

High-latitude climate variability and its effect on fisheries resources as revealed by fossil cod otoliths

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Cod (*Gadus morhua*) otoliths from archaeological sites in northern Norway were analysed to reconstruct the temperature regime and determine the age structure, growth, and population identity of the fish harvested. Otoliths were selected from late- and post-medieval sites (700–300 years ago) to evaluate historical changes in the geographic region that matches the present-day stocks of Northeast Arctic cod (NEAC) and Norwegian coastal cod (NCC). Seasonal temperature cycles were reconstructed from stable isotope ($\delta^{18}\text{O}$) measurements along transects representing fish ages 1.5–3 years old. Reconstructions of the size, age, and growth characteristics of individual fish were based on otolith growth increments. The geographical source and stock identity of the individuals were estimated based on otolith elemental composition and otolith growth features. Both NCC and NEAC fish were represented at Måsøy and Vanna. The results indicate that fishing at Vanna exploited NEAC during their spawning migration, compared with fishing at Måsøy, which was restricted to more coastal fish. Fish growth patterns appeared to be affected by changes in the temperature regimes as estimated from otolith $\delta^{18}\text{O}$ and back-calculated fish length-at-age, with evident differences between pre- and post-1600 periods.

Keywords: back-calculated growth, climate change, historical fisheries, otolith microchemistry, oxygen isotope ratios, temperature effects.

Introduction

One of the biggest challenges for climate change studies is the problem of scale. It is particularly challenging to match the resolution between available environmental proxies and the time-frame that is of interest. Events occurring at geological time-scales can be associated with evolutionary changes, but it is shorter time-scales that are of most interest when it comes to societies and the effects of changing climate on our use of marine resources. Evidence of the historical interactions between climate and fish populations may be contained in the fossil remains of fish found at archaeological sites. Sites that have been occupied over a long period can yield material that may provide a time-series of fish populations with clues about the environment they inhabited.

Until recently, there was little collaboration between palaeozoologists and population biologists who work on modern populations, limiting the exchange of information and tools for looking at long-term changes in populations and resource exploitation. Amorosi *et al.* (1994) presented the case for multi-disciplinary studies to integrate findings from zooarchaeology and fisheries biology, using the example of the North Atlantic cod fisheries over the past 1000 years. Many new insights

about fish and fisheries have resulted from the increased exchanges between researchers in these fields, and there is a much better understanding of early harvesting patterns and how humans influenced marine food sources (Limburg *et al.*, 2008). Analysis of fossil otoliths has revealed important changes in the development of fisheries during early historical periods, for example, pinpointing the rise of intensive fisheries for cod and herring and its potential link to climate in relation to the “Medieval Warm Period” (Amorosi *et al.*, 1994; Barrett *et al.*, 2004). These insights are extremely valuable for studies of settlements in high latitudes, because they reveal how patterns of fish resource use have changed over repeated warming and cooling cycles. This information may help to refine models to examine changes at time-scales that are relevant to humans, such as seasonal, annual, and decadal.

By combining archaeological and modern fish population techniques, changes in fish populations can be studied over longer periods. Neer *et al.* (1999) used plaice otoliths from medieval sites to reconstruct the population age structure and growth to serve as “pristine” conditions for measuring the population effects of modern fishing pressure. Limburg *et al.* (2008) analysed

a large number of otoliths from Neolithic and modern cod populations in the Baltic Sea and determined that growth patterns had changed significantly over time. There was also evidence of fishery selectivity in the Neolithic remains.

Several techniques used to analyse modern fish populations are based on the analysis of otolith structure and growth. For example, the seasonal nature of historical fishing activities has been assessed by examination of the marginal increment of otoliths, although it is not reliable to determine the season of fishing based on the presence of an opaque or translucent edge from only a few otoliths (Neer et al., 2004). Geochemical methods can also be applied to otolith samples and add important information about local temperature and water masses to the biological and archaeological data. Oxygen isotope ratios measured along transects across the otolith provide seasonal temperature signals that can help to determine the seasonality of fishing (Hufthammer et al., 2010).

Fish otoliths in the Osteology Collection (Natural History Collections, Bergen Museum, at the University of Bergen) provide an unusual opportunity to examine long-term changes in both fish populations and fishing patterns in high latitudes. Studies at high latitudes are particularly important for evaluating climate change, because these systems undergo extremes of seasonality, giving annual ranges that can be contrasted against average annual values. Both fish and human populations are often at the limit of their distributions at high latitudes and are therefore more likely to change distributions and behaviour over time in response to climate variation. Archaeological sites in Norway allow access to a combination of key features, with 25% of the coast above the Arctic Circle, a long coastline with different fish populations and remains of human settlements and their fisheries along the coast dating from Neolithic to present day.

