

Makarevich PR (1996) Planktonic communities. In: Matishov GG (ed) Ecosystems, biological resources and anthropogenic pollution of the Pechora Sea. Publishing Company of the Kola Branch of the Russian Academy of Sciences, Apatity, pp 50–54 **(in Russian)**

Makarevich P, Druzhkova E, Larionov V (2012) Primary producers of the Barents Sea. In: Mahamane A (ed) Diversity of ecosystems, InTech. https://www.intechopen.com/books/diversity-of-ecosystems/primary-producers-of-the-barents-sea

Makarevich P, Druzhkova E, Larionov V (2014) Structure of phytoplankton seasonal succession in the Barents and Kara seas: regulation or autoregulation? In: Matishov GG (ed) Marine ecosystems and communities in the conditions of current climate changes. Renome, Saint-Petersburg, pp 99–121 **(in Russian)**

Malavenda SV, Shoshina EV, Kapkov VI (2017) Species diversity of macroalgae in different areas of the Barents Sea. Vest Murm Gos Tek Univ (Bull Murm State Tech Univ) 20(2):336–351 **(in Russian)**

Martynov VG (2007) Atlantic salmon *Salmo salar* L. in the North of Russia. Ural Branch of Russian Academy of Sciences, Ekaterinburg **(in Russian)**

Matishov GG, Denisenko SG (1996) Biooceanological research by MMBI in the Pechora Sea in 1992–1994. In: Matishov GG (ed) Ecosystems, biological resources and anthropogenic pollution of the Pechora Sea. Publishing Company of the Kola Branch of the Russian Academy of Sciences, Apatity, pp 9–13 **(in Russian)**

Matishov GG, Ognetov GN (2006) Beluga whale of the Arctic seas of Russia: biology, ecology, protection and resources use. Publishing Company of the Kola Branch of the Russian Academy of Sciences, Apatity **(in Russian)**

Matishov G, Moiseev D, Lyubina O, Zhichkin A, Dzhenyuk S, Karamushko O, Frolova E (2012) Climate and cyclic hydrobiological changes of the Barents Sea from the twentieth to twenty-first centuries. Polar Biol 35:773–790. https://doi.org/10.1007/s00300-012-1237-9

Metelskiy AA (2014) To the flora of macroalgae of the Pechora Sea. Bull South Sci Cent Russ Acad Sci (Vestnik Yuzhnogo Nauchnogo Tsentra RAS) 10(1):50–54 **(in Russian)**

Mitskevich IV, Telitsina LA (2002) Assessment impact of bottom sediments pollutions byhydrocarbons on macrozoobenthos state in the White and the Pechora Seas. In: Anonimous (ed) Materials of fishery research in the basins of the European North. Scientific publications. SevPINRO, Arkhangelsk, pp 5–11 **(in Russian)**

Musaeva EI, Suntsov AV (2001) On the distribution of the Pechora Sea zooplankton (on the materials collected in August 1998). Oceanology 41(4):508–516

Musaeva EI, Suntsov AV (2003) Chapter 7. Zooplankton. In: Romankevich EA, Lisitzin AP, Vinogradov ME, (eds) The Pechora sea: integrated research. More, Moscow, pp 207–216 (**in Russian**)

Murmansk UGMS (1988–1993) Yearbook of the water quality by hydrochemical traits in the Barents, Norwegian and Greenland Seas. Murmansk UGMS, Murmansk(**in Russian**)

Nikolaeva NG, Spiridonov VA, Krasnov YV (2006) Existing and proposed marine protected areas and their relevance for seabird conservation: a case study in the Barents Sea region. In: Boere GC, Galbraith CA, Stroud DA (eds) Waterbirds around the world. The Stationery Office, Edinburgh, pp 743–749

Novikov MA, Draganov DM (2018) Background levels of the content of heavy metals in the waters of the Barents Sea and their application. In: Rudneva II (ed) Pollution of marine environment: ecological monitoring, bioassay, standardization: collection of the papers of the Russian scientific conference with international participation devoted to 125th anniversary of Prof. V.A. Vodyanitsky, Colorit, Sevastopol, pp 167–172 **(in Russian)**

Novoselov AP, Studenov II, Bezumova AL, Bulatova IV, Borovskoy AV, Lukin AA (2012) The Pechora basin whitefish stocks in conditions of the multifactor anthropogenic impact. Arktika 4(8):26–35 **(in Russian)**

Pautova LA (2001) Structure of the main components of microphytoplankton of the Pechora Sea in summer. In: Lisitzin AP, Vinogradov ME, Romankevich EA (eds) An experience of the system oceanographic researches in the Arctic. Nauchny Mir, Moscow, pp 356–363 **(in Russian)**

Pautova LA (2003) Phytoplankton of the Pechora Sea. In: Romankevich EA, Lisitzin AP, Vinogradov ME (eds) Pechora Sea: system researches. More Press, Moscow, pp 171–194 **(in Russian)**

Potanin VA, Lagutin BL (eds) (1984) Hydrometeorological conditions of the shelf zone of the seas of the USSR (1984) V. 6. Barents Sea. Iss. 3. South-eastern part. Murmansk **(in Russian)**

Regoli F, Hummel H, Amiard-Triquet C, Larroux C, Sukhotin A (1998) Trace metals and variations of antioxidant enzymes in Arctic bivalve populations. Arch Environ Contam Toxicol 35:594–601

