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Radioactivity in the Arctic Seas

Report for the International Arctic Seas Assessment Project (IASAP)

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FOREWORD

From 1993 to 1996 the International Atomic Energy Agency's Marine Environment Laboratory (IAEA-MEL) was engaged in the IAEA's International Arctic Seas Assessment Project (IASAP) in which emphasis has been placed on a critical review of environmental conditions in the Arctic Seas.

The IAEA-MEL programme, organized in the framework of the IASAP included:

(i) an oceanographic and an ecological description of the Arctic Seas;

(ii) the provision of a central database facility for the IASAP programme for the collection, synthesis and interpretation of data on marine radioactivity in the Arctic Seas;

(iii) participation in official expeditions to the Kara Sea organized by the joint Russian–Norwegian Experts Group (1992, 1993 and 1994), the Russian Academy of Sciences (1994), and the Naval Research Laboratory and Norwegian Defence Research Establishment (1995);

(iv) assistance with in situ and laboratory based radiometric measurements of current radionuclide concentrations in the Kara Sea;

(v) organization of analytical quality assurance intercalibration exercises among the participating laboratories;

(vi) computer modelling of the potential dispersal of radionuclides released from the dumped waste and of assessment of the associated radiological consequences of the disposals on local, regional and global scales;

(vii) in situ and laboratory based assessment of distribution coefficients (K_d) and concentration factors (CF) for the Arctic environment.

This report summarizes the work done under parts (i), (ii), (v) and (vii). The results obtained under parts (iii), (iv) and (vi) have already been published in the scientific literature and the modelling components (vi) will also be included in a report of the Modelling and Assessment Working Group currently in preparation. The source term component of the IASAP has been treated in the report of the Source Term Working Group, Predicted Radionuclide Release from Marine Reactors Dumped in the Kara Sea (IAEA-TECDOC-938 (1997)). The present report should be read in conjunction with the main report of the IASAP project, Radiological Conditions of the Western Kara Sea (Radiological Assessment Reports Series, IAEA, Vienna (1998)) so that the full radiological context is appreciated.

This work was co-ordinated in the IAEA's Marine Environment Laboratory in Monaco and the responsible officer was P.P. Povinec. The success of the project was due to the full collaboration of the institutions participating in the IASAP programme. The IAEA would like to express its gratitude to the Governments of Germany, Norway, the Russian Federation and the United States of America for their generous support. The IAEA also extends its thanks to several institutions, namely the Norwegian Defence Research Establishment (Horten, Norway), the Norwegian Radiation Protection Authority (Osteras, Norway), SPA Typhoon (Obninsk, Russian Federation), the Murmansk Marine Biology Institute of the Russian

Academy of Sciences (Murmansk, Russian Federation), the Arctic and Antarctic Research Institute (St. Petersburg, Russian Federation), MAFF (Lowestoft, United Kingdom) and others for their help in providing radionuclide data and other information necessary for the completion of this report.

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EDITORIAL NOTE

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SUMMARY

From 1993 to 1996 the International Atomic Energy Agency carried out an International Arctic Seas Assessment Project (IASAP) in order to assess the consequences of the dumping of radioactive wastes in the Arctic Seas on human health and the environment. In the framework of this project, the IAEA's Marine Environment Laboratory in Monaco (IAEA-MEL) has participated in several activities including the review of the oceanography and ecology of Arctic Seas and assisting as a central facility for the collection, synthesis and interpretation of data on marine radioactivity in the Arctic Seas.

This report provides comprehensive information on environmental conditions in the Arctic Seas as required for the study of possible radiological consequences from dumped high level radioactive wastes in the Kara Sea. The report describes the oceanography of the regions, with emphasis on the Kara and Barents Seas, including the East Novaya Zemlya Fjords. The ecological description concentrates on biological production, marine food-webs and fisheries in the Arctic Seas.

Further, IAEA-MEL, within the IASAP programme, has been acting as a central facility for the collection, synthesis and interpretation of data on marine radioactivity in the Arctic Seas. The data have been included in the Global Marine Radioactivity Database (GLOMARD) which has been developed to store all data on marine radioactivity in seawater, sediments and biota. The database provides critical input to the evaluation of the environmental radionuclide levels in the region and to the assessment of the radiation doses to local, regional and global human populations and to marine biota. Concentrations of anthropogenic radionuclides in the Kara and Barents Seas are studied over two time intervals — before and after 1992 — when new data, especially from the joint Russian–Norwegian cruises, became available. On the basis of data stored in the GLOMARD database on concentrations of several radionuclides in water, sediment and biota sampled at the major dumpsites in the Abrosimov, Stepovoy and Tsivolka Fjords and the Novaya Zemlya Trough, as well as in the open Kara Sea and the Ob and Yenisey estuaries, it can be concluded that, with the exception of limited areas in Abrosimov and Stepovoy Fjords, only minor contamination exists relative to background levels. The open Kara Sea is relatively uncontaminated, the main contributions being due to direct deposition and catchment runoff from global fallout caused by nuclear weapons tests, discharges from reprocessing plants in western Europe and the former Soviet Union, local fallout from tests performed at Novaya Zemlya and Chernobyl fallout.

The concepts of the distribution coefficient (K_d) and the concentration factor (CF) have been used to intercompare the relative degrees of uptake of marine contaminants by different sediment types and marine biota, respectively. Laboratory and field studies were carried out to investigate the environmental parameters that might affect K_d and CF values for Arctic environments. From laboratory experiments, suspended matter concentration and sediment characteristics were identified as the most important sources of variation for K_ds. The effects of temperature and salinity fluctuations on K_ds are negligible. Field based determinations from 35 locations in the Kara Sea confirm that K_ds exhibit a wide range of values in response to variable environmental conditions. CFs were computed using field measurements of radionuclide and/or stable element concentrations in organisms, as well as data derived from laboratory radiotracer experiments. Both K_ds and CFs recommended for use in radiological modelling for the IASAP are within the range of values recommended in the

IAEA Technical Reports Series No. 247, Sediment $K_d$sand Concentration Factors for Radionuclides in the Marine Environment. Seaweeds (*Fucus*) and molluscs (*Macoma*) are recommended for use as bioindicators for monitoring radioactive contamination in the Kara Sea.

1. INTRODUCTION

According to the first available information [1] the dumping activities of the former Soviet Union had added a total of up to 90 PBq to the inventory of radionuclides in the marginal Arctic Seas, primarily as nuclear reactor assemblies (some including spent nuclear fuel) and entire vessels (89 PBq) but also as liquid (0.9 PBq). Considering all waste types, over 95% of the total activity of the nuclear material was located in the Kara Sea. No disposals of objects with spent nuclear fuel were reported for the Barents Sea, although the nuclear-powered and armed submarine Komsomolets which sank accidentally in the Norwegian Sea in 1989 adds 5.5 PBq to the region's inventory.

More recent estimates [2, 3] have suggested that the present inventories of radionuclides in the Kara Sea reactors can be (a) for fission products, about 4.1 PBq, ^{137}Cs and ^{90}Sr contributing 1 and 0.9 PBq respectively, (b) for the activation products, about 0.5 PBq, the largest contribution being from ^{63}Ni (0.3 PBq) and ^{60}Co (0.1 PBq) and (c) for the actinides, about 0.1 PBq (the highest contribution (0.08 PBq) being from ^{241}Pu). From the point of view of the total activities in the disposed materials, Tsivolka Fjord is the dominant dump site (2.2 PBq), although Abrosimov and Stepovoy Fjords and the Novaya Zemlya Trough contain important inventories of fission products (1.4, 0.8 and 0.3 PBq, respectively), while Techeniye Fjord hosts 0.005 PBq of activation products.

As the dumping of high level radioactive wastes took place only in the Kara Sea, the main interest in the study of environmental conditions has been centred on this particular sea. However, for predictions of possible environmental consequences from dumped wastes, other Arctic Seas have been under focus as well for a better understanding of the oceanography and ecology of the region.

The International Atomic Energy Agency carried out during 1993–1996 an International Arctic Seas Assessment Project (IASAP) in order to assess the consequences of the dumping of radioactive wastes in the Arctic Seas on human health and the environment. In the framework of this project, the IAEA's Marine Environment Laboratory in Monaco (IAEA-MEL) has participated in several activities with the main aim of reviewing environmental conditions in the Arctic Seas and assisting as a central facility for the collection, synthesis and interpretation of data on marine radioactivity in the Arctic Seas.

The present report begins with an oceanographic description of the region and some observations on the food chain pathways prevailing there. This information is fundamental to understanding the transfer routes for any anthropogenic radionuclides released from the dumped objects. This theme of radionuclide transfer is continued in Section 4 of the report which examines, via new experimental research conducted at IAEA-MEL, whether low-temperature (Arctic) conditions change the parameters of marine radionuclide transfer into marine organisms and sediments (relative to the commonly published data for temperate latitudes). Finally the report presents data on radionuclide concentrations in the Kara and Barents Seas and uses these data to estimate the inventories of radionuclides currently in the marine environment of the Kara and Barents Seas.

2. DESCRIPTION OF THE REGION

2.1. OCEANOGRAPHY

2.1.1. Arctic Ocean

The Arctic Ocean (Fig. 1) is nearly land-locked and is divided into two major basins: the Eurasian Basin and the Canadian Basin, separated by the Lomonosov Ridge. Both the Eurasian Basin, with maximum depths of around 4000 m, and the Canadian Basin, with maximum depths of about 5000 m, are further subdivided by lesser submarine ridges. Another important topographic feature is the continental shelf, underlying about 30% of the area of the Arctic Ocean and comprising several shallow marginal seas (Fig. 2). The shelf bordering Eurasia extends out to 500–1700 km, while along the Alaskan and Greenland coastlines its width is under 200 km. The total area of the Arctic Ocean is $9.5 \cdot 10^6$ km^2 and its volume is $1.7 \cdot 10^7$ km^3. The most important connection of the Arctic Ocean with the rest of the World Ocean is through the 2600 m deep Fram Strait between Greenland and Svalbard. Shallower openings in the land belting the Arctic Ocean connect it to the Pacific and to the Atlantic through the Bering Strait and the Canadian Archipelago, respectively.

Three main water masses can be defined in the Arctic Ocean: surface water, Atlantic water and bottom water [4]. The surface water layer originates in the marginal shelf seas and from local mixing of waters below the sea-ice cover following the freeze/melt cycle. It is the most variable of the water masses, its properties being influenced by the seasonality of ice formation and shelf/river water input. It can be divided into the surface polar mixed layer, 30 to 50 m deep, containing fresh, cold (–1.4°C to –1.7°C) water, and the underlying halocline, down to about 200 m, with increasing salinity and temperatures up to 0°C. The warm and salty Atlantic water layer extends below the pycnocline down to depths of 800–900 m and is characterized by a mid-depth temperature maximum ranging between 0.5°C and 4°C. This water mass is generated from the North Atlantic waters inflowing through the Fram Strait and over the Barents and Kara Sea shelves. The deep waters, extending below the Atlantic layer to the ocean floor, have relatively high and uniform salinity (34.93 to 34.99‰) and temperature (–0.7 to –0.8°C in the Eurasian Basin and –0.3 to –0.4°C in the Canadian Basin). Besides the three main water masses described, in the Canadian Basin there is a thin interlayer of Pacific water, underlying the surface waters.

The circulation in the Central Arctic is well understood (Fig. 3). The flow pattern in the Polar Mixed Layer is closely related to that of the overlying sea-ice. The prominent long term features are the Beaufort Gyre in the Canadian Basin and the Transpolar Drift Stream, directed from the Pole towards the Fram Strait. Circulation in the halocline is driven by anticyclonic flows on the shelves. The flow in the Atlantic layer is generally cyclonic. It appears to occur in boundary currents, is influenced by processes on the shelves (mainly those of the Barents and Kara Seas) and may be steered by topographic features. Most of the Atlantic water enters the Arctic Ocean through the Fram Strait in the West Spitsbergen Current and leaves it in the East Greenland Current. A branch of the Norwegian Atlantic Current also brings Atlantic water into the Arctic Basin over the Barents and Northern Kara Sea shelves. At depth, the Central Arctic Basins are decoupled from extensive exchange. There, cyclonic flows appear to exist around the boundaries of the Canadian and Eurasian Basins. A summary of main inflows and outflows for the Arctic Ocean is given in Table I.

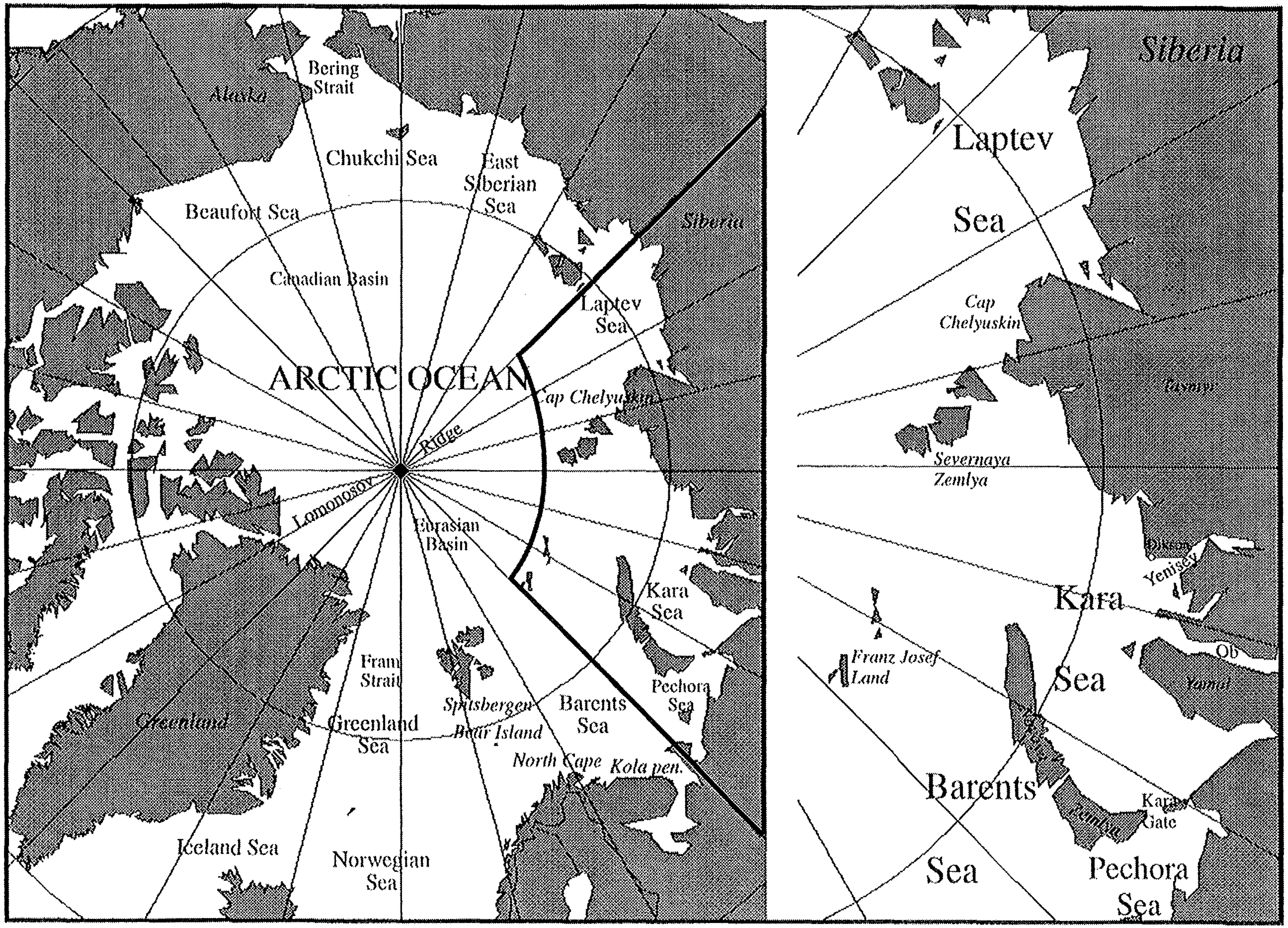


FIG. 1. The Arctic Ocean.

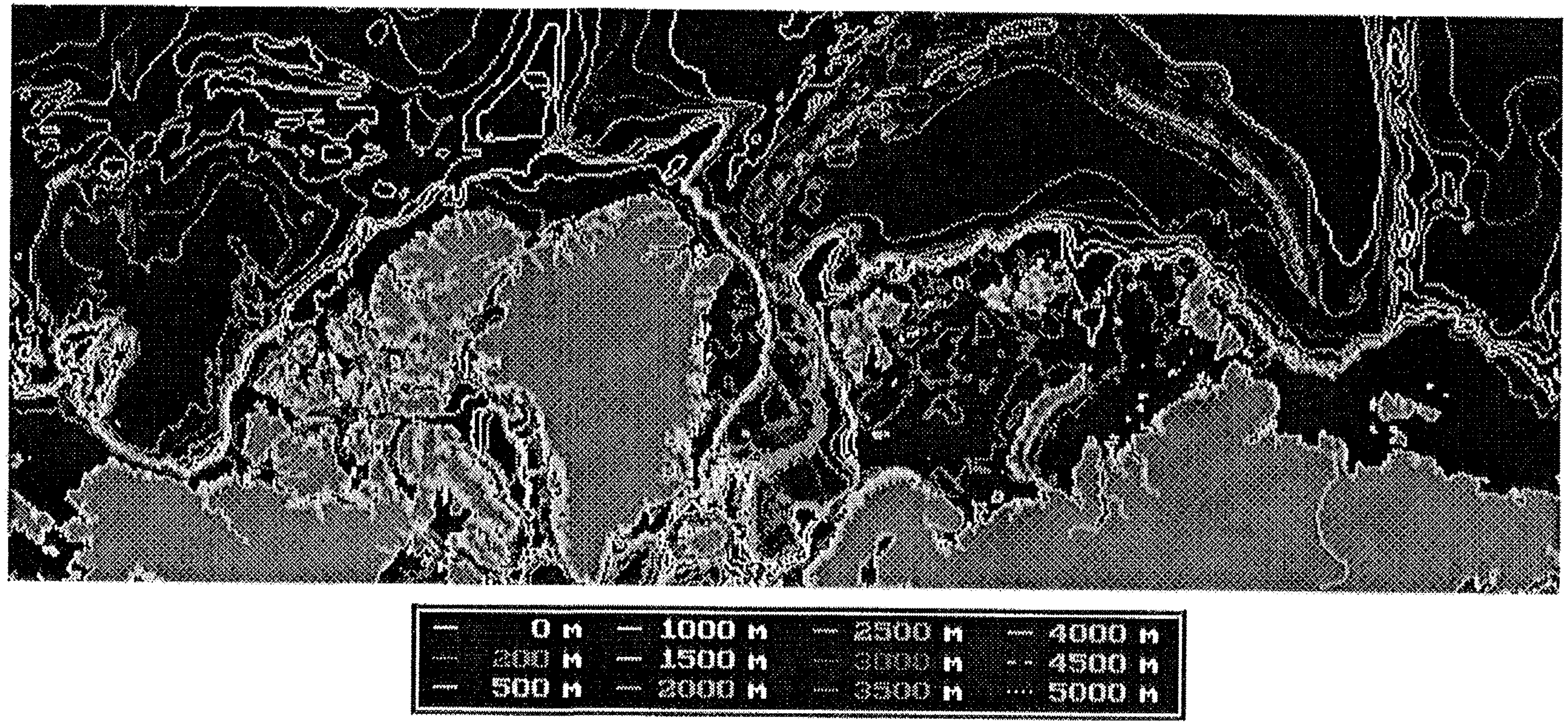


FIG. 2. Bathymetry of the Arctic Ocean.

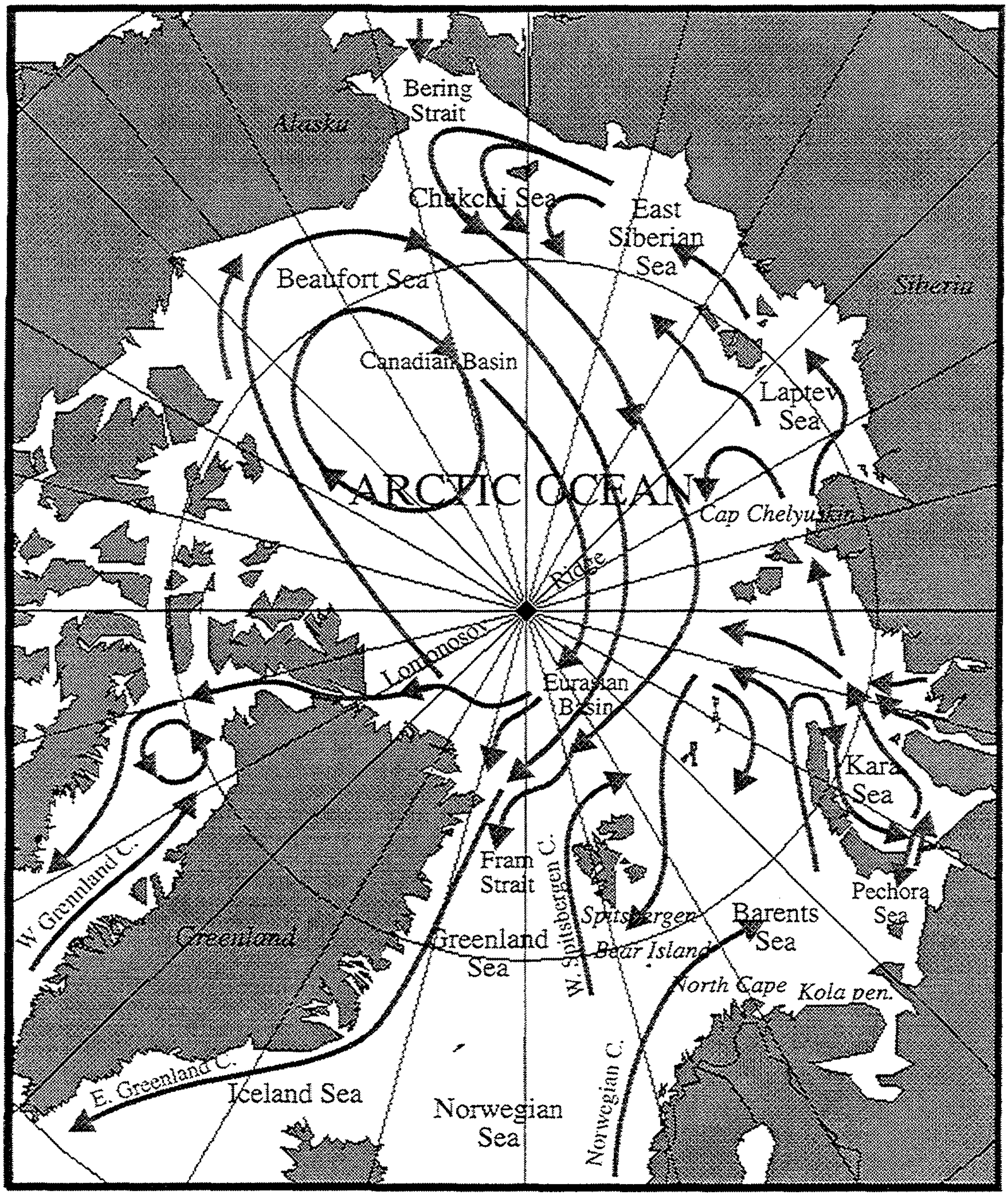


FIG. 3. Main surface currents in the Arctic Ocean (drafted from [3]).

TABLE I. MAIN WATER FLOWS IN THE ARCTIC [5]

From	To	Through	Flow (Sverdrup)*
Atlantic Ocean	Arctic Ocean	Fram Strait	4
Atlantic Ocean	Barents Sea	Bear Island–North Cape	3.1
Arctic Ocean	Atlantic Ocean	Fram Strait	5
Arctic Ocean	Atlantic Ocean	Canadian Archipelago	2.1
Arctic Ocean	Barents Sea	Spitzbergen–Franz Josef Land	0.5
Pacific Ocean	Arctic Ocean	Bering Strait	0.8–0.9
White Sea	Barents Sea	Gorlo Strait	0.015
Barents Sea	Atlantic Ocean	Spitzbergen–Bear Island	1.2
Barents Sea	Arctic Ocean	Franz Josef Land–Sv. Anna Trough	1.2
Barents Sea	Kara Sea	Franz Josef Land–Novaya Zemlya	0.15–0.54
Barents Sea	Kara Sea	Kara Gate	0.04–0.6
Kara Sea	Arctic Ocean	W of Severnaya Zemlya	0.6–0.7
Kara Sea	Laptev Sea	Severnaya Zemlya–mainland	0.16–0.3

* 1 Sverdrup = 10^6 m^3 s^{-1}.

The central Arctic is permanently covered by sea-ice, the exchange with the atmosphere being thus limited to polynyas and leads. This, together with the sharp pycnocline at about 200 m, almost completely isolates the deep ocean from non-particulate vertical exchange with the upper waters [5]. In the Polar Mixed Layer brine release leads to limited vertical mixing. The halocline is a permanent, advective feature and appears to be never penetrated. Its waters are formed during winter freezing on the marginal shelves and advected into the central Arctic Basins, sinking underneath the Polar Mixed Layer due to their relatively high density. The salty Atlantic waters get cool enough in reaching the Fram Strait to sink beneath the Arctic upper waters. For the deep waters of the Arctic Basin, vertical mixing is restricted to near boundary convection, which may ventilate water masses down to the bottom of the ocean. Waters entering/exiting the Arctic Ocean through the Fram Strait are affected by open-ocean convection which reaches down to the bottom in the Greenland Gyre and to mid-depths in the Iceland Sea.

