A TIME HISTORY OF PRE- AND POST-BOMB RADIOCARBON IN THE BARENTS SEA DERIVED FROM ARCTO-NORWEGIAN COD OTOLITHS

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ABSTRACT. Radiocarbon measured in seawater dissolved inorganic carbon (DIC) can be used to investigate ocean circulation, atmosphere/ocean carbon flux, and provide powerful constraints for the fine-tuning of general circulation models (GCMs). Time series of ^{14}C in seawater are derived most frequently from annual bands of hermatypic corals. However, this proxy is unavailable in temperate and polar oceans. Fish otoliths, calcium carbonate auditory, and gravity receptors in the membranous labyrinths of teleost fishes, can act as proxies for ^{14}C in most oceans and at most depths. Arcto-Norwegian cod otoliths are suited to this application due to the well-defined distribution of this species in the Barents Sea, the ability to determine ages of individual Arcto-Norwegian cod with a high level of accuracy, and the availability of archived otoliths collected for fisheries research over the past 60 years. Using measurements of ^{14}C derived from Arcto-Norwegian cod otoliths, we present the first pre- and post-bomb time series (1919–1992) of ^{14}C from polar seas and consider the significance of these data in relation to ocean circulation and atmosphere/ocean flux of ^{14}C. The data provide evidence for a minor Suess effect of only 0.2‰ per year between 1919 and 1950. Bomb ^{14}C was evident in the Barents Sea as early as 1957 and the highest ^{14}C value was measured in an otolith core from a cod with a birth date of 1967. The otolith ^{14}C data display key features common to records of ^{14}C obtained from a Georges Bank mollusc and corals from the tropical and subtropical North Atlantic.

INTRODUCTION

General circulation models (GCMs) are considered the most effective means of understanding dynamics of carbon flux through the biosphere, but existing and future models require fine-tuning on the basis of spatially and temporally varying tracers. Cosmogenic and anthropogenic radiocarbon has the greatest potential to elucidate the complexities of both oceanic circulation and carbon flux between the atmosphere and ocean and are essential tools to constrain GCMs. These two sources of ^{14}C make it possible to investigate ocean mixing and CO_2 flux on decadal to millenial time scales. However, the ability to apply the ^{14}C tracer to GCM validation is hampered by relatively poor spatial and temporal coverage of ocean ^{14}C data, particularly at high latitudes.

Uncertainties regarding the role of high latitude oceans in global climate and atmosphere/ocean carbon flux can be partly attributed to the lack of ocean time series from these regions. To date, there are no published pre- and post-bomb time series of ^{14}C from polar seas. The Barents Sea is of particular interest because of its role in the formation of Arctic waters (Midtun 1985) and as a sink for atmospheric CO_2. The Norwegian Atlantic Current transports North Atlantic Water (NAW) along the west coast of Norway and into the shallow Barents Sea where the water experiences heat loss and increased salinity causing increased density in winter and decreased density in summer due to incorporation of ice melt-water (Aagaard and Carmack 1989). Sea-ice also plays a major role in the variable, but highly productive Barents Sea (Wassmann and Slagstad 1991).

Measurements of ^{14}C in seawater dissolved inorganic carbon (DIC) have been achieved since the 1950s and extensive measurements have been made as part of the Geochemical Ocean Sections Study (GEOSECS), North Pacific Experiment (NORPAX), Transient Tracers in the Ocean (TTO), South Atlantic Ventilation Experiment (SAVE), World Ocean Circulation Experiment (WOCE), and

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others. Nevertheless, sampling is inadequate to provide appropriate constraints and further measurement of ocean ^{14}C has been achieved by the use of proxies. Several proxies of ^{14}C in seawater DIC have been established, but the most valuable are those capable of providing time series of ^{14}C variation over seasonal, annual, and decadal time scales. Hermatypic corals (e.g. Druffel 1989), bivalve molluscs (e.g. Weidman and Jones 1993), and fish otoliths (e.g. Kalish 1993) have all been used to determine pre- and post-bomb ^{14}C; however each of these data sources has limitations. Corals are restricted to warm and shallow waters; bivalves are closely associated with sediments potentially affecting the dynamics of carbon incorporation, and interpretation of the annual sequence of zones can be problematic; and otoliths are relatively small and annual zones can be difficult to identify. Although there may be difficulties associated with each proxy, a combination of all groups is capable of providing broad spatial and temporal coverage of ^{14}C variability. Both otoliths (Kalish 1993) and bivalves (Weidman and Jones 1993) are of special interest due to their ability to provide data across all oceans. Fish otoliths are of further value because they can act as proxies over a range of ocean depths.

