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MARINE CONTAMINATION IN THE ARCTIC OCEAN

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Abstract

Research is being conducted to clarify a situation concerning the dumping of nuclear submarines, etc. into the Arctic Ocean by the former Soviet Union. Waters in the dumping areas are very shallow and close to land. Flow analysis which was conducted by using observation data (water temperature, salinity) and applying a method for obtaining the exchange flow in such a way that the inter-box input and output of salinity, heat and seawater volume was balanced, made it possible to successfully express the actual flow patterns. Concentration analysis was conducted on the basis of a release scenario with considerations given to nuclide decay, mixing, scavenging and interaction between undersea particles and the bottom sediment layer.

KEYWORDS: *Arctic Ocean, radioactive contamination, concentration calculation*

1. Introduction

Research is underway to clarify a situation concerning the dumping of nuclear submarines, etc. into the Arctic Ocean (Barents Sea and Kara Sea). Recently, joint on-site investigations were also conducted between Norway and Russia. Waters in the dumping areas are very shallow and close to land. This problem has been continuously investigated and researched by a large number of scientists. However, it goes without saying that the behavior of radioactive materials in the seas is deeply related to the marine characteristics of the Arctic Ocean.

Through the establishment of a specialists panel, (Russia, Denmark, United States, England and Japan), IAEA is presently carrying out exposure dose assessments, in addition to the analysis of flows in these seas and the construction of diffusion models.

Using observation data (water temperature and salinity), a research was conducted by applying a method for obtaining the exchange flow in such a way that the inter-box input and output of salinity, heat and seawater volume was balanced. Concentration calculation of radioactive materials was carried out using this exchange flow; taking into consideration the decay of nuclides, mixing (caused by diffusion, upwelling current or settling current) and adsorption or settling due to the interaction between undersea particles and sea-bottom sediments. Prior to making concentration analysis on various nuclides, benchmark sensitivity analysis was conducted on Pu239 using distribution coefficients, the concentration of suspended solids (SS) in

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the ocean, and the settling velocity of suspended load as parameters. The effects of the particle size for each factor on the concentration of nuclides in the seawater and the concentration of sea-bottom soil were studied.

2. Method of Flow Analysis

2.1 Data used

To analyze the diffusion of radionuclides and make an exposure dose assessment by determining the circulation of seawater in these areas in the future, it will be necessary to identify the flow characteristics of the seas. However, little research has been conducted insofar as these sea areas are concerned. Moreover, these sea areas have a peculiar characteristic that in winter most of their surfaces are blocked in by masses of ice, thus little information has been available with respect to the marine characteristics of the seas. Accordingly, available data and past research are considerably limited. In this research, the authors were fortunately able to make special use of data on salinity and water temperature which were observed in these sea areas, and also used information provided by IAEA.

What kind of impacts will the actual dumping of radioactive wastes into the Arctic Ocean have in the future? As the first step of our research, the authors decided to investigate the mechanism of the flow in the Barents Sea and the Kara Sea in the Arctic Ocean according to water temperature and salinity distributions in these seas. Based on the data obtained by NOAA's observations, water temperature and salinity in the range of $64^\circ \sim 85^\circ$ north latitude and $0^\circ \sim 120^\circ$ east longitude were obtained and graphically represented at intervals of 0.1 ℃ and 0.1 ‰ respectively, and were used to examine the marine characteristics of these seas. In the model used here, it is necessary to divide the sea area. The sea area was divided as shown in Fig.1. The sea area covered was divided $4^\circ \times 1^\circ$ horizontally. Also, the sea area was vertically divided into 6 layers (0~50m, 50~100m, 100~200m, 200~500m, 500~900m and 900~2500m). Salinity and water temperature data were given to each box.

2.2 Density Structure of Arctic Seawater

It can be considered that, as its water structure, the Barents Sea has four major water masses ①~④ as shown in Figure 1.

① The Atlantic water mass which enters from the west as a surface-layer current, and Atlantic water mass which enters from the north and northeast with a certain depth from the Arctic water areas
② The Arctic water mass which enters from the north as a surface-layer current
③ The Coastal water mass (entering from the continent)
④ The Barents Sea water mass which stays there after mixing.

The structure of water masses in the Kara Sea is dominated by water inflows from the Arctic Ocean and the Barents Sea as well as by river water inflows. Four major water masses △1~△4 exist in this sea area.

△1 The Barents seawater originating from the Atlantic water with higher water temperature and salinity is supplied from three directions – from the north ; from the northwest between the Franz-Josef Islands and the Novaya Zemlya Islands; and from the southwest through the Kara Strait.

