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Forty years of warming: Environmental change in marine coastal habitats on Svalbard between 1981 and 2022

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Abstract: Temperature rise, together with resultant ice cover retreat in Svalbard, changes in hydrology and geomorphology of fjords and coastal waters, is presented as forming force for the marine habitats. Satellite data show increase of habitat complexity following the tidal glaciers retreat and emergence of new (315 km) and complex shoreline. Most evident changes occur in the inner-fjord settings of the west coast of the archipelago, while habitats of exposed marine shores and eastern sector of Svalbard remain little changed. It is hypothesized, that decrease in ice cover opens more space for life compared to the cold period.

Keywords: European Arctic, coast, climate change, marine habitats.

Introduction

Arctic is commonly regarded as most rapidly warming region of the world (ACIA 2005), and the large-scale international effort was directed to understand the processes in the ice-covered central Arctic, which has been considered as the key area for the assessment of the change (Forbes *et al.* 2011). The coastal waters were somehow neglected and only recently it turned out that coastal waters in the European Arctic are critically important for the conservation of the Arctic species, the fishery, tourism, and additionally, it is a place of massive deposition of plastic litter (Soreide *et al.* 2020). The authors have been working in the fields of coastal oceanography and marine biology of Svalbard since 1977, with activities run almost every year. The research focus was put especially to Hornsund and Kongsfjorden (Węsławski *et al*. 2017), as well as the intertidal zone around the archipelago; see https://old.iopan.pl/projects/SIP/SIP-2008/index.html. Satellite imagery analyses and GIS modeling for the large-scale assessment of the coast served as important addition to the direct observations on the ground (Urbański and Litwicka 2022).

This paper presents the collection of the observations published and reported in different databases from the marine habitat point of view. We regard this approach as a key for understanding of the ongoing biodiversity and ecosystem functioning change, that follows borealisation of the European Arctic (Csapó *et al*. 2021) and sea ice loss (Linse *et al.* 2021). There is a consensus that last climate optimum on Svalbard, about 9,500 years BP was warmer than today, which was manifested in different forms, *e.g.*, by the lack of glaciers in the archipelago (Svendsen and Magnerud 1997), massive occurrence of thermophilic molluscs over the whole area (Salvigsen *et al*. 1992), and the polar bear retreat to the cold refugia (Seppä *et al.* 2023). Our aim is to assess the present-day tendencies of the coastal habitats change of the area and point out its possible consequences.

Material and methods

The analysis of changes in the coastline and fjord surfaces was conducted for three periods: 1936, 1985, and 2022. The coastline shape was extracted from aerial and satellite imageries with a resolution of 10–30 meters and manually classified into three categories: glacier fronts, new coastline compared to 1936, and the unchanged coastline. For the year 1936, orthophotomosaic data from 1936/1938 with a resolution of 20 meters were used (Geyman *et al*. 2021). For the years 1985 and 2022, Landsat 5 satellite imagery data (U.S. Geological Survey, 2022; https://earthexplorer.usgs.gov/) and Sentinel 2 imagery data downloaded from the Copernicus Open Access Hub were used (Copernicus Sentinel data 2022; https://scihub.copernicus.eu/dhus/#/home). Since the cloud-free Landsat 5 images from 1985 did not cover the entire analyzed area, they were supplemented with images from the 1983–85 period. The coastline data were converted into vector format, and data analysis was performed using the GIS software. The classification of the new coastline was based on the analysis of the MAXAR high-resolution data from the ESRI World Imagery within the ArcGIS Pro environment (ESRI 2022). The available classification schemes were generalized into the following classes: moraine beach, low soft beach, rocky coast, and mudflats.

Changes in sea surface temperature from 1980 to 2020 were analyzed by comparing the average temperature distributions of surface water for two, five-year periods: 1982–1986 and 2016–2020. The analysis utilized the Arctic Sea and ice surface temperature product, which is based on reprocessed AVHRR, (A)ATSR, and SLSTR SST observations from the ESA CCI project, the Copernicus C3S project, and the AASTI dataset. This product provides daily interpolated rasters with a resolution of 0.05 degrees (E.U. Copernicus Marine Service Information CMEMS; doi: 10.48670/moi-00123; Accessed on 10-05-2023). In cases where ice cover was present, the product includes ice surface temperature, which was converted to the freezing temperature of oceanic water (–1.9 °C).

For the other hydrographic and marine ecological data, the papers cited in the text were used. As coastal habitats, we consider all those within fjords and from outer coastline up to 100 m depth, *i.e.*, within direct influence of land/sea interactions. The typology of marine habitats was adopted from the EUNIS (https://www.europa.eu/data-and-maps/data/eunis-habitat-classification-1). When necessary, local modifications were introduced following the Norwegian Mareano project (www.mareano.no<http://www.mareano.no).

Results

Surface water temperature. — Surface water temperature rise compared to 1980, in coastal waters and in fjords (Fig. 1) is clearly linked to the bathymetry and flow of Atlantic waters, with warmed up deep parts of NW Spitsbergen and shallows at the entrance to Hornsund in the southern Spitsbergen isolated from Atlantic inflow that remains relatively cold. The temperature increase is pronounced especially in NW sector of Svalbard, Isfjorden and Kongsfjorden systems (increase above 2.3 °C), while coastal areas of NE Svalbard remain little changed.

Tidal glaciers retreat. — The results of our analysis presented in Fig. 2 show that the reduction in the length of tidal glacier fronts in Svalbard over the past 40 years amounts to 80 km, which represents approximately 8% of their total length. On Spitsbergen, the rate of change has been decreasing. In the period from 1936 to 1985, glacier fronts were receding at a rate of 1 km per year, and from 1985 to 2020, by 0.6 km per year; see Table 1.

