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Anthropogenic iodine-129 in the Arctic Ocean and Nordic Seas: Numerical modeling and prognoses

V. Alfimov [a,*], G. Possnert [a], A. Aldahan [b]

[a] Tandem Laboratory, Uppsala University, Box 529, SE-751 20 Uppsala, Sweden
[b] Department of Earth Sciences, Uppsala University, SE-752 36 Uppsala, Sweden

Abstract

A numerical model simulation has been used to predict extent and variability in the anthropogenic ^{129}I pollution in the Arctic Ocean and Nordic Seas region over a period of 100 years. The source function of ^{129}I used in the model is represented by a well-known history of discharges from the Sellafield and La Hague nuclear reprocessing facilities. The simulations suggest a fast transport and large inventory of the anthropogenic ^{129}I in the Arctic and North Atlantic Oceans. In a fictitious case of abrupt stop of the discharges, a rapid decline of inventories is observed in all compartments except the North Atlantic Ocean, the deep Nordic Seas and the deep Arctic Ocean. Within 15 years after the stop of releases, the model prediction indicates that near-equilibrium conditions are reached in all compartments.

Keywords: Iodine-129; Compartment model; Arctic Ocean; Nordic Seas; North Atlantic; Chemical tracer; Sellafield; La Hague

1. Introduction

The anthropogenic radionuclide ^{129}I (half-life 15.7 Myr) presently represents a significant chemical tracer in oceanic waters. This significance stems from the facts that (1) the source of ^{129}I is well-defined geographically (nuclear reprocessing facilities at Sellafield, UK and La Hague, France) and has a documented history of discharges and that (2) iodine has a predictable chemical behavior in the ocean (occurs in dominantly one chemical form). An additional factor is the availability of an analytical technique (accelerator mass spectrometry) capable of detecting extremely low concentrations in a reasonable amount of sample. Although the data sets on ^{129}I distribution in the world oceans are rather limited, a number of measurements have been reported for the Arctic Ocean, Nordic Seas (Norwegian, Greenland, and Iceland Seas) and the Labrador Sea (Edmonds et al., 1998, 2001; Buraglio et al., 1999; Smith et al., 1998, 1999, 2002; Alfimov et al., 2004a,b). The dominant portion of released ^{129}I from the nuclear facilities is transported through the Nordic Seas to the Arctic Ocean. Several studies show that ^{129}I pollution is rapidly increasing in the Arctic region (Raisbeck and Yiou, 1999; Alfimov et al., 2004a).

Numerical models that simulate the pathways of anthropogenic releases have been presented for the Nordic Seas and the Arctic Ocean (e.g., Hallstadius et al., 1987; Nielsen et al., 1995, 1997; ANWAP, 1997; Karcher et al., 2004; Gao et al., 2004). However, numerical modeling specifically targeting ^{129}I transport has been limited to only one study (Edmonds et al., 2001), which encompassed the period until 1995 and included only the major parts of the Nordic Seas and the Arctic Ocean.

The model used in the present study is a modified version of the Risk Assessment Integration Group model (RAIG model) (ANWAP, 1997), which has successfully been used for a radioactive risk assessment (mainly,

* Corresponding author. Address: Institute of Particle Physics, ETH Hönggerberg, HPK H33, 8093 Zürich, Switzerland. Tel.: +41 44 633 6505; fax: +41 44 633 1067.
E-mail address: alfimovv@phys.ethz.ch (V. Alfimov).

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^{137}Cs, ^{241}Am, ^{239}Pu, ^{90}Sr) in connection with an eventual nuclear accident in the Kara Sea. The modifications of the model undertaken in this study are aimed to take into consideration specific location of ^{129}I releases and the present day understanding of water mass circulation in the Nordic Seas (Mauritzen, 1996; Rudels et al., 1999; Hansen and Osterhus, 2000; Alfimov et al., 2004a,b). The objective of the model is to predict how the distribution of the released ^{129}I pollution will evolve in the Arctic Ocean and Nordic Seas on a time scale of a hundred years.