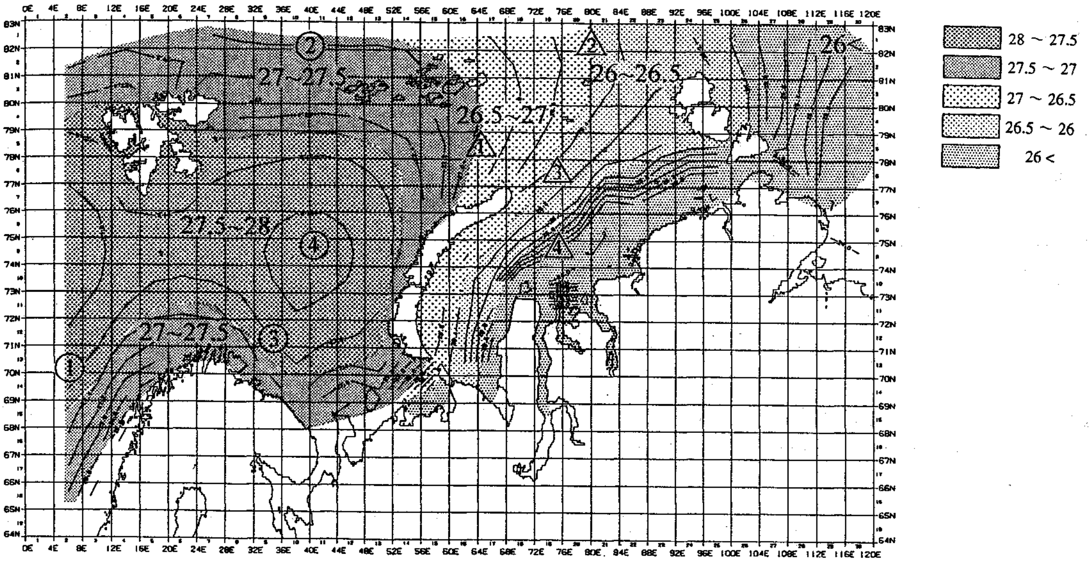


Figure 1. Density distribution $\sigma(s, t, p_{25})$ (density at a depth of 25m)(0~50m layer, warm weather season)

△2 Surface-layer water in the Arctic sea areas

△3 Kara Sea and surface-layer water

△4 Inflow of low-salinity water from the Ob and Yenisey rivers and relatively high-temperature (7~10 ℃) water in summer.

2.3 Method of Flow Analysis

In this research, the method of analysis based on the box (compartment) model was used. Usually, it is also possible to perform flow analysis using the model based on equations of fluid motion, equation of continuity and equations of diffusion concerning water temperature and salinity. However, the authors decided to use the box (compartment) model because it can establish boundary conditions easily and offers more natural features. The model is considered to be suitable to determine the flow field if high-quality observation data (water temperature, salinity, meteorological data, river inflow conditions) are available.

This model meets the requirements for carrying out longterm material concentration analysis in which the conservation of mass holds not only in each box but also as a whole system. This technique, which is aimed at determining the field of flow corresponding to the actual field of density . In groups of equations, the number of unknown variables and the number of equations do not necessarily agree, and the exchange flow rate must be non-negative. Instead of allowing the three equations of preservation to hold strictly, therefore, the solution with least error obtained.

With respect to each box, three equations of preservation were established. With attention paid to box i, the following equations of preservation were taken into consideration:
(1) Equation of the preservation of seawater mass

$$\sum_{j\neq i} W_{ji}\rho_j - \sum_{j\neq i} W_{ij}\rho_i + \sum_r R_{ri}\rho'_r + P_i - E_i = 0 \quad [\text{ton/s}] \tag{1}$$

Where, $W_{ij} \geqq 0$: exchange flow from box i to box j [m^3/s], ρ_i: density of seawater in box i [ton/m^3], which is obtained by Knudsen's formula, ρ'_r: density of river water [ton/m^3]. R_{ri}: inflow of river water from river r to box i, P_i : precipitation into box i [ton/s], E_i : evaporation from box i to the atmosphere [ton/s].

(2) Equation of the preservation of salinity

$$\sum_{j\neq i} W_{ji}\rho_j S_j - \sum_{j\neq i} W_{ij}\rho_i S_i + \sum_r R_{ri}\rho'_r (S_r - S_i) = 0 \quad [\text{ton/s}] \tag{2}$$

Si : salinity in box i [‰], S'_r : salinity in river r [‰]

(3) Equation of the preservation of heat

$$\sum_{j\neq i} W_{ji}\rho_j T_j C - \sum_{j\neq i} W_{ij}\rho_i T_i C + H_i = 0 \quad [\text{ton/s}] \tag{3}$$

Ti : water temperature in box i [℃], H_i : heat entering from the atmosphere into box i [Mcal/s], C : specific heat of seawater [cal/g • ℃], which is presently set at 1.0.

Linear equations with non-negative condition are converted into least error scheme problem with non-negative condition.

$$\begin{aligned}\in = \sum_i \{ \; & \alpha_i(\text{left side of the equation of the preservation of mass (1) in Box } i)^2 \\ + \; & \beta_i(\text{left side of the equation of the preservation of salinity (2) in Box } i)^2 \\ + \; & \gamma_i(\text{left side of the equation of the preservation of heat in Box } i)^2 \}\end{aligned} \tag{4}$$

Where, $\in$ the error sum of squares, which is a function of exchange flow rate W_{12}, W_{13}, ...

Exchange flow rate can be obtained from making the function $\in$ least, under non-negative condition of W_{ij}. This problem is usually called as NNLS (Non-Negative Least Squares).

