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The growing capability of proxy ocean temperature data from months to millennia

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In the century since the inception of ICES, the ability to make precise measurements using modern oceanographic instruments with ever increasing frequency and geographical coverage and to store and analyze these data using ever more powerful computers, has driven an explosion in our understanding of the oceans. It is sometimes easy to forget, then, that our longer-term knowledge of ocean variability is almost entirely built upon indirect fossil indicators or biorecords. Proxy records, spanning hundreds, thousands, and millions of years, give our handful of decades of instrument data needed perspective. Complementing the sophistication of today's electronic sensors is the growing capability of paleoceanographic methods to provide unprecedented detail about ambient conditions in the modern as well as the ancient ocean. For the ICES centennial, this paper briefly reviews the development of one of the most widely used of these methods – the oxygen isotope composition of marine carbonates as a proxy for ocean temperature – from its origins over a half century ago to its expanding uses today. The paper focuses on recent developments that have sharpened the temporal resolution of these records. As examples, work on fish otoliths and the shells of long-lived bivalves from the North Atlantic Ocean, which have provided new and necessary insights for ICES investigations and have set the only available long-term context of change for ICES science and planning, are discussed.

Keywords: mollusks, ocean temperatures, otoliths, oxygen isotopes, paleoceanography.

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Introduction

In the very first article published in the *Journal du Conseil*, Johan Hjort (1926), near the end of his paper on fish population fluctuations, concluded, "the simultaneous investigation of meteorology, hydrography and biology seems the only way to a deeper understanding of the conditions in which the destiny of the spawned ova is being decided." That focus on the interaction between fisheries biology and the physical environment has continued to be widely on display in ICES forums and publications over the years. However, a central problem arises in studying this complex interaction – how do we obtain the long and detailed environmental and biological records required for such an undertaking? This problem was directly addressed when the ICES Working Group on Cod and Climate Change set up its Backward-Facing Workshop in the mid-1990s. According to the Workshop's first Chair, Bob Dickson, its mission was to look far enough back in time so that the effects of fishing would be less dominant (ICES, 1995). Compiling historical data was important to this process, but what was new was the use of environmental proxies to break through the time and space constraints of human experience.

What misty panorama of earth's climate history we do possess has been painstakingly reconstructed through the development of paleontological methods over the last two centuries. For the first half of the 20th century, the unfolding story continued to be propelled by the great revolutions in biology and geology of the 19th century. The dawning of quantum physics and the atomic age in the early-to-mid 20th century unleashed a host of new geochemical and radiological methods for deciphering the details of past environments and precisely dating the timing of prehistoric events. At the same time, a technological revolution occurred in our capacity to observe the current state of our environment. Our ability to rapidly analyze vast amounts of remotely sensed information is outstripped only by our ability to collect it. And yet, our 21st century need to gauge the dimensions and consequences of future global climate change – a change driven perhaps by this same fast-paced development of human society – demands an even more exacting picture of how the earth's climate varied in the past. The growing capabilities of paleo-