2. The model

The Arctic Ocean and North Seas are divided into n boxes (compartments) with shallow regions represented by one layer compartments and deeper regions represented by two layer compartments (Fig. 1 and Table 1). The interaction between the compartments follows linear kinetics, which means that at any time t the rate of radionuclide removal from the compartment is proportional to the radionuclide inventory. In this approximation, ^{129}I concentration inside each compartment is assumed to be completely and instantly mixed. The model is analytically described by a system of linear first-order differential equations. The amount C_i (atoms) of radionuclide in compartment i of n-compartment model is given by

$$\frac{dC_i}{dt} = \sum_{j=1}^{n} k_{ji} C_j - \sum_{j=1}^{n} k_{ij} C_i + Q_i(t), \quad (1)$$

where k_{ij} is the rate of radionuclide transfer (yr^{-1}) from compartment i to compartment j. The additional term $Q_i(t)$ (atoms) addresses a time-varying source of radionuclide in compartment i. The radioactive decay is not taken into consideration due to the long half-life of ^{129}I.

The rate of radionuclide transfer k_{ij} is calculated from the estimated volumetric flow rate F_{ij} (m^3 yr^{-1}) of water from compartment i to compartment j and from the volume V_i (m^3) of compartment i (Tables 1 and 2):

$$k_{ij} = \frac{F_{ij}}{V_i}. \quad (2)$$

The system of differential equations is numerically solved with the Runge–Kutta method of the fourth order (the ODE45 solver from Matlab®). For each integration step, the relative and analytical error tolerances are set to $T^{rel} = 10^{-3}$ and $T^{abs} = 10^{-6}$, respectively. An estimated error e_i of y_i component of the solution vector has to satisfy:

$$|e_i| \leqslant \max(T^{rel} \cdot |y_i|, T_i^{abs}). \quad (3)$$

The initial integration step is set to 1 year and thereafter is automatically refined by the method to obtain the required accuracy.

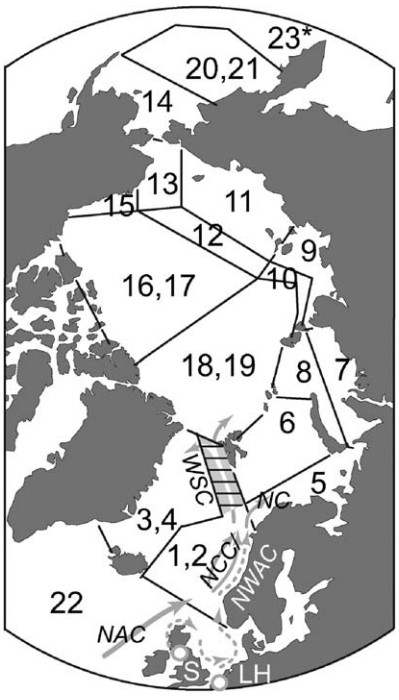

Fig. 1. Map of the Arctic Ocean and Nordic Seas showing locations of water compartments used in this study. Boxes are numbered according to ANWAP (1997) with an exception for box #23*, which was created for a separate representation of the Pacific and Indian Oceans in the modified RAIG model. Two numbers in a single area denote upper and lower compartments of a two-layer structure. Hatched gray area of compartments 3 and 4 of the original RAIG model was transferred to compartments 1 and 2 of the modified RAIG model. S = Sellafield, LH = La Hague, NAC = North Atlantic Current, NCC/NWAC = Norwegian Coastal Current and Norwegian Atlantic Current, WSC = West Spitzbergen Current, NC = North Cape Current. Dashed arrows represent the pathway of the ^{129}I discharge from Sellafield and La Hague. Solid arrows represent surface water currents.

Table 1
Compartment volumes and depths in the modified RAIG model of this study

	Box #	Volume V_i ($\times 10^{13}$ m^3)	Depth d_i (m)
Norwegian Sea, upper	1	50	460
Norwegian Sea, lower	2	190	1700
Greenland Sea, upper	3	48	430
Greenland Sea, lower	4	150	1400
Barents Sea, south	5	13	230
Barents Sea, north	6	23	280
Kara Sea, estuary	7	2.9	73
Kara Sea	8	10	270
Laptev Sea, coastal	9	2.4	51
Laptev Sea, shelf	10	16	970
East Siberian Sea, coastal	11	4.4	60
East Siberian Sea, shelf	12	26	640
Chukchi Sea	13	2.3	73
Bering Sea, north	14	6.7	98
Beaufort Sea	15	7.7	660
Canadian Basin, upper	16	130	460
Canadian Basin, lower	17	560	2000
Eurasian Basin, upper	18	100	480
Eurasian Basin, lower	19	560	2600
Bering Sea South, upper	20	55	480
Bering Sea South, lower	21	300	2600
Atlantic Ocean	22	40,000	3400
Pacific and Indian Oceans	23	60,000	3400