We analysed cod (*Gadus morhua*) otoliths from two archaeological sites in Norway to reconstruct the temperature regime

experienced by fish and determine the age structure, growth, and stock identity of the populations represented. Elemental, isotopic, and microstructure analyses were combined on individual otoliths and the results used to estimate: (i) the temperature regime experienced by the fish (average yearly and seasonal range), (ii) the growth of the fish, and (iii) the geographic source of the fish. Specifically, seasonal temperature cycles were reconstructed from stable isotope ($\delta^{18}\text{O}$) measurements along transects representing 1.5–3 years of life. Reconstructions of the size, age, and growth characteristics of individual fish and the population were based on otolith growth increments. The geographical source and stock identity of the individuals were estimated based on the measured elemental composition of the otolith and analysis of the otolith shape.

Material and methods

The farm mounds of coastal North Norway represent the accumulations produced by long periods of settlement at the same location (Holm-Olsen, 1981; Bertelsen, 1984). Subsistence at these farm mound sites was based on a combination of fishing and farming; therefore, their location depended on optimal access for a combined economy. The stability of the fisheries resources was important in determining the success of these settlements.

Fossil cod otoliths were selected from two archaeological sites at farm mounds representing late- and post-medieval settlements in the north of Norway; Måsøy in Finnmark and Vanna in Troms (Figure 1). The farm mound at Måsøy was excavated by Tromsø Museum in 1982. The faunal material includes almost 40 000 bones of fish, birds, and domestic and wild mammal species. Cod is the dominant species, with more than 20 000 bones. The farm mound “Torsvåg gardshaug” at Vanna in Troms was excavated by Tromsø Museum in 1976 (Holm-Olsen, 1981). From

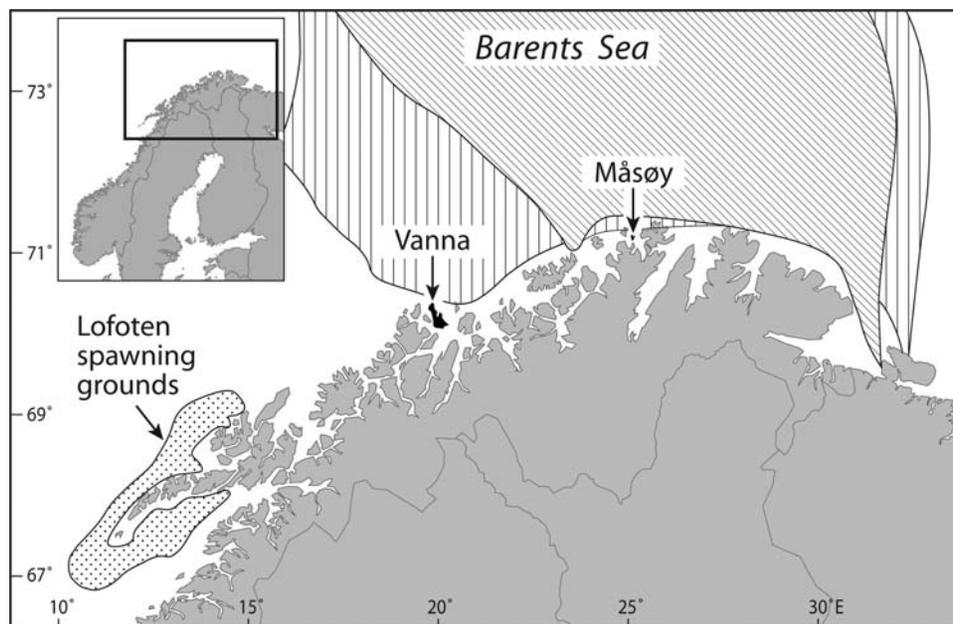


Figure 1. Map of Norway with locations of the Måsøy ($70^{\circ}59'N$ $24^{\circ}39'E$) and Vanna ($70^{\circ}07'N$ $19^{\circ}48'E$) sites. Spawning migration of NEAC runs south from the Barents Sea to Lofoten in February–April and some NCC migrate from the coast and fjords to spawn at Lofoten at the same time. Eggs and larvae are carried north by the coastal current, with NCC mostly settling inshore and NEAC continuing to be carried into the Barents Sea, where they remain as juvenile and immature fish (diagonal shading). Wintering and feeding grounds for older fish (>4 years) in the southern Barents Sea are illustrated (vertical shading). Map based on Vikebø et al. (2005).

the eight different settlement horizons of the mound, more than 17 500 bones have been collected of which 8500 have been identified to the level of species. The dominant species is cod, representing 68% of the sample. In all, 17 cod otoliths were selected from the Vanna bone material J.S. 574 and 26 from the Måsøy samples J.S. 673. Each otolith was washed in distilled water and brushed clean of any surface material with a soft nylon brush. The otoliths were photographed and a small section (29–53 mg) of material was sampled from the antistrozum for radiocarbon dating (^{14}C), as well as being examined by X-ray crystallography to confirm the carbonate structure. The otolith samples were radiocarbon dated at Poznan Radiocarbon Laboratory (Supplementary Table S1), and all the ^{14}C ages were calibrated with the Internet program Calib 6.0, using IntCal09 (Reimer *et al.*, 2009).

