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The 1882 tilefish kill — a cold event in shelf waters off the north-eastern United States?

ROBERT MARSH,[1] BRIAN PETRIE,[2] CHRISTOPHER R. WEIDMAN,[3] ROBERT R. DICKSON,[4] JOHN W. LODER,[2] CHARLES G. HANNAH,[2] KENNETH FRANK[2] AND KEN DRINKWATER[2]

[1] *James Rennell Division for Ocean Circulation, Southampton Oceanography Centre, Empress Dock, Southampton, SO14 3ZH, United Kingdom*
[2] *Department of Fisheries and Oceans, Bedford Institute of Oceanography, Dartmouth, Nova Scotia, Canada B2Y 4A2*
[3] *Department of Marine Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA 02543, USA*
[4] *The Centre for Environment, Fisheries and Aquaculture Science, The Laboratory, Lowestoft, Suffolk NR33 OHT, United Kingdom*

ABSTRACT

A mass mortality of 'warm-water' tilefish in the Middle Atlantic Bight between April and August of 1882 suggests an episode of extreme cold in the shelf waters off the north-eastern United States. This cooling is hypothesized to be a consequence of enhanced equatorwards transport of cold water in the Labrador Current, coincident with a minimum in the North Atlantic Oscillation (NAO) index during the early 1880s.

Although there is little direct evidence for this historical event, an analogue for the 1880s cooling is found in the 1960s, at the most recent NAO-index minimum. Post-1945 observations in the Middle Atlantic Bight / Gulf of Maine region reveal changes in winter baroclinic circulation between cool and warm decades, with greater equatorward penetration of south-westwards flow along the shelf-edge during the cool 1960s. Over the period 1934–77, the NAO is found to account for 17% of the interannual variance in Labrador Current transport around the Grand Banks.

Proxy evidence for the cold episode of the early 1880s is sought. Records of bottom temperature in the Middle Atlantic Bight region are reconstructed using stable oxygen isotopic analysis on the annual bands of shells of a bivalve mollusc (*Arctica islandica*) and an empirical model of covariability with local air temperature. The result is confirmation of the presence of anomalously cold water during the early 1880s.

Key words: Labrador Current, NAO, tilefish kill

INTRODUCTION

In March/April 1882, there was a mass mortality of two species of fish – the tilefish, *Lopholatilus chameleonticeps*, and the deep-sea robin, *Peristedion miniatum* – observed over an estimated 13 000 km^2 area of the Middle Atlantic Bight from off the Delaware Capes to Cape Cod (Fig. 1), summarized by Cushing (1982). The characteristics and habitats of these fish are summarized as follows (Bigelow and Schroeder, 1953). Tilefish are large and both fish are distinctive (*Lopholatilus* up to 100 cm in length, 20 kg in weight, and brilliantly multicoloured; *Peristedion* up to 35 cm, 0.3 kg, and bright crimson). Both are bottom-living fish inhabiting the upper slope in burrows, at depths of 100–250 m, where *Lopholatilus*, at least, has a preference for temperatures in the range 8–12°C. Prior to spring 1882, a northerly tilefish stock extended from Cape Hatteras to Georges Bank (a more southerly stock is found in the South Atlantic Bight and Gulf of Mexico).

A great many fish were killed in 1882. Collins (1884) calculated that 1000 million tilefish died, although he based his calculation on one-twentieth of the observed maximum areal coverage of dead fish. Even if we discount this estimate by two orders of magnitude, the tilefish kill was clearly a major event. The fish are described as being killed suddenly, with fresh eyes and blood, everted stomachs, and no signs of parasitism or disease. There was no reported seismic activity at the time. Contemporary reports

Correspondence: R. MARSH (fax: +44 (0) 1703 596 204; e-mail: R.Marsh@soc.soton.ac.uk)

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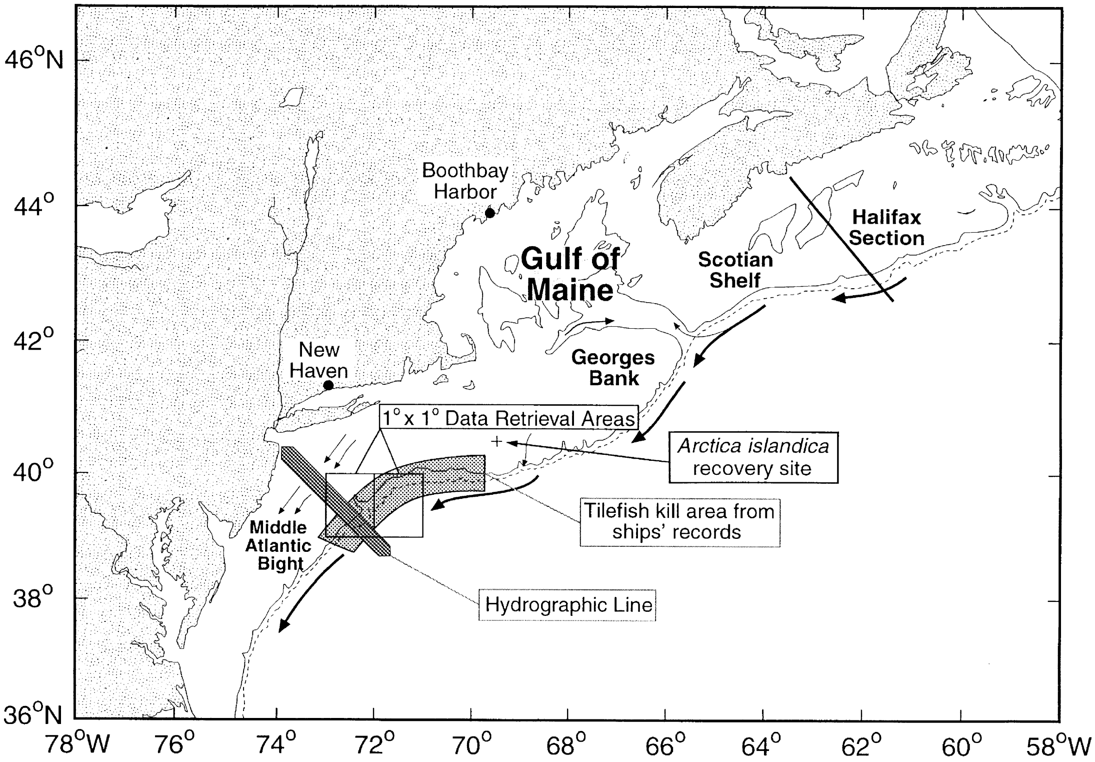
Figure 1. The Middle Atlantic Bight/Gulf of Maine region, indicating locations of sampling for the various data sets and location of the tilefish kill. Schematic regional circulation is indicated by arrowed flows. The 200 m and 1000 m isobaths are shown as solid and dashed contours, respectively.



