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The use of Cs and Sr isotopes as tracers in the Arctic Mediterranean Seas

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The Arctic Mediterranean Seas constitute an oceanic region in which the thermohaline circulation has a strong advective component and deep ventilation processes are very active relative to other oceanic areas. Details of the nature of these circulation and ventilation processes have been revealed through use of Cs and Sr isotopes from bomb-fallout and nuclear-waste sources as ocean tracers. In both cases, their regional input is dominated by advective supply in the Norwegian Atlantic Current and Norwegian Coastal Current, respectively. The different temporal, spatial, and compositional input patterns of these tracers have been used to study different facets of the regional circulation. These input differences and some representative applications of the use of these tracers are reviewed. The data discussed derive from samples collected both from research vessels and from Arctic ice camps. The topics addressed include: (*a*) the role of Arctic Intermediate Water as source, supplying recent surface water to North Atlantic Deep Water via the Denmark Strait overflow; (*b*) deep convective mixing in the Greenland Sea; (*c*) circulation or recirculation of Atlantic water in the Arctic basins; and (*d*) the role of Arctic shelfwaters in the ventilation of intermediate and deep water in the Eurasian and Canadian basins.

1. The Arctic Mediterranean Seas

The term Arctic Mediterranean Seas has been collectively applied to the seas lying north of the Greenland–Scotland ridge (see figure 1). In terms of global oceanic circulation, they represent the major northern source of ventilation of the world ocean (Mantyla & Reid 1983). The early studies of Helland-Hansen & Nansen (1909) laid the groundwork for an understanding of the nature of the circulation of the seas south of Fram Strait, the Nordic Seas. The understanding of this regional circulation has recently taken on a new dimension in the light of the critical link it represents between the atmosphere and the abyssal ocean. Accordingly, the pace of circulation studies has quickened and now tracer tools, based on anthropogenic sources, have been added to the more traditional suite of physical and chemical methods available. The circulation in the Arctic basins north of Fram Strait is less well studied because of the obstacle to sampling access represented by the ice cover. The most recent review of the circulation of the Arctic Mediterranean Seas both to the north and south of Fram Strait is contained in a paper by Aagaard *et al.* (1985). The traditional site of deep-water formation in the region is in the Greenland Sea. It is only the intermediate waters there and in the Iceland Sea that contribute to the dense overflows over the Greenland–Scotland ridges that ventilate the deep water to the south. The deep waters of the Greenland Sea are too dense to pass over these southern ridges and hence are forced to circulate in the deep basins of the Nordic Seas and the Arctic Ocean, through Fram Strait, the deep connection between Greenland and Spitzbergen.

The major feature of the upper-water circulation in the region is driven by the Norwegian–

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FIGURE 1. Arctic sampling locations in Atlantic inflow and outflow regions around Fram Strait and interior Arctic.

Atlantic Current, a northward extension of the Gulf Stream. This current, as the West Spitzbergen Current, separates into several branches in the Fram Strait region. The westernmost waters recirculate southward in the cyclonic Greenland Sea gyre. The eastern branches enter the Arctic as the West Spitzbergen Current (Perkin & Lewis 1984) and drive the main circulation of Atlantic water in the Arctic basins. There the Atlantic water underlies the less-saline polar waters that, with contributions from the Bering Sea, form the water masses shallower than the sharp Arctic halocline (Aagaard *et al.* 1981) that eventually exit through western Fram Strait as the East Greenland Current.

The traditional view (Helland-Hansen & Nansen 1909) held that deep convective mixing in the Greenland Sea drove the deep regional circulation. Greenland Sea Deep Water (GSDW) was then supposed to flow into the Norwegian Sea to form Norwegian Sea Deep Water (NSDW). This water mass in turn was thought to feed the deep Arctic basins by inflow through eastern Fram Strait (figure 1). A return flow of Arctic Ocean Deep Water (AODW) left the deep Arctic basins on the western side of Fram Strait, along the Greenland margin (figure 1). This scheme has proven to be oversimplified. The deep inflow has been shown to consist of more than pure NSDW. Occasional contributions of GSDW have been noted (Swift *et al.* 1983). The deep Arctic has too high a salinity to be fed from the south. In the water-mass progression, GSDW–NSDW–EBDW (Eurasian Basin Deep Water) – CBDW (Canadian Basin Deep Water), the salinities and temperatures increase steadily. The solution to this paradox appears to lie in a supply of a brine-enriched shelf water end-member to the deep Arctic (Aagaard *et al.* 1985). As will be

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discussed later, anthropogenic tracer evidence supports this proposition in the Eurasian Basin. However, in the Canadian Basin, the deep waters studied in this and previous studies lack a measurable anthropogenic tracer signal (Aagaard & Reed 1987; Östlund 1982; Östlund *et al.* 1987; Top 1984; Wallace & Moore 1985) and renewal rates of *ca.* 700 years (Aagaard & Reed 1987; Östlund *et al.* 1987). This slow rate may explain the lack of a recent shelf tracer signal from the locations that have been studied. They do not include any so far that are close to the basin boundary. Current and future efforts should help to address this question more fully.

In addition to the use of nutrients as classic chemical tracers in the Arctic seas (Jones & Anderson 1986), use has been made of both naturally occurring chemical tracers, e.g. Zn, Cd, Cu and Al (Moore 1981), radium isotopes (Moore 1980), and anthropogenic tracers, e.g. tritium (Östlund 1984; Östlund *et al.* 1982; Moore *et al.* 1983; Smethie *et al.* 1986; Peterson & Rooth 1976), carbon-14 (Östlund *et al.* 1982; Östlund *et al.* 1987; Smethie *et al.* 1986; Peterson & Rooth 1976), krypton-85 and argon-39 (Smethie *et al.* 1986), chlorofluoromethanes (Bullister & Weiss 1983; Smethie in Swift 1984*c*; Wallace & Moore 1985) and artificial radioisotopes from nuclear-weapons testing fallout and European nuclear-waste disposal (Aarkrog *et al.* 1983; Bowen & Sugihari 1964; Holm *et al.* 1983; Kautsky 1980; Livingston *et al.* 1982*a*, *b*; Livingston *et al.* 1984, 1985; Swift *et al.* 1983; Vakulovskiy *et al.* 1985). These various tracers include both transient and steady-state tracers, cover a range of chemical reactivities with respect to particle association and operate over a range of timescales from several years to thousands of years. Because their mode of introduction to the region varies with each tracer or tracer family, they find use in different ways in respect to the processes that they may trace. It is the purpose of this paper to review the ways in which the artificial radionuclides from nuclear-weapons testing fallout and European coastal nuclear-waste disposal have been used as tracers in regional circulation studies.

