



Climate change dynamics and mercury temporal trends in Northeast Arctic cod (*Gadus morhua*) from the Barents Sea ecosystem[☆]

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ABSTRACT

The Northeast Arctic cod (*Gadus morhua*) is the world's northernmost stock of Atlantic cod and is of considerable ecological and economic importance. Northeast Arctic cod are widely distributed in the Barents Sea, an environment that supports a high degree of ecosystem resiliency and food web complexity. Here using 121 years of ocean temperature data (1900–2020), 41 years of sea ice extent information (1979–2020) and 27 years of total mercury (Hg) fillet concentration data (1994–2021, $n = 1999$, $\geq 71\%$ Methyl Hg, $n = 20$) from the Barents Sea ecosystem, we evaluate the effects of climate change dynamics on Hg temporal trends in Northeast Arctic cod. We observed low and consistently stable, Hg concentrations (yearly, least-square means range = 0.022–0.037 mg/kg wet wt.) in length-normalized fish, with a slight decline in the most recent sampling periods despite a significant increase in Barents Sea temperature, and a sharp decline in regional sea ice extent. Overall, our data suggest that recent Arctic amplification of ocean temperature, “Atlantification,” and other perturbations of the Barents Sea ecosystem, along with rapidly declining sea ice extent over the last ~30 years did not translate into major increases or decreases in Hg bioaccumulation in Northeast Arctic cod. Our findings are consistent with similar long-term, temporal assessments of Atlantic cod inhabiting Oslofjord, Norway, and with recent investigations and empirical data for other marine apex predators. This demonstrates that Hg bioaccumulation is highly context specific, and some species may not be as sensitive to current climate change-contaminant interactions as currently thought. Fish Hg bioaccumulation-climate change relationships are highly complex and not uniform, and our data suggest that Hg temporal trends in marine apex predators can vary considerably within and among species, and geographically. Hg bioaccumulation regimes in biota are highly nuanced and likely driven by a suite of other factors such as local diets, sources of Hg, bioenergetics, toxicokinetic processing, and growth and metabolic rates of individuals and taxa, and inputs from anthropogenic activities at varying spatiotemporal scales. Collectively, these findings have important policy implications for global food security, the Minamata Convention on Mercury, and several relevant UN Sustainable Development Goals.

1. Introduction

The effects of climate change on temporal trends of total mercury (Hg) in Arctic biota (Dietz et al., 2006; Dietz et al. 2009; Dietz et al. 2019; Dietz et al., 2022a) are of considerable importance to natural resource managers and have important policy implications for research and biomonitoring programs (Rigét et al., 2011). Evaluating these effects is crucial for legally binding environmental conventions such as the

United Nations Minamata Convention on Mercury (Bank, 2020). Hg ecosystem fluxes, cycling, post depositional processes, and trophic transfer in Arctic biota are difficult to assess, especially in the context of a rapidly changing climate, and several process-based mechanisms regarding Hg uptake in Arctic organisms remain poorly understood (Dietz et al., 2022a). Strong evidence has emerged demonstrating that climate change, in general, has had measurable effects on increasing export and transport of terrestrial catchment Hg from thawing

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permafrost, glacier melting, and coastal erosion pathways to downstream marine ecosystems (Chételat et al., 2022). Furthermore, translating these changes and effects into predictive models for Arctic marine biota is highly complex and constrained by several ecological uncertainties in responses of biota to sea ice dynamics, wind patterns, increased rainfall, climate oscillation, species northward distribution shifts, and changes in organism physiology and body condition (Dastoor et al., 2022; McKinney et al., 2022).

The patterns identified for temporal trends of Hg in Arctic biota inhabiting terrestrial and marine ecosystems are inconsistent. Time trend reporting and information for Hg in Arctic biota are often highly variable, data limited, and thus often not suitable to support robust statistical analyses due to low sample numbers and/or brevity of the investigation period (Rigét et al., 2011). Additionally, it is uncommon and rare for climate change contaminant investigations to concomitantly assess large spatial areas with long-term empirical ocean temperature, sea ice extent, species prey use, and temporal Hg data for Arctic ecosystems such as the Barents Sea (BS).

The BS is a shallow and productive Arctic marine environment (Wassmann et al., 2006) with a high degree of ecosystem and food web resilience (Griffith et al., 2019), even though significant impacts from fisheries, recent crab species introductions (Jørgensen and Nilssen, 2011; Holt et al., 2021; Zakharov et al., 2021), and other ecosystem-scale perturbations have been reported (Smedsrud et al., 2013; Sonne et al., 2022). Climate change factors such as increasing ocean temperatures and declining sea ice have caused significant changes in the ecosystem with fish distribution shifts and range expansions, as well as significant modifications in the distribution and occurrence of Arctic water masses (Fossheim et al., 2015; Oziel et al., 2016; Ingvaldsen et al., 2021). Specifically, the BS is experiencing an “Atlantification” (Lind et al., 2016; Tesi et al., 2021), a complex process driven by inflow of Atlantic Ocean water which has increased warming in the southern BS and shifted the Arctic water masses further north, and with subsequent effects on regional fish communities due to species distributional shifts (Fossheim et al., 2015; Ingvaldsen et al., 2021).