Time series of ^{14}C in seawater DIC at temperate latitudes have been derived relatively recently from accelerator mass spectrometry (AMS) analyses of selected regions of fish otoliths and bivalve shells. Records of a similar form from polar seas would be of value due to the critical nature of these systems in ocean circulation and global climate. The predictable nature of the distribution of juvenile Arcto-Norwegian cod (*Gadus morhua*), also called northeast Arctic cod, combined with the fact that otoliths are excellent proxies for ^{14}C in seawater DIC, make it possible to use this species' otoliths as recorders of ^{14}C variation in Norwegian Atlantic Current Water (NACW) in the southwestern Barents Sea. The Arcto-Norwegian cod fishery is among the largest fisheries in the world with catches exceeding one million tons in some years and considerable effort has been expended in developing a complete understanding of the species' biology and ecology. As part of this research effort the Institute of Marine Research in Bergen (Norway) has collected and archived otoliths from Arcto-Norwegian cod since the 1930s. Traditionally, these samples have been used to determine the age structure of the exploited cod population; however, the development of new applications based on otoliths (see Secor et al. 1995) has increased the value of these structures to a range of disciplines (e.g. Kalish 1995; Campana et al. 1996).

Early life-history of the Arcto-Norwegian cod stock has been studied intensively and spawning seasons, larval drift and juvenile nursery areas are well-described (see Dragesund and Gjøsaether 1988; Sundby 1994). Arcto-Norwegian cod spawn during March and April along the northern coast of Norway. The eggs and larvae are advected northward in the Norwegian Coastal Current and Norwegian Atlantic Current and, finally, into the Barents Sea. The distribution of juvenile Arcto-Norwegian cod less than one year of age (0-group fish) is largely determined by the extent of warm water, derived from the Norwegian Atlantic Current (NAC) in the southern and central Barents Sea (Figure 1) (Saetersdal and Loeng 1987). Annual surveys of the abundance and distribution of 0-group Arcto-Norwegian cod in the Barents Sea region have been completed since 1965 (Anon 2000) and clearly demonstrate that these juvenile fish are restricted to the warmer waters south and west of the Polar Front (also called the Arctic Frontal Zone). Furthermore, maximum abundance of 0-group cod is clearly associated with the core of warm NACW as it enters the Barents Sea in all years (Figures 1 and 2).

METHODS

Arcto-Norwegian cod otoliths were selected from archives maintained at the Institute of Marine Research, Norway (IMR). The IMR has collected cod otoliths for fisheries management purposes

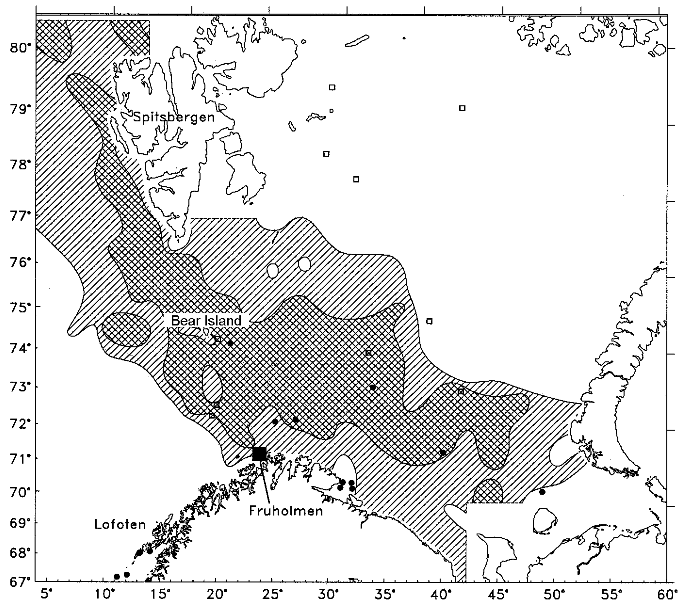

Figure 1 Distribution of 0-group cod. The example is from August-September 1992 and shows a general distribution pattern of a good yearclass. The open squares show the sampling locations for measurements of ^{14}C in seawater DIC, the filled square shows the sampling location for atmospheric ^{14}C at Fruholmen, and the dots show the sampling locations of cod otoliths.

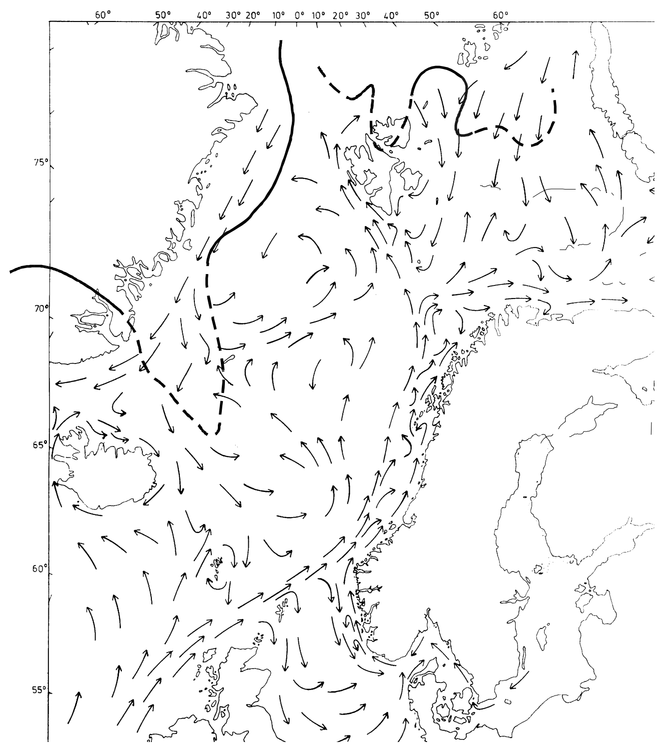

Figure 2 Main features of surface currents in the northeast Atlantic. The bold line indicates the mean position of the Arctic Frontal Zone (AFZ). The dotted line indicates where the position of the AFZ is most varying.

