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Sammendrag / Summary

Transport of sediment-bound contaminants by sea ice has been identified as a potential route for re-distribution of contaminants in the Arctic. An evaluation of the magnitude of this pathway was carried out for a variety of contaminants (heavy metals, radionuclides, persistent organic pollutants) as part of the Norwegian Ministry of the Environment and Ministry of Foreign Affairs Program, "Transport and Fate of Contaminants in the Northern Seas."

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Prosjektleder / Project manager

Kvalitetskontroll / Quality control

JoLynn Carroll, Ph.D.

Kristina Olsson, Ph.D.

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1 Introduction

The biological resources of the polar seas exist under extreme environmental conditions, including cold temperatures, large seasonal fluctuations, and short growing seasons. These conditions affect the productivity, species diversity, and food web characteristics of arctic ecosystems that in turn affect the vulnerability of Arctic ecosystems to stressors including contaminants. Understanding the outcome of interactions between natural and human-induced changes to the environment requires knowledge of the underlying processes controlling these changes. The aim of this project is to quantify the amount of contaminants incorporated into frazil ice during formation in order to estimate the transport of contaminant-laden sea ice from the Kara Sea into the Transpolar Drift current.

The ubiquitous presence of 'dirty ice' throughout the eastern Arctic (Nuernberg et al., 1993; Pfirman et al., 1995) led to the hypothesis that sediments in sea ice may serve as an important entry point for contaminants into biota (Dethleff et al., 1998; Pfirman et al., 1995; Weeks, 1994; Reimnitz et al., 1990). Sea ice is discoloured by biogenic and fine-grained lithogenic material. Lithogenic material can only be incorporated into ice formed in the shallow coastal seas (Rigor and Colony, 1997). In addition to being a source of lithogenic materials, Arctic marginal seas receive contaminants from land via atmospheric, riverine and marine conduits (AMAP 1996). The Kara Sea is an area well-known to be impacted by a variety of anthropogenic contaminant sources (AMAP, 1998; Layton et al., 1997; Povinec et al., 1997).

The principal mechanism for entraining contaminant-laden lithogenic materials into sea ice is associated with the formation of frazil ice in turbid seawater (Rigor and Colony, 1997). The general scenario is that contaminants are entrained during the freezing process and encapsulated by the thickening ice. After entrainment, the pollutants would be transported by the motion of the sea ice which has a possible lifetime of 3-4 years and a potential net travel distance of thousands of kilometres (Rigor and Colony, 1997). Contaminants may also be deposited onto sea ice from the atmosphere. Ultimately the polar sea ice melts in the Greenland and Norwegian Seas, releasing its sediment load and contaminants to the biologically rich surface waters. Biomagnification through the Arctic food web may then lead to the transfer of contaminants to higher trophic level organisms.

Both the Laptev Sea (Pfirman et al., 1995; Dethleff et al., 1998) and the Kara Sea (Pfirman et al., 1997) have been identified as key regions of ice-formation that are important with respect to the supply of ice to adjacent seas and the central Arctic Basin. But the mechanisms of sediment entrainment into sea ice are not well quantified. This knowledge is essential in order to obtain estimates of the natural variability in the uptake of sediments into sea ice which then can be used to evaluate the role of ice-associated sediments as a contaminant transport mechanism. The key processes associated with ice production in marginal seas are summarised in Figure 1.

Knowledge of the drift patterns and volume flux through boundaries is also essential toward determining how much of the sea ice incorporated sediment is subsequently transported from marginal seas into the Arctic Basin. Both mechanisms of sediment uptake and sea ice transport are highly variable over multiple temporal scales. Sediment uptake occurs only if sufficient turbulence is generated in the water column leading to the suspension of seabed sediments into the water column during periods of ice formation (Smesrud, 2000a). Sea ice transport itself exhibits a high degree of interannual variability. This has been shown

previously by Pfirman et al. (1997) through an assessment of the back trajectories of drifting Arctic sea ice.

In order to consider the processes controlling sediment uptake and contaminant transport via sea ice, a probability analysis involving simulations of contaminant fluxes from the Kara Sea was carried out for a variety of individual contaminants (heavy metals, radionuclides, chlorinated pesticides, and persistent organic pollutants (designated as POPs-industrial products)). The probability analysis approach was chosen due to the limited amount of data available with which to assign, with a high degree of confidence, values for contaminant concentrations in ice-associated sediments. The flux estimates derived in this investigation assume that all of the ice exiting the Kara Sea between Novaya Zemlya and Franz Josef Land originated from the Kara Sea Shelf. This is a conservative assumption because ice formation also occurs along the Novaya Zemlya coastline (Dethleff et al., 2000).

This analysis utilises results from three separate assessments carried out within the Transport and Effects Programme: (1) the identification of key contaminants in the Arctic marine environment (Carroll, 2000), (2) a determination of the quantity of sediment entrained in sea ice (Smesrud, 2000b), and (3) a determination of the quantity of sea ice transported from the Kara Sea into the Eurasian Basin (Korsnes and Pavlova, 2000). Interested readers are referred to the original source documents for more information on the component projects. A schematic representation of the information used to quantify contaminant fluxes is presented in Figure 2.

Flaw Lead Processes

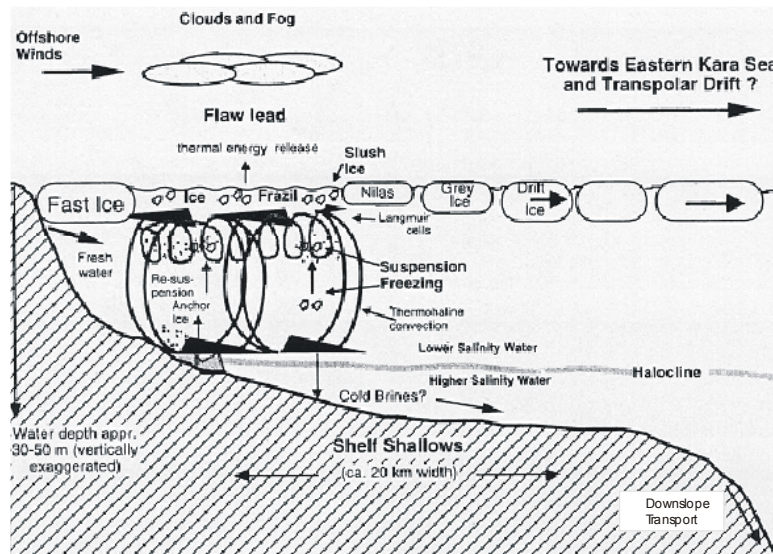


Figure 1: Possible hydrodynamic processes of turbid ice formation over Arctic shelves (after Dethleff et al., 2000).