Most Arctic Hg is emitted at lower latitudes and long-range

atmospheric transport northwards is common (Dastoor et al., 2022). Hg measured in precipitation and air at Svalbard and at the coast of Northern Norway has also decreased over recent decades (MacSween et al., 2022). Riverine Hg export is a considerable source of Hg to the marine environment worldwide (Liu et al., 2021) and recently investigators have shown significant declines in Hg sediment exports from Russian rivers entering the Arctic (Zolkos et al., 2022).

Northeast Arctic cod (NEAC - *Gadus morhua*) are abundant in the BS and represents a significant and commercially valuable fish stock (Julshamn et al., 2013; Kjesbu et al., 2014; Townhill et al., 2021; Directorate of fisheries, 2022). In 2021, the total catch of NEAC was 758,000 tons, and in 2022 the nominal value of Norwegian landings alone was about 9.3 billion NOK (about 0.9 billion USD; Directorate of Fisheries, 2022). Furthermore, NEAC was ranked 12th, during 2020, for world fisheries landings (FAO, 2022) highlighting its economic importance and role in global food security. This species has an ecologically important role as an apex predator in the BS with high mobility and varied diet (Holt et al., 2019). The ecology and life history of this stock is discussed in detail by Yaragina et al. (2011).

Here, we assessed and tested for temporal trends of Hg measured in NEAC fillet tissue collected in BS during 1994–2021. To put this work into a broader context we also evaluated NEAC Hg temporal patterns with respect to historic and long-term ocean temperature trends using data collected from fixed stations sampled along the BS ‘Kola Transect’ during 1900–2020 (Fig. 1, Fig. 2, Fig. 3, Fig. S1), and during a period with substantial declines in sea ice extent (1979–2020, Fig. 4). These three independent data sets represent a unique opportunity to evaluate the role of climate and global environmental change factors on mercury exposure regimes in a commonly consumed seafood species from a large and important, commercial fishery. Specifically, we tested the following hypotheses and *a priori* predictions: cod fillet mercury concentrations would increase positively with fish length and would be independent of both declining sea ice extent, and increasing sea temperature.

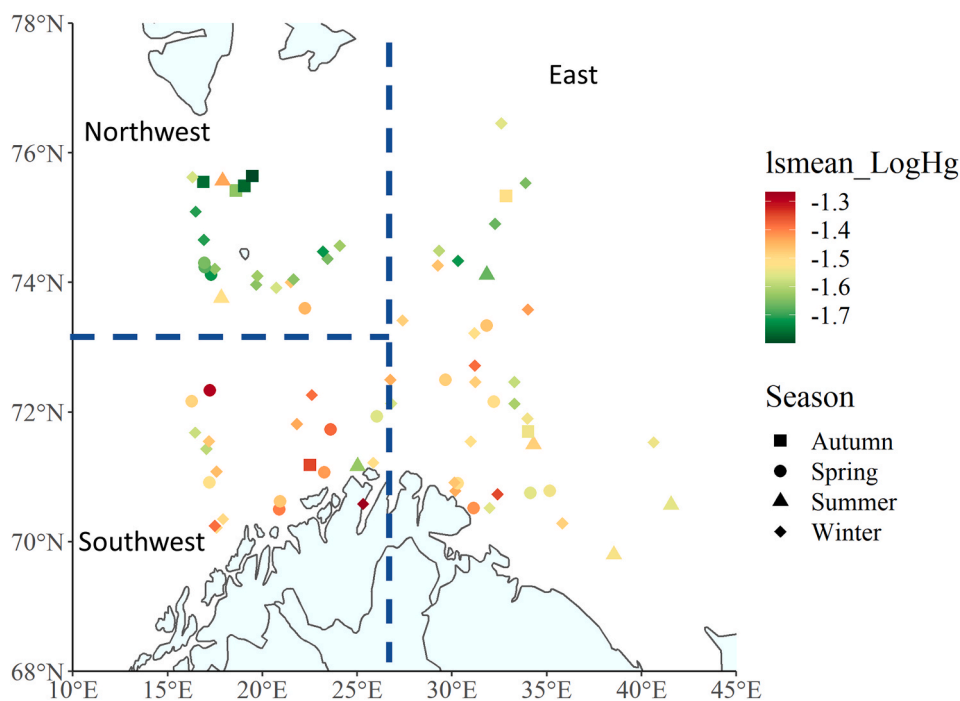


Fig. 1. Sampling areas, and spatial and seasonal distribution of THg in cod fillets from the Barents Sea, 1994–2021. Least square means of log transformed THg concentrations (mg/kg ww) are indicated by different colors. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

