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ON THE BALANCES OF ^{90}Sr AND ^{137}Cs IN THE BALTIC SEA

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The total amounts of ^{90}Sr and ^{137}Cs that accumulated in the water of the Baltic Sea in the years 1960–67 are estimated on the basis of 10–15 samples collected annually in different parts of the Baltic Sea. The changes found in the amounts are compared with evaluated effects of decreasing and increasing processes.

The concentrations of ^{137}Cs and ^{90}Sr in sea water samples collected from different parts of the Baltic Sea (see Fig. 1) during the years 1960–67 were determined. Using these data, the total quantities of these radionuclides in the Baltic can be roughly estimated. The amounts of the same nuclides deposited on Finnish land and their concentrations in the largest rivers were also measured. Together with other available information, our data render it possible to discuss the balances of these nuclides in the Baltic.

The origin data on the Finnish determinations of radionuclides in water were published earlier (Paakkola & Voipio 1965, Salo & Voipio 1966, Salo 1966, 1967, 1968).

The total amount of each radionuclide in the Baltic Sea was calculated by multiplying the concentrations in different water masses by the volumes of the latter. The volumes used were:

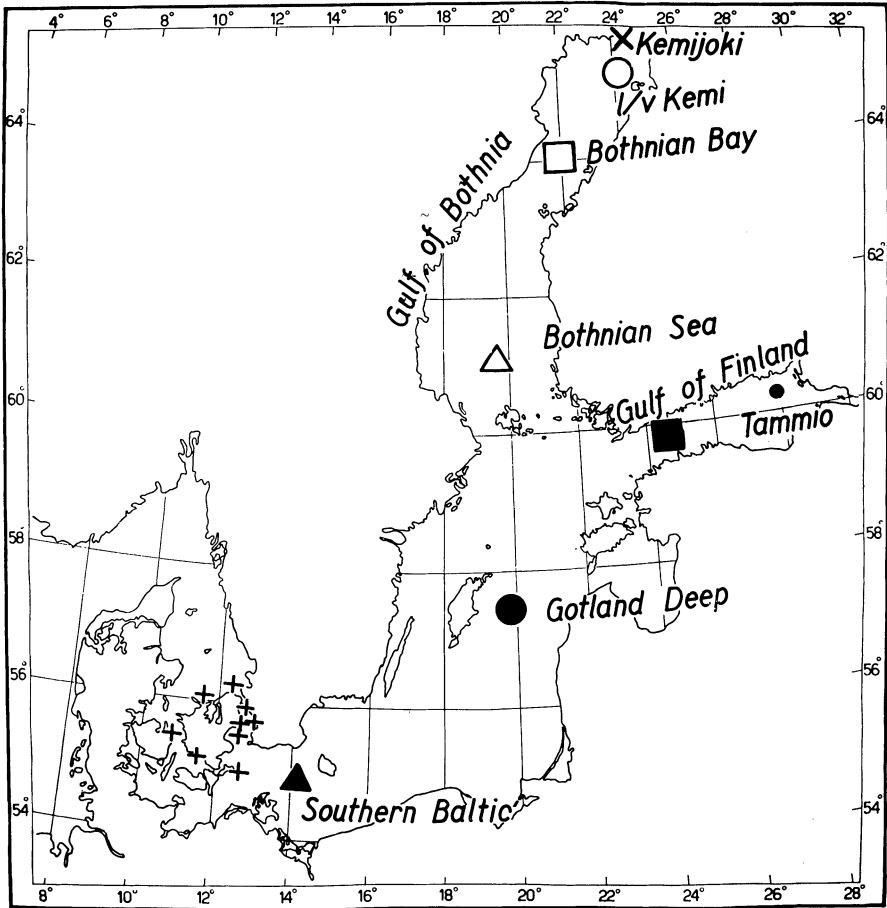


Fig. 1.
The sampling stations.

	km ³
Bothnian Sea	1,500
Bothnian Bay	5,200
Gulf of Finland, above halocline	900
below halocline	200
Baltic Proper, above halocline	10,000
below halocline	3,500
	<hr/>
	21,300

On the Balances of ⁹⁰Sr and ¹³⁷Cs in the Baltic Sea

The water balance of the Baltic Sea is given by the equation (cf. Brogmus 1952):

$$\begin{array}{cccccc}
 \text{Runoff} & & \text{Precipitation} & & \text{Inflow} & = & \text{Outflow} & + & \text{Evaporation} \\
 500 \text{ km}^3 & + & 200 \text{ km}^3 & + & 500 \text{ km}^3 & = & 1,000 \text{ km}^3 & + & 200 \text{ km}^3
 \end{array}$$

Because the errors in the radionuclide determinations are of the order of 10–20 per cent, rather rough values were used for the other data.