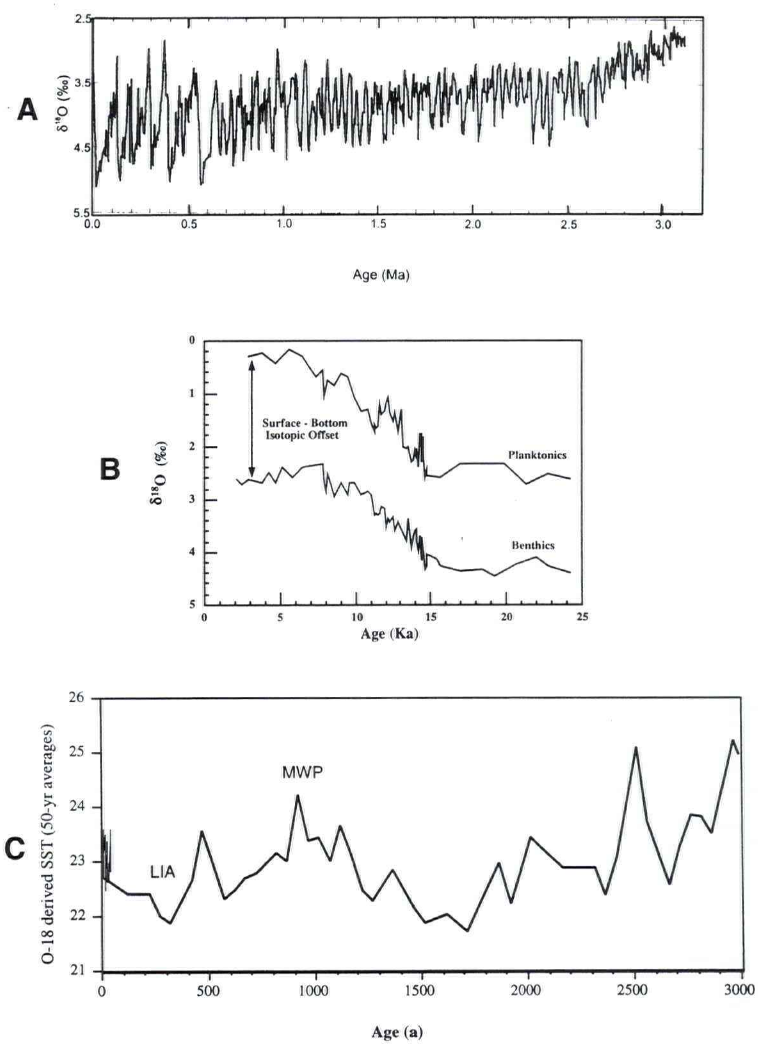

Figure 1. Deep-sea sediment $\delta^{18}O$: (A) Benthic foraminifera record of the last ~ 3 million years from the equatorial Atlantic (from Raymo, 1992). The large oscillations are thought to record earth's sea level/ice volume variations associated with continental glaciations. (B) Planktonic and benthic foraminifera records for the last ~ 20 thousand years from the North Atlantic (43°N) (data from Keigwin and Lehman, 1994). The offset between the records largely reflects temperature differences between surface and bottom waters, while the large trend between 7 and 14.5 Ka reflects the melting of the continental ice sheets at the end of the last Ice Age. (C) SST record for the last 3 thousand years derived from planktonic $\delta^{18}O$ from a high-sedimentation rate site near Bermuda (from Keigwin, 1996). The record suggests 2–3°C variations for sub-tropical North Atlantic SSTs associated with such climate extrema as the Little Ice Age (LIA) and the Medieval Warm period (MWP).

ceanography can be used to provide that picture, and this makes it deeply relevant to ICES. As Dickson (2002) reminds us here in this volume, "the pioneering efforts to describe ocean variability, its causes, and effects on the ecosystem, began in European waters, and the standing committees of ICES have long taken responsibility for maintaining these initiatives and developing them into a science."

Quantitative proxy methods of estimating past ocean temperatures have been in use now for almost half a century. Having produced much of the evidence for global climate variability on millennial and greater time-scales (e.g., ice ages), they supply the background for understanding our own historical climate interlude. Some applications are also capable of shorter-term detail more familiar to our life spans and our synoptic grasp of oceanographic and atmospheric processes. In the last decade or so, new methods have been developed that allow for unprecedented temporal resolution, nearly matching that of historical instrument records. Proxies also provide information about remote regions and depths where few observations exist, and so extend our understanding of the spatial patterns of ocean variability. Since these methods rely on the products of nature to reflect and record their environments, they require no scientific foresight or efficiently designed sampling strategies for monitoring future conditions – they are already deployed everywhere and working. The essential task is the ability to decode and interpret them correctly.

Oxygen isotopes and ocean climate

This past century has seen the invention of a host of ingenious scientific methods of deciphering the earth's ancient climates (Bradley, 1999). Arguably, one of the most important of these achievements was Harold Urey's (1948) discovery and, along with other workers (McCrea, 1950; Urey *et al.*, 1951; Epstein *et al.*, 1953), development of the methods for using the oxygen isotope composition of the carbonate skeletons of marine organisms for the estimation of ocean temperature. The significance of using stable oxygen isotope composition for ocean climate reconstruction is two-fold. The first part relies on the slight temperature dependence of fractionation between the lighter and most common isotope ^{16}O and the heavier and rarer isotope ^{18}O during the precipitation of carbonate from water. Colder water temperatures result in greater fractionation and more of the heavier isotope (^{18}O) in the skeletal parts of marine organisms. Warm and cold waters will be reflected in lower and higher $^{18}O/^{16}O$ ratios, respectively. Today, a number of slightly different paleotemperature equations are in use (see Wefer and Berger, 1991; Kim and O'Neil, 1997, for recent reviews). However, all of the relationships indicate a 4–5°C shift in temperature for each 1‰ change in the $\delta^{18}O$ of carbonate, where:

$\delta^{18}O = {}^{18}O/^{16}O$ sample / $^{18}O/^{16}O$ standard (VPDB or VSMOW)

and where VPDB and VSMOW refer to the international standards for reporting the oxygen isotope composition of carbonate and water, respectively (Coplen *et al.*, 1983).

The other important aspect of oxygen isotope paleoceanography relies on the slightly greater ease with which the lighter molecules of water ($H_2{}^{16}O$) are evaporated from the ocean's surface to form water vapor in the earth's atmosphere, while the heavier molecules of water ($H_2{}^{18}O$) are preferentially left behind. This molecular fractionation mimics the hydrologic process that drives salinity variations in the surface ocean (water is evaporated while salt is left behind). As a result, the correlation between a given water mass's salinity and its oxygen isotope composition is quite linear, with seawater isotopic composition varying by about 0.4 times its salinity (Epstein and Mayeda, 1953; Fairbanks, 1982). Marine organisms forming carbonate will directly reflect the isotopic composition of ambient seawater as well as its temperature.

