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Ice Cod *Arctogadus glacialis* (Peters, 1874) in Northeast Greenland—A First Sketch of Spatial Occurrence and Abundance

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Abstract: Based on bottom trawl catches during the years 2002–2017, we present the first large-scale baseline on the spatial distribution and abundance of ice cod *Arctogadus glacialis* (Peters, 1874) in the fjords and on the shelf in Northeast Greenland (latitudes 70 °N–78 °N). Ice cod abundance peaked in the secluded sill fjords such as Bessel Fjord, Brede Fjord, Clavering Ø fjord system and Kong Oscar Fjord as compared to the offshore shelf. The mean biomass was estimated as 3.9 kg/km^2 on the shelf and 49.3 kg/km^2 in the fjords. Nearly 45% of the biomass was restricted to temperatures < −1.0 °C and almost 90 % of the biomass occurred within 200–600 m depth. This corresponds well with the deep, subzero fjords along the Northeast Greenland coast which, thus, appear the most suitable habitat for ice cod. Moreover, there was a gradual decrease in ice cod biomass on the shelf over the years 2002–2017. This apparent relocation of ice cod matches the ongoing warming of the Northeast Greenland shelf waters. Given that the overall temperature space of ice cod spans less than 4 ºC in Northeast Greenland, it is likely that the species is particularly vulnerable to climate change as warmer waters before long enter the fjords, i.e., the main habitat for ice cod.

Keywords: *Arctogadus*; ice cod; distribution; abundance; Northeast Greenland

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1. Introduction

According to our fish collection build during the TUNU Expeditions (2002–2017), as well as historic records, 55 fish species are currently reported from the fjords and continental shelf of Northeast Greenland [1–3]. Among them are two cryopelagic (i.e., ice-associated) codfishes that both play a decisive role in the formation of Arctic food webs, i.e., the well-known polar cod *Boreogadus saida* (Lepechin, 1774) and the little-studied ice cod *Arctogadus glacialis* (Peters, 1874) [4,5]. Of these two codfishes, polar cod is undoubtedly the most dominating in terms of occurrence and abundance across the Arctic seas [6] and accompanied by ice cod mainly in the fjords and coastal waters of Northeast Greenland. The ice cod is an Arctic circumpolar endemic, relatively common in the North Atlantic between latitudes 70 °N and 80 °N and which even occur in the Central Arctic Ocean [3,7,8]. The holotype specimen representing the genus *Arctogadus* was sampled near Sabine Ø (latitude ~74° N) in Northeast Greenland during Die Zweite Deutsche Nordpolarfahrt (Karl Koldewey, 1869–1870). Two species were previously considered valid in genus *Arctogadus*, namely ice cod *A. glacialis* (Peters, 1874) and East Siberian cod *A. borisovi* Drjagin, 1932 [9]. However, genetic analyses place *A. borisovi* as the junior synonym to *A. glacialis* and currently makes *Arctogadus* a monotypic taxa analogous to genus *Boreogadus* [10,11]. The distribution of ice cod is uneven and, given the scarce data, the species is considered to be confined to the Arctic continental shelves rather than the deeper waters of the Central Arctic Ocean [12]. In the European Arctic, ice cod has been found near Iceland, Jan Mayen Island, north and east of Svalbard Archipelago and around Franz Josef Land [3,12–14]. One

specimen was caught in the central Barents Sea in 2000 [15]. Ice cod is apparently rare and less numerous from the Kara Sea and eastwards to the Chukchi Sea, i.e., areas previously considered the main habitat of *Arctogadus borisovi* [3,7,8,16–18]. In the Canadian Arctic, the occurrence of ice cod has been little investigated, but its abundance seems scarce [3,19–21]. By contrast, ice cod is relatively common in Northwest Greenland [1] and appears most numerous in Northeast Greenland [22–24]. Here, densities according to bottom trawl catches spanned 62–4789 specimens per km^2, equivalent to biomasses of 3–187 kg/km^2 [25]. These first quantitative data of ice cod abundances represent the Northeast Water Polynya (NEW) in year 1990 with catches as far north as latitude 81.5 °N. During our expeditions to Northeast Greenland (2002–2017) under the auspices of the TUNU Programme [2], we noticed that the occurrence and abundance of ice cod differed markedly between fjord and shelf habitats. Here, we present a brief overview of the distribution of ice cod in relation to temperature and depth on the shelf and in the fjords of Northeast Greenland. The survey area covers latitudes 70–78 °N, i.e., from Scoresby Sund in the south to Dove Bugt and Belgica Banke in the north.