Residence times of 2.5–3.5 years have been derived for fresh water on the Barents and Kara Sea shelves [5]. The mean residence time of freshwater in the upper layers of the Arctic Basin is 10 years, possibly 2–6 years shorter for surface waters than for the halocline. Conservative tracers transported from the shelves to the upper layers of the Arctic Basin could therefore exit through the Fram Strait in about 5 years. Renewal times of tens of years, 50–100 years and 250–300 years have been estimated for the intermediate, deep and bottom waters of the Arctic Basin, respectively.

2.1.2. Barents Sea

The Barents Sea (Fig. 1), with an area of 1 424 000 km^2 and a volume of 316 000 km^3, lies mainly on the northern European continental shelf. It has a complicated bottom topography, which contributes to the complexity of distributions of water masses and sedimentation regimes. For the most part, its depth varies between 100 and 350 m and only drops to below 500 m over 1% of the sea's area, with a maximum of about 600 m attained at the boundary with the Norwegian Sea. The Barents Sea has a very unstable climate [6]. The atmospheric Arctic front forms at the boundary between the predominantly temperate air masses in the south and the cold Arctic air masses in the north. Considerable changes occur across the Barents Sea in the mean air temperature (in winter 0°C in the south-west, –10°C in the south-east and –24°C at Spitsbergen; in summer 9°C in the south and 0°C in the north), precipitation (annual average values of 300 mm in the north-east and up to 1000 mm in the south-west) and dominant winds.

Besides its main connections to the Atlantic and central Arctic, the Barents Sea also communicates with the Kara Sea and the White Sea. It receives runoff from rivers on the mainland (Fig. 4) either directly, notably the Pechora River (about 130 km^3 a^{-1}), or through the White Sea, mainly the Severnaya Dvina, Mezen and Onega (altogether 136 km^3 a^{-1}). There is a number of smaller rivers flowing into the Barents Sea from the Scandinavian and Kola coasts, amounting to about 10% of the total river runoff to the Barents Sea. Rivers from Spitsbergen, Franz Josef Land and the Novaya Zemlya add about 36, 3.7 and 33 km^3 a^{-1} respectively. Snow/ice melting on the mainland and the islands also contributes to the fresh water input [8]. Run-off significantly affects only the south-eastern part of the sea.

Four main water masses can be identified in the Barents Sea [7]. The Atlantic water, warm (4–12°C) and saline (about 35‰), incoming from the west but also from the north, through the Arctic basin, is located in the western part of the sea. The surface, cold (<0–1°C), less saline (33–34‰) Arctic water, flows in from the north. The relatively fresh (28–34.5‰) coastal water, with significant variation in seasonal temperature and salinity extends along the mainland and western Novaya Zemlya coasts. The Barents Sea waters, forming as a result of mixing between the previously described water masses and transformation under the effect of local conditions, reside mainly in the eastern and northern parts of the sea. A characteristic feature is the polar front forming at the boundary between the cold Arctic and warm Atlantic waters, with temperature and salinity gradients reaching maxima of 1.3°C km^{-1} and 0.2‰ km^{-1}, respectively. It strongly influences water circulation and affects chemical and biological conditions in its vicinity, leading to increased contents of biogenic elements and a general abundance of life.

The general water circulation in the Barents Sea is cyclonic. The strongest and most stable flow runs eastward along the northern coast of Norway. It is formed from waters of the Norwegian Atlantic Current and of the Norwegian Coastal Current [9] entering the Barents Sea south of Bear Island, and is called the North Cape Current. Further east it bears the name of Murmansk Current, and at about 30°E is divided into a coastal branch and a northward flowing branch, part of which recirculates westwards. In the Barents Sea there are also a number of cold currents, flowing westwards and southwards. Important from the point of view of possible dispersion of contaminants from the Kara Sea is the Litke Current, coming into the Barents Sea through the northern part of the Kara Gate. Its intensity is not well known, but appears to be a factor of at least 7–10 times weaker than the current flowing eastward through the Kara Gate [10]. Main water inflows and outflows for the Barents Sea are summarized in Table I.

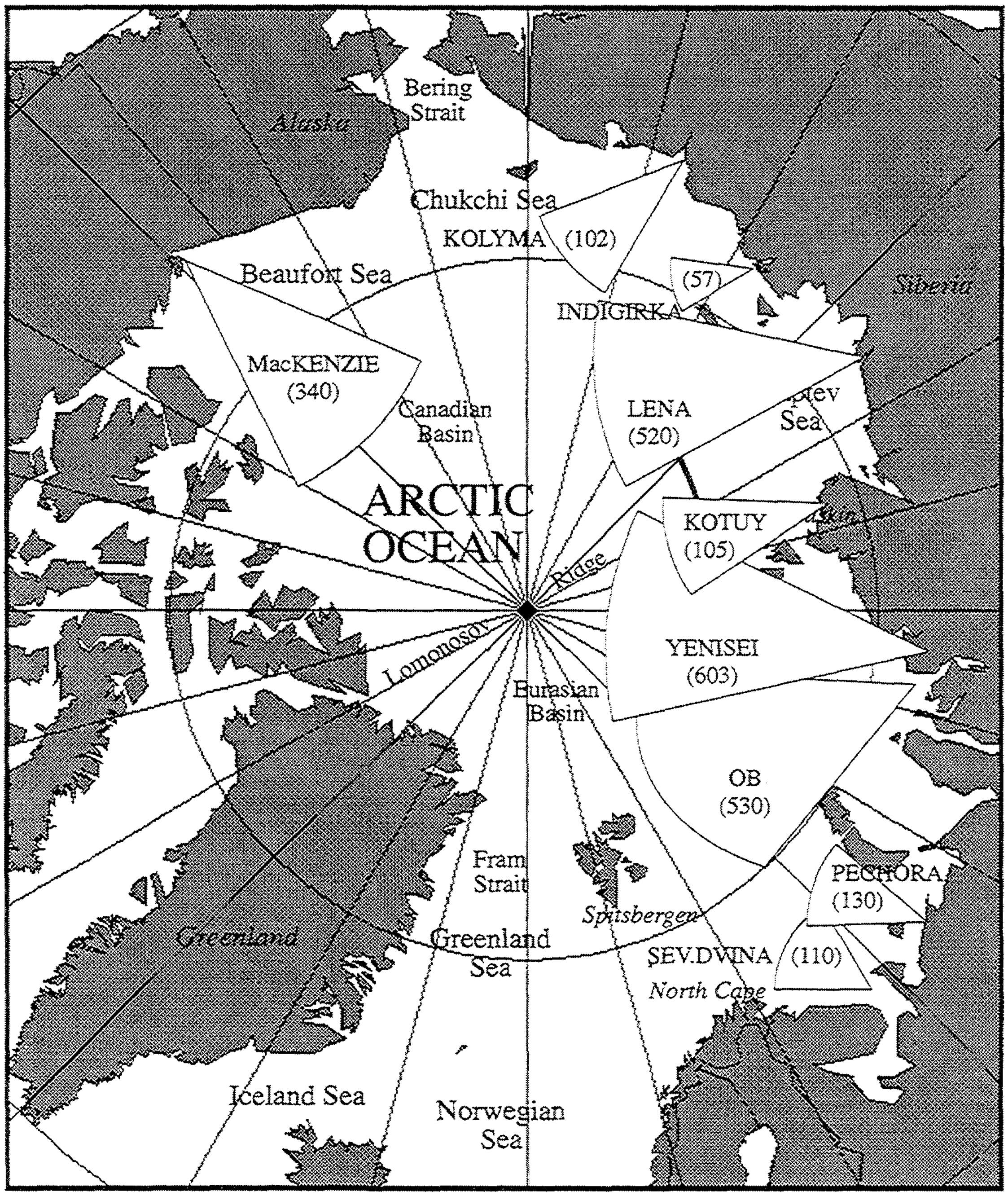


FIG. 4. Mean Annual runoff to the Arctic Ocean (km^3y^{-1}) (drafted from [6]).

Tides decrease in amplitude towards the northeast, from extreme maxima attained at Strait Gorlo of the White Sea (6 m), at the North Cape and in Murmansk fjords (4 m) to lesser maxima at Spitsbergen (1 m), Franz Josef Land (0.8 m) and Novaya Zemlya (0.8–1.4 m).

The sea is stratified in the warm season but convective mixing occurs in winter. In summer the halo-, thermo- and pycnoclines are situated at depths of 25–50 m. Due to the bottom topography, there are quasipermanent zones of downwelling and upwelling, like the Bjornoya Trough and the northeastern region [6].

As a consequence of the intensive vertical mixing, the Barents Sea waters are well ventilated. The surface waters are oversaturated with oxygen in summer and even in winter the oxygen saturation is not less than 70–80% [4]. Due to low temperatures, the deep layers of water are enriched in carbon dioxide.

Due to the inflow of warm Atlantic waters, the Barents Sea is never completely ice-covered. A typical feature of the Barents Sea ice regime is the large seasonal and interannual variability. The largest ice extent is usually observed in April and it varies from 55–60% of the sea surface area in warm winters to over 70% in cold winters [6]. The smallest ice extent is recorded in August–September, when, in specially warm years, the sea is completely ice-free, while in anomalously cold years the ice cover persists over 40–50% of the sea area. The annual average, minimum and maximum ice cover extents are 38%, 22% and 52% respectively. Stable fast ice forms near the coasts. The ice thickness does not usually exceed 0.3 m at the margins of the sea. Drifting ice reaches maximum thicknesses of 0.8 m in the south-eastern Barents Sea and 1.5 m in the north. In winter, northward ice drift prevails, while in summer the southward transport dominates. Extensive polynyas are formed near the coasts of the islands due to local winds. The ice formed in the Barents Sea itself is usually predominant, with some import from the Arctic Ocean and the Kara and White Seas. Ice import is considerably larger than export (Table II). However, the ice exchange of the Barents Sea is insignificant compared with the ice volume in the sea.

The Barents Sea is characterized by a typical polar sedimentogenesis, with relatively low sedimentation rates and marked predominance of terrigenous sediments over bio- and chemo-genic ones [11]. A total of about 7.5 10^7 tonnes of terrigenous material is supplied to the Barents Sea every year, mainly by coastal and sea floor abrasion, but also by rivers and by deposition from the atmosphere. The White Sea receives an input of 9.3 10^7 t a^{-1}. Suspended sediment loads range from few mg l^{-1} in the open Barents Sea and southern coastal area to several tens, even hundreds of mg l^{-1} in some of the fjords on the western coast of Novaya Zemlya. Besides key factors like the complex topography of the sea floor and hydrodynamics, which control sedimentation regimes and mechanical characteristics of the bottom sediments, the presence of large permanently ice-free areas contributes to active resuspension of bottom sediments. This process mainly occurs during the stormy autumn–winter period, when wave action can affect sea floor sediments at depths up to 80 m and even deeper. Due to the existing system of permanent bottom currents, the resuspended sediment is entrained in long range transport. Sedimentation rates of 0.1 to 0.5 mm a^{-1} have been estimated for the Barents Sea at large [7], but values an order of magnitude higher can be expected for the western Novaya Zemlya fjords. The whole spectrum of lithological types of bottom deposits is represented in the Barents Sea. South of 72°N sands are dominant, whereas to the north mud prevails. Generally, at depths of less than 100 m the sea floor is covered mainly by sand, often containing boulders, gravel and shells. Deeper basins are covered with mud. Clayey mud occurs especially in the northern part of the sea. Due to the active hydrodynamic regime, bimodal grain-size distributions, as well as polycomponent sediments are dominant, monogranular sediments being very rare. Light minerals (quartz, feldspar) and, in the fine-grained sediments, also clay minerals (mainly illite) predominate [4]. Heavy minerals in the surface layer are in general between 1 and 5%, rarely more. The SiO_2 ranges from 85% in sands to 58% in muds and clayey muds, while metallic oxides vary from 8 to 25%, showing a clear correlation between the chemical and mechanical compositions. Manganese content increases from 0.01% in the sands of southern Barents Sea to about 0.6% in the northern muds. The organic matter content in Barents Sea sediments ranges between 0.15–3.12% for carbon and 0.02–0.42% for nitrogen, both increasing in proportion with the clay content. The phosphorus content increases from below 0.05% in the south to 0.32% in the north. Active chemical processes are related to precipitation of compounds leached by rivers from the mainland and occur principally in the fresh water–sea water mixing area. Densities between 1.35 and 1.99 g cm^{-3} and water contents of 30 to 67% have been generally observed for bottom sediments [11].

2.1.3. Kara Sea

The Kara Sea (Fig. 5) lies on the western part of the Arctic continental shelf of Asia and is connected with the Barents Sea to the west, the Arctic Basin to the north and the Laptev Sea to the east. It has an area of 883 000 km^2 and a volume of 98 000 km^3. The sea is rather shallow, having 82% of its area lying on the continental shelf, with depths under 200 m, and only reaching depths of more than 500 m over 2% of its area [6]. The most prominent topographical features are three submarine rifts: the Svyataya Anna and Voronin Troughs in the north and the Novaya Zemlya Trough in the south-west, along the eastern coast of Novaya Zemlya, with maximum depths of 620 m, 450 m and 430 m respectively. The Novaya Zemlya and Svyataya Anna Troughs are separated by a 100 m deep sill. The northern troughs form pronounced reentrants from the Arctic Basin into the shelf and play important roles — particularly the Svyataya Anna Trough — in shaping the water circulation between the Barents Sea, the Kara Sea and the central Arctic.

Strong winter cooling and weak summer warming, unstable weather in the cold season and relatively calm atmospheric conditions in summer are characteristic features of the Kara Sea climate [7]. Mean monthly air temperatures range between –20°C and –28°C in winter and 1°C to 6°C in summer. The extreme air temperatures recorded are –48°C and 20°C. In summer–fall winds are generally between 4–7 m s^{-1}, the frequency of winds less than 11 m s^{-1} winds being of 88%. Extreme winds of 40–60 m s^{-1} — the boras — occur near the mountainous coasts of Novaya Zemlya and Severnaya Zemlya, typically lasting several hours, but possibly lasting 2–3 days in winter. Storms are most frequent in the western Kara Sea. In winter 6–7 storm days a month are recorded. Precipitation amounts to 20–30 cm a^{-1}.

There are five main water masses in the Kara Sea [6]. The distribution and extent of these water masses has not only a seasonal variation, related to ice formation and melting, but also an interannual variability, which is controlled by atmospheric processes generated by the dominance of either the Icelandic depression or the Arctic pressure maximum. The surface waters of the Arctic Basin come in through the north from the central Arctic and are located in the upper layers of the Kara Sea. They are characterized by rather small seasonal changes in salinity and temperature around typical values of, respectively, 32‰, slightly increasing with depth, and –1.8°C — that is, close to the freezing point.

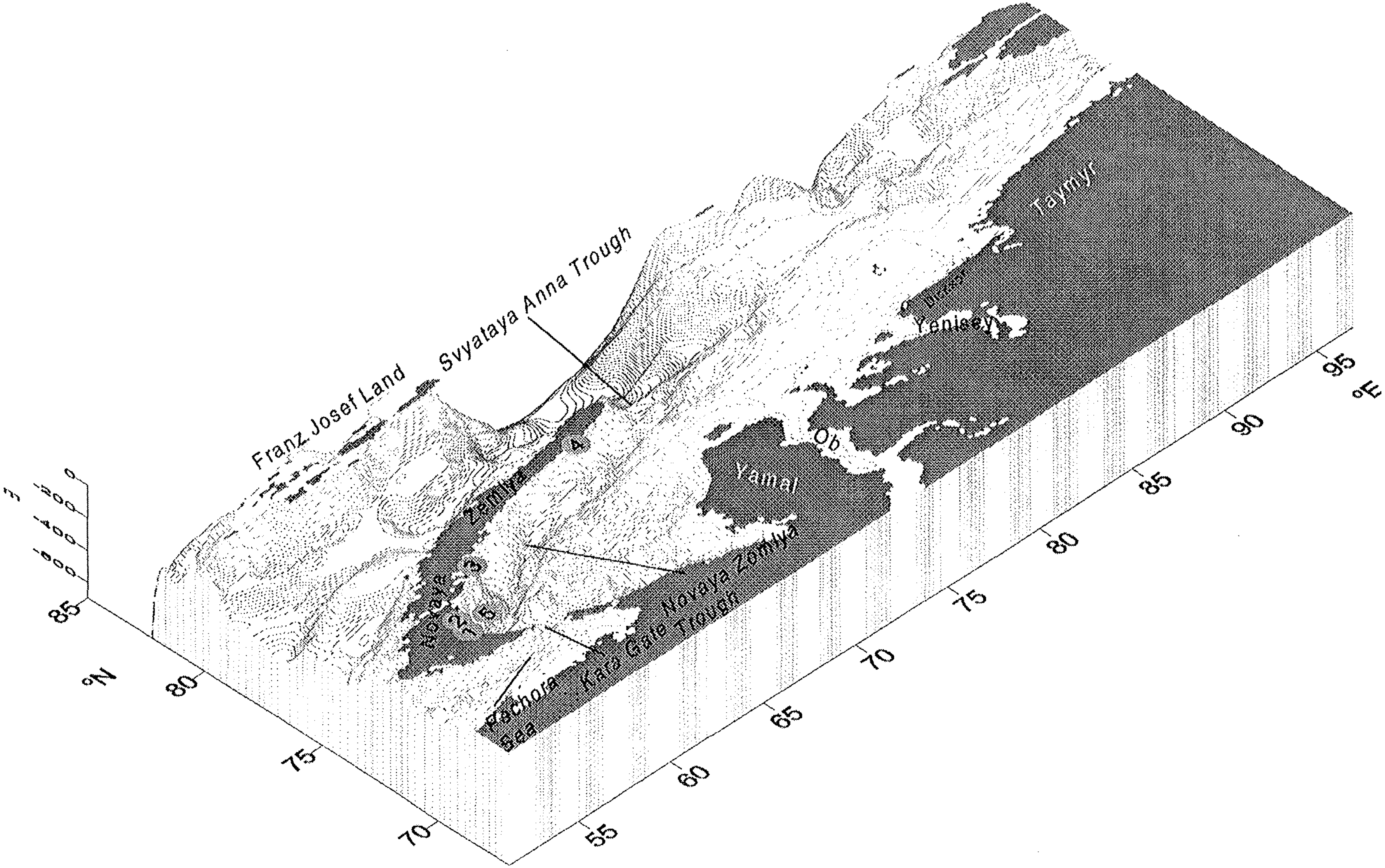


FIG. 5. Bathymetry of the Kara Sea.

The surface Kara Sea water can suffer modifications due to ice formation and mixing with other water masses. It is therefore characterized by significant seasonal fluctuations of salinity and temperature: between 25‰ and –1.4°C respectively in winter, and 22‰ and 7°C in summer. The Barents Sea waters originate in the Atlantic and come into the Kara Sea between the northern tip of Novaya Zemlya (Mys Zhelaniya) and Franz Josef Land and also through the Southern Novozemel'skiye straits, mainly between the southern tip of Novaya Zemlya and Vaygach Island (Kara Gate). This water mass is characterized by high salinity all year round: 35.3‰ in summer to 35.6%0 in winter. Its temperature is vertically homogeneous and varies from –1.9°C in winter to 6°C in summer. The salty and warm Atlantic water mass is formed from water flowing into the Kara Sea at depth from the Arctic Basin through the Svyataya Anna and Voronin Troughs. It presents no significant seasonal variation of salinity (35‰) and temperature (2.2°C).

The river waters have a strong influence on the hydrological regime of the Kara Sea. Their temperature ranges between 0°C in winter and 11.7°C in summer. The extent of the water mass formed by river water discharge, usually defined by an upper limit of salinity of 25‰, may reach up to 30% of the area of the Kara Sea. A strong frontal zone develops where river runoff meets more saline shelf waters. Five main rivers flow into the Kara Sea from the mainland : Yenisey, Ob, Pyasina, Taz and Pur, the first two delivering more than 90% of a total estimated mean inflow of 1100 to 1500 km^3 a^{-1} [8]. Several small rivers run into the Kara Sea from Novaya Zemlya, totalling less than 3% of the inflow from mainland rivers. As in the Barents Sea, there is a small contribution of fresh water inflow related to melting of snow and ice along the coastlines.

The water circulation pattern in the Kara Sea is strongly influenced by river inflow. A cyclonic gyre forms in the southwestern Kara Sea, while in its northeastern part northward and eastward currents dominate [9] (Fig. 6). The main flows in and out of the Kara Sea are given in Table I. It can be noticed that the dominant paths of water flowing out of the Kara Sea are northward, to the Arctic Basin, and eastward, to the Laptev Sea.

Tides have average values ranging between 30 and 80 cm [6]. Maximum values of 1.8 m are observed in the northern part of the Ob estuary. Along the shores of Novaya Zemlya tidal amplitudes reach 0.5–0.9 m.

During summer, due to melting of sea-ice, increased river discharge and insolation, well-defined thermo-, halo- and pycnoclines form at 6–8 m in shallow parts of the sea and at 20–30 m in deeper regions [12]. Cooling and ice formation accompanied by brine release result in strong vertical mixing during winter. Zones of upwelling and downwelling persist in the region of the continental slope and the troughs [7].

Oxygen concentrations are fairly high throughout the Kara Sea waters. Even in the relatively enclosed Novaya Zemlya Trough, oxygen values are typically up to only 15% lower than on the adjacent shelf [12]. Ventilation occurs due to convection following ice formation, so that only near the bottom at depths in excess of 300 m are oxygen values less than 70% saturation, indicating reduced renewal of waters.

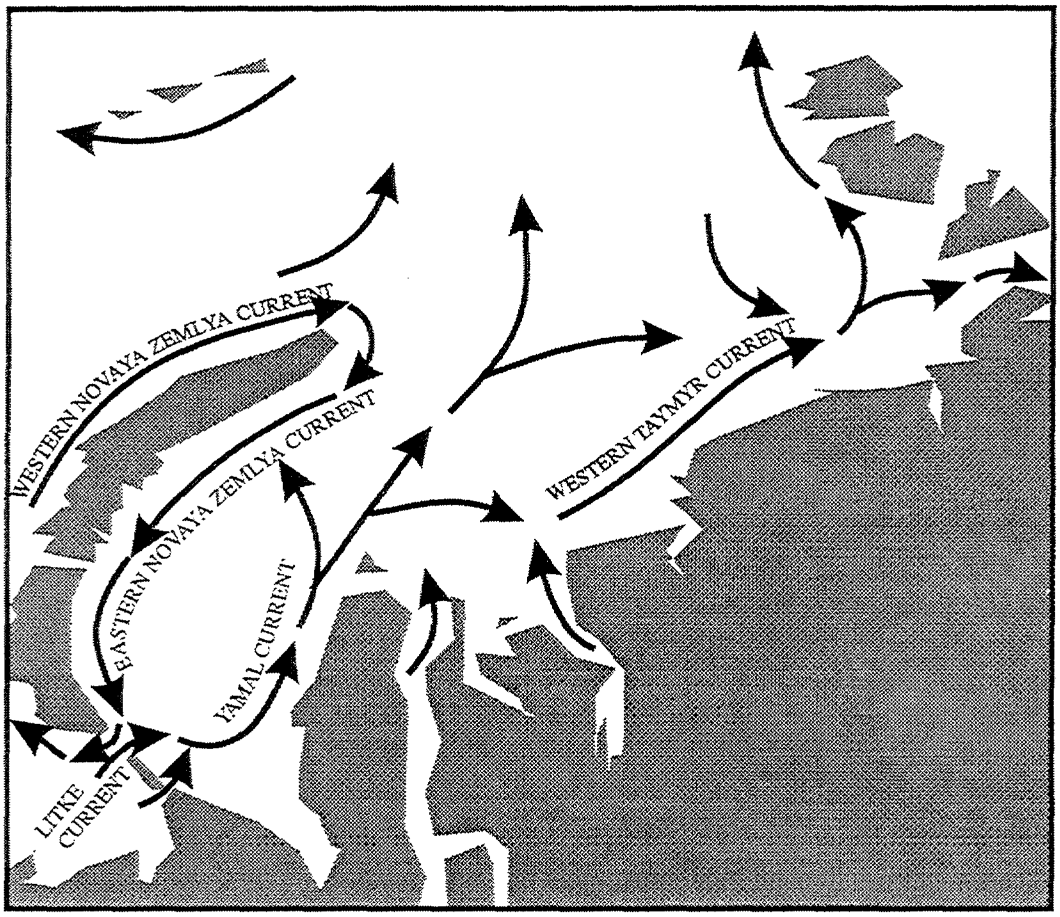


FIG. 6. Currents in the Kara Sea (drafted from [9]).

Due to its severe climate, the Kara Sea freezes over in fall–winter and is never totally ice-free [9], (Fig. 7). New ice formation starts in September in the north and about one month later in the south. On the average, from October to May, about 94% of the area of the Kara Sea is covered by ice. Mean thickness of fast ice is between 1.2 m in the southwest to 1.8 m in the northeast. Drifting ice in the central part of the Kara Sea can reach thicknesses of 1.5–2 m. The Novaya Zemlya ice massif generally melts in late summer but is a perennial feature in some years. In the northern regions ice persists all year round. Icebergs are observed in the southwestern Kara Sea, generally along the coast of Novaya Zemlya and appear to be calved mostly from glaciers on the northern island of Novaya Zemlya. It is noted [12] that most of the icebergs generated by glaciers on Novaya Zemlya are trapped in the shallow fjords. There is a net outflow of ice from the Kara Sea and a dominant flux northward. The average transit time required for ice to drift from the Kara Sea through the Arctic Basin to Fram Strait is 2–2.5 a [12, 13], considerably faster than the 5–8 a transit time estimated for water. The total ice export to the Barents and Laptev Seas and to the Arctic Basin exceeds 400 $km^3\ a^{-1}$ (Table II).