All otoliths were well preserved, with their outer edges intact (Figure 2a). They were embedded individually in Epofix™ Cold-Setting Embedding Resin, which was allowed to cure at room temperature. The otoliths in resin were cut in the transverse plane with a slow-speed, diamond, wafering blade, to give a 500- μm section containing the core and growth increments. When sectioned, the growth increments were clearly visible (Figure 2b). The sections were secured to geological slides with Crystalbond™ 509 thermoplastic adhesive, then polished to give a smooth flat surface.

Several types of analysis were carried out on each otolith (Supplementary Table S1):

- Population type—based on the dimensions and shape of the otolith core and inner growth zones (Berg *et al.*, 2005);
- Individual fish size at harvest—based on the otolith size–fish size relationship for Northeast Arctic cod (NEAC) and Norwegian coastal cod (NCC; Stransky *et al.*, 2008);
- Individual growth trajectory—based on the width of growth increments and back-calculation of size-at-age (Li *et al.*, 2008);
- Temperature experienced as juveniles—based on stable isotope ($\delta^{18}\text{O}$) measurements of carbonate samples extracted from the growth increments formed during the second year of life (Hoie *et al.*, 2004);

- Geographical differences in the area of residence at different life-history stages—based on the analysis of elemental composition measured by LA-ICPMS (laser ablation-inductively coupled mass spectrometry) of the otolith core, settlement zone, transect across the growth increments, and otolith edge (Higgins *et al.*, 2010).

The sections were photographed, and measurements of the growth increments and dimensions of the otolith cores and total otolith size were made on the digital images. Separate fish lengths were estimated by back-calculation for NEAC and NCC based on otolith length and fish length data from Stransky *et al.* (2008). The back-calculation was based on using the distal radius data and applying a non-linear scale proportional hypothesis procedure (Li *et al.*, 2008). There was no difference in the log distal radius vs. log estimated fish length relationship between assigned NCC and NEAC fish (GLM, $p < 0.2$), and a common exponent of 0.63 based on data from Li *et al.* (2008) was used in the back-calculation.

High-resolution samples of carbonate (27–35 μg) for stable isotope ($\delta^{18}\text{O}$) measurements were micromilled along a transect crossing the second year growth increments (Hufthammer *et al.*, 2010). The milled otolith carbonate was transferred to glass vials and analysed on a Finnigan MAT 253 mass spectrometer. The long-term reproducibility of the MAT 253 is $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$ (standard deviation) for sample sizes between 6 and 90 μg , based on replicate measurements of an internal carbonate standard over a period of months, corresponding to $\pm 0.5^\circ\text{C}$ when converted to a temperature estimate based on the temperature– $\delta^{18}\text{O}$ relationship for cod (Hoie *et al.*, 2004). Temperatures corresponding to the carbonate samples were estimated from the resulting $\delta^{18}\text{O}$ values, using a temperature– $\delta^{18}\text{O}$ relationship for cod (Hoie *et al.*, 2004). Approximation of the appropriate water $\delta^{18}\text{O}$ was made based on the salinity record for the two areas.

Elemental composition was determined by LA-ICPMS analysis of the otolith sections, previously cleaned with Milli-Q water. Ablation spots of 50 μm diameter were produced by a New Wave 213 nm laser, and the ablated material was analysed using the coupled Finnigan Element 2 ICPMS. Ablation spots were located in the otolith core (three spots), within and adjacent to the zone of settlement (3 \times 3 spots), along a transect of the

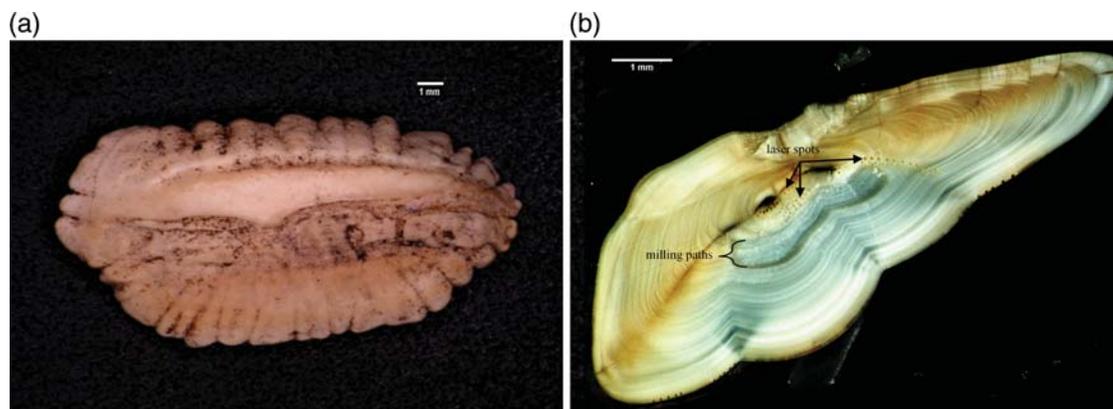


Figure 2. Example of fossil otolith from archaeological collection: (a) whole otolith, and (b) otolith section with area milled for stable isotope analysis ($\delta^{18}\text{O}$) indicated by bracket, and ablation spots from LA-ICPMS analysis of elemental composition indicated by black arrows. This otolith (5V) is from the Vanna collection, dated to 1762 and displays ten annual growth increments. Based on the ratio of second to first growth increment, the fish has been classified as NEAC.