2. Cs and Sr input patterns

Detailed discussion of the temporal and spatial input pattern of Cs and Sr isotopes from bomb fallout and nuclear-fuel reprocessing discharges have appeared at some length elsewhere (Kupferman *et al.* 1979; Livingston *et al.* 1982*a*; Livingston 1985). In the context of the present paper, it is convenient to summarize the important features of these input patterns and various characteristics of their behaviour or composition that have bearing on their use as tracers in the Arctic regions.

Whether introduced to the oceans from bomb fallout or coastal nuclear-fuel reprocessing discharge, the association of both Cs and Sr isotopes with particles is small enough that their removal via particle association may be disregarded for practical purposes. Their chemistries, as an alkali metal and an alkaline earth, respectively, assure that their oceanic behaviour closely resembles that of the other conservative members of these families, and hence they act as tracers of water transport, or, at least, of its dissolved salt content. The radioactive half-lives of the longest-lived fission-product nuclides of these elements are ^{90}Sr (28 years) and ^{137}Cs (30 years). Because of the close similarity in half-life, their activity ratios to each other are not changed very significantly by radioactive decay over the timescales presently studied. Therefore, because no other process causes them to fractionate with respect to each other, their relative composition (or activity ratio) is a water-mass characteristic linked to one or more of their input sources. Other than input-source composition effects, the only other process that effects a change in

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their relative composition is riverine input. In terrestrial systems, ^{137}Cs exhibits strong particle reactivity and is associated largely with freshwater sediments and soils; ^{90}Sr, in contrast, is mobilized in freshwater systems and, like tritium, is delivered via rivers to the oceans at relatively high concentrations. The effect of this is to reduce the ratio ^{137}Cs:^{90}Sr in coastal waters. In the Arctic this has been noted in low-salinity surface waters of the Polar Water layer by a reduction in this ratio to about 1, as opposed to the value of 1.5 that characterizes open ocean waters containing these isotopes only from bomb fallout (Livingston *et al.* 1984).

(*a*) *Nuclear-weapons testing fallout*

As noted above, an important source identification diagnostic of ^{137}Cs and ^{90}Sr from fallout sources in open ocean water is the constancy of the activity ratio ^{137}Cs:^{90}Sr at 1.5 (Bowen *et al.* 1974) in proportion to their fission yields. The input of fallout ^{137}Cs and ^{90}Sr to the Arctic Ocean regions needs to be viewed as having two principal components. The first, direct input of fallout to the surface ocean, came at two intervals: (1) an early, relatively small input in the mid-1950s; and (2) a larger input in the early 1960s. However, because the Arctic regions are north of 60° N and because fallout delivery rates were much higher at mid-latitudes than at high latitudes (Kupferman *et al.* 1979), a major continuing input to the surface waters of the Norwegian and Greenland Seas came in the form of the advective influx from the south via the Norwegian Atlantic current. Between 1960 and 1981 the ^{137}Cs concentrations of this water mass rose to a maximum in 1963–1964 and declined rapidly thereafter, reaching slowly declining levels in the 1970s and 1980s at around 20–25% of peak values (Livingston *et al.* 1985). This input is primarily a tracer for the high-salinity Atlantic water flowing into the Arctic regions, in contrast to the following source.

(*b*) *Nuclear-fuel reprocessing discharges*

The major contributor to this source is the low-level discharge of liquid waste from the British Nuclear Fuels Plant at Sellafield (formerly Windscale) on the northeast coast of the Irish Sea. Much smaller discharges come from the French plant at Cap de la Hague on the Normandy coast, or from the Scottish plant at Dounreay. The time history of the amounts, composition, and advective transport of these discharges into the Arctic Mediterranean Seas has been described in earlier reports (Livingston *et al.* 1982*a*, *b*). The features of greatest relevance in their use as regional tracers are as follows.

(1) Discharges of ^{137}Cs began to increase in 1970, peaked in 1975 and have since declined steadily to pre-1970 levels.

(2) Over much of the history of releases during the high ^{137}Cs discharge period, the input was characterized by a ^{137}Cs:^{90}Sr ratio of around 10, which is substantially higher than that characterizing bomb fallout.

(3) The discharges were carried northward in the shelf circulation and appeared in the northern Norwegian Sea about five years after their release to the Irish Sea.

(4) As they travel northwards, the discharges are diluted continuously by mixing with inflowing Atlantic water carrying ^{137}Cs and ^{90}Sr at fallout levels and ratios. As this mixing occurs, the ratio of ^{137}Cs:^{90}Sr is reduced substantially. For example, dilution of the releases during the peak of ^{137}Cs discharges was such that, on arrival in the northern Norwegian Sea, the ratio of ^{137}Cs:^{90}Sr was reduced to the range 3–4 (Casso & Livingston 1984).

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(5) Because of their coastal origin, these discharges serve to trace the coastal circulation and shelf-water contributions to the larger-scale circulation in the Arctic regions.

(6) In contrast to ^{137}Cs and ^{90}Sr from fallout, the nuclear-waste source has an association with a relatively lower salinity signal, derived from its low-salinity coastal end member. This low-salinity signal is scarcely detectable as high-salinity Atlantic water, mixed with coastal contributions, recirculates in the Greenland Sea gyre or circulates in the Eurasian or Canadian basins of the Arctic Ocean.