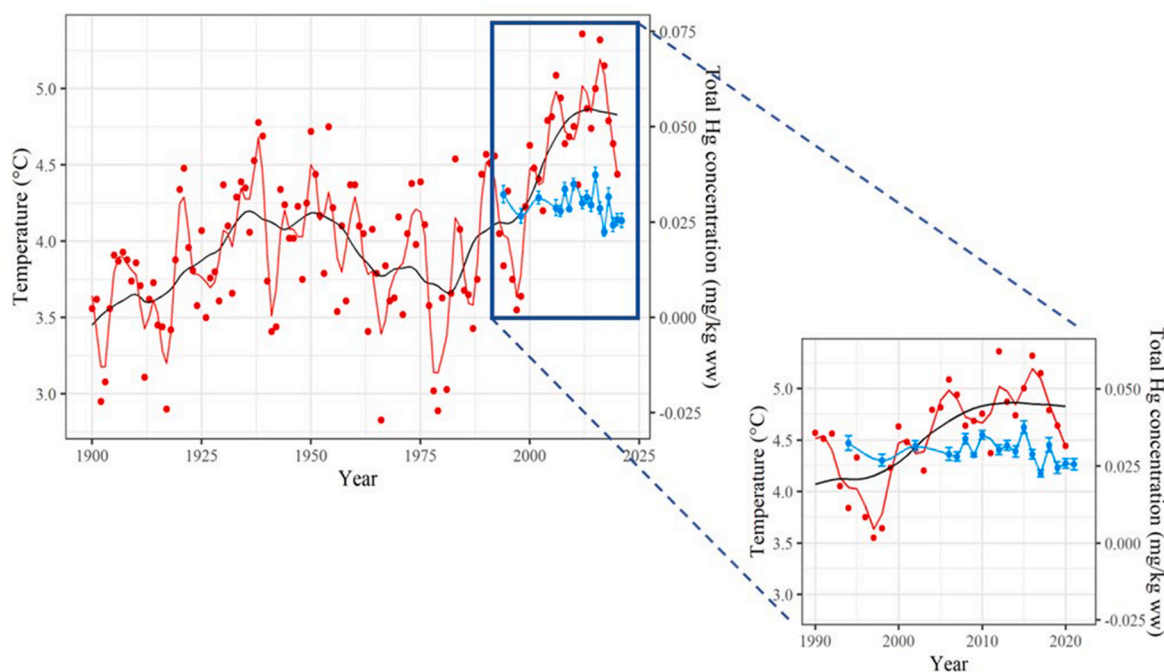


Fig. 2. Temporal trend of BS seawater temperature ($^{\circ}\text{C}$) measured along the ‘Kola Transect’ from 1900 to 2020 (red dots and line) and mean \pm SE total mercury (mg/kg wet weight) in NEAC fillet tissue from 1994 to 2021 (blue dots and line). For sea temperature both the 5-year (red solid line) and 20-year (black line) Lowest regression smoothing functions are presented. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

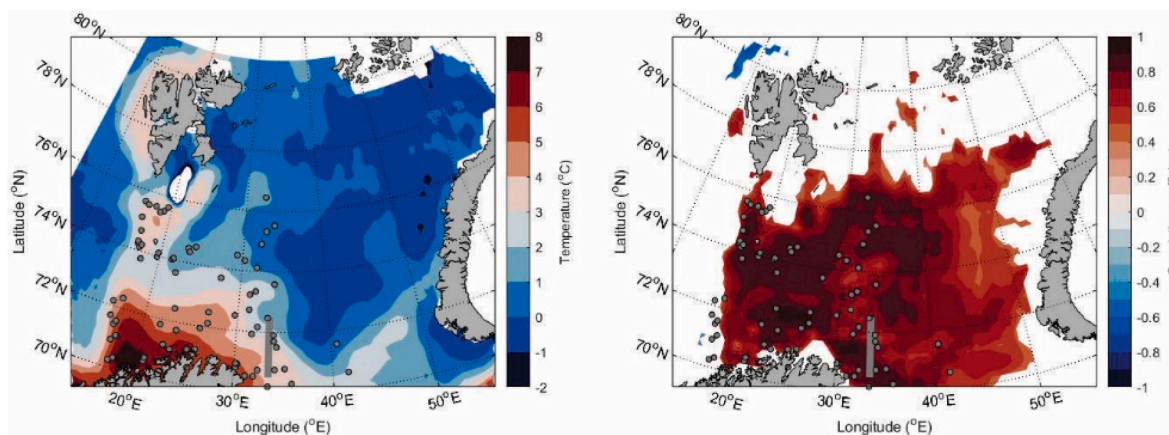


Fig. 3. Mean water temperature at seabed during August–September 1994–2021 (left). Correlation coefficients between annual mean Kola section transect temperature and seabed temperature during 1994–2021 (right). Only significant correlation coefficients ($P < 0.05$) are included. Grey circles indicate cod sampling locations, and the grey line shows the location of the Kola section sampling transect. Seawater temperature data are from the Institute of Marine Research (Norway) and the Polar branch of the Russian Federal Research Institute of Marine Fisheries and Oceanography (Russia).