(summarized in Collins, 1884) emphasized the quantity of drift ice ["... never before have they seen such a large quantity of drift-ice on the coast of Nova Scotia, neither have they known of its being so far to the southwest."] and implicated the Labrador Current ["... it seems reasonable to suppose that the polar current, flowing to the southwest, inside the Gulf Stream, may have carried this cold water to an unusual distance ..."]. Despite several exploratory voyages by the Bureau of Fisheries schooner *Grampus*, tilefish apparently did not return to these waters until 1892, when they were caught in ones and twos (as reported by the US Commission of Fish and Fisheries in 1895).

The relationship between climatic change and impacts on fish stocks has been recently considered by a 'Backward Facing' Study Group of the ICES GLOBEC Cod and Climate Working Group (ICES, 1995). The group identified four possible mechanisms of local to large-regional scale which may have acted singly or in concert to promote the rapid water-cooling at the shelf-break required to kill the tilefish. These are summarized as follows.

1 An increase in the amount of cold Labrador Water west of the Grand Banks, primarily as a result of stronger Labrador Current transport during a minimum in the North Atlantic Oscillation (NAO) index. This was also observed during the recent NAO minimum of the mid 1960s.

2 A short-circuiting (so-called 'Scotian Shelf cross-over') of the normal water circulation around the Gulf of Maine. Analysis of satellite sea surface temperature (SST) data sets shows that the flow of cold, relatively fresh Scotian Shelf Water (SSW) across the Northeast Channel and onto southern Georges Bank may often occur in winter/spring, driven by north-easterly winds (Bisagni *et al.*, 1996).

3 Winter formation of cold water in the western Gulf of Maine owing to atmospheric cooling. Intensified cold air outbreaks and storm activity over the eastern US seaboard have been shown to accompany the circulation changes prevailing at the time of the 1960s NAO minimum (Dickson and Namias, 1976). Cooling of Maine Intermediate Water north of Georges Bank and subsequent spill-over through Great South Channel may place cold water over the shelf-break, adjacent to the tilefish habitat.

4 Displacement of Warm Slope Water away from the shelf-break as a result of unusually strong storm

activity or other influences on the positions of the shelf/slope front or Warm/Labrador Slope Water boundary. Shelf-break upwelling, bringing relatively cool, deeper waters to the upper continental slope and onto the shelf, has been observed for the Scotian Shelf (Petrie, 1983), thus promoting cooling along the lower side of the shelf-break front.

One, or a combination, of these mechanisms could have caused a lowering of tilefish habitat bottom temperature to values well below their preferred range. The burrow-inhabiting tilefish, unable to migrate quickly out of the region, might succumb quickly to this cooling of their habitat.

In this paper we attempt to reconstruct the ocean climate of the Middle Atlantic Bight region during the early 1880s, with a view to evaluating whether, and why, cold conditions, leading to an extensive fish kill, prevailed off the north-eastern seaboard of North America during this period. We shall focus on the following conceptual model. A stream of water of Labrador origin moved along the shelf-break to the Middle Atlantic Bight. The coldest (< – 1°C) subsurface water in Flemish Pass along 47°N, east of Newfoundland, occurs from August to October (Petrie *et al.*, 1988). If this were the water that contributed to the tilefish kill in April 1882, a transit of ≈ 2500 km in 6–8 months implies a mean current of 10–15 cm s^{-1}. This is not inconsistent with shelf-break currents along the likely path of the flow. Petrie and Buckley (1996) found currents of 20–45 cm s^{-1} along the eastern edge of the Grand Banks, and recent numerical model studies with realistic observational forcing, indicate seasonal-mean shelf-edge flows of 5–20 cm s^{-1} on the Scotian Shelf and Georges Bank (Naimie, 1996; Han *et al.*, 1997). We hypothesize that the shelf-edge stream, maintaining relatively low temperatures, overran the tilefish site, killing the resident fish. This is supported by Petrie and Drinkwater's (1993) finding that, during periods of strong westwards Labrador flow, subsurface slope water temperature could decrease by 3–4°C between the Grand Banks and the tilefish area.

We first present a brief discussion of the physical oceanography of the tilefish kill area, followed by descriptions of the NAO and interannual variability in the north-west Atlantic. We then describe a well-documented cold episode of the mid 1960s, substantiating the relationship between anomalously cold water in the Middle Atlantic Bight and greater equatorward penetration of south-westwards flow along the shelf-edge. This is followed by presentation of evidence for an early 1880s 'cold event' in two independent records of reconstructed bottom temperature for the tilefish habitat. Finally, we review the tilefish kill in the light of the cold 1960s analogue and our 1880s reconstructions, and discuss the significance of these findings.