Table 1 Otolith and ^{14}C data from Arcto-Norwegian cod (*Gadus morhua*) collected in the Barents Sea. Values of $^{14}\delta^{S}_{N}$ are reported with ±1 standard deviation.

Sample nr (Arizona)	Sample nr (ANU)	Collection location	Collection date	Birth date	Fish age	Sex	Otolith weight (g)	Sample weight (mg)	$^{14}\delta^{S}_{N}$ (‰)	± error (‰)	$\delta^{13}C$ (‰)
AA 15855	ANU 1	N67°30′ E11°40′	19-Apr-34	1919	15	f	0.9818	18.2	–48.9	5.4	–2.2
AA 15856	ANU 2	N67°30′ E11°40′	19-Apr-34	1920	14	m	0.8018	16.3	–45.4	5.7	–2.4
AA 15857	ANU 3	N67°30′ E11°40′	19-Apr-34	1925	9	m	0.5321	17.0	–50.8	4.7	–2.7
AA 15858	ANU 4	N67°30′ E11°40′	22-Mar-39	1930	9	m	0.6871	17.4	–52.3	4.0	–2.0
AA 15859	ANU 5	N70°20′ E31°20′	6-Jun-39	1933	6	f	0.3372	18.2	–59.6	4.1	–2.4
AA 15860	ANU 6	N70°20′ E31°20′	6-Jun-39	1934	5	f	0.4138	18.2	–54.4	4.6	–3.2
AA 15861	ANU 7	N67°42′ E12°20′	30-Mar-46	1935	11	—	0.8089	18.6	–55.0	4.5	–2.8
AA 15862	ANU 8	N67°42′ E12°20′	21-Mar-47	1940	7	m	0.4939	16.4	–49.0	4.5	–3.2
AA 15863	ANU 9	N73°00′ E34°00′	27-Apr-50	1945	5	—	0.2802	18.6	–53.3	4.4	–2.2
AA 15864	ANU 10	N68°00′ E13°40′	27-Mar-55	1950	5	f	0.5357	18.5	–55.2	4.0	–2.8
AA 15865	ANU 11	N68°03′ E13°50′	16-Mar-60	1955	5	m	0.5585	18.5	–43.8	4.2	–2.8
AA 15866	ANU 12	N68°03′ E13°50′	4-Mar-63	1957	6	—	0.5113	16.7	–24.1	4.1	–2.5
AA 15867	ANU 13	N67°42′ E12°20′	1-Mar-66	1959	7	f	0.4701	19.6	–31.8	4.1	–3.2
AA 15868	ANU 14	N67°42′ E12°20′	23-Mar-68	1961	7	f	0.4632	17.9	9.1	4.4	–2.3
AA 15869	ANU 15	N74°20′ E21°50′	6-Sep-68	1963	5	f	0.4263	14.6	14.5	4.0	–3.4
AA 15870	ANU 16	N68°10′ E14°30′	26-Mar-72	1965	7	m	0.564	18.2	80.7	5.9	–2.3
AA 15871	ANU 17	N71°25′ E24°50′	27-Apr-72	1967	5	f	0.297	17.3	136.2	3.8	–2.7
AA 15872	ANU 18	N71°25′ E24°50′	27-Apr-72	1969	3	f	0.0956	15.5	91.7	4.7	–2.5
AA 15873	ANU 19	N71°30′ E40°42′	2-Apr-74	1971	3	m	0.1292	18.2	76.3	3.9	–2.4
AA 15875	ANU 21	N70°45′ E32°20′	21-Jan-77	1975	2	m	0.1021	19.6	110.5	4.1	–2.8
AA 15876	ANU 22	N72°20′ E27°20′	8-Feb-83	1980	3	f	0.0971	14.9	86.9	4.0	–3.5
AA 15877	ANU 23	N70°48′ E31°57′	2-Feb-87	1985	2	m	0.064	14.0	79.3	4.0	–2.5
AA 15878	ANU 24	N72°10′ E25°50′	28-Feb-92	1990	2	m	0.0665	14.8	57.8	7.0	–3.4
AA 19650	ANU 26	N71°25′ E24°50′	27-Apr-72	1967	5	m	0.3316	17.9	121.9	6.1	–3.0
AA 19651	ANU 27	N71°25′ E24°50′	27-Apr-72	1969	3	m	0.1015	18.5	99.4	5.3	–2.9
AA 19652	ANU 28	N71°30′ E40°42′	5-Apr-74	1971	3	m	0.0945	19.1	109.6	7.4	–1.8

Table 1 Otolith and ^{14}C data from Arcto-Norwegian cod (*Gadus morhua*) collected in the Barents Sea. Values of $^{14}\delta^{S}_{N}$ are reported with ±1 standard deviation *(Continued).*