2. Materials and methods

2.1. Fish sampling (1994–2021)

A total of 1999 Northeast Arctic cod were sampled between $69^{\circ}30'N$ and $76^{\circ}30'N$ and between $16^{\circ}E$ and $42^{\circ}E$ in the Barents Sea in 1994–2021 (Fig. 1). Complete and detailed fish sampling protocols can be found in Ho et al. (2021), Azad et al. (2019), and Julshamn et al. (2004, 2013).

2.2. Kola Transect & seawater temperature (1900–2020)

Temperature data were taken from the Kola section along $33^{\circ}30'E$ (Fig. 3), provided by the Polar branch of the Russian Federal Research

Institute of Marine Fisheries and Oceanography (PINRO). Sampling of this section started in 1900, and sampling has been conducted 6–15 times each year (Boitsov et al., 2012). Missing values have been interpolated by PINRO. For this study we used mean temperature between surface and 200 m depth, in the region between $70^{\circ}30'N$ and $72^{\circ}30'N$. Spatial temperature data (1994–2021) at the seabed were taken from Norwegian–Russian ecosystem surveys, conducted jointly by the Norwegian Institute of Marine Research and PINRO during August and September of each year. The Kola section time series correlate well ($R > 0.5$) with horizontal seabed temperature fields in the entire southern BS (Fig. 3), indicating that the time series data are robust and a good representation of regional seabed temperature variability (Loeng, 1991; Ingvaldsen et al., 2003).

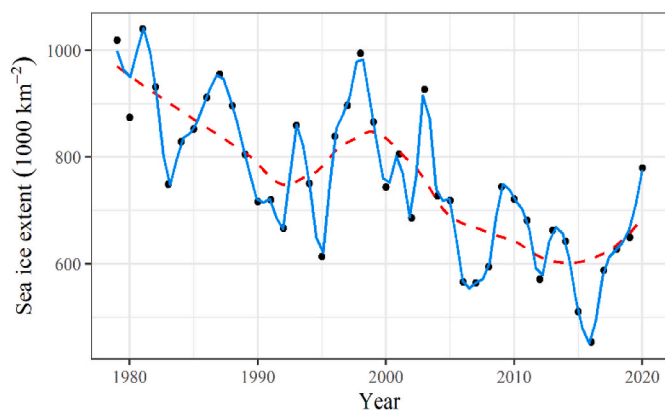


Fig. 4. Sea ice extent (km^2) during April in the BS ecosystem, 1979–2020. Data are from the Norwegian Polar Institute and used with permission. Lowess regression smoothing functions are presented for both the 5-year (blue solid line) and 20-year (red dashed line) trend lines. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

2.3. Laboratory analyses

A complete and reproducible description of all materials and methods for sample preparation and total mercury (Hg) analysis can be found in Julshamn et al. (2013), and Ho et al. (2021). Twenty samples of cod fillet were also analyzed for methylmercury (MeHg) and a complete and reproducible description of the MeHg analyses and QA/QC for Hg speciation of the same sample batch when NEAC fillet samples were analyzed is given in Bank et al. (2021).

2.4. Statistical analyses

All Hg concentration data were log-transformed. Temporal comparisons of Hg in NEAC fillets were performed using analysis of covariance (ANCOVA) on the least square means of log-transformed Hg concentration with fish length selected as a covariate to control for the effects of individual size. In the ANCOVA tests, residual plots were carried out to examine normality of the data. Furthermore, a Lowess (Locally weighted scatterplot smoothing) fit in the general additive model (GAM) was used for annual trend analyses of seawater temperature (yearly mean), sea ice extent, and the least square Hg concentrations (length adjusted). Both 5-year (short term) and 20-year (long term) Lowess regression smoothing were applied to evaluate trends and relationships between selected variables. To evaluate the relationship between yearly mean sea temperature and NEAC Hg concentrations we used general linear regression with log-transformed Hg concentration data as the dependent variables and seawater temperature and fish length as independent variables.

Temporal comparisons of growth rate were also performed. First, the least square means of fish length at different years were calculated with fish age selected as a covariate using ANCOVA to control for age effects. Growth rate means were subsequently calculated by dividing least-square means of fish length by the mean age. Akaike's Information Criterion (AIC) was computed to evaluate model performance (Burnham and Anderson, 2002) in addition to R-squared values (R^2). Statistical analyses were performed using statistical programming language R (R Core Team, 2020) running in RStudio (version 1.3.959; RStudio Team, 2015).