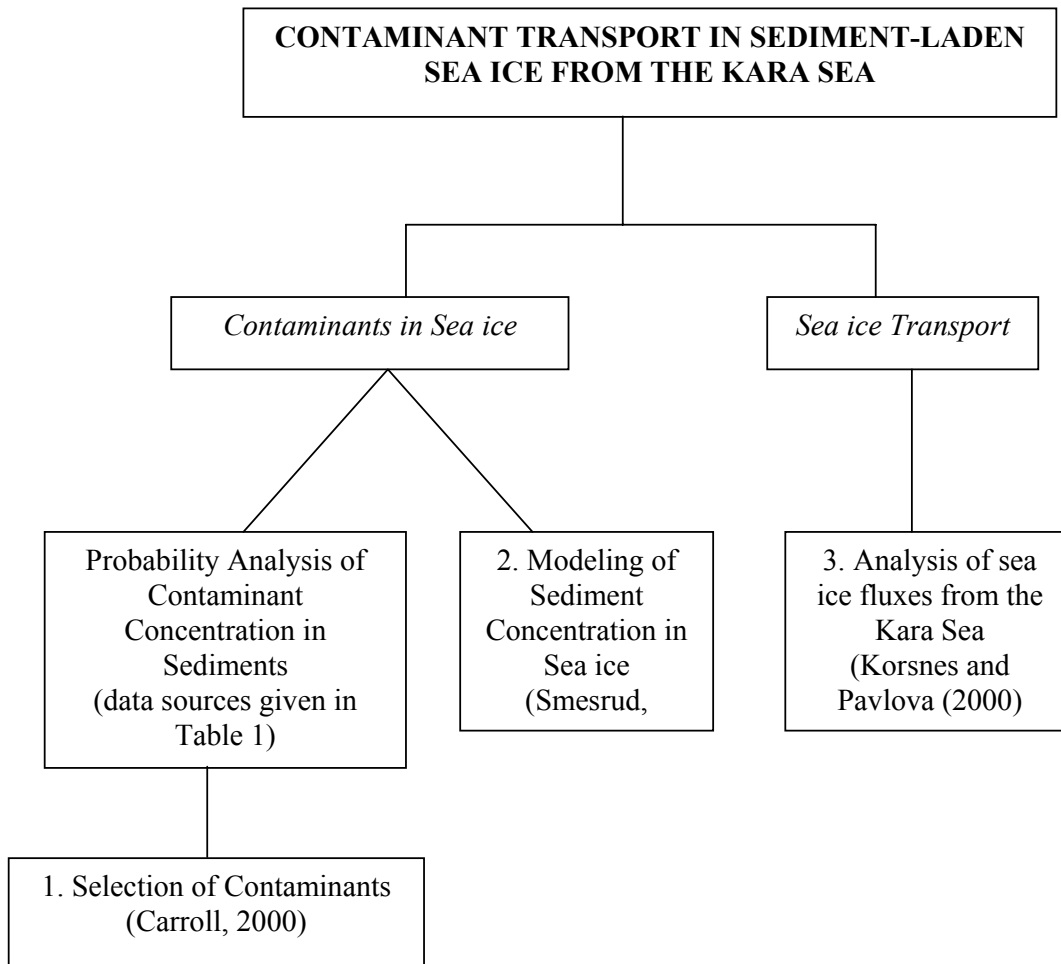


Figure 2: Schematic representation of components used in this analysis of contaminant transport via sediment-laden sea ice from the Kara Sea to the Eurasian Basin.

2 Contaminant concentrations in sediments

The contaminants evaluated in this project are a subset of the contaminants previously identified by the Arctic Monitoring and Assessment Programme (AMAP). The abbreviated list was selected as part of a separate program carried out within the Transport and Effects Programme (Carroll 2000). The programme, 'Key Contaminants for the Arctic Marine Environment: Survey Results,' was carried out to assist in the development of a list of contaminants to be investigated as part of future monitoring programmes in Arctic Seas. The list of priority contaminants is provided as an appendix within this report (Appendix I).

Sediment concentrations of the contaminants selected for evaluation in this investigation are presented in Table 1. These include contaminants classified according to AMAP as heavy metals, radionuclides, POPs-industrial products, and chlorinated pesticides. Additional details are given in Appendix II about the type of contaminants investigated, data locations, and original references for the data. Abbreviated contaminant names used in this report are also explained in Appendix II. These abbreviated names are identical to the names used within AMAP.

Because exact distributions of contaminants are not available for most areas in the Arctic, probability distribution functions were constructed for each contaminant of interest. For those contaminants for which we have mean and standard deviations, contaminant concentrations were modelled using a normal distribution curve. For those concentrations having only minimum and maximum values, we estimated the mean value as the average of the minimum and maximum values and contaminant concentrations were modelled as a Pert distribution function (See Appendix III).

Table 1: Data for calculating fluxes of contaminants in sediment-laden sea ice.