2. Materials and Methods

Nine marine biological TUNU Expeditions were conducted regularly in the coastal waters and on the continental shelf of Northeast Greenland during the years 2002–2017 (TUNU Programme; [2]). The research effort comprised 83 stations in total within an estimated survey area of about 275 thousand km^2 (Table 1; Figure 1). Sampling was carried out in summer and early autumn (July–October) using a Campelen-1800/96 NOFI fine-mesh bottom trawl (10 mm mesh size in the cod end) deployed from the RV Helmer Hanssen, UiT, The Arctic University of Norway. The duration of the trawling varied between 20 and 30 min and, in order to compare samples, data were converted to catches per one hour of trawling. Depth (m) of sampling and the corresponding in situ temperature (°C) were recorded simultaneously at the stations using a SeaBird-sensor mounted on the gear. Ice cod *Arctogadus glacialis* and polar cod *Boreogadus saida* were separated morphologically, counted (N) and the biomass (B) weighed. For each station, a simple mean body mass of ice cod was estimated as B/N (g). Further sampling procedures and calculations are given in [4,26]. It should be noted that the identification of small-sized ice cod and polar cod (body length < 10 cm) often requires a thorough morphological examination to avoid mix-up of the two species and thus false proportions of abundance (Karamushko, unpublished ID-key, 3). In cases of doubt, diagnostic genetic methods should be applied [27].

Table 1. Number and biomass of ice cod *Arctogadus glacialis* sampled in fjords and on the shelf in Northeast Greenland during years 2002–2017. A total of 83 stations were sampled during the survey period, cf. Figure 1.

Year	Specimens, N	Biomass, kg	Fjord Stations	Shelf Stations	Comment
2002	387	5.901	4	8	
2003	3291	65.260	11	7	
2005	146	5.777	3	4	
2007	129	2.868	4	0	
2008	2	0.460	0	6	Jan Mayen Island
2010	780	21.274	10	1	
2013	506	19.227	5	3	
2015	2	0.062	0	8	
2017	1112	24.542	4	5	
Total	6355	145.371	41	42	

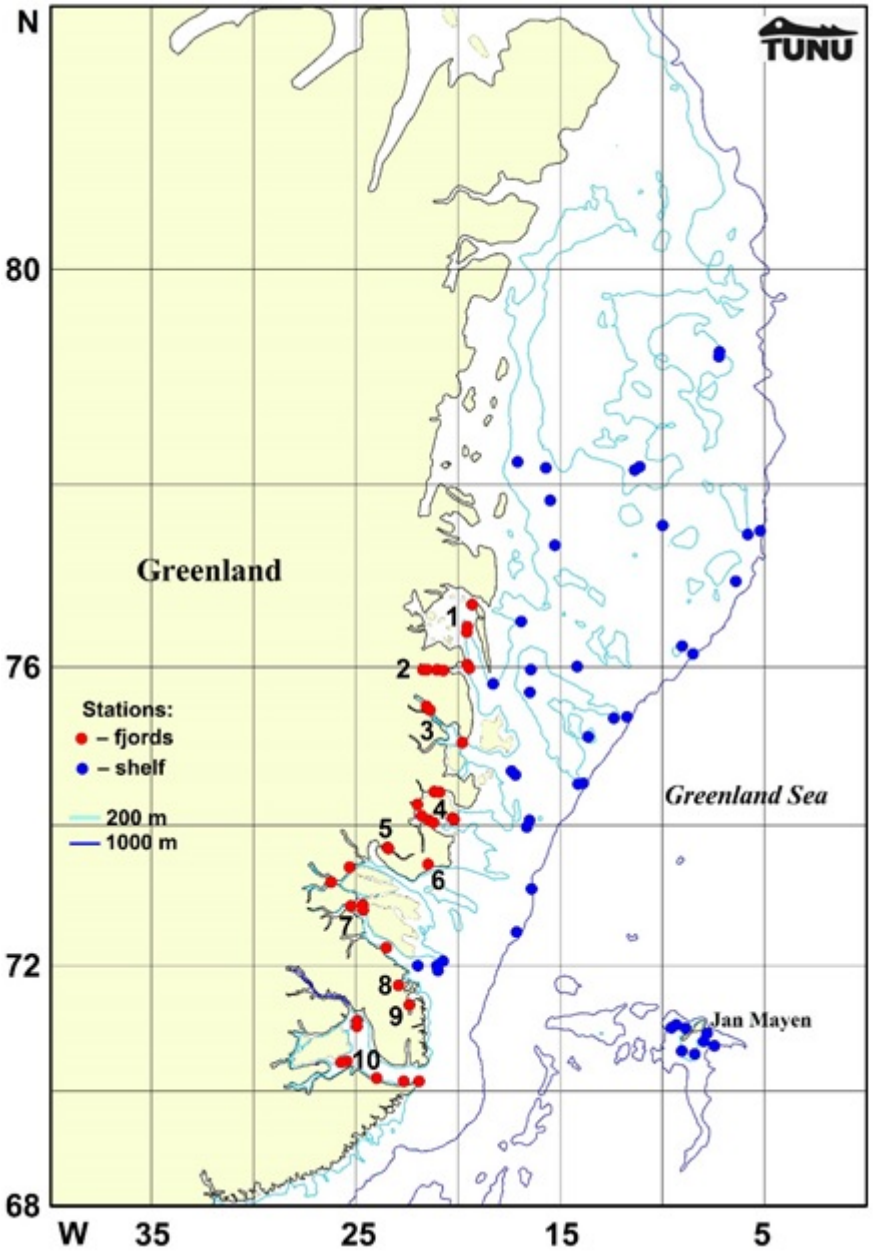

Figure 1. Fjord and shelf stations (N = 83) sampled in Northeast Greenland and at Jan Mayen Island during years 2002–2017. The investigated fjords comprise: 1—Dove Bugt, 2—Bessel Fjord, 3—Brede Fjord, 4—Clavering Ø fjord system, 5—Moskusokse Fjord, 6—Myggbukta, 7—Kong Oskar Fjord, 8—Fleming Fjord, 9—Carlsberg Fjord, 10—Scoresby Sund fjord system.