3. Results and discussion

Our results provide empirical evidence for significant environmental change in the BS (Fig. 2, Fig. S1, Fig. 4). BS water temperature (total yearly mean \pm SE = $4.0\text{ }^\circ\text{C} \pm 0.05\text{ }^\circ\text{C}$, range = $2.8\text{ }^\circ\text{C}$ – $5.4\text{ }^\circ\text{C}$) has

increased since 1900 (Boitsov et al., 2012; Drinkwater et al., 2014), with a faster rate of increase beginning around 1990, during the same period when NEAC Hg was first measured (Fig. 2). BS ice extent declined rapidly during 1979–2020 (Onarheim et al., 2018; Efstathiou et al., 2022) (Fig. 4). During the period of significant increase in BS ocean temperature and corresponding decrease in sea ice extent (Fig. 4), NEAC fillet Hg concentrations ($n = 1999$) in length-normalized individuals were generally low and remarkably stable over the 27-year investigation (yearly least-square means range = 0.022 – 0.037 mg/kg wet wt.) and had a slight decline during the most recent sampling years ($P < 0.05$, Fig. 2, Table 1). NEAC Hg concentrations were not related to sea temperature ($P = 0.781$, Table 2). MeHg, a highly neurotoxic form of Hg, comprised $\geq 71\%$ of the total Hg measured in NEAC fillets ($n = 20$).

Fish were sampled from a large area of BS (Figs. 1 and 3, Table 1), with low to moderate spatial variability (Fig. 1, Julshamn et al., 2013), and with negligible observed seasonal effects on NEAC Hg concentrations (Fig. S2). Our data suggest that significant increases in sea water temperatures and decreases in sea ice extent in the BS had no major effect on Hg in the generalist, apex marine predator, NEAC, a highly mobile, long-lived species (Figs. 2 and 4, Table 1, Fig. S1). Additionally, Hg concentrations in NEAC were largely stable over time with only a very slight decrease in the most recent sampling years, and despite strong decadal scale declines in regional (Bank et al., 2021) and Arctic atmospheric Hg (MacSween et al., 2022), and Hg export from Arctic rivers to the Arctic Ocean (Zolkos et al., 2020; Zolkos et al., 2022).

Despite the change in ocean temperature, growth rates of NEAC were generally similar over the study period where data were available (Fig. S3). Some potential NEAC BS prey items, polar cod (*Boreogadus saida*) and capelin (*Mallotus villosus*) also had relatively low Hg concentrations, that declined over similar time periods to this investigation (Fig. S4). Furthermore, stable, long-term, Hg concentrations in NEAC (Fig. 2, Table 1) were in strong accordance with findings for length-adjusted analyses of Atlantic cod from the heavily impacted Oslofjord in Norway reported by Ruus et al. (2017). Although Hg concentrations were significantly higher in Atlantic cod from Oslofjord, no temporal trend for length-normalized individuals was detected in their 33-year study during 1984–2017 (Ruus et al., 2017).

Our study has a few caveats that need to be considered regarding the interpretation of data and results, and the potential limitations in scaling up or extrapolating our findings to other regions. For example, sea

Table 1

Least-squares means (length-adjusted) of Hg concentrations (mg/kg wet wt.) in Northeast Arctic cod fillet tissue ($n = 1999$) from the Barents Sea sampled between 1994 and 2021. ANCOVA analysis was used for comparison of log Hg concentrations. Values with different letters in the group column indicate significant differences ($P < 0.05$) between the years.

Year	LS Mean Hg concentrations	Lower 95% Confidence Limit	Upper 95% Confidence Limit	Group	n
1994	0.0323	0.0260	0.0401	bcd	50
1998	0.0266	0.0214	0.0331	abcd	50
2002	0.0314	0.0269	0.0366	bcd	100
2006	0.0287	0.0231	0.0357	abcde	50
2007	0.0279	0.0238	0.0327	abcd	95
2008	0.0337	0.0289	0.0392	cde	100
2009	0.0284	0.0268	0.0302	bc	631
2010	0.0350	0.0308	0.0396	de	150
2012	0.0301	0.0257	0.0352	bcd	94
2013	0.0316	0.0271	0.0368	bcd	99
2014	0.0295	0.0247	0.0353	abcde	73
2015	0.0374	0.0320	0.0438	e	97
2016	0.0287	0.0243	0.0338	abcd	89
2017	0.0224	0.0193	0.0261	a	100
2018	0.0316	0.0255	0.0393	bcd	50
2019	0.0243	0.0194	0.0304	ab	46
2020	0.0257	0.0215	0.0307	abc	75
2021	0.0254	0.0205	0.0315	abc	50

Table 2

Linear regression output used for analyzing potential relationships between log-transformed Hg concentrations in Northeast Arctic cod (NEAC) fillets and BS annual temperature (°C) from the Kola transect, and fish length (cm) during 1994–2021. Fish length was positively and significantly associated with Hg, and the relationship between sea temperature and Hg concentration in NEAC was not significant.