	Units	Min/Max	Mean \pm S.D.	Source
Heavy Metals				
Cd	mg/kg		0.11 \pm 0.05	1
Hg	mg/kg		0.03 \pm 0.02	1
Pb	mg/kg		21.3 \pm 1.5	1
Radionuclides				
Cs-137	Bq/kg	0/71.4	14.9	2
Pu-239	mBq/kg	4.2/856	239	2
POPs-Industrial Products*				
PCB 8	μ g/kg	0/6.48	3.2	1
PCB 11	μ g/kg	0/7.36	3.7	1
PCB28	pg/g	10/35	22	4
PCB52	pg/g	9/35	22	4
PCB101	pg/g	1/40	21	4
PCB118	pg/g	2/35	19	4
PCB153	pg/g	2/40	21	4
PCB180	pg/g	1/40	21	4
5-CB	μ g/kg	0.2/3.39	1.8	1
HCB	μ g/kg	0.2/2.9	1.6	1
TCDD	pg/g	0.9/6.2	3.6	3
PnCDD	pg/g	0.1/5.1	2.6	3
HxCDD	pg/g	0.7/6.1	3.4	3
HpCDD	pg/g	0.4/8	4.2	3
OCDD	pg/g	0.8/15	7.9	3
TCDF	pg/g	0/11	5.5	3
PnCDF	pg/g	0/20	10	3
HxCDF	pg/g	0/27	13.5	3
HpCDF	pg/g	0/14	7	3
OCDF	pg/g	0.2/14	7.1	3
PCDD/Fs	pg/g	0.1/2.8	1.5	3
Chlorinated Pesticides*				
α HCH	μ g/kg	0.2/1.23	0.7	1
γ HCH	μ g/kg	0.05/0.25	0.2	1
OCS	μ g/kg	0.05/0.12	0.1	1
pp-DDE	μ g/kg	0.05/1.19	0.6	1
pp-DDD	μ g/kg	0.08/0.83	0.5	1
pp-DDT	μ g/kg	0.05/2.1	1.1	1
Trans-chlor	pg/g	6/30	18	4
Cis-chlor	pg/g	6/40	23	4
Trans-nonachlor	pg/g	8/23	15.5	4
Cis-nonachlor	pg/g	6/25	15.5	4

*Mean contaminant concentrations were estimated as the mean value of the minimum and maximum concentrations. (POPs = persistent organic pollutants).

1 Evenset et al., 1999

2 Baskaran et al., 1996

3 AMAP 1998

4 Olsson et al. 1998

3 Fluxes of sediment-laden sea ice

The calculation of fluxes of sediment-laden sea ice depends upon knowing both the amount of sediment incorporated into sea ice during formation and the amount of sea ice transported from the Kara Sea. Sediment uptake into frazil ice is efficient when sufficient mixing of the water column is established with simultaneous high concentrations of ice crystals and suspended sediments. The amount of sediment incorporated into sea ice was quantified using a numerical model first developed by Eidsvik (1998) and later modified by Smesrud (2000a). The two-dimensional numerical model simulates the processes of aggregation between suspended sediments and ice crystals under varying temperature and meteorological conditions. Tank validation studies are used to validate model results (Smesrud, 2000a). These studies indicate that the uptake of sediment into sea ice occurs primarily during extreme weather episodes (Eidsvik, 1988).

Korsnes and Pavlova (2000) carried out an assessment of monthly mean sea ice fluctuations from the Kara Sea through the region extending from the tip of Novaya Zemlya to Franz Josef Land for the period 1988-1994. Combining the results of Smesrud (2000) and Korsnes and Pavlova (2000), the volume of sediment that is transported by sea ice from the Kara Sea was estimated for the following years: 1976, 1985, 1987, and 1988. These years were chosen because meteorological data was available that could be used to perform realistic simulations of the amount of sediment incorporated into the sea ice. The analysis was carried out for the months October through May. This period corresponds to the time of year when ice formation may occur. A sensitivity analysis was performed to consider the importance of variations in ice volume flux and wind speed on sediment resuspension and incorporation into sea ice. As was previously indicated by Eidsvik (1998), the amount of sediment incorporated into sea ice was highly dependent upon wind speed. Therefore, it was only necessary to consider the mean ice volume flux for the remainder of the analysis. The resulting sediment fluxes for the different years were then compared to a worst-case scenario developed based on the assumption that during all storm events, the maximum amount of sediment is always incorporated into sea ice. These results are summarised in Table 2.

Table 2: Mean monthly fluxes of ice-associated sediment with sea ice. Fluxes of sediment are given in millions of tons.

	1985	1987	1988	1976	Worst Case Scenario
October	4,3	4,3	0,1	0,1	17
November	22	0,1	0,1	0,1	30
December	9,8	0,4	9,8	56	94
January	0,4	0,4	0,4	0,4	104
February	6,0	0,2	6,0	0,2	52
March	3,2	0,1	0,1	0,1	28
April	0,1	0,1	0,1	0,1	19
May	0,1	0,1	0,1	0,1	11
Total	46	5,8	16	58	355

4 Contaminant fluxes in sediment-laden sea ice

Having determined the amount of sediment exported out of the Kara Sea by sea ice, it was then necessary to consider the contaminant concentration of the sea ice sediments. The probability distribution functions of contaminant concentration explained in Section 2 of this report were used for this purpose. The use of a distribution of contaminant concentrations allowed for the determination of a range of realistic fluxes for each contaminant. The annual flux in kilograms (Bq for radionuclides) for each contaminant was then quantified using a simulation analysis.