annual growth increments (ten spots) and at the otolith edge (three spots). Four analytical standards were analysed: glass standards NIST 610 and 612 and fish otolith standards FEBS-1 and NIES-22. Standards were measured at the start and the end of each otolith run. Eight elements were detected reliably for this study: Li, Na, Mg, Mn, Rb, Sr, Ba, and Pb. Elemental concentrations were calculated using instrument counts with the Glitter v.4 signal processing software (ARC National Key Centre for Geochemical Evolution and Metallogeny of Continents, Macquarie University; Van Achterbergh *et al.*, 2001), which produced LOD (limit of detection) estimates of 0.02–4.23 for Li, 0.51–57.82 for Na, 0.01–1.46 for Mg, 0.02–4.34 for Mn, 0.006–1.31 for Rb, 0.005–1.51 for Sr, 0.01–10 for Ba, and 0.002–0.13 for Pb.

We assumed that certain characteristics of the otoliths were applicable from modern samples to the fossil otolith samples. We also assumed that the relationship used to estimate water temperature from cod otolith carbonate samples today would give reasonable estimates of past water temperature, even without exact data on the water $\delta^{18}\text{O}$ corresponding to the fossil otoliths, using a salinity proxy instead. The chemical and stable isotope compositions were interpreted in the same way for these fossil otoliths as for modern samples, assuming that there was no contamination or digenesis of the aragonite. The X-ray crystallography results were taken to confirm the stability of the otolith structure.

Results

From the total set of otoliths, we characterized the populations that were fished in the two settlements (Table 1). At Vanna, the material recovered represented fishing over a 400-year period, from 1390 to 1770 (Table 1, Supplementary Table S1). The fish ranged in size from ca. 600 to 900 mm and were 5–14 years old at capture. Nearly half the otoliths displayed characteristic spawning zones. Based on the ratio of the first and second growth increments, 62% (10 of 17) of the otoliths were classified as NCC and 38% (7 of 17) as NEAC.

At Måsøy, the material recovered represented a shorter fishing period, overlapping with the fishing at Vanna for the period 1620–1770. The otoliths found at Måsøy were estimated to come from cod ranging from ca. 460 to 780 mm long and 3–10 years old at capture. Fewer otoliths from Måsøy displayed characteristic spawning zones. Based on the ratio of the first and second growth increments, 61% (16 of 26) of the otoliths were classified as NCC and 39% (10 of 26) as NEAC, similar to the ratio observed for the Vanna samples (Fisher test, $p > 0.8$).

Detailed analyses were carried out on comparable subsets of otoliths from the two settlements, dated to the 1600–1700s. Some striking differences were apparent, which suggest different strategies in the utilization of fish resources in these areas, as well as differences in the fish that were available for harvest (Table 1).

The NCC at Vanna were similar in size, but older than those found at the more northern settlement of Måsøy (Figure 3). The NEAC, conversely, were larger and older at Vanna than at Måsøy. All indications from the reconstructed fish size and age are that most of the fish utilized at Måsøy were from cod that had not yet reached maturity, being significantly smaller and younger.

Analysis of the otolith elemental composition revealed differences in the environmental histories of the fish found at the two sites (Supplementary Table S2). Sr concentrations were lower in the section of the otolith corresponding to the end of the first

Table 1. Means (s.e.) of fish and environmental data estimated from a subset of the otoliths collected at Måsøy and Vanna archaeological sites (Supplementary Table S2), with remains from Vanna separated into those dated to be pre- or post-1600.

Site	Population	n	Age (year)	Fish length (mm)	^{14}C dated (calibrated age)*	est. Temperature (°C, annual mean) [mean (s.e.)]	est. Temperature (°C, annual minimum) [mean (s.e.)]	est. Temperature (°C, annual maximum) [mean (s.e.)]
Måsøy	NCC	6	8.2 (0.5)	703 (22)	1728 (17)	2.1 (0.5)	0.8 (0.4)	3.3 (0.5)
Måsøy	NEAC	5	6.2 (0.8)	606 (20)	1707 (24)	1.5 (0.3)	0.2 (0.1)	3.2 (0.8)
Vanna	NCC	3	10.7 (0.3)	695 (53)	1711 (41)	2.7 (2.6)	0.6 (1.2)	4.6 (0.2)
Vanna	NEAC	3	11.7 (1.2)	819 (57)	1706 (51)	1.8 (1.0)	0.7 (0.9)	2.9 (1.1)
Vanna pre1600	NCC	6	9.8 (1.3)	696 (14)	1473 (31)	4.6 (1.2)	2.9 (1.1)	6.3 (1.3)
Vanna pre1600	NEAC	3	7.7 (1.5)	702 (29)	1513 (38)	6.8 (1.6)	5.1 (1.3)	8.9 (2.1)
	Site x population						pre- vs. post 1600	
			$F_{1,35}=17.2$	$F_{2,35}=7.04$			$F_{1,19}=10.4$	$F_{1,19}=8.4$
			$p < 0.001$	$p = 0.012$			$p = 0.004$	$p = 0.005$

Estimated temperatures (est. Temperature) indicate the group mean of the average annual temperature and the group maximum or minimum temperatures estimated from approximately monthly samples of otolith carbonate. Emboldened entries indicate significant differences between sites or populations, with effect sizes indicated at the bottom of columns.