The estimation of the scale of this phenomenon is presented in Table 2. This process occurs most intensively on Spitsbergen, which total coastline is currently (in 2022) 4,550 km. In the period from 1936 to 1985, a new coastline of 469 km was formed on Spitsbergen, representing an increase of almost 10%, and in the subsequent period (1985–2022), an additional 275 km of new coastline formed. In the entire Svalbard archipelago, there were 316 km of new coastline (Table 3).

Fast ice reduction. — Fast ice reduction on Svalbard, is most pronounced in NE sector of the archipelago and inner fjord basins. The limited change of fast ice on the warm, west coast is caused by its ocean exposure, so it was never covered with stable fast ice. The change of fast ice in sheltered fjords is however, dramatic, *e.g.*, Wijdefjord, Woodfjord and inner Hornsund (Fig. 3). The lack of stable winter ice causes higher exposure of coastline to the waves and more severe fetch, as illustrated on Fig. 4 for Isfjorden. The prominent increase was calculated for central North coast of Isfjorden – increasingly exposed to SW storms.

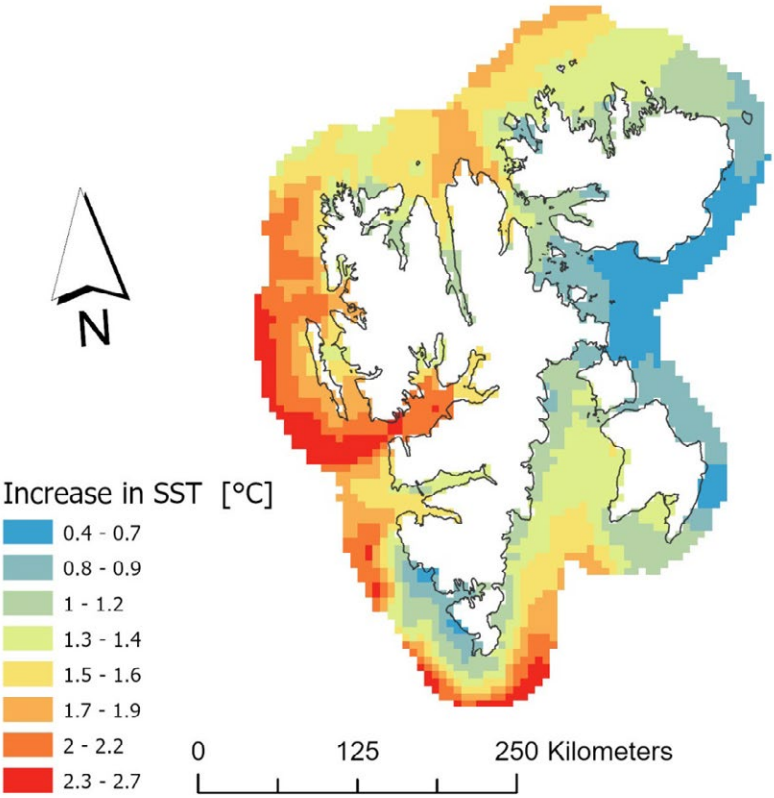

Fig. 1. Sea surface temperature rise on Svalbard, based on satellite data, increase between 1980 and 2020, data based on AVHRR, SLSTR SST observations the Copernicus C3S project, details described in Material and methods section.

Fjords topography. — Table 3 presents the areas of seven fjords on Spitsbergen for the years 1936, 1985, and 2022. The area (free of glaciers) of Hornsund increased by 50% during the period from 1936 to 1985 and by over 100% in the years from 1936 to 2022. Significant changes in the fjord areas also occurred during this time period in Kongsfjorden and Krossfjorden, with an increase of approximately 25% (Table 3).

Coastal change. — Majority of the new shoreline are moraine coasts and low soft beaches (50%), with relatively few new tidal flats (8%) and rocky shores exposed (12%). Hard substrate coast, *i.e.*, cliffs, rocks and skjerra, are being exposed by retreating glaciers, yet not in the large scale (Table 4).

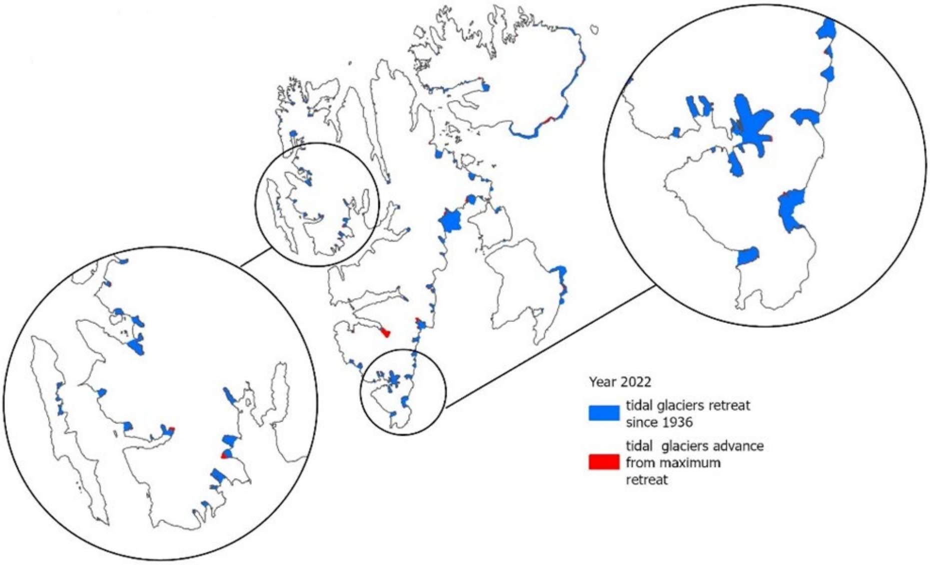

Fig. 2. Tidal glaciers retreat on Svalbard archipelago between 1936 and 2020, analyzed based on Landsat 5 satellite imagery and Sentinel 2 imagery from Cepernicus Open Access Hub, details in the Material and methods section, see also data in Tables 1 and 2.