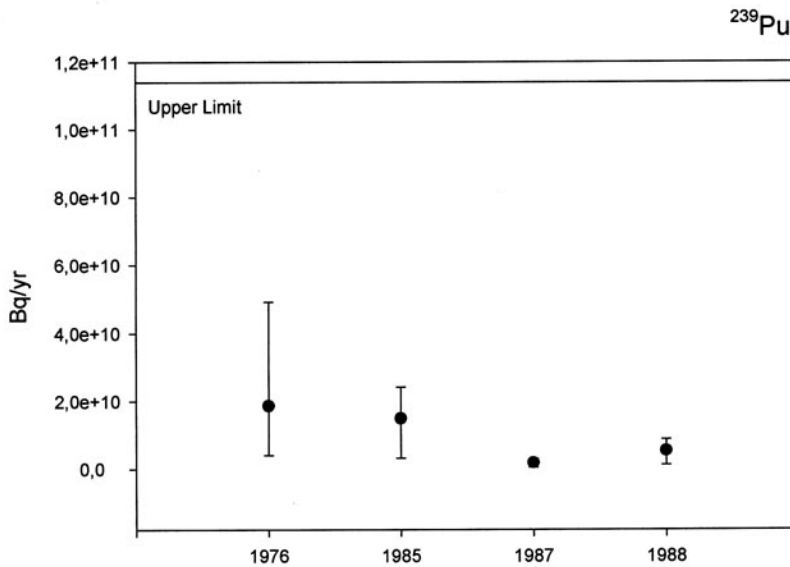
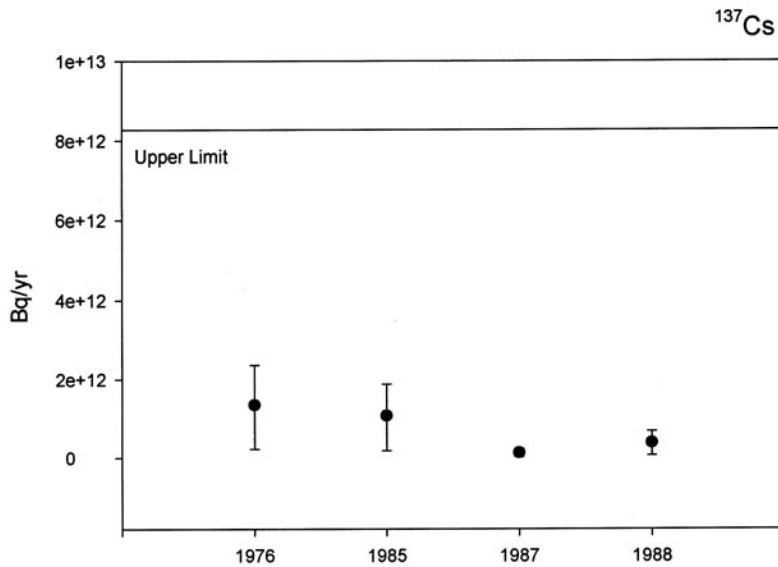
The simulation analysis operates as follows. Values of contaminant concentration were chosen from their probability distribution functions (Table 2) using Latin Hypercube sampling. Latin Hypercube simulation is a more recent development in sampling technology than the standard Monte Carlo method (Inman and Conover, 1980; McKay *et al.*, 1979). The two methods of sampling a probability distribution differ in the number of iterations required until sampled values approximate input distributions. Monte Carlo sampling often requires a large number of samples to approximate an input distribution. Latin Hypercube sampling forces the samples drawn to correspond more closely with the input distribution and thus converges faster on the true statistics of the input distribution. Compared to Monte Carlo simulation, which uses random numbers to sample from a probability distribution, the samples in Latin Hypercube simulations more accurately reflect the distribution of values in the input probability function. In our simulation analyses, sampling from the contaminant concentration probability distributions continued until the rate of change for the mean and standard deviation of the output probability distributions for contaminant fluxes were less than 2.5% per 100 iterations. This approach has previously been used to evaluate the distribution and behaviour of radioactive contaminants in marine systems (e.g. Carroll and Harms, 1999; Carroll and Lerche, 1996).

The results of the simulation analyses are presented as a series of figures grouped according to the following designations: heavy metals, radionuclides, POPs-industrial products, and chlorinated pesticides. Annual fluxes for the years 1976, 1985, 1987, and 1988 are given for each contaminant on pages 10-22 of this report.

Contaminant fluxes during the different years are considerably smaller than would be predicted based on the worst-case scenario (upper limit) due to the dependence of contaminant fluxes on the amount of sediment incorporated into sea ice. The worst-case scenario represents the theoretical upper limit of contaminant incorporation into sea ice based on the unrealistic condition that the intensity of all storm events results in the maximum amount of sediment incorporation into sea ice. This assumption is unrealistic because wind forced mixing which entrains sediments into ice is highly intermittent in both time and space. However, few data are available with which to compare the estimates derived in this study. The worst-case scenario estimates provide some perspective on the contaminant fluxes associated with realistic wind forcing during different years. In all cases, contaminant fluxes during the different years investigated are far below the theoretical limits.