Sample nr (Arizona)	Sample nr (ANU)	Collection location	Collection date	Birth date	Fish age	Sex	Otolith weight (g)	Sample weight (mg)	$^{14}\delta^{S}_{N}$ (‰)	± error (‰)	$\delta^{13}C$ (‰)
AA 19654	ANU 30	N70°15′ E32°30′	5-May-34	1925	9	—	0.8585	18.8	–57.5	5.9	–2.7
AA 19655	ANU 31	N70°15′ E32°30′	5-May-34	1925	9	—	0.7243	19.2	–55.9	3.1	–2.4
AA 19656	ANU 32	N73°00′ E34°00′	27-Apr-50	1945	5	m	0.2166	16.7	–60.4	3.4	–3.2
AA 19657	ANU 33	N70°00′ E49°00′	21-Aug-93	1992	1	—	0.0182	14.5	57.1	3.7	–2.9
AA 19658	ANU 34	N68°00′ E13°40′	21-Mar-55	1950	5	m	0.5029	16.2	–55.1	3.9	–3.1

since the 1930s. These otoliths had been used to estimate the age of individual fish based on the quantification of opaque and translucent zones in sectioned otoliths. The method of age estimation for this species has been validated (Rollefsen 1933; Kalish et al. 1995) and only otoliths that could be interpreted with confidence were used in subsequent analyses. Otoliths had been stored dry in paper envelopes and, in some cases, had been collected as early as 1934 (Table 1). Samples were selected to span the greatest time period and included otoliths from 14 fish spawned prior to the presence of detectable bomb ^{14}C in the ocean (~1955) and 17 fish spawned during the "post-bomb" period (Table 1). The sample collection locations for the cod otoliths are shown in Figure 1.

Calcium carbonate deposited within the first year of the fish's life was isolated by sculpting one sagitta from each fish with a fine dental-type drill. This was achieved by "sculpting" from the larger otolith, an otolith that was representative of a cod of about one year of age. The final product was a single piece of otolith aragonite. Sample weights ranged from about 14.0 to 19.6 mg (Table 1). This material would provide ^{14}C data indicative of Barents Sea DIC during the year of birth for an individual fish. Otolith carbonate was converted to CO_2 by reaction in vacuo with 85% phosphoric acid. The CO2 was then sublimed into flame-sealed glass tubes for further treatment and measurement at the NSF-Arizona Accelerator Facility for Radioisotope Analysis. An aliquot of the CO_2 was used to determine $\delta^{13}C$ by mass spectrometry for each sample and the remaining CO_2 was graphitized for analysis of ^{14}C. ^{14}C levels in each sample were determined by accelerator mass spectrometry (AMS). In order to obtain a precision of 4–5‰, several accelerator targets were applied (Donahue et al. 1990). ^{14}C is here reported in $^{14}\delta^{S}_{N}$ values, given in permil deviation from the recent standard (the oxalic acid at 1950) when corrected for age and isotopic fractionation ($\delta^{13}C$). This $^{14}\delta^{S}_{N}$ symbol recently introduced by Mook and van der Plicht (1999), is the same as the $\Delta^{14}C$ symbol (Stuiver and Polach 1977) for geochemical samples, and includes correction for isotopic fractionation ($\delta^{13}C$) and for decay to 1950 AD.

RESULTS

^{14}C data obtained from the otoliths of Arctic cod with birth dates between 1919 and 1992 display general trends similar to those presented in other time series of ocean ^{14}C (Figure 3; Table 1). The average pre-bomb (1919–1950) $^{14}\delta^{S}_{N}$ value in the Barents Sea was –53.8‰ and increased to a maximum of 134.2‰ in 1967. During the late 1960s until 1975 ^{14}C concentration appears highly variable and a secondary peak in $^{14}\delta^{S}_{N}$ of 110.5‰ occurred in 1975. The decline in $^{14}\delta^{S}_{N}$ from 1919–1950 suggests a Suess effect of about 0.2‰ per year in the Barents Sea. However, based on linear regression the trend is not significant (n=14, p=0.13). There is good evidence of bomb ^{14}C in the 1957 sample, which had a $^{14}\delta^{S}_{N}$ value of –24.1‰, 30‰ greater than the mean of pre-bomb measurements and 20‰ greater than the datum from 1955. $^{14}\delta^{S}_{N}$ declined linearly (n=5, r^2=0.97, p=0.002) from 1973 until 1992 at the rate of 3.1‰ per year.

DISCUSSION

Comparison with High Latitude Ocean Δ Records

Previous measurements of ^{14}C made directly on seawater DIC or through proxies (e.g. bivalve shells) in north polar latitudes have provided only snapshots of ^{14}C variability in this region. Data from the otolith-based Barents Sea time series of ^{14}C agree closely with past measurements made in the region directly on seawater DIC or through proxies, notably molluscan $CaCO_3$ (Table 2 of other data from Barents Sea region; Figure 3). These results, coupled with the well-defined distribution of 0-group Arcto-Norwegian cod, provide strong support for the hypothesis that these data can serve as a measure of ^{14}C in NACW of the southwestern Barents Sea.