3. Deep convection in the Greenland Sea

Despite considerable effort, most recently during the winter cruise of C. S. S. *Hudson* in 1982 (Clarke *et al.* 1986), direct observation of deep convective events has not been made. Perhaps the nearest to direct observations were those of Malmberg (1983) who found uniform properties from 500 m to the bottom in the central Greenland Sea in February. Killworth (1979) pointed out that the convection events could be both short-lived and localized and easily escape observation. The main evidence for the existence of the process is the finding that deep water in the central Greenland Seas has properties suggesting very recent connection with the sea surface. Various anthropogenic tracers have supported this finding and have led to a series of estimates of deep Greenland Sea residence times with respect to exchange with surface water, namely 24–34 years (Smethie *et al.* 1986), 26–31 years (Peterson & Rooth 1976), and 35–42 years (Bullister & Weiss 1983).

In addition to deep convection, Aagaard *et al.* (1985) have shown that a deep flow from the Eurasian Arctic Basin, relatively warm and salty, enters the northwest Greenland Sea through Fram Strait (figure 1) and propose that this mixes with Greenland Sea water around the outer edges of the Greenland Sea gyre, eventually entering the Norwegian Sea through deeper sections of the mid-ocean ridge. An updated and expanded study of this process has been made very recently (Swift & Koltermann 1988). Smethie *et al.* (1986) reported that tracer and hydrographic observations from the 1981 Transient Tracers in Oceanography (TTO) cruise in the Norwegian–Greenland Seas also support this proposition and obtained similar residence times for NSDW with respect to exchange with GSDW (19–30 years) to those reported by Bullister & Weiss (1983).

Data for Cs and Sr isotopes are also relevant to the question of the ventilation of the deep Greenland and Norwegian Seas. The measurements described here cover the time period 1972–1981. This is a significant interval because it spans the transition created when input from the nuclear-waste discharges began to add to the pre-existing bomb-fallout distribution of ^{137}Cs and ^{90}Sr. The evolution of this transition has been described elsewhere (Livingston 1985). In summary, between 1972 and 1981 the following changes were noted in tracer properties of central Greenland Sea deep water. Fallout concentrations of ^{137}Cs and ^{90}Sr remained essentially unchanged, i.e. the rate of supply from the surface being balanced by the rate of loss through exchange to the deep Norwegian Sea. Deep tritium concentrations increased by more than 50%, but the reason for this increase relative to ^{137}Cs and ^{90}Sr was believed to reflect parallel changes in surface-water composition over the previous two decades.

The most remarkable change in the deep-water properties of these isotopes came from a comparison of the 1972 and 1979 inventories and concentrations. For ^{137}Cs, there was an average increase of 45% over the 1972 fallout levels, the increase essentially all being

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attributable to the new nuclear waste source. The presence of the fresh input was verified by the finding of a deep-water ratio of ^{137}Cs:^{90}Sr of 1.7, up from the fallout value of 1.5 noted in 1972. What this tells us is the rapidity with which the deep water is responding to changes at the surface. It was noted in another report (Livingston *et al.* 1985) that the nuclear-waste ^{137}Cs signal could not have been in central Greenland Sea surface waters before 1978. The deep-water increase noted in 1979 seems to offer evidence of either continuing active annual ventilation or unusually intense deep convection during the 1978–1979 winter. In any event, it serves to illustrate the action of a ventilation process that keeps the deep Greenland Sea in contact with the surface ocean over very short timescales.

Perhaps the most compelling indirect evidence that deep ventilation occurs in the central Greenland Sea and then spreads laterally, comes from a comparison of surface and deep-water tracer concentrations in the Nordic Seas in 1979–1982 (Livingston 1986). In addition to measurements made in my laboratory, tritium data by H. G. Östlund (University of Miami) and tritium and ^{137}Cs data reported by P. Schlosser (University of Heidelberg) were used in this comparison. For both tritium and ^{137}Cs, a consistent reversal exists between surface and deep concentration patterns (see figure 4). In surface waters, concentrations are *highest* in the periphery of the Greenland Sea gyre and *lowest* in the interior. In deep waters, concentrations are *lowest* in the gyre periphery and *highest* in the interior. This does not argue against the deep inflow of Arctic Ocean water through the western side of Fram Strait referred to earlier. Rather, it serves to emphasize the classical view of the primary role in ventilation of the regional deep waters that takes place in the centre of the Greenland Sea gyre.

4. Connections to North Atlantic Deep Water

The two dense overflows into the North Atlantic that pass over the Greenland–Scotland sills have long been recognized as the vehicles that propagate surface-ocean properties into the deep North Atlantic. In both cases the outflows have been shown not to be outflows of deep water from the north, but rather of intermediate waters formed at the surface in the Greenland and Iceland Seas in winter (Swift 1986; Swift *et al.* 1980). The two overflows, Iceland–Scotland and Denmark Strait, eventually combine to form North Atlantic Deep Water (Swift 1984*a*, *b*, *c*). The detection of a plume of tritium in the deep water of the western boundary current at 30° N in 1977 served to highlight the route and rate of the southward-spreading ventilation process (Jenkins & Rhines 1980). The TTO cruise in 1981 presented an opportunity to study the nature of this process in greater detail. By 1981 the new nuclear-waste signal had been in the overflow waters long enough to permit it to be propagated southward and used to set some further constraints on the dynamics of the connection between North Atlantic Deep Water and its northern source waters.

