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SUPPLEMENT ARTICLE

Importance of oceanographical background for a conservation priority areas network planned using MARXAN decision support tool in the Russian Arctic seas

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Abstract

1. The aim of the present study is to assess a conservation priority area (CPA) network proposed for the Russian Arctic seas (47 areas) with regard to underlying oceanographical features and to discuss further development of marine conservation planning.
2. The oceanographical features included in the analysis were obtained from the literature or inferred from schemes of climatic oceanography.
3. The most frequent oceanographic feature associated with a particular CPA is constant advection of a particular water mass, followed by local water mass transformation, seasonal ice zones, flaw polynyas, and external sources of nutrients. Particularly important are major frontal zones, and coastal phenomena such as coastal/offshore waters transition zones, massifs of fast ice and specific regimes of semi-isolated fjords and bays.
4. Each Arctic sea in the study area or its large part (in the Barents Sea) is characterized by a distinct combination of oceanographical features associated with the respective CPAs.
5. Although most oceanographical features were not involved in the process of developing the CPA network directly, the resulting CPAs are shown to have a solid oceanographical background.
6. While this oceanographical background needs further understanding, it provides the possibility to refine the MPA boundaries and plan future studies. Furthermore it allows evaluation of potential resistance and resilience of CPAs to climate change by focusing on relevant oceanographical processes and the adaptive potential of biota on an area by area basis.

KEYWORDS

advection, biodiversity, marine protected areas, polynyas, sea ice, spatial conservation, water masses

1 | INTRODUCTION

The spatial conservation approach came to the marine realm from land and dealt initially with ecosystems within easily demarcated spatial boundaries such as coral reefs, isolated seamounts or well-defined bays (Roff & Zacharias, 2011). With the extension of the approach to huge pelagic areas such as marine protected areas (MPAs) within the Convention for Conservation of Antarctic Marine Living Resources (CCAMLR, 2016), closed areas of the North-east Atlantic Fishery Convention (NEAFC, 2017) or extensive pelagic MPAs within the EEZ of the USA around the Hawaiian Islands, the question arises how the spatial approach can be correctly applied for conservation of ecosystems in such extensive areas governed by large-scale oceanographical processes.

Spatial marine conservation planning for the Arctic seas becomes particularly important with the onset of a new epoch of the Arctic industrial development coinciding with the current trends of climate change. These are, for instance increasing the input of Atlantic and Pacific waters, decreasing summer sea ice cover and average thickness of ice, shrinking of the fraction of multiyear sea ice, melting down of coastal glaciers and the thermoabrasion of permafrost shores (Drewnik et al., 2016; Grebmeier & Maslowski, 2014; Hunt et al., 2016; IPCC, 2013; Maslanik, Stroeve, Fowler, & Emery, 2011).

Solovyev et al. (2017) presented a network of 47 conservation priority areas (CPAs) encompassing from 25 to 30% of most Russian Arctic seas (Figure 1a) which may be further developed into a network of MPAs or their analogies in marine spatial planning. They used the MARXAN package (Ball & Possingham, 2000) as a decision support tool complemented with extensive evaluation and post-MARXAN analysis. Conservation features (CFs) were identified as spatially

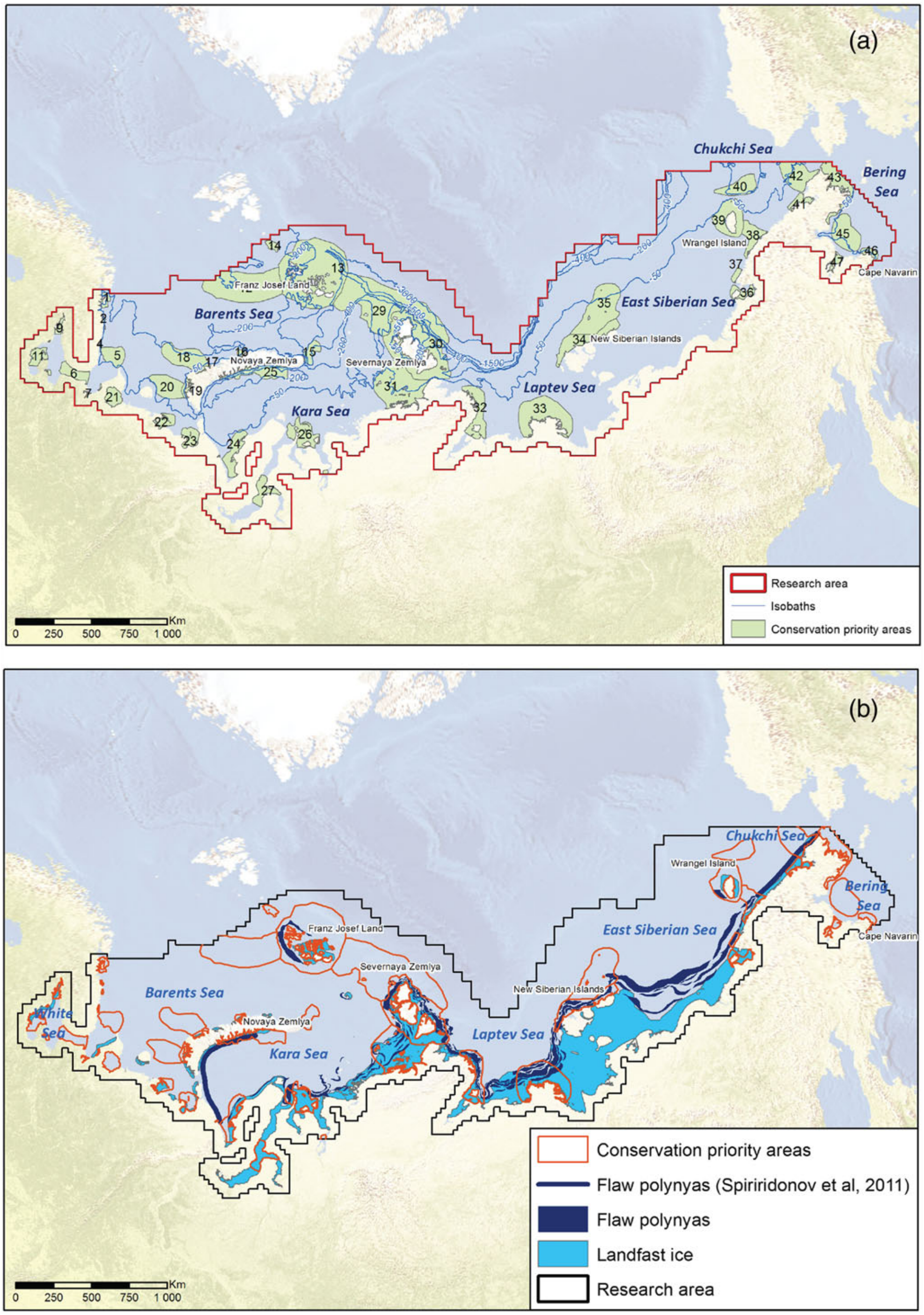

FIGURE 1 Conservation priority areas (CPAs) network in the Russian Arctic sea. **(a)** Location and identification numbers of CPAs developed in the process of MARXAN and post-MARXAN analysis (Solovyev et al., 2017) in the Russian Arctic seas in relation to general bathymetry. **(b)** Location of CPAs in relation to flaw polynyas and extensive areas of landfast ice. The figure is based on Figure 3 from Solovyev et al. (2017) with additions of polynyas data from Popov and Gavrilo (2011) for the western Kara Sea and Chukchi Sea