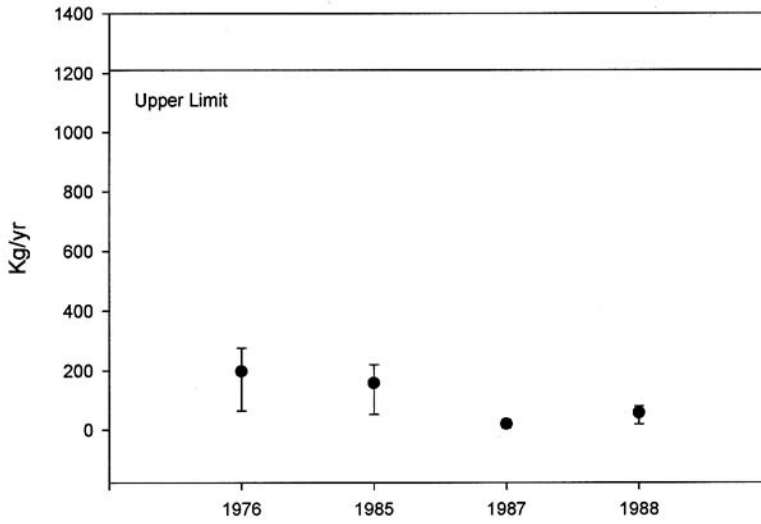
4.1 Heavy metals

4.2 Radionuclides

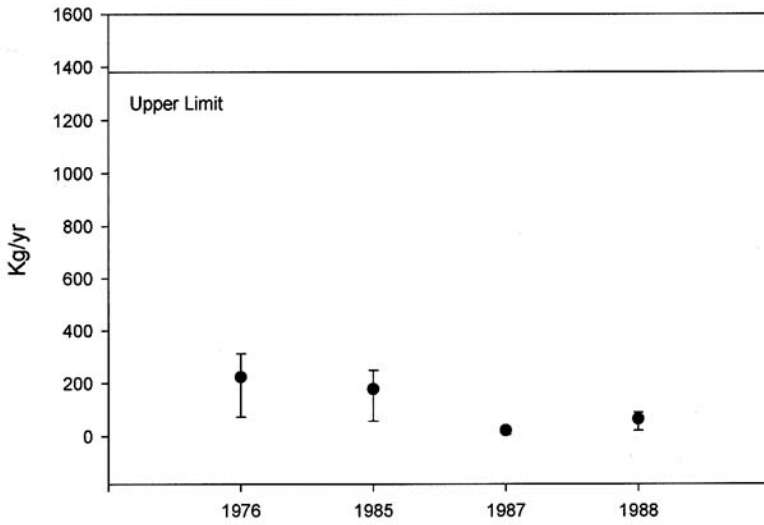


4.3 POPs-industrial products

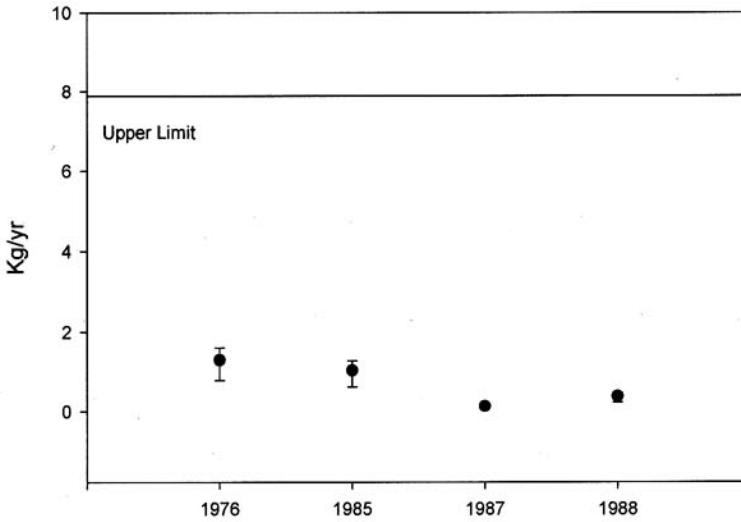
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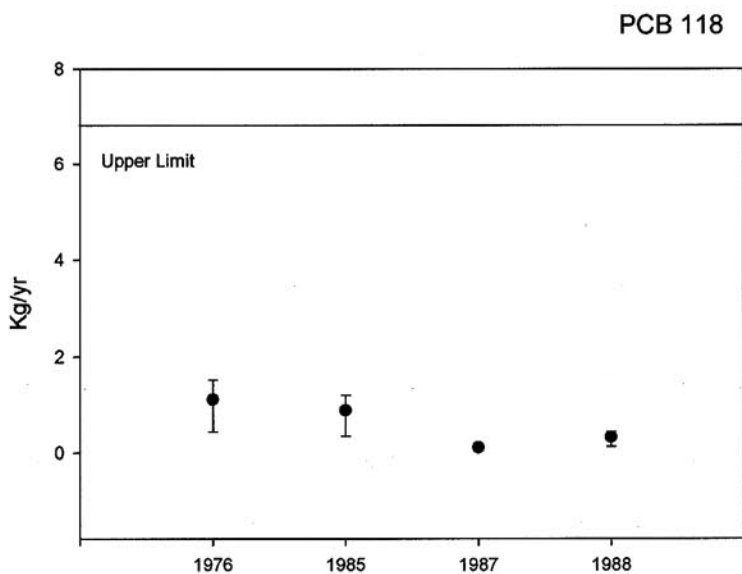
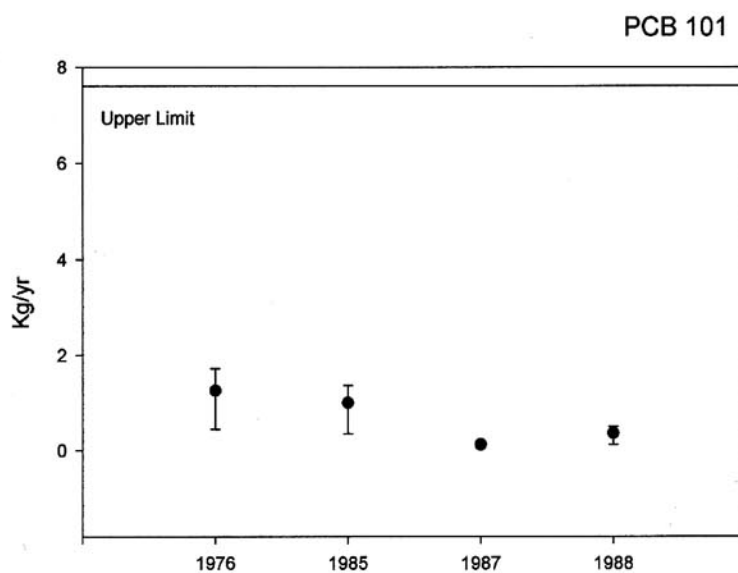
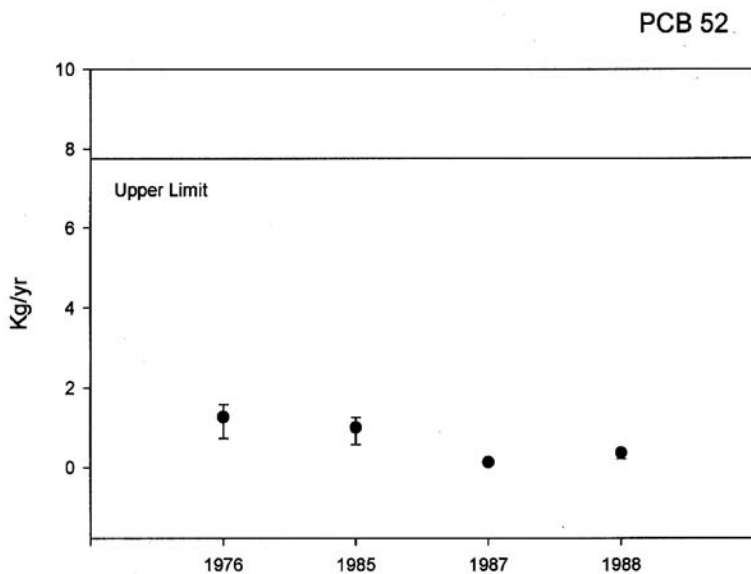