Livingston *et al.* (1985) described the detection of the nuclear-waste signal in deep overflow water along a section just south of Denmark Strait. The location included a reoccupation of GEOSECS station 11, and hence there was the chance to compare the changes in tracer properties that had taken place between 1972 and 1981. All of the radionuclide-tracer concentrations reported (tritium, ^{137}Cs and ^{90}Sr) had increased between 1972 and 1981. This increase paralleled a shift in salinity and temperature of northern North Atlantic deep waters during the same interval (Swift 1984*a*, *b*, *c*; Brewer *et al.* 1983). All the tracers were inversely correlated with salinity in the overflow water with the tracer maxima corresponding to the salinity

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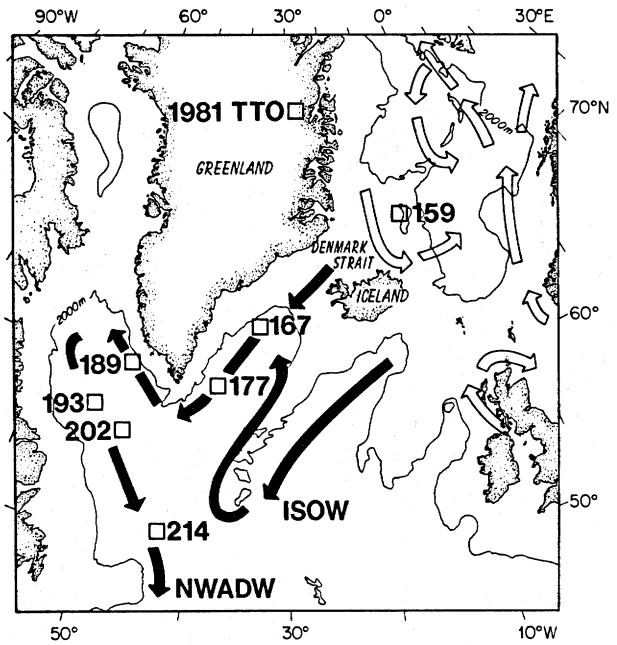

FIGURE 2. Sampling locations south of Denmark Strait during the 1981 Transient Tracers in Oceanography – North Atlantic Study. Open arrows represent the surface North Atlantic current inflow (as the Norwegian Atlantic Current). The solid arrows represent the deep outflow from the Nordic Seas, the Denmark Strait Overflow Water and the Iceland–Scotland Overflow Water. Water depths at these stations were: 159–2168 m, 167–2339 m, 177–3180 m, 189–2970 m, 193–3522 m, 202–3630 m and 214–4382 m.

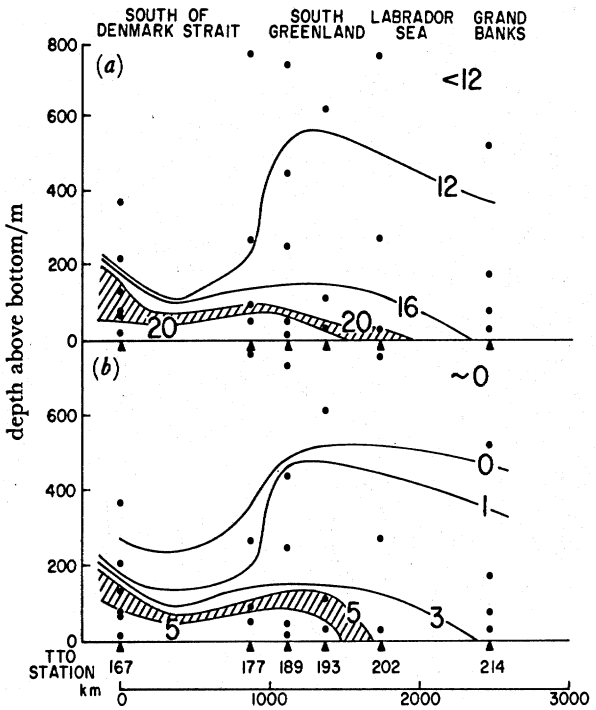

FIGURE 3. Distributions of ^{137}Cs in Northwest Atlantic Bottom Water, Denmark Strait–Grand Banks section. (*a*) Total ^{137}Cs concentration contours. (*b*) Nuclear-waste ^{137}Cs concentration contours (resolved from total ^{137}Cs data by method described by Livingston (1985)).

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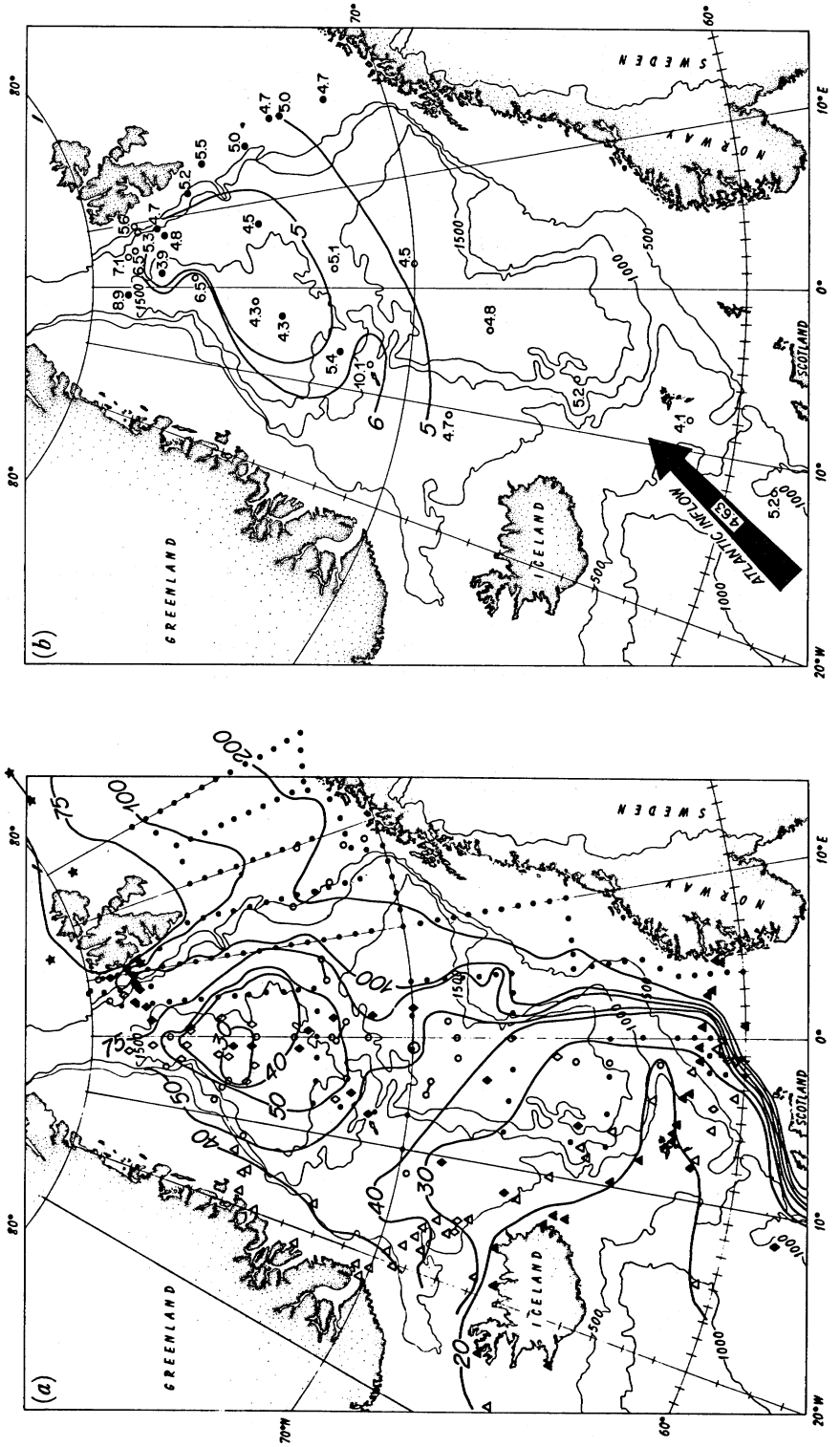