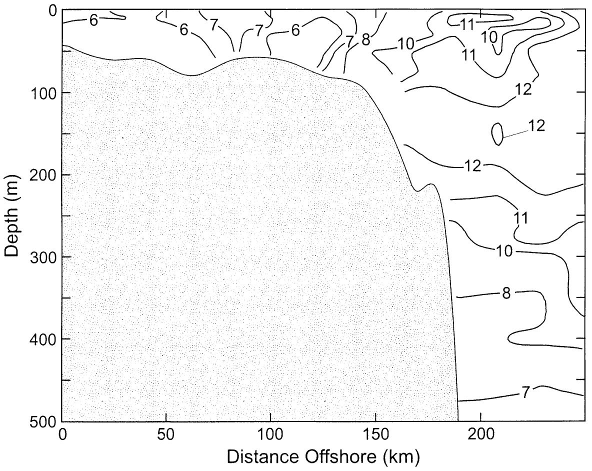
BACKGROUND

Middle Atlantic Bight circulation and hydrography

From the mid 1800s to the early 1900s, oceanographers believed that the currents on the shelf of the Middle Atlantic Bight originated from the north and moved slowly in a south-westwards direction (Beardsley and Boicourt, 1981). The relatively fresh and cool shelf water is separated from warmer, more saline offshore waters by a sharp transition zone near the shelf-break. By the mid 1900s, the circulation in the slope water region adjacent to the shelf-break was also thought to be towards the south-west. The idea of a mean south-westwards drift over the shelf has been confirmed generally by direct current measurements which show long-term (records as long as 3 years), near-bottom mean flows of 1–5 cm s^{-1} (Beardsley *et al.*, 1976; Mayer *et al.*, 1979; Beardsley *et al.*, 1985). Bottom currents on the upper slope are generally to the south-west and are comparable, ranging from less than 1 cm s^{-1} (Beardsley *et al.*, 1985) to nearly 7 cm s^{-1} (Csanady *et al.*, 1988) for records of 6–8 months' duration. The slope water circulation pattern of Csanady and Hamilton (1988), based on hydrographic and direct current evidence, features a cyclonic gyre over the slope with south-westwards flow in the area of the tilefish kill.

The mean temperature along a hydrographic line through the tilefish kill area (Fig. 1) was determined using a database (covering the years 1910–1997) obtained from the national data services of the United States and Canada. This line offered the greatest number of observations in the region. The climatological mean temperature distribution for April, the month of the tilefish kill, features temperatures of 6–7°C on the shelf, increasing to 8–10°C at the shelf-break (Fig. 2). On the upper slope, the temperature reaches a maximum exceeding 12°C at about 150 m depth and remains above 10°C to a depth of nearly 300 m. The temperature maximum zone coincides approximately with the preferred depth range of the tilefish. Salinities in the zone of the temperature maximum are in the range of 35.0–35.6, indicating the influence of the Gulf Stream. On a monthly basis, the near-bottom temperatures on the slope are quite stable; for example, at a depth of 200 m the minimum monthly mean temperature of 11°C occurs in March

Figure 2. April climatological temperature (°C) across the New York Bight on the hydrographic line indicated in Fig. 1.



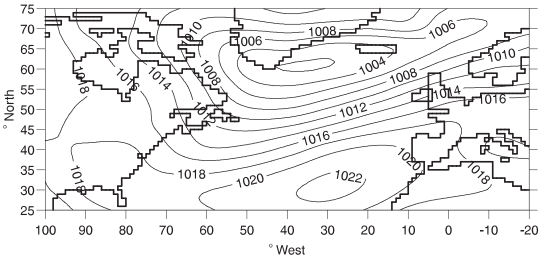
while the maximum monthly value of 12.9°C is found in July. The temperature maximum zone is not a feature that is unique to the upper slope of the Middle Atlantic Bight. The regional distribution of climatological winter (January–March) bottom temperature features a band of relatively high temperature (> 8°C) extending eastwards to the slope area south of Georges Bank and the western half of the Scotian Shelf (Loder *et al.*, 1997).

The North Atlantic Oscillation (NAO)

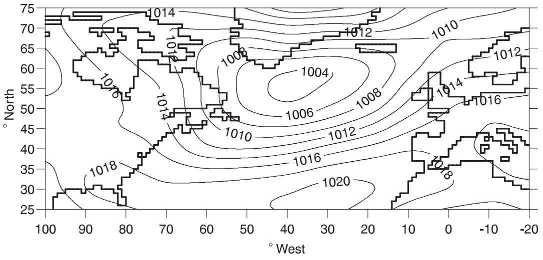
The NAO is a large-scale alternation of atmospheric mass between the Icelandic Low and the Azores High. It is the dominant mode of atmospheric behaviour in the North Atlantic, accounting for at least 36% of the variance in winter (December to March) sea level pressure (SLP) over the period 1899–1994 (Hurrell, 1995). Northern Hemisphere monthly mean SLP fields for the period since 1873 have been gridded on a 10°× 5° grid in the zone 25°–75°N, using principal component analysis to reconstruct each monthly SLP field (Jones, 1987). In Fig. 3 we show maps of the mean winter (December–April) SLP over the North Atlantic, averaged over the period 1873–1991 (i.e. a climatological mean state), for the recent mid 1960s NAO minimum, and for the exceptional winter of 1880/81. Note the southwards displacement of the Icelandic Low and the mid-latitude pressure gradient (i.e. the westerlies) in the mid 1960s (Fig. 3b), in contrast to a deeper Icelandic Low, a more extensive Azores High, and stronger pressure gradients in the climatology (Fig. 3a). The SLP pattern for the winter of 1880/81 (Fig. 3c), characterized by a Low situated ≈ 1000 km due east of the Grand Banks and no discernible Azores High, is an extreme case of the NAO minimum state.

Figure 3. Charts of winter mean sea level pressure (in mbar) over the North Atlantic, averaged: (a) over 1873–1991 (i.e. climatological); (b) during the most recent period of NAO-index minima (1962/63–1965/66), and (c) for the winter of 1880/81.