The presence of the extensive ice-cover for at least 10 months a year, considerably damping wave action and river discharge are critical factors controlling the sedimentation regime in the Kara Sea. A total of $1.4 \cdot 10^8$ t a^{-1} terrigeneous material is supplied to the Kara Sea, 80% of which comes from coastal abrasion [6]. The main rivers discharge approximately $3 \cdot 10^7$ t a^{-1} of suspended matter, 80% of it being deposited in the estuaries. The Novaya Zemlya fjords are an important source of clayey material for the Kara Sea. However, only 1.5% of the particles discharged to the Kara Sea are dispersed beyond it [5]. The suspended matter content in southwestern Kara Sea waters is below 10 mg l^{-1}, generally between 3 and 7 mg l^{-1}. Sedimentation is slow on the Kara Sea shelf and is not masked by organic oozes, since the metabolic productivity rates are also low. Sedimentation rates are estimated to be between 0.1 and 4 mm a^{-1}, the higher values being attained in areas of the Novaya Zemlya fjords. In the Kara Sea, bigranular silts (55%), sands (20%) and muds (20%) are dominant. In coastal areas and on rises, sandy and gravelly sands prevail whereas the deep sea bottom is dominated by clayey and silty sediments (Fig. 8). As typical for an Arctic continental shelf area with important river inflow, large numbers of ferromanganese nodules are found in some areas of the Kara Sea [4], along the coast and in the fjords of Novaya Zemlya (as observed during the Joint Russian–Norwegian 1994–1995 expeditions). Feldspar-quartz and micaceous-quartz varieties of terrigeneous sediments are dominant [4]. In the western Kara Sea, densities of 1.40 to 1.65 g cm^{-3} and water contents of 32 to 60% were determined for bottom sediments [7]. The organic carbon content is in the range of 0.27 to 1.99% [4].

TABLE II. ICE TRANSPORT IN THE ARCTIC [5]

From	To	$km^3\ a^{-1}$
Barents Sea	Arctic Ocean	32–33
Kara Sea	Barents Sea (Kara Gate)	4.6
Kara Sea	Barents Sea (Northern top of N. Zemlya)	140–198
Barents Sea	Kara Sea	20
Kara Sea	Laptev Sea	50
Kara Sea	Arctic Ocean	170
Arctic Ocean	Barents Sea	43.5–58
Barents Sea	White Sea	50
White Sea	Barents Sea	13.6
Arctic Ocean	Greenland Sea by the E. Greenland Current via Fram Strait	2600

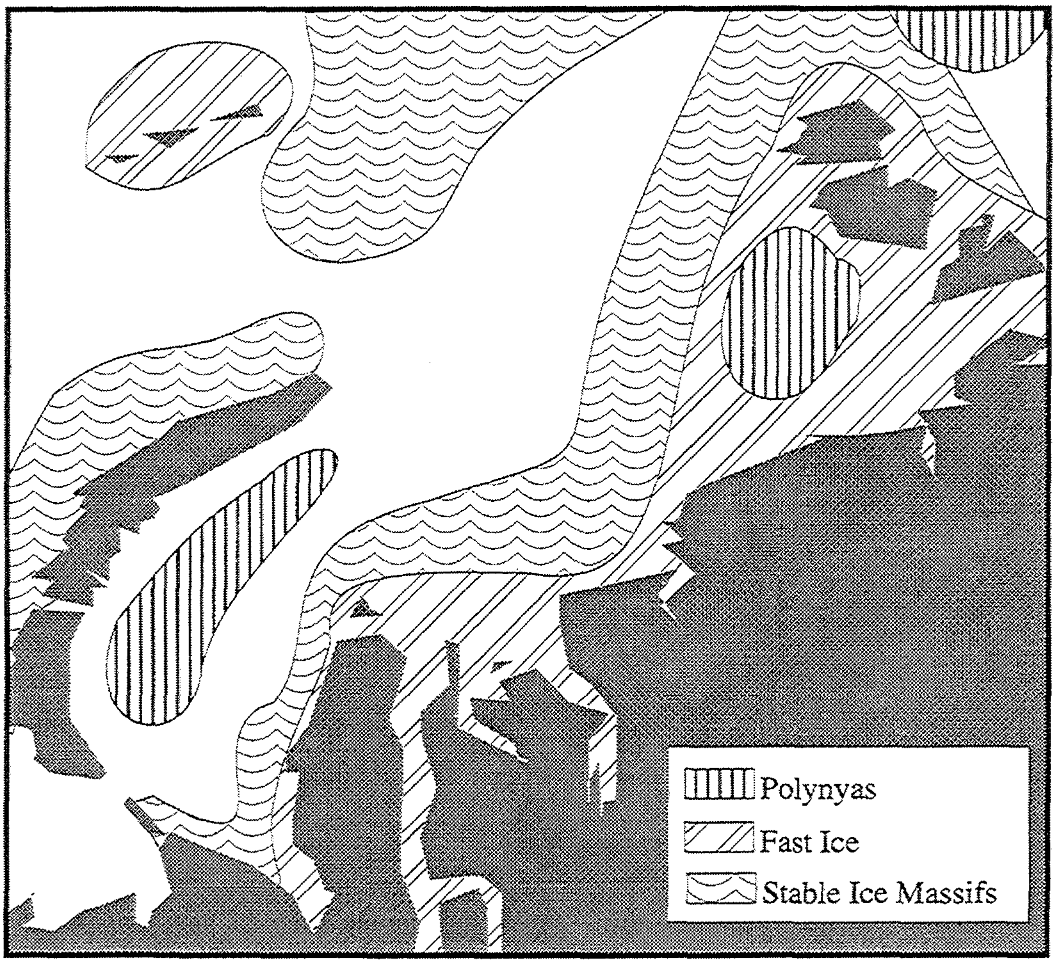


FIG. 7. Ice characteristics of the Kara Sea (drafted from [9]).

FIG. 8. Kara Sea sediments (drafted from [3]).

2.1.4. Kara Sea dumpsites

The only specific information available for the sites where radioactive waste has been dumped is derived from reports of the 1992–1994 joint Russian–Norwegian expeditions to the Kara Sea [14–16].

Abrosimov Fjord (Fig. 9) has smooth topography, with depth reaching maximum values of about 20 m inside the fjord [16]. There are two inflowing rivers, the main inflow occurring through Abrosimov River. The fjord is clearly under the influence of Barents Sea waters flowing into the Kara Sea through the relatively nearby Kara Gate. High salinity (33.4‰ to 34.1‰, except for a very thin desalinated surface layer) and temperature (0.4°C at the surface to over –1.2°C at the bottom) were recorded in August–September, and several water masses can be clearly identified from the CTD profiles. Bottom sediment generally consists of fine mud, with clayey mud covering the central part of the fjord. The bottom of the shallow areas at the mouths of the rivers is covered with sand. At the mouth of the fjord there are coarse sands covered with gravel. Life is relatively abundant in Abrosimov Fjord.

Stepovoy Fjord has widths below 2 km on the 10 km stretch investigated in 1993 and 1994 (Fig. 10). A shallow sill at about 20 m depth separates the inner, deeper part (maximum depth 60 m) from the outer part of the fjord (depths up to 40 m). A dissolved oxygen profile measured in the inner part of the fjord indicates good ventilation of bottom waters [16]. In September, the inner basin was relatively strongly stratified as compared to the outer part of the fjord and the nearby coastal area. In the inner basin, the water temperature went from 3.7°C at the surface to –1.7°C near the bottom while salinity ranged from about 20‰ in the top 10 m to 34.8‰ at the bottom [15, 17]. Temperature and salinity were quite constant below 35. In the outer part of the fjord temperature varied very little with depth, being in the range of 2.6–3.4°C. Salinities slowly increased from 17‰ to 28‰ in the central part of the outer basin, while at the mouth of the fjord they were constant at 18‰ down to 15–20 m, then gradually increased to 24‰ near the bottom. The fresh water component is thus more important in the outer part of the fjord. The bottom sediments in this area also indicate strong flushing of the bottom. In the inner basin gravel and concretions line the bottom close to the shores and to the sill. The deepest region is covered with fine silt.

Tsivolka Fjord is a relatively open inlet (Fig. 11) with typical fjord-like topography. In September, the water temperature was 3.5°C at the surface and –1.5°C at the bottom, with a thermocline at around 20 m depth [15, 17]. Salinity ranged between 14‰ at the surface and 38.4‰ at the bottom. In the bottom layer water turbidity was high. Except for shallow nearshore sites and high bottom current areas at the mouth of the fjord, the bottom sedimentary material consists of fine mud. The fjord is rich in benthic fauna, particularly sea-stars (*Ophiuroidea*), isopods and amphipods (*Gammarida*). The most abundant species of seaweed are *Fucus evanescens* and *Laminaria digitata* [17]. Fish are rare.

The fjords are completely frozen in for at least 10 months a year. Average flushing times of a few months can be expected on average, somewhat slower in winter due to the ice cover [18]. Complete flushing of the fjords, especially the smaller, shallower ones, can occur during a couple of days under storm events. No signs of ice scouring were seen at visual inspection of the fjord bottoms.

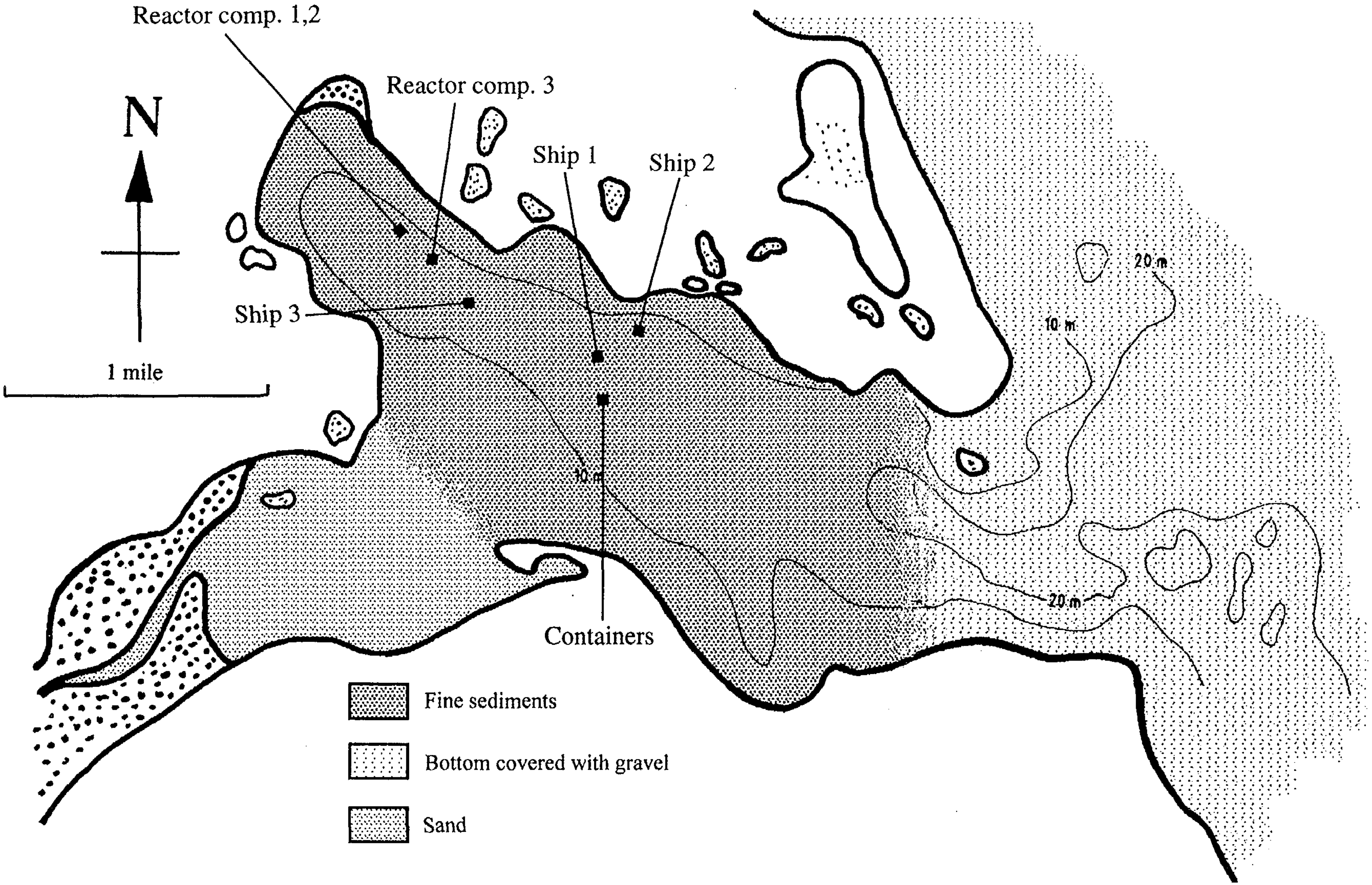


FIG. 9. Bathymetry of Abrosimov Fjord with localized dumped objects.

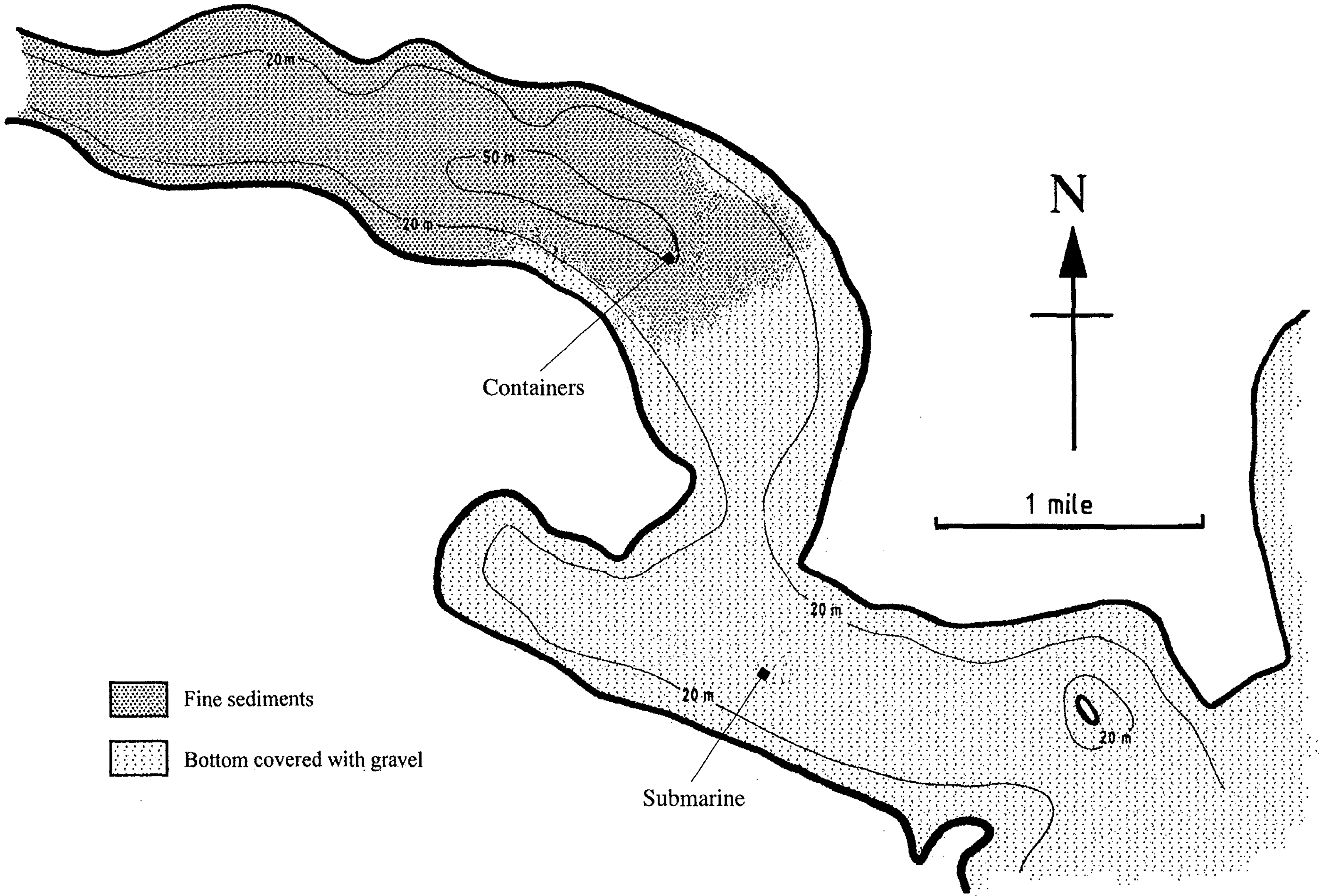


FIG. 10. Bathymetry of Stepovoy Fjord with localized dumped objects.

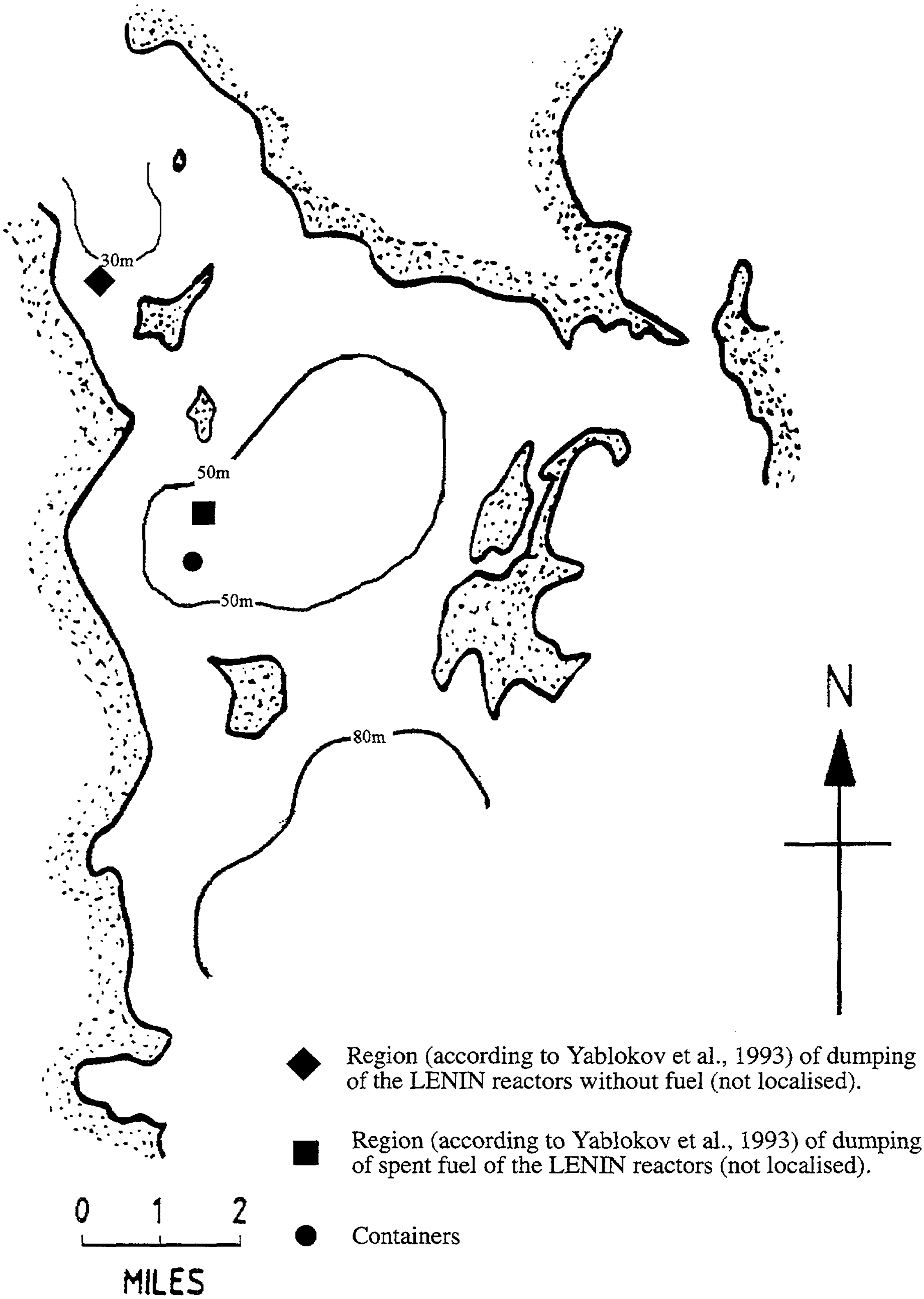


FIG. 11. Bathymetry of Tsivolka Fjord with localized dumped objects.

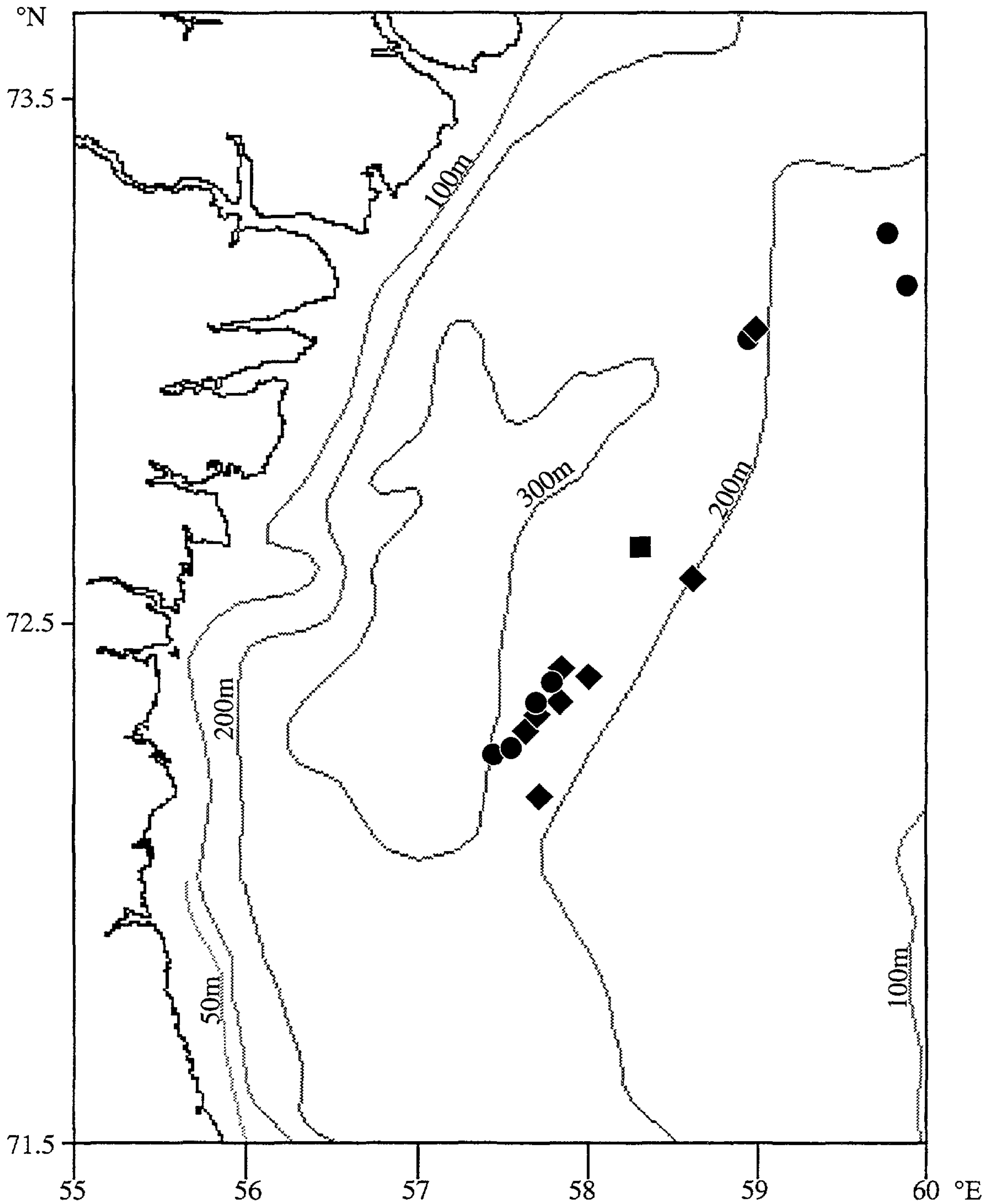
Novaya Zemlya Trough (Fig. 12) reaches depths up to about 430 m. Temperature and salinity profiles [15] have allowed identification of four main water masses, in which the influence of river water, of water of Atlantic origin and of processes related to ice formation can be recognised [17]. The surface layer has relatively low salinity (about 32‰) and high temperature (2–2.5°C). Below the sharp halocline at 20 m, the salinity smoothly increases with depth from about 34.5‰ to almost 35.4‰. The temperature, however, is constant at –1.75°C down to about 100 m, increases to a maximum of about –1.2°C at 150 m, then slowly decreases to –1.86°C (near-freezing temperature) near the bottom. The high density of the bottom water will obviously lead to increased residence time of water in the lower layers of the trough. At the investigated sites the bottom is covered with fine sediments and is inhabited by a benthic fauna composed mainly of brittle stars and amphipods.