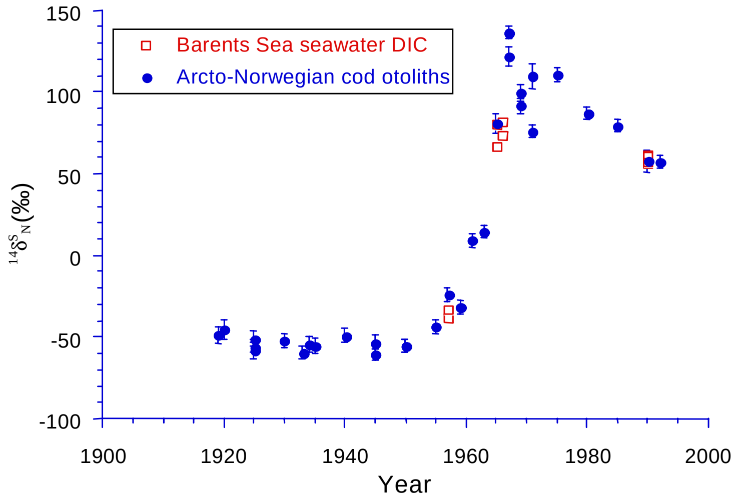

Figure 3 ^{14}C data ($^{14}\delta^S{}_N$) obtained from Arcto-Norwegian cod otoliths (this paper) and Barents Sea seawater (Østlund and Engstrand 1963; Nydal et al. 1991, 1998).

Mangerud and Gulliksen (1975) reported mean pre-bomb $^{14}\delta^S{}_N$ of –57 ± 4‰ and –61 ± 4‰ for northern Norway and Spitsbergen, respectively. These estimates were based on a range of bivalve mollusc species collected between 1857 and 1926 (Table 2). Therefore, these estimates are most comparable to the earliest cod otolith data presented in this study. Mean $^{14}\delta^S{}_N$ value in otoliths from cod spawned between 1919 and 1925 was –51.7 ± 5‰ (n=5) which is not significantly different from the mean based on mollusc shells from northern Norway.

^{14}C data from several locations in the Barents (Nydal et al. 1991; Nydal 1998), Norwegian and Greenland (Gislefoss et al. 1995; Nydal and Gislefoss 1996) Seas provide independent validation of otolith ^{14}C. The majority of these data were collected between 1989 and 1992. Several measurements were, however, made during the 1950s and 1960s. Barents Sea $^{14}\delta^S{}_N$ in seawater DIC was –35.8 ± 3.4‰ in July 1957 (Table 2) and demonstrates that bomb ^{14}C was detectable in that region in the early phases of intensive atmospheric testing of nuclear weapons. Cod otolith $^{14}\delta^S{}_N$ was –25.8±4.1‰ in 1957, only slightly higher than that measured directly on seawater DIC in the same year, however, $^{14}\delta^S{}_N$ of –33.5 ± 4.1‰ measured in otolith aragonite deposited in 1959 was in statistical agreement with measurements on seawater DIC collected in July 1957. Measurements of $^{14}\delta^S{}_N$ in Barents Sea DIC in 1965 and 1966 were 73.2 ± 9.9‰ (n=2) and 77.6 ± 6.4‰, respectively and are in statistical agreement with $^{14}\delta^S{}_N$ of 78.7 ± 5.9‰ measured in a cod otolith from a fish spawned in 1965. In 1990 Barents Sea $^{14}\delta^S{}_N$ measured in seawater DIC had decreased to 58.9 ± 2.2‰ (n=5), very similar to otolith $^{14}\delta^S{}_N$ of 56.0 ± 7.0‰ in the same year.

Individual measurements of $^{14}\delta^S{}_N$ in surface seawater DIC in polar latitudes of the northeast Atlantic were made by the GEOSECS and TTO expeditions in 1972 and 1982, respectively (Figure 4). These measurements were made west of the warm inflow of NACW and the Arctic Frontal Zone (AFZ) and within Arctic Water (AW) dominated by East Greenland Current Water (EGCW) and are not directly comparable with measurements from the cod otolith proxy. The AFZ represents the meridional interface between warm, saline waters derived from the North Atlantic Drift (NAD), Norwegian Atlantic Water (NAW) to the east, and colder, less saline AW from the Greenland Sea to the

Table 2 ^{14}C in seawater (DIC) and mollusc shell Ca CO_3 at various times in the Barents Sea