Output	F-statistic	R ² (P-value)	AIC
Linear regression	117.9	0.11 (<0.001)	−235.95
Coefficients	Estimate	Standard Error	P-value
(Intercept)	−1.944	0.0804	<0.001
Sea Temperature (°C)	−0.00426	0.0153	0.781
Fish Length (cm)	0.00681	0.000446	<0.001

temperature measurements in the upper 200 m of the water column measured along a single fixed transect likely do not precisely reflect the actual temperatures experienced by all sampled fish throughout the entire BS. Nonetheless, the Kola transect temperature time series gives a very good representation of the temperature variability and trend of the entire southern BS (Ingvaldsen et al. 2003). Furthermore, since the temperature conditions in the southern Barents Sea are rather homogenous between the seasonal mixed layer and the bottom (Loeng, 1991), the Kola section temperature data also gives a good representation of the temperature at the seabed (Fig. 3). Our data also show that ocean temperature increases were seasonally consistent (Fig. S1).

Although we provide empirical evidence for stable Hg in NEAC from BS, the ultimate and proximate causes of the observed trends are essentially unknown. Here, we present a few conservative predictions, and hypotheses as to why Hg in NEAC may be generally stable despite significant increases in sea temperature, declines in sea ice extent, and with regard to other global environmental change factors: 1) ecosystem resilience and stable food webs may be strong enough to support viable food habit niches and space use opportunities such that potential effects from climate change on NEAC Hg over time are negligible and undetectable at the population scale, 2) multiple abiotic and biotic conditions and a high degree of ecosystem complexity may counterbalance simultaneously decreasing and increasing Hg concentrations fluxes, and exposure regimes in different abiotic and biotic ecosystem compartments, and 3) the degree of climate change is currently not substantial enough to govern processes responsible for dramatically increasing or decreasing Hg concentrations in NEAC. Different trends, for example, could be observed in warmer environments, such as equatorial, tropical marine ecosystems. Ocean warming may also enhance seawater Hg⁰ evasion, while climate induced decreases in wind speed may counterbalance this by reducing losses to the atmosphere via air-sea exchange (Wang et al., 2023). These investigators also postulate that climate change may affect the ocean's biological carbon pump and reduce bi-directional, vertical mixing of MeHg in the water column, and that sea ice loss may increase photodemethylation of MeHg (Wang et al., 2023). Ocean stratification may also have important, yet largely unknown, impacts on marine Hg biogeochemical cycling via limited upward mobility of legacy Hg, and changes in primary productivity, and the distribution of low oxygen zones and subsequent effects on methylation and demethylation processes (Sonke et al., 2023). Furthermore, and collectively, the long-term stability of NEAC Hg in both BS and Oslofjord suggests that there are important, albeit poorly understood, relationships between individual toxicokinetics, physiology, metabolic processing, bioenergetics, growth rates, and potential lipid dilution effects (Jardine et al., 2009), physiology, and internal demethylation dynamics that likely regulate MeHg and Hg in this species. NEAC Hg concentrations were lower than the highly impacted Oslofjord (Ruus et al., 2017) yet similar to NEAC from the BS measured by Gopakumar et al. (2021). Furthermore, our findings for NEAC Hg were also in good accordance with results reported by Renedo et al. (2021) who showed that MeHg concentrations in marine predators (seabirds) from the Peruvian coast

were not sensitive to climate change factors. Our results contrasted with a theoretical modeling study by Schartup et al. (2019) who postulated that ocean warming would be a major driver of MeHg bioaccumulation regimes in marine predators, however we agree with their proposed theory that fisheries management regimes could be a potential driver because of changes in species prey use. Fisheries may also impact climate change, in general, through disruption of the ocean's biological carbon pump creating potential climate feedback loops (Bank et al., 2020; Bianchi et al., 2021).

Long term and high-resolution stomach contents data from NEAC, at decadal scales, (Holt et al., 2019; Townhill et al., 2021) show a high degree of individual and interannual variation in food habits and diet for this species over the same period of investigation (Fig. 5). Despite the high degree of interannual variation in the NEAC diet, Hg remained consistently low and remarkably stable over time. Hg measurements in NEAC were biased to the southern region of BS, yet stomach contents analyses (Fig. 5) were conducted throughout the entire BS ecosystem (Holt et al., 2019; Townhill et al., 2021). Nonetheless, it is widely accepted that NEAC are highly mobile predators with a diverse and generalist diet, such that their bioaccumulation regimes likely reflect broad spatiotemporal scales to support our long-term, length-normalized fish analyses.