The material balance for the Baltic Sea can be described by a general equation of the form:

$$c_P V_P + c_R V_R + c_I V_I - c_O V_O - c_E V_E - D + G + B = A$$

where A is the net change in the total amount of a single radionuclide, c is the radionuclide concentration, and the V the water volume in the following steps in the hydrological cycle: precipitation (P), runoff (R), inflow through the Danish Sounds (I), outflow through the Sounds (O), and evaporation (E). The decrease due to physical decay is given by D , and the other quantities are the changes in the radionuclide concentrations caused by geochemical (G) and biological (B) processes.

As far as the present authors know, there are no significant sources of the radionuclides in the studied area other than atmospheric deposition on land and sea surface.

To start with, we assumed that the changes due to geochemical and biological processes are of minor importance compared with the other terms in the balance equation. Also the term representing evaporation can be neglected in the case of strontium and caesium.

Because of insufficient data, the amount of precipitation multiplied by its nuclide concentration did not prove useful in the evaluation of the direct deposition on the sea surface. For instance, the distribution of rainfall at open sea is quite uneven and not known in detail (Simojoki 1949, Brogmus 1952). Local differences in radionuclide deposition per unit area, however, are rather small. For example, the total amounts of ⁹⁰Sr deposited during 1962 in Denmark (Risø), Norway (Oslo), Germany (Hannover and Berlin), and Finland (17 stations) were 5.9, 5.6, 5.9 and 6.7 microcuries per sq. kilometer, respectively (Cambray et al. 1963, 1964, Seelentag 1963, Aarkrog et al. 1963, Salo 1966). Therefore, the deposition on the sea surface was estimated by multiplying the area of the Baltic Sea, 365,000 km², by the deposition values observed in Finland. Since the sea water samples were collected in June–July, mean deposition values for the twelve preceding months were used.

For evaluating the term representing runoff, there are no detailed observations on the nuclide concentrations in rivers discharging into the Baltic Sea or on the total runoff in different years. On the other hand, the annual fluctuations in runoff around the northern parts of the Baltic Sea are fairly small due to the high lake percentages there. The unconsolidated sediments in the countries around the southern parts through which the rivers flow do not differ much from those in Finland. For these reasons, the mean discharge of 500 km³/year and the nuclide concentrations found in the Finnish rivers were used to evaluate the amounts of nuclides carried by the runoff.

The amounts of strontium-90 transported by the inflow of 500 km³/year through the Danish Sounds were evaluated both from Danish values (Aarkrog et al. 1962–68) and from our own data. The amounts of caesium-137 were evaluated partly from our own data and partly by means of the Cs/Sr ratio. In the latter case, a ratio of 1:2 was used because the saline water flowing into the Baltic Sea is a mixture of ocean water with a Cs/Sr ratio of 1.6 and Baltic surface water with a ratio usually somewhat less than 1.0 and because according to salinity values (Brogmus 1962), the ratio of ocean water to Baltic surface water in the mixed water is about 1:2. The mean ratio calculated from our observations agrees well with the used ratio of 1:2 (Salo & Voipo 1966).

The amounts of nuclides transported by the outflow through the Danish Sounds were evaluated from the nuclide concentrations found in the surface waters of the southern Baltic and the Danish Sounds, and the mean outflow.

The calculated values of the terms included in the balance equation are given in Table 1. The net increases in the total amounts of the nuclides calculated from the sea water analyses, i. e. the values of *A*, are shown in Fig. 2. In the same figure "predicted values" are also plotted, the values of *A* in 1961 plus the sums of terms estimating the effects of deposition, runoff, inflow, outflow, and physical decay.

From the diagram in Fig. 2, it can be seen that, except those for 1967, the strontium-90 values agree fairly well. The difference in 1967 may be due to analytical errors which may have been in opposite directions in 1966 and 1967. With regard to caesium-137, the differences are somewhat larger. Up to 1965, for which there is a large deviation, the observed increases in the total amounts agree well with the values predicted on the basis of the data for deposition, runoff, inflow and outflow. There is almost a constant difference between the observed and predicted values for the last two years.