3. Results and Discussion

3.1. Overall Occurrence and Abundance

In Northeast Greenland, ice cod is quite numerous, although it occurs in noticeably smaller quantities than the main ecosystem-forming polar cod. This applies also for the early life stages in the Greenland Sea, where ice cod was outnumbered by polar cod [28]. Over the 15 years of sampling (2002–2017), we caught 6355 specimens of ice cod, equivalent to a total biomass of about 145 kg, at 53 stations out of a total of 83 surveyed stations (Table 1). The mean proportion of ice cod to polar cod (or ice cod fjord to shelf) in terms of biomass, hereafter proportional biomass, ranged between 0.2% and 19.7% for ice cod (Figure 2). In other words, polar cod constituted at least 80% of the biomass for the two species pooled. However, in different years and at certain locations, the situation may be

reversed, with ice cod being the dominating species of the two cryopelagic codfishes. So, in the Northeast Water Polynya (latitude ~81° N) north of our research area (Figure 1), ice cod was significantly more numerous than polar cod [25]. This was a very unusual find given the vast geographical coverage of our own long-term survey in Northeast Greenland [2], and suggests that polynyas may provide particularly suitable conditions for ice cod on the shelf. A predominance of ice cod over polar cod was also noted at one winter station in the Central Arctic Ocean north of the East Siberian Sea. The other catches in the same area contained only polar cod [8]. A general trend from our survey in Northeast Greenland shows that catches of ice cod are always accompanied by polar cod but not vice versa. This further supports the omnipresent nature of polar cod [6].

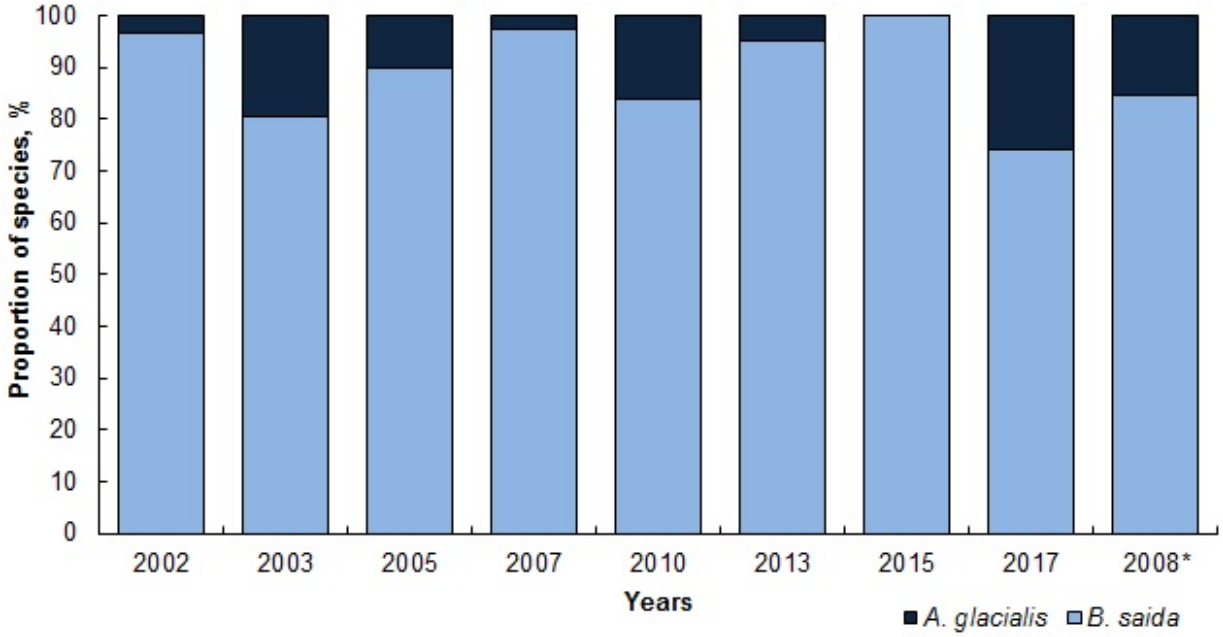

Figure 2. The overall proportional biomass in catches revealed by the cryopelagic fishes, ice cod *Arctocgadus glacialis* and polar cod *Boreogadus saida* in Northeast Greenland waters. * Note, the year 2008 represents only one station near Jan Mayen Island (Figure 3), and in 2015, only the shelf was sampled. The number of fjord and shelf stations is shown in Table 1.