2.2. ECOLOGY

2.2.1. Biological production in the Arctic

Biological production in high latitudes is usually low and very uneven throughout the year. The very poor illumination over much of the year with darkness over the extreme winter months, loss of light due to reflection, and the greatly reduced penetration due to the thick ice cover, severely limit primary (phytoplankton) production. A marked seasonal change in primary production may be evident, however, since over the very brief summer of long days, a bloom of phytoplankton, mainly diatoms, is possible. Seeding of diatoms is normally satisfactory at high latitudes because some species, especially those which have resting stages, can survive in the ice. As soon as the snow cover disappears and the ice thins producing melt ponds, sufficient light can penetrate for growth even at very low temperatures because some indigenous species photosynthesise at temperatures below 0°C, though growth may not be efficient.

In the Arctic Ocean, light penetration through the snow-covered ice is so poor that production increases only in late June to a fairly low maximum in August. The productive cycle lasts only about 3 months and primary production is not exceptionally high even over that period. [19] suggested that, in mid-summer, production in Arctic waters could reach 1 g C m^{-2} d^{-1} but, where ice cover was maintained, it could be as low as 0.03 g C m^{-2} d^{-1}. During winter, production is undetectable. With the extremely brief summer, annual production must be poor although determinations of annual biological productivity are very few. An assessment of the annual rate of new production, or the fraction of total biological productivity which depends on the resupply of nutrients to the continental shelves, can be made from chemical measurements. Regional average new production derived from total carbonates measured in the upper halocline was estimated to be 45 g C m^{-2} a^{-1} [20]. A second estimate for new production was derived from the apparent oxygen utilisation rates, which were determined from modelling profiles of chlorofluoromethanes, salinity, temperature, and oxygen in the water column [21]. The value obtained for shelf production, subject to several qualifications, was between 8 and 21 g C m^{-2} a^{-1}. These numbers can be compared to values for total production in the Arctic Ocean ranging between 12 and 98 g C m^{-2} a^{-1} [22]. As a general rule, at any latitude, inshore waters tend to be more productive than offshore waters. Occasionally, offshore waters can show high rates of production comparable to inshore areas, but these are due to temporary enrichment and are not sustained, and annual production is always greater in inshore areas. This also applies to the Arctic Ocean and biological production will be generally more important in the marginal seas than in the central basin.



■ Nuclear submarine reactor with spent fuel (not localised).

◆ Barges and ships with solid radioactive wastes.

● Other radioactive wastes.

FIG. 12. Bathymetry of Novaya Zemlya Trough dumpsite with localized objects.

The fate of pelagic biological production is grazing by marine animals and/or sedimentation of particles. Grazing of phytoplankton by zooplankton is the basic step in any pelagic food web. Still, in polar regions, herbivorous activity by pelagic crustaceans (copepods, euphausiids) does not appear to be as important as passive sinking (as far as controlling phytoplankton biomass and distribution is concerned). This seems especially true in shallower regions and marginal ice zones, where there are large amounts of new production which are apparently not used within the euphotic zone by herbivores. This material apparently sinks from the surface layer and supports a large and active benthic community [23]. There are deeper regions, however, in which grazing is relatively more important.

2.2.2. Marine food-webs in the Arctic

Marine food-webs in polar regions are short, with only 2 to 3 carbon transfers between diatoms and apex predators. The apex predators include baleen and toothed whales, seals, walruses, bears and seabirds of several families. In the Arctic Basin, sea ice is greatly consolidated except at its periphery, and over much of its surface never melts. Negative effects of this ice coverage in terms of production and energy transfer through the food-webs are the prevention of access of land/air predators to the water column and, as already mentioned, the inhibition of light penetration and, thus, of the photosynthetic processes necessary for pelagic food-webs [24]. Positive effects of ice include the plankton blooms associated with ice margins, the provision of substrate from which micro- and macronekton seek refuge against predators, and a rich epontic community (i.e. living below the marine ice) that provides important inputs to pelagic food-webs [25].

Another habitat feature that strongly affects the trophic levels in the Arctic is the physiographic setting. The Arctic basin is characterized by broad, relatively shallow continental shelves and the majority of the surface is ice-covered year-round; this results in a relatively unproductive ocean. The Bering Sea provides a narrow connection to the Pacific Ocean, and the East Greenland and Labrador Seas connect the Arctic with the Atlantic Basin. These connections provide important inputs of productive waters to small portions of the Arctic Ocean. They also exert a major influence on the regional zoogeography of the Arctic marine biota, i.e. there is marked longitudinal as well as latitudinal change in faunal composition. The intense cold that overlies the region during winter as a result of the surrounding land masses and the important spatial and temporal changes in temperature and salinity of the surface waters (see physico-chemical description above) result in dramatic seasonal large-scale east-west and north–south migrations of many species.

In sub-polar waters, many of the fish and invertebrates that are the important links between primary consumers and higher levels of the food web are also species of great commercial importance, e.g. capelin (*Mallotus villosus*), herring (*Clupea harengus*), sandlace (*Ammodytes hexapterus*), and squid (*Illex*) in the North Atlantic low Arctic zone; and walleye pollock (*Theragra chalcogramma*) and herring in the Bering Sea low Arctic [26]. Thus, a great deal is known about the life cycles, abundance, and distribution of these important species. In high Arctic waters, however, the important secondary consumers are relatively less well known. Most of what is known about Arctic cod (*Boreogadus saida*), a key species in Arctic food-webs, has come through studies of predators, especially ringed seals (*Phoca hispida*) and thick-billed murres (*Uria lomvia*) [27].

In the Arctic Ocean, two trophic webs have been identified, one associated with the shallow nearshore and the other with the pelagic offshore habitats [26]. Arctic cod, the pagophilic amphipod (*Apherusa glacialis*), euphausiids (*Thysanoessa*), and copepods (*Calanus*) are central to the pelagic web and are important in that of the nearshore, but in the latter, organisms of the epibenthos contribute substantially to energy flow. Arctic cod in their first year feed principally on copepods, but as juveniles and adults they switch more to amphipods such as *Parathemisto* [27]. Although a number of mammals are components of the Arctic marine food-webs year-round, especially polar bears (*Ursus maritimus*), ringed seals, and bearded seals (*Erignathus barbatus*), there are only two avian predators: black guillemot (*Cepphus grylle*) and ivory gull (*Pagophila eburnea*) [28]). Polynyas (areas within the ice pack almost always clear of ice and with enhanced productivity at their ice edges) are particularly important to the development of these Arctic Ocean food-webs.

Several apex predators winter in large numbers in the marginal annual ice of the Bering, Labrador, East Greenland and Barents Seas. Where large polynyas occur, these predators can be found within the pack ice as well. Included among the mammals are the bowhead (*Balaena mysticetus*), narwhal (*Monodon monoceros*), white whale (*Delphinapterus leucas*), ribbon seal (*Histriophoca fasciata*), and walrus (*Odobenus rosmarus*) [28]. Major components of avian fauna are the ivory gull, as well as glaucous, Iceland, slaty-backed, and Ross's gulls (*Larus glaucescens*, *L. leucopterus*, *L. schistisagus*, and *Rhodostethia rosea*) and thick-billed murres (*Uria aalge* and *U. lomvia*) [29]. At the Bering Sea ice edge, walleye pollock, capelin, euphausiids, and a pelagic amphipod (*Parathemisto libellula*) are the mainstays of the midwater food web; walrus feed on molluscs of the benthos, and ribbon seals feed on demersal fish [30]. Copepods are important primary consumers. At high Arctic ice edges, Arctic cod, copepods (*Calanus*), *Parathemisto*, and pagophilic amphipods are important in the intermediate trophic levels [31]. Farther south, Arctic cod, capelin, and *P. libellula* are the major prey of upper-level predators.

During summer, a number of migrants increase the numbers of predators, but most do so only in ice-free waters. For example, harp seals move north to feed in the epibenthos on the shelves of the eastern Canadian Arctic as do Gray whales, fin whales and other baleen whales, as well as fur seals which frequent oceanic waters along continental slopes. Also moving into polar waters are many species of seabirds, the most abundant of which are oldsquaw and eider ducks in the nearshore (where they feed in the epibenthos), and shearwaters, northern fulmars, kittiwakes, murres, auklets and dovekies.

Arctic cod is paramount to the food web of high Arctic areas, but key prey vary regionally in low Arctic areas. For example, in the eastern Barents Sea during summer, Arctic cod is the main prey of seabirds, but in the western Barents Sea, which is strongly influenced by the warm North Atlantic Current at that time, sandlace, capelin, and herring are important food items to predators [31].

The central zone of the Kara Sea is low in productivity, with few and small-sized fish. Echinoderms dominate as predators; therefore, the energy transfer to the higher trophic levels through the food-web there is small. The trophic chain to higher organisms and humans in the more coastal environment of this sea is shown in Fig. 13 which highlights the major energy flows in the shallow waters of the sea, the potential seafood sources for humans and the paths through which radionuclides or other contaminants in the environment may reach humans.

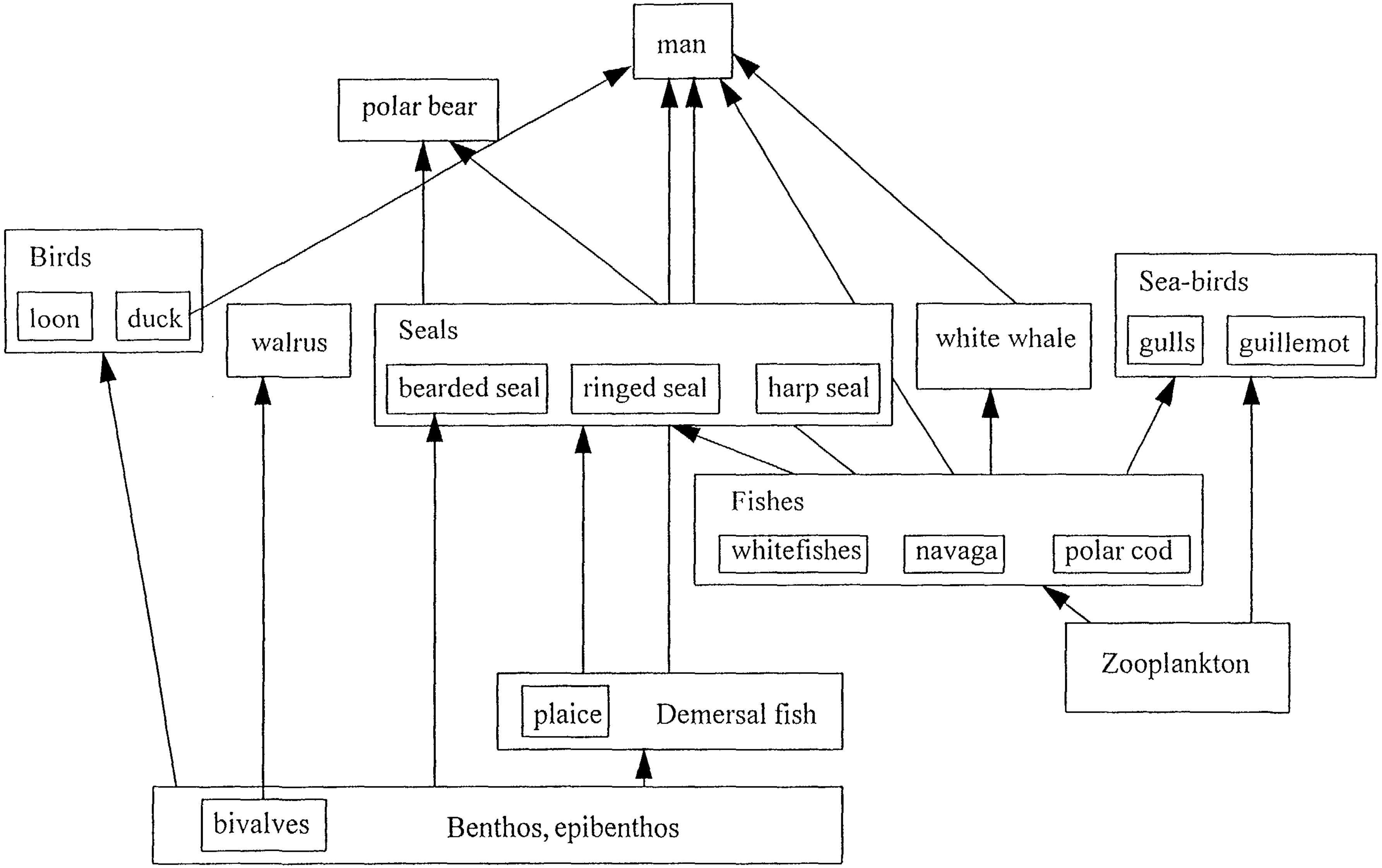


FIG. 13. Food-web of the upper trophic levels in the shallow Kara Sea and potential food sources for man.

2.2.3. Fish and fisheries in the Barents and Kara Seas

The estimated average annual primary production of the Barents Sea of 110 g C m^{-2} a^{-1} is far more than the average for the central warm ocean (<50 g C m^{-2} a^{-1}) and the ice-free parts of the Antarctic ocean (<20 g C m^{-2} a^{-1}), but is a little less than that estimated for the Bering Sea and on the continental shelf off Norway [33].

This primary production is the basis for the animals grazing on it, i.e. the secondary production or better, the zooplankton production. The main zooplankton populations consist of the copepods (mainly *Calanus finmarchicusm*, *C. hyperboreus* and *C. glacialis*) and krill (mainly the smaller species *Thysanoessa inermis*, *T. raschii* and *T. longicaudata*). Amphipods have also an important role in the Arctic ecosystem. Of these *Parathemisto libellua* is the most abundant and important. As a predator on smaller zooplankton, it forms an important link to the next step in the food web, i.e. seals, polar cod and diving birds [36].

The Barents Sea ecosystem contains some of the largest fish stocks of the world, i.e. the capelin (*Mallotus villosus*) which had a maximum registered stock size in the mid seventies of about 7.5 million tonnes [34], the Northeast Arctic cod (*Gadus morhua*) with a stock size of about 6 million tonnes just after the second World War [35] and partly the Norwegian spring spawning herring (*Clupea harengus*) which had a maximum stock size of 10 million tonnes before it collapsed in 1970 [37].

The annual harvest is from 2–3.5 million tonnes and the catches for the most, divided between Norway and Russia. There are strong interactions between these stocks, and variations in the year-class strength of the various fish stocks have a marked influence on other components of the ecosystem [34].

In addition to the direct harvest of the area, the Barents Sea is important as a feeding ground for fish populations harvested further south on the Norwegian shelf. The Norwegian shelf from 62°N and northwards is a spawning ground for the most important fish populations of the northeast Atlantic. Fish-egg and fish-larvae are transported via the Norwegian Coastal Current into the Barents Sea, where fish fry may have the benefit of abundant food.

The Kara Sea ichyofauna are far poorer than the rich selection of commercial fish of the Barents Sea. Fish are kept away by the severe climatic conditions found in the Kara Sea. The Atlantic boreal and arcto-boreal species have a limited occupational area in the Kara Sea and are found mainly in the southwestern sectors. There are 24 families of fish with 53 representatives in the Kara Sea. Polar cod (*Boreogadus saida*) is the most abundant and widespread species in the Kara Sea whereas navaga (*Eleginius navaga*) and polar plaice are usually found in the coastal and brackish waters.

The fish population is very small within the central area which is characterized by brown muds and may justifiably be called "the fishless zone". This is explained by the generally lower productive properties of this body of water and by the brown mud possessing conditions unfavourable to fish-life. The bottom fish community of the deep waters consists primarily of small-sized members of the Cyclopteridae, Zoarcidae and Cottidae families (*Artediellus, Ulcina, Licodes, Liparis* and *Triglops*). However, even these small-sized fish are extremely rare. The only Barents Sea species also found in the brown mud is the long rough dab (*Hippoglossoides platessoides*) that lives in small numbers as immature specimens or mature dwarfs. They are small in size and grow slowly. For example, a 6 to 7 year old dab is

15.5 to 17.5 cm long in the Kara Sea while at this age the species measures 30 to 31 cm in the Barents Sea.

Close to the shore, the situation is different and fish are far more abundant. The mouths of the great rivers Ob, Yenisey and Pyasina abound in fish. Suitable conditions for local brackish water fisheries exist in the southern part of the Sea, off the mainland and along the coast of Novaya Zemlya; industrial fisheries have been developed in the relatively productive Ob-Yenisey sector [35]. The northern char (*Salmo alpinus*) is found in the mouth of the rivers of Novaya Zemlya. Other major fish are the Arctic Sea whitefishes (*Coregonus*), frostfish (*Osmerus*), navaga, Arctic cods (*Gadidae*) and the Polar dab and goby. Many other fish caught there belong to the coregonids and salmonides (beardie, *Stenodus leucicthus nelma*, grayling and others). Polar cod (*Borogdadus saida*) is fairly frequently caught off the Novaya Zemlya coast, especially within the regions of the Kara Strait and Matochkin Strait.

There is no commercial catch of fish in the open area of the Kara Sea. Closer to the coast, navaga and polar cod are of commercial use among sea fish and, in the Ob-Yenisey sector, migratory and semi-migratory species are of commercial importance (frostfish, whitefish, nelma (*Stenodus*) and golets (*Salverius*)). The fishing of the latter group usually takes place during spawning in the mouth of the rivers. Separate statistics on fisheries for the Kara Sea do not exist. This Sea is included by FAO in their vast fisheries area 18, i.e. 'The Arctic Sea' whereas by ICES is included in the Barents Sea zone (ICES area 1). National fishery data exist for the largest gulfs of the Sea: in 1990, the total catch in the Ob estuary was 1526 tonnes of sea and brackish water fish and 836 tonnes of freshwater fish whereas the total fish catch was 228 tonnes in the Yenisey basin [7]. Whitefish were the most abundant species in the catches at both places.

3. RADIOACTIVITY OF THE KARA SEA

3.1. MARINE RADIOACTIVITY DATABASE

The IAEA-MEL, within the IASAP programme, has been acting as a central facility for the collection, synthesis and interpretation of data on marine radioactivity in the Arctic Seas. The data have been included in the IAEA-MEL Global Marine Radioactivity Database (GLOMARD) which has been developed to store all data on marine radioactivity in seawater, sediments and biota [39]. The database is designed to serve the following functions (i) to provide immediate and up-to-date information on radionuclide levels in the seas and oceans, (ii) to provide a snap-shot of activities at any time in any location, (iii) to investigate changes in radionuclide levels with time and (iv) to identify gaps in available information.

The data format has been rigorously prescribed to meet programme objectives and ensure maximum utility of the information contained in the database. The degree of detail is extensive (general sample information including type, method of collection and location as well as physical and chemical treatment) to allow the data to be validated and its quality assured. In addition, the database has links to IAEA-MEL's in-house analytical quality control database allowing immediate checks on laboratory practice. Information is stored in such a way as to facilitate data interrogation and analysis.

The database provides critical input to the evaluation of the environmental radionuclide levels of the region and to the assessment of the radiation doses to local, regional and global human populations and to marine biota.

The database enables :

(a) Evaluation of nuclide ratios — allows the identification of the individual radionuclide contributions to radioactivity in the region, which is critical given the multiple nature of the source terms.

(b) Investigation of time trends — given the temporally varying nature of the known sources of radionuclides in the region, the database helps to estimate source contributions to the environmental concentrations and thus increases the sensitivity with which any small residual change or trend may be detected.

(c) Inventory calculations — the ability to carry out budget calculation may again permit the detection of any imbalances.

(d) Model validation — to provide reliable predictions of the impact of real or hypothetical discharges, it is necessary to use validated models and this requires access to the existing appropriate experimental data (either in the form of time series of observation or a snap-shot of activities).

About 50 MB of data (6000 inputs) from the Arctic Seas have already been entered, with initial emphasis on the extensive joint Norwegian–Russian data, IAEA-MEL's own measurements and data obtained from other institutions.

3.2. PRE-1992 RADIONUCLIDE CONCENTRATIONS

Results of radionuclide measurements in water, sediment and biota of the Arctic Ocean are sparse as can be seen from Fig. 14, where sampling stations of ^{137}Cs is surface water are shown. The density of data is so low that sophisticated methods of data analysis cannot be used for data evaluation. The evaluation of time trends may be carried out only for the Norwegian, Barents and Kara Seas.

3.2.1. Water

Fig. 15 (a) shows the evolution of yearly averaged surface concentrations of ^{90}Sr and ^{137}Cs with time in Barents Sea surface water. The only well-documented record available is for ^{90}Sr [40] and partially also for ^{137}Cs [41, 42]. ^{90}Sr levels are gradually decreasing from an average 19 Bq m^{-3} in 1964 to the present value of about 4 Bq m^{-3}. A slight increase in concentrations at the end of the seventies and the beginning of the eighties may be associated with Sellafield peak releases in the mid-seventies. This is, however, much better documented by ^{137}Cs records, although there are also values missing for several of these years. An approximate transit time from Sellafield to the Barents Sea can be estimated to be 4–5 years. The data from GLOMARD show that there has been a decrease in the anthropogenic radioactivity of the Kara Sea in recent years (Fig. 15 (b)). For example, the ^{137}Cs content of surface Kara Sea water decreased from (18–27) Bq m^{-3} in 1982 in the south-west Kara Sea [40] to (3–8) Bq m^{-3} at present. This trend may reflect a considerable decrease in weapons testing fallout and probably also the reduction in ^{137}Cs discharges from the Sellafield reprocessing plant. ^{90}Sr in surface waters shows similar trends, the levels having decreased from (7–21) Bq m^{-3} in 1982 [40] to present values of (3–11) Bq m^{-3}.

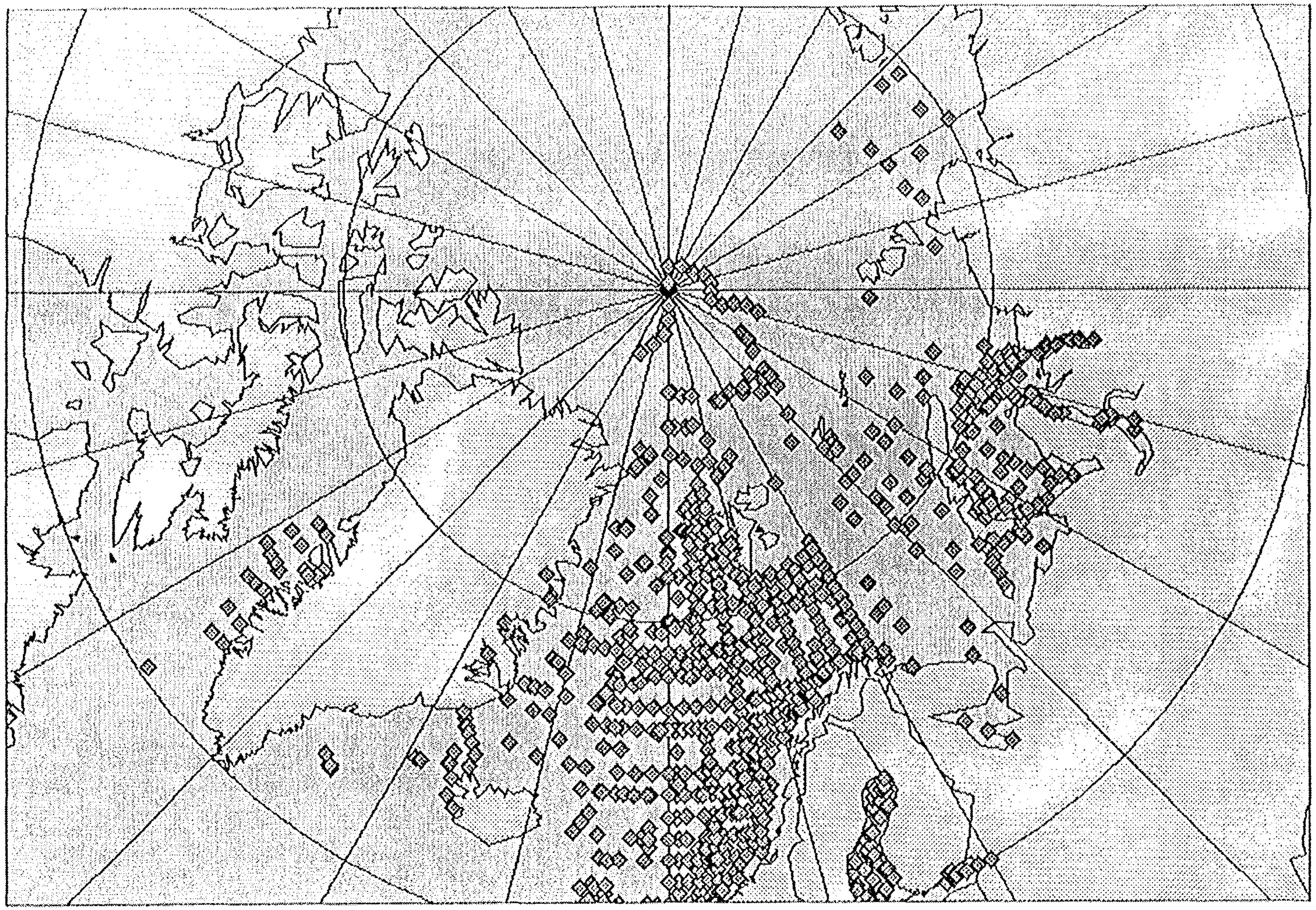
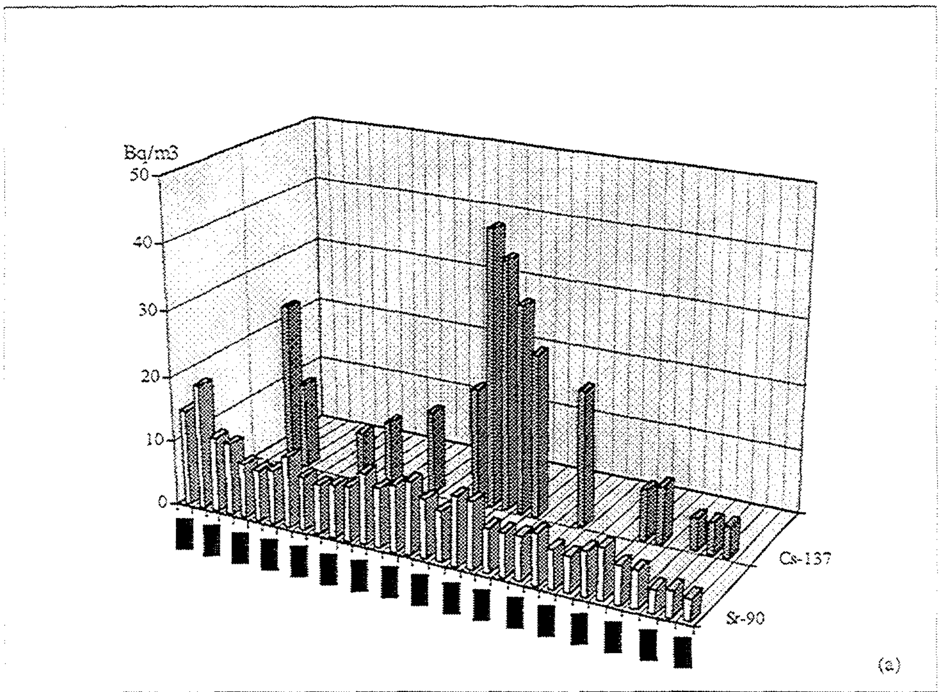


FIG. 14. Sampling stations in the Arctic Seas for Cs-137 surface water (1965–1995).