2.4 Results of Analysis

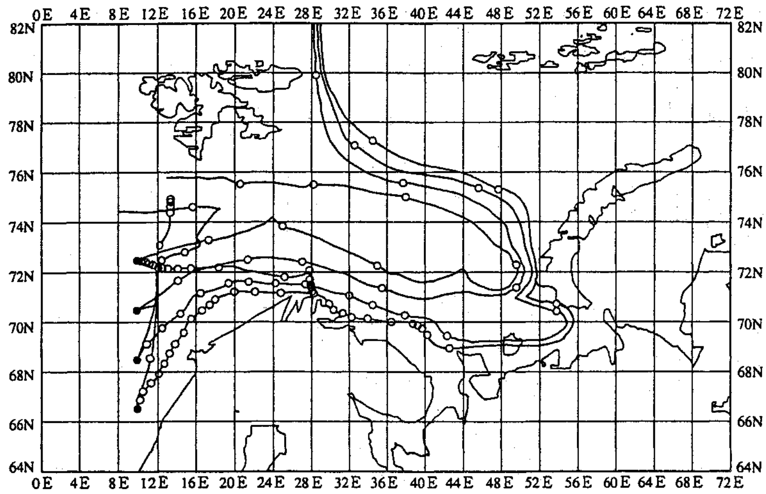
Based on the so-called Lagrangian consideration on the flow velocity obtained from exchange flows in the box model, the tracking of particles from each box and river mouths in the Arctic Seas was performed and the movement of seawater particles was studied.

BARENTS SEA

According to the results of tracking (Fig. 2(1)), the Atlantic water which enters the Barents Sea along the Norwegian Peninsula circulates counterclockwise in the Barents Sea and then flows through the Arctic Ocean and the Norwegian Sea again. The river water flowing out of the Pechora river is connected to this circulation. This flow is in agreement with the conventional known data.

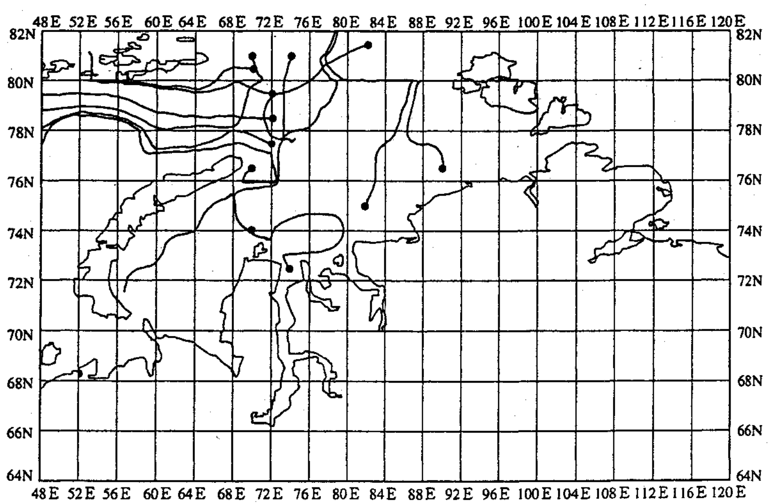
KARA SEA

The northern sea area has a current which enters from the central Arctic Ocean due to the trenches of 80 to 125m deep and the ocean current which flows into the Barents Sea between



• : Particle injection point,
o : Position of particles every 50days)

Figure 2. (1) Results of tracking



• : Particle injection point,
o : Position of particles every 50days)

Figure 2. (2) Results of tracking

the Franz-Josef Land and the Novaya Zemlya Islands. According to the results of tracking (Fig. 2(2)), the aspect of inflow from the central Arctic Sea to the Kara Sea in the second layer (50~100m) and third layer (100~200m) was accurately reproduced.

The western sea area of the Kara Sea has the Novozemelskaya Ocean Current which advances from northeast to southwest along the east coast of the Novaya Zemlya Islands. The tracking results of the model ocean currents are shown in Fig. 2(2). This figure clearly represents that the particles riding on the Novozemelskaya Ocean Current advance southward along the east coast of the Novaya Zemlya Islands.

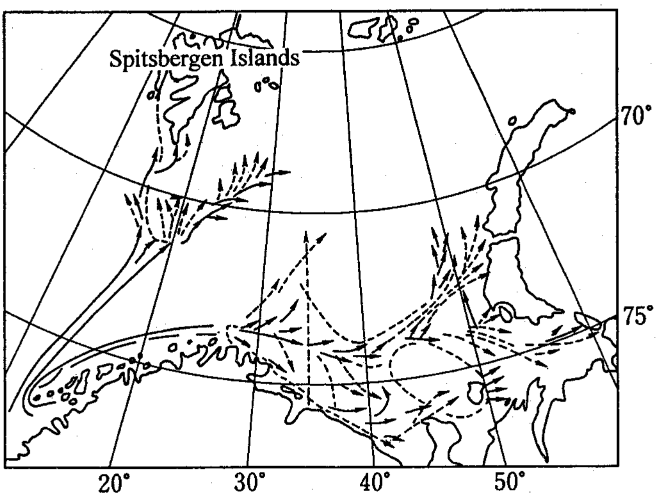


Figure 3. Migration of cods in the Barents Sea (Maslov (1987))

2.5 Results and Considerations

The results of flow analysis were compared with the migration routes of cods. It is generally considered that Haddock cods live in seas of 4 to 10 ℃ in water temperature. The coastal area of the continent and the Atlantic water mass areas with high water temperatures are the sea areas which meet these conditions in the Barents Sea. The migration routes observed are also located in these sea areas, as shown in Figure 3.

The migration routes of cods were compared with the results of flow analysis by the box model Fig.2(1). As a result, high similarity was recognized. Particularly, the route of cods entering the Barents Sea from the coast of Norway and migrating along the continent agrees with the results of the tracking.