The abundance of ice cod varied markedly among stations. The largest catches were obtained in the secluded sill fjords (from north to south)—Bessel Fjord, Brede Fjord, Clavering Ø fjord system and Kong Oscar Fjord (Figure 3). By contrast, ice cod was relatively scarce and often absent in the catches at the open shelf stations. Maximum catches for ice cod reached 100.2 kg/h in the fjords and 7.4 kg/hour on the shelf, whereas mean catches were 14.1 kg/h (49.3 kg/km^2) in the fjords and 1.1 kg/h (3.9 kg/km^2) on the shelf. Our catches, however, appeared lower than those reported for the Northeast Water Polynya, where ice cod catches by Agassiz trawl amounted up to 187 kg/km^2 [25]. Recent acoustic surveys revealed mesopelagic layers at 100–600 m depths over the deep waters near the North Pole, but the presence of ice cod has not been verified by physical samples [29].

Throughout our investigation period, the proportional biomass of ice cod was strikingly higher in fjord compared to shelf stations, except for the year 2002, where catches were similar for the two cryopelagic cod fishes (Figure 4). This indicates that ice cod selects secluded habitats such as the sill fjords along the Northeast Greenland coast rather than the open continental shelf. Moreover, there was also a gradual proportional decrease in shelf catches of ice cod over years from 11.7% in 2003 to 3.8% in 2017 (Figure 4). This coincides well with the ongoing warming reported for Northeast Greenland, where waters of Atlantic origin deflect onto the continental shelf via the West Spitsbergen Current [30].