* $\delta^{18}\text{O}$ values and formal ^{14}C dating results for each otolith are given in Supplementary Table S1.

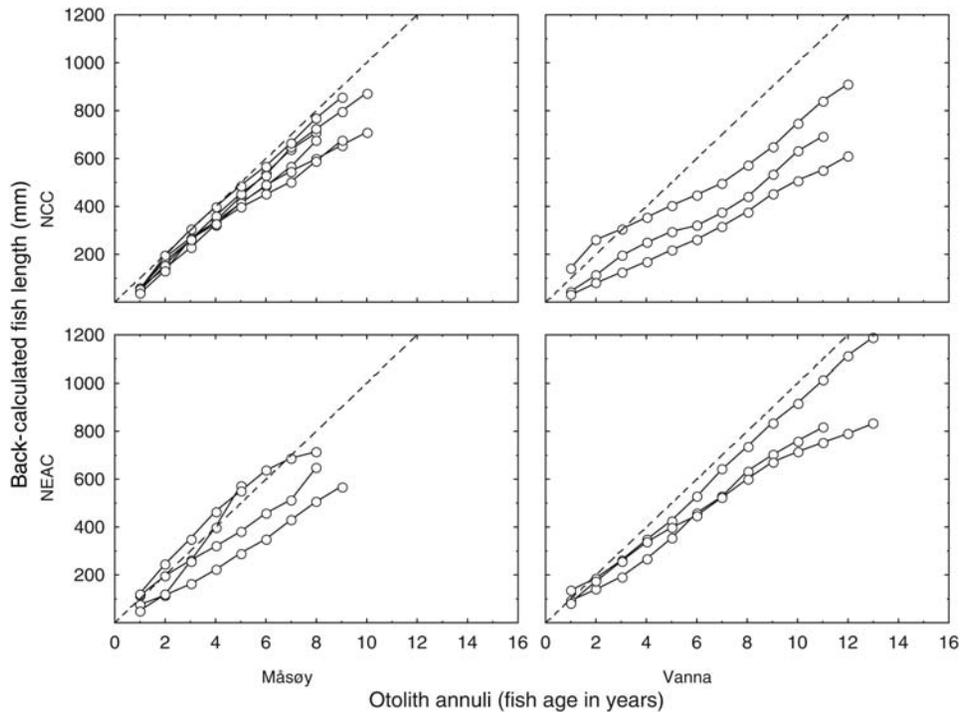


Figure 3. Differences in age, length, and back-calculated growth of individual cod from NCC and NEAC populations fished at Vanna and Måsøy originating after 1600. Dashed lines represent an average 10 cm growth per year (Jørgensen, 1992).

summer in otoliths classified as coming from NCC individuals collected at Vanna (ANOVA Site \times origin $F_{1,11}=9.5$, $p=0.02$). This may indicate movement into less saline waters, such as coastal fjords, compared with the NEAC individuals or NCC that settle farther north along the Barents Sea. Ba concentrations in the core sections of the otolith were lower in the NCC collected at Måsøy (ANOVA Site \times origin $F_{1,11}=7.3$, $p=0.02$), which may also reflect an area with lower primary productivity, or situated farther offshore.

The seasonal temperature cycle experienced by each individual during its second to third year of life was reconstructed from the $\delta^{18}\text{O}$ ratios of samples milled from the corresponding growth increments. Each sample represents ~ 1 month in the life of the fish (Figure 4). The transects across the opaque and translucent zones corresponding to the second year confirmed that translucent zones corresponded to warmer temperatures and most likely represent seasonal temperature cycles. Temperature estimates for the NCC otoliths recovered from Vanna (those dated to 1600–1700s) varied between 4 and 6°C, decreasing to close to 0°C towards the end of the second growth increment (Figure 4b). The otoliths of the NEAC fish indicated a seasonal temperature range of 0–4°C, gradually rising during the course of their second year of life. The fish caught at Måsøy seemed to have experienced a stronger seasonal temperature regime, based on the otolith (which were all dated to 1600–1700s) $\delta^{18}\text{O}$ ratios (Figure 4a). The NCC fish and NEAC fish displayed almost mirror images in their temperature cycles. The temperature increased in the early part of the growth period, followed by a decreasing temperature for the NCC fish. However, for the NEAC fish, the growth zone began with decreasing temperatures, followed by a temperature maximum approximately three-fourths through the growth increment, then followed by a second decrease in estimated temperature. Barents Sea cod (NEAC) move into coastal waters to feed

on spawning capelin and this is potentially when they were more available to fishing (Jørgensen, 1992).