3. Diffusion Calculations of Radioactive Materials

3.1 Diffusion Model

The objectives of a model used herein are to calculate the migration and diffusion of radionuclides released into coastal waters, and determine the change of concentrations in each box with the lapse of time, using the results of exchange flow analysis. The undersea behavior factors of radionuclides include (1) decay of nuclides, (2) vertical mixing (due to diffusion, upwelling current or settling current), (3) horizontal mixing (due to diffusion or advection), and (4) adsorption or settling due to the interaction between undersea particles and sea-bottom sediments.

In the ocean, a scavenging mechanism is working, in which the material supplied to the sea surface is transported to a deep layer and sea-bottom sediments. In the present model, an emphasis is placed on this point, as compared with conventional models. The most principle individuals in the scavenging of trace elements in the ocean are organic sedimentation particles, and it is therefore important to precisely elucidate the behavior of these particles.

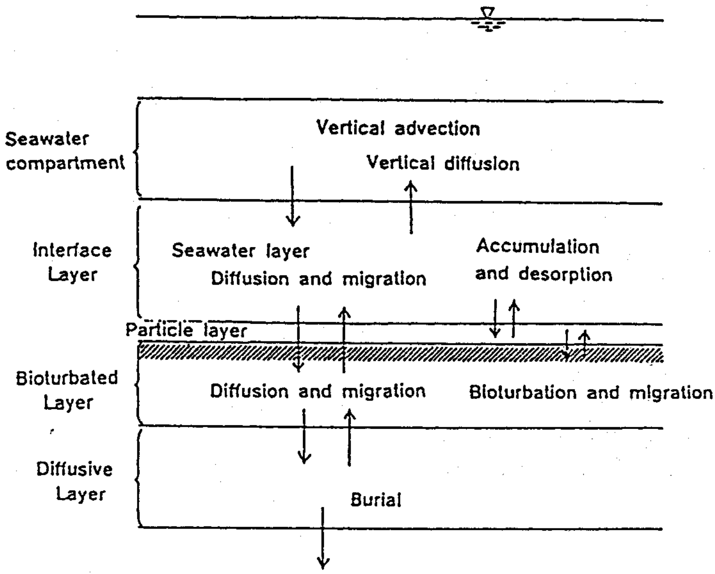


Figure 4. Sea-bottom sediment layer model

Model equations for calculating the concentration of seawater are as follows:
With respect to box i $(i = 1 \sim N)$,

$$\begin{aligned} V_i \cdot dC_i/dt \quad = \quad & -\sum_j W_{ij} \cdot C_i - \sum_j W_{ij} \cdot S_i K_d C_i + \sum_j W_{ij} \cdot C_j + \sum_j W_{ij} \cdot S_j K_d C_j \\ & + \sum_j A_{ji} \cdot K \cdot (C_j - C_i)/L_{ji} - V_i \cdot B \cdot C_i \cdot A_{ui} \cdot V_{down} \cdot S_u K_d C_u \\ & - A_{iL} \cdot V_{down} \cdot S_i K_d C_i \end{aligned} \quad (5)$$

where, C_i : Concentration of nuclides in box i [Bq/m^3] , V_i : Volume of box i [m^3], L_{ij} : Average length between box i and box j [m], length between the centers of boxes, W_{ij} : Exchange flow from box i to box j [m^3/s], S_i : SS concentration in box i [kg/m^3], K_d : Distribution coefficient of nuclides [m^3/kg], B : Decay constant of nuclides [l/s], V_{down} : Mean sedimentation rate of SS [m/s], K: Diffusion coefficient [m^2/s], A_{ij} : Contact area between box i and box j [m^2], N : Number of boxes, Σ refers to boxes other than box i and means summation with respect to all boxes j adjacent to box i, $A_{ui} V_{down} S_i K_d C_u$: Sedimentation from upper layer in adsorbed state (u:box number in upper layer), $A_{iL} V_{down} \cdot S_i K_d C_i$:Sedimentation from bottom in adsorbed state (L:box number in bottom layer).

On the other hand, the behavior of scavenged nuclides in the sea-bottom can be calculated by the model in which the bottom material is divided into 3 layers as shown in Fig.4.

The model is intended to calculate the interaction of 4 layers including the seawater layer (interface layer) in contact with the sea-bottom surface.

1. W-layer (interface seawater layer)
2. P-layer (interface particle layer)
3. B-layer (bioturbated layer)

4. D-layer (diffusive layer)

The changes of radionuclide concentration in three bottom-material layers with the lapse of time can be expressed by the following equations.

1) About box i in W layer (interface seawater layer)

$$V_i \cdot dC_i/dt = +A_{ui} \cdot V_{down} \cdot S_u K_d C_u + A_{ui} \cdot K \cdot (C_u - C_i)/Z_i - V_i \cdot B \cdot C_i - V_i \cdot K_i \cdot C_i + V_L \cdot K_2 \cdot C_L - V_i \cdot \lambda_{d1,3} \cdot C_i + V_k \cdot \lambda_{d3,1} \cdot C_k \quad (6)$$

Where,

Z_1 : Thickness of interface layer (W layer + P layer) [m]
K_1 : Radionuclide sorption rate [l/s]
K_2 : Radionuclide elution rate (desorption rate)[l/s]
$\lambda_{d1,3}$: Transfer rate by diffusion from W layer to B layer [l/s]
$\lambda_{d3,1}$: Transfer rate by diffusion from B layer to W layer [l/s]