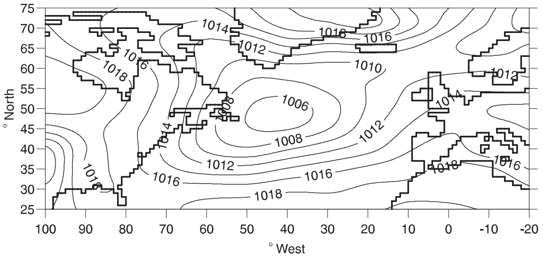
(a) December-April climatology



(b) 1963/63-1965/66



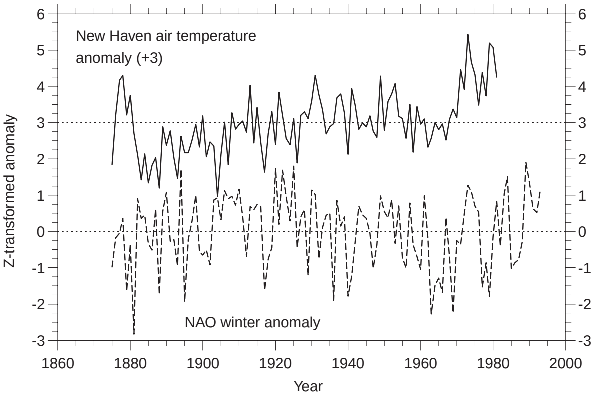
(c) 1880/81



A classical index of NAO variability is the difference in winter SLP between Iceland and the Azores (Rogers, 1984). In Fig. 4 we plot the time series of this index for the period 1873–1993, revealing a century-long evolution of the NAO, with low values in the late 1870s to early 1880s and in the mid 1960s. Note, in particular, the all-time low value for the winter of 1880/81.

Long-term climate variability in the study region is apparent in an 1874–1981 time series of the annual air temperature anomaly at New Haven (Fig. 1), which is also shown in Fig. 4. Regional evidence for low-frequency NAO-related climatic variability in this time series is rather weak. The NAO index is dominated by

Figure 4. Time series for the period 1875–1981 of the Z-transformed anomaly (i.e. the anomaly divided by the standard deviation of the series) for the New Haven annual-mean air temperature (continuous line; offset by 3 standard deviations) and the NAO index (dashed line).



high-frequency variability, whereas lower-frequency variability plays a greater role in the New Haven air temperature record. The correlation based on the detrended time series is 0.20. However, there was a sharp decline in air temperature following the large negative NAO anomaly of 1881, and both series show a decreasing tendency from the early 1950s to the mid 1960s.

Interannual variability of the Labrador Current

There are two distinct regimes of the Labrador Current (Lazier and Wright, 1993): the 'traditional' Labrador Current, a baroclinic, buoyancy-driven current, located over the shelf and upper continental slope; and the 'deep' Labrador Current, a barotropic, wind-driven current, located over the lower continental slope. Thompson *et al.* (1986) established that interannual variability of the 'deep' Labrador Current is driven by changes in the large-scale North Atlantic wind field. Myers *et al.* (1989) showed that the baroclinic component of the 'traditional' Labrador Current (considering transport in the upper 100 m only) is significantly correlated with the inverse of the North Atlantic Oscillation (NAO) index, finding higher baroclinic transport during periods of low NAO index.

The Labrador Current extends as far south as the Tail of the Grand Banks, where a fraction of the flow turns to continue westwards along the Scotian Shelf break (Soule *et al.*, 1961). Petrie and Drinkwater (1993) report low-frequency variability of geostrophic transports (relative to 1000 dbar) around the Tail of the Grand Banks over the period 1934–77. In particular, westwards geostrophic transport at the Tail of the Grand Banks increased from about 1 Sv in the early 1950s to about 4 Sv in the mid 1960s, decreasing to near zero in the late 1960s. South-westwards transport through a more heavily sampled section ('A3') on the eastern slope of the Grand Banks varied in a similar fashion, with transport increasing from about 3 Sv in the early 1950s to about 6 Sv in the mid 1960s, then decreasing to 2 Sv by the mid 1970s.

Petrie and Drinkwater (1993) assert that temperature and salinity variability in the Scotian Shelf / Gulf of Maine region over the period 1945–1990 can be attributed to changes in the 'mix' of constituent water masses, particularly Labrador Sea Water, which is more prevalent when the Labrador Current is strong. We propose that a significant fraction of temperature variability in the study region is thus driven by variations in Labrador Current transport, which may be related to the NAO.

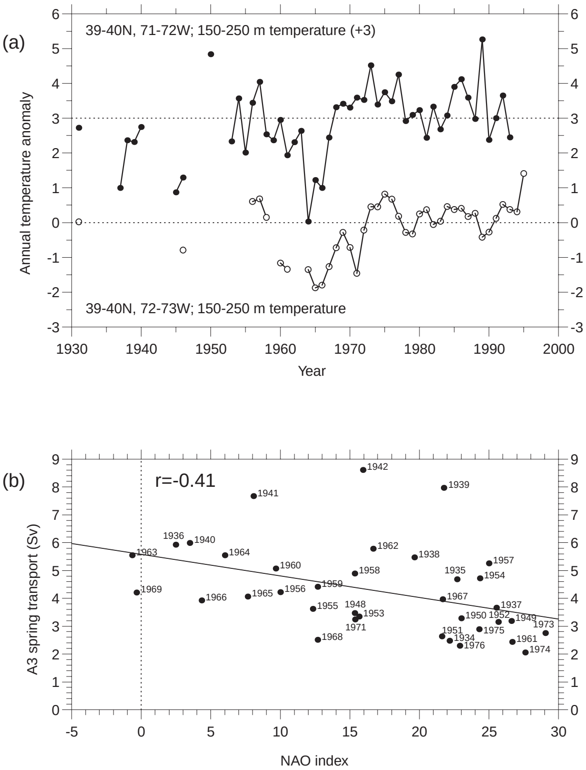
A RECENT COLD EPISODE IN THE STUDY REGION

During the 1960s, Labrador Current transport around the Tail of the Grand Banks was strong, and anomalously cool water was observed in the Scotian Shelf / Gulf of Maine region (Petrie and Drinkwater, 1993). Colton (1968) reported that, in the mid 1960s, water properties were affected as far south-westwards as the Middle Atlantic Bight, where temperatures were reduced by up to 3°C at 200 m depth in the slope water.