definable components of biodiversity and ecological processes, such as species and population ranges, representative coastal and benthic habitats, communities' biotopes, and locations of distinct areas having importance for particular life-history phases of endangered species. Underlying oceanographical and bio-oceanographical (i.e. primary production and nutrients cycling) features (phenomena and processes) were not explicitly used in the analysis. Only flaw polynyas and the marginal ice zone were directly considered (Solovyev et al., 2017). The large (up to 90 000 km^2) size of many of the resulting CPAs highlights the necessity for a better understanding of their internal structure and the processes shaping essential biodiversity features used in the conservation planning.

Several oceanographical phenomena and processes were shown to be highly important for maintaining the present day condition of Arctic marine populations and communities. Advection of Atlantic and Pacific water masses is influencing the sea ice regime, creating oceanographical fronts and patterns of water circulation within particular seas, transporting nutrients and shaping distribution of pelagic and benthic organisms (Carmack et al., 2006; Hunt et al., 2016). Just as important for biological processes in the interior shelves of Siberian seas is the advection of river runoff water (Carmack et al., 2006; Lapin, 2012; Petryashov & Novozhilov, 2004). Water mass transformation shaping the regional oceanographical basis of the ecosystem occurs in the inflow such as the Barents Sea shelf and interior shelves, the Siberian shelves (for definitions see Carmack et al., 2006), on shelf banks (Adrov, 1958), in the coastal areas (Boitsov & Nesvetova, 1995; Makarevich & Druzhkova, 2010; Pantyulin, 2003, 2012), and also in particular bays and straits under the influence of mixing by strong tidal currents (Pantyulin, 2012). Marginal and seasonal sea ice zones with particular ice edge effects play a tremendous role in primary production processes and integration of sea ice communities into the general Arctic marine ecosystem (Carmack & Wassmann, 2006; Gradinger, 1995; Kohlbach et al., 2016; Wassmann et al., 2006). Flaw polynyas are extensive areas of open water or of new unstable ice up to 30 cm thick that are regularly developing in particular areas during the winter season between landfast ice and close pack ice. The polynyas in the Siberian shelf are formed as a result of specific atmospheric processes, in particular regular winds pushing drifting ice offshore (Popov & Gavrilo, 2011; Zakharov, 1996). They are considered to be extremely important for the Arctic marine biodiversity and ecosystem (Carmack et al., 2006; Gavrilo & Popov, 2011; Gavrilo, Popov, & Spiridonov, 2011; Kupetsky, 1961; Popov & Gavrilo, 2011). A number of other oceanographical and sea ice features may also have a strong impact on area-specific characteristics of biological productivity and diversity in the Arctic seas: upwellings, stationary eddies (Sirenko, Denisenko, Gagaev, Golikov, & Petryashov, 2009), external sources of nutrients (i.e. with the runoff of small but numerous rivers) (Sapojhnikov, Arjhanova, & Mordasova, 2012), reverse tidal circulation (Solyanko, Spiridonov, & Naumov, 2011a), extensive landfast ice or pack ice massifs (Laidre et al., 2015), and specific regimes of semi-landlocked basins (Semenov, 1988).

As the CPA network proposed for the Russian Arctic seas accounted for oceanographical features mostly implicitly, its oceanographical background needs to be assessed along with underlying bio-oceanographical processes. This will facilitate understanding of the functionality of the network and its possible effectiveness, and its resistance, resilience and redundancy characteristics in changing climatic conditions. The aim of the present study is to assess CPAs proposed for the Russian Arctic seas by Solovyev et al. (2017) with regard to the underlying oceanographical background (phenomena and processes) and discuss further development of marine conservation planning using this basis.

2 | MATERIAL AND METHODS

The network of CPAs (Figure 1a) was derived using MARXAN and Post-MARXAN analysis (Solovyev et al., 2017). Conservation features used for the analysis and general characteristics of the network are described in Solovyev et al. (2017). Identification numbers of particular CPAs and their distribution in particular seas and in relation to bathymetry are shown in Figure 1a. Sea ice data to support CPA planning (Figure 1b) are based on remote sensing information as described by Solovyev et al. (2017). The climatic oceanography scheme used in the project (Figure 2 in Solovyev et al., 2017; Figure 2a) is based on the NOAA Arctic Regional Climatology atlas (Boyer et al., 2012; Seidov et al., 2015).

For visualization of climatic near bottom water temperature a special map was constructed. Original data were obtained as a grid of temperature measurements from the National Centres for Environmental Information website (NCEI, 2017). Temperature data for closest to the bottom depth at a particular station were used for subsequent analysis. Interpolation of the data was done using several algorithms in the software ArcGIS 10.2 (for details see Pantyulin & Chuprina, 2015).

The oceanographical features included in the analysis were obtained from the literature or inferred from schemes of climatic oceanography such as Figure 2 in Solovyev et al. (2017) and schemes of sea ice conditions (Figure 1b), coastal oceanography (Figures 1b, 2a), and the climatic distribution of near bottom water temperature in the Russian Arctic seas (Figure 2b). The primary focus has been given to the following phenomena. First, advection of water masses with specific characteristics was considered, i.e. Atlantic or Pacific water masses, or river runoff water influencing the thermal and salinity regimes and the introduction of freshwater and brackish water plankton. There can also be advection of transformed water, such as the waters of the Barents, Kara, and White seas. With regard to transformation of water masses, particular attention was paid to summer warming in large bays, tidal mixing, or deep winter convection but also to the areas of water transformation throughout most of the Arctic coastal zone (Figure 2a). Other oceanographical features used in the assessment and obtained from the literature included frontal zones, flaw polynyas, seasonal sea ice zone, pack ice massifs, extensive landfast ice massifs, stationary eddies, upwelling, external nutrient sources such as river runoff, strong reverse tidal currents, and specific oceanographical regimes of semi-landlocked areas.