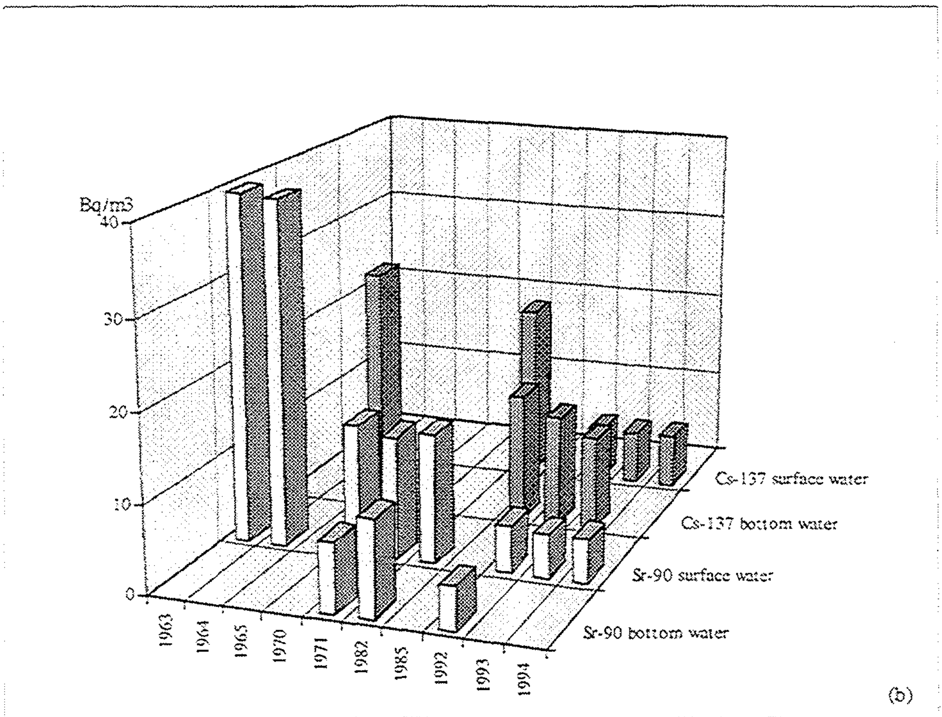


FIG. 15. Average concentrations of Sr-90 and Cs-137 in surface and bottom water in the Barents (a) and Kara (b) Seas.

In the histogram shown in Fig. 15 (b) for the Kara Sea, high ^{90}Sr concentrations (about 39 Bq m^{-3}) can be observed in the sixties which may be associated with local fallout [43]; medium concentrations (below 15 Bq m^{-3}) in 1970, 1971 and 1982, and low concentrations (about 5 Bq m^{-3}) have been observed in recent years. The ^{137}Cs data are only available from 1982, and the value for that year (about 20 Bq m^{-3}) is consistent with mean ^{90}Sr values. Present concentrations are much smaller (about 6 Bq m^{-3}) and therefore one can speculate that the 1982 value may represent the peak Sellafield signal in the Kara Sea. The approximate transit time from Sellafield to the Kara Sea would then be 6–7 years. No pre-1992 data are available for $^{239+240}Pu$ concentrations in Kara Sea waters.

The spatial distribution of ^{137}Cs in the Barents and Kara Sea surface and bottom waters for time intervals in the period 1965–1995 is shown in Figs. 16 and 17, respectively. The effect of transport of Sellafield ^{137}Cs to the Barents Sea, especially for the years 1981–1985 and the recent decrease in ^{137}Cs concentrations can be clearly seen.

Because of the above temporal trends coupled with residence time, deeper waters (>50m) in the open Kara Sea show higher concentrations of ^{137}Cs and $^{239+240}Pu$ than surface waters, by about a factor of 2–3.

The spatial distribution of ^{90}Sr in Barents and Kara Sea surface waters depicted in Fig. 18 also shows a considerable decrease of ^{90}Sr levels in the open Kara Sea. Remarkably higher ^{90}Sr concentrations have been observed in the central and eastern Kara Sea, which may be due to discharges of radioactive wastes from the former Soviet Union's nuclear plants to the Ob river but also due to runoff of global fallout from the catchment areas of the Siberian rivers and discharges from reprocessing plants in Western Europe.

The Pu-data for the Barents and Kara Seas' waters are very sparse. However, it can be seen from Fig. 19 that the $^{238}Pu/^{239+240}Pu$ ratio in Barents Sea water was above 0.1, which would indicate its transport from the Irish Sea

3.2.2. Sediment

Pre-1992 radionuclide data for sediments in the Kara Sea are very sparse. The highest ^{137}Cs levels (around 200 Bq kg^{-1} dw) were observed in the seventies in the central and eastern Kara Sea (Fig. 20). Data from the eighties show (4–20) Bq kg^{-1} dry weight for ^{137}Cs in surface sediment [40] which can be compared with the present values (18–32) Bq kg^{-1} dw [44–47]. There are no pre-1992 data available for $^{239+240}Pu$ concentrations in Kara Sea sediments.

3.3. PRESENT RADIONUCLIDE CONCENTRATIONS IN THE KARA SEA

3.3.1. Dumpsites

Radionuclide analyses of water, sediment and biota sampled at the major dumpsites in Tsivolka, Stepovoy and Abrosimov Fjords and the Novaya Zemlya Trough show that radionuclide concentrations are generally low, similar to those observed in the open Kara Sea. However, very localized contamination of sediment has been observed from leakage of waste containers in Abrosimov and Stepovoy Fjords (Table III).

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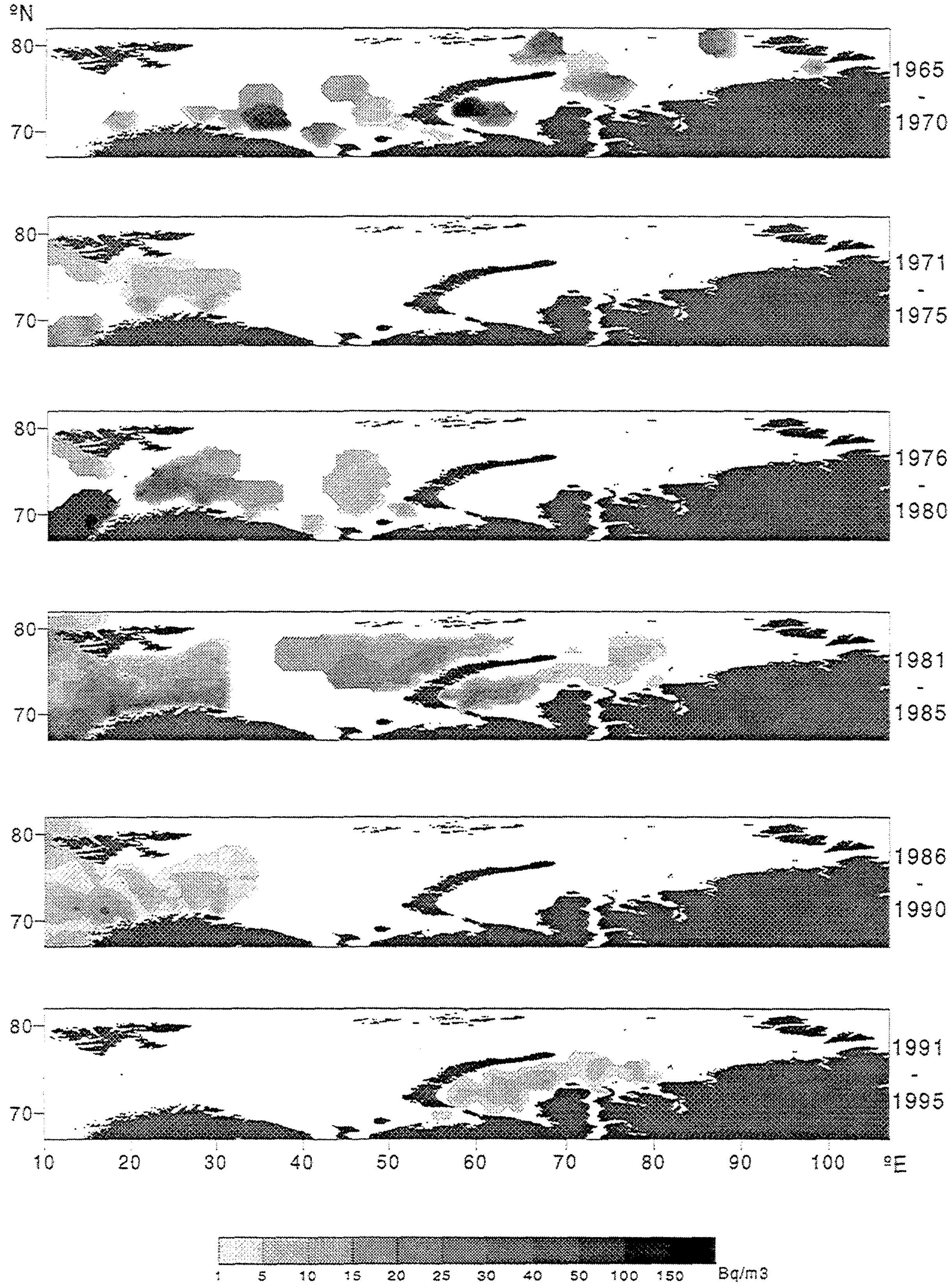

FIG. 16. Cs-137 in Barents and Kara Seas surface waters.

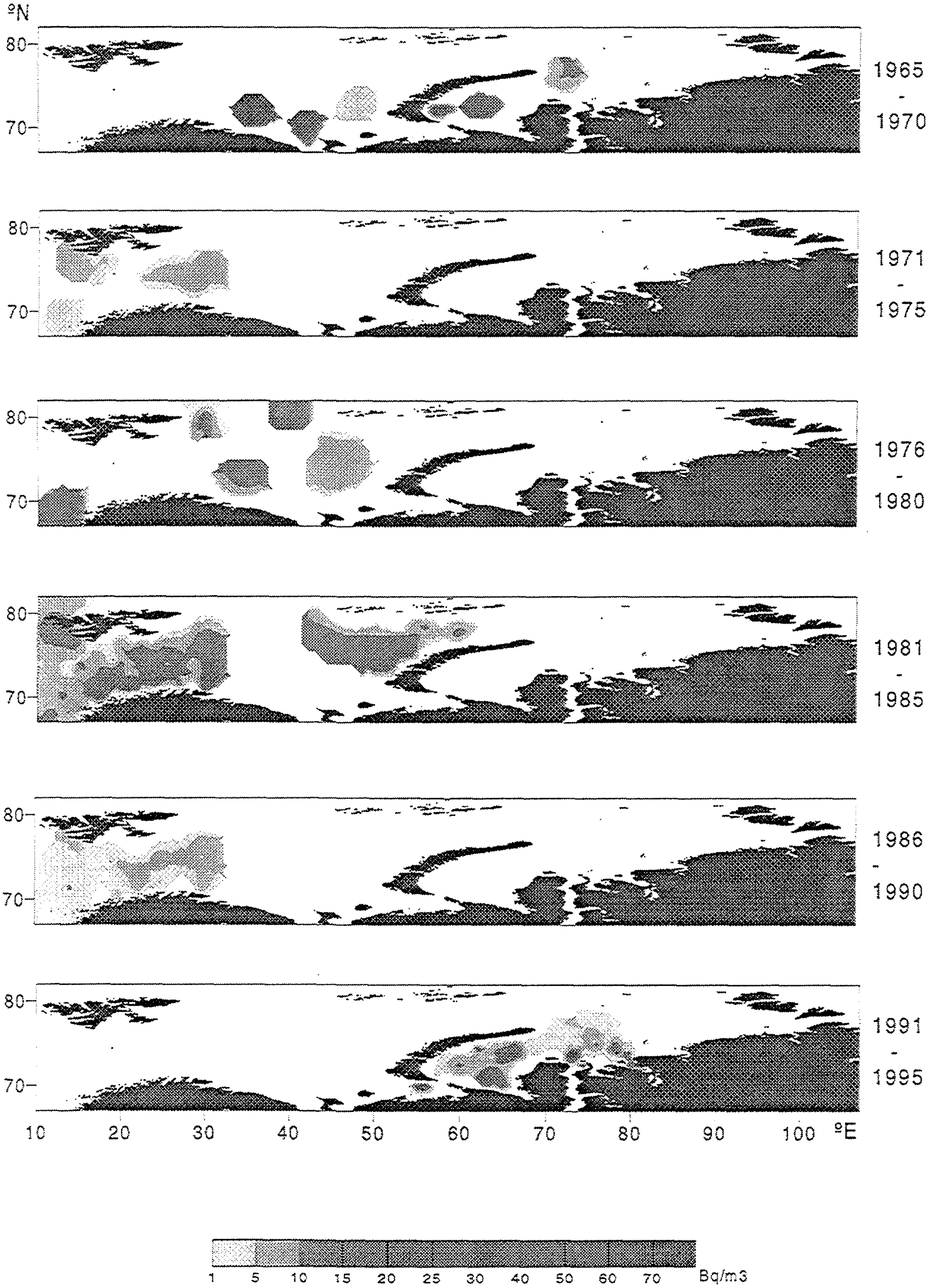

FIG. 17. Cs-137 in Barents and Kara Seas bottom waters.

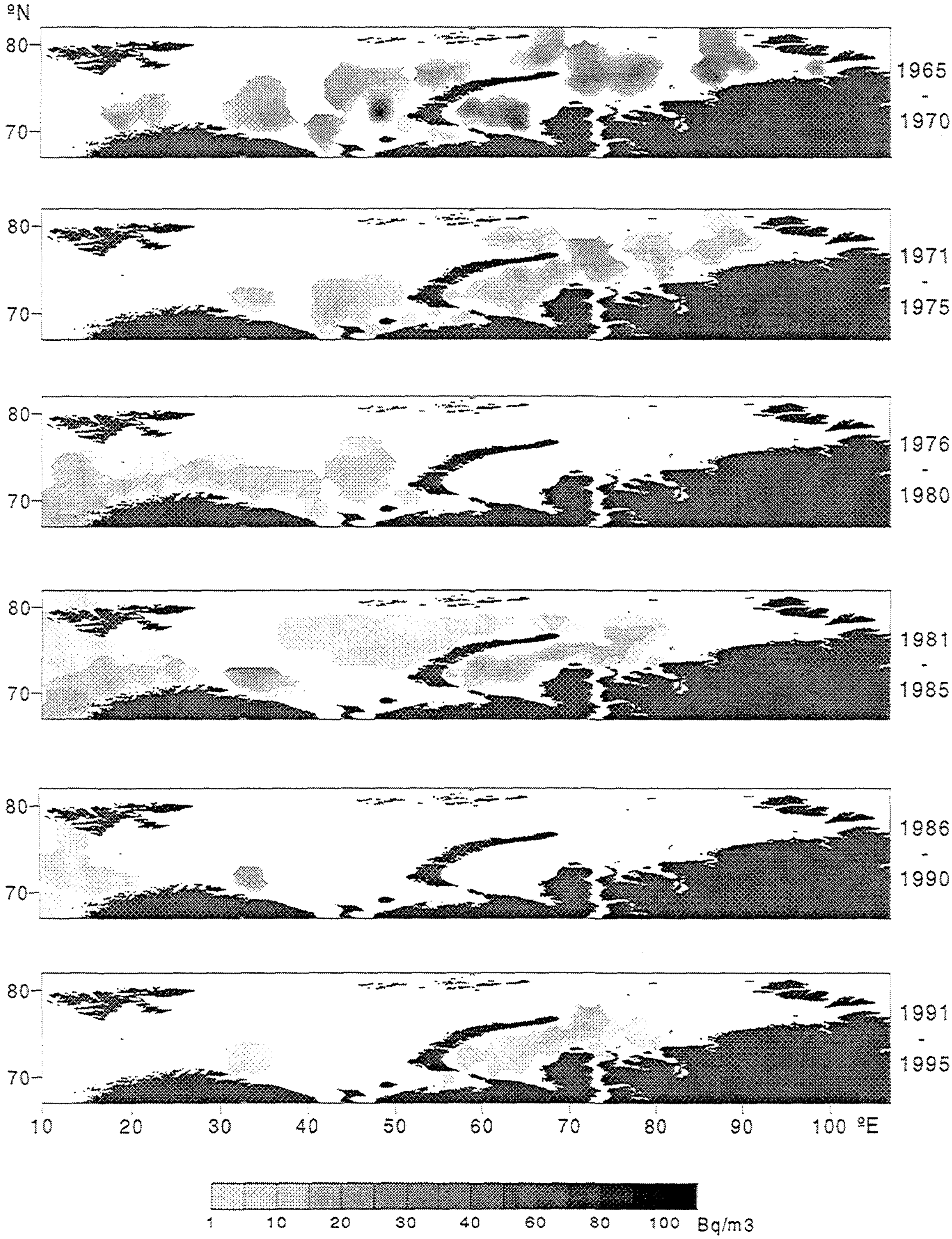

FIG. 18. Sr-90 in Barents and Kara Seas surface waters.

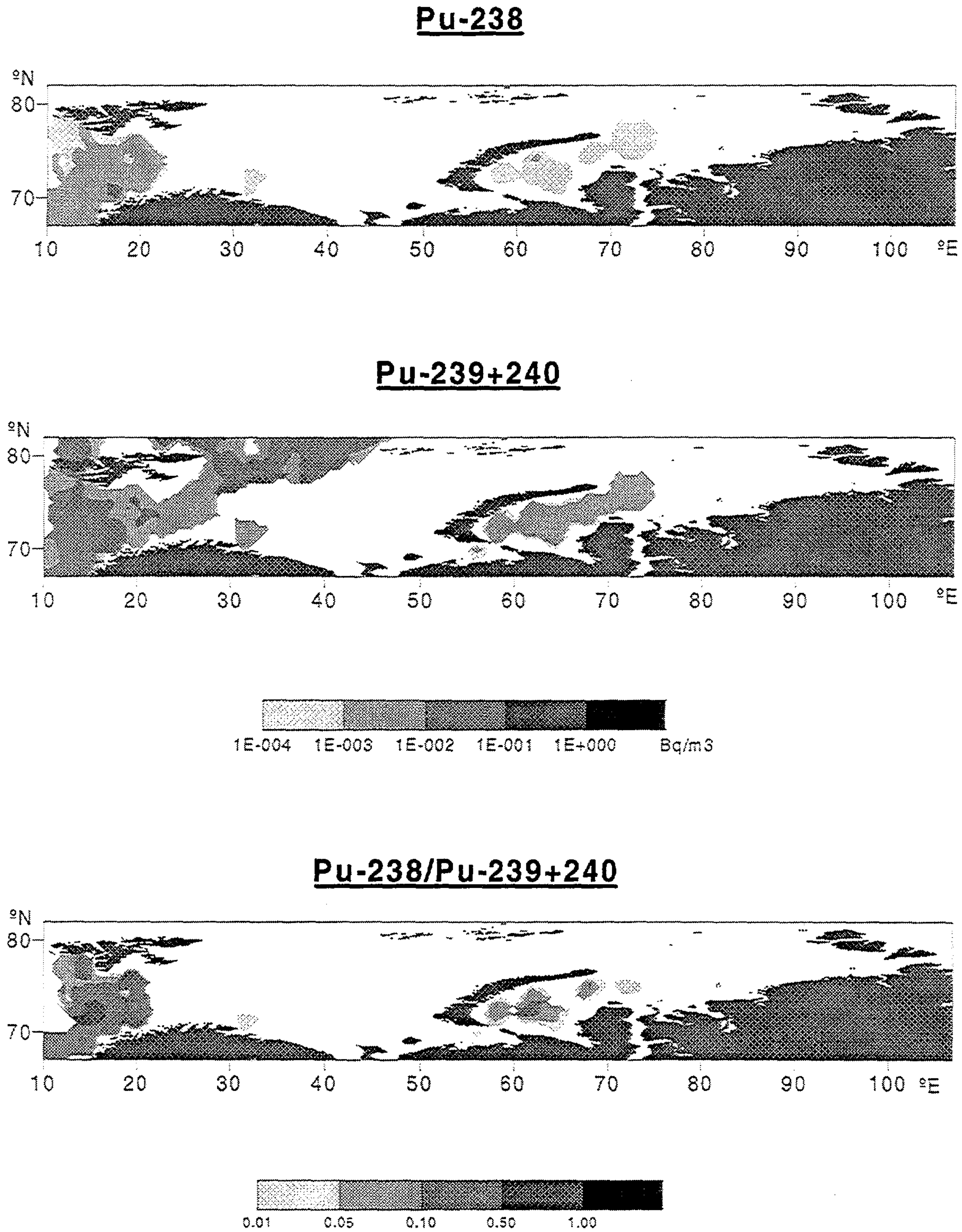

FIG. 19. Pu in Barents and Kara Sea waters (1980–1995).

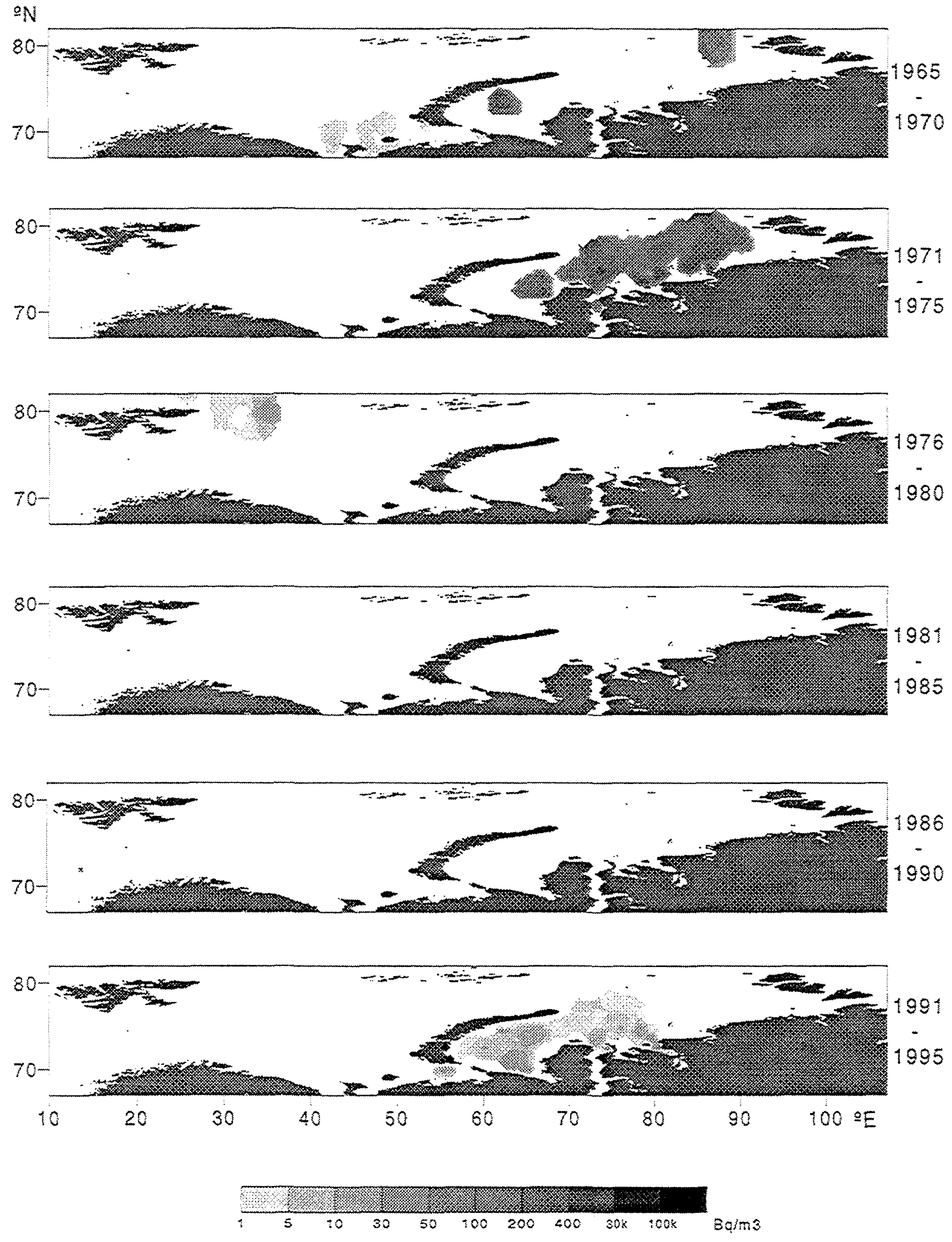

FIG. 20. Cs-137 in Barents and Kara Seas surface sediments.