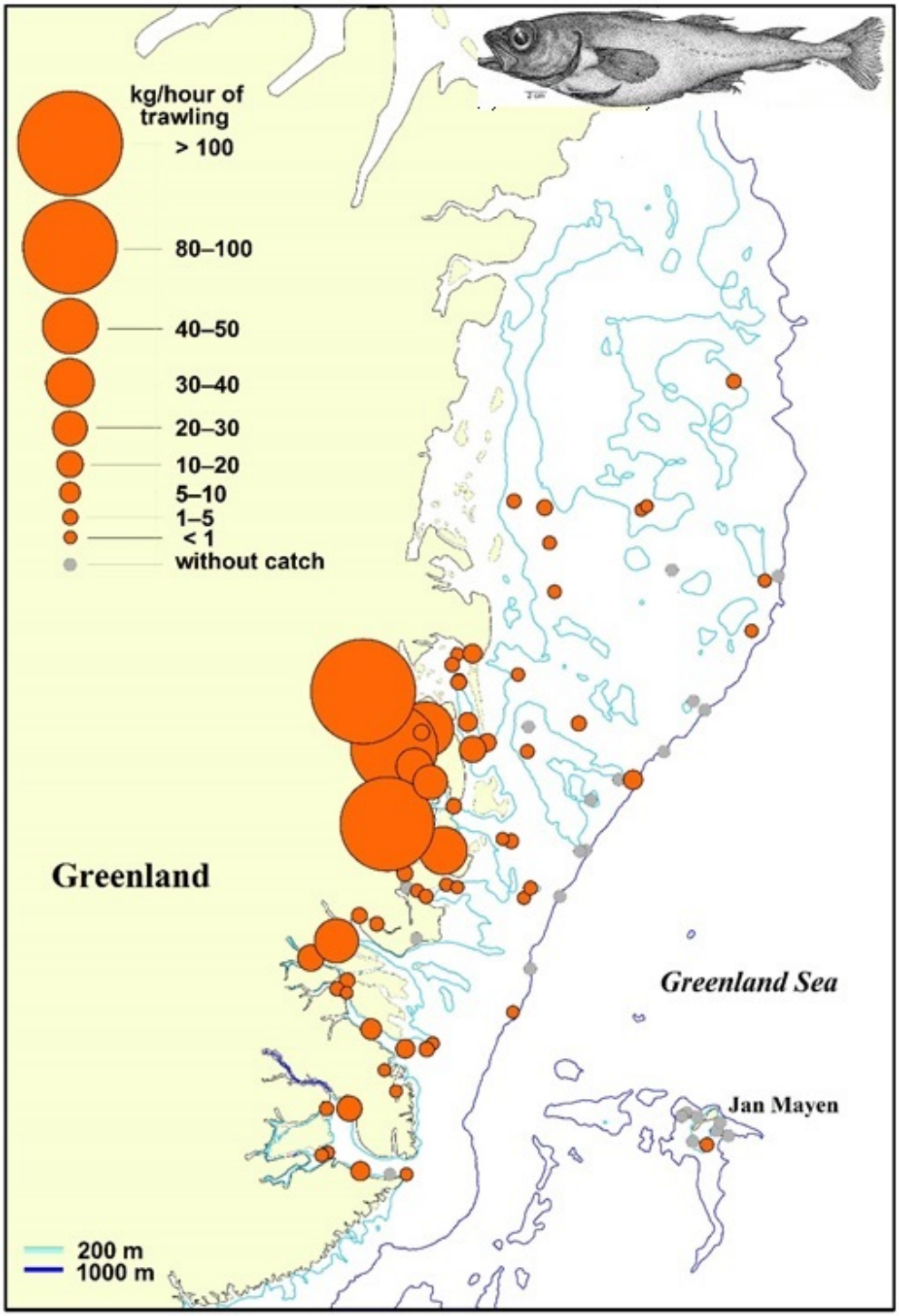

Figure 3. Geographic occurrence and abundance of ice cod *Arctogadus glacialis* across fjords and shelf stations (N = 53) in Northeast Greenland, cf. Table 1. Filled symbols show catches of ice cod in kg/h. Inserted illustration of ice cod, courtesy of Birgitte Rubæk (https://www.birgitterubaek.work/, accessed on 1 November 2022).

Arctic warming brings boreal fishes such as Atlantic cod *Gadus morhua* to the Northeast Greenland shelf [31,32] and even to the North Pole [33]. The Northeast Greenland sill fjords and the Northeast Water Polynya further north, on the other hand, are still less affected by the inflow of warmer Atlantic water [30].

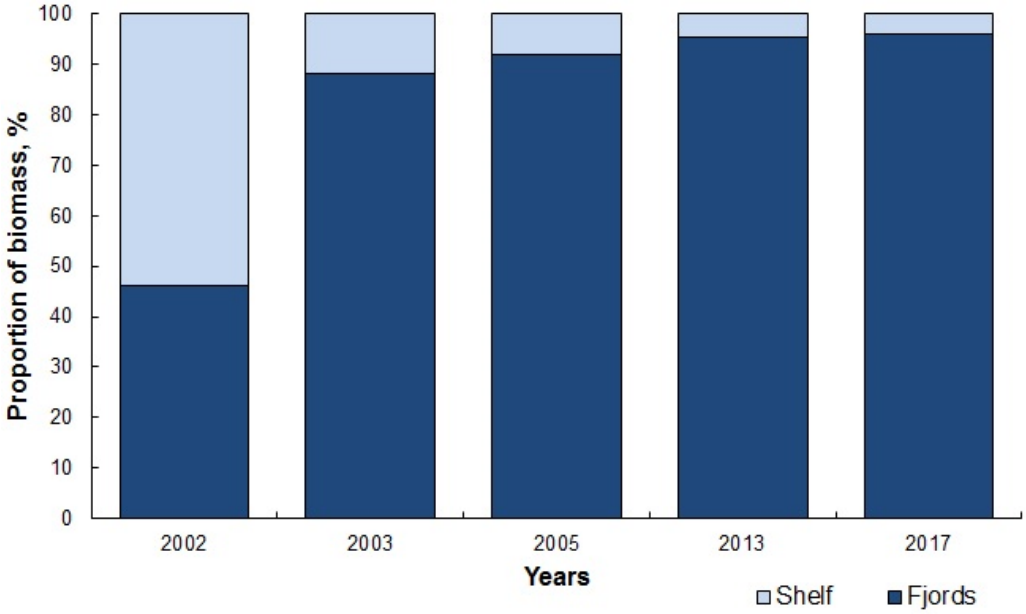

Figure 4. The proportional biomass of ice cod *Arctogadus glacialis* in fjords and on the shelf in Northeast Greenland. Total number of specimens N = 5442. Note, years 2007, 2010 and 2015 are excluded from comparisons because in these years stations were confined to either fjords or the shelf, cf. Table 1 and Figure 1.

3.2. Ice Cod Abundance in Relation to Temperature and Depth

During the entire survey period (2002–2017), ice cod occurred at temperatures from −2.0 to 1.8 °C and as much as 44.6% of the biomass was obtained in subzero waters less than −1.0 °C (Figure 5). Hence, the temperature space occupied by ice cod in Northeast Greenland is very narrow, spanning less than 4 °C at the most and only 2 °C for the majority of the fish.