We have extracted temperature data for two 1° by 1°squares that encompass the tilefish kill area (Fig. 1). The annual temperature anomalies in the depth range 150–250 m (the tilefish habitat), shown in Fig. 5(a), reveal significant cooling from the early 1950s to the mid 1960s, similar to that reported by Colton (1968) and Petrie and Drinkwater (1993). This period is followed by a rapid return to above-normal temperatures by the early 1970s, particularly for the 71–72°W square, as was seen for the Scotian Shelf and the Gulf of Maine (Petrie and Drinkwater, 1993).

We have also calculated the spring mean transport for the A3 section of Petrie and Drinkwater (1993), and compare it with the NAO index in Fig. 5(b). The A3 transport represents, on average, the mean of 3 hydrographic sections for each year. Given the nature of the sampling, it is quite likely that the data series could be aliased. For example, in three successive years 1966–1968, when the section was frequently occupied (7, 12 and 8 times, respectively), standard deviations in mean transport were 1.5, 2.7 and 1.6 Sv – the same order of magnitude as the interannual variability. Nevertheless, we find a correlation of − 0.41 between A3 spring geostrophic transports and the NAO index,

Figure 5. (a) 1931–1995 time series of annual-mean anomalies in temperature (°C) averaged over the depth range 150–250 m and over two 1° × 1° areas (39–40°N, 71–72°W and 72–73°W) in the proximity of the tilefish habitat (the upper temperature record is offset by + 3°C). (b) Geostrophic transport (Sv) of the Labrador Current relative to 1000 dbar, measured over the period 1934–77 at US Coast Guard section A3 off the Grand Banks (data from Petrie and Drinkwater, 1993), plotted against the 'raw' NAO index (as opposed to the Z-transformed NAO index in Fig. 4). A linear regression line is fitted.



which is consistent with our argument that strong Labrador Current transport corresponds to a low NAO index and vice versa. Removing transports for 1939, 1941 and 1942 (clear outliers) from the data set improves the correlation from − 0.41 to − 0.57, nearly doubling the amount of transport variance (from 17% to 32%) accounted for by the NAO.

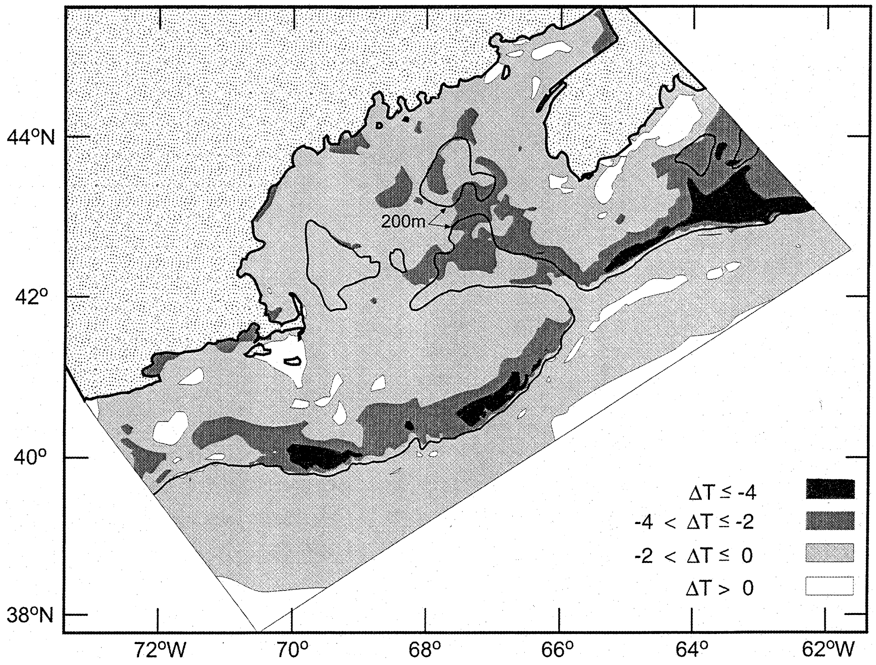
Although we obtain a reasonably strong correlation between Labrador Current transport and the NAO index, the mid-1960s NAO minimum seems several years 'late' to account for the forcing of strongest Labrador Current transports in the early 1960s. The first (and lowest) NAO index minimum during the 1960s occurred in 1963, and coincided with a strong Labrador Current transport of 5.6 Sv; the transport maximum in 1962 corresponded to an average value of the NAO index. The second lowest value of the index was in 1969, when the transport of 4.2 Sv was a near-average value.

Information is now presented on the spatial structure of decadal-time scale variability in the study region, drawing from the work of Loder *et al.* (1996, 1997). We consider the difference between regional hydrography and circulation in winters (January–March) of recent 'cool' years (1955–1956 and 1958–1968) and 'warm' years (1969, 1972–1981 and 1983–1987), henceforth referred to as the 'cool 1960s' and the 'warm 1970s', respectively. The cool (warm) years correspond to times with large negative (positive) temperature anomalies in the deep temperature record at Emerald Basin on the Scotian Shelf (Petrie and Drinkwater, 1993). Figure 6 shows the 'cool minus warm' difference in bottom temperature, indicating that anomalously cold bottom water was generally widespread in the Gulf of Maine and adjacent regions during the 1960s, with the largest bottom temperature differences (below − 4°C) along the shelf-edge and in deep channels which extend into the shelf basins. The largest upper-ocean temperature differences were also over the continental slope. Lower salinities were generally associated with these lower temperatures.