Ocean sediments

Perhaps the most significant application of oxygen isotopes this century is its use in revealing past ocean history from deep-sea sediment cores (e.g., Ruddiman *et al.*, 1989; Raymo, 1992) (Figure 1A). These types of proxy records originated with Cesare Emiliani's (1954, 1955) work on the oxygen isotope composition of fossil tests of planktonic and benthic foraminifera. The subsequent work of Emiliani (1969) and others (e.g., Shackleton, 1967; Duplessy, 1978) established that the $\delta^{18}O$ variations recorded in sediment cores were broadly similar throughout the world's oceans and directly related to the cyclic glacial and interglacial stages of the Pleistocene Epoch (last 2.5 Ma). The chronology of sediment cores can be directly dated by radiocarbon techniques only over the last 30–40 Ka (the effective limit of radiocarbon dating) and beyond that by linkages with independently dated events such as paleomagnetic reversals and maximizing the fit of the isotope record with other sediment and ice-core records and astronomical cycles. The temporal resolution of these records is directly dependent on sedimentation rate and the local intensity and depth of bioturbation – the blending of the top sediment layers by marine organisms. With a typical bioturbation depth of 8–10 cm and even very high sedimentation rates of 100 cm/Ka or more, resolution in sediment cores is rarely better than a century.

A key early discovery of this sediment work was that the large signal variations in $\delta^{18}O$, which roughly repeated every 100 000 years over the last three-quarters of a million years, related to changes in ice volume/ sea level as well as past temperature changes (Shackleton, 1967, 1987). Because the continental ice sheets would have been made up of water originally evaporated from the ocean, it would have consumed isotopically lighter waters, leaving behind an isotopically enriched ocean as sea level lowered. The current consensus is that the greater part of the glacial/ interglacial isotope signal is caused by land ice/ocean volume variation (two-thirds or more of the signal) (Duplessy, 1978).

An important opportunity afforded by very long ocean sediment records has been the attempt to understand the apparent strong periodicity of the climate signals. Current consensus leans towards earth's orbital variations: eccentricity (100 Ka), obliquity (41 Ka), and precession (23 Ka) – the so-called Milankovitch cycles (Milankovitch, 1930) – as playing the role of maestro in this symphony (Hays *et al.*, 1976). A higher frequency climate signal that has drawn considerable interest lately is a ~1500-year cycle found in both ice and sediment core records (Mayewski *et al.*, 1997). For oceanographers, the period of this oscillation is intriguingly close to that of the estimated timing of the global ocean turnover rate, and so, ocean-atmospheric dynamics have been offered as possible mechanisms (Ghil *et al.*, 1987; Keigwin *et al.*, 1991).

These discoveries of large climate shifts feed into the heart of today's concerns over human-induced climate change. A persistence forecast based on the last million years would suggest that we are likely enjoying the relatively short and warm few thousand years before gradually descending into the next long ice age – that is unless anthropogenically enhanced atmospheric CO_2 levels push us out of this very long-term climate pattern. Zooming in on more "modern" times, Figure 1B from Keigwin and Lehman (1994) shows the nearly parallel, though offset, $\delta^{18}O$ trends of two species (one planktonic and one benthic) for the period from the last glacial maximum ~20 Ka to about ~3 Ka from a core in the central North Atlantic (43°N). The offset between the records, averaging about 2‰, implies a temperature difference of about 10°C between the surface and bottom at this site (assuming the isotopic difference between surface and bottom seawater is relatively small). An abrupt upward shift in both curves about 14.5 Ka is followed by a variable but consistent lowering of isotopic values until leveling off around 6–8 Ka. Most of this shift and the following trend reflect the return of isotopically lighter waters to the oceans as the continental ice sheets melted. However, the abruptness of the climate shift at 14.5 Ka (definable within a few centuries in these records, and even less in some ice-core records) requires an explanation in terms of atmospheric and oceanic mechanisms that can change the earth's climate so quickly. Such mysteries arising out of long-term proxy records encourage the need for higher resolution to examine the nature of these rapid shifts.

Moving yet closer to our own era, Figure 1C from Keigwin (1996) shows a very high-resolution (50–100 years) $\delta^{18}O$-derived SST record from a top layer of bottom sediments near Bermuda. The record spans the last 3000 years and reflects some well-known historical climatic periods such as the Medieval Warm Period (ca. 800–1100 AD) and the Little Ice Age (ca. 1600–1900 AD). Note several other maxima and minima in this record, such as the relatively warm period before 2000 and at 400–600 years ago, as well as the colder times holding sway 1200–1700 and 600–800 years ago. There is no real indication of a 20th century warming in this ocean record, but the century-scale resolution may not be enough to catch it.