One of the most interesting aspects of the otolith collection from these sites is the availability of samples from the late 14th and 15th century, which pre-date the so-called “Little Ice Age” at these latitudes and may correspond to the end of the medieval warm period (Amorosi *et al.*, 1994; Barrett *et al.*, 2004). Otoliths of fish dated to pre-1600 were only available from Vanna and the temperature range estimated from oxygen isotopes for these fish was 0–12°C, with warmer estimates and higher variation among individuals (Figure 4c). As stated previously, all the later otoliths gave estimated mean temperatures $<6^\circ\text{C}$ (Figure 4).

The difference in the estimated temperature regime in these two periods appears to have had a predictable effect on fish growth. Individual growth patterns were estimated from back-calculated fish lengths at each age increment. The growth patterns of the fish that experienced estimated temperatures $<6^\circ\text{C}$ were slower than those that experienced higher temperatures, and the difference was more pronounced for NCC than for NEAC (Figure 5). For example, NCC growing at $<6^\circ\text{C}$ were on average 70 mm shorter at age 2 than those growing at $>6^\circ\text{C}$. Comparable NEAC were only 60 mm shorter at age 2.

Discussion

Historical fisheries along the Norwegian coast have exploited both migratory and local populations (Øiestad, 1994). The NEAC population is a large population, characterized by residence in the Barents Sea, with long spawning migrations south along the Norwegian coast. Spawning areas now are mostly in the area of Lofoten, but have been more extensive both north and south of that area in earlier times (Jørgensen *et al.*, 2008; Opdal, 2010). The eggs and larvae are carried north by the coastal current and the juveniles become demersal some time during their first

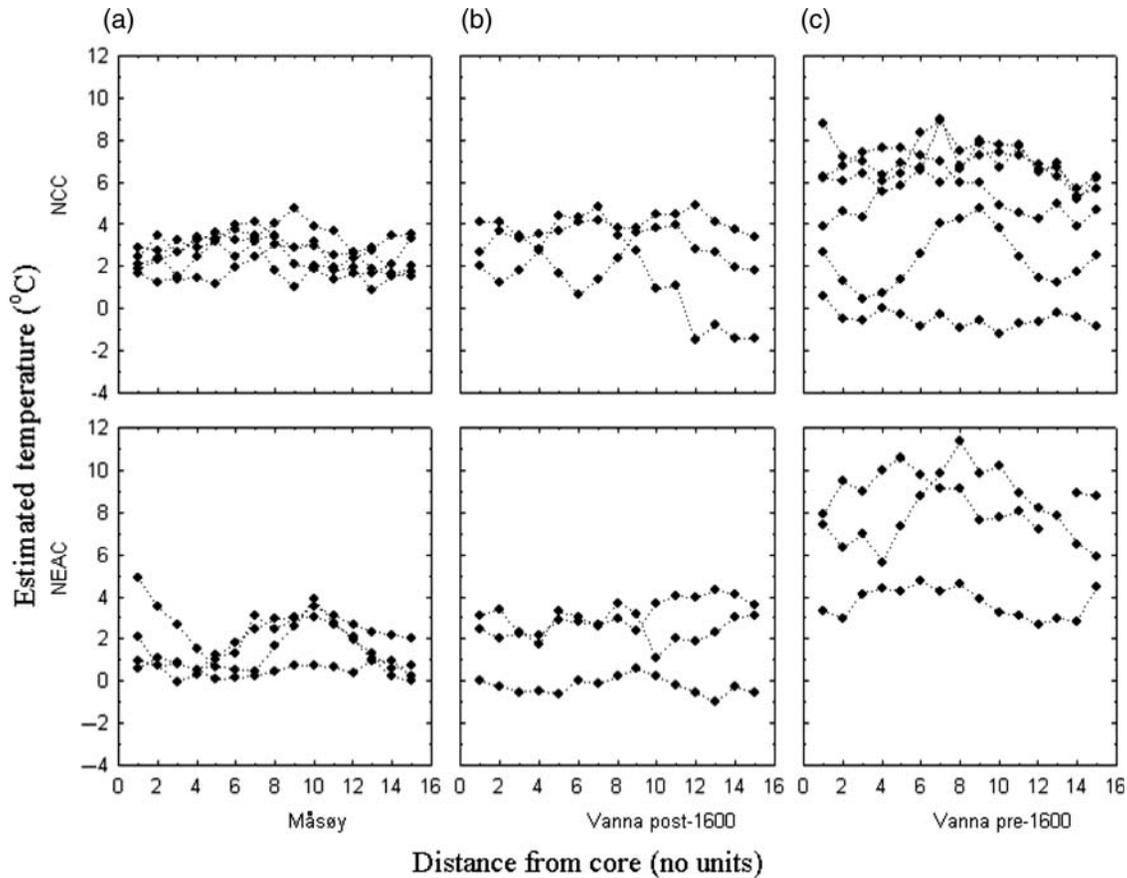


Figure 4. The seasonal temperature regime experienced by each individual during its second to third year of life, reconstructed from the $\delta^{18}\text{O}$ ratios of samples milled from the corresponding growth increments. Rows illustrate the pattern for NCC (top) and NEAC (bottom). The estimated seasonal patterns derived from otoliths recovered at Måsøy (a, all dated to post-1600) and Vanna (b, post-1600; c, pre-1600) are displayed in separate columns. Each sample represents ~ 1 month in the life of the fish. Symbols connected by dotted lines represent transect from one otolith.