The location of peak changes in hydrographic properties is consistent with an advective origin along the upper slope (Petrie and Drinkwater, 1993). The magnitude of the peak differences indicates that major interdecadal hydrographic variations associated with the subpolar gyre can extend equatorwards to Georges Bank and the Middle Atlantic Bight. The bottom temperature distributions indicate that, during the 1960s, warm (> 9°C) slope water along the upper slope off Georges Bank (Loder *et al.*, 1997) was replaced by colder Labrador Slope Water. Furthermore, changes in winter baroclinic circulation (between the cool 1960s and warm 1970s) indicate greater equatorward penetration of south-westwards flow during the 1960s, both around the Gulf of Maine and along the shelf-edge. There are not enough data in the tilefish kill area (particularly salinity observations) to examine comprehensively the local geostrophic current differences between the cool and warm periods. However, a detailed comparison can be made for a standard hydrographic line farther to the north-east, the Halifax Section (Fig. 1), which was occupied on an irregular basis across the central Scotian Shelf and Slope region from the early 1950s to the late 1970s.

Figure 7 shows the winter (January–March) estimates for the cool 1960s and the warm 1970s of temperature, salinity and along-shelf current (positive north-eastwards). The deep temperatures and salinities

Figure 6. Difference in winter bottom temperature (°C) between the cold 1960s and warm 1970s (see text for the exact definitions of these periods) in the Middle Atlantic Bight / Gulf of Maine region (from Loder *et al.*, 1996).



were higher over the continental shelf and slope during the warm period, consistent with a greater contribution of warm Slope Water. On the other hand, salinities and (to a lesser extent) temperatures were lower at shallower depths, particularly over the continental slope, apparently related to increased St Lawrence River run-off during the warm period. A key result is the indication of significant changes in the current structure over the slope. During the cool period the baroclinic flow was to the south-west, whereas during the warm period the flow was to the north-east. The combination of reduced temperatures, reduced salinities and south-westwards flow during the cool period is consistent with a greater influence of Labrador Slope Water. Moreover, it is an indication that waters of Labrador origin can penetrate farther to the west and south. The validity of this scenario for the currents over the slope does not change from season to season. These changes in circulation are consistent with the advective origin for interdecadal hydrographic variability proposed by Petrie and Drinkwater (1993).

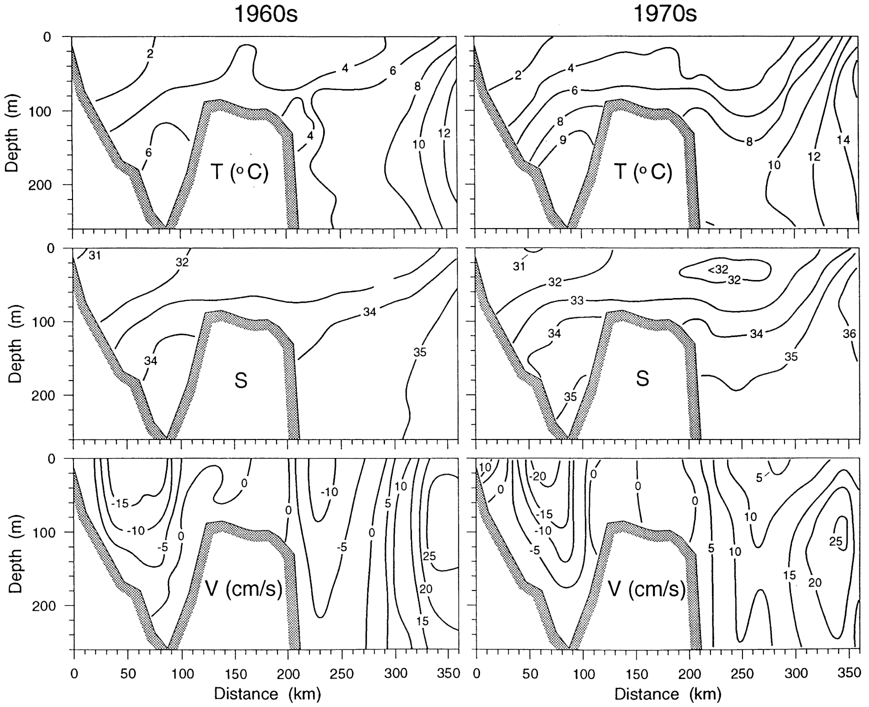
Although less data are available for the computations, a similar picture emerges for Georges Bank (not shown here). During the cool period, there was strong south-westwards baroclinic flow over the upper slope, amounting to an estimated transport of 1.5 Sv. In contrast, the south-westwards flow during the warm period was weaker and confined inside the 250 m isobath. We conclude that significant decadal-scale variability in the Middle Atlantic Bight is associated with variable equatorwards penetration of Labrador Slope Water at the shelf-break.

RECONSTRUCTING THE COLD EPISODE OF 1882

Although there were no subsurface temperature measurements in the study region during the early 1880s, a variety of sources provide evidence, as shown below, for a cold episode at that time: SST data for 1882 reveal the presence of cold water in the region, while reconstructed bottom temperature records indicate the occurrence of anomalously cold water on the shelf.

Jones and Briffa (1992) have compiled a monthly time series, for the period 1854–1991, of global (5° × 5° resolution) temperature anomalies. Maps of winter and spring SST anomalies for the years 1880–1882 reveal anomalously low temperatures over the subpolar gyre (ICES, 1995). Extracting monthly SST anomalies in five 5°× 5° gridboxes centred on 42.5°N, between 45°W and 70°W, we plot in Fig. 8 the 1882 monthly SST anomalies along the eastern seaboard, between the Grand Banks and the Gulf of Maine. SST was anomalously low along this zone in 1882 (indicated by the predominant grey-shading in Fig. 8). A band of particularly strong SST anomalies

Figure 7. Temperature, salinity and geostrophic velocity (positive is north-eastwards) on the Halifax section (indicated in Fig. 1), averaged for the cool 1960s and warm 1970s.