These few examples of sediment $\delta^{18}O$ records illustrate their power to capture the lower frequency climate signals that are simply not possible for us to witness within the time frame of our own experience. In rare cases, very high-resolution sediment records are just on the order of an average human life span, but still unable to capture the detail of climate variation that matches our short-term understanding of meteorology and oceanography.

Corals

The need for long ocean records with more detail has been partially fulfilled over the last 20 years by applying various proxy techniques to tropical reef corals, which can live for several centuries and provide seasonal to annual resolution (Dunbar and Cole, 1993). The climate signals in corals have been derived in a number of ways including $\delta^{18}O$ (e.g., Dunbar *et al.*, 1994; Kuhnert *et al.*, 1999). Unfortunately, especially from an ICES perspective, their application is limited to the warm lower latitude areas of the world, and, until recently, no comparable means existed for the cold higher latitude oceans.

Shells

Mollusks exist in all of the world's oceans and, as a group, are not constrained by latitude, temperature, or depth. Bivalves, with their well-defined periodic shell growth patterns, have long been identified as important archives of environmental information (Rhoads and Lutz, 1980). They are extremely well represented in the fossil record because their hard parts tend to be preserved in the surrounding sediments. So, it is no accident that bivalve shells were targeted in the first studies of carbonate oxygen isotope composition (McCrea, 1950; Urey *et al.*, 1951; Epstein and Mayeda, 1953). Critical to its application, bivalve shell $\delta^{18}O$ has been found to be generally in equilibrium with ambient ocean conditions and is, therefore, considered a dependable tool for climate studies (Wefer and Berger, 1991). This stands in contrast to many foraminfera and coral species, where $\delta^{18}O$ is often in disequilibrium and must first be calibrated in order to derive appropriate corrections. However, mollusks are relatively short-lived, with average life spans on the order of one to several decades (Heller, 1990), which generally makes them inappropriate for building long records. Also, the few longer-lived species tend to be very slow growing, making sampling by conventional means difficult. Improvements in sampling methods in the 1990s (Dettman and Lohmann, 1993; Wurster *et al.*, 1999), along with the identification of long-lived mollusk species has altered this situation.

Some of these new developments and their potential were brought to the attention of ICES at the first Backward-Facing Workshop with this author's work on the bivalve *Arctica islandica* (ICES, 1995). *A. islandica* is a widespread denizen of the temperate-to-boreal North Atlantic continental shelves (35–70°N) and is an extremely long-lived species. Individuals 100 years old are common, with one specimen documented at 221 years (Ropes *et al.*, 1984). The species is sufficiently abundant to support a major fishery (for clam chowder) in the northeast United States (Murawski and Serchuk, 1989). Thompson *et al.* (1980a, 1980b) and Jones (1980) were the first to recognize the great potential of

