An investigation of deep water mass formation in the Greenland and Norwegian Seas using ^{85}Kr and tritium as tracers

Extended abstract

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^{85}Kr is a radioactive inert gas with a half-life of 10.76 years. It forms when uranium undergoes fission and its concentration in the atmosphere prior to the nuclear age was extremely low. The major sources to the atmosphere at present are nuclear weapons testing, nuclear power plants, and plutonium production for nuclear weapons. Its concentration in the atmosphere increased rapidly during the 1960s when there were both nuclear weapons testing and an increasing number of nuclear power plants, but during the 1970s its rate of increase slowed down (Fig. 1). Since the early 1980s, there has been a rise in the rate of increase. Most ^{85}Kr produced is injected into the northern hemisphere troposphere and then mixes throughout the troposphere. ^{85}Kr enters the ocean by gas exchange with an equilibration time of approximately 1 month (Broecker et al. 1980) and it is conservative in the ocean, except for its radioactive decay. Tritium in the form of water, HTO, was introduced into the global environment mainly during 1962 and 1963 by atmospheric nuclear weapons testing. It was injected into the northern hemisphere and has entered the ocean mainly in the northern hemisphere by precipitation, water vapour exchange, and river runoff. In the ocean, it is conservative except for its radioactive decay (12.44 year half-life).

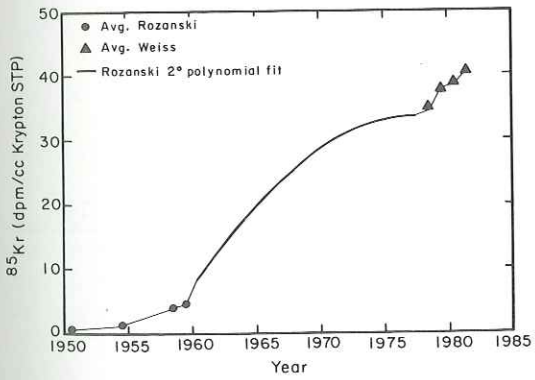

Fig. 1. Krypton-85 atmospheric time history in the northern hemisphere. ● annual mean (Rozanki, 1979) in the northern hemisphere. — 2° polynomial fit to all reported atmospheric measurements in the northern hemisphere (Rozanki, 1979). ▲ annual mean (Weiss et al. 1983) in the northern hemisphere.

During the North Atlantic Study of the Transient Tracers in the Ocean (TTO) programme, the distributions of ^{85}Kr and tritium were measured in the Greenland and Norwegian Seas. Station locations are given in Figure 2 and the data are presented as vertical sections in Figure 3. The ^{85}Kr and tritium distributions are similar. The concentration in the deep Greenland Sea is high relative to the concentration in the deep

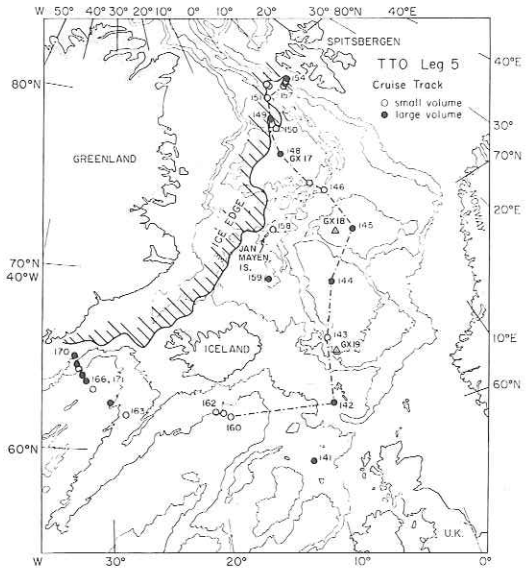

Fig. 2. Station location map for TTO and GEOSECS (GX) stations in the Greenland and Norwegian Seas. Stations where ^{85}Kr and tritium data were collected are shown in Fig. 3.

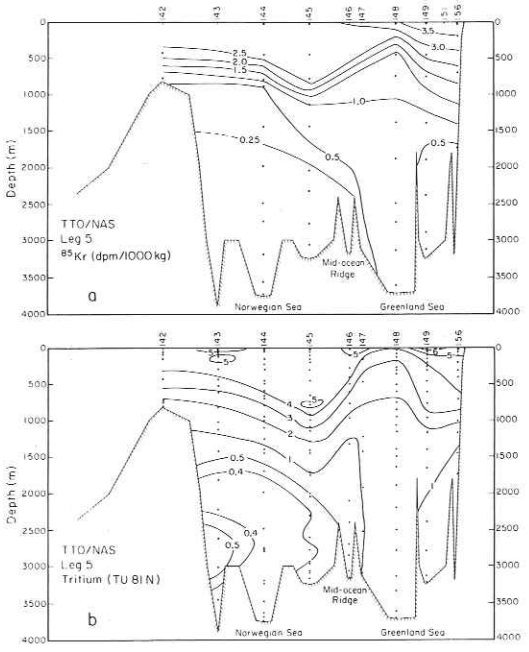

Fig. 3. a) Vertical section of krypton-85 (dpm/1000 kg) and b) tritium (TU 81 N) in the Norwegian and Greenland Seas from the TTO/NAS expedition.