Laboratory reference	Sample date	Sample location	Sample type	Depth	Salinity	Temp.	$^{14}\delta^{S}_{N}$ (‰)	± error (‰)
ST-335	3-Jul-57	72°51′N 41°51′E	Seawater DIC	337	34.98	–0.7	–38	6
ST-336	4-Jul-57	73°51′N 33°50′E	Seawater DIC	0	35.08	4.5	–33	6
SV-00001	15-Nov-65	72°32′N 20°04′E	Seawater DIC	4	34.81		80.2	11.0
SV-00002	21-Nov-65	74°40′N 39°00′E	Seawater DIC	4	35.19		66.2	10.0
SV-00008	2-Jun-66	74°14′N 20°11′E	Seawater DIC	4	34.95	0.1	73.1	9.0
SV-00009	13-Jun-66	72°14′N 19°38′E	Seawater DIC	4	37.83	5.8	82.1	9.0
LA1-00001	21-Jul-90	77°43′N 32°30′E	Seawater DIC	4		2.7	61.5	4.4
LA3-00001	23-Jul-90	79°22′N 30°20′E	Seawater DIC	6	33.68	4.8	56.2	4.2
LA4-00001	27-Jul-90	79°01′N 41°54′E	Seawater DIC	5		2.7	60.3	3.8
LA2-00002A	23-Jul-90	78°12′N 29°50′E	Seawater DIC	50	33.58	3.5	59.4	4.6
LA5-00002A	30-Jul-90	80°31.0′N 29°12.0′E	Seawater DIC	5	33.63	–1.1	57	4.6
GEOS-17	18-Aug-72	74°56′N 1°07′W	Seawater DIC	4			33.9	4
GEOS-18	22-Aug-72	70°00′N 0°05′W	Seawater DIC	4			67.3	4
GEOS-19	24-Aug-72	64°12′N 5°34′W	Seawater DIC	4			47.3	4
TTO-144	26-Jul-81	67°41.1′N 3°20.1′W	Seawater DIC	12			54..3	4
TTO-145	27-Jul-81	69°59.7′N 2°29.0′E	Seawater DIC	11			59.9	4
TTO-159	8-Jun-81	68°43.5′N 10°33.6′W	Seawater DIC	12			55.7	4
T-1534	1857	69°39′N 18°58′E	Chlamys islandicus				–56.0	6.0
T-1536	1857	70°04′N 29°45′E	Astarte crenata				–55.0	6.0
T-1535	1876	70°30′N 28°30′E	Astarte crenata	232			–61.0	9.0
T-1537	1900	74°07′N 19°04′E	Chlamys islandicus	90			–57.0	6.0
T-958	1922	70°16′N 23°24′É	Mytilus edulis	0–10			–63.0	9.0
T-1538	1926	77°40′N 14°16′É	Chlamys islandicus	120–190			–60.0	6.0
T-1539	1925	78°07′N 14°08′E	Chlamys islandicus	150–165			–57.0	6.0
T-1540	1878	78°15′N 15°36′E	Astarte borealis				–66.0	9.0
T-1541	1878	79°34′E 10°40′E	Astarte borealis	40–80			–67.0	9.0

west (Van Aken et al. 1995). The distribution of Arcto-Norwegian cod spawning grounds and catches of 0-group cod in the Barents Sea indicate that these fish do not occur to the west of the AFZ during these life history stages. Therefore, ^{14}C from the cod otoliths is representative of NAW, whereas the GEOSECS and TTO measurements north of 68°N latitude would have AW as their predominate influence. This west-east transition in water mass characteristics is reflected in the difference between GEOSECS, TTO, and otolith $^{14}\delta^S_N$ data (Figure 4). Otolith $^{14}\delta^S_N$ values were about 35‰ greater than the GEOSECS and TTO polar North Atlantic measurements, collected in 1972 and 1981, respectively.

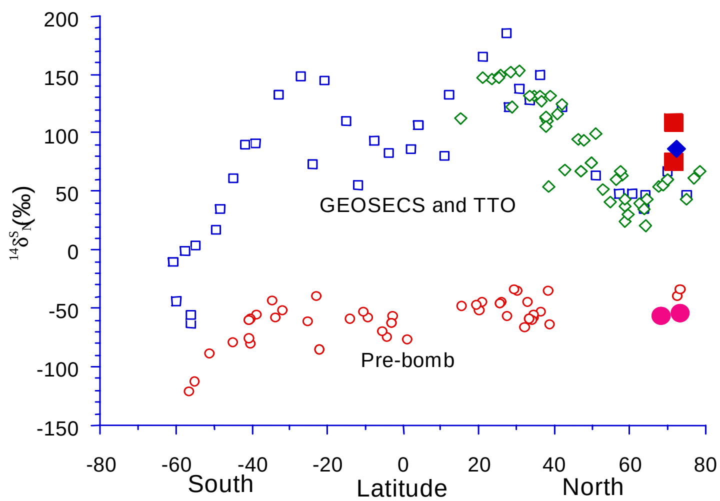

Figure 4 ^{14}C data ($^{14}\delta^S_N$) in surface seawater DIC made by the GEOSECS (open squares) and TTO (open diamonds) expeditions in 1972 and 1982, respectively. These data are compared with pre-bomb otolith data (filled circles) and otolith data from 1972 and 1982 (filled squares). Pre-bomb data (open circles) are from Broecker and Peng (1982).

Comparisons with Temperate and Subtropical Ocean ^{14}C Time Series

Several ^{14}C time series have been developed for the subtropical, tropical, and temperate North Atlantic on the basis of hermatypic corals (Druffel and Linick, 1978; Nozaki et al. 1978) and a bivalve (Weidman and Jones 1993) and these series display several features in common with Barents Sea ^{14}C from otoliths (Figure 5).

Pre-industrial $^{14}\delta^S_N$ value in Florida coral was estimated to be –51‰ and declined to –62‰ by 1954 due to the burning of fossil fuels (Druffel and Linick 1978). No pre-industrial data were collected from the cod otoliths, but the earliest data from 1919 and 1920 had a mean of –49‰, which is in good agreement with the Florida coral data.