2) About box i in P layer (interface particle layer)

$$V_i \cdot dC_i/dt = +V_i \cdot B \cdot C_i + V_u \cdot K_1 \cdot C_u - V_i \cdot K_2 \cdot C_i + V_L \cdot \lambda_{d3,2} \cdot C_L - V_i \cdot \lambda_{d2,3} \cdot C_i - V_i \cdot \lambda_{s2,3} \cdot C_i \quad (7)$$

Where,

$\lambda_{d3,2}$: Transfer rate by diffusion from B layer to P layer [l/s]
$\lambda_{d2,3}$: Transfer rate by diffusion from P layer to B layer [l/s]
$\lambda_{s2,3}$: Burial rate from P layer to B layer [l/s]

3) About box i in B layer (bioturbated layer)

$$V_i \cdot dCi/dt = +V_u \cdot \lambda_{d1,3} \cdot C_u - V_i \cdot \lambda_{d3,1} \cdot C_i + V_k \cdot \lambda_{b2,3} \cdot C_k + V_k \cdot \lambda_{s2,3} \cdot C_k - V_i \cdot \lambda_{b3,2} \cdot C_i - V_i \cdot \lambda_{d3,4} \cdot C_i - V_i \cdot \lambda_{s3,4} \cdot C_i + V_L \cdot \lambda_{d4,3} \cdot C_L - V_i \cdot B \cdot C_i \quad (8)$$

Where,

$\lambda_{d1,3}$: Transfer rate by diffusion from W layer to B layer [l/s]
$\lambda_{d3,1}$: Transfer rate by diffusion from B layer to W layer [l/s]
$\lambda_{b2,3}$: Transfer rate by bioturbation from P layer to B layer [l/s]
$\lambda_{b3,2}$: Transfer rate by bioturbation from B layer to P layer [l/s]
$\lambda_{s2,3}$: Burial rate from P layer to B layer [l/s]
$\lambda_{s3,4}$: Burial rate from B layer to D layer [l/s]

4) About box i in D layer (diffusive layer)

$$V_i \cdot dC_i/dt = -V_i \cdot \lambda_{d4,3} \cdot C_i + V_u \cdot \lambda_{d3,4} \cdot C_u + V_u \cdot \lambda_{s3,4} \cdot C_u - V_i \cdot \lambda_{s4} \cdot C_i - V_i \cdot B \cdot C_i \quad (9)$$

Where,

$\lambda_{d3,4}$: Transfer rate by diffusion from B layer to D layer [l/s]
$\lambda_{d4,3}$: Transfer rate by diffusion from D layer to B layer [l/s]
$\lambda_{s3,4}$: Burial rate from B layer to D layer [l/s]
λ_{s4} : Burial rate in D layer [l/s]

Table 1. Sensitivity Analysis Cases

Parameter / Case	k_d (cm^3/g)	Concentration of suspended load in seawater	Sedimentation rate
Case 0 (basic case)	10^5	10	1
Case 1 (k_d is changed)	10^4	10	1
Case 2 (k_d is changed)	10^6	10	1
Case 3 (S is changed)	10^5	1	1
Case 4 (S is changed)	10^5	100	1
Case 5 (V_{down} is changed)	10^5	10	0.1
Case 6 (V_{down} is changed)	10^5	10	10

3.2 Parameters Concerning Suspended Load

(A) SS concentration S_i in box i [kg/m^3] (Marietta et al (1987))

-SS concentration in the surface-layer box is given as data.

-SS concentration in the area deeper than the second layer is assumed to decrease exponentially with depth, and it is calculated by the following equation:

$$C = Co \cdot 10^{-0.0005d}$$

Where, d : Depth [m]

Co : SS concentration [kg/m^3] at depth 0 [m]

C : SS concentration [kg/m^3] at depth d [m]

(B) Mean sedimentation rate of SS : V_{down}[m/s]

The suspended particles are divided into large and small diameters as described below. (OECD (1985))

Component ratio	Sedimentation rate
Large diameter $\alpha_1 = 0.04$	$V_{down1} = 100$ [m/day]
Small diameter $\alpha_2 = 0.96$	$V_{down2} = 100/365$ [m/day]

Accordingly, $V_{down} \fallingdotseq \alpha_1 V_{down1} + \alpha_2 V_{down2} = 4.263$ [m/day]

4. Sensitivity Analysis

The details of sensitivity analysis are as follows:

Nuclide : ^{239}Pu

Parameters : Distribution coefficient (k_d), concentration of suspended load in seawater (S) and sedimentation rate (V_{down})

Source position : Novaya Zemlya Trench

Items studied : Concentration in seawater at 2 points (72°N, 65°E and 78°N, 92°E) in the Kara Sea and 1 point (79°N, 58°E) in the Barents Sea (Bq/m^3), the maximum value of concentration in the sea-bottom layer (Bq/kgdw), and the number of years to reach the maximum value.