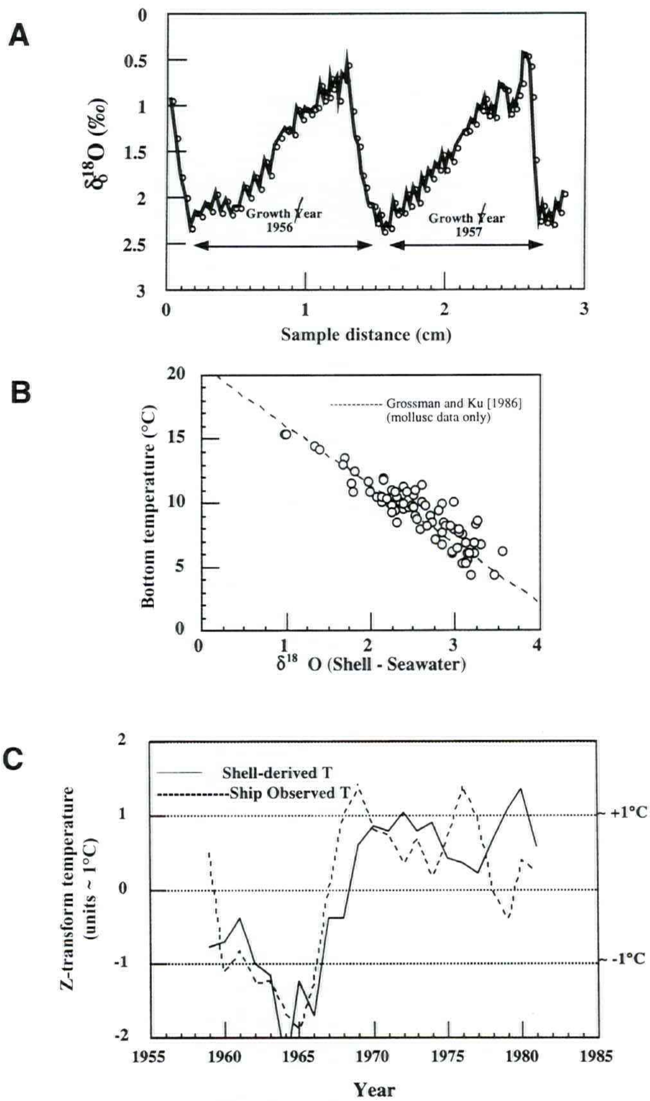

Figure 2. Mollusk $\delta^{18}O$: (A) Very high-resolution (~ weekly) two-year record from an *Arctica islandica* (Bivalvia) shell. The ~ 2‰ annual range is equivalent to ~ 9–10°C, slightly less than the observed for the same years – evidence that the shell ceases growth during the winter. (B) 12-year comparison of shell "monthly" $\delta^{18}O$ values (adjusted for seawater $\delta^{18}O$) versus observed mean monthly bottom temperatures for the shell's growth period (May–December) (from Weidman *et al.*, 1994). A comparison with Grossman and Ku's (1986) paleotemperature equation for aragonite indicates an accuracy of ~ 1.1°C. (C) 25-year record comparison between *A. islandica* shell $\delta^{18}O$-derived and observed spring bottom temperature anomalies (curves are Z-transformed 3-year running means) on the Scotian Shelf. Both records indicate a sharp ~ 3°C shift in sub-surface temperatures from minima in the mid-1960s to a warmer conditions in the 1970s.

this species as an archive of marine environmental history, though it would be another decade or so before sampling technologies developed to take advantage of it (Weidman and Jones, 1993a, 1993b; Weidman *et al.*, 1994; Witbaard *et al.*, 1994; Weidman, 1995). Figure 2A shows a two-year $\delta^{18}O$ record from an *A. islandica* shell from Nantucket Shoals with approximately weekly resolution (~ 50 samples/annual band). Figure 2B shows a comparison of "monthly" $\delta^{18}O$ values from this same shell with contemporary bottom temperatures from a nearby site and indicates an ability to estimate ocean temperatures accurately to within about 1°C.

The focus of the third Backward-Facing Workshop was on ocean climate anomalies in the northwestern Atlantic during the 1960s and 1970s and its consequences for gadoid populations (Werner *et al.*, 1999). During that meeting, several 25-year long *Arctica*-derived seasonal bottom-temperature records from dif-

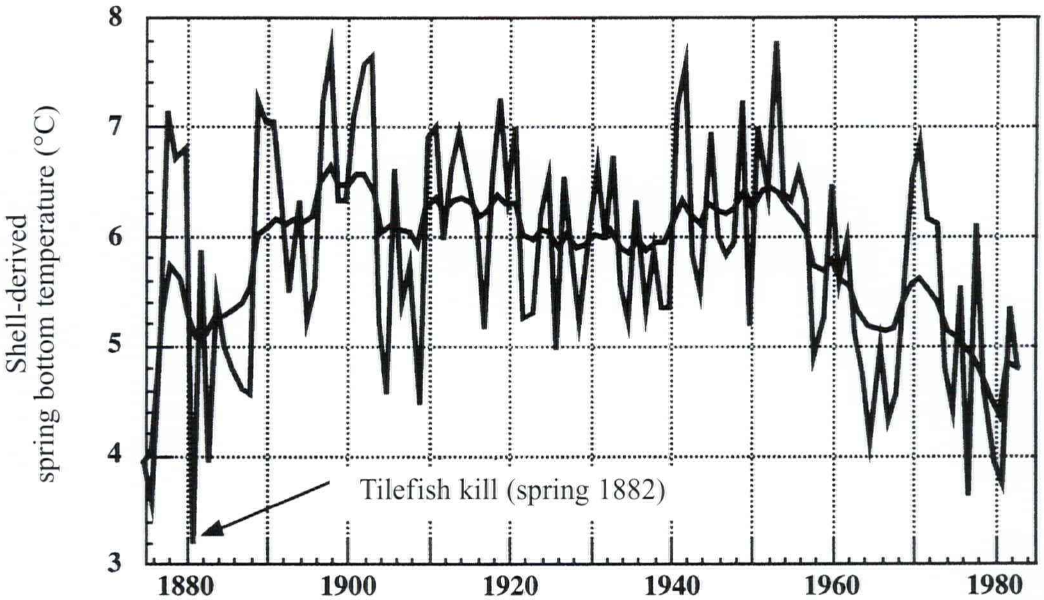

Figure 3. More mollusk $\delta^{18}O$: 109-year (1875–1983) record of estimated annual spring bottom temperatures from overlapping $\delta^{18}O$ individual records of four live-captured *A. islandica* shells. A ~3°C total range in spring shelf temperatures is indicated, with the coldest decades in the 1880s, 1960s, and 1970s. Shells were collected from a site only 40 km from the reported location of the great 1882 massive "tilefish kill". The extreme minima shown in the early 1880s portion of the record has recently is "cold" evidence for what may have caused this mortality event.