Table 1.

Length of glaciers ice fronts in km on various islands of Svalbard.

Location/Year	1936	1985	2022
Spitsbergen	462	425	396
Nordaustlandet	?	294	299
Kvitøya	?	109	97
Edgeøya	82	80	57
Prins Karls Forland	14	22	5
Barentsøya	25	14	13
Storøya	?	12	10
Total	?	956	876

Table 2.

Increase Svalbard's various island coastline from 1936 to 2022 due to glacier retreat.

Location	Coastline in 2022 [km]	New coastlines 1936–1985. In parentheses, the mean new coastlines length over the course of the year [km]	New coastlines 1985–2022. In parentheses, the mean new coastlines length over the course of the year [km]
Spitsbergen	4551	469 (9.6)	275 (7.4)
Nordaustlandet	1950	?	18 (0.5)

Location	Coastline in 2022 [km]	New coastlines 1936–1985. In parentheses, the mean new coastlines length over the course of the year [km]	New coastlines 1985–2022. In parentheses, the mean new coastlines length over the course of the year [km]
Edgeøya	486	21 (0.4)	8 (0.2)
Barentsøya	254	16 (0.3)	8 (0.2)
Prins Karls Forland	271	11 (0.2)	6 (0.2)

Table 3.

Increase areas of selected Spitsbergen fjords from 1936 to 2022 due to glacier retreat. In parenthesis percentage change relative to 1936.

Location	Area in 1936 [km^2]	Area in 1985 [km^2]	Area in 2022 [km^2]
Isfjorden	2294	2345 (2.3)	2371 (3.3)
Wijdefjorden	997	1003 (0.5)	1010 (1.3)
Woodfjorden	732	740 (1)	744 (1.6)
Van Mijenfjorden	507	518 (2.2)	519 (2.4)
Hornsund	127	191 (49.8)	267 (109.8)
Kongsfjorden	199	217 (9.4)	245 (23.4)
Krossfjorden	162	185 (11.1)	206 (26.6)

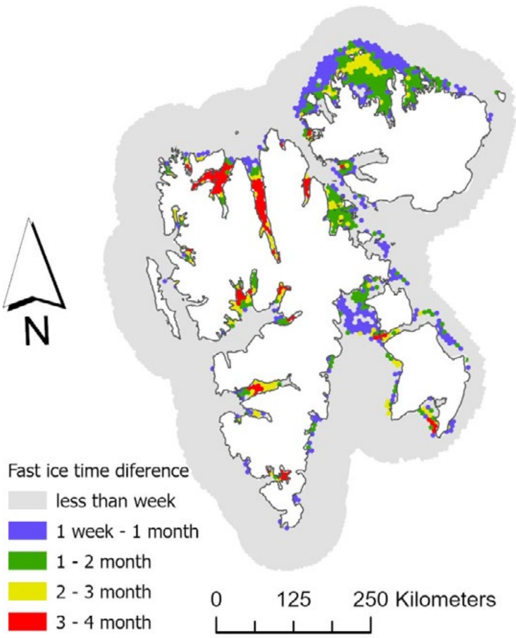

Fig. 3. The change between years 2000 and 2020 of annual fast ice duration on Svalbard, based on satellite imagery data from the Copernicus C3S project and AASTI dataset, details in Material and methods section.

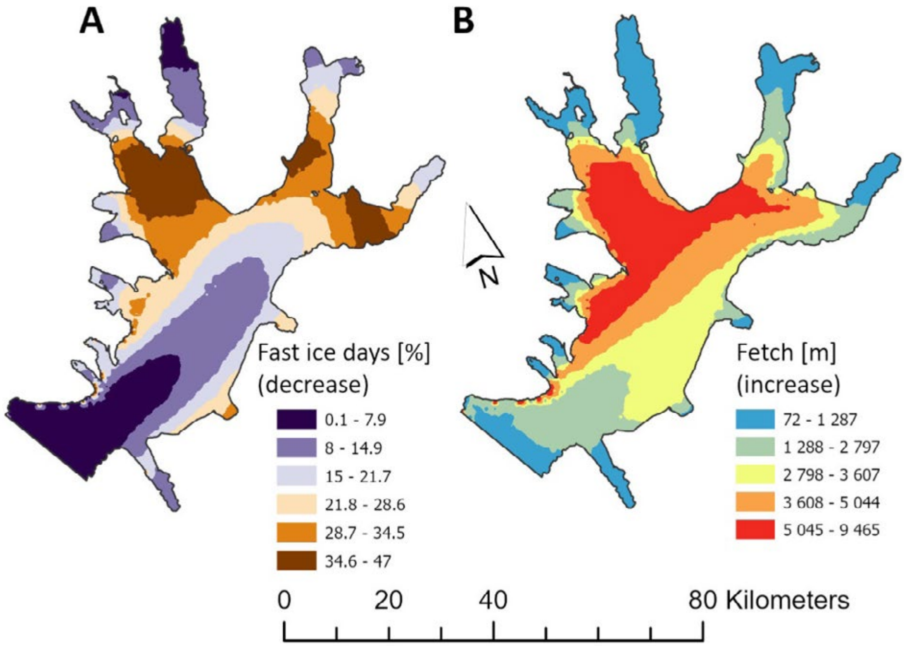

Fig. 4. Decreases in fast ice in Isfjorden, central West Spitsbergen (**A**), and consequent fetch increase (**B**), ice situation based on Copernicus C3S project and AASTI dataset, fetch calculated from the Norwegian Meteorological Office data on regional wind pattern in 2010–2020 years.

Table 4.