FIGURE 4. (*a*) Surface distributions of ^{137}Cs (disintegrations per minute per 100 kg, as of 1 January 1981) in the Norwegian–Greenland Seas. Solid symbols are stations occupied in 1981 by the ships indicated; open symbols are for 1982. Symbols: ◆, *Knorr*; ●, *Cirolana*; ▲, *Smyril*; ★, *Lance*; ◇, *Hudson*; ○, *Meteor*; △, *Nella Dan*. (1 disintegration per minute (d.p.m.) = 60 Bq.) (*b*) Surface distributions of ^{3}H (tritium units, as of 1 January 1981). Open circles are for stations occupied by R. V. *Knorr* in 1981, and solid circles for R. V. *Hudson* in 1982.

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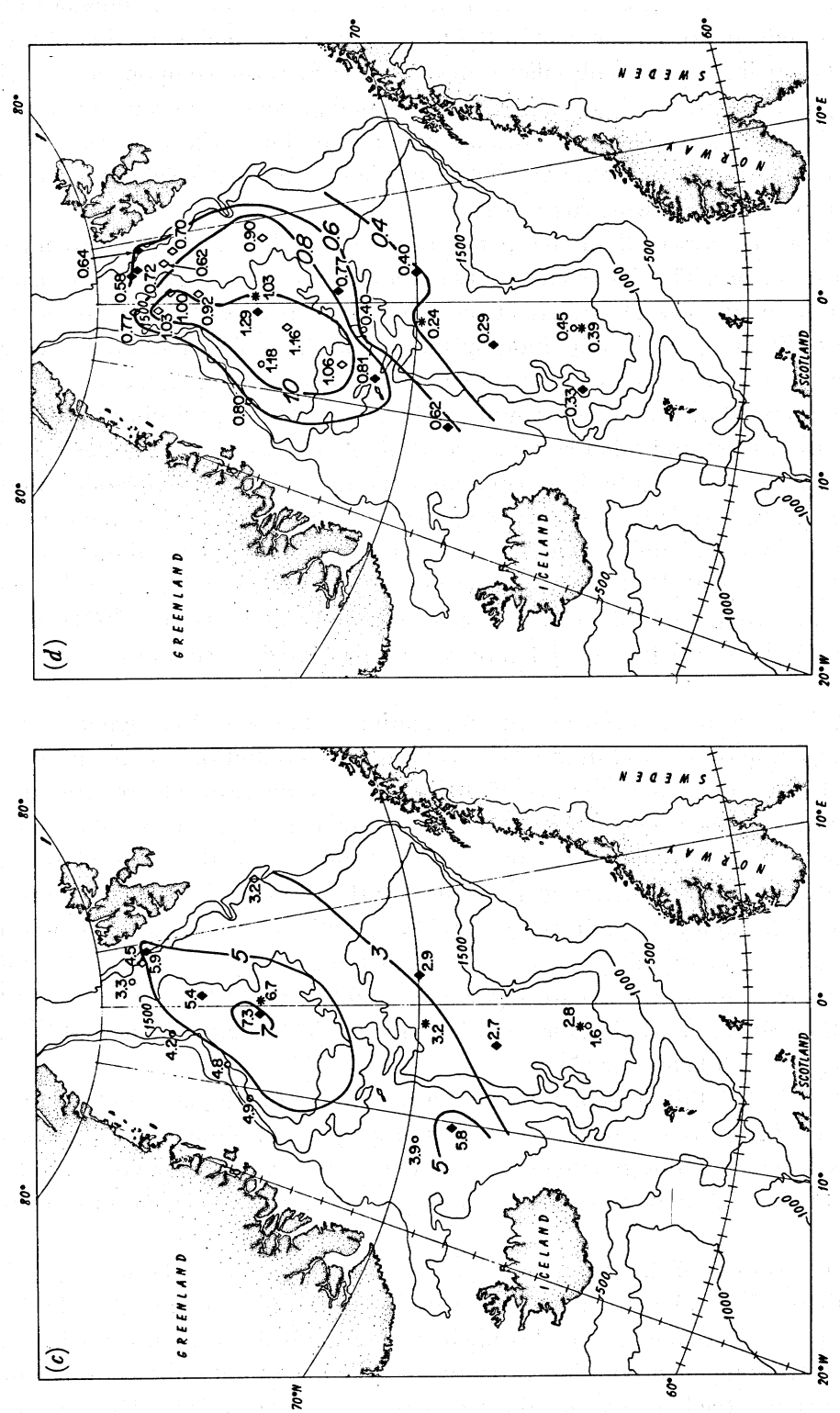

FIGURE 4. (*c*) Average ^{137}Cs concentrations (disintegrations per minute per 100 kg, as of 1 January 1981) in deep water, and (*d*) average ^{3}H concentrations (tritium units as of 1 January 1981) in deep water. Symbols denote ship and year of collection: ✱, *Meteor* 1979; ◆, *Knorr* 1981; ◇, *Hudson* 1982; ○, *Meteor* 1982.