ferent locations on Georges Bank and the Scotian Shelf were presented to expand the spatial and temporal temperature coverage for that time period. Figure 2C shows a comparison between an *Arctica*-derived temperature anomaly record from Middle Bank (Scotian Shelf) and one from ship observations from the nearby Emerald Basin. Both shell and instrument records show the deep minimum in shelf temperatures in the mid-1960s followed by a large (~3°C) shift to a warmer temperature regime over the next decade. This shift has been linked to broader basin-scale changes in the Labrador Sea/ northwestern North Atlantic during this period (Petrie and Drinkwater, 1993; Werner *et al.*, 1999).

A century-long, continuous seasonal $\delta^{18}O$ record was compiled by overlapping four individual shell records (Weidman, 1995). Estimated spring bottom temperatures derived from this shell record (Figure 3) were used as evidence at the first Backward-Facing Workshop to investigate the cause of the mysterious massive tilefish (*Lopholatilus chameleonticeps*) kill event off the northeast coast of the United States in early spring of 1882 (ICES, 1995; Marsh *et al.*, 1999). The shells were collected from a site only 40 km from one of the reported centers of the sudden "die-off". The shell record indicates that an extreme cold period occurred in the spring at about the same time as the mortality event. Also, note that the anomalous cold conditions in the 1960s in this shell record are echoed by the Scotian Shelf shell and ship records 600–800 km to the east (Figure 2C). At that first Backward-Facing Workshop, Dickson noted that both the 1880s and 1960s ocean temperature minima were coincident with sustained century-scale minima in the North Atlantic Oscillation (NAO) index – a condition that was also linked with the possible southwestward extension of cold Labrador Current waters along the shelf slope (Anon., 1995; Marsh *et al.*, 1999).

In recent and yet-unpublished work by this author, the length of high-resolution $\delta^{18}O$ records have been extended back 1000 years using dated sub-fossil shells of *A. islandica*. Radiocarbon dating on marine material is too imprecise during the last approximately 500 years for this work, so aspartic-acid racemization dating has been used, which allows the construction of a precise chronology (±10–20 years) of fossil shells with overlapping coverage (Marchitto *et al.*, 2000). Work is now in progress to tighten this long chronology even further, with the objective of establishing a continuous annual record in the western North Atlantic using sclerochronological methods or growth bandwidth matching (Witbaard, 1996; Marchitto *et al.*, 2000). Preliminary results from the 1000-year record suggest an average warming of 2–3°C for shelf bottom temperatures in the western North Atlantic from the depths of the Little Ice Age in the early 1600s to the 20th century.