Change in the Svalbard coastal habitats between 1980 and 2022.

Coast type	Area or length	Change 1980–2022	Main ecological consequences
Tidal glacier front (water column and seabed)	870–960 km	loss of 80 km of ice cliffs, 316 km of new coast due to glaciers retreat.	top predators feeding ground change, bottom communities change
Soft sediment shore (mud, sand, gravel, stones)	length of Svalbard shore is 7770 km	increasing (100–150 km) mainly of moraine coast and low soft beach	limited local fauna, increase of haul out ground space
Fast ice on fjords	4580 km^2 (median 1980)	loss of 60% of iced area to 1800 km^2 (median 2022)	ringed seals breeding habitat
Rocky shores (cliffs, skjerra, boulders)	11.6% (800 km) of the non-iced coastline as of 2022	small increase by 75 km since 1936	more space for encrusting fauna
Rivers, lakes, lagoons	158 km^2 as of 2022	increasing area; strong increasing for lagoons	new habitat for fresh and brackish water species

Table 4 – *continued.*

Coast type	Area or length	Change 1980–2022	Main ecological consequences
Tidal flats	91.3 km^2, 155 km (2.3%) of the non-iced coastline as of 2022	small increase by 15 km of coastline since 1936, change from seasonal to permanent	important feeding ground for wading birds
Water column in fjords (surface, inter-mediate and near bottom waters)	water surface area (Spitsber-gen fjords only) 5925 km^2	surface area of the fjords has increased by 133 km^2, of which the surface area of the Hornsund fjord has increased by 76 km^2, constituting 40% of its total area; increased turbidity, increased salinity gradient, increased intermediate layer, disappearance of winter cold water at the bottom.	stratification separates lower and upper part of water column and creates separate pelagic habitats

Discussion

Rising Sea Surface Temperature. — Sea Surface Temperature (SST) increase was documented in Hornsund, Isfjorden and Kongsfjorden and adjacent shelf in direct oceanographic measurements over the years (Walczowski and Piechura 2006; Pavlov *et al.* 2013; Promińska *et al*. 2017; Tverberg *et al.* 2019). The warmed-up water column in coastal areas is important habitat for larvae and juveniles of benthic species and neritic plankton (Głuchowska *et al.* 2016). Warming brings more freshwater to this system through glacial melt, that increases turbidity and stratification (Beszczyńska-Moller *et al*. 1997; Błaszczyk *et al.* 2009; Konik *et al*. 2021; Moreno and Szeligowska 2023). This process reduces primary production in the inner fjord basin (Smoła *et al*. 2017) and promotes brackish water species to colonize the fjords (Wiktor *et al*. 2016). Second water column habitat in fjords are seabed depressions that use to be filled with cooled, dense "winter water". Those water bodies were important as refugia for cold water species (Drewnik *et al*. 2016) and are clearly disappearing from fjords impacted most by the Atlantic water inflows (Promińska *et al.* 2017). Rising temperature promotes the establishment of thermophilic species that are transported with Atlantic waters (Thyrring *et al*. 2017).

Tidal glaciers retreat. — From the small scale, detailed studies like those of Hansbreen, over 40 years of continuous observations (Vieli *et al*. 2002), or Kongsbreen (Torsvik *et al*. 2019) to broad satellite-based analysis in the scale of whole archipelago (Błaszczyk *et al*. 2009), tidal glaciers are generally retreating on Svalbard, although occasional surge occurs and for a short-time glaciers may claim new area of coast and seabed (Błaszczyk *et al*. 2009). For the marine habitats, the main effect of tidal glaciers retreat is the creation of new coastline and ice-free seabed (Ziaja and Ostafin 2015, 2019; Cygankiewicz-Truś and Ziaja 2021). For the coastal waters, glacier retreat means also intense sediment outflow and freshwater discharge. The change in tidal glacier fronts impacts the local food web, especially seabirds that use this specific habitat (Stempniewicz *et al*. 2017; Bertrand *et al.* 2021; Hop *et al*. 2023). Shoreline areas free from the glacier are inhabited by minute mobile fauna like Oligochaeta or *Gammarus* assemblages (Węsławski *et al*. 1993a, b). To some extent, the new coastline may serve as a haul out ground for walruses and harbor seals (Lydersen *et al.* 2017).

Fast ice reduction. — This habitat is essential for the Ringed Seal breeding as well as for Polar Bear successful hunt (Smith and Lydersen 1991). Fast ice has important role in the reduction of intertidal vegetation and encrusting organisms through the ice scouring (Wxęsławski *et al*. 2010). There is no specific ice fauna associated with this ice type, all observed taxa belong to shallow water coastal species that may turn back to live on the seabed in the absence of ice (Węsławski *et al*. 1993a, b). Fast ice retreat is connected also with the increased exposition of coastline to the wave fetch (Fig. 5) that directly enhance erosion.

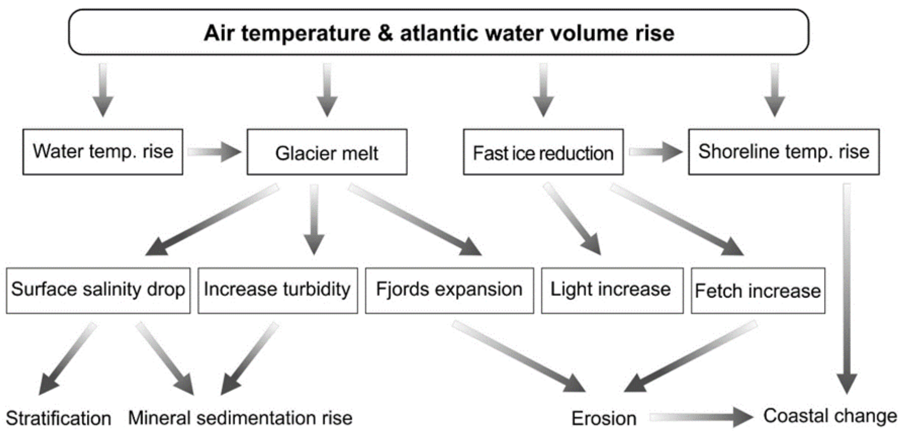

Fig. 5. Key driving factors of the coastal marine habitats change on Svalbard.