Our preliminary bottom sediment analyses give direct evidence for the minor importance of any rapid geochemical process of removal of these nuclides, especially of strontium-90, from the Baltic Sea water. Even in sediment samples taken near river mouths, only 0.4 – 2 mCi/km² of strontium-90 and 4 – 30 mCi/

Table 1.
Strontium-90 and caesium-137 balances in the Baltic Sea

Year	Total storage (A)	Annual change of A (Δ)	Deposi- tion (P)	Runoff (R)	Inflow (I)	Outflow (O)	Decay (D)	P+R+I+ O+D $\equiv \Delta'$	$\Delta - \Delta'$	$100 \frac{\Delta - \Delta'}{A}$
	Ci	Ci	Ci	Ci	Ci	Ci	Ci	Ci	Ci	%
⁹⁰ Sr										
1960	5.650									
1961	7.700	2.050								
1962	8.500	800	1.550	350	250	- 500	- 200	1.450	- 650	- 7.6
1963	11.650	3.150	2.650	350	400	- 800	- 200	2.400	+ 750	+ 6.4
1964	16.000	4.350	4.200	1.050	450	- 900	- 300	4.500	- 150	- 0.9
1965	18.350	2.350	1.450	900	500	-1.000	- 400	1.450	+ 900	+ 4.9
1966	17.200	- 850	750	700	350	- 900	- 450	450	- 1.300	- 7.6
1967	20.600	3.400	450	700	350	- 800	- 400	300	+ 3.100	+15.0
¹³⁷ Cs										
1960	5.300									
1961	8.200	2.900								
1962	10.300	2.100	2.450	200	300	- 700	- 200	2.050	+ 50	+ 0.5
1963	17.000	6.700	4.250	250	600	- 900	- 250	3.950	+ 2.750	+16.2
1964	20.350	3.350	5.800	450	550	-1.200	- 400	5.200	- 1.850	- 9.1
1965	(16.000)	(-4.350)	2.500	250	500	- 1.100	- 450	1.700	(- 6.050)	(-37.8)
1966	20.100	(+4.100)	1.150	200	450	- 1.100	- (350)	350	(+ 3.750)	(+18.7)
1967	20.100	-	600	150	400	- 900	- 450	-200	+ 200	+ 1.0

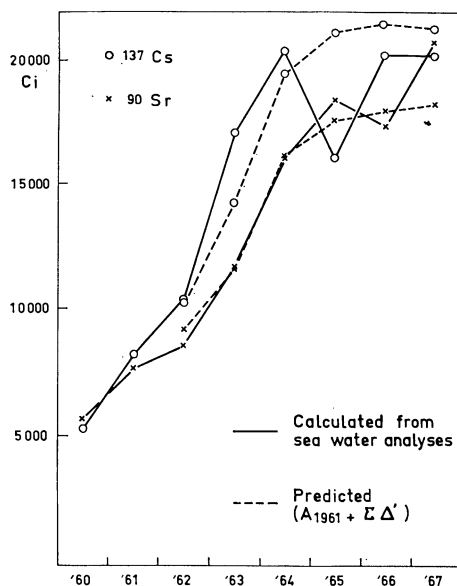


Fig. 2.

The total amounts of ^{90}Sr and ^{137}Cs accumulated in the Baltic Sea. Δ' is the sum of terms estimating the effects of deposition, runoff, inflow, outflow, and physical decay.

km^2 caesium-137 were found; the upper limits refer to coastal waters with limited water exchange, such as semi-enclosed embayments and separate basins.

If we assume a mean deposition on the sea floor of 0.5 mCi/km^2 of strontium-90 and 5 mCi/km^2 of caesium-137 and multiply these values by the surface area of the Baltic Sea, total amounts of about 200 Ci of strontium and 2000 Ci of caesium are obtained. Thus, 1 per cent the strontium and 10 per cent of the caesium would be deposited in the bottom sediments. In the case of strontium, the balance calculation could hardly be expected to reveal such a small removal of strontium from the water, but in the case of caesium, as seen in Fig. 2, the difference between the predicted and observed amounts in the two last years is also of the order of 10 per cent.

The estimated balance of strontium-90 based on the present data is in accordance with the known fact that the strontium concentration is a conservative property of sea water. The above estimate does not indicate any rapid removal of caesium-137 from Baltic Sea water by geochemical or biological processes.

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