Pre-bomb, post-industrial $^{14}\delta^S_N$ value in Arcto-Norwegian cod between 1950 and 1955 was –52.5 ± 6.1‰ (n=3) a value that falls between data from a similar time period derived from Florida and Bermuda corals. For Bermuda corals Nozaki et al. (1978) measured a pre-bomb value of –50‰ in 1950 and Druffel (1989) determined pre-bomb $^{14}\delta^S_N$ value to be –48.3 ± 4.9 (n=5). Florida corals contained slightly less ^{14}C and averaged –59.5 ± 5.2‰ (n=6) between 1950 and 1955 (Druffel

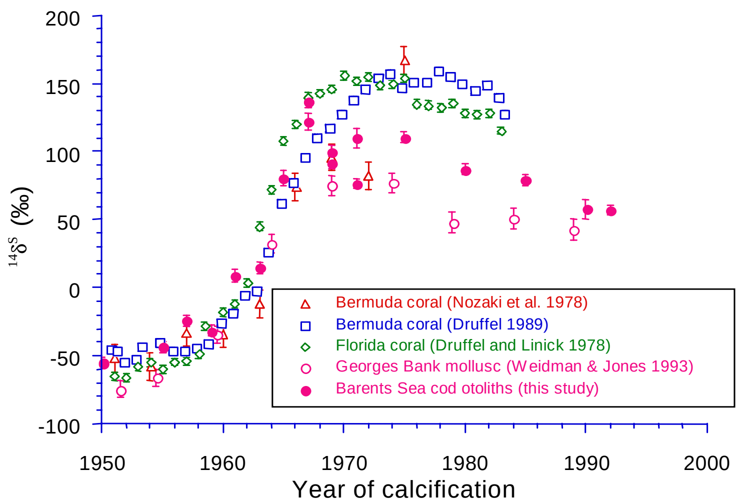

Figure 5 Comparison of several ^{14}C series developed for the subtropical, tropical, and temperate North Atlantic on the basis of corals, molluscs and cod otoliths

and Linick 1978). Data from a bivavle, *Arctica islandica*, collected at 41°N latitude provided a $^{14}\delta^S_N$ series that is representative of water dominated by a deepwater source derived from polar latitudes (Weidman and Jones 1993) and pre-bomb $^{14}\delta^S_N$ was –70.6‰, significantly lower than that measured in the Arcto-Norwegian cod otoliths from north of 70°N latitude.

Bomb ^{14}C is clearly present in Arcto-Norwegian cod otoliths from fish spawned in 1957 when $^{14}\delta^S_N$ was –25.8 ± 4.1‰ and this is similar to the time when bomb ^{14}C was first detectable in corals from Bermuda (Druffel 1989), Florida (Druffel and Linick 1978) and the Pacific (Druffel 1987), but somewhat earlier than the first evidence of bomb ^{14}C from the temperate bivalve from Georges Bank (Weidman and Jones 1993).

The Barents Sea ^{14}C series appears to be in phase with both the Florida (Druffel and Linick 1978) and Bermuda coral series (Druffel 1989) during the 1960s when bomb ^{14}C was increasing most rapidly. In 1967, cod otolith $^{14}\delta^S_N$ increased dramatically to 128.1 ± 8.7‰ (n=2) and this was significantly greater than mean $^{14}\delta^S_N$ of 110.5‰ in Bermuda corals for a similar time period (Druffel 1989), but less than a $^{14}\delta^S_N$ of 140‰ measured in corals from Florida (Druffel and Linick 1978). Although this correspondence between Florida and Barents Sea data suggests similar levels of atmospheric ^{14}C inputs, there are significant differences in later years that are likely to be related to differences in vertical mixing and require more detailed analysis for interpretation.

Comparisons with Atmospheric ^{14}C Time Series

Atmospheric records from Fruholmen (Nydal and Løvseth 1996) and ocean records from the Barents Sea both show a gradual decrease in $^{14}\delta^S_N$ after the peak in the middle to late 1960s (Figure 6). This gradual decrease indicates that the ^{14}C pulse associated with atmospheric atomic tests has yet to equilibrate with surface waters of the ocean and that ocean ^{14}C continues to be distributed to other pools of inorganic and organic carbon. Continued input of ^{14}C-free CO_2 associated with the burning of fossil fuels will also contribute to the decline in atmospheric ^{14}C, but this effect is more difficult to confirm in Barents Sea waters. The decrease in $^{14}\delta^S_N$ in the polar atmosphere and surface Barents Sea between the years 1975 to 1992 is about 15‰ per year and 3‰ per year, respectively. This suggests that the flux of ^{14}C between the atmosphere and ocean is five times greater than its movement from the surface Barents Sea or incorporation into other carbon pools. This apparent slow turnover time for ^{14}C in the Barents Sea may be linked to the magnitude of volume transport into the southern Barents Sea (e.g. ~1.6 Sv from the NAC; Loeng et al. 1993).