Snow cover. — Temperature rise will impact the snow cover on the coasts and on fast ice. It gives protection from the weathering and fast decomposition of the kelp deposits, that in turn impacts the nutrients turnover in the tundra and its return to the sea (Parmentier *et al*. 2017; Moriana-Armendariz *et al*. 2022). The lack of snow cover will enhance the organic matter turnover along the shores with rich algal vegetation. Snow on the coastal fast ice is also essential for the breeding success of Ringed Seal (Smith and Lydersen 1991), hence its reduction will impact the local seal population. The predictions for the snow cover on Svalbard are variable, as the warming generates more humidity and precipitation, yet it was reported to shrink with less snow on the ground (Van Pelt *et al.* 2016).

Fjords topography. — Changes due to the tidal glacier retreat are well documented in Hornsund (Moskalik *et al*. 2013; Grabiec *et al*. 2017). In the course of the last 100 years, the fjord surface nearly doubled. Number of tidal glaciers of Svalbard still covers the fjord branches, straits, bays and complicated coastscapes that can be read today only from radar measurements (Grabiec *et al*. 2017). The glacial retreat not only gives more space of the seabed, but introduces to the coastal waters huge sediment load. Estimated deposition in Hornsund during last glaciation is over 100 m in thickness (Kowalewski *et al.* 1991). Furthermore, as the distance from the shelf waters to the inner basin increases, the turbid waters remain in the inner basin and marine species visiting fjord can easily avoid the turbid-water zone (Drewnik *et al.* 2016).

Coastal change. — The soft sediment shores, *i.e.*, sandy to gravel and stony beaches, form permeable shoreline that is a dynamic habitat that serves limited number of species on Svalbard – mainly interstitial meiofauna (Węsławski *et al.* 1993a, b; Szymelfenig *et al*. 1995). Beach forms an important habitat that acts as a bioconvertor, helping self-cleaning of waters that percolate through the porous medium (Huettel *et al.* 2014). Newly-exposed soft sediment shores will be prone to the coastal erosion (Kavan *et al*. 2022). Specific type of the soft sediment shore includes tidal flats, that are formed in sheltered areas, where flat land rivers carry sediment load and deposit it at their mouth. On Svalbard, tidal flats were usually associated with retreating glaciers that left moraine material, or with board valleys with braided rivers (Węsławski and Szymelfenig 1999). Such areas are important for wading birds, on Svalbard, mainly purple sandpipers *Calidris maritima* (Regelin 2011). Recent reduction of fast ice, that used to freeze through the sediment and kill the organisms within, results in more space and time for species that can stabilize the sediment in summer (Wiktor *et al.* 2016; Elster *et al*. 2023). In sheltered places, the hard shore provides substrate for encrusting organisms, especially benthic algae, that rapidly increase biomass and primary production in the area due to the ice reduction (Krause-Jensen and Duarte 2014; Smoła *et al*. 2017).

Lakes and lagoons. — These freshwater bodies are important as habitats for anadromous fish, namely Arctic charr and gorbusha (Bengtsson *et al.* 2023). Number of new freshwater bodies appeared on the coastline after the glacial retreat (Urbański 2022). The discharge of freshwater to the coastal sea and change from the tidal glacier to river outflow modify the hydrography of coastal waters and reduce suspensions load in fjord, deposited in the lagoon or tidal flat (Szczuciński and Zajączkowski 2012; Lydersen *et al.* 2014).

Considerations on biodiversity change driven by changing coastal habitats. — The chain of above discussed drivers that modifies coastal habitats on Svalbard, is illustrated in Fig. 5, with overarching factor of air temperature rise and associated Atlantic waters flow. Changes in the coastal (shoreline and fjords seabed) habitats, discussed above, are unlikely to cause the regional biodiversity loss in terms of species absence causing local extinctions. The main reason is the lack of endemism on Svalbard, where almost all invertebrate fauna is a subsample of the North Norwegian Sea marine domain (Sirienko 2001; Palerud *et al.* 2004; Deja *et al*. 2016). With increasing advection of Atlantic waters and warming, the import of populations and species from the south will be enhanced, what was already demonstrated among crustaceans (Legeżynska *et al.* 2017; Csapó *et al.* 2021). Arrival of boreal fish, birds and sea mammal species to Svalbard is being reported (Renaud *et al.* 2012; Berge *et al*. 2015; Descamps and Strøm 2021; Bengtsson *et al.* 2022). The Arctic, cold stenotherms can find a refuge in the deep inner fjord basins. Such observation has been already reported (Lydersen *et al.* 2014; Drewnik *et al.* 2016). Svalbard Arctic coastal sea mammals (polar bear, walrus, ringed seal, beluga, bearded seal) are highly mobile and adaptive (Stempniewicz *et al.* 2021) as well as protected, so their local extinction is unlikely, with possible threat to the ringed seal, species directly dependent on the fast ice (Smith and Lydersen 1991).

Climate change causes the retreat of the iconic tidal glaciers and fast ice on Svalbard, resulting in the creation of new and variable coastal forms. We do not expect the ongoing coastal change to result in any specific species or ecosystem function loss, with likely exception of the ringed seal. The climate change results in increase of coastline length, shoreline complexity as well as the increase of fjords volume. Together with the emerging new brackish water habitats and advection of boreal species from the south, it may lead to local biodiversity increase and probably associated ecosystem stability (Wesławski *et al.* 2017). West coast fjords, especially inner basins are most changed, while open coast of NE remains in its previous condition. Such information shall be of importance for the nature conservation plans and the management of increasing tourism (Hovelsrud *et al.* 2023).