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minima. The sharp increase noted for ^{137}Cs was attributed to the presence of ^{137}Cs from the nuclear-waste source on the basis of the elevated ratio ^{137}Cs:^{90}Sr and the presence of ^{134}Cs (both diagnostic indicators). At the core of the tracer plume, the major fraction of the ^{137}Cs present could be attributed to bomb fallout and the nuclear-waste component comprised a little over 25% of the total. This nuclear-waste ^{137}Cs signal presence confirmed the rapidity of transport of surface water from northern formation regions to the overflow. It was argued that the source waters derived from Arctic Intermediate Water from the Iceland and Greenland Seas and that transport took two years or less.

Additional data are presented in this paper that extend this study downstream of the overflow-water trajectory. The data come from samples in and above the southward extension of Denmark Strait Overflow water, referred to elsewhere as Northwest Atlantic Bottom Water, (NWABW) (Lee & Ellett 1967). The positions of the stations for which data are presented are shown in figure 2. They extend the sampling of NWABW from near Denmark Strait to the Grand Banks. The only data shown are from samples colder than 3 °C and fresher than 34.95‰. Complete data from these and other stations are available elsewhere (Casso *et al.* 1988).

In the upper panel (*a*) of figure 3 are contoured the total ^{137}Cs concentrations along the section. The tongue of high ^{137}Cs water, inversely correlated with salinity, extends nearly all the way to TTO station 214 off the Grand Banks. The core of the low-salinity plume was characterized by water with ^{137}Cs:^{90}Sr ratios ranging up to 2, clear evidence of the nuclear-waste component. Strontium-90 data were used to resolve the bomb fallout ^{137}Cs signal from the nuclear-waste ^{137}Cs (see legend of figure 3) and the latter is contoured in the lower panel (*b*).

It is evident that the speed of southward propagation of the new ^{137}Cs signal exceeds the sampling strategy employed. No samples were collected for Cs and Sr isotope measurement south of TTO 214. Although the intensity of the plume was upstream of TTO 214, the deep samples there still contained measurable traces of nuclear-waste ^{137}Cs. It is unfortunate that no further downstream samples were collected to define better the limit of southward penetration at that time. Nevertheless, it is evident that the transfer of this surface signal from the Iceland and Greenland Seas to deep water off Newfoundland was achieved in a period of two years. The absence of any nuclear-waste ^{137}Cs above the deep plume shows that only the Denmark Strait overflow water is carrying a measurable signal. The overlying Iceland–Scotland Overflow Water and Labrador Sea Water show ^{137}Cs concentrations and ^{137}Cs:^{90}Sr ratios indicative of bomb-fallout origin.

It is worth noting that this deep distribution pattern traces the dispersion of any material originating on the European coastal shelves that is propagated into the deep North Atlantic. Therefore, it is likely that this represents one of the routes by which environmental contaminants from industrial activity in Western Europe are being introduced into the abyssal ocean.

The inverse correlation of the tracer signal with salinity raises an interesting question in connection with the freshening trend in the deep North Atlantic mentioned earlier in this section. Swift (1984*b*) speculated that this phenomenon might have been caused by wind-forcing shifts, allowing the incorporation of relatively more low-salinity surface water into the overflows. He suggested the East Greenland Current as a potential candidate. Given the finding that the low-salinity plume is accompanied by a ^{137}Cs-rich tracer signal, rather than by a tritium or ^{90}Sr-rich signal, which would signal an East Greenland Current component, the

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possibility emerges that we are witnessing a freshening originating in proportionately more low-salinity shelf water from the Norwegian side mixing into the water overflowing the sill at Denmark Strait. The absence of nuclear-waste ^{137}Cs in the Iceland–Scotland Overflow Water may be also relevant to this point but may reflect the longer surface–deep water path lengths, dilution patterns, and transport times for the formation of this water mass.

5. Atlantic water circulation in the Arctic basins

The Atlantic water in the Arctic basins is typically characterized by a temperature maximum. It is generally viewed as being fed by the warm and salty inflow of the West Spitzbergen current through Fram Strait. This current has a complex input, splitting into several branches on the basis of the bathymetry of the Yermak Plateau (Perkin & Lewis 1984), and recirculation with short-circuited return flows southward in the Fram Strait region (Quadfasel *et al.* 1987). Those branches of the current that enter the Arctic basin are subsequently found to be below the southward-bound, fresh and cold polar water that feeds the East Greenland Current. The core of the Atlantic water, as defined by the temperature maximum, is found to be at progressively greater depths and with lower temperature maxima as its transit through the Arctic Basin is followed. This is generally believed to follow a broad anticlockwise trajectory, ending up at the western side of Fram Strait as relatively old water relative to its time of inflow to the Eurasian Basin.

If this was the only mechanism whereby Atlantic water circulated in the basin, one would expect that a tracer maximum would be found to correspond with the temperature maximum for those types of tracer having an input with the Atlantic water. For Cs and Sr isotopes, this should be seen as an older fallout-characterized signal, followed by a later nuclear-waste derived signal. This scenario seems to be met at locations near the inflow, e.g. at the stations PS-325 (1984) and FRAM-4 (1983) in figure 1. At these, as seen in figure 5*a*, *b* (and at other stations in the area (Casso *et al.* 1988)) the inflowing water is characterized by a high ^{137}Cs concentration and a high ^{137}Cs:^{90}Sr ratio at the temperature maximum.

Only four stations (figure 1) have been occupied at interior Arctic locations where the lower temperature maxima imply a significant time interval since their Atlantic cores passed north of Fram Strait. The stations are as follows.

(1) LOREX (Lomonosov Ridge Experiment), an ice station near the North Pole occupied in 1979, at which the first Arctic Cs and Sr isotope profile was measured (Livingston *et al.* 1984). Situated at the Lomonosov ridge, it is expected to be a location at which one would find Atlantic water that had travelled around the basin boundary and back across the mid-ocean ridge.