Coastal rivers have recently been identified as an important and overlooked source of mercury to marine coastal zones and open ocean environments with important ramifications for global flux models (Fisher et al., 2012; Liu et al., 2021). Furthermore, Arctic rivers in Russia are an important source of Hg to the Arctic Ocean (Fisher et al., 2012), and recent empirical data have reported significant long-term declines in particulate Hg and sediment export to the Arctic Ocean, at a decadal scale (Zolkos et al., 2022). During recent decades atmospheric and riverine inputs of Hg to the BS have decreased (Zolkos et al., 2022; MacSween et al., 2022). Our data suggest that independently or collectively, ocean warming, declining sea ice extent, “Atlantification” and “borealization” of the BS ecosystem (Fossheim et al., 2015; Tesi et al., 2021; Ingvaldsen et al., 2021) or declining inputs of Hg (Zolkos et al., 2020; Zolkos et al., 2022; MacSween et al., 2022) were not overtly important drivers of NEAC Hg temporal bioaccumulation trends. Our results have important implications for fisheries management and sea-food safety, especially since NEAC is part of the borealization process and is one of the species benefitting from higher ocean temperatures and becoming more dominant in the northern BS (Fossheim et al., 2015; Johannesen et al., 2020; Tesi et al., 2021; Ingvaldsen et al., 2021).

Recently the state of the science of Arctic mercury cycling was addressed in a special journal issue on this topic (Dietz et al., 2022b), and researchers have shown that modeling of mercury fluxes between abiotic and biotic ecosystem compartments, in the context of climate change, is complex and highly uncertain making Hg models difficult to develop and constrain (Dietz et al., 2022a).

Some important questions remain regarding the effects of climate change on mercury cycling, methylation, trophic transfer dynamics, and growth based Hg bioaccumulation regimes (Chételat et al., 2021; Chételat et al., 2022). It is likely that the development of a unified, marine fish Hg model will be rather challenging to develop and validate, especially given the varying degrees of uncertainty since Hg bioaccumulation regimes, in this context, are highly context and species specific and will vary across ocean Hg pollution gradients that exist globally (Lamborg et al., 2014). Furthermore, the relationship between climate change, sea temperature, fish growth rates, and Hg bioaccumulation is poorly understood, data limited with inconsistent results, highly complex, and extremely variable across fish life stages, species, study designs, and geography (Chételat et al., 2021 and references therein). Future research should evaluate these inconsistencies along with other global change factors that may influence fish growth rates and Hg bioaccumulation regimes in the context of a rapidly changing climate (Eagles-Smith et al., 2018).