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References

ACIA 2005. Arctic Climate Impact Assessment. ACIA Overview report. Cambridge University Press. 1020 pp.

Bengtsson O., Lydersen Ch. and Kovacs K.M. 2022. Cetacean spatial trends from 2005 to 2019 in Svalbard, Norway. *Polar Research* 41: 7773. doi: 10.33265/polar.v41.7773

Bengtsson O., Lydersen Ch., Christiansen G., Węsławski J.M. and Kovacs K. 2023. Marine diets of anadromous arctic char and alien pink salmon on Svalbard. *Polar Biology* 46: 1219–1234. doi: 10.1007/s00300-023-03196-8

Berge J., Heggland K., Lønne O.J., Cottier F., Hop H., Gabrielsen G.W., Nøttestad L. and Misund O.A. 2015. First records of Atlantic mackerel (*Scomber scombrus*) from the Svalbard archipelago, Norway, with possible explanations for the extension of its distribution. *Arctic* 68: 54–61. doi: 10.14430/arctic4455

Bertrand P., Bêty J., Yoccoz N.G. *et al.* 2021. Fine-scale spatial segregation in a pelagic seabird driven by differential use of tidewater glacier fronts. *Scientific Reports* 11: 22109. doi: 10.1038/s41598-021-01404-1

Beszczyńska-Moller A., Węsławski J.M., Walczowski W. and Zajączkowski M. 1997. Estimation of glacial meltwater discharge to Svalbard coastal waters. *Oceanologia* 39: 289–298.

Błaszczyk M., Jania J.A. and Hagen J.O. 2009. Tidewater glaciers of Svalbard: Recent changes and estimates of calving fluxes. *Polish Polar Research* 30: 85–142.

Csapó H.K., Grabowski M. and Węsławski J.M. 2021. Coming home – Boreal ecosystem claims Atlantic sector of the Arctic. *Science of the Total Environment* 771: 144817

Cygankiewicz-Truś A. and Ziaja W. 2021. From glaciated landscape to unglaciated seascape: Transformation of the Hambergbreen–Hambergbukta area, SE Spitsbergen, 1900–2017. *Annals of the American Association of Geographers* 111: 1949–1966. doi: 10.1080/24694452.2021.1904818

Deja K., Węsławski J.M., Borszcz T., Włodarska-Kowalczuk M., Kukliński P., Bałazy P. and Kwiatkowska P. 2016. Recent distribution of Echinodermata species in Spitsbergen coastal waters. *Polish Polar Research* 37: 511–526. doi: 10.1515/popore-2016-0027

Descamps S. and Strøm H. 2021. As the Arctic becomes boreal: ongoing shifts in a high-Arctic seabird community. *Ecology* 102: e03485. doi: 10.1002/ecy.3485

Drewnik A., Węsławski J.M, Włodarska-Kowalczuk M., Łącka M., Promińska A., Zaborska A. and Głuchowska M. 2016. From the worm's point of view. I: Environmental settings of benthic ecosystems in Arctic fjord (Hornsund, Spitsbergen). *Polar Biology* 39: 1411–1424. doi: 10.1007/s00300-015-1867-9

Elster J., Souquieres C-E., Jadrná I., Škaloud P., Søreide J.E. and Kvíderová J. 2023. Invasive *Vaucheria* aff. *compacta* (Xanthophyceae) and its distribution over a high Arctic tidal flat in Svalbard. *Estuarine, Coastal and Shelf Science* 281: 108206. doi: 10.1016/j.ecss.2022.108206

Forbes D.L. (ed.). 2011. *State of the Arctic Coast 2010 – Scientific Review and Outlook.* International Arctic Science Committee, Land-Ocean Interactions in the Coastal Zone, Arctic Monitoring and Assessment Programme, International Permafrost Association. Helmholtz-Zentrum, Geesthacht, Germany.

Geyman E., Kohler J., Van Pelt W., Maloof A. and Aas H.F. 2021. 1936/1938 DEM of Svalbard [Data set]. Norwegian Polar Institute. doi: 10.21334/npolar.2021.f6afca5c

Głuchowska M., Kwaśniewski S., Promińska A., Olszewska A., Goszczko I., Falk-Petersen S. and Węsławski J.M. 2016. Zooplankton in Svalbard fjords on the Atlantic–Arctic boundary. *Polar Biology* 39: 1785–1802. doi: 10.1007/s00300-016-1991-1

Grabiec M., Ignatiuk D., Jania J.A., Moskalik M., Głowacki P., Błaszczyk M., Budzik T. and Walczowski W. 2017. Coast formation in an Arctic area due to glacier. *Earth Surface Processes and Landforms* 43: 387–400. doi: 10.1002/esp.4251

Hop H., Wold A., Vihtakari M., Assmy P., Kukliński P., Kwaśniewski S., Griffith G.P., Pavlova O., Duarte P. and Steen H. 2023. Tidewater glaciers as "climate refugia" for zooplankton-dependent food web in Kongsfjorden, Svalbard.Front. *Marine Science* 10: 1161912. doi: 10.3389/fmars.2023.1161912

Hovelsrud G.K., Olsen J., Nilsson A.E., Kaltenborn B. and Lebel J. 2023. Managing Svalbard tourism: inconsistence and conflicts of interest. *Arctic Review on Law and Politics* 14: 86–106. doi: 10.23865/arctic.v14.5113

Huettel M., Berg P. and Kostka J.E. 2014. Benthic exchange and biogeochemical cycling in permeable sediments. *Annual Review of Marine Science* 6: 23–51.