The data for each CPA with respective references are presented in the Supplementary material.

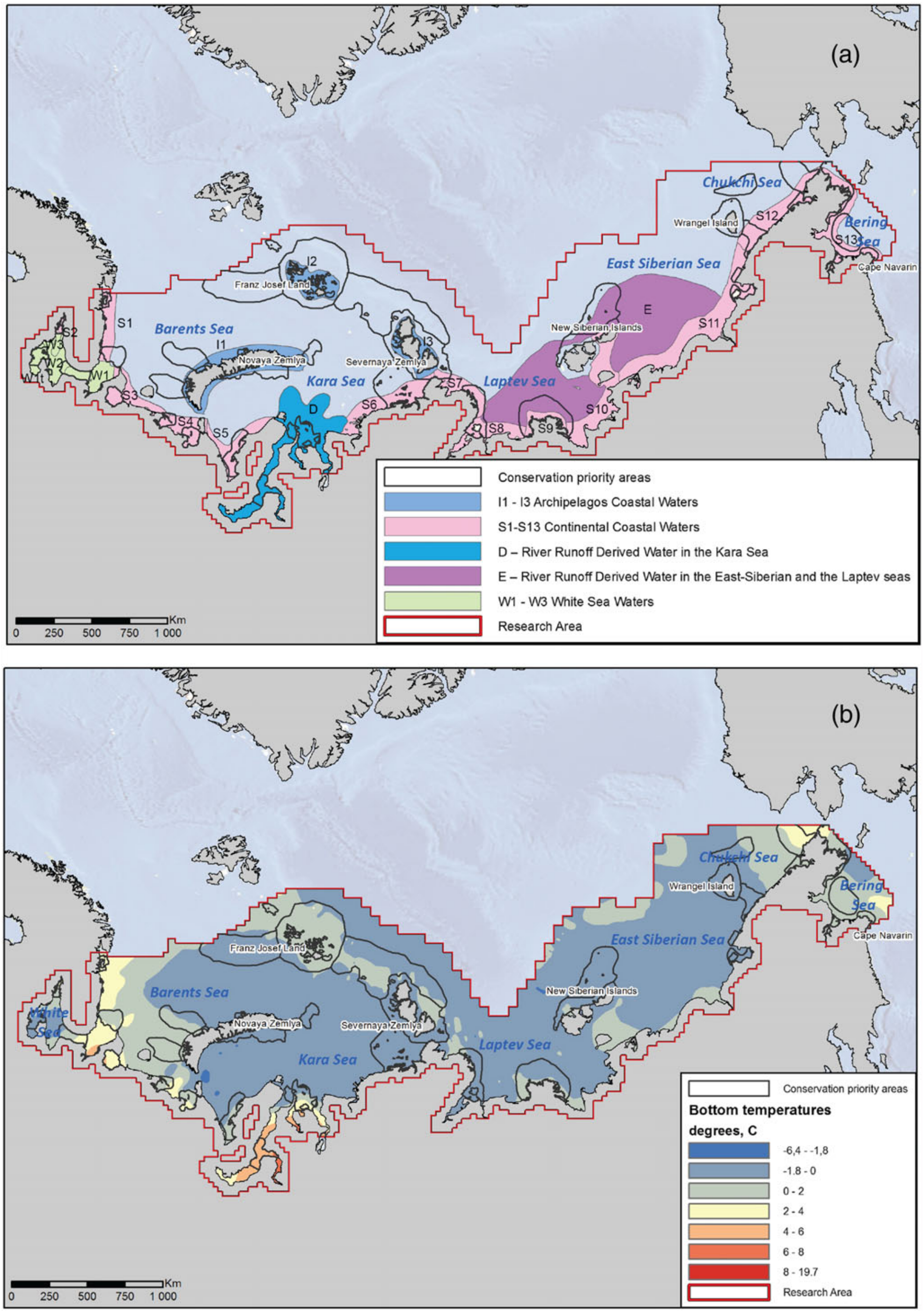

FIGURE 2 Conservation priority areas (CPAs) network in the Russian Arctic seas in relation to particular oceanographical features. **(a)** Location of CPAs in relation to coastal waters and the waters of river runoff (the scheme based on climatic oceanography obtained from Boyer et al., 2012). **(b)** Location of CPAs in relation to climatic distribution of near bottom temperature (for explanation see text)

3 | RESULTS

3.1 | Association of particular oceanographical phenomena with conservation priority areas

All CPAs are associated with particular oceanographical features, ranging in number from one to six (modal number is four, median number is four, mean number equals 3.9 ± 0.2) (Figure 3a). Areas with four to six features account for 61% of all CPAs. Only two small coastal areas off the western coast of the Novaya Zemlya Archipelago (areas 17 and 19; Figure 1a) are characterized by a single feature, and are represented by the specific oceanographical regimes of fjords and skerry bays. However, the oceanography of the coastal waters of Novaya Zemlya is not well studied and probably this poor representation simply reflects the current level of knowledge. The maximum number of associated oceanographic features is observed in relatively large areas, such as the southern shelf of the Barents Sea on the boundary with the White Sea (area 5), Franz Josef Land Archipelago (area 13), Geese Bank area in the Barents Sea (area 18), Baidara Bay (area 24), the waters of the north-eastern coast of Novaya Zemlya and the Novaya Zemlya Trough