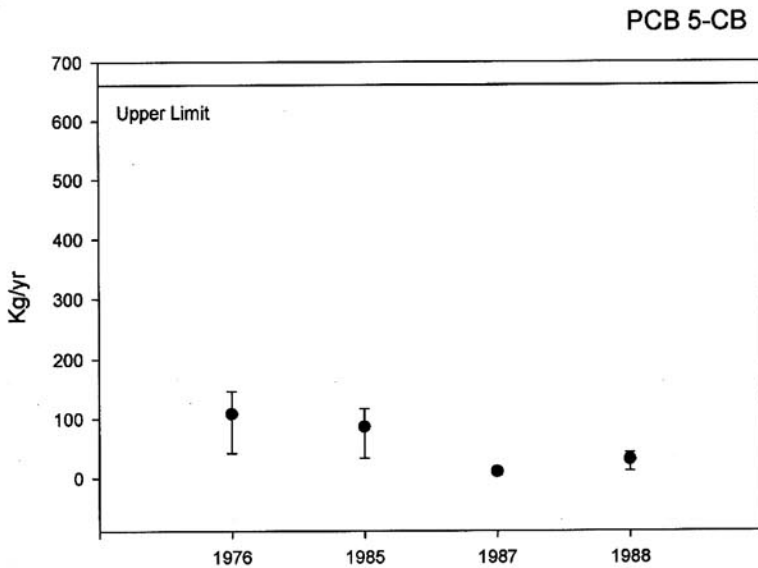
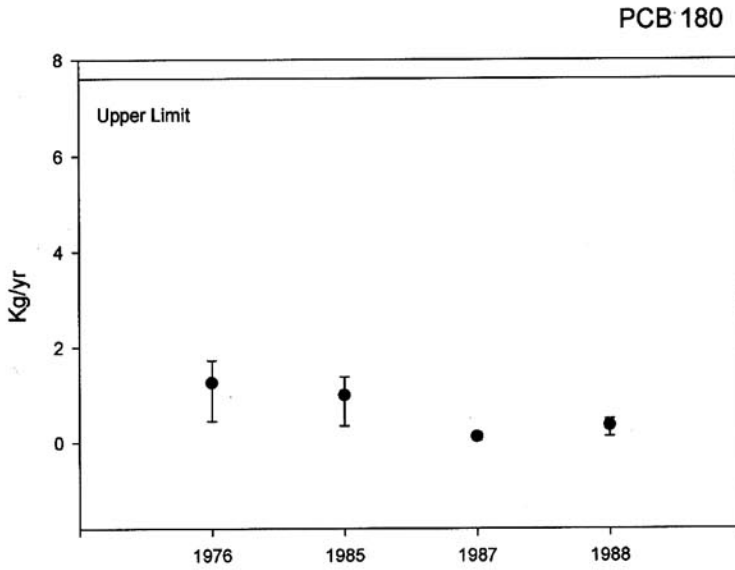
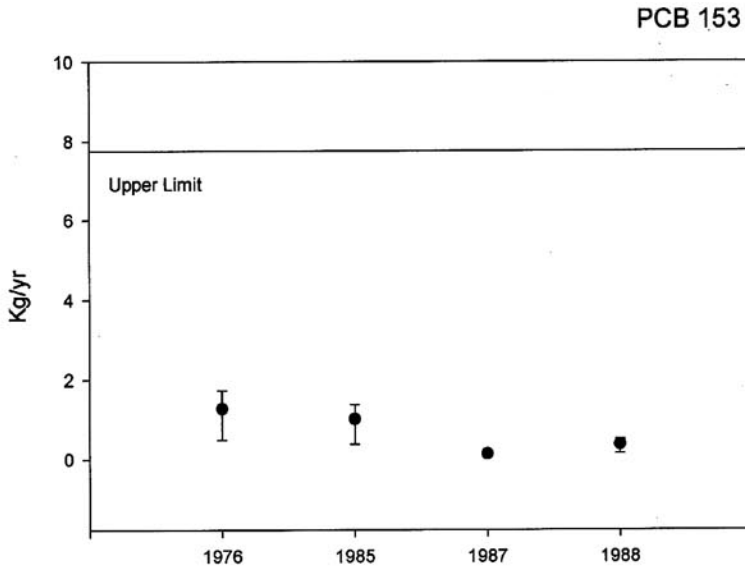
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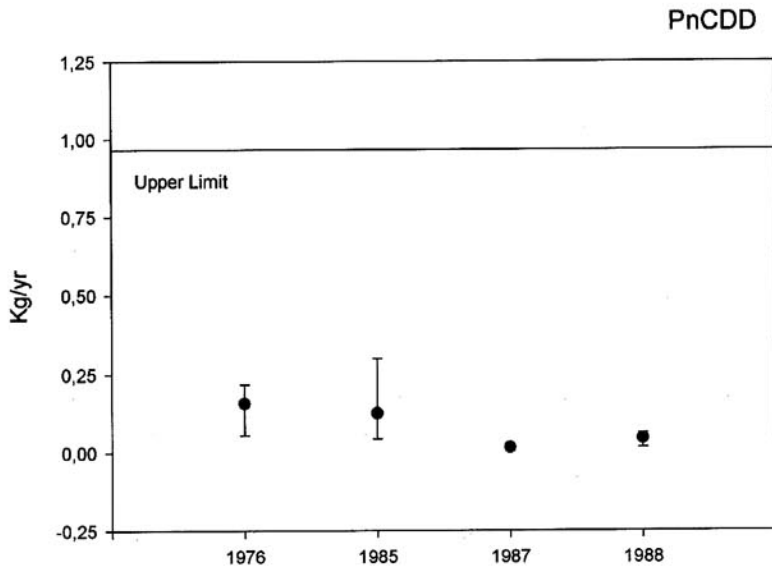
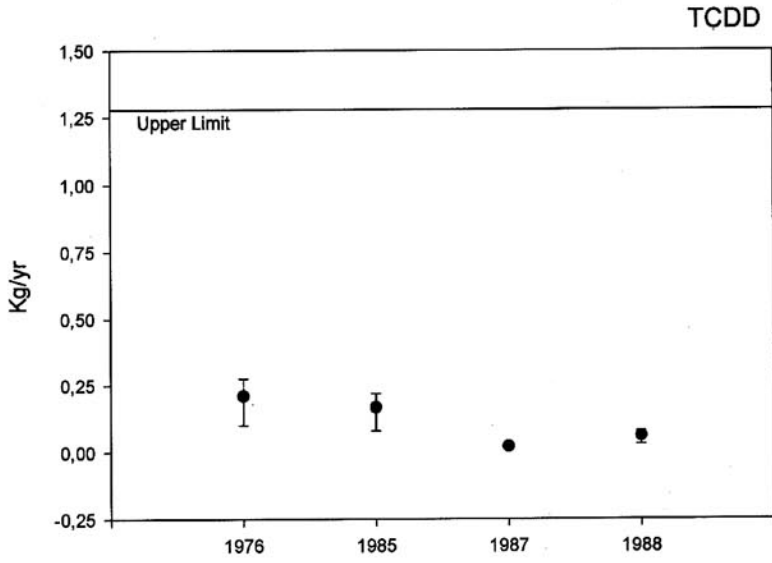
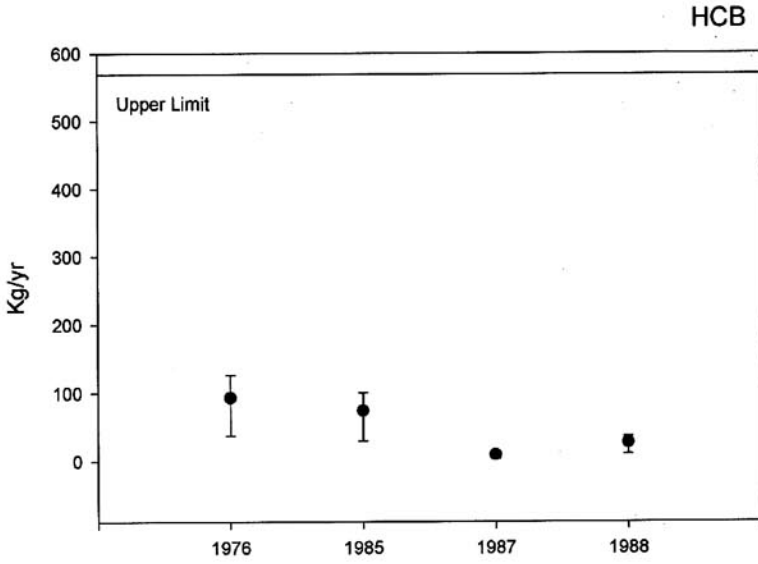