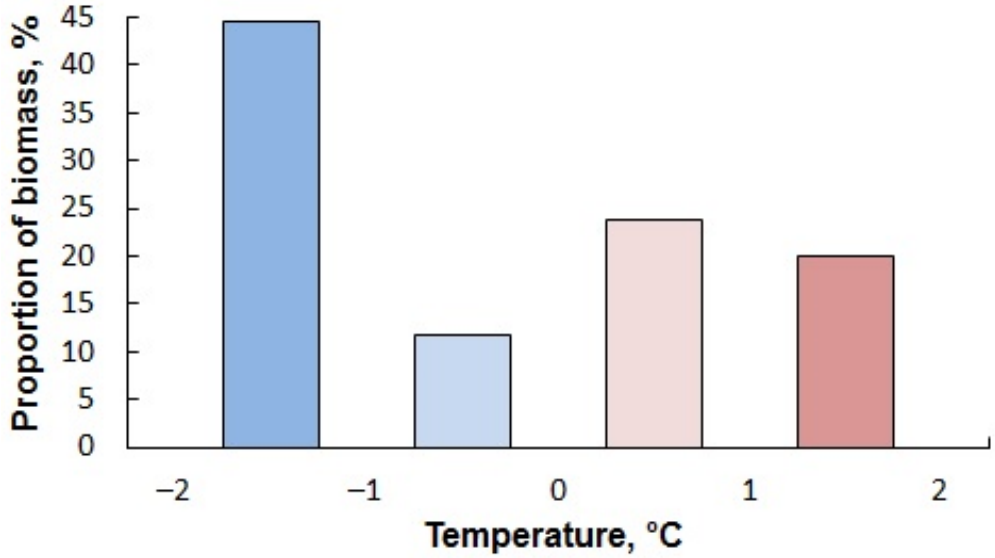

Figure 5. The proportional biomass of ice cod *Arctogadus glacialis* with temperature across fjord and shelf stations in Northeast Greenland (cf. Table 1 and Figures 1 and 3).

Fishes are extremely sensitive to temperature changes and regulate their body temperature through behavioural means by selecting or avoiding certain temperatures to optimise living conditions [34]. However, the strong association of ice cod with subzero temperatures in Northeast Greenland may also lie in the different environmental and ecological

conditions of fjord vs. shelf habitats rather than in a species-specific temperature preference [34]. The observed gradual decrease in ice cod abundance on the shelf over 15 years (Figure 4) nevertheless suggests that higher temperatures are avoided and underscores that the warming shelf water is an important contributor to the apparent relocation of ice cod (Figures 4 and 5).

The tolerance to freezing temperatures has been elaborately studied in polar fishes, including ice cod [35]. Ice cod has been encountered at temperatures as high as 2.7 °C off Svalbard Archipelago [12] and 3.5 °C in the eastern Laptev Sea (MMBI unpublished data, 2014), but the upper temperature tolerance for this cryopelagic species has not yet been established.

The depth of bottom trawl catches with ice cod varied between 98 m and 769 m. The highest proportional biomass of ice cod (62.6%) was encountered at depths 200–400 m, and up to 88% of the biomass was found within the 200–600 m layer (Figure 6). This corresponds well with the bottom depth of the subzero sill fjords along the Northeast Greenland coast. Similar data were obtained also for other areas in the European Arctic [12].

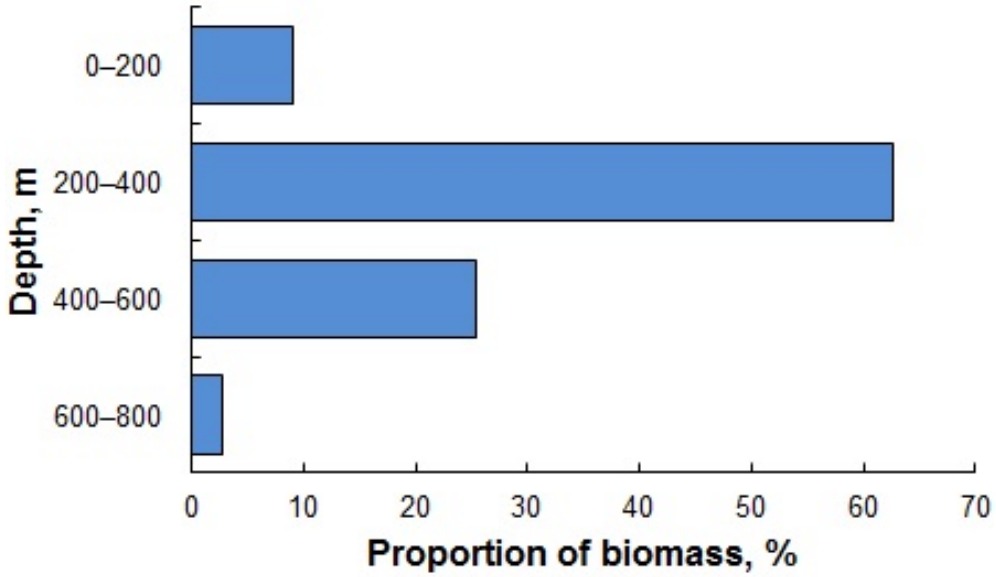

Figure 6. The proportional biomass of ice cod *Arctogadus glacialis* with depth of sampling across fjord and shelf stations in Northeast Greenland (cf. Table 1 and Figures 1 and 3).

3.3. Ice Cod Body Mass in Relation to Temperature and Depth

Overall, larger ice cod were caught in 2005 and 2013 and smaller ones in 2002, but with large interannual fluctuations in mean body mass, ranging from about 15 g in 2002 to 40 g in 2005 (Figure 7). The mean body mass of ice cod was 24 ± 2 g across all stations and tended to be slightly higher (27 ± 3 g) in the fjords and lower (19 ± 2 g) on the shelf.

The mean body size of ice cod in the fjords revealed that the larger specimens occurred only at temperatures above 0.4 °C (Figure 8a). On the shelf, on the other hand, both small and large ice cod were encountered at all temperatures (Figure 8b).