Norwegian Sea and the isopleths dome near the surface within the Greenland Sea gyre.

We have used these data in a box model (Fig. 4) to estimate ventilation rates for the deep Greenland and Norwegian seas. The high tracer content of the deep Greenland Sea is apparently the result of deep convection in the Greenland gyre during winter. This convection is represented as volume transports of equal magnitudes between the surface and deep Greenland Sea, T_1. Greenland Sea Deep Water (GSDW) is denser than Norwegian Sea Deep Water (NSDW) and thus flows into the Norwegian Sea. However, NSDW is more saline than GSDW and therefore, must be a mixture of GSDW and a saltier component. Swift et al. (1983) have pointed out that deep Eurasian Basin water has the proper temperature and salinity characteristics to mix with GSDW on a 50:50 basis to form NSDW. Although the exact mechanism of the formation of NSDW is not known at this time, for our modeling effort we have assumed that NSDW is a 50:50 mixture of GSDW and deep Eurasian Basin water. The volume transports have been defined accordingly, i.e. the transport from the deep Greenland

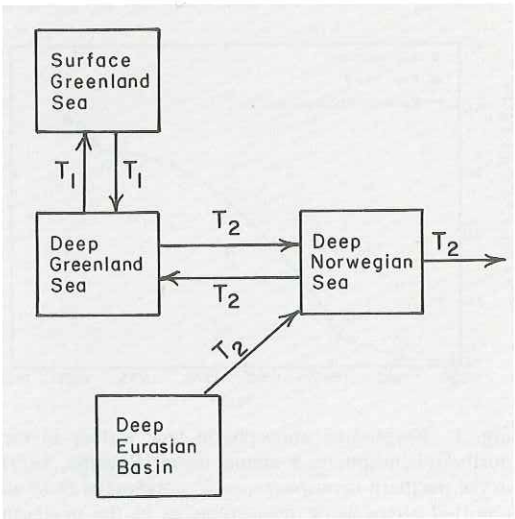

Fig. 4. Schematic diagram of the Greenland-Norwegian Sea two-box model.

Sea to the deep Norwegian Sea is equal to the transport from the deep Eurasian Basin to the Norwegian Sea. The deep Eurasian Basin probably receives its water from the deep Norwegian Sea and from dense continental shelf water (which forms by brine rejection during sea ice formation) flowing into the deep portion of the basin.

The model is a time dependent two-box model with tracer concentrations specified for the surface Greenland Sea as a function of time. The equations describing the tracer concentration for the deep Greenland Sea and the deep Norwegian Sea are:

$$\frac{dC_1}{dt} = \frac{T_1 (C_0 - C_1) + T_2 (C_2 - C_1)}{V_1} - \lambda C_2 \quad (1)$$

and

$$\frac{dC_2}{dt} = \frac{T_2 (C_1 + C_3 - 2C_2)}{V_2} - \lambda C_1 \quad (2)$$

where C_0, C_1, C_2 and C_3 are respectively tracer concentrations in the surface Greenland Sea, the deep Greenland Sea, the deep Norwegian Sea and the deep Eurasian Basin, T_1 is the volume transport between the surface and deep Greenland Sea, T_2 is the volume transport between the deep Greenland and deep Norwegian Seas and between the deep Eurasian Basin and the deep Norwegian Sea, V_1 is the volume of the deep Greenland Sea (5.73×10^5 km^3 below 1700 m), V_2 is the volume of the deep Norwegian Sea (8.63×10^5km^3 below 1700 m), t is time, and λ is the radioactive decay constant. The volumes were calculated from an areal hypsography diagram for the Greenland and Norwegian seas presented in Aagard et al. (1985).

The time dependent ^{85}Kr content of the surface Greenland Sea was calculated from the ^{85}Kr atmospheric time history (Fig. 1) and the solubility of krypton (Weiss and Kyser 1978) at winter temperature (−1.2°C) and salinity (34.8‰). The surface water was assumed to be in equilibrium with the atmosphere. For tritium, Driesigacker and Roether's (1978) time history for the North Atlantic between 20° and 60°N was used, but it was adjusted to fit tritium measured in Greenland Sea near surface water during GEOSECS (Fig. 5). It was also linearly extended to pass through TTO tritium measurements for the near surface Greenland Sea.