TABLE III. RANGE OF CONCENTRATIONS OF RADIONUCLIDES IN KARA SEA WATERS AND SURFACE SEDIMENTS (1992–1994) [17, 44, 54]

Site	^{137}Cs Water ($Bq\ m^{-3}$) Surface	^{137}Cs Water ($Bq\ m^{-3}$) Bottom	^{137}Cs Sediment ($Bq\ kg^{-1}dw$)	^{90}Sr Water ($Bq\ m^{-3}$) Surface	^{90}Sr Water ($Bq\ m^{-3}$) Bottom	^{90}Sr Sediment ($Bq\ kg^{-1}dw$)	$^{239+240}Pu$ Water ($mBq\ m^{-3}$) Surface	$^{239+240}Pu$ Water ($mBq\ m^{-3}$) Bottom	$^{239+240}Pu$ Sediment ($Bq\ kg^{-1}dw$)	^{60}Co Sediment ($Bq\ kg^{-1}dw$)
Abrosimov Fjord	4–7	4–9	9–8400	2–4	2–4	0.3–3500	3–7	3–5	1–18	<1–66
Stepovoy Fjord	3–9	6–32	7–103000	2–7	3–26	0.4–300	2–5	2–18	0.1–15	0.1–3100
Tsivolka Fjord	4–6	6–14	4–30	4–6	3–4	0.4–1	4–10	5–8	0.03–0.5	<1–4
N Z Trough	4–7	7–14	7–30	2–3	2–4	0.8	3–4	7–12	1	<2
Open Kara Sea	3–8	8–20	2–33	3–11	4–6	0.3–0.8	2–8	5–16	0.4–1.3	

3.3.1.1. Abrosimov Fjord

An example of a profile of ^{60}Co, ^{90}Sr, ^{137}Cs and Pu isotopes in sediment collected in 1994 at the container dumpsite in Abrosimov Fjord is shown in Fig. 21. The concentrations of all detected radionuclides were higher by a factor of 10 to 1000 than those at uncontaminated sites. Contamination by fission products (^{137}Cs up to 30 kBq kg^{-1} and ^{90}Sr up to a few kBq kg^{-1} dw), activation products (^{60}Co up to a few hundreds of Bq kg^{-1} dw) and actinides ($^{239+240}$Pu up to 18 Bq kg^{-1} dw) have been observed in sediment profiles [48–54]. The ^{238}Pu/$^{239+240}$Pu activity ratio, a strong indicator of plutonium origin in the marine environment, ranges from 0.3 to 0.7 which differs significantly from the value for global fallout (0.03) and suggests a waste origin for plutonium in the sediment core. The sampling site where the highest contamination is observed does not contain reactor compartments, only low-level wastes packed in containers. This observation implies that leakage probably occurred from dumped containers due to their poor quality. However, the leakage has not led to a measurable increase of radioactivity in the outer part of the Fjord. The highly localized character of the contamination suggests that leakage probably occurred in particulate form. Some radioactive particles have also been identified in the sediment samples [51].

Fig. 22 shows a map of Abrosimov Fjord with localized dumped objects and contours of elevated ^{137}Cs concentrations in surface sediments calculated on the basis of data reported in [52–54]. A similar distribution has been observed for ^{60}Co, ^{90}Sr and $^{239+240}$Pu. However, ^{3}H, ^{90}Sr, ^{137}Cs and $^{239+240}$Pu levels observed in the water of the fjord are within the typical range for the open Kara Sea. This would imply that leakage is not continuing at present and that the sediment contamination observed occurred in the past.

Radionuclide inventories in sediments for ^{137}Cs are up to 3000 kBq m^{-2} at locations where leakages have been observed. Similarly ^{60}Co and $^{239+240}$Pu inventories are up to about 3 and 0.2 kBq m^{-2}, respectively [53].

3.3.1.2. Stepovoy Fjord

Perhaps the single most persuasive piece of confirmatory evidence of background radionuclide levels in the Fjord is IAEA-MEL's sea-bed gamma-spectrum from the sediment surface at the Stepovoy Fjord dumpsite (Fig. 23). This spectrum obtained using IAEA-MEL's underwater survey system which includes a propane-cooled HPGe detector [18, 50 ,55], is one of the first sets of high resolution gamma-spectra ever recorded in situ in the marine environment. The spectrum shows at a glance the predominance of the gamma ray lines from naturally occurring (background) radionuclides, namely from ^{40}K and the U and Th decay series. The only identifiable anthropogenic radionuclide is ^{137}Cs at a concentration which is clearly well below those of natural radionuclides, indicating that, even near to this major nuclear waste dumpsite, the gamma ray flux is essentially natural in composition and in intensity [18].

Higher concentrations of ^{137}Cs, ^{60}Co, ^{90}Sr and Pu isotopes (^{137}Cs up to 110 kBq kg^{-1}, ^{60}Co up to 3 kBq kg^{-1}, ^{90}Sr up to 0.3 kBq kg^{-1} and $^{239+240}$Pu up to 10 Bq kg^{-1}) have been measured only at very localized places around dumped containers [14, 59, 50] (Fig. 24). As in Abrosimov Fjord, the leakage has not led to a measurable increase in radionuclide contamination the outer part of the Fjord.

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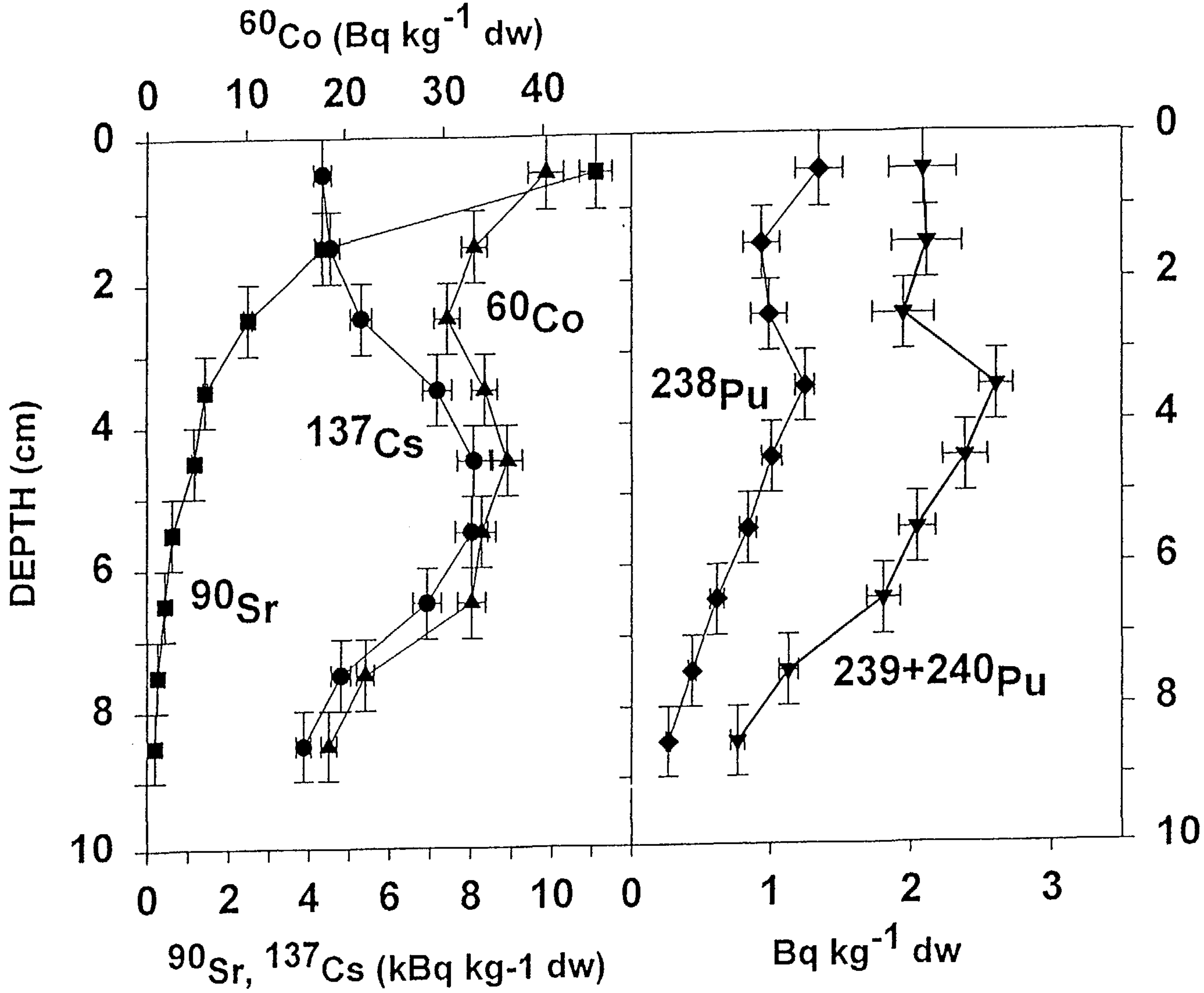

FIG. 21. Radionuclide profiles in a sediment core collected at Abrosimov Fjord in 1994 at Station 1A.

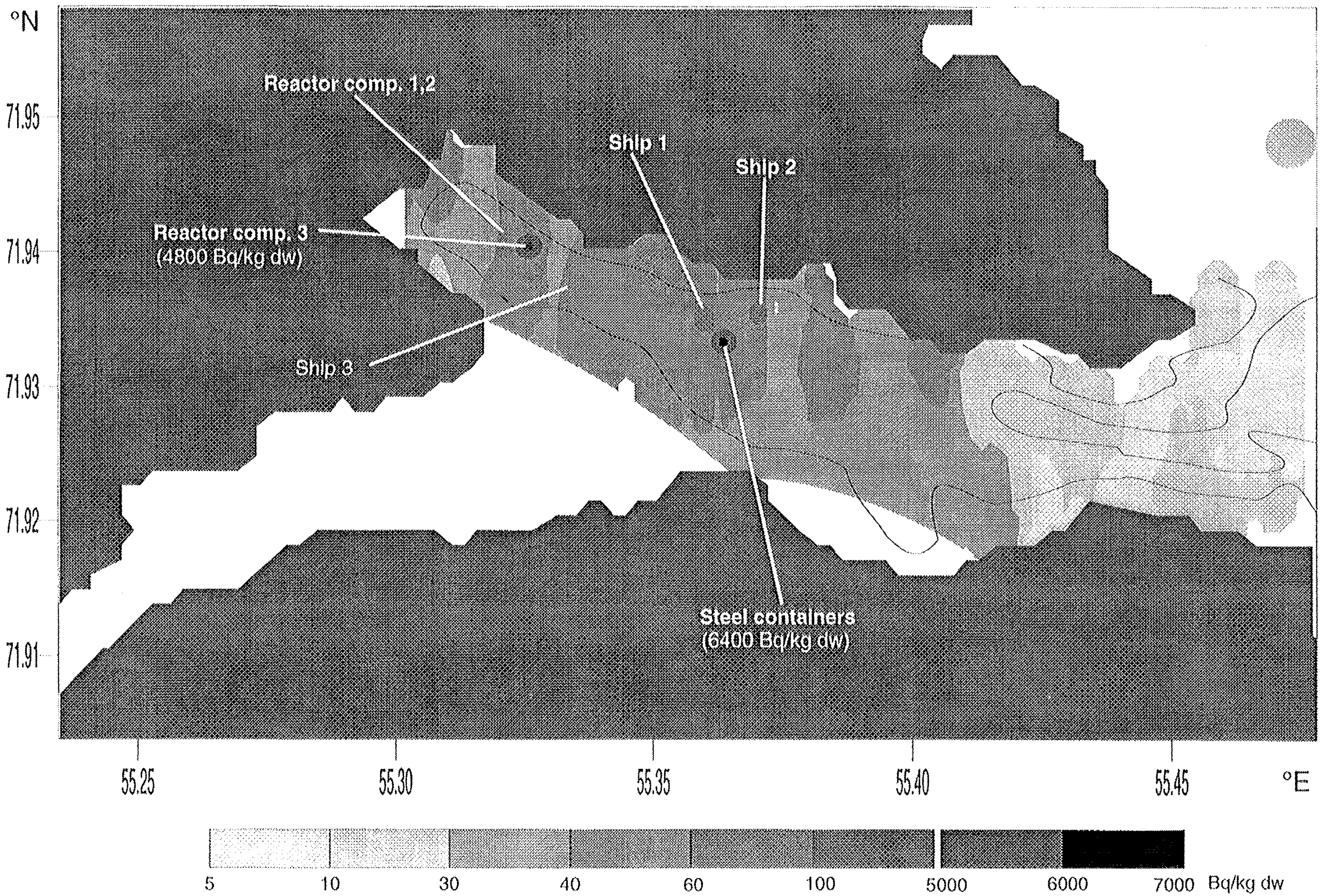

FIG. 22. Cs-137 in Abrosimov Fjord surface sediments.

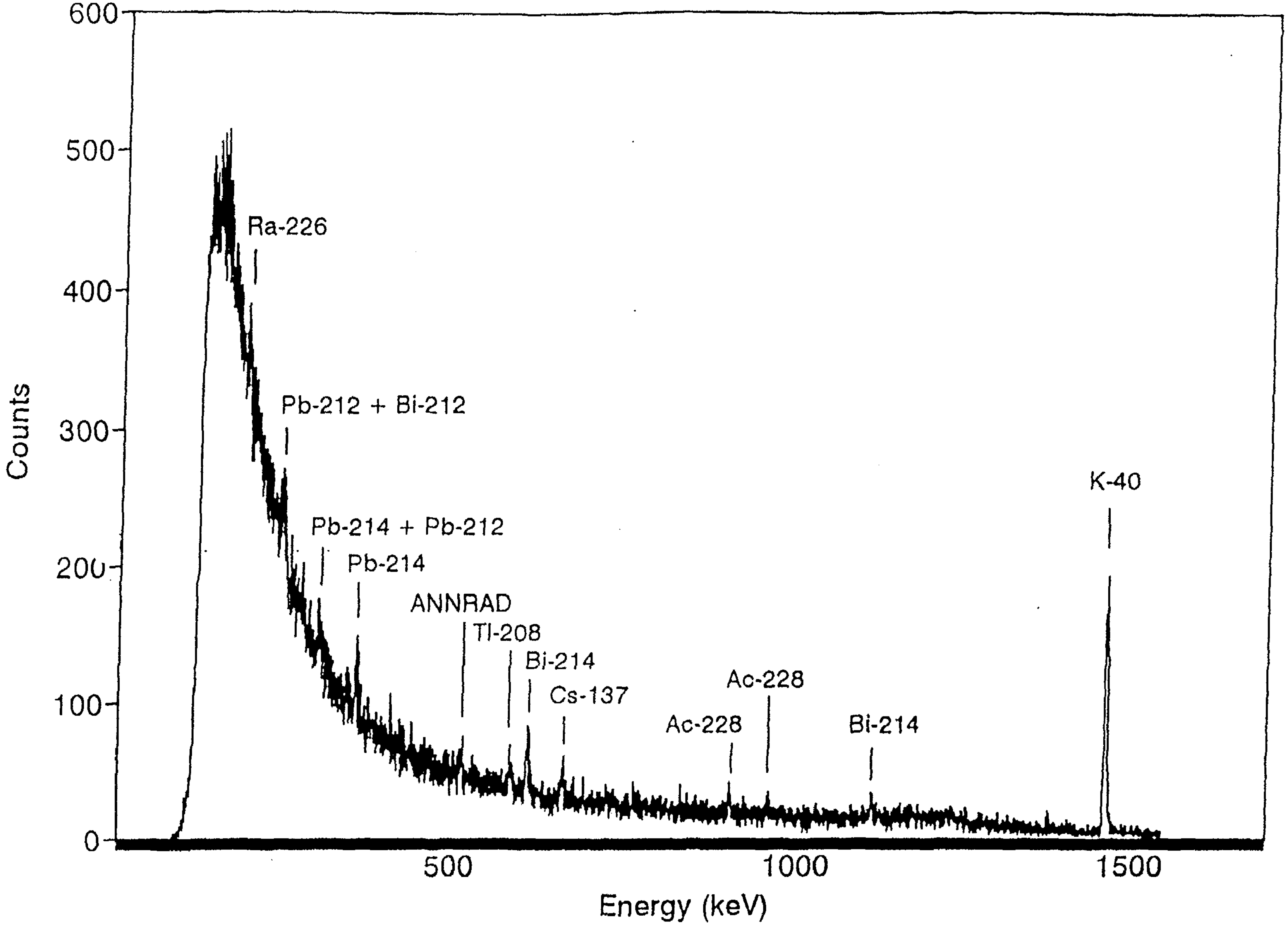

FIG. 23. In-situ sea-bed gamma-spectrum measured by an underwater HPGe spectrometer in Stepovoy Fjord in 1993. Spectrum accumulation time was 9500s.

FIG. 24. Cs-137 in Stepovoy Fjord surface sediments.

Measured concentrations of ^{90}Sr, ^{137}Cs and $^{239+240}Pu$ in the inner part of the fjord bottom water are by a factor of 3–5 higher than in a surface water, indicating a leakage from containers. In the outer part of the fjord, the concentrations are typical of those in the open Kara Sea.

Radionuclide inventories in sediments may vary for ^{137}Cs from below 1 kBq m^{-2} in uncontaminated locations to 110 kBq m^{-2} indicating that leakage has occurred. Similarly ^{60}Co and $^{239+240}Pu$ inventories are up to 26 and 0.2 kBq m^{-2}, respectively [53].

3.3.1.3. Tsivolka Fjord

Sediment cores analysed from Tsivolka Fjord have shown ^{137}Cs and $^{239+240}Pu$ concentrations comparable with those in open Kara Sea sediment [17, 52, 53] (Fig. 25). However, the presence of traces of ^{60}Co suggest a local source of contamination. The observed radionuclide profiles indicate a fast deposition of sedimentary material and effective mixing by physical and/or biological processes.

The spent nuclear fuel of the icebreaker's reactor has not been localized yet, and any possible leakage associated with this waste has not been reported. Radionuclide concentrations in water are typical of the open Kara Sea.

Radionuclide inventories in sediment range for ^{137}Cs from 0.3 to 3 kBq m^{-2}, for ^{60}Co and for $^{239+240}Pu$, up to about 0.3 and 0.02 kBq m^{-2}, respectively [53].

3.3.1.4. Novaya Zemlya Trough

No local contamination of sediment has been observed [46, 47, 59], (Fig. 26). However, the nuclear reactor dumped in the Novaya Zemlya Trough has not yet been properly localized.

As mentioned previously concentrations of ^{137}Cs and $^{239+240}Pu$ are expected to be higher in deep waters. While the ^{137}Cs concentration in surface water varies between 4 and 7 Bq m^{-3}, bottom water ^{137}Cs concentrations are 7–14 Bq m^{-3}.

^{137}Cs and $^{239+240}Pu$ inventories in sediment are in the range 0.3–0.8 and up to about 0.02 kBq m^{-2}, respectively [53].

3.3.2. The open Kara Sea

The concentrations of anthropogenic radionuclides in Kara Sea water sediment and biota are generally very low. ^{137}Cs data show almost constant spatial distribution, however, ^{90}Sr data, especially $^{90}Sr/^{137}Cs$ activity ratio in sea water vary across the Kara Sea. The ratio anticorrelates with salinity and indicates the importance of the ^{90}Sr input from the Ob river (Fig. 27).

The ^{137}Cs inventory in the water column ranges from 1 to 4 kBq m^{-2} and shows a relatively smooth and linear correlation with water depth. This implies that there are no point sources of radioactivity near the sampling stations [47].

The sediment column inventories, ranging from 0.5 to 0.9 kBq m^{-2}, show an inverse correlation with water depth, suggesting an enhanced rate of nuclide scavenging in the higher particle fluxes associated with shallower waters [47].

The total ^{137}Cs inventories in the open Kara Sea range from 1.5 to 4.5 kBq m^{-2} [53]. In comparison with the amounts of radioactive fallout deposited in the northern hemisphere [56], we estimate that the contribution of global fallout to the ^{137}Cs inventory in the Kara Sea should be about 0.5 kBq m^{-2}. This value is lower than the average measured value weighted over the mean water depth in the Kara Sea (1.5 kBq m^{-2}), suggesting that the difference may reflect contributions from local fallout and from discharges from the Sellafield reprocessing plant. Indeed, in the Pechora Sea, the observed ^{137}Cs concentrations are much higher [46, 57, 58] which reflect its close proximity to the Guba Chernaya underwater nuclear test site.

^{210}Pb has been assayed in order to estimate sediment mixing and accumulation rates and to reconstruct radionuclide levels in the past [46]. The data confirm that mixing plays a dominant role in controlling the radionuclide concentrations in surface sediments of the Kara Sea. The estimated sedimentation rate is from 1 to 4 mm a^{-1}. The ^{137}Cs depth distribution is affected by sediment mixing (bioturbation) and post-depositional migration of caesium, as the penetration of ^{137}Cs in sediment is deeper than would be expected from the ^{210}Pb age determination.

The $^{239+240}Pu$ inventory in sediments is between 0.01 and 0.03 kBq m^{-2} [53]. The $^{239+240}Pu/^{137}Cs$ inventory ratios are about 0.03. $^{238}Pu/^{239+240}Pu$ ratios in sediments are between 0.02 and 0.05 suggesting a global fallout origin for the plutonium in sediment (Fig. 28).

3.3.3. Ob and Yenisey estuaries

The Ob and Yenisey rivers are important suppliers of fresh water to the Kara Sea and possibly of contaminants (e.g. ^{90}Sr and ^{137}Cs) from land based sources. The data clearly show ^{137}Cs and $^{239+240}Pu$ depletion from water at low salinity [59]. Therefore, fast sedimentation and scavenging occur at locations of low salinity resulting in relatively high sediment inventories of ^{137}Cs (1–5 kBq m^{-2}) [53].

3.3.4. Biota

There are no data available on pre-1992 radionuclide concentrations in biota of the Kara Sea. From post-1992 data, we can conclude that typical concentrations of ^{137}Cs in the benthic fauna of the Kara Sea are around 1 Bq kg^{-1} dw. ^{137}Cs and $^{239+240}Pu$ concentrations in gammarids were found around 1.5 and 0.01 Bq kg^{-1} dw, respectively. Brittle stars (*Ophiurdea*) showed $^{239+240}Pu$ concentrations around 0.1 Bq kg^{-1} dw. Higher values of ^{137}Cs were observed for Polychaeta (*Spiochaetopterus*) between 6–17 Bq kg^{-1} in the tubes. For fish (Polar cod) caught in the open Kara Sea and in Abrosimov Fjord, ^{137}Cs concentrations were about 1 Bq kg^{-1} dw. Algae samples showed ^{137}Cs levels below 3 Bq kg^{-1} dw [52, 60, 61].

Generally, the concentrations of ^{137}Cs, ^{90}Sr and $^{239+240}Pu$ in biota samples from the Kara Sea are very low (the latter two radionuclides often below detection limits of 0.5 Bq kg^{-1} and 0.01 Bq kg^{-1} dw, respectively).