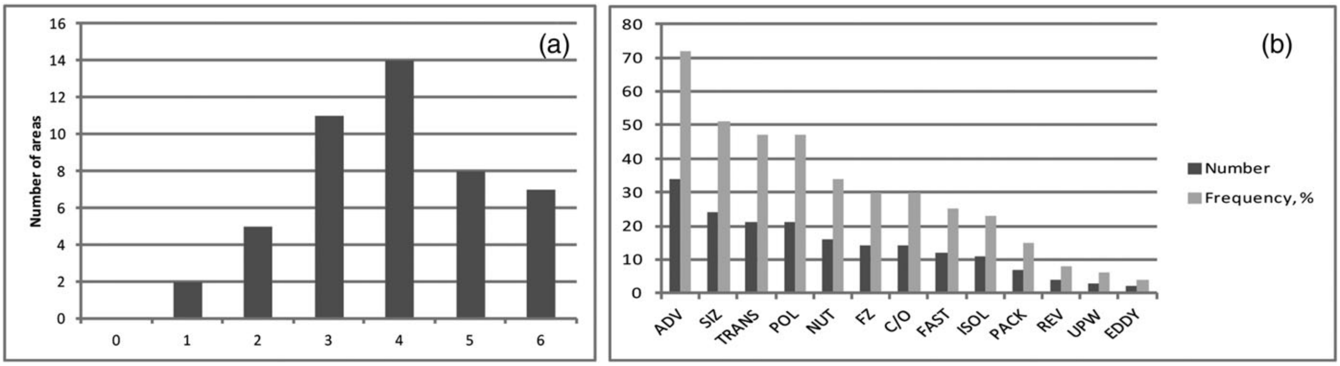

FIGURE 3 Frequency of oceanographical features associated with CPAs. **(a)** distribution of CPAs with particular number of oceanographical features; **(b)** ranking of oceanographical features. ADW – Advection; SIZ – Seasonal ice zone; TRANS – Transformation of water masses; POL – Polynyas; NUT – External sources of nutrients; FZ – Frontal zones; C/O – Coastal offshore transitional zones; FAST – Landfast ice; ISOL – Specific oceanographical regime of semi-landlocked bays, fjords and lagoons; PACK – Long existing massifs of pack ice; REV – Strong reverse tidal currents; UPW – Upwelling; EDDY – Stationary eddies (see Supplementary material for data sources)

(area 25), and the south-eastern shelf with numerous islands (area 31) in the Kara Sea (Figure 1a).

The most frequent feature is the advection of particular primary or secondary water masses (in 72% of CPAs), followed by local water mass transformation, seasonal marginal ice zones and flaw polynyas, and external sources of nutrients (ranging from 47 to 51% of CPAs). Particularly important are major frontal zones, and coastal phenomena such as coastal/offshore waters transition zones, massifs of fast ice and specific regimes of semi-isolated fjords and bays (25–30%). Massifs of pack ice, upwelling, and stationary eddies are less frequently associated with CPAs (4–15%). (Figure 3b).

3.2 | Combinations of oceanographical features and bio-oceanological processes supporting conservation features in particular areas

In the generally ice free south-western and southern Barents Sea, CPAs are located mostly in the coastal zone (areas 1–4 and partly 5, Figure 1a). The most common combination of oceanographical features there is the impact of advection of Atlantic water with the Murmansk Current or Murmansk Coastal Current and locally transformed coastal water masses. There may be also local fronts formed by tides and interaction of the coastal waters and the waters of Murmansk Coastal Current. Of particular importance are the specific regimes of semi-enclosed fjords and fjordic lagoons (Supplementary material).

Advection of the Atlantic water is also important for the Geese Bank CPA (area 18, Figure 1a) but for most other parts of the eastern and northern Barents Sea it is the transformed Barents Sea water that is advected and interacting with coastal (Figure 2a), Arctic (areas 13, 14) or Kara Sea waters (area 15). The advection impact on biodiversity is often associated with the effect of the Polar Front (in its eastern fuzzy segment; area 18), the St. Anna Trough Front (area 15) and with the seasonal ice zone in spring (Supplementary material). Only in the very north of the Barents Sea, off the Franz Josef Land Archipelago (area 13) flaw polynyas play a significant role.

In the south-eastern Barents Sea (areas 20–23, Figure 1a) the oceanographical features that underlie CPAs are diverse. Here Atlantic water advection has little importance but instead the advection of the River Pechora runoff-derived water, nutrient supply from river discharge and ice edge conditions in spring are often combined. Of particular importance is the water mass transformation, i.e. river runoff in area 22, and a specific mixing by tidal currents in the Chioshskaya Bay (area 21) resulting in an oasis of relatively warm near bottom water (Figure 2b).

The White Sea is a relatively small semi-landlocked enclave of the Arctic Ocean. All CPAs there are characterized by specific processes of water mass transformation and formation of a diversity of water column structures (Pantyulin, 2012). In four of six CPAs this is combined with the presence of partially isolated water bodies, i.e. fjords, fjordic lagoons or lagoons of accumulative origin with specific oceanographic regimes. External sources of nutrients, reverse tidal currents and winter polynyas have a pronounced impact on the biodiversity in half of the CPAs of this sea (Supplementary material).

All CPAs in the Kara Sea are affected by advection of one or another water mass: the Baidara Bay (area 24) by the Barents Sea water, the north-eastern Novaya Zemlya area (25) by the Kara shelf water, all CPAs in the south and the east of the sea by the water of the Ob and Yenisei rivers runoff, either directly by river water (areas 27, 28) or the water transformed in the huge combined Ob–Yenisei outer estuarine system (areas 26, 31) (Figures 1a, 2a). In the north-eastern Kara Sea large CPAs are associated with the area of advection of the Arctic water in the surface and subsurface layers and the transformed Atlantic water in the deep layers, so that warmer bottom water temperature is characteristic of parts of areas 29 and 30 (Figure 2b). Advection is most frequently combined with stationary polynyas, and with the ice edge zone in spring (in five of eight CPAs), and with pack ice massifs and external (river runoff) sources of nutrients (in four CPAs).

In the Laptev Sea (areas 32–35, Figure 1a) the impact of advection is also important and is associated with all CPAs. It is the river runoff water mostly originating from the discharge of Lena River that strongly influences the oceanographical regime and distribution of various groups of organisms in the Laptev Sea shelf (Figure 2a). All CPAs are also located within the area of flaw polynyas formation

(Figure 1b), and are influenced by the conditions of the ice edge zone in summer, and all but one coincides with coastal to offshore transition (Figure 2a).

There are only two CPAs in the East Siberian Sea proper (areas 35 and 36, Figure 1a). Both of them include coastal waters and are influenced by long-lasting fast ice.

The CPAs in the Chukchi Sea (including the boundary area between the East Siberian Sea) are all influenced by advection (except coastal area 41, in a large lagoon where local transformation of water masses is more important). The advected water in the east comes from the Pacific through the Bering Strait (areas 40, 42, Figure 1a) while in the west it is the transformed Chukchi Sea water (areas 38, 39, Figure 1a). Advection is commonly combined with polynyas and/ or the seasonal ice edge zone (in three of five CPAs).

In the north-western Bering Sea polynyas and advection appear to be oceanographical features most frequently associated with CPAs, but there are several others, forming various combinations.

Thus each Arctic sea in the studied area or a large part (in the case of the Barents Sea) is characterized by a distinct combination of oceanographic features associated with CPAs.