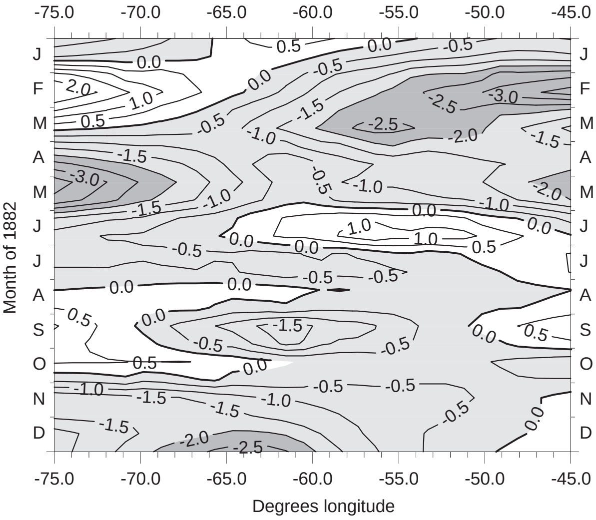


'originate' at the Grand Banks (45–50°W) in February, extending further west by March (the − 1.0°C isotherm reaching the Scotian Shelf, at 60–65°W). This supports the hypothesis that a substantial fraction of ocean temperature variability in this region can be attributed to variations in the extension of the Labrador Current around the Tail of the Grand Banks. However, it must be noted that the SST field in this region is subject to strong surface fluxes (i.e. advected SST anomalies are rapidly modified by local fluxes), and can therefore reveal only limited details of the strength and extent of subsurface temperature anomalies (of relevance to the tilefish kill). Furthermore, very large negative anomalies over the tilefish grounds (70–75°W) in April appear to spread from the *east* (i.e. from the continental United States). It should, however, be pointed out that the 70–75°W gridbox consists largely of land (Fig. 1), and hence reveals stronger (misleading) surface temperature variability.

An independent record of annual bottom (150–250 m depth) temperatures is therefore reconstructed using a linear regression model that correlates the bottom temperature anomalies for the two areas 39–40°N, 71–72°W and 72–73°W (Fig. 5a) with New Haven air temperature anomalies (Fig. 4) for the period 1931–1981. Respective correlations of 0.36 and 0.43 (between New Haven air temperature and bottom temperature in the two areas) are significant but not high. The reconstructions for 1870–1900 are shown in Fig. 9(a). Predicted annual average bottom temperatures for both regions from 1870 to 1900 show a decline of about 1°C from 1880 to 1883. By 1882, predicted temperatures are about 1°C below normal and remain that way until 1888, therafter increasing by around 0.5°C. This picture does not feature the very sharp decline of temperature which, we believe, led to the rapid tilefish kill; on the other hand, reconstructed anomalies of around − 1°C during the period 1882–1889 are consistent with our hypothesis of a persistent Labrador Water influence, and agree with the biogenic proxy record presented below.

A 109 year record (1875–1983) of bottom temperatures on Georges Bank was compiled using stable oxygen isotopic analysis of the annual bands of shells of the bivalve mollusc *Arctica islandica* (Weidman, 1995). Sampling constraints permitted sampling only the inner (earliest) 25–45 annual bands of each shell, so the 109 year record is compiled by overlapping the individual isotope records from four specimens of different ages. All four specimens were captured live from

Figure 8. Monthly anomalies in surface temperature (°C) centred on 42.5°N, in the longitude range 45–75°W for 1882 (negative anomalies are shaded).

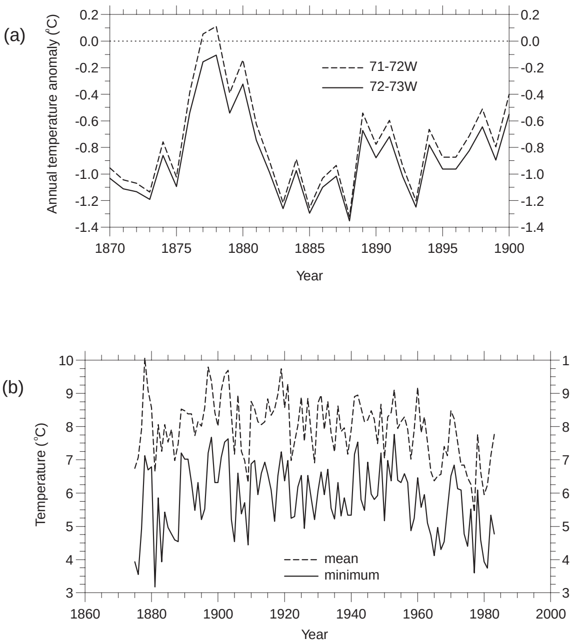


the same dredge haul during the 1992 NMFS Clam Survey in June 1992 at 40°28′ N, 69°29′ W, in water of 65 m depth (Fig. 1). The specimen capture site is about 40 km north of the along-slope area where large numbers of dead tilefish were reported in April 1882.

The chronology of the shell-derived bottom temperature record, which is based on annual band counting, is year-accurate for the period 1924–1983, and accurate to 1 year for the period 1875–1923. Weidman *et al.* (1994) calibrated the accuracy of their temperature estimates from *A. islandica*'s oxygen isotope composition to be approximately 1.2°C. The shell-derived bottom temperature record has a temporal resolution of eight 'monthly' values per year, roughly spanning the period from May to December. From the timing of the tilefish kill (March–April), the annual spring minimum (May) temperature seems of most relevance, and is shown in Fig. 9(b), along with the annual mean. This annual minimum record is not a true reflection of the annual minimum as the shells do not grow during the coldest months (January–April). However, the record does reflect spring bottom temperatures when they are only slightly elevated from their coldest late-winter values, and the interannual variations in this record should reflect real spring-to-spring variations.