(2) CESAR (Canadian Expedition to Study the Alpha Ridge), another ice station (1983) over the Alpha Ridge where the low-temperature maximum led to an expectation of relatively old Atlantic water, especially with its location being away from the dynamically active basin boundaries.

(3) AIWEX (Arctic Internal Wave Experiment). This 1985 ice station in the Canadian Arctic was sampled for Cs and Sr isotopes in the expectation that it would act as a representative of a location where the ventilation predated the nuclear-waste ^{137}Cs signal, an erroneous expectation as will be noted.

(4) PS-331. This 1984 station from the POLARSTERN Arktis II-3 cruise sampled very old

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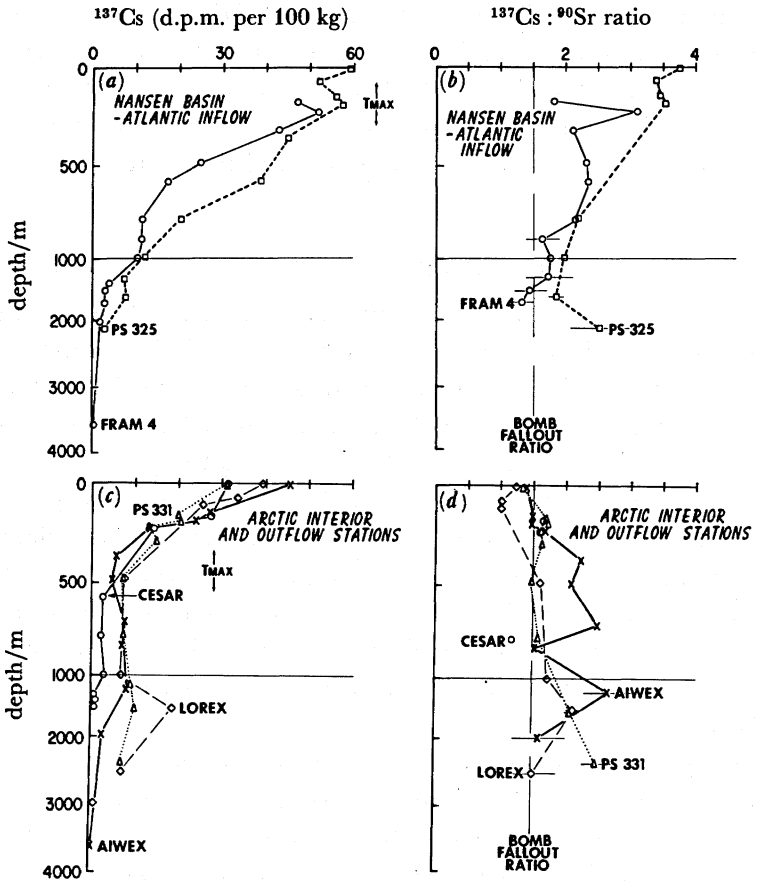

FIGURE 5. (*a*) Concentration profiles of ^{137}Cs at Atlantic inflow stations POLARSTERN-325 and FRAM-4. (*b*) Ratios of ^{137}Cs:^{90}Sr at above station. (*c*) Concentration profiles of ^{137}Cs at interior Arctic and Atlantic outflow stations. (*d*) Ratios of ^{137}Cs:^{90}Sr at above stations. Where error bars are not indicated in the figure, measurement errors are comparable with, or less than, symbol size.

Arctic basin water, assumed to have taken 'the Grand Tour' around the Arctic basins before moving southwards through Fram Strait.

At none of these four stations is there any suggestion of a tracer maximum corresponding to the temperature maximum (figure 5*c*). This trend also characterized other anthropogenic tracers when they were measured at these stations (Östlund 1982, 1985; Östlund *et al.* 1987; Smethie in Swift 1984*c*; Top 1984). In fact, when the patterns of the ^{137}Cs:^{90}Sr ratio with depth are examined (figure 5*d*), there is a trend of increase in ratio with depth in the lower Atlantic water and deeper layers at the AIWEX, LOREX and PS-331 stations. Only at the AIWEX station is the Atlantic core characterized with water with ^{137}Cs:^{90}Sr ratios higher than the typical fallout value of 1.5. The discussion of these various features properly belongs in the final section.

6. SHELF VENTILATION OF THE ARCTIC BASINS

In recent years there have been various suggestions that the formation and export of cold and saline water by brine rejection during freezing on the broad Arctic shelves may be an important process in regard to ventilation of the basin interior. Initially this process was proposed for halocline ventilation (Aagaard *et al.* 1981). Subsequently, this idea was extended to the deeper

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water masses (Aagaard *et al.* 1985). In fact, the possibility of deep-water penetration by shelf waters was raised by the failure of a model developed for the Arctic halocline to simulate properties below 200 m (Killworth & Smith 1984). Aagaard *et al.* (1985) noted that in the Eurasian Basin the shelf waters are already saline because of their Atlantic origin and can become denser through cooling alone, without the need to invoke a brine rejection mechanism. Both processes may contribute to a range of dense waters available for off-shelf ventilation and the Barents Sea has been cited as a potential site for ventilation water formation. Midttun (1985) has described the observation of bottom water more saline than 34.95‰ and near the freezing point in channels north of Novaya Zemlya that connect with channels to the Arctic Ocean from the Barents and Kara Seas. Samples collected in September 1985 in this same region confirm that water formed there is carrying a strong tracer signal from the southern nuclear-waste source. In figure 6, ^{137}Cs concentrations measured in bottom-water samples are plotted. The corresponding surface values are somewhat higher (Casso *et al.* 1988). Both the high values and the ratios of ^{137}Cs:^{90}Sr in the 3–5 range reinforce the expectation that this signal will provide a unique and readily detectable tracer for water of shelf origin found in the deep Arctic basins. Hence this offers a powerful tool for studying the process of deep Arctic ventilation from the Eurasian shelf. The pattern of Cs and Sr distribution and their ratios to each other at the various locations indicated on figure 4 speak to this ventilation hypothesis.