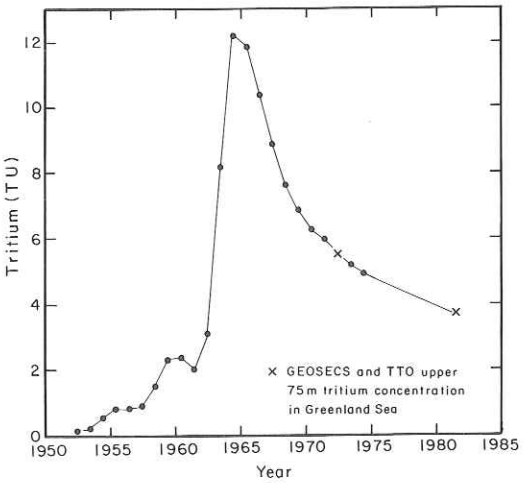

Fig. 5. Tritium time history in the surface Greenland Sea. This was produced by multiplying Driesigacker and Rother's (1978) data for the North Atlantic by 0.69 which forced their temporal trend through the Greenland Sea GEOSECS observation in 1972.

There is very little tracer data for the deep Eurasian basin. One of us (Smethie) has measured chlorofluoromethanes (CFM) on samples collected north of the Fram Strait (82.5°N, 6.5°W) in the summer of 1984 and found that the CMF content of Eurasian Basin deep water at this location is similar to that observed by Bullister and Weiss (1983) in the deep Norwegian Sea in 1982. Also the tritium concentration in the deep water at the Fram III ice station (81°N, 10°E) (Östlund et al. 1982) is similar to that observed in the deep Norwegian Sea during TTO. Therefore, we have assumed that the tracer content of the deep Eurasian Basin is equal to the tracer content of the deep Norwegian Sea, i.e. $C_2 = C_3$.

Equations 1 and 2 were solved numerically with the boundary conditions: C_0 specified as a function of time and $C_0 = 0$ at $t = 0$. The starting point for the model, i.e., $t = 0$, was 1945. Iterative solutions were obtained, varying T_1 and T_2 until C_1 and C_2 matched the observations.

The results of the model runs are summarized in Table 1. The volume transports required to fit the ^{85}Kr observations in 1981 are $T_1 = 0.52$ Sv and $T_2 = 1.33$ Sv. The corresponding residence times are 34.9 years for the deep Greenland Sea (V_1/T_1) and 20.6 years for the deep Norwegian Sea (V_2/T_2). The tritium content of the deep Greenland and Norwegian Seas has been measured at two points in time, GEOSECS in 1972 and TTO in 1981. The model would not fit both sets of observations with constant volume transports. However, by using different transports for the 1945–1972 period and the 1972–1981 period, a fit could be obtained. The volume transports obtained from the model are $T_1 = 0.45$ Sv for 1945–1972, 0.67 Sv for 1972–1981 and $T_2 = 0.50$ Sv for 1945–1972, 1.50 Sv for 1972–1981. Using these volume transports for ^{85}Kr, the model predicted higher ^{85}Kr concentrations than were observed (Fig. 6). But, the ^{85}Kr observations could be fit if the surface water of the Greenland Sea was at 90% equilibrium with the atmosphere instead of 100%.

TABLE 1

Box model results for ventilation rates of the deep Greenland and Norwegian Seas.

	Tracer	*1945–1981*	*1945–1972*	*1972–1981*
T_1	^{85}Kr	0.52 Sv	—	—
τ_1	—	34.9 years	—	—
T_2	—	1.33 Sv	—	—
τ_2	—	20.6 years	—	—
T_1	Tritium	—	0.45 Sv	0.67 Sv
τ_1	—	—	40.3 years	27.1 years
T_2	—	—	0.50 Sv	1.50 Sv
τ_2	—	—	54.9 years	18.3 years

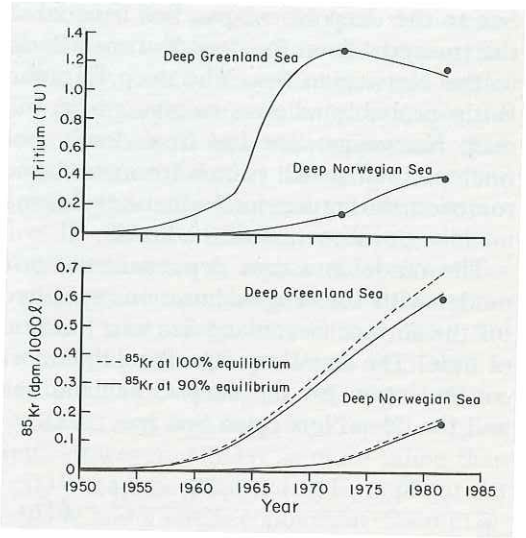

Fig. 6. Simulated time histories of tritium and krypton-85 in the deep Greenland and Norwegian Seas calculated from the two-box model.

This is certainly possible. It has been postulated that during periods of deep convection, which occurs in the Greenland Sea, water would be advected to the surface and then advected back downward before complete equilibration with the atmosphere could occur. Also, surface water undersaturated with respect to oxygen was observed in the Greenland Sea in the late winter of 1982 (J. Swift, personal communication).

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