The mean body mass of ice cod with depth of sampling revealed no trend, and all size groups appeared evenly distributed throughout the entire depth interval irrespective of habitat (Figure 9a,b).

In conclusion, the occurrence of different-sized ice cod across stations suggests little spatial size segregation, although the smaller specimens with a body mass < 15 g prevailed in subzero waters (Figure 8a).

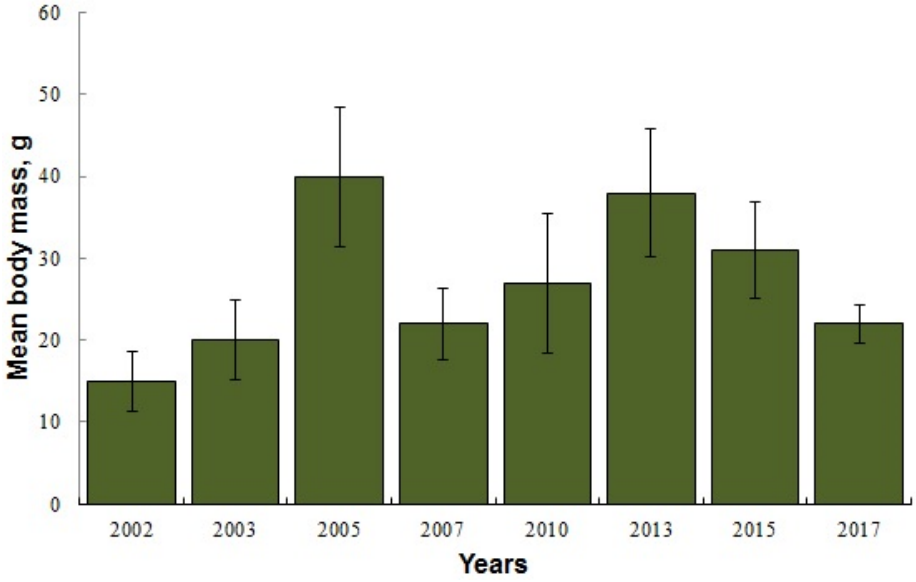

Figure 7. Overall mean body mass (g) of ice cod *Arctogadus glacialis* (±S.E.) across fjord and shelf stations in Northeast Greenland (cf. Table 1 and Figures 1 and 3). Only 2 specimens were caught in 2015.

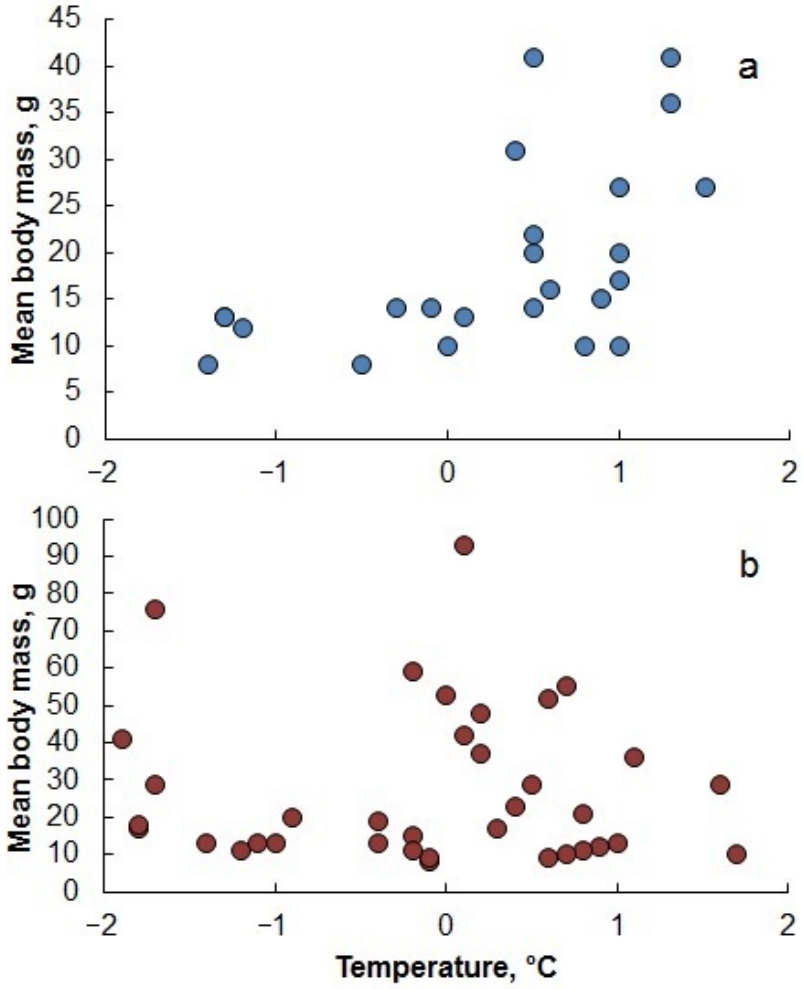

Figure 8. Mean body mass (g) of ice cod *Arctogadus glacialis* across fjord (**a**) and shelf (**b**) stations in Northeast Greenland in relation to ambient temperature (cf. Table 1 and Figures 1 and 3).