4 | DISCUSSION

4.1 | Oceanographical background of conservation priority areas

The pattern of association of oceanographical features and CPAs indicates profound and diverse relationships between oceanographical processes and phenomena and conservation features used for systematic conservation planning in the Russian Arctic (Solovyev et al., 2017). However, studies which focus on the specific ways of shaping biodiversity features in particular CPAs by oceanographical features are limited.

Seasonal changes in advection, stratification/ mixing, oceanographical fronts formation and nutrient cycling in the coastal waters explains high pelagic productivity and patterns of plankton distribution in the coastal CPAs of the Rybachiy and Kola peninsulas in the Barents Sea (areas 1–4, partly 5, Figure 1a). As a result, the coastal zone off Kola Peninsula which comprises 3% of the shelf area provides 9–13% of its annual net primary production (Makarevich & Druzhkova, 2010). Coastal zooplankton may reach high biomass as a result of a combination of local processes in the coastal pelagic ecosystem and advection of the dominant copepod species *Calanus finmarchicus*, seasonal development of meroplankton (Kamshilov, 1958), and aggregating of krill facilitated by eddies and coastal fronts (Drobysheva, 1994; Zelikman, 1961). This pelagic production along with the production of kelp forests is the basis for organisms of upper trophic levels in both pelagic (ending in seabirds and marine mammals) and benthic (ending in demersal fishes, king crab *Paralithodes camtrchaticus*, eiders and partly seals such as bearded seal *Erignathus barbatus*) food chains which are particularly interconnected in the coastal zone. Rocky shores, complex topography and the specific oceanographical regime of fjords and inlets provide suitable coastal habitats for colonial seabirds (Bakken et al., 2000; Gavrilo, 2011b), and a diversity of hard and soft subtidal bottom habitats and respective communities (Bobkov, Mai, Lazareva, & Spiridonov, 2013; Bobkov, Strelkov, & Ilyina, 2010; Britayev, Rzhavsky, Pavlova, & Dvoretskij, 2010; Propp, 1971; Semenov, 1988; Sharonov, 1948; Zatsepin, 1962).

An example demonstrating how a combination of tidal currents, water mass transformation and specific sea ice regime shape biodiversity features in a CPA is provided by the Gorlo, a relatively shallow and narrow strait connecting the outer and inner parts of the White Sea. There strong tidal currents form local circulations, create high turbulence and mix the whole water column (Kosobokova et al., 2004; Pantyulin, 2003, 2012). The Gorlo area is remarkable, owing to its specific role in forming the unique oceanographic regime of the White Sea (i.e. formation of cold deep water owing to winter mixing of the unstratified water column). This cold water spreads to the south and fills the deep areas of the inner White Sea at depths from 60 to 70 m to the maximum depth of about 330 m and retains sub-zero temperature year round (Kosobokova et al., 2004; Pantyulin, 2003, 2012) thus playing a key role in maintaining an Arctic enclave in the White Sea, which is partly located south of the Polar Circle. This oceanographical regime results in a highly distinctive pattern of benthic diversity in the Gorlo and may act as a filter for Atlantic species penetrating the White Sea (Solyanko et al., 2011a). Strong tidal currents provide an effective supply of phytoplankton for blue mussels (*Mytilus edulis*) which form abundant shallow subtidal beds along the eastern shore of the Kola Peninsula (Milyutin & Sokolov, 2006) serving as feeding ground for eiders (Krasnov, Spiridonov, & Dobrynnin, 2012; Krasnov, Strøm, Gavrilo, & Shavykin, 2006). An important feature of the sea ice regime of the White Sea is the regular export of the ice flows to the Barents Sea (Krasnov, Gavrilo, & Spiridonov, 2011; Pantyulin, 2012). The discharge of the Severnaya Dvina River and the pattern of mesoscale water circulation combine to create so-called spiral eddies; this is a prerequisite for the formation of large and stable ice floes in the Gorlo of the White Sea. These ice habitats attract harp seals (*Pagophilus groenlandicus*), which arrive in February and March from the Barents Sea and the adjacent North-east Atlantic to breed and moult (Melentyev & Chernook, 2009). Water circulation and wind create a stable system of polynyas and stretches along the coast of Kola Peninsula (spatially coincidental with the belt of mussel beds) which function as a wintering ground for several species of eiders (Krasnov et al., 2006, 2011).

The boundary between the Barents and the Kara Sea to the north of Novaya Zemlya Archipelago (area 15, Figure 1a) is dominated by the current bringing the Barents Sea water along the north-western coast of North Island of Novaya Zemlya. In the slope area of St. Anna Trough this warmer and saltier water meets the cold and freshened Kara Sea water forming an abrupt front (Flint, Poyarkov, & Soloviev, 2015; Zatsepin et al., 2015). This front creates conditions for two distinct benthic faunas within this CPA (Vedenin, Minin, & Galkin, 2015). The slope frontal zone provides conditions for the accumulation of phytoplankton and zooplankton biomass reaching the highest levels found in the Kara Sea values (Flint et al., 2015; Sergeeva et al., 2015). Thus this front forms a hotspot of productivity and intensive trophic interactions at basic trophic levels (Flint et al., 2015), which probably is a key factor in attracting organisms of upper trophic levels. High abundance of Greenland halibut (*Reinhardtius hippoglossoides*) and polar cod

(*Boreogadus saida*) are known to be associated with the St. Anna Trough (Borkin, Vasiliev, & Chetyrkina, 2008).

In the southern Kara Sea the Ob–Yenissean mouth CPA (area 26, Figure 1a) ecosystem provides an example of an ecosystem governed by river runoff and advection of transformed riverine waters and estuarine fronts. Taxonomic diversity and biomass of communities follow the actual (for plankton) and averaged over time (for benthos) salinity gradient (Galkin, Kucheruk, Minin, Raiskyi, & Goroslavskaya, 2010; Polyak et al., 2002; Stepanova, 2000; Vedenin, Galkin, & Kozlovsky, 2015; Vinogradov, Shushkina, Lebedeva, & Gagarin, 1994). The main estuarine front is located in the mouth of the Ob Gulf and extends offshore to a distance of about 100 km. This front separates nutrient-rich waters discharged by the River Ob that fuel high activity of brackish water phytoplankton. The maximum productivity of the brackish water phytoplankton in the frontal zone is reached in summer when turnover of nutrients coming from dying off freshwater phytoplankton cells is particularly high (Lapin, 2012). Processes in the estuarine front of the Ob Gulf result in the enhanced biomass of estuarine zooplankton at the inshore periphery of the estuarine front (Vinogradov et al., 1994) and high benthic biomass at the marine side of the front (Denisenko, Sandler, Denisenko, & Rachor, 1999; Galkin et al., 2010; Stepanova, 2000). Along with the ice regime (extensive landfast ice and a flaw polynya, see Figure 2b) they also profoundly influence feeding and migration behaviour of fish and marine mammals (UNEP/CBD/EBSA/WS, 2014).