Table 2 Result of Sensitivity Analysis on Nuclide Concentration in Arctic Ocean
(Nuclide: Pu-239)

		Release Location		72° N65° E		78° N92° E		79° N58° E	
		Bq/m3 Bq/m2	yr.	Bq/m3 Bq/m2	yr.	Bq/m3 Bq/m2	yr.	Bq/m3 Bq/m2	yr.
Case 0	LAYER1	3.0E-02	2→10	2.6E-04	5→10	2.0E-08	7→11	1.3E-09	6→11
	LAYER2	3.3E-02	7→10	7.5E-04	10	—	—	5.6E-09	10
	LAYER3	—	—	—	—	—	—	1.3E-08	9→11
	SEDIMENT	7.4E+01	10	1.7E+00	10	4.5E-05	11	3.4E-05	11
Case 1	LAYER1	1.9E-01	8→10	3.6E-02	10	1.8E-04	11→12	1.2E-04	11→13
	LAYER2	2.4E-01	10	9.1E-02	10	—	—	3.1E-04	12
	LAYER3	—	—	—	—	—	—	8.2E-04	13→14
	SEDIMENT	1.4E+01	10	5.2E+00	11	1.0E-02	13	6.3E-02	15→16
Case 2	LAYER1	3.4E-03	2→10	8.3E-06	7→10	1.7E-10	5→11	1.3E-12	4→10
	LAYER2	3.2E-03	8→10	1.6E-05	8→10	—	—	6.9E-12	6→10
	LAYER3	—	—	—	—	—	—	1.3E-11	5→10
	SEDIMENT	1.0E+02	9→10	5.1E-01	10	5.5E-06	11	4.6E-07	11
Case 3	LAYER1	1.5E-01	3→10	1.5E-02	6→10	3.7E-05	10→11	2.2E-05	10→11
	LAYER2	1.0E-01	7→10	2.1E-02	7→10	—	—	3.8E-05	11
	LAYER3	—	—	—	—	—	—	4.7E-05	11
	SEDIMENT	3.5E+01	10	7.3E+00	11	1.2E-02	10→13	1.6E-02	12→13
Case 4	LAYER1	3.4E-03	2→10	9.4E-06	9→10	2.1E-10	9→11	1.8E-12	7→10
	LAYER2	4.4E-03	6→10	3.1E-05	8→10	—	—	1.1E-11	7→10
	LAYER3	—	—	—	—	—	—	3.0E-11	9→10
	SEDIMENT	9.5E+01	10	6.5E-01	10	4.4E-06	11	7.8E-07	11
Case 5	LAYER1	3.1E-02	4→10	4.1E-04	10	4.1E-08	11	3.4E-09	11
	LAYER2	5.5E-02	10	2.2E-03	10	—	—	1.8E-08	11
	LAYER3	—	—	—	—	—	—	7.0E-08	14→15
	SEDIMENT	1.1E+02	9→10	4.4E+00	11	7.9E-05	12	2.1E-04	15→20
Case 6	LAYER1	4.4E-05	11	2.2E-04	2→10	1.5E-08	6→10	8.2E-10	4→10
	LAYER2	2.2E-02	2→10	3.4E-04	5→10	—	—	3.1E-09	4→10
	LAYER3	—	—	—	—	—	—	4.7E-09	6→10
	SEDIMENT	4.7E+01	10	7.2E-01	10	3.1E-05	11	9.9E-06	11

* [Bq/m³] for concentration in LAYER 1～3, [q/m²] for concentration in SEDINENT

** LAYER 1: 0～5m, LAYER 2: 50～100m, LAYER 3 : 100～200m

Table 3 Efficacy of Parameters

Parameters			Efficacy of parameters in basic equations	Efficacy of parameters against nuclide concentration
Distribution coefficient	k_d		The nuclides dissolved in the seawater are adsorbed into suspended load, and the amount of nuclides proportional to ($k_d \cdot S_s$) settles. If kd increases, there is an increased migration of nuclides in bed material mainly from W-layer (first layer) to P-layer (second layer).	Scavenging takes effect as k_d increases, and the following tendency appears: the concentration of nuclides in the seawater in a shallow layer becomes low, the concentration in a deep layer becomes high and the concentration in sediment becomes high. If k_d increases, there is an increased migration of nuclides from W-layer (first layer) to P-layer in bed material, thus causing frequent entrainment of nuclides in the seawater into bed material. Accordingly, the function of making the concentration in bed material denser becomes larger than that of making S_s larger by the same portion.
Concentration of suspended load in sea-water	S_s	mg/l	The nuclides dissolved in the seawater are adsorbed into suspended load, and the amount of nuclides proportional to ($k_d \cdot S_s$) settles.	Scavenging takes effect as S_s increases, and the following tendensy appears: the concentration of nuclides in the seawater in a shallow layer becomes low, the concentration in a deep layer becomes high and the concentration in the sediment becomes high.
Sedimentation rate	V_{down}	mm/y	If V_{down} increases, there is an increased migration of nuclides in bed material mainly from P-layer (second layer) to B-layer (third layer) and from B-layer to D-layer (fourth layer).	This time, attention is paid to the surface concentration (average of W-layer and P-layer) of sediments. If V_{down} increases, there is an increased migration of bed material from a shallow layer (W-layer, P-layer) to a deep layer (B-layer, D-layer), and it appears a tendency that the surface concentration of sediments becomes low.

Table 4. Release Points

Symbol	Release point	Water depth at release point
A	Novaya Zemlya Bay	30m upward from sea bottom
B	Novaya Zemlya Trench	300m
C	Barents Sea	1m

Table 5. Release Patterns and Radionuclides considered for Assessments

Parameter		Symbol	Unit	Set value		
Nuclide data	Nuclide			Cs-137	Pu-239	Tc-99
	Quantity released	Q	Bq	1×10^{10}	1×10^{10}	1×10^{10}
	Half-life	T_r	y	3.0×10	2.41×10^4	2.13×10^5
	Distribution coefficient	K_d	cm^3/g	2×10^3	1×10^5	1×10^2
	Form of release	Instantaneous total release				

The range of parameters is as shown in Table 1, in which Case 0 is considered as a basic case.