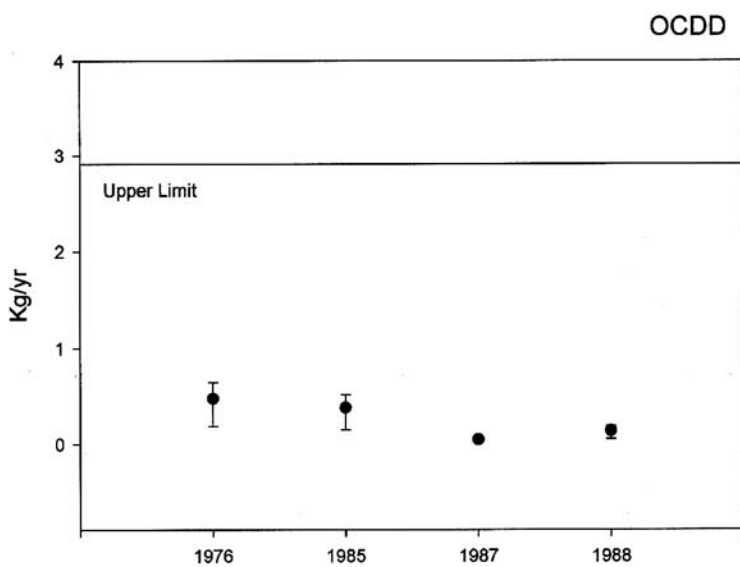
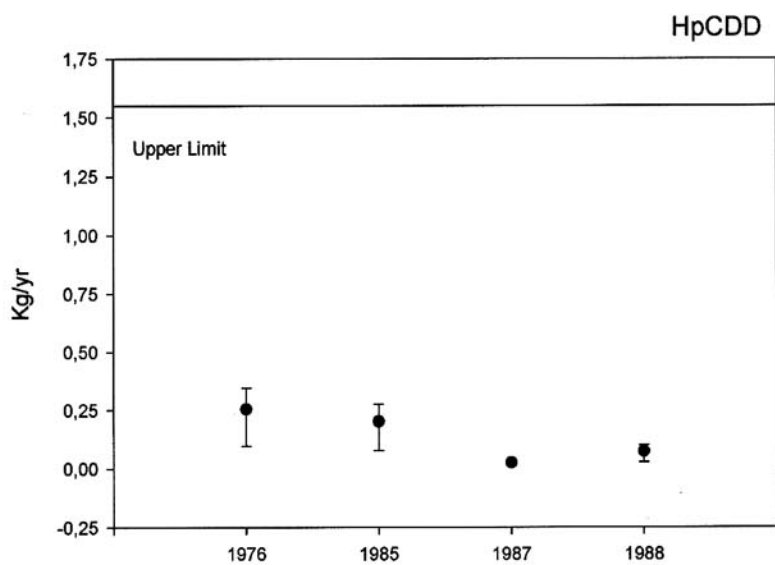
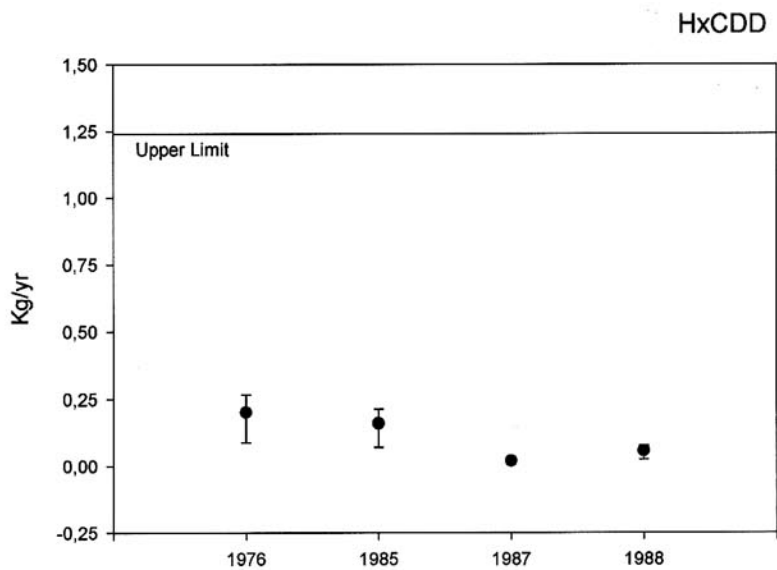
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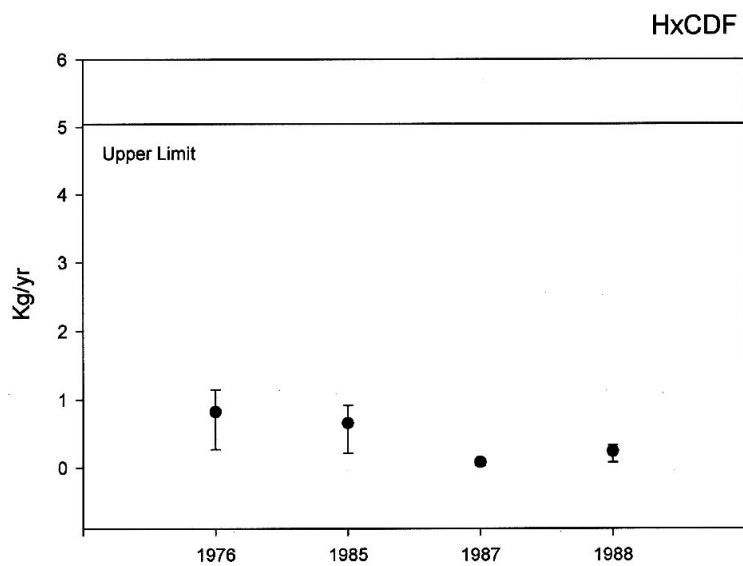
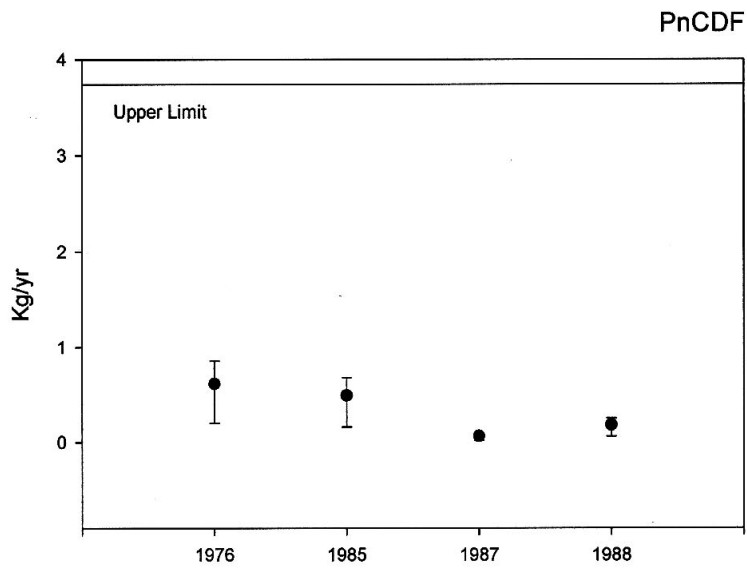
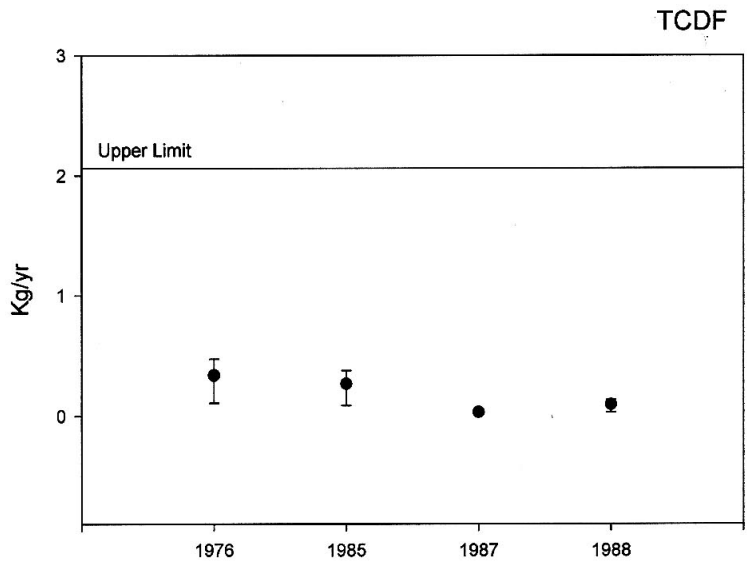