Advection of the transformed water from river runoff (Figure 2a) and a changing salinity regime are the main oceanographic factors shaping distribution of zooplankton and macrobenthic species in the waters in the western Laptev Sea (area 32, Figure 1a). Salinity gradients along the eastern coast of Taymyr Peninsula and inter-annual variability of oceanographical conditions lead to a complex distribution of species and communities, representing practically all known Laptev Sea eco-faunistical assemblages of zooplankton (Abramova & Tuschling, 2005) and benthos (Petryashov, Golikov, Schmid, & Rachor, 2004; Petryashov & Novozhilov, 2004). A significant role in creating the ecological distinctness of this CPA is played by the Anabar-Lena and the East Taymyr polynyas (Gavrilo et al., 2011) which are associated with areas of higher annual primary production (Vetrov & Romankevich, 2011; Vetrov, Romankevich, & Belyaev, 2008), and increased benthic biomass (Petryashov et al., 2004; Schmid et al., 2006). Light conditions and early development of plankton in the years of optimal polynyas expansion facilitate recruitment of polar cod, the basic prey for vertebrate predators at upper trophic levels (Bouchard & Fourtier, 2008). Polynyas to the east of Taymyr Peninsula also support colonies and migration routes of seabirds, the wintering and feeding grounds of the Laptev population of Pacific walrus (*Odobenus rosmarus divergens*), concentrations of ringed seals (*Phoca hispida*) and its main predator the polar bear (*Ursus maritimus*) (Gavrilo et al., 2011).

In the Chukchi Sea an interesting case study is related to area 42 (Figure 1a). There a frontal zone is formed between the Bering Sea–Anadyr Current bringing the warm, salty and nutrient rich Pacific water, and the cold, freshened and nutrient poor Siberian shelf water, the so called Chukotka or Siberian Coastal Current (Brugler et al., 2014; Rusanov, 1980). Increased primary production associated with this zone (Rusanov, 1980) and other frontal zones of the Chukchi Sea makes this sea one of the most productive Arctic seas (Grebmeier & Maslowski, 2014). Within the frontal zone a large stable eddy or gyre is formed. This gyre, first discovered by Ratmanov in 1937, provides a supply of nutrients, facilitates high primary production, retention of planktonic larvae of benthic species and provides organic matter flux to the bottom that is the basis for the persistence of stable and biomass-rich benthic communities (Pisareva et al., 2015; Sirenko et al., 2009). Abundant seabed communities are particularly important as a food resource for benthos-eating marine mammals, such as grey whale and Pacific walrus (Grebmeier & Maslowski, 2014; Kędra et al., 2015). The narrow strip of open water in spring, the so called Chukotka Lead is the main corridor for seasonal migration of marine mammals and seabirds from the Bering Sea to the Arctic shelf (Gavrilo et al., 2011).

These examples illustrate how such diverse bio-oceanological mechanisms make particular areas outstanding from the biodiversity standpoint. Although, as shown in the present study, there are certain patterns of combination of CPA-relevant oceanographical features in particular Arctic seas, the ways of shaping biodiversity features in particular CPAs by oceanographical features may be unique. An important practical consequence for spatial conservation planning is a need to account for the spatial and temporal scales of these underlying oceanographical features which are essential for understanding what is required for conservation of marine communities and ecosystems (Mokievsky, 2009). Targeted collection and analysis of data and area-specific modelling are also required. In developing the proposed CPA network into a MPA network, care will need to be taken when defining the MPA boundaries, and a regime of protection, management and monitoring will need to be developed on the basis of the detailed oceanographical and bio-oceanological characteristics.

4.2 | CPA network resistance and resilience based on its oceanographical background

Solovyev et al. (2017) state that the resistance and resilience of the CPA network in the Russian Arctic seas to climate-induced ecosystem changes needs a special examination. This is an enormous task which necessarily involves different methodologies. However, focusing on particular oceanographic features which shape conservation features in CPAs may prove to be a productive approach.

Although it is not clear how the current trends towards the warmer Earth will interact with the cyclical nature of the Arctic climate, most experts agree that over the next few decades there will be an increase in advection of the Atlantic, and probably Pacific water in the Arctic, a reduction of summer sea ice cover and an increase in the duration of the open water season, and a decrease of the amount of multi-year ice (Hunt et al., 2016; IPCC, 2013).

The advection of the Atlantic and Pacific waters and spring to summer sea ice conditions, i.e. the effect of ice edge, are among the most important oceanographical features for CPAs in the Russian Arctic seas. An obvious biological consequence of the increasing inflow of the Atlantic water into the Barents Sea are the borealization of the biota (Fossheim et al., 2015; Hunt et al., 2016), changing of timing of the spring phytoplankton bloom (Eamer et al., 2013; Kahru, Brotas, Manzano-Sarabia, & Mitchell, 2011), additional coccolithophore blooms (Eamer et al., 2013) and respective changes in the food web (Kędra et al., 2015; Kortsch, Primicerio, Fossheim, Dolgov, & Aschan, 2015).

Business as usual model simulation predicts continuation of the current trend of decreasing summer sea ice cover and increasing open water season following the increased input of warm Atlantic and Pacific waters to the Arctic Ocean (Barnhart, Miller, Overeem, & Kay, 2015). By the year 2050 this study forecasts most parts of the Barents Sea and Chukchi Sea to become ice free year round and the duration of open water season in the Laptev Sea to increase up to about 5 months. If this happens, the role of the sea ice ecosystem and the effects of ice edge on ecosystem processes will be reduced in a number of CPAs. The CPAs in the south-eastern Barents Sea and in the southern Chukchi Sea may be most affected. In the first case the absence of sea ice will threaten the transport of algal production to the benthos (Denisenko, 2013; Eamer et al., 2013; Kędra et al., 2015) which in turn is an important food resource for Atlantic walrus (*Odobenus rosmarus rosmarus*) and eiders (see respective conservation features in Supplement to Solovyev et al., 2017). However, in such shallow areas as the south-eastern Barents Sea, that are surrounded by land and influenced by river runoff, the formation of winter sea ice shows significant regional variability and may not follow the trend predicted for deeper areas. In the years 2007–2017 a significant coverage of sea ice was observed in the south-eastern Barents Sea at least up to mid-May when most of the Barents Sea was ice free (AARI, 2007–2017).