Kavan J., Tallentire G.D., Demidionov M., Dudek J. and Strzelecki M.C. 2022. Fifty years of tidewater glacier surface elevation and retreat dynamics along the south-east coast of Spitsbergen (Svalbard archipelago). *Remote Sensing* 14: 354. doi: 10.3390/rs14020354

Konik M., Darecki M., Pavlov A., Sagan S. and Kowalczuk P. 2021. Darkening of Svalbard fjords waters observed with satellite ocean color imagery in 1997–2019. *Frontiers in Marine Science* 8: 699318. doi: 10.3389/fmars.2021.699318

Kowalewski W., Rudowski S. and Zalewski S.M. 1991. Seismoacoustic studies in Hornsund, Spitsbergen. *Polish Polar Research* 12: 353–361.

Krause-Jensen D. and Duarte C. 2014. Expansion of vegetated coastal ecosystems in the future Arctic. *Frontiers in Marine Science* 1: 77. doi: 10.3389/fmars.2014.00077

Legeżyńska, J., Włodarska-Kowalczuk, M., Gluchowska, M., Ormańczyk, M., Kędra, M., and Węsławski, J.M. 2017. The malacostracan fauna of two Arctic fjords (west Spitsbergen): the diversity and distribution patterns of its pelagic and benthic components. *Oceanologia* 59: 541–564. doi: 10.1016/j.oceano.2017.01.004

Linse K, Peeken I. and Tandberg A.H.S. 2021. Editorial: Effects of ice loss on marine biodiversity. *Frontiers in Marine Science* 8: 793020. doi: 10.3389/fmars.2021.793020

Lydersen C., Vaquie-Garcia J. and Lydersen E. 2017. Novel terrestrial haul-out behaviour by ringed seals (*Pusa hispida*) in Svalbard, in association with harbour seals (*Phoca vitulina*). *Polar Research* 36: 1374124.

Lydersen C., Assmy P., Falk-Petersen S., Kohler J., Kovacs K.M., Reigstad M., Steen H., Strøm H., Sundfjord A., Varpe Ø., Walczowski W., Węsławski J.M. and Zajączkowski, M. 2014. The importance of tidewater glaciers for marine mammals and seabirds in Svalbard, Norway. *Journal of Marine Systems* 129: 452–471.

Moreno B. and Szeligowska M. 2023. Browning and blueing – what is the fate of polar coasts? *Frontiers in Ecology and Environment* 21: 156–156. doi: 10.1002/fee.2617

Moriana-Armendariz M., Nilsen L. and Cooper E.J. 2022. Natural variation in snow depth and snow melt timing in the High Arctic have implications for soil and plant nutrient status and vegetation composition. *Arctic Science* 8: 767–785. doi: 10.1139/as-2020-0025

Moskalik M., Grabowiecki P. and Tęgowski J. 2013. Bathymetry and geographical regionalization of Brepollen (Hornsund, Spitsbergen) based on the bathymetric profiles interpolation. *Polish Polar Research* 34: 1–22.

Palerud R., Gulliksen B., Brattegard T., Sneli A. and Vader W. 2004. The marine macroorganisms in Svalbard waters. *In:* Prestrud P., Strøm H., Goldman H.V. (eds.) *A catalogue of the terrestrial and marine animals of Svalbard*. Norwegian Polar Institute, Tromso.

Parmentier Fj., Christensen T.R., Rysgaard S., Bendtsen J., Glud R.N., Brent E. Van Huissteden J., Sachs T., Vonk J.E. and Sejr M.K. 2017. A synthesis of the arctic terrestrial and marine carbon cycles under pressure from a dwindling cryosphere. *Ambio* 46: 53–69. doi: 10.1007/s13280-016-0872-8

Pavlov A.K., Tverberg V., Ivanov B.V., Nilsen F., Falk-Petersen S. and Granskog M.A. 2013. Warming of Atlantic Water in two west Spitsbergen fjords over the last century (1912–2009). *Polar Research* 32: 11206. doi: 10.3402/polar.v32i0.11206

Promińska A., Cisek M. and Walczowski W. 2017. Kongsfjorden and Hornsund hydrography comparative study based on a multiyear survey in fjords of west Spitsbergen. *Oceanologia* 59: 397–412.

Regelin B. 2011. Purple sandpipers (*Calidris maritima*) feeding in an Arctic estuary: tidal cycle and seasonal dynamics in abundance. M.Sc. Thesis. Uppsala University. https://www.ibg.uu.se/digitalAssets/164/c_164775-l_3-k_regelin-beke-arbete.pdf

Renaud P.E., Berge J., Varpe O., Lønne O.J., Nahrgang J., Ottesen C. and Hallanger I. 2012. Is the poleward expansion by Atlantic cod and haddock threatening native polar cod, *Boreogadus saida*? *Polar Biology* 35: 401–412. doi: 10.1007/s00300-011-1085-z

Salvigsen O., Forman S.L. and Miller G.H. 1992. Thermophilous molluscs on Svalbard during the Holocene and their paleoclimatic implications. *Polar Research* 11: 1–10.

Seppä H., Seidenkrantz M-S., Caissie B. and Fauria M.M. 2023. Polar bear's range dynamics and survival in the Holocene. *Quaternary Science Reviews* 317: 108277. doi: 10.1016/j.quascirev.2023.108277

Sirenko B.I. 2001. List of species of free-living invertebrates of Eurasian Arctic seas and adjacent deep waters. *Exploration of the Fauna of the Seas* 51: 131.