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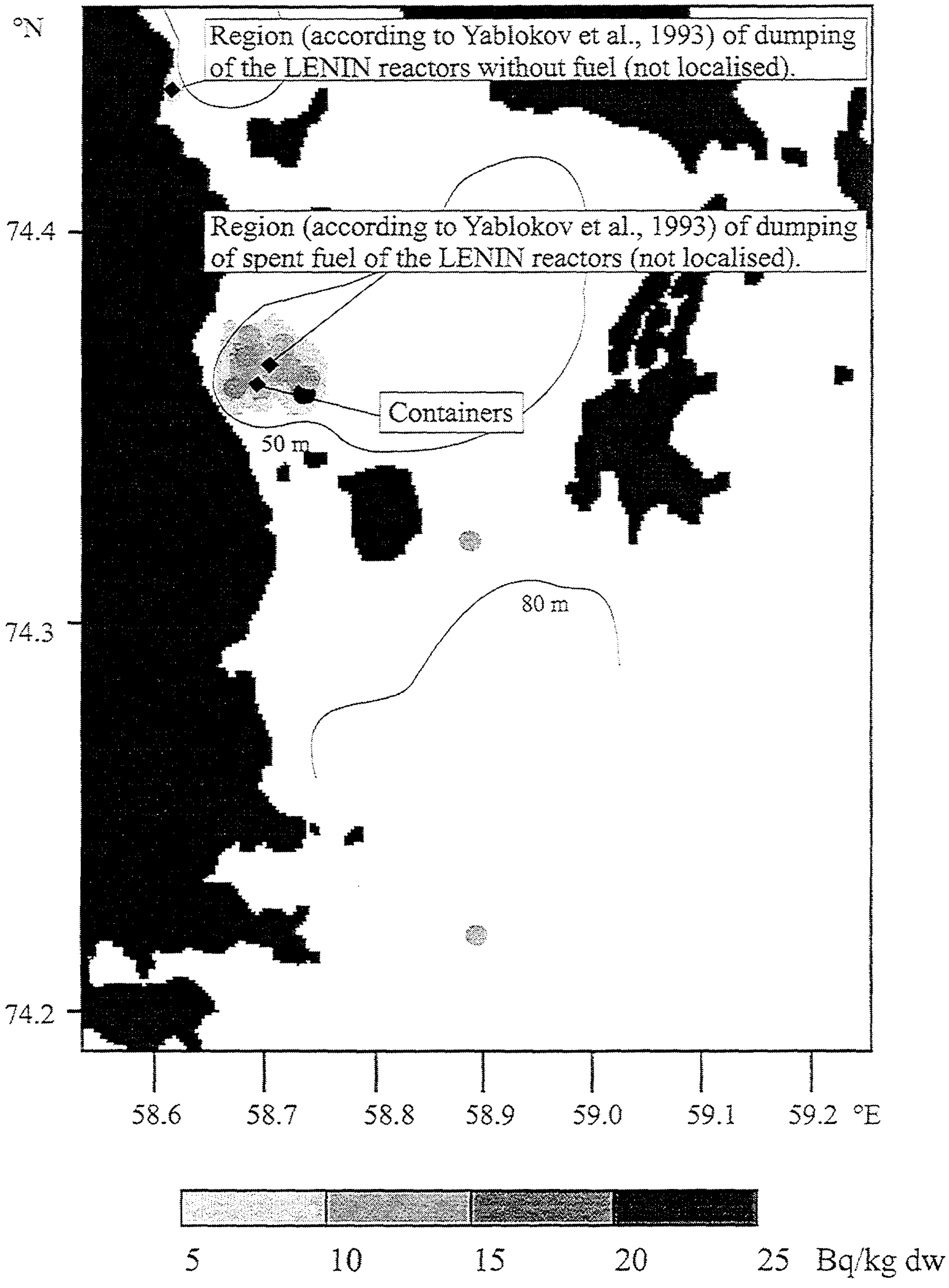

FIG. 25. Cs-137 in Tsivolka Fjord surface sediments.

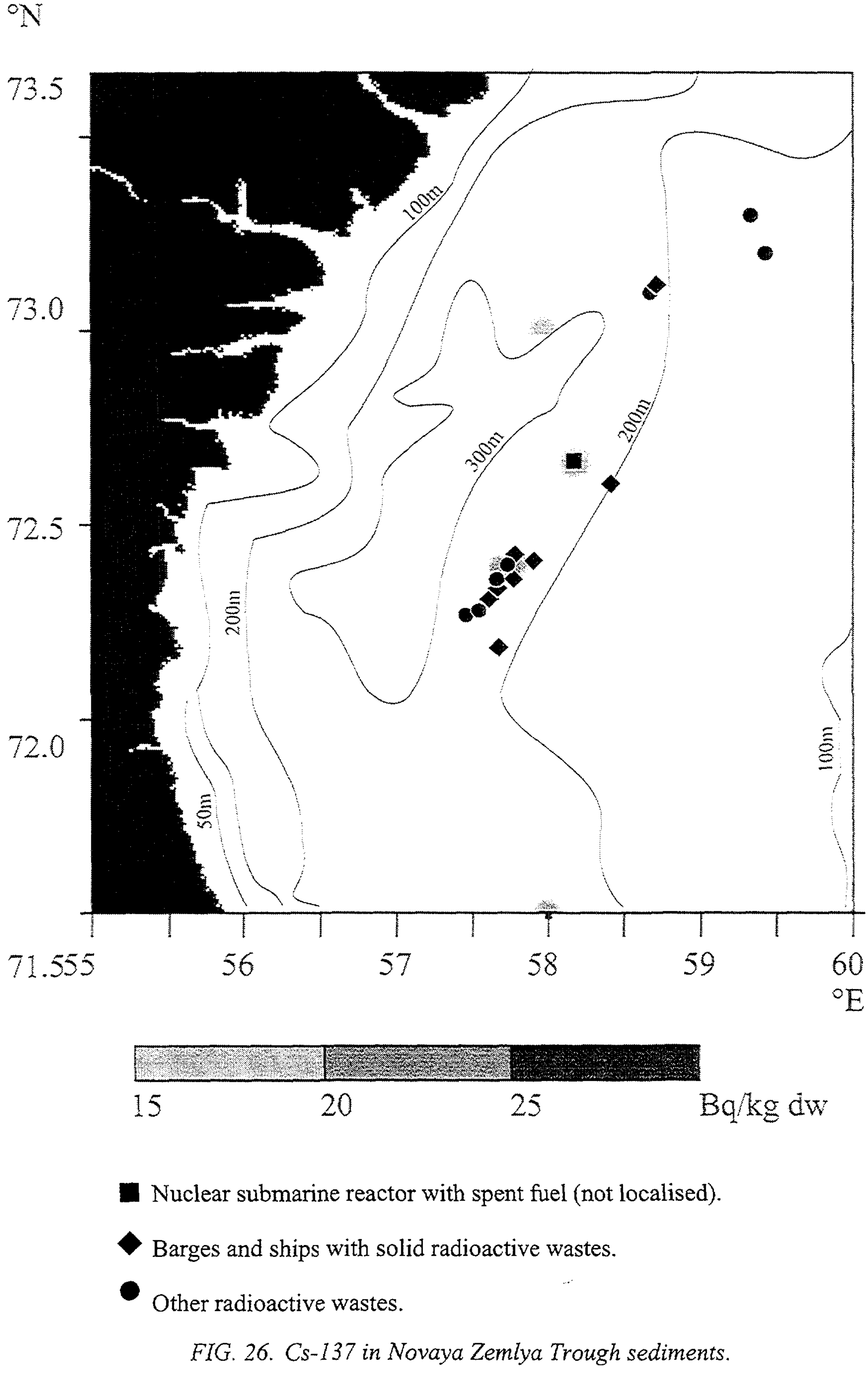

FIG. 26. Cs-137 in Novaya Zemlya Trough sediments.

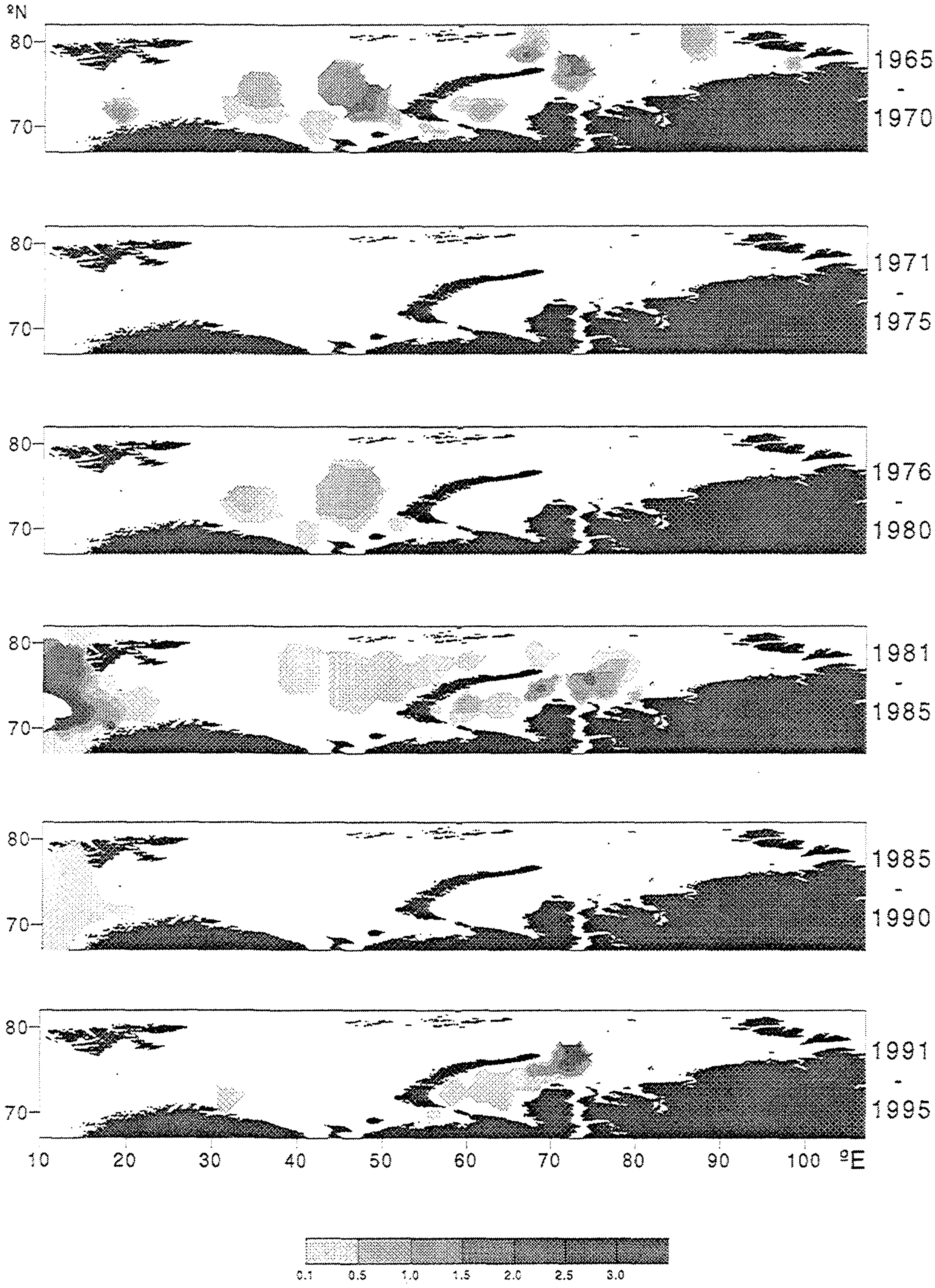

FIG. 27. Sr-90/Cs-137 in Barents and Kara Seas surface waters.

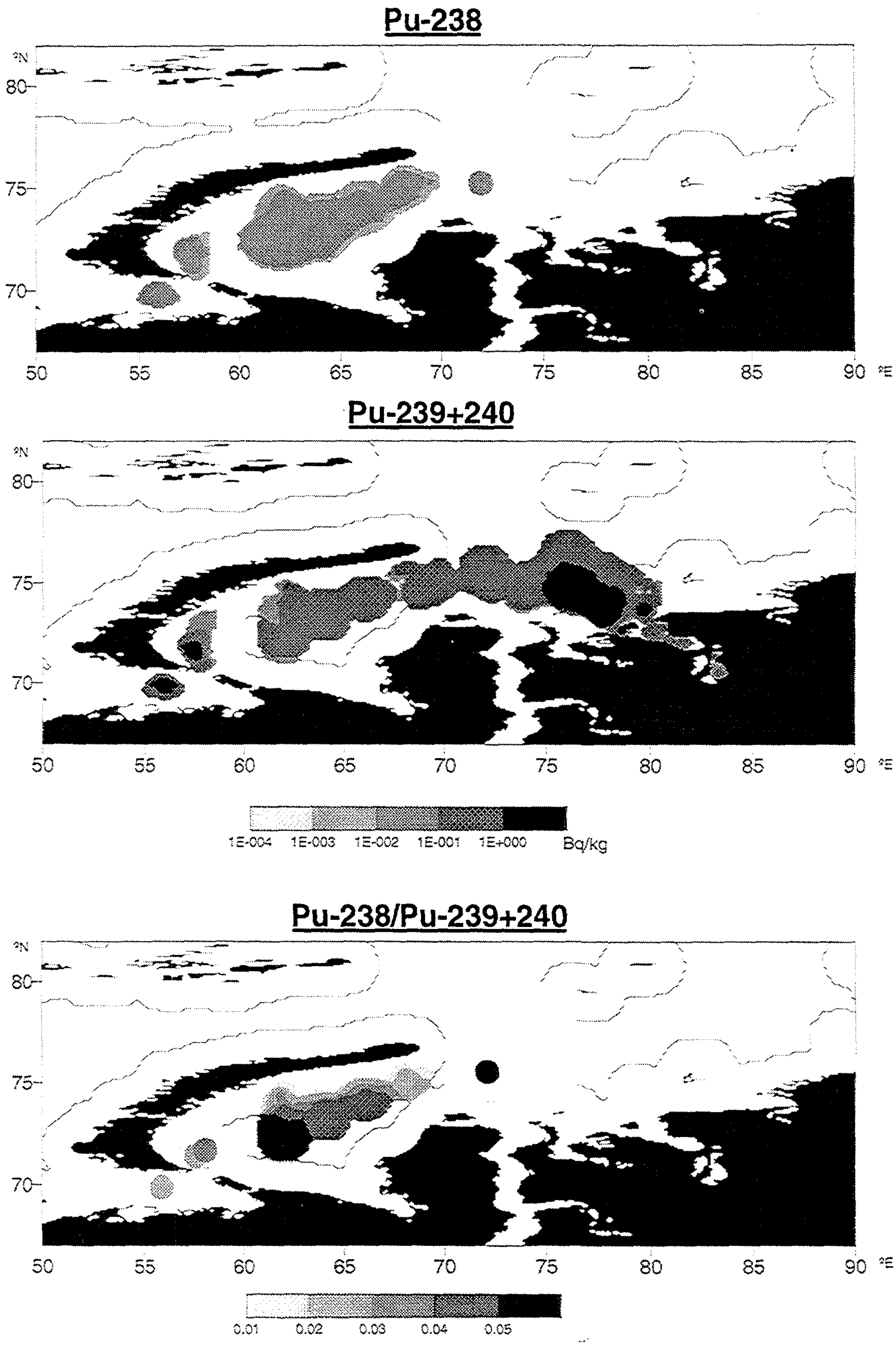

FIG. 28. *Pu in Kara Sea sediments (1992–1995).*

3.3.5. Intercomparison exercises

Intercomparison exercises were organised by IAEA-MEL for the laboratories performing analyses on samples collected during the 1992–1994 joint Russian–Norwegian expeditions to the Kara Sea, covering relevant categories of environmental matrices: sediment, sea water and seaweed. For each exercise, results were requested to be reported for at least ^{90}Sr, ^{137}Cs and $^{239+240}Pu$ - the basic group of radionuclides which have been routinely analysed and reported for Kara Sea environmental samples. The radionuclide concentrations in the intercomparison samples were representative of the levels generally encountered in the Kara Sea. Detailed results of the intercomparison exercises are reported in the Joint Russian–Norwegian Experts Group reports on the 1992, 1993 and 1994 expeditions [60, 17, 52].

As these exercises were organised for a small number of laboratories, their purpose was not to define reference values for radionuclide concentrations in the respective samples, but rather to check the agreement between results reported by the participants. On the basis of the intercomparison exercises, it was concluded that, generally, the reliability of the analytical methods used by the participating laboratories is appropriate and that the laboratories produce radionuclide concentration data which are in reasonably good agreement. For all three intercomparison materials, the best concordance amongst individual results was obtained for ^{137}Cs (around 10% standard deviation from the mean for sediment and seaweed, 5% for sea water). Good agreement was also obtained for ^{90}Sr in sea water (10% standard deviation from the mean). Due to the very low ^{90}Sr concentration in sediment and the small number of reported results for seaweed, it proved difficult to evaluate the participants' performance in these cases. For $^{239+240}Pu$, the agreement is not as good (up to 25% standard deviation from the mean) reflecting the analytical difficulties associated with its determination in environmental matrices.

3.3.6. Conclusions on radionuclide inventories in the Kara Sea

On the basis of the extensive joint Norwegian–Russian data [17, 45, 47, 49, 51, 52, 54, 60] and of IAEA-MEL [18, 44, 47, 48, 50, 53, 55, 59–64] and other results stored in the GLOMARD database [36], on measurement of concentrations of several radionuclides (^{3}H, ^{60}Co, ^{90}Sr, ^{99}Tc, ^{129}I, ^{137}Cs, ^{238}Pu $^{239+240}Pu$ and ^{241}Am) in water, sediment and biota sampled at the major dumpsites in Abrosimov, Stepovoy and Tsivolka Fjords and the Novaya Zemlya Trough as well as in the open Kara Sea and the Ob and Yenisey estuaries, it can be concluded that, with the exception of limited areas in Abrosimov and Stepovoy Fjords, only minor contamination exists relative to background levels. In-situ gamma-spectra recorded at the dumpsites indicate that the contamination has a localized character and, at sites outside the disposal areas, no contribution from local sources can be observed [16, 18]. The most marked contamination of sediment appears to be associated with leakage from dumped containers but this is confined to the immediate vicinity of the containers.

The open Kara Sea is relatively uncontaminated, the main contributions being due to direct deposition and catchment runoff from global fallout caused by nuclear weapons tests, discharges from reprocessing plants in Western Europe and the former Soviet Union, local fallout from tests performed at Novaya Zemlya and Chernobyl fallout [62–64].

4. DISTRIBUTION COEFFICIENTS AND CONCENTRATION FACTORS

Obtaining basic information on the potential uptake of contaminants by marine particles and biota is fundamental to an evaluation of the transport pathways and risks posed by waste-derived radionuclides in the Kara Sea. The concepts of distribution coefficient (K_d) and concentration factor (CF) have been used to intercompare the relative degree of uptake of marine contaminants by different sediment types and marine biota, respectively.

K_ds are used by numerical modellers in their models of radionuclide dispersion to establish the partitioning of radionuclide concentration between particulate matter and sea water. Concentration factors are used to establish the partitioning between marine biota and sea water radionuclide concentrations regardless of the pathways by which these radionuclides are taken up.

The actual values for K_d and CF are not known for many areas of the ocean and furthermore they vary spatially and temporally and are often affected by environmental and biological variables. For the Arctic, data are particularly sparse because access has been limited until recently. With little field data available, modellers have relied on values published by IAEA [65]. K_ds in this report were estimated from both stable element geochemical data and the proportions of the particulate phase abundance of the elements that are likely to be exchangeable with the aqueous phase. CFs were computed using field measurements of radionuclide and/or stable element concentrations in organisms as well as data derived from laboratory radiotracer experiments.

This chapter describes results of laboratory and field work aimed at elucidating environmental parameters that might affect K_d and CF values for arctic environments. Such information is necessary for evaluating K_ds and CFs that should be used in radiological models for specific dumpsites in the Arctic Seas.

4.1. DISTRIBUTION COEFFICIENTS

The uptake potential for radionuclides on suspended or deposited particulate matter (sediment) in marine systems is a function of the relative influence of the chemical properties of the radionuclides, sediment characteristics and the moderating influence of the environment. The unitless parameter used to quantify this potential is known as K_d and is defined as the ratio of the concentration of radionuclide on sediment (C_{sed}, in Bq/kg^{-1} dry weight) and in water (C_{water}, in Bq kg^{-1}):

$$K_d = \frac{C_{sed}}{C_{water}} \cdot$$

A paucity of data on K_d exists for shallow Arctic Seas. A programme, initiated to identify a few of the interdependencies among environmental variables and to determine site-specific K_d values for waste-related elements, consisted of: (i) theoretical investigation of the sensitivity of the modelling parameter, known as a partition coefficient, to ranges and uncertainties for suspended matter concentrations and K_d [59]; (ii) laboratory investigations on the influence of specific environmental parameters on K_d [67]; and (iii) a field investigation, conducted in summer 1995, in which K_ds for caesium, americium and cobalt were determined at sea at 35 locations.

In radionuclide dispersion models, a parameter known as the partition coefficient is used to establish the equilibrium between radionuclide concentrations in sediment and seawater. The partition coefficient for sea water (PC_w) ranges from zero to one and is a function of K_d and suspended matter concentration C. It is defined in dispersion models as:

$$PC_w = \frac{1}{1 + K_d C},$$

where PC_w represents the fraction of the total radionuclide activity in a parcel of water which remains in solution. If PC_w is close to one, then most of the radioactivity is predicted to remain dissolved in sea water; if PC_w is close to zero then most of the radioactivity is expected to attach to sediments.

With little field data available for K_d and C, a risk analysis was conducted to determine the range of values predicted for partition coefficients. The analysis was conducted using the IAEA [65] K_d estimates for primary waste-related radionuclides and from the expected ranges of C for the Novaya Zemlya Fjords and the open Kara Sea. The ranges of K_d and C define the precision of PC_w used in the models. The analysis illustrates that for caesium and strontium modellers must accept a 20% variation in PC_w. The ranges are much greater for the other waste-related radionuclides (Fig. 29). Partition coefficients are also sensitive to suspended matter concentration. For all radionuclides, higher suspended matter concentrations in the fjords resulted in lower PC_w estimates (Fig. 30).

4.1.1. Results of laboratory experiments

As a result of the difficulty in accurately defining partition coefficients based on the IAEA [62] estimates alone, laboratory experiments were subsequently developed to assess the influence of key environmental parameters operating in the Kara Sea which might account for some of the uncertainty in the values of K_d, C and hence PC_w. Experiments were conducted to examine the influence on K_d of changes in the ionic strength of sea water, suspended matter concentration and temperature using Kara Sea water and surficial bottom sediments collected from Abrosimov and Stepovoy Fjords during a 1994 joint Russian-Norwegian expedition. The range of K_ds determined in these experiments for each radionuclide is given in Table IV.

In response to experimental fluctuations in salinity, notable changes in distribution coefficients were observed at low salinities (0–10‰) only. The salinity of Abrosimov Fjord and Stepovoy Fjord waters are not expected to decrease below 15‰ suggesting that variations in salinity at the dumpsites need not be considered. Suspended matter concentrations in the fjords of Novaya Zemlya are likely to fluctuate within the range typically measured in coastal fjords; i.e. 10s to 100s of mg/L. As previously predicted, such large variations are expected to play a significant role in the sorption behaviour of radionuclides. Indeed, in laboratory experiments, K_d values for several waste-related radionuclides (Am, Co, Ru and Sr) were sensitive to fluctuations in concentration of suspended matter.

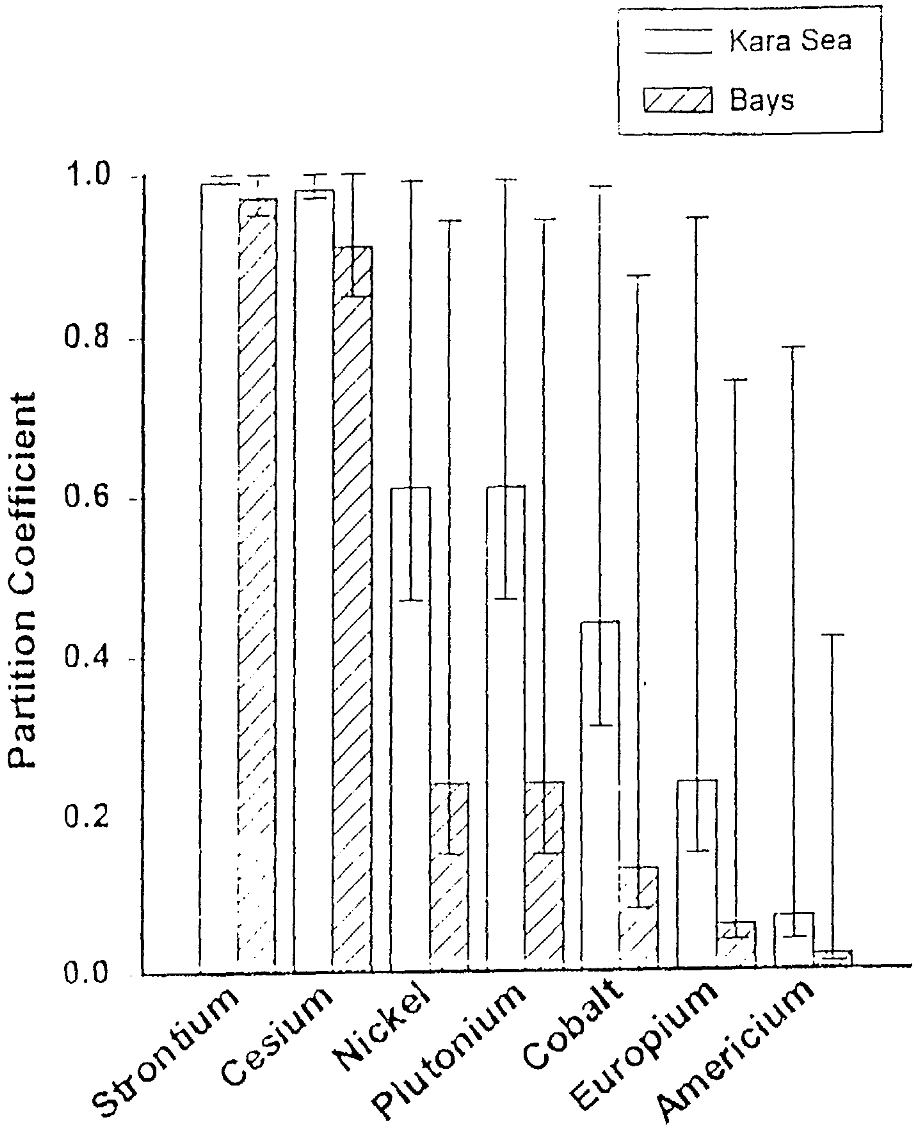

FIG. 29. Ranges of PC_w for waste-related radionuclides determined by risk analysis for low sediment environments (Novaya Zemlya Trough) and high sediment environments (shallow fjords).