According to the data presented by Fossheim et al. (2015) the zone of progressing borealization of the fish assemblages is currently affecting areas 18 and 20 in the eastern Barents Sea, and the southern part of area 12 in the central part of the sea (Figure 1a). Along with changing timing of seasonal impact of the ice edge (see below) this borealization process may seriously change the conditions of the respective CPAs towards decreasing or negligible contribution of sea ice algae production, an earlier and reduced phytoplankton maximum (Kahru et al., 2011), reorganization of the consumers' food web, and probably lower export of pelagic production to benthic communities (Kędra et al., 2015). However, these areas are associated with banks on the deep Barents shelf which play a significant role in the formation of the Barents Sea water in winter (Adrov, 1958; Loeng, 1991), secondary fronts and upwelling (see Supplementary material). Thus they will likely maintain this function and continue to provide the basis for productivity and diversity of the boreal and Arctic-boreal species but with a smaller contribution or even absence of cold water Arctic species (Fossheim et al., 2015; Zimina, Lyubin, Jørgensen, Zakharov, & Lyubina, 2015).

The coastal CPAs in the Barents Sea particularly influenced by the advection of Atlantic water or its derivatives (i.e. areas 1–5) are, from the biogeographical standpoint, boreal areas in the Arctic latitudes. This coastal ecosystem already comprises boreal and Arctic-boreal species which can tolerate low winter temperature (Zatsepin, 1962). Their productivity is controlled by specific processes in the coastal zone (Makarevich & Druzhkova, 2010) and may, of course vary in response to changes in the Atlantic water inflow. However, this oscillating regime has been experienced by the coastal ecosystems in the southern Barents Sea for millennia (Breivik, 2014).

The advection of the Pacific water is highly important for the thermal regime, and maintaining productivity of the Chukchi Sea has been highly variable for decades (Luchin & Panteleev, 2014). However, benthic communities that are essential for feeding of several marine mammals in the Chukchi Sea (Laidre et al., 2015) are responding to averaged oceanographical conditions at the scale of years to decades (Pisareva et al., 2015; Sirenko et al., 2009). This variability will likely continue in the future and the importance of such areas as CPA 42 (Figure 1a) covering the frontal zone and a local gyre will likely persist.

The future for CPAs influenced by advection of the Arctic water is far more difficult to forecast. This is especially true for such complex areas as the one around the Franz Josef Land Archipelago (area 13, Figure 1a). In simple terms the situation is that for the Arctic Basin, the Kara Sea waters are advected towards the archipelago in the surface layers, the Barents Sea water comes in the subsurface layers, while the Atlantic water enters the area in the deep layers resulting in an increase in near bottom temperature (Figure 2b). A variety of factors have an impact on the marine biota of the CPA, such as the complex coastline, seabed topography, and water circulation, glacial runoff, local fronts and upwellings, fast ice, polynyas (Figure 1b), and an overlap with the Transpolar Sea Ice Drift (Supplementary material). Although the ecosystem of the archipelago waters is certainly influenced by the increasing inflow of the Atlantic water, changing ice conditions and acceleration of summer glacial melt, the complexity of the processes in the area may also create refugia for sea ice biota, High Arctic species of benthic invertebrates and fishes, and the communities of high-latitude types. The area of Franz Josef Land Archipelao will certainly maintain its priority for conservation in the future.

The areas in which the conservation features are shaped by river runoff water advection will likely also maintain their importance. While the river discharge volume and seasonal pattern may change in the future, salinity gradients, freshwater ice formation, estuarine fronts and river plumes will remain essential features influencing the biological processes.

The CPAs associated with transformation of water masses are best exemplified by the White Sea, an Artcic enclave in the subarctic latitudes. Palaeontological, palaeoecological, and archaeological data demonstrate that during the Holocene temperature maximum, when the coasts of the White Sea were covered by broad-leaf forests, marine ecosystems retained the Arctic features (Spiridonov, Naumov, Chikina, & Simakova, 2015). Physical mechanisms of resistance to changes are determined by the processes in Gorlo (area 6, Figure 1a), a narrow and shallow strait connecting the outer and the inner part of the sea. There tidal mixing and formation of cold, deep water takes place which buffers conditions in the water column below the seasonal thermocline in most subtidal habitats of the White Sea (Solyanko, Spiridonov, & Naumov, 2011b; Spiridonov et al., 2015).

Another example of CPAs governed by water mass transformation is Chioshskaya Guba (area 21, Figure 1a), a large shallow bay in the south-eastern Barents Sea, which may be considered as a characteristic boreal biogeographical enclave surrounded by areas hosting Arctic biota and ecosystems. An essential oceanographical phenomenon that shapes biodiversity features in this area is the same as in the Gorlo (area 6), namely strong tidal currents which have in many respects a different effect on the biological processes. Owing to complete mixing of the water column and the input of warmer fresh water in spring–summer, near bottom temperature is relatively high (Figure 2b), numerous small rivers provide a significant supply of nutrients, and the shallow depth facilitates the transport of phytoplankton production to the bottom. This allows boreal benthic species to thrive in species-rich communities with high biomass (Denisenko, Denisenko, Lehtonen, Andersin, & Sandler, 2007). As the system is maintained by tidal driven processes it appears to be resistant to climatic changes and the Chioshskaya Guba will likely remain a distinct biodiversity hotspot even in the face of advancing borealization of the surrounding areas.

Flaw polynyas of the Kara and the Laptev Sea and their spatial–temporal inter-annual variability are a product of the interaction of processes associated with three atmospheric centres: the Icelandic Minimum, the Arctic and the Siberian Maxima. Deepening of the Icelandic Minimum intensifies the Atlantic cyclones, which receive their energy from the Kara Sea polynyas, to cross the Taymyr Peninsula and form a wind system which facilitates the development of polynyas in the western Laptev Sea (Gavrilo et al., 2011; Popov & Gavrilo, 2011). Strengthening of the Arctic Maximum leads to the development of polynyas in the eastern Laptev Sea. Comparison of the characteristics of the Laptev Sea polynyas during the period 1936–1970 with the situation in the 2000s indicates that the frequency of occurrence and the numbers of recurring polynyas in the last two decades have increased (Gavrilo et al., 2011) which is likely to have had a positive impact on the ecosystem productivity. Indeed modelling, based on the remote sensing data, indicated slight positive trends of average and total phytoplankton production in the Laptev Sea up to the year 2007. On the other hand, total sea ice algae production has shown a slight decrease, and thus the resulting overall production remains almost unchanged (Vetrov & Romankevich, 2009, 2011). Models and forecasts of polynyas development for the next few decades are lacking because of the extremely complex interaction of the processes leading to polynya formation. However, it is unlikely that the pattern of influence of winter sea ice and polynyas on ecosystems and species in the CPAs of the Kara Sea and Laptev Sea will change significantly over the next several decades.