Romankevich EA, Danyushevskaya FI, Belyaeva AN, Rusanov VP (1982) Biogeochemistry of organic matter in the Arctic seas. Nauka, Moscow **(in Russian)**

Samokhina LA (2009) Assessment of benzo(a)pyrene influence on quantitative characteristics of zoobenthos in the White Sea and the southeastern Barents Sea. Bull Pomor Univ 2:76–82 **(in Russian)**

Savinov VM, Savinova TN (1996) Heavy metal contents in the bottom animals. In: Matishov GG (ed) Ecosystems, biological resources and anthropogenic contamination of the Pechora Sea. Kola Science Center RAS, Apatity, pp 113–121 **(in Russian)**

Semenova VS, Boltunov AN, Nikiforov VV (2015) Study and preservation of the Atlantic walrus in the southeastern part of the Barents Sea and adjacent areas of the Kara Sea. Research results 2011–2014. World Wildlife Fund (WWF), Murmansk **(in Russian)**

Semenova V, Boltunov A, Nikiforov V (2019) Key habitats and moving of the Pechora Sea walruses during the ice-free season studied by satellite telemetry. Polar Biol. https://doi.org/10.1007/s00300-018-02451-7

Semushin AV, Novoselov AP, Sherstkov VS, Levitsky AL, Novikova YV (2019) Long-term changes in the ichthyofauna composition of the Pechora Sea (South-Eastern Barents Sea) as a result of the temperature factor. Polar Biol. https://doi.org/10.1007/s00300-018-2405-3

Shavykin AA, Ilyin GV (2010) An assessment of the integral vulnerability of the Barents Sea from oil contamination. Murmansk Marine Biological Institute, Murmansk **(in Russian)**

Shevchenko VP, Politova NV, Aybulatov NA et al (2003) Chapter 10. Suspended material and its flows. In: Romankevich EA, Lisitzin AP, Vinogradov ME (eds) The Pechora Sea: integrated research. More Press, Moscow, p 247262

Sirenko BI (2001) Introduction. In: Sirenko BI (ed) List of species of free-living invertebrates of Eurasian Arctic seas and adjacent deep waters. Exploration of the Fauna of the Seas, Proceedings of the Zoological Institute RAS, vol 51, no 59, pp 5–10 **(in Russian)**

Smith JN, Ellis KM, Polyak L, Ivanov G, Forman SL, Moran SB (2000) ^{239,240}Pu transport into the Arctic Ocean from underwater nuclear tests in Chernaya Bay, Novaya Zemlya. Cont Shelf Res 20:255–279

Streltsov VE (1966) Quantitative distribution of polychaetes in the southern part of the Barents Sea. In: Composition and distribution of plankton and benthos in the southern part of the Barents Sea. Nauka, Leningrad, pp 71–91 **(in Russian)**

Sukhotin AA, Strelkov PP, Maximovich NV, Hummel H (2007) Growth and longevity of *Mytilus edulis* (L.) from northeast Europe. Mar Biol Res 3:155–167. https://doi.org/10.1080/17451000701364869

Sukhotin AA, Krasnov YuV, Galaktionov KV (2008) Subtidal populations of the blue mussel *Mytilus edulis* as key determinants of waterfowl flocks in the southeastern Barents Sea. Polar Biol 31:1357–1363. https://doi.org/10.1007/s00300-008-0474-4

Timofeev SF, Shirokolobova OV (1996) Zooplankton and its importance in the system of ecological monitoring. In: Matishov GG (ed) Ecosystems, bioresources and anthropogenic pollution of the Pechora Sea. KNC RAN Publ, Apatity, pp 54–60 **(in Russian)**

Troshkov VA, Gnetneva LV (2000) Zooplankton of the southeastern part of the Barents Sea. In: Biological resources of the coastal zone of Russian Arctic. Russian Research Institute of Fisheries and Oceanography, Moscow, pp 143–150 **(in Russian)**

Usov N, Khaitov V, Smirnov V, Sukhotin A (2019) Spatial and temporal variation of hydrological characteristics and zooplankton community composition influenced by freshwater runoff in the shallow Pechora Sea. Polar Biol. https://doi.org/10.1007/s00300-018-2407-1

Vasyutina NP (1991) Phytoplankton of the South-Eastern part of the Barents Sea in July-August 1977. In: Agarova IYA, Gupalo EYu (eds) Phytoplankton studies in the monitoring system of the Baltic Sea and other seas of the USSR. Gidrometeoizdat, Moscow, pp 127–134 **(in Russian)**

Vedernikov VI, Gagarin VI, Vetrov AA (2003) Primary production and chlorophyll. In: Romankevich EA, Lisitzin AP, Vinogradov ME (eds) Pechora Sea: system researches. More Press, Moscow, pp 195–206 **(in Russian)**

Zelikman EA (1961) Planktonic characteristic of the southeastern part of the Barents Sea (according to the data of August 1958). In: Hydrological and biological peculiarities of the coastal waters of the Murman. Murmansk, pp 39–58 **(in Russian)**

Zelikman EA (1966) Notes on the composition and distribution of the zooplankton in the southeastern part of the Barents Sea in August-October 1959. Composition and distribution of the zooplankton and benthos in the southern part of the Barents Sea. Proc Murm Marine Biol Inst 11:34–49 **(in Russian)**

Zenkevich LA (1927) Quantitative recording of the bottom fauna of Pechora region of the Barents Sea and the White Sea. Proc Float Marine Res Inst 2(4):3–64 **(in Russian)**