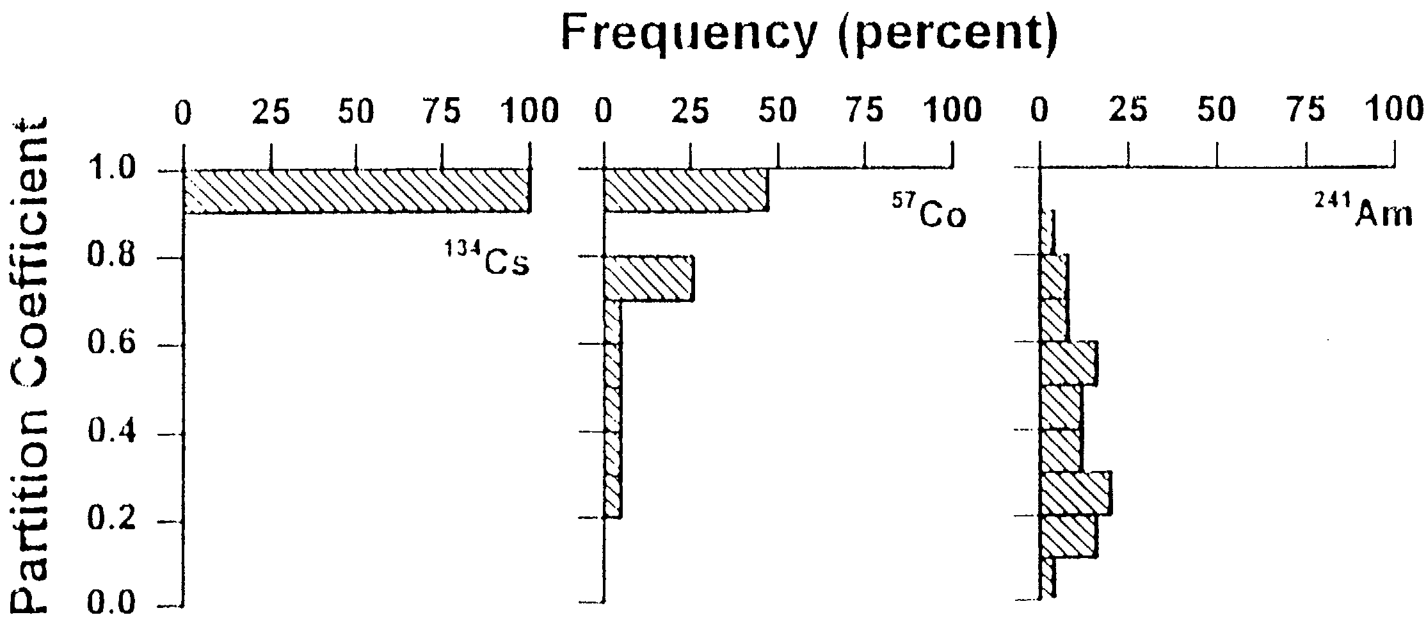

FIG. 30. Frequency distribution of PC_w for field based experimental determination of K_d and sediment concentration.

TABLE IV. IASAP SELECTED K_ds FOR MODELLING COMPARED WITH EXPERIMENTAL DATA AND IAEA VALUES

	Fjords[a] Stepovoy	Abrosimov	Kara Sea[b]	IAEA[c] [65]	IASAP Selected Values[d]
Americium	$(0.1–1) \times 10^6$	$(0.1–3) \times 10^6$	$(0.1–4) \times 10^5$	$1 \times 10^5–2 \times 10^7$	1×10^6
Plutonium	$0.5–1 \times 10^5$	$0.5–1 \times 10^5$	[e]$0.2–5 \times 10^5$	$1 \times 10^4–1 \times 10^6$	1×10^5
Cobalt	$(1–2) \times 10^6$	$(1–2) \times 10^3$	$(0.5–5) \times 10^4$	$2 \times 10^4–1 \times 10^6$	1×10^6
Europium	$(1–2) \times 10^5$	$(1–2) \times 10^5$	1×10^5	$1 \times 10^5–2 \times 10^6$	7×10^5
Strontium	$(0.1–1) \times 10^2$	$(0.1–1) \times 10^2$	[e]$(0.1–5) \times 10^1$	$1 \times 10^2–5 \times 10^3$	1×10^2
Caesium	$(3–6) \times 10^2$	$(2–3) \times 10^2$	0.15×10^2	$1 \times 10^2–2 \times 10^4$	5×10^3

[a] Laboratory experiments.
[b] Shipboard experiments.
[c] Coastal sediments.
[d] Used in IASAP model calculations.
[e] Estimated K_d ranges based on measured radionuclide concentrations in water and sediment samples.

Temperature affects the rate and endpoint of all chemical exchange reactions. Because K_d fundamentally represents the equilibrium endpoint of a chemical reaction, colder temperatures in arctic waters (–4 to 4°C) may result in different equilibrium K_d values from values previously reported for warmer climates. However, the dependency of K_d on temperature was determined to be insignificant over the range of water temperatures expected in the world ocean.

From these experiments elucidating the effect of salinity, suspended matter concentration and temperature on K_d, only suspended matter concentration and the grain size was observed to be important. A large difference in K_d for Co, was measured for sediments from the two fjords. Higher K_d values were observed for sediments from Stepovoy Fjord and may be related to differences in sediment grain size. The mean particle diameter of Stepovoy Fjord sediment samples (6.0 μm) is approximately one-half the mean particle diameter of Abrosimov Fjord sediment samples (13.1 μm). Other differences in the characteristics of the sediments such as the cation exchange capacity or clay mineral content are also likely to be important.

4.1.2. Results of field experiments

A drawback of conducting laboratory studies to understand the influence of environmental parameters on K_d is that, after sample collection, changes begin to occur to sediment and sea water as these environmental materials age. Experiments should be conducted as soon as possible after sample collection. This limitation poses difficulties when conducting research in remote areas such as the Arctic. A second limitation of laboratory investigations is that typically only a few water and sediment samples are collected. This limits the extrapolation of results determined for a limited number of sites to a large region such as the Kara Sea. In response to these limitations, K_d determinations at sea using freshly collected materials were conducted in 1995 as part of a Joint Norwegian–US expedition.

Batch experiments were conducted using ^{241}Am, ^{60}Co, and ^{134}Cs radionuclides which exhibit varying degrees of particle affinity. Partition coefficients (PC_w) may be calculated directly from the experimental data. These data confirm the finding of the laboratory experiments that distribution coefficients and partition coefficients both exhibit a wide range of variation for the Kara Sea. Caesium is the only radionuclide exhibiting a well-constrained K_d [(0.14 ± 0.02 m^3/kg)] with 99% in solution.

4.1.3. Conclusions on distribution coefficients

The three-phase approach has rendered site-specific information on K_d values and their ranges of uncertainty.

(1) Theoretical: The results of a risk analysis conducted by computer simulation demonstrate that most of the waste-related radionuclides residing in the Kara Sea are expected to exhibit large ranges of variation for PC_w. The only exceptions are radionuclides with low K_d, i.e. caesium and strontium.

(2) Laboratory: From laboratory experiments suspended matter concentration and sediment characteristics were identified as the most important sources of variation for K_d. The effects of temperature and salinity fluctuations on K_d are negligible.

(3) Field based: Field based determinations from 35 locations in the Kara Sea confirm that K_ds exhibit a wide range of values in response to variable environmental conditions. Partition coefficients calculated directly from the field data demonstrate that the modelling parameter, PC_w, will vary significantly in response to both K_d and suspended matter concentration in the Kara Sea.

Appropriate ranges of both K_d and suspended matter concentration values therefore must be examined as part of the radionuclide dispersion and risk assessment modelling investigations.

Experimentally-determined K_d values for Novaya Zemlya Fjords and the open Kara Sea are given in Table IV.

4.2. CONCENTRATION FACTORS

The radioactive wastes disposed on the sea floor of the Kara and the Barents Seas in recent years may be released from their containers, leading to potential contamination of the fauna living on the sea bottom. Released radionuclides may be retained in benthic organisms and then transferred to a higher trophic level of the Arctic marine foodchain. Realistic models for assessing biological uptake under Arctic conditions require precise estimates of the rate of transfer of key radionuclides from sediment or sea water to organisms representative of the Arctic community [64]. Since little is known about radioecological processes in Arctic marine foodwebs, laboratory experiments were carried out on benthic organisms. The objectives of these experiments were to select sentinel organisms and evaluate transfer factors and concentration factors for a variety of radionuclides selected on the basis of estimated waste inventories for the Kara Sea.

4.2.1. ^{137}Cs and ^{60}Co transfer factors for Arctic clams

Transfer factors (TF) were evaluated in order to define the fraction of total contaminant available for accumulation from sediment by benthic organisms. Arctic clams of the species *Chlamys islandicus* were maintained in aquaria reproducing the environmental conditions of Abrosimov Fjord in the Kara Sea (2°C, 35‰ salinity, bulk sediment collected from the upper 10 cm). After 79 days of exposure to the contaminated sediment, clams and sediment were collected for gamma-counting and TF were computed as follows:

$$\mathrm{TF} = \frac{A_{clam}}{A_{sed}},$$

where A_{clam} and A_{sed} represent the measured activities in Bq kg^{-1} dw.

Activities in the soft parts of the organisms were very close to the detection limit; therefore, the TF obtained were less than 0.01 and 1.0 for the long-lived radionuclides ^{137}Cs and ^{60}Co, respectively. These results are similar to those previously reported for ^{241}Am uptake by benthic bivalves from temperate latitudes.

4.2.2. Concentration factors for Arctic benthic organisms

As previously reported, the benthic communities of the Kara Sea are dominated by brittle stars (echinoderms). Bivalve molluscs and brown algae, present in the shallow Arctic marine environment, have been routinely used in temperate latitudes as biomonitors of both radionuclide and trace metal pollution. Hence, short term exposure experiments (12 days) were conducted with these organisms (i) to assess the validity of extrapolating CF obtained under temperate conditions to Arctic ecosystems, (ii) to help model the radiological impact of pulsed contaminant exposures (e.g. leakage from dumped nuclear reactors or waste containers) and (iii) to select benthic organisms as bio-indicators of radionuclide contamination and dispersion in the Arctic Seas. The experimentally-derived concentration factors are defined as:

$$\mathrm{CF} = \frac{A_{organism}}{A_{water}},$$

where $A_{organism}$ and A_{water} represent the measured concentrations in Bq kg^{-1} wet weight and Bq kg^{-1} water, respectively. Accumulation and depuration rates of radiotracers of key radionuclides were compared at 2°C (typical of the Arctic Seas) and at 12°C (typical of temperate seas) for the macroalga (*Fucus vesiculosus*) [68] and the brittle star (*Ophiothrix fragilis*) [69]. Results are presented in Tables V and VI, respectively.

TABLE V. CFs IN *FUCUS VESICULOSUS* COMPARED TO CF IN MACROALGAE

Waste Radionuclides	Radiotracers	CF (2°C)	CF (12°C)	CF [65]
^{137}Cs	^{134}Cs	3.3 ± 0.3	4.6 ± 0.9	30–100
^{60}Co	$^{57}Co_{org}$	241 ± 6	186 ± 43	–
	^{60}Co	101 ± 6	353 ± 23	1000–10000
^{241}Am	^{241}Am	329 ± 10	437 ± 73	5000–10000
$^{152,154,155}Eu$	^{152}Eu	470 ± 38	614 ± 67	300–5000
	^{106}Ru	88 ± 6	*	300–5000
	^{109}Cd	51 ± 3	286 ± 21	1000–10000
	^{133}Ba	210 ± 9	292 ± 18	10–30

* The experiment was not completed due to insufficient Ru tracer available.

TABLE VI. CF IN *OPHIOTHRIX FRAGILIS*

Waste radionuclides	Radiotracers	CF (2°C)	CF (12°C)
^{137}Cs	^{134}Cs	3	4
^{60}Co	$^{57}Co_{org}$	69	360
	^{60}Co	16	29
^{241}Am	^{241}Am	48	53
	^{106}Ru	9	10
	^{109}Cd	34	46
	^{133}Ba	1	2

At 2°C, CF values for *Fucus vesiculosis* were highest for Eu followed by Am, Co_{org}, Ba, Co_{inorg}, Ru, Cd and Cs, in that order. The general order of accumulation at 12°C, Eu > Am > Co_{inorg} > Ba > Cd > Co_{org} > Cs, was somewhat different from that noted at 2°C especially for the two Co forms. The CF values generated from both experiments ranged over two orders of magnitude, from several hundred for Eu, Am, Co_{inorg} Ba, Cd and Co_{org} to less than 5 for Cs.

There was a clear influence of temperature on accumulation of $^{60}Co_{inorg}$ and ^{109}Cd at the end of the 12-d experiment, whereby the final concentration factor was significantly greater at the higher temperature ($p < 0.001$). As supported by the literature, the temperature effect noted for Co_{inorg} uptake might be a consequence of the oxidation (mediated by bacteria and enhanced at higher temperature) of Co(II) to Co(III)), a more particle-reactive form. For the remaining tracers, temperature had no significant influence ($p < 0.001$ level) on the CF. The CFs obtained at 12°C for most of the radionuclides in these experiments were lower than values cited in the literature [65], and probably reflect the fact that the literature values were based on long term chronic periods of exposure rather than short term laboratory exposure experiments.

For the brittle star (*Ophiothrix fragilis*) radionuclide CFs obtained at the end of the uptake period (13 days) at 2° and 12°C are presented in Table VI. At 2°C $^{57}Co_{org}$ was concentrated to the greatest degree by *O. fragilis* followed by ^{241}Am, ^{109}Cd, $^{60}Co_{inorg}$, ^{106}Ru and ^{134}Cs. ^{133}Ba was not concentrated at 2°C. The general order of accumulation was the same at 12°C. All tracers were concentrated to a greater degree at the higher temperature, with organic ^{57}Co showing the greatest response to temperature. After 13 days of uptake, there was no significant difference ($p < 0.05$) in the body distribution (arms and disc) of radionuclide concentrations. Increases in accumulation rates at higher temperature may be partially due to increased metabolic activity (animals observed to be much more active at 12°C than at 2°C).

For the seaweeds, depuration of the radionuclides was followed daily over 14 days at 2°C and 12°C. Linear regressions for radionuclide loss were calculated for the exponential portion of the loss curve between days 2 and 14 of depuration. Elimination rates obtained at 2°C were significant ($p < 0.05$) for ^{241}Am, ^{133}Ba and ^{152}Eu. At 12°C significant rates of depuration were obtained for ^{133}Ba, ^{134}Cs and ^{60}Co. ^{133}Ba was rapidly eliminated by *F. vesiculosus*, whereas the other radionuclides remained relatively firmly bound to the alga. Considering the entire 14-d depuration experiment (first two days and the exponential portion of the loss curve), the percentages of time zero activity retained for all elements except Ba and Cs ranged between 71% (Eu) and 91% (Cd) at 2°C, and between 85% (Co_{org}.) and 100% (Eu and Cd) at 12°C (Table VII).

TABLE VII. RADIONUCLIDE ELIMINATION DATA FOR *FUCUS VESICULOSUS*

Waste Radionuclides	Radiotracers	% retained after 14 days		Biological half-lives (days)
		2°C	12°C	
^{137}Cs	^{134}Cs	53 ± 6	72 ± 17	96
^{60}Co	$^{57}Co_{org}$	82.5 ± 1.9	85 ± 25	106
	^{60}Co	90 ± 12	92 ± 5	540
^{241}Am	^{241}Am	85.6 ± 4.4	92 ± 13	80
$^{152,154,155}Eu$	^{152}Eu	71 ± 8	100 ± 1	27
	^{106}Ru	89.9 ± 4.4	–	99
	^{109}Cd	91 ± 9	100 ± 1	∞
	^{133}Ba	30.4 ± 2.7	32.5 ± 3.6	9

Compared to other radionuclides the retention values obtained for Cs and Ba were much lower, *viz.* 53% and 30% at 2°C, 72% and 32% at 12°C, respectively. Temperature had a significant effect only ($p < 0.001$) on retention of ^{152}Eu. An explanation for the greater ^{152}Eu elimination observed at 2°C is not immediately evident; however, it may be related to morphological and biochemical changes taking place in the fruiting algae at 12°C which, in turn, could result in enhanced retention of the radionuclide.

During the exponential phase of depuration (2 to 14 days) corresponding to the "long term" loss pool, only ^{241}Am (2°C), ^{152}Eu (2°C), ^{134}Cs and $^{60}Co_{inorg}$ (12°C), and ^{133}Ba (2° and 12°C) were significantly released. In the case of ^{133}Ba, rapid depuration resulted in very low percentages retained after 14 days. Therefore, ^{133}Ba, like ^{134}Cs, does not appear to be accumulated and retained in *F. vesiculosus,* unlike the other radionuclides which are relatively firmly bound to the brown algae. Biological half-lives computed for the depuration rate constants presented in Table VII, show that values ranged from 9 days for ^{133}Ba to infinity for ^{109}Cd at both 2°C and 12°C.

For the brittle star, radionuclide depuration was followed daily over 14 days at 2°C and 12°C. ^{241}Am and $^{60}Co_{inorg}$ were significantly ($p < 0.05$) eliminated from the brittle stars at 2°C. At 12°C, only the loss of inorganic ^{60}Co and ^{134}Cs was significant at the $p < 0.05$ level. As there was no significant difference in long term loss rates at 2°C and at 12°C, temperature variations within the range examined would not exert a major influence on excretion of radionuclides accumulated from sea water by ophiuroids.

The retention times obtained at 2°C were very long. Biological half-lives were not different from infinity for most radionuclides except ^{241}Am ($Tb_{1/2}$ = 16 days) and inorganic ^{60}Co ($Tb_{1/2}$ = 19 days), supporting the view that ophiuroids efficiently retain a record of their exposure to soluble radioactive contaminants.

4.2.3. Concentration factors for a Kara Sea bivalve

A long term exposure (1 month) laboratory uptake study was performed under Arctic conditions using a bivalve mollusc (*Macoma*) collected from Abrosimov Fjord sediment in the Kara Sea. This benthic organism, a deposit-feeder living buried in the upper 10 cm of the sediment, was exposed to a relatively constant source of the contaminant radionuclides ^{60}Co, ^{134}Cs and ^{241}Am in sea water. After 36 days of exposure, accumulation of these radionuclides reached steady state only for ^{134}Cs. Concentration factors obtained for ^{241}Am, ^{60}Co and ^{134}Cs were 380,300 and 14, respectively. For ^{241}Am and ^{60}Co, these concentration factors are somewhat lower than the values reported in the literature for temperate zones.

Compared with the activities measured in the clam at the end of the uptake period, the percentages of radionuclide retained after 80 days of depuration were 88% for ^{241}Am, 84.5% for ^{60}Co and only 7.5% for ^{134}Cs. Radionuclides were mainly located in the soft tissues for ^{241}Am (60%), in the shell for ^{60}Co (90%), and were equally distributed between shell and soft tissues for ^{134}Cs. Therefore, once accumulated from sea water, ^{241}Am and ^{60}Co will remain tightly bound to the clam. The ^{241}Am located in the soft tissues has the potential for trophic transfer to higher levels of the foodchain through predation, whereas ^{60}Co, mainly adsorbed on shell, would be less available for biological uptake. ^{134}Cs is concentrated from sea water to a very low degree by the clam and is rapidly eliminated. Therefore, ^{134}Cs would remain mainly in the dissolved form and would not readily enter the food chain via consumption of this bivalve.

4.2.4. Conclusions on concentration factors

Given the paucity of information on the bioavailability of waste radionuclides at low temperatures in the marine environment, the findings of the short term experiments should be useful in modelling the radiological impact due to leakages from nuclear reactors or waste containers dumped in the Kara Seas. The main conclusions of the studies are:

(1) Previous CF data obtained under temperate conditions should be applicable to the Arctic ecosystem for the benthic macroalga (*Fucus vesiculosus*), since there is no temperature effect for the waste radionuclides tested except with inorganic ^{60}Co. Nevertheless, care must be taken in ensuring that the same environmental conditions (e.g. salinity, light intensity and duration of the exposure) are considered when extrapolating these results to Arctic waters. For $^{60}Co_{inorg}$, very low temperatures (2°C) could decrease bioconcentration by (*Fucus vesiculosus*) possibly through greatly reduced microbially-mediated processes. For the brittle star (*Ophiothrix fragilis),* CFs obtained for Am and organic and inorganic Co under temperate conditions are not applicable to the Arctic ecosystem.

(2) Once accumulated from water, contaminants may be lost at nearly identical rates in high and low temperature regimes by both seaweeds and brittle stars. ^{133}Ba, ^{134}Cs, ^{152}Eu and ^{241}Am are eliminated by *Fucus vesiculosus* whereas ^{106}Ru, Co-cobalamine, inorganic ^{60}Co and ^{109}Cd remain tightly bound to the brown alga. For the brittle star (*Ophiothrix fragilis*) most of the radionuclides (except ^{241}Am and inorganic ^{60}Co) were not significantly eliminated. Long retention times should increase the potential for trophic transfer of these contaminants to predators such as grazers or flatfish for seaweeds and brittle stars, respectively.

(3) For the purpose of monitoring radioactive contamination and dispersion in the Kara Sea, the seaweeds (*Fucus*) and the molluscs (*Macoma*) are recommended for use as bioindicators.

Recommended CFs for the Arctic ecosystem are given in tables VIII and IX.

TABLE VIII. RECOMMENDED CFs FOR BIO-INDICATORS

Brown Seaweed *Fucus*[1]	Bivalve *Macoma*[2]	Ophiuroid *Ophiothrix*[1]
3×10^0	1×10^0	3×10^0
1×10^2	3×10^2	2×10^1
2.4×10^2	–	7×10^1
4.7×10^2	–	–
3.3×10^2	4×10^2	5×10^1
8.8×10^1	–	9×10^0
5×10^1	–	1×10^0
2.1×10^2	8×10^1	3×10^1

[1] 2 weeks.
[2] 1 month.

TABLE IX. SELECTED CFs FOR MODELLING COMPARED WITH EXPERIMENTAL DATA AND IAEA VALUES[a]

	Fish (muscle)	Sea Birds	Marine mammals	IAEA [65] Fish (muscle)	IASAP Selected values for fish[b]
Pu	$(1–4) \times 10^3$	$<2 \times 10^1–1.5 \times 10^2$	3	$5 \times 10^{-1}–1 \times 10^2$	4×10^1
Cs	$(0.3–3) \times 10^2$	$(0.04–1.1) \times 10^3$	$(0.13–1.8) \times 10^2$	$(0.1–3) \times 10^2$	1×10^2
Sr	$(2–9) \times 10^1$	–	0.4–3	$(0.3–1) \times 10^1$	4
Ni	1×10^2	7×10^2	–	$(0.05–1) \times 10^3$	1×10^2
Sb	–	–	1×10^{-1}	$(0.1–1) \times 10^3$	–

[a] This table is based on data provided by experts (F. Boisson, J. Carroll, N. Fisher, S. W. Fowler, K. Rissanen, B. Salbu, K-L. Sjoeblom, T. Sazykina) participating in the IASAP Consultants' Meeting organized in Monaco from 27–29 November 1995.

[b] Used in IASAP model calculations

5. CONCLUSIONS

On the basis of comprehensive investigations of environmental and radiological conditions in the Arctic Seas carried out during the years from 1992–1996, it can be concluded that the region has not been affected by the dumping of radioactive wastes in the Kara and Barents Seas.

From the data stored in the GLOMARD database on the measurement of concentrations of several radionuclides in water, sediment and biota sampled at the major dumpsites in Abrosimov, Stepovoy and Tsivolka Fjords and the Novaya Zemlya Trough, as well as in the open Kara Sea and the Ob and Yenisey estuaries it can be concluded that, with the exception of limited areas in Abrosimov and Stepovoy Fjords, only minor contamination exists relative to background levels. In-situ gamma-spectra recorded at the dumpsites indicate that the contamination has a localized character and, at sites outside the disposal areas, no contribution from local sources can be observed. The most marked contamination of sediment appears to be associated with leakage from dumped containers but this is confined to the immediate vicinity of the containers in cases where suitable measurements exist. The open Kara Sea is relatively uncontaminated, the main contributions being due to direct deposition and catchment runoff from global fallout caused by nuclear weapons tests, discharges from reprocessing plants in Western Europe and the former Soviet Union, local fallout from tests performed at Novaya Zemlya and Chernobyl fallout.

The concepts of distribution coefficient (K_d) and concentration factor (CF) have been used to intercompare the relative degree of uptake of marine contaminants by different sediment types and marine biota, respectively. Results of laboratory and field work aimed at elucidating environmental parameters that might affect K_d and CF values for arctic environments. Such information is necessary for evaluating K_ds and CFs that should be used in radiological models for specific dumpsites in the Arctic Seas. From laboratory experiments suspended matter concentration and sediment characteristics were identified as the most important sources of variation for K_ds. The effects of temperature and salinity fluctuations on K_ds are negligible. Field based determinations from 35 locations in the Kara Sea confirm that K_ds exhibit a wide range of values in response to variable environmental conditions. Partition coefficients calculated directly from the field data demonstrate that the modelling parameter, PC_w, will vary significantly in response to both K_d and suspended matter concentration in the Kara Sea. CFs were computed using field measurements of radionuclide and/or stable element concentrations in organisms and sea water as well as data derived from laboratory radiotracer experiments. Both K_ds and CFs recommended for use in radiological modelling for the IASAP are within the range of values recommended in the IAEA Technical Reports Series No. 247. Seaweeds (*Fucus*) and molluscs (*Macoma*) are recommended for use as bioindicators for monitoring radioactive contamination in the Kara Sea.

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