The future of extensive areas of the fast ice, which is also important for particular conservation features is out of the scope of the current sea ice variability modelling. Fast ice formation is governed by a variety of local factors, and extensive and long-lasting fast ice cover may be maintained even in the relatively low latitude Arctic, such as the Mezen Bay of the White Sea (area 7, Figure 1a) (Demidenko, Rzhanitsyn, & Krylenko, 2012).

The examples discussed above are mainly related to physical resistance issues while the resilience of biodiversity features depends in many respects on the adaptive potential of the Arctic biota. It is probably not so important in terms of thermal tolerance of benthic species. Low near bottom temperature in most of the CPAs and their surrounding area, except for external inflow shelves of the Barents and Chukchi seas and the areas of deep advection of the Atlantic water at the northern shelf break (Figure 2b) is determined by winter production of cold and salt water, such as on the banks of the Barents Sea (Adrov, 1958), in the Gorlo of the White Sea (Kosobokova et al., 2004; Pantyulin, 2012), or in the polynyas. These winter processes will likely not change much in the coming decades. Thus the most important issue for benthic biota and communities will be adaptation to a changing regime of pelagic production and transport of organic matter to the bottom (Kędra et al., 2015).

The most discussed topic in the literature (Eamer et al., 2013; Hunt et al., 2016; Kędra et al., 2015; Melnikov, 2008) is the ability of sea ice associated biota and ecosystems to maintain their distribution and functions in changing sea ice conditions. The CPAs of the proposed network remain poorly studied with regard to the sea ice associated community of primary producers and invertebrate consumers. However, observations of sea ice specific forms of marine nematodes indicate that in the seasonally ice covered White Sea (area 9, Figure 1a) the same species that live in the pack ice of the Arctic Basin survive the ice free seasons thanks to some as yet unknown mechanism (Tschesunov, 2006). Understanding these mechanisms is critical for forecasting possible changes in sea ice biota under a changing climate.

Other topics that need to be explored for the CPA network are related to its ability to provide refugia and/or possibility to maintain migrations for several high-latitude Arctic species of fishes and a few high-latitude species of seabirds such as ivory gull, *Pagophila eburnea* (Gavrilo, 2011a; Gilg et al., 2010), cetaceans, such as narwal, *Monodon monoceros*, and sea ice dependent polar bear (Laidre et al., 2015). While being threatened by sea ice habitat shrinkage or loss in summer, ice-dependent seabirds and marine mammals need extensive areas of special protection and monitoring where their populations would be able to realize their adaptive potential.

Overall, a highly important scientific and conservation problem associated with the current climate trends in the Arctic is changes in the composition and spatial structure of the Arctic biota. Increased advection of the Atlantic and Pacific waters and the summer sea ice loss leads to an increase in general biodiversity due to expansion of boreal species and milder conditions suitable for the boreal type communities, including those currently existing in isolated refugia, such as seagrass communities in the Barents and the Bering seas. Thus the importance of CPAs associated with these boreal and Arctic-boreal components of biota (i.e. areas 1–5, 9–11, 18, 21, 42, 43, 46 in Figure 1a) will be very likely maintained in the future. On the other hand, high Arctic, endemic species and specific communities, such as sea ice communities (Eamer et al., 2013; Melnikov, 2008) or benthic communities of glacial fjords (Drewnik et al., 2016) will be declining. The CPAs relevant for these species and communities include very extensive areas around the Franz Josef Land Archipelago (area 13), shelf break and slope of the Kara Sea (area 29), waters around the Severnaya Zemlya Archipelago (30), south-eastern part of the Kara Sea with numerous islands and small archipelagoes (31), the waters of the northern part of the Novosibirskie Islands Archipelago (areas 34 and 35), and the waters around Wrangel Island (area 39 in Figure 1a). All these areas are poorly studied with regard to the oceanographical processes determining the current condition of marine populations and ecosystems. However, all of them also include a variety of complex coastal and offshore features that are expected to diversify their response to climate change. In particular, the Kara part of the Severnaya Zemlya area (30) hosts a colony of the Arctic endemic ivory gull at Domashniy Island (Gavrilo, 2011a; see also Figure 27 in Eamer et al., 2013). The nesting population abundance strongly depends on the development of a local polynya. This in turn is related to the winter ice cover which is expected to be maintained in the eastern Kara Sea in the next decades even under scenarios of increasing length of the open water season (Barnhart et al., 2015). This supports their selection as potential refugia of high latitude biota and as areas of high conservation priority.

The present systematic conservation planning project ultimately aims at establishing new MPAs and/or protection regimes within potential marine spatial planning schemes in the Russian Arctic (Spiridonov, Gavrilo, Nikolaeva, & Krasnova, 2011). Progress in implementation of the MPA network, and/or development of marine spatial planning in Russia and elsewhere depends on a variety of economical, social, political, and institutional circumstances, stakeholders motivations, and even on personal attitudes of particularly important players. Currently it is difficult to predict the pace of this process. Even if implementation of this MPA network is slowed down owing to conflicts with economic development, or for institutional, financial, or political reasons, the CPAs may function as a basis for the large-scale monitoring incorporated in the Circumpolar Biodiversity Monitoring Programme of the Arctic Council (CAFF, 2017).

5 | CONCLUSIONS

The CPA network for the Russian Arctic seas developed through the application of MARXAN and post-MARXAN analysis was largely based on the biodiversity, coastal and seabed habitat features. Although most oceanographical features were not involved in the analysis directly the resulting CPAs are shown to be grounded on oceanographical processes and phenomena, such as advection of primary or transformed water masses, water mass transformation, seasonal sea ice edge and extensive fast ice area, and flaw polynyas, riverine sources of nutrients and various oceanographical fronts. Although this oceanographical background needs further understanding and more detailed information, it provides a possibility to refine the boundaries of MPAs. Furthermore it allows evaluation of the potential resistance and resilience of CPAs to climate change by focusing on relevant oceanographical processes on an area by area basis.

The conservation of Arctic marine ecosystems in the time of global change cannot be achieved without a coordinated effort across the entire Arctic ocean and its coastal zone. We hope that an approach to conservation planning similar to that described here with the linking of conservation features to the oceanographical background will be adopted by other nations that have interests and responsibilities in the Arctic.

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DISCLOSURE/CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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