Three variables were used as parameters. Table 2 shows the result of sensitivity analysis on nuclide concentration for ^{239}Pu. In Table 3, the efficacy of parameters in the basic equations and the sensitivity of each parameter are described.

5. Concentration Analysis in the Arctic Ocean

5.1 Release Scenario (IAEA (1994))

Next, the bay of Novaya Zemlya Island, its offshore trench and the Barents Sea were selected as release points, and concentration analysis was conducted on three nuclides (Cs-137, Pu-239, and Tc-99).

The location of release points is shown in Figs. 5 and 6, and water depths at these release points are shown in Table 4.

Assessments were made regionally and globally. The regional assessment was conducted at two points, *i.e.*, the sea area of 72°N, 65°E and the sea area of 68°N, 50°E. The global assessment was conducted in both the Kara Sea and the Barents Sea.

Data on released nuclides is shown in Table 5.

5.2 Results of Concentration Calculations

(A) Time history of nuclide concentration

(1) Regional assessment:

For Cs and Tc the maximum concentration appears within 5 years after the release, and then the concentration decreases rapidly. For Pu, the

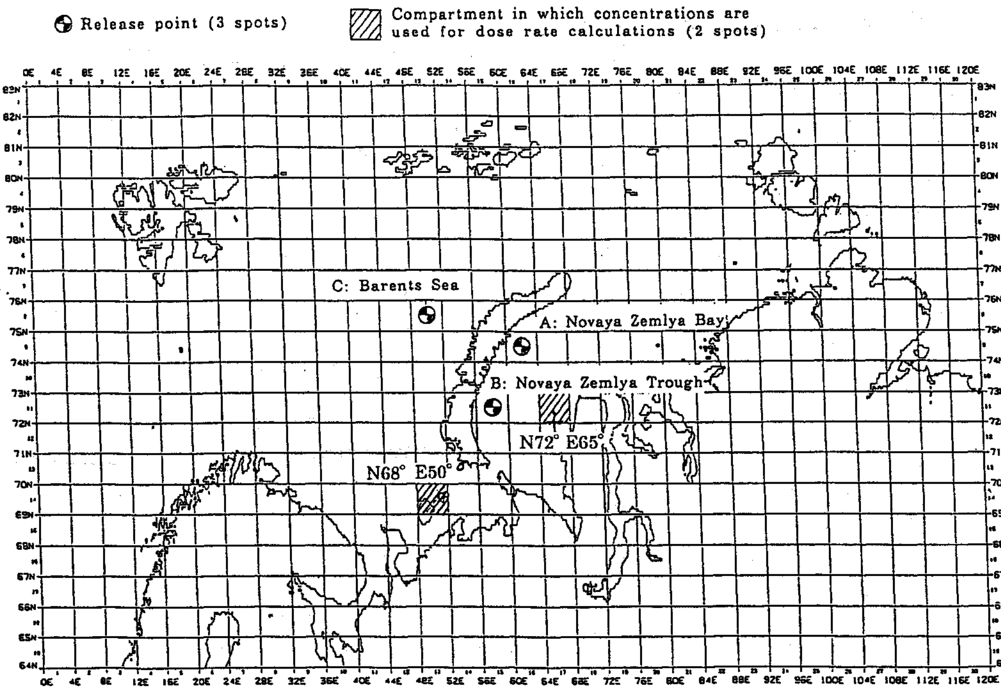


Figure 5. Release Points and Assessment Sea Areas (Regional)

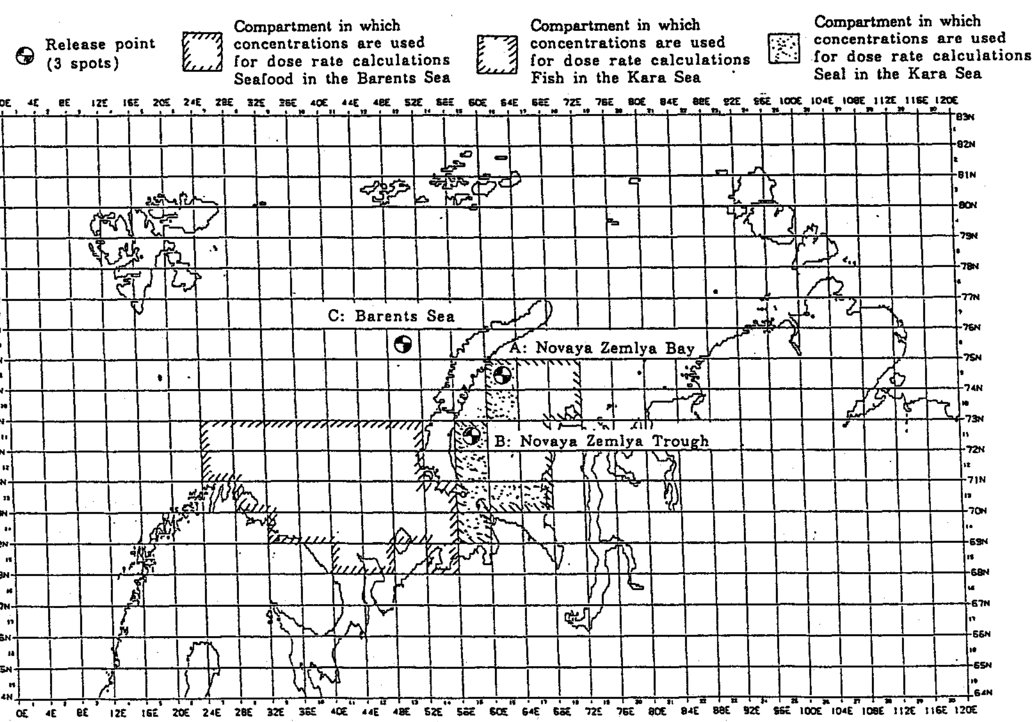


Figure 6. Release Points and Assessment Sea Area (Global)

maximum concentration appears 30 years after the release; the rate of decrease in the concentration is slow.
This seems to be attributable to a large distribution coefficient and an increased scavenging effect.