The observations made in 1979 at the LOREX ice-station near the North Pole (Livingston *et al.* 1984) provided the first clue that shelf ^{137}Cs and ^{90}Sr signals were being rapidly transmitted into the Arctic Ocean interior. At that time, the sampling was limited and the only unequivocal signal seen was the high ^{137}Cs concentration and ratio of ^{137}Cs:^{90}Sr at 1500 m, on the Eurasian side of the Lomonosov ridge. The LOREX data are reproduced in figure 5*c*, *d* and serve as a contrast and comparison with the data for the other Arctic interior or outflow stations.

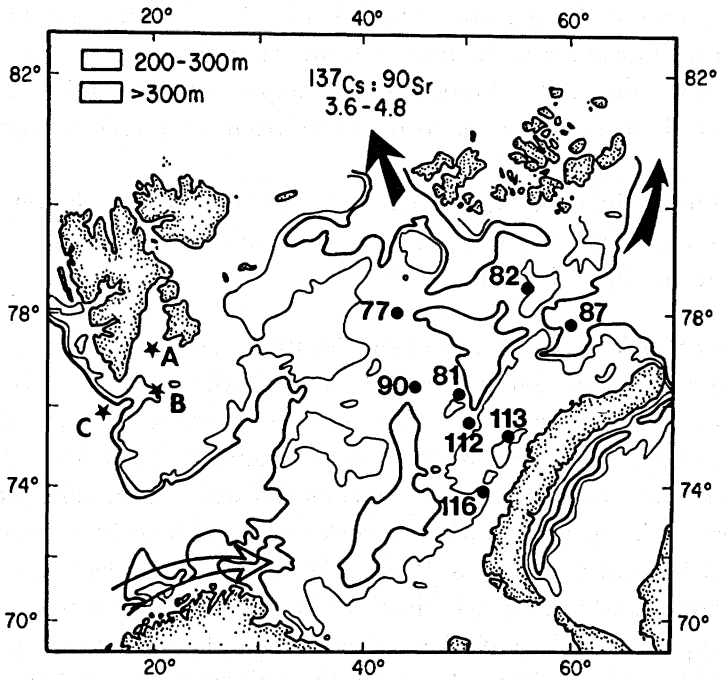

FIGURE 6. Concentrations of ^{137}Cs in September 1985 in bottom water in the eastern Barents Sea (in units of d.p.m. per 100 kg).

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As noted in the previous section, there is no evidence at these stations of a nuclear-waste signal advected directly with the core of the Atlantic water, as defined by the temperature maxima. With the exception of the data from the CESAR station, at all three other locations there is a significant trend of increase in $^{137}Cs:^{90}Sr$ ratio with increasing depth below the Atlantic core (figure 5*d*). At the Canadian Basin station (AIWEX), 500 km north of Prudhoe Bay, there is also a trend of increasing ^{137}Cs concentration with depth, at least to about 1200 m. The absence of any nuclear-waste signal below 1500 m suggests that the Lomonosov ridge sill at that depth may have prevented deeper water, bearing the tracer signal, from moving into the Canadian Basin from the Eurasian side. Otherwise, the pattern with depth is consistent with that observed previously at the LOREX station. The data from all the profiles sampled at the AIWEX station suggested that this location was characterized by water with fairly high dynamic properties with decadal scale renewal times at mid-water depths (Swift *et al.* 1987). The CESAR station data show very low Cs and Sr isotope signals and no indications of any source except bomb fallout. The location on the Alpha Ridge must represent a central basin situation where the ventilation rate is relatively slow.

Finally, the data from the POLARSTERN Arktis II-3 station 331 are relevant to the shelf-ventilation question. The water sampled at this station had properties in the Atlantic layer that implied long residence in the Arctic Basin (Swift 1984*c*). At greater depths both the hydrographic properties and the chlorofluoromethan tracer data (Smethie *et al.* 1987) were indicative of Arctic Ocean Deep Water before its proposed passage into the northern Greenland Sea to act as a parent water mass for Norwegian Sea Deep Water (Swift & Koltermann 1988) after mixing with Greenland Sea Deep Water. The ^{137}Cs concentrations at this station (figure 5*c*) reflect bomb-fallout origins in the Atlantic core, as evidenced by their $^{137}Cs:^{90}Sr$ ratios at these depths (figure 5*d*). Below this depth, ^{137}Cs concentrations pass through a maximum at about 1500 m thus at a depth where the salinity of 34.925‰ is evidence of the presence of Arctic Ocean Deep Water. Furthermore, the ratio of $^{137}Cs:^{90}Sr$ increases across this depth and reaches a maximum value of 2.5 in the near-bottom water. These deep-water trends, especially at depths greater than the 1500 m Lomonosov sill depth, provide indications that ventilation of these deep layers is being observed to originate from such shelf locations as the Barents Sea.

In the Arctic Ocean in general, these indications of shelf ventilation seem to be more pronounced than lateral advective ventilation with the propagation of inflowing Atlantic water coming into the Arctic through Fram Strait.

Much effort went into sampling at remote locations. Special mention and thanks go to R. M. Moore (LOREX), R. M. Moore and D. W. R. Wallace (CESAR), G. C. Anderson and J. H. Swift (AIWEX), P. J. Stern and A. Baggeroer (FRAM-IV), Lars Midttun and the officers and crews of R. V. *Knorr*, R. V. *Polarstern*, and R. V. *Michael Saars*. These were major group efforts and would not have been achieved without the skill and dedication of all these people. Likewise, in the laboratory, the work would not have been completed without the expertise and hard work of S. A. Casso, W. R. Clarke, J. M. Palmieri, and L. D. Surprenant, as is true for the secretarial skills of M. Hess. All of this assistance was greatly appreciated.

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Discussion

P. D. Killworth (*Hooke Institute, University of Oxford, U.K.*). The sinking of dense brine from central Arctic shelves presents a great problem for dynamicists. No 'plume' model has succeeded in moving water even a fraction of the total depth.