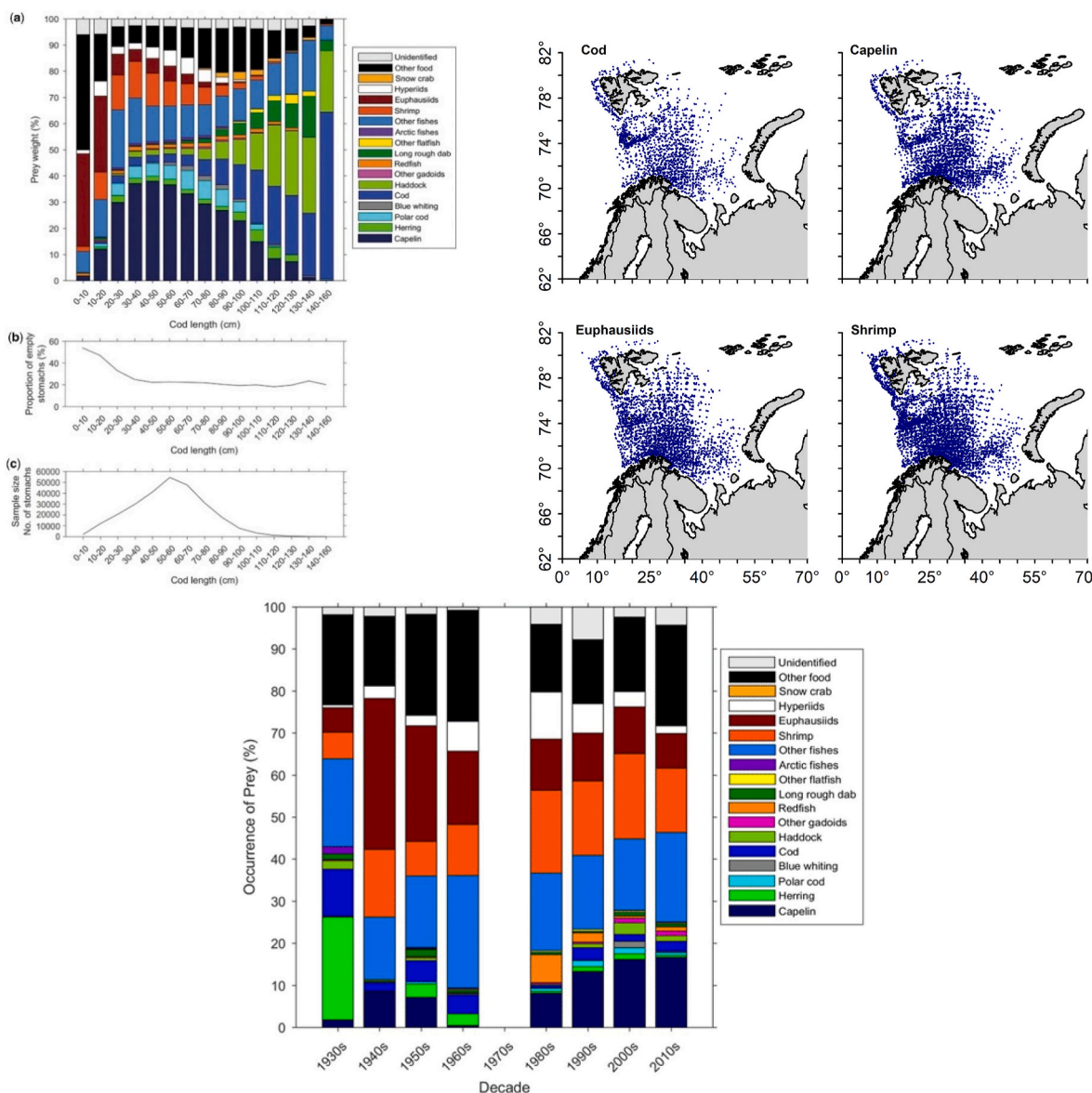


Fig. 5. Long-term NEAC diet and food habits in the BS. Left Panel: (a) Weight of prey species/groups (%) in stomachs of NEAC pooled across the years 1984–2016 for different length groups, (b) % empty stomachs in each length group, and (c) sample sizes for each length group (data from [Holt et al., 2019](#)). Right Panel: Main prey species in NEAC stomachs pooled across all years from 1930s to 2018. Each dot represents a stomach sample (data from [Townhill et al., 2021](#)). Bottom Panel: NEAC diet (% prey occurrence) from BS at the decadal scale from 1930's-2018 (data from [Townhill et al., 2021](#)). All data adapted and reprinted from [Holt et al. \(2019\)](#) and [Townhill et al. \(2021\)](#) with permission (Creative Commons Attribution 4.0 License).

4. Conclusions

Climate and global environmental change factors did not have a strong effect on long-term Hg concentrations in our population scale assessment of NEAC from the BS ecosystem. Our results presented here are specific to BS and NEAC and future research questions and predictive models should consider other regions and taxa as well as species bioenergetics, physiology, kinetics, and marine fish MeHg demethylation mechanisms. We also encourage similar studies using other legacy and emerging contaminants. Our investigation and synthesis demonstrate that a key bioindicator species, NEAC, inhabiting a large and rapidly warming Arctic marine ecosystem, had Hg concentrations that were generally low and stable over a long time (i.e., >25 years) with a very modest and slight decline in the most recent sampling years. These declines were deemed minor regarding potential ecotoxicological effects, and statistical significance was largely driven by the large sample sizes of NEAC (n = 1999) analyzed in the study. Our results have important

fisheries and seafood safety implications for a large and commercially relevant cod fishery that can be considered by policy makers. Our empirical data may also support further discussions surrounding climate change and contaminants in general and can be used for future climate change and ecosystem modeling scenarios in support of the UN Minamata Convention on Mercury. Our data suggest that BS ecosystem resilience and Hg atmospheric deposition regimes (i.e., air-sea exchange) may have a more dominant influence on NEAC Hg bioaccumulation regimes than climate induced changes via long-term increases in sea temperature, and declining sea ice extent. Changes in food web dynamics, and riverine and atmospheric inputs of Hg are critical factors that modulate Hg cycling in Arctic marine ecosystems and will require further research to identify the underlying mechanisms and drivers between these factors and climate change, and marine fish Hg bioaccumulation regimes ([Schartup et al., 2022](#); [Zolkos et al., 2020](#); [Zolkos et al., 2022](#)).

Code availability

The codes that support the methods of this study are available from the corresponding authors upon reasonable request.

CRedit authorship contribution statement

Michael S. Bank: Conceptualization, Methodology, Formal analysis, Funding acquisition, Resources, Supervision, Writing – original draft, Writing – review & editing. **Quang Tri Ho:** Formal analysis, Methodology, Data curation, Investigation, Writing – review & editing. **Randi B. Ingvaldsen:** Formal analysis, Methodology, Data curation, Investigation, Writing – review & editing. **Arne Duinker:** Investigation, Formal analysis, Writing – review & editing. **Bente M. Nilsen:** Investigation, Formal analysis, Writing – review & editing. **Amund Maage:** Investigation, Formal analysis, Writing – review & editing. **Sylvia Frantzen:** Formal analysis, Methodology, Data curation, Investigation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.envpol.2023.122706>.

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