(2) Global assessment:
For Cs and Tc, the maximum concentration appears within 10 years after the release, and then the concentration decreases rapidly. For Pu, the maximum concentration appears 40 years after the release; the rate of decrease in the concentration with the lapse of time is slow.

(B) Difference by release points (see Fig.6)

(1) Release point A (N.Z. Bay: 50m in depth):
After diffusing into the southwestern part of the Kara Sea, the nuclides spread into the Barents Sea, riding on a westward exchange flow in the first to second layers (0-100m in depth) off the northern coasts of the N.Z. Islands. (see Fig.7)

(2) Release point B (N.Z. Bay: 300m in depth):
The nuclides diffuse into the southwestern part of the Kara Sea, with a speed slower than that at release point A. This may be attributable to a large water depth. The diffusion into the Barents Sea is also conspicuous in the route which passes through the straits to the south of the N.Z. Islands, to which the westward exchange flow in the second layer (50-100m) of the straits is contributing.

(3) Release point C (center of the Barents Sea: 1m in depth):
The release point is 1m in depth, and the nuclides diffuse widely and rapidly in the whole Barents Sea, riding on a relatively large exchange flow in the first layer (0-50m in depth).

6. Conclusions

1) Flows in the Barents Sea are affected by inflows from the neighboring seas (North Atlantic Ocean, Arctic Ocean). On the other hand, it can be pointed out that the inflow of river water from the Ob, Yenisey, etc. has the largest effect on changes in flows in the Kara Sea.
2) The flows obtained by the compartment model agree with the flows based on known data. On the other hand, with respect to medium-layer and deep-layer zones, it will be necessary to carry out further studies on the reproducibility of flows because only a slight amount of data is available on Arctic deep-layer water.
3) The tracking of particles was performed and compared with measured surface-layer flows. As a result, reproducibility was recorded with considerably high accuracy. However, the movement of particles was found slower than known data. Its effect may be due to the size of mesh.
4) High similarity is also recognized between the migration routes of cods and analyzed flow patterns.
5) Sensitivity analysis was conducted on Pu239 using three factors which affect nuclide concentration.
6) Concentrations of three nuclides in water and sediment were evaluated using the release scenarios.

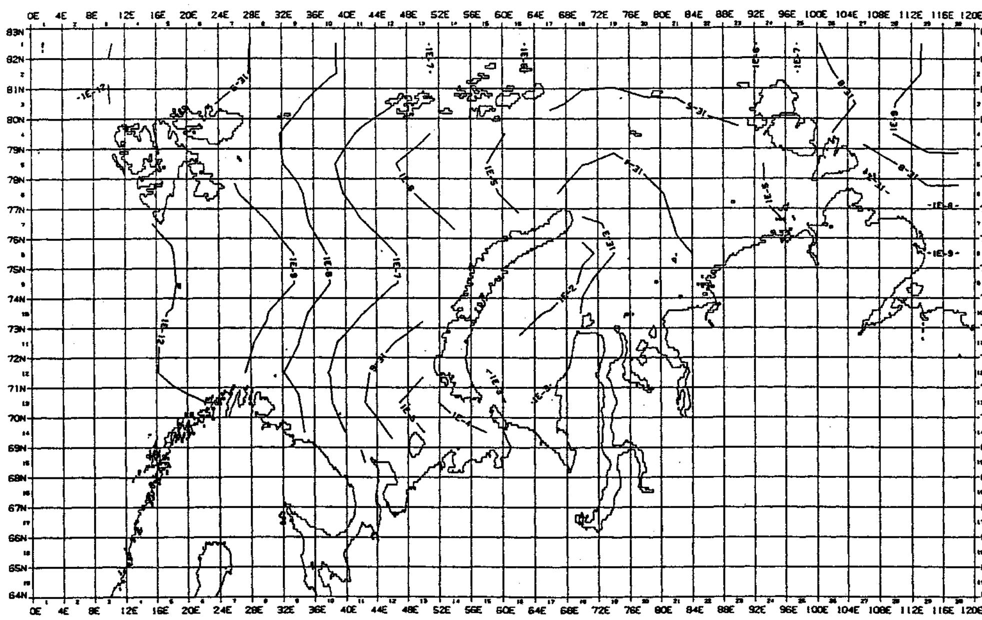


Figure 7. Nuclide Concentration Distribution for Pu239 released from point A.

The method of analysis used in this research was aimed at determining the field of flows on the basis of observation data such as water temperature and salinity. Therefore, the importance of this data is unfathomable. Most notably regarding the Arctic Ocean, the availability of meteorological data is very limited compared to other seas, thus a further accumulation of data is required.

References

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