The spring minimum temperatures in Fig. 9(b) emphasize two cold periods, one at the beginning of the record, from 1875 to about 1890, and another at the end of the record, from about 1955 to 1970. The means of these colder periods are both ≈ 5°C, whereas the remainder of the record (1890–1955) is warmer, with a

Figure 9. Reconstructed bottom temperature records. (a) 1870–1900 empirically reconstructed annual mean temperature anomalies (°C) for 150–250 m depth in the two 1° × 1° retrieval areas (39–40°N, 71–72°W and 39–40°N, 72–73°W). (b) 1875–1983 annual mean (dashed line) and annual minimum (continuous line) temperature (°C), derived from the isotopic composition of the shells of the bivalve mollusc, *Arctica islandica*, collected at 40°28′N, 69°29′W.



mean of ≈ 6°C. The period from 1875 to 1890 includes several periods of extreme interannual difference. The years 1875–76 are extremely cold (3.9°C and 3.5°C, respectively), and 1877 is still moderately cold (4.9°C). The years 1878–1880 are warm (6.7–7.1°C), but the following year, 1881, has the coldest minimum (3.2°C) in the entire 109 year record, and 1882–1888 are cold to moderately cold years. The 1881 extreme minimum, which represents a spring value, is very close in time to the spring 1882 tilefish kill, and within the 1 year uncertainty of our chronology for this period. This evidence would support the hypothesis that very cold shelf water, appearing on a once-a-century basis, spread landward of the tilefish grounds at about the time of the tilefish kill.

DISCUSSION

The evidence presented suggests that the leading hypothesis to explain the tilefish kill of 1882 was a sudden cooling in the region as a consequence of enhanced equatorwards transport of cold water in the

Labrador Current, coincident with an all-time minimum in the North Atlantic Oscillation (NAO) index during the early 1880s. The clearest expression of the NAO is in large-scale changes of sea level pressure patterns and the associated wind field. Although the NAO-minimum wind field over the Labrador Sea (easterlies and north-easterlies) might be expected to drive a *weaker* offshore branch of Labrador Current, the associated southwards migration of westerlies allows the subpolar gyre to expand into the mid-latitudes, and may thus increase the wind-driven 'catchment area' of the gyre which feeds the western boundary current, furthermore permitting more of that current to 'leak' around the Tail of the Grand Banks.

This tendency is demonstrated in modelling sensitivity studies, reported in ICES (1995, 1996). In a pilot study, five years of idealized NAO-minimum wind forcing was applied to a General Circulation Model of the North Atlantic (ICES, 1995). In a more realistic study which followed, the reconstructed monthly wind forcing of 1877–1882 was applied to the model (ICES, 1996). Both model experiments suggested that the subpolar gyre (and hence part of the Labrador Current) intensify under NAO-minimum wind forcing, leading to local cooling. In the latter study (ICES, 1996), subsurface temperatures fell by up to 6°C in a region inshore of the Gulf Stream and to the south and west of the Grand Banks. Additionally, at a depth of 200 m, negative temperature anomalies in excess of 2°C extended along the Scotian Shelf break in 'spring 1882' of the simulation.

Another mechanism (which might enhance Labrador Current transport) is anomlaous buoyancy forcing. Lazier and Wright (1993) recently showed that transport by the inshore, 'traditional', branch of the Labrador Current (which lies over the shelf) exhibits a maximum in October and a minimum in March–April, and speculate that this seasonality is a consequence of the annually varying freshwater flux onto the shelf (strongest during the summer). They show how this annual cycle could be buoyancy driven, owing to the joint effect of baroclinicity and relief (JEBAR). In the context of the present study, we can hypothesize that JEBAR likewise drives interannual variability in the inshore, baroclinic, branch of the Labrador Current, and that anomalous freshwater forcing (e.g. increases in the run-off of spring–summer meltwater) during spring 1882 might have led to increased transport of cold water along the shelf-break.

A regional hydrographic database reveals the detailed structure of a more recent cold episode in the 1960s. Differences in winter baroclinic circulation (between the 'cool' years of the 1960s and the 'warm' years of the 1970s) indeed indicate greater equatorward penetration of south-westwards flow during cool years, both around the Gulf of Maine and along the shelf-edge. We conclude therefore that significant decadal-scale hydrographic variability in the Scotian Shelf, Gulf of Maine and Middle Atlantic Bight regions is generally associated with variable equatorwards penetration of Labrador Slope Water at the shelf-break.

An additional, contributory factor (accounting for the *sudden* presence of anomalously cold water) may involve the winter formation of cold, dense water in the western Gulf of Maine which is sufficiently dense to subsequently spill over into the tilefish kill area via the Great South Channel (sill depth about 70 m). The likelihood of such an over-spill will depend on the density of the winter Gulf of Maine water relative to that of the ambient Slope Water. To determine this likelihood, we checked the regional hydrographic database used to develop the climatology of Loder *et al.* (1997), and established that, at depths of 150–250 m in the tilefish kill area, climatological mean densities are in the range 1027.0–1027.1 kg m^{-3}. Meanwhile, the maximum observed density (since 1912) in the western Gulf of Maine at depths of 5–250 m is about 1027.0 kg m^{-3}, and the temperature associated with this extreme is less than 5°C. It therefore appears that water could form in the winter in the western Gulf of Maine which is roughly the same density as the water in the 150–250 m depth range on the slope (the tilefish habitat). These colder (fresher) waters are potentially lethal for tilefish, reported to tolerate the rather narrow temperature range of 9–14°C (Bigelow and Schroeder, 1953). However, we find no evidence (in the database) of such cold water at 150–250 m on the slope, and therefore regard an over-spill as less likely to be the primary factor.

In conclusion, we propose that variations in the strength and equatorwards extension of the Labrador Current beyond the Tail of the Grand Banks, associated with NAO-minimum wind and buoyancy forcing during the late 1870s and early 1880s (most extreme in the winter of 1880/81), led to a cold event in the tilefish habitat. However, the NAO may play only a supporting, rather than definitive, role, forcing changes in the amount of Labrador-type water circulating the shelves and slopes of the south-east Canadian and north-east US seaboards. It may be that increased Labrador Current transport during the early 1880s moderately cooled and preconditioned both the ocean and atmosphere in the region. Shorter-time-scale local events (the 'cross-over' of cold Scotian Shelf Water to Georges Bank; intensified winter cooling of Maine Intermediate Water; storm-driven inshore displacement of the offshore cold shelf/slope front) might then have resulted in a more abrupt and extreme cooling, sufficient to yield a kill of tilefish as massive as that reported in 1882.

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