autumn, settling in southern areas of the Barents Sea. Immature NEAC remain in the Barents Sea, coming closer to the coast to feed on capelin in late winter/early spring. NCC are found along most of the Norwegian coast and some also spawn at Lofoten in spring. NCC are distinguished genetically from NEAC, as well as by growth and morphology (Larsen *et al.*, 1997), and it is likely that there are distinct subpopulations (Stransky *et al.*, 2008). NEAC grow more slowly in their early years and mature at a larger size and later age than NCC. Average temperatures experienced by NCC and NEAC are probably similar, but NCC would be expected to experience a greater temperature range over the annual cycle. NEAC would be expected to experience their minimum temperatures in summer, when they feed in colder, off-shore waters. The growth pattern of the two populations would also be expected to respond differently to the temperature regime, because the “cold temperature” genotype is more prevalent in NEAC, which is linked to faster growth at lower temperatures (Immsland *et al.*, 2004). As expected, back-calculated growth rates of NCC were lower for those fish experiencing estimated temperatures $< 6^\circ\text{C}$. Over a longer temporal scale, the individuals dated to pre-1600s experienced generally warmer temperatures and faster growth rates than individuals harvested post-1600s.

Both NCC and NEAC were harvested at the two settlements, as seen from the otoliths recovered from archaeological sites. Fish at

Vanna included older and bigger fish and these are likely to be the NEAC, which would not be within reach of fishers until the fish were old enough to start spawning migrations. In contrast, smaller and younger fish were more representative in the catches at Måsøy, which may indicate availability of juvenile NEAC and smaller NCC. Because the otoliths of the NEAC suggested that these fish were larger and older at Vanna than at Måsøy, presumably they were fished on their way to the spawning grounds at Lofoten, 500 km farther south (Jørgensen *et al.*, 2008). The presence of spawning zones in the otoliths further supports the scenario that these came from a seasonal fishery focused on the spring-spawning migration of fish from the Barents Sea to Lofoten. NCC also spawn at Lofoten and they were likely caught while moving out of the fjords to the east of this settlement towards the spawning grounds.

The fish represented in the samples were mostly harvested during the post-medieval period, although the Vanna samples also included otoliths that dated to earlier periods. These samples cover a period of changing environment, as well as fishing pressure, and follow the rise of commercial fisheries based on the dried cod trade (Amorosi *et al.*, 1994). The activities at the two sites are reflected in the data, and Måsøy, which is slightly farther north and east and less accessible, was brought into use later, well into the commercial fishing period (Øiestad,