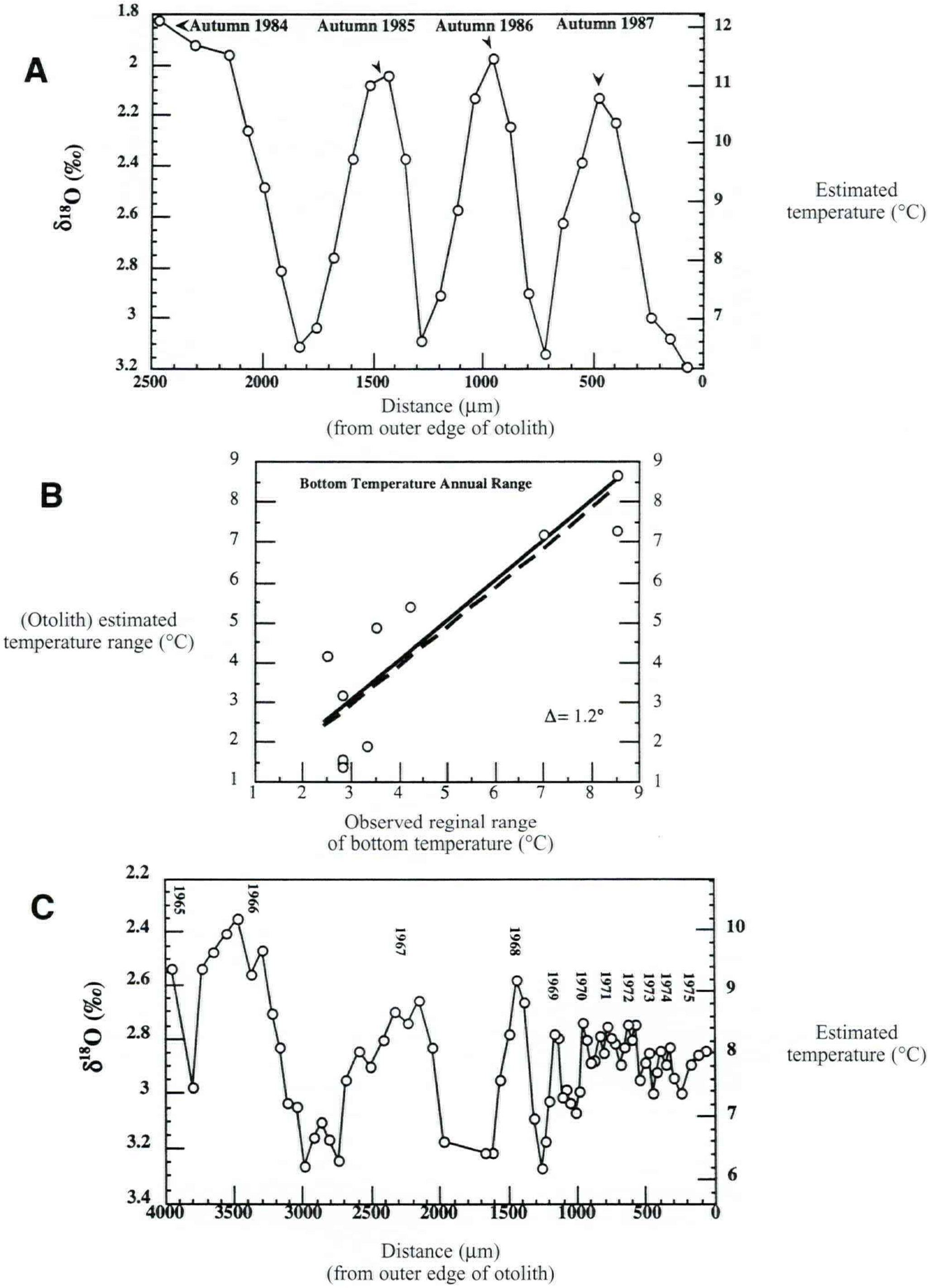

Figure 4. Otolith $\delta^{18}O$: (A) Record from a 4-year-old cod from the northern North Sea, shown with equivalent temperature estimates. (B) Comparison between the otolith $\delta^{18}O$-derived annual temperature rangs from young (≤2years) and the observed bottom temperature ranges for capture locations, indicating a nearly 1-to-1 relationship (dashed line is 1-to-1, solid line is regression fit). (C) Record from a 10-year-old cod from the Faroes region. The sharp reduction in seasonal range (from about 3-4°C to 1°C) after the 4th or 5th year of growth, indicates a change in migrational behavior (remaining within the same isotherm ~8°C) after reaching maturity.

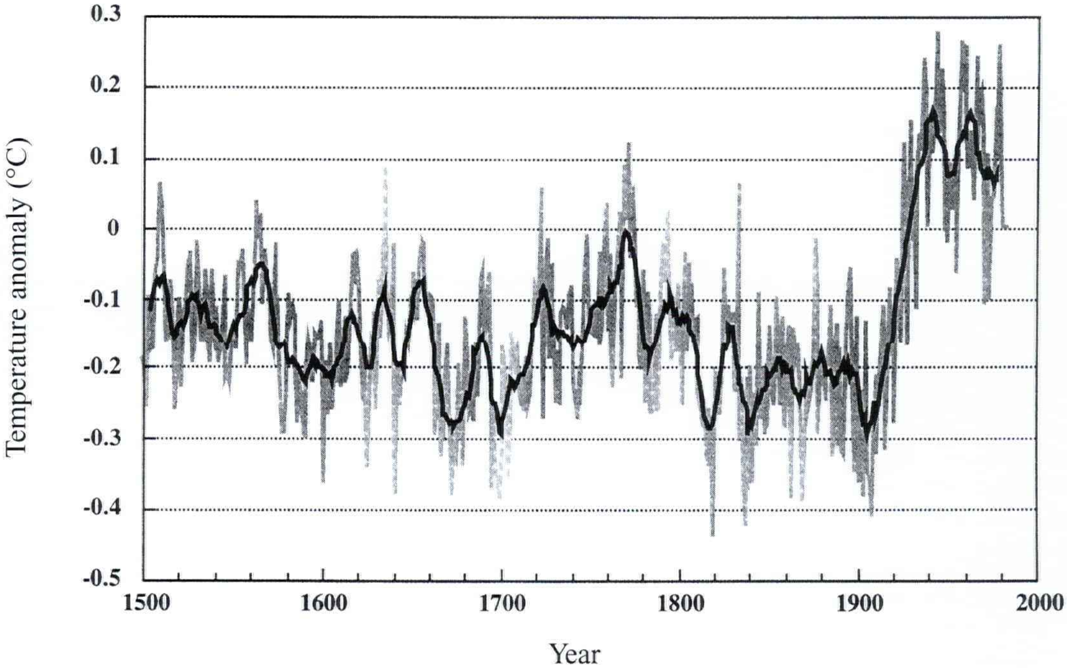

Figure 5. Linked proxy records: 600-year estimated annual surface temperature record for the Northern Hemisphere based on a statistically combined array of historical and proxy temperature records (data from Mann *et al.*, 1998). Total range of this hemispheric record is about 0.6°C. The record shows decadal- to century-scale temperature excursions, with notable cool periods in the late 1600s and 1800s, warmth in the 1700s, and a significant warming above previous centuries in the 20th century.