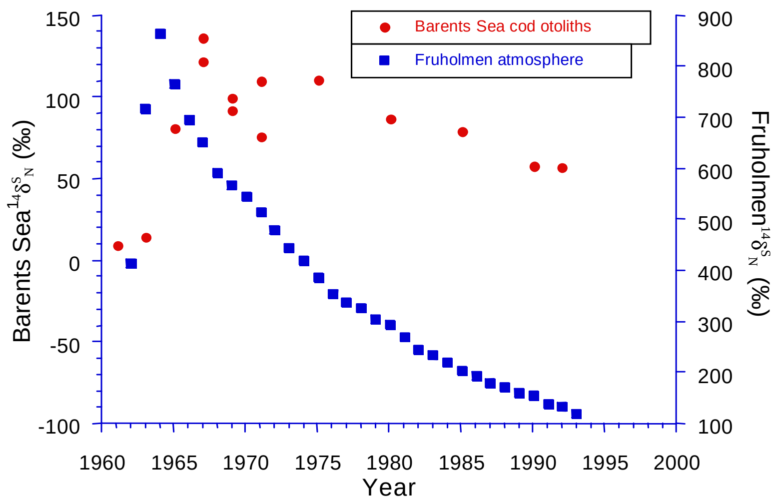

Figure 6 Comparison of atmospheric ^{14}C records from Fruholmen and ocean records (cod otoliths) from the Barents Sea

Atmospheric ^{14}C measured at Fruholmen between 1970 and 1993 is well described by an exponential function with the highest rate of decline from the mid-1960s to mid-1970s (Figure 7). The difference between $^{14}\delta^S_N$ measured at Froholmen and in the Barents Sea declined at a rate of about 37‰ during this time, whereas the rate of decline was only 12‰ per year from the mid-1970s to the early 1990s. The differential between Fruholmen and Barents Sea $^{14}\delta^S_N$ near the bomb peak was about 700‰ and would have resulted in increased rate of ^{14}C flux to the surface ocean.

Data on ^{137}Cs in Barents Sea surface waters show peaks in the mid-1960s and around 1980 (Kershaw and Baxter 1993). The peak in the 1980s is associated with releases of ^{137}Cs from the Sellafield Reprocessing Plant off the west coast of Great Britain, whereas the peak in the 1960s resulted from fallout from atmospheric atomic tests, a large number of which were conducted between 1957 and 1963 at the Novaya Zemlya test site that borders the eastern Barents Sea. Given the close proximity of this site to the nursery grounds of 0-group Arcto-Norwegian cod, it is possible that this area was exposed to close-in fallout ^{14}C produced by atomic testing. Clearly, there are several factors in the mid-1960s that would contribute to a relatively early peak of ^{14}C in the Barents Sea. Time series of ^{14}C from hermatypic corals in the tropical North Pacific show peak activities in the late 1960s to early 1970s and this was likely to be a manifestation of the corals' close proximity to atmospheric atomic tests in the North Pacific (Druffel 1987).

CONCLUSION

Cod otoliths provide the first pre- and post-bomb time series of ^{14}C from polar waters. Changes in both ocean and atmospheric inputs of ^{14}C are likely to have a strong influence on Barents Sea ^{14}C. Close-in fallout from atmospheric tests at Novaya Zemlya may have resulted in a relatively early

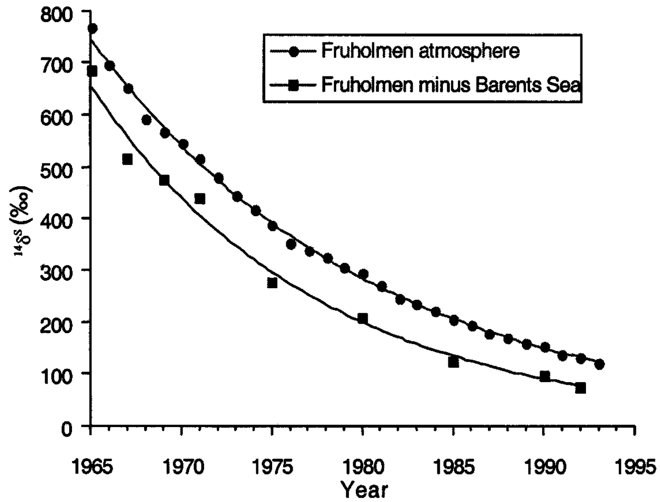

Figure 7 Atmospheric ^{14}C measured at Fruholmen between 1965 and 1993, and the difference between atmospheric Fruholmen records and oceanic Barents Sea records

peak in ^{14}C in the Barents Sea in 1967, earlier than measured in other Atlantic Ocean time series. Although the otolith-derived series of ^{14}C data from the Barents Sea has a relatively coarse temporal resolution, it suggests that more detailed data sets produced from a similar source could be used to investigate annual changes in ocean circulation as has been achieved by others using corals (e.g. Druffel 1989). Further understanding of production of deepwater from the northeastern region of the Atlantic could be derived from a similar study of otoliths from Icelandic stocks of cod, another stock of cod with a well-defined distribution during early life. The 0-group cod from these stocks are present in water derived from the East Greenland and East Icelandic Currents. Other species of fish with long histories of commercial exploitation and relatively long life spans can enhance our understanding of ocean circulation and ^{14}C flux in a broad range of habitats.

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