Smith T.G. and Lydersen C. 1991. Availability of suitable land-fast ice and predation as factors limiting ringed seal populations, *Phoca hispida*, in Svalbard. *Polar Research* 10: 585–594. doi: 10.3402/polar.v10i2.6769

Smoła Z.T, Tatarek A., Wiktor J.M, Wiktor Jr. J.M., Kubiszyn A.M. and Węsławski J.M. 2017. Primary producers and production in Hornsund and Kongsfjorden – comparison of two fjord systems. *Polish Polar Research* 38: 351–373. doi: 10.1515/popore-2017-0013

Søreide J.E., Pitusi V., Vader A. *et al.* 2020. Environmental status of Svalbard coastal waters: coastscapes and focal ecosystem components (SvalCoast). The State of Environmental Science in Svalbard. an annual report Publisher: Svalbard Integrated Arctic Earth Observing System (SIOS). doi: 10.5281/zenodo.4293849

Stempniewicz L., Goc M., Kidawa D. *et al.* 2017. Marine birds and mammals foraging in the rapidly deglaciating Arctic fjord – numbers, distribution and habitat preferences. *Climatic Change* 140: 533–548. doi: 10.1007/s10584-016-1853-4

Stempniewicz L., Kulaszewicz I. and Aars J. 2021. Yes, they can: polar bears *Ursus maritimus* successfully hunt Svalbard reindeer *Rangifer tarandus*. *Polar Biology* 44: 2199–2206. 10.1007/s00300-021-02954-w

Svendsen J.J. and Mangerud J. 1997. Holocene glacial and climatic variations on Spitsbergen, Svalbard. *Holocene* 25: 1197–1207.

Szczuciński W. and Zajączkowski M. 2012. Factors controlling downward fluxes of particulate matter in a glacier contact and non- glacier contact settings in a subpolar fjord (Billefjorden, Svalbard). *International Association of Sedimentology. Special Publication* 44: 369–386.

Szymelfenig M., Kwaśniewski S. and Węsławski J.M. 1995. Intertidal zone of Svalbard 2. Meiobenthos density and occurrence. *Polar Biology* 15: 137–141.

Thyrring J., Blicher M.W., Sorensen J.G., Wegeberg S. and Sejr M.K. 2017. Rising air temperatures will increase intertidal mussel abundance in the Arctic. *Marine Ecology Progress Series* 584: 91–104.

Torsvik T., Albretsen J., Sundfjord A., Kohler J., Sandvik A.D., Skarðhamar J., Lindbäck J. and Everett A. 2019. Impact of tidewater glacier retreat on the fjord system: Modeling present and future circulation in Kongsfjorden, Svalbard. *Estuarine, Coastal and Shelf Science* 220: 152–165. doi: 10.1016/j.ecss.2019.02.005

Tverberg V., Skogseth R., Cottier F., Sundfjord A., Walczowski W., Inall M.E., Falck E., Pavlova O. and Nilsen F. 2019. The Kongsfjorden transect: Seasonal and inter-annual variability in hydrography. *In:* Hop H., Wiencke C. (eds.) The Ecosystem of Kongsfjorden, Svalbard. *Advances in Polar Ecology* 2. Springer. doi: 10.1007/978-3-319-46425-1_3

Urbański J.A. 2022. Monitoring and classification of high Arctic lakes in the Svalbard Islands using remote sensing. *International Journal of Applied Earth Observations and Geoinformation* 112: 102911. doi: 10.1016/j.jag.2022.102911

Urbański J.A. and Litwicka D. 2022. The decline of Svalbard land-fast sea ice extent as a result of climate change. *Oceanologia* 64: 535–545.

Van Pelt W.J., Kohler J., Liston G.E., Hagen J.O., Luks B., Reijmer C.H. and Pohjola V.A. 2016. Multidecadal climate and seasonal snow conditions in Svalbard. *Journal of Geophysical Research, Earth Surface* 121: 2100–2117. doi: 10.1002/2016JF003999

Vieli A., Jania J. and Kolondra L. 2002. The retreat of a tidewater glacier: observations and model calculations on Hansbreen, Spitsbergen, *Journal of Glaciology* 48: 592–600.

Walczowski W. and Piechura J. 2006. New evidence of Warming propagating towards the Arctic Ocean. *Geophysical Research Letters* 33: L12601.

Węsławski J.M. and Szymelfenig M. 1999. Community composition of tidal flats on Spitsbergen: consequence of disturbance? *NATO ASI Series E* 59: 185–193.

Węsławski J.M., Kwaśniewski S. and Wiktor J. 1993a. Observations on the fast ice biota in the fjords of West Spitsbergen. *Polish Polar Research* 14: 331–343.
Węsławski J.M., Wiktor J, Zajączkowski M. and Swerpel S. 1993b. Intertidal zone of Svalbard. 1. Macroorganisms distribution and biomass. *Polar Biology* 13: 73–108.
Węsławski J.M., Wiktor J.Jr. and Kotwicki L. 2010. Increase in biodiversity in the Arctic rocky littoral, Sorkappland, Svalbard after 20 years of climate warming. *Marine Biodiversity* 40: 123–130.
Węsławski J.M. Buchholz F., Głuchowska M. and Weydmann A. 2017. Ecosystem maturation follows the warming of the Arctic fjords. *Oceanologia* 59: 592–602. doi: 10.1016/j.oceano.2017.02.002
Wiktor J., Tatarek A., Węsławski J.M., Kotwicki L. and Poulin M. 2016. Colonies of *Gyrosigma eximium*: a new phenomenon in Arctic tidal flats. *Oceanologia* 58: 336–340. doi: 10.1016/j.oceano.2016.04.007
Ziaja W. and Ostafin K. 2015. Landscape–seascape dynamics in the isthmus between Sørkapp Land and the rest of Spitsbergen: Will a new big Arctic island form? *Ambio* 44: 332–342. doi: 10.1007/s13280-014-0572-1
Ziaja W. and Ostafin K. 2019. Origin and location of new Arctic islands and straits due to glacial recession. *Ambio* 48: 25–34. doi: 10.1007/s13280-018-1041-z

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