Otoliths

Micro-sampling capabilities have also brought high-resolution access to environmental information in other marine skeletal structures. Otoliths, small carbonate ear "stones" located in a fish's inner ear canal, are a prime example. They grow continuously throughout an individual's lifetime, laying down a pattern of both daily and annual increments. These periodic structures have long been an accepted means of ageing many species of fish throughout the ICES Area, and so have helped to solve issues of longevity, sexual maturity, and growth rate (Dannevig, 1955; Pannela, 1974; Campana and Neilson, 1985; Campana, 1999). Unlike the skeletal parts of sedentary marine organisms, which can be used to investigate ambient conditions at a specific location, the use of fish otoliths offers a mobile tag capable of recording ambient conditions that a fish experiences as it moves about throughout its lifetime (Campana, 1999). The study of otolith $\delta^{18}O$ also has a long history (Devereaux, 1967; Degens *et al.*, 1969; Kalish, 1991a, 1991b; Patterson *et al.*, 1993, Gauldie *et al.*, 1994; Thorrold *et al.*, 1997; Weidman and Millner, 2000), with the general conclusion that otolith carbonate is formed in oxygen isotopic equilibrium with local seawater and, consequently, is a reliable environmental indicator.

ICES provided some early encouragement and a forum in its second Backward-Facing Workshop to discuss some of the first exploratory work using micro-sampling methods and $\delta^{18}O$ analysis applied to cod otoliths (Anon., 1996). This work was later expanded on and presented at the third Backward-Facing Workshop (Werner *et al.*, 1999). Figure 4A shows a $\delta^{18}O$ record (and associated estimated temperature) obtained from a 4-year-old cod caught in the North Sea. Its estimated seasonal temperature range of about 6°C is quite consistent for all four years of growth, and upper and lower temperature limits are consistent with observed bottom conditions in the area of capture (Weidman and Millner, 2000). Figure 4B further confirms this by showing the nearly 1-to-1 relation between the $\delta^{18}O$-derived annual temperature range experienced by young cod (ca. 2 years old) in the northeastern North Atlantic and the observed annual range of bottom temperatures at their capture locations. However, in this same study, older cod exhibited a reduced seasonal temperature range with age. The $\delta^{18}O$ signal from a 10-year-old cod from the Faroes (Figure 4C) shows a sharp reduction in its seasonal signal after the 4th or 5th year of growth, suggesting a migratory behavior selective of a more limited temperature range in later life.

Otolith $\delta^{18}O$ records longer than about a decade have not yet been reported. This is probably because the otoliths of longer-lived species and older individuals are still quite difficult to sample even with the new sampling capabilities. To overcome this obstacle, advantage might be taken of archived otolith collections in order to compile a series of individual records. For prehistorical times, fossil otoliths can be dated and linked together in a similar way as described above for bivalve records.

Future: linking proxy records

Proxy records are invaluable for understanding the longer-term behavior of the earth's climate system – not least because they provide the only reference for comparing the climate conditions we have experienced (and measured) over the last one or two centuries. It is true that individual records, whether from modern instruments or derived from the isotopic composition of shells, only characterize conditions at a given location (otoliths being a possible exception) for some limited length of time. To achieve a global perspective or to get a sense of variation over distance and depth, multiple and overlapping records are required. Time scale is also important. Since our scientific grasp of ocean climate is most advanced at the synoptic scale, seasonal-to-decadal proxy records are most compatible with our ability to interpret them.

For future ICES planning in this regard, attention is drawn to recent work by Mann *et al.* (1995, 1998). Their work has combined both historical and proxy climate data into a single worldwide annual surface temperature database extending back the last 600 years (Figure 5). Their composite time-series for the Northern Hemisphere quite clearly shows the extent of cooler conditions prior to the 20th century and lends powerful backing to the idea of recent human-induced global warming. Spatial and frequency analysis carried out on their detailed time-series reveals ENSO and NAO-like modes as primary principal components with strong interdecadal and century-scale variations, exactly the kind of information needed to begin to understand the patterns of climate variability. But, it is the record's indication of the unprecedented warming conditions of this past century that spotlights the need for proxy data. It serves notice that our short-term investigations of the interaction between fisheries biology and the physical environment have transpired under the extremely unusual conditions of the 20th century. We have entered, quite literally, uncharted waters. The future capacity of ICES to explore the patterns of life in the oceans is very much connected to its ability to obtain a clearer picture of it past.

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