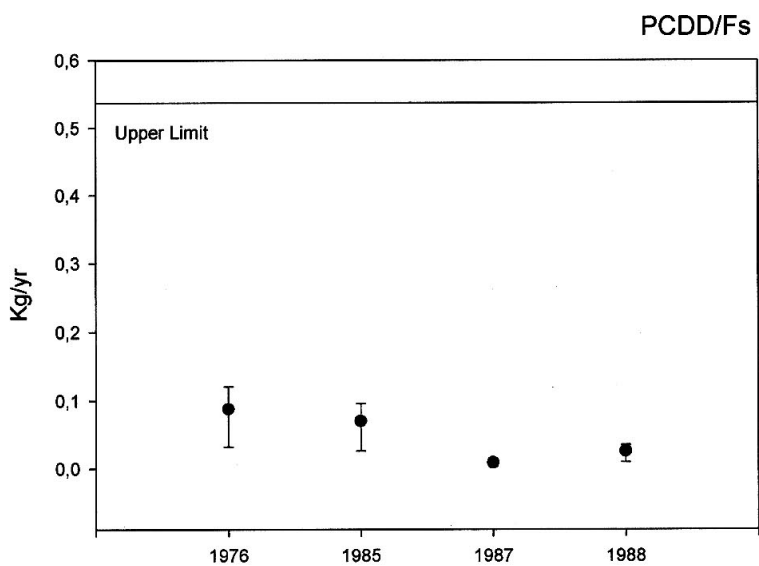