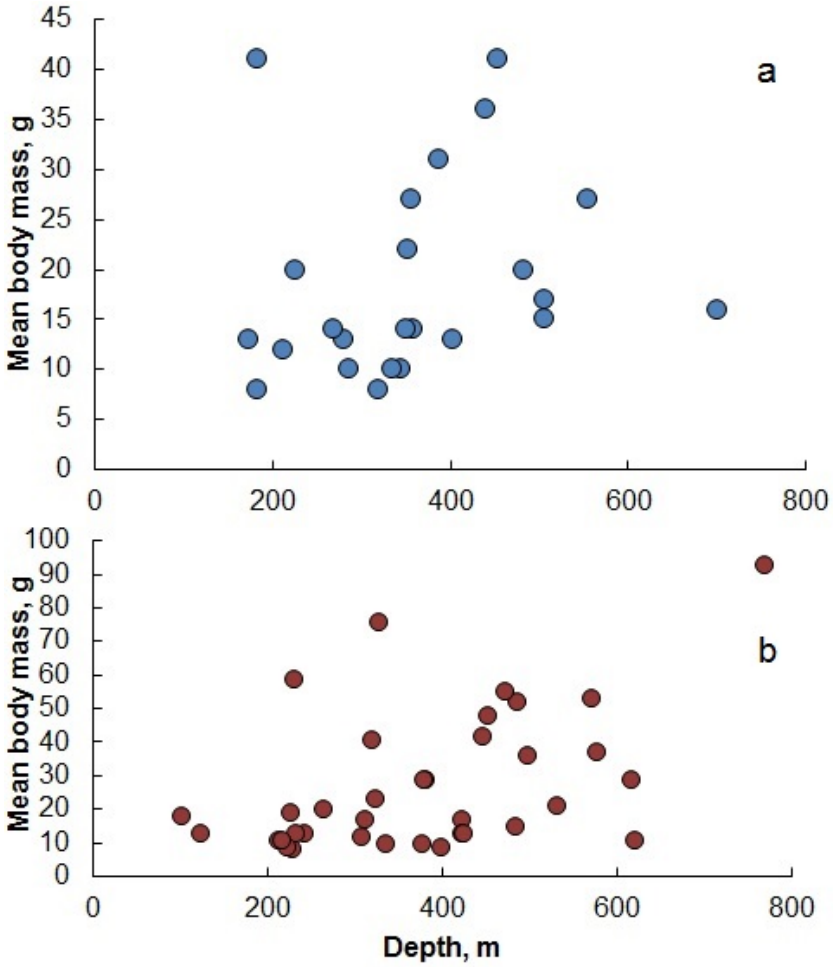

Figure 9. Mean body mass (g) of ice cod *Arctogadus glacialis* across fjord (**a**) and shelf (**b**) stations in Northeast Greenland in relation to depth of sampling (cf. Table 1 and Figures 1 and 3).

Exceptionally large ice cod with a mean body mass of 230 g was observed at one station near Jan Mayen Island (latitude 71 °N) and separated by the deep waters ~390 km east of the Northeast Greenland shelf (Figure 3). During years 1995–2008, a total of 206 specimens were caught at Jan Mayen Island [14]. Whether these fish are strays from Northeast Greenland or represent a population of its own remain to be verified by population genetics [36].

Our TUNU Expeditions sketch the first large-scale baseline of the occurrence and abundance of ice cod in the Northeast Greenland fjord and shelf habitats. Here, within the Northeast Greenland National Park, primeval natural conditions still prevail, although commercial enterprises such as fisheries and tourism are emerging fast [37]. So, future baselines are deemed to be affected directly by human activity in addition to ongoing ocean warming and climate change.

4. Conclusions

The TUNU Expeditions (years 2002–2017) give the first insight to ice cod distribution and abundance in the fjords and on the shelf in Northeast Greenland. The deep (200–600 m), cold (<−1.0 °C) and secluded sill fjords along the coast are conclusively the main habitat for ice cod with mean catches about 12 times higher in the fjords (~50 kg/km^2) as compared to the shelf (~4 kg/km^2). Furthermore, the biomass of ice cod on the shelf decreased during the survey period parallel to the ongoing warming of the shelf waters.

Throughout the Arctic seas [3], the ice cod appears most numerous in Northeast Greenland. Here, the sill fjords serve as suitable habitats and as important refugia for this cryopelagic

cod fish. Given Arctic amplification [38], ice cod is likely threatened because warmer shelf water is expected to pass the sills and, thus, change the fjord ecology profoundly [30].

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Institutional Review Board Statement: We used specimens that were caught only by trawl.

Data Availability Statement: The data is available from the authors upon reasonable request.

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Conflicts of Interest: The authors declare no conflict of interest.

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