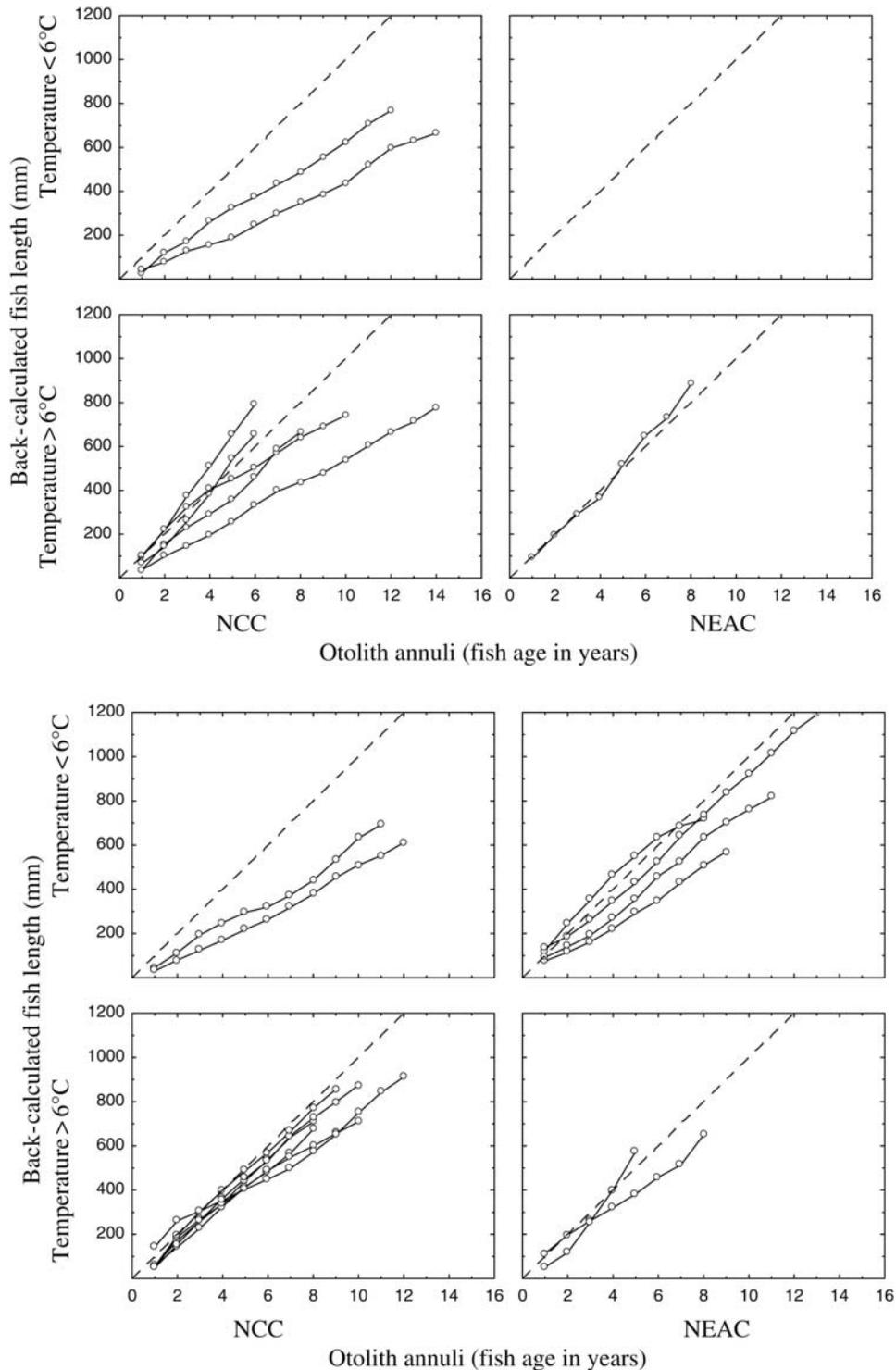


Figure 5. Back-calculated growth pattern of NCC and NEAC from otoliths collected at the Vanna and Måsøy sites combined. The growth patterns are illustrated for fish from average water temperature $>6^{\circ}\text{C}$ or $<6^{\circ}\text{C}$, based on measured otolith $\delta^{18}\text{O}$. Growth and temperature estimates were made on an individual otolith basis. Growth responses during warmer and colder periods are illustrated for fish otoliths with ^{14}C dates of capture pre-1600 (top panel) and post-1600 (bottom panel). There were no NEAC in the pre-1600, $<6^{\circ}\text{C}$ category. Dashed lines represent an average 10 cm growth per year (Jørgensen, 1992).

1994). Måsøy is located at 71°N and became a fishing and administrative centre during the 1700s, although there are also Stone Age settlements in the area. Vanna has a long history of settlement, with a mixture of human populations on both the outer coasts

and facing the inner waterways and fjord entrances (Bertelsen, 1984).

Generally, the fish caught at Vanna seem to display stronger differences between the two cod populations, NCC and NEAC.

This is most likely because the NEAC were mature and migrating individuals harvested on their way to the spawning grounds. However, the data also provide supporting evidence of the existence of different subpopulations of NCC. For example, it is clear from the elemental analysis, Sr and Ba concentrations especially, that the NCC harvested at Vanna settled in different locations than those at Måsøy. The observed differences in the back-calculated growth patterns conform to the current information for the modern populations. NCC grow faster during their first years, whereas NEAC grow more slowly, but ultimately reach a larger size (Imsland *et al.*, 2004).

Fishing patterns change over time—targeting different stocks and with different selectivity. That these developments in fishing patterns have altered natural fish populations within the past century is evident from both scientific and fishing records (Opdal, 2010). Less obvious is the relationship between fishing selectivity and populations in the past, but it can be assumed that medieval and even Neolithic fishing was selective (Barrett *et al.*, 2004; Neer *et al.*, 2004; Limburg *et al.*, 2008). It is clear from the characteristics of the fish represented at the two settlements that different fishing strategies were in use, targeting locally available parts of the populations for Måsøy and including seasonally available migrating fish for Vanna. It is also apparent that climate conditions, represented by water temperature, had a significant effect on the growth of individual fish in the targeted populations, as seen by the different growth patterns during the warmer period pre-1600. Because growth and recruitment in modern cod stocks can be correlated with temperature regimes (Brander, 1995, 2000; Mantzouni and MacKenzie, 2010), it is possible that similar variations in productivity were present in the warmer (pre-1600s) and colder (post-1600s) periods represented by the material analysed from Vanna. Historical fluctuations in cod fisheries along the Norwegian coast and across the North Atlantic have been documented and can be linked to climate fluctuations (Amorosi *et al.*, 1994; Øiestad, 1994).

Fish otoliths recovered from archaeological sites are a significant resource allowing a holistic view of the temperature regime, the fish populations, and the human harvesting patterns over a wide regional area over the past 1000 years. Methods of analysing modern fish populations based on otolith features are suitable for application to these fossil otoliths and produce relevant results for studying effects of climate change over useful time-scales. Our multisignal study should encourage a combined approach using expertise in climate research, fisheries biology, geochemistry, palaeozoology, anthropology, and archaeology to study historical climate in high-latitude areas and its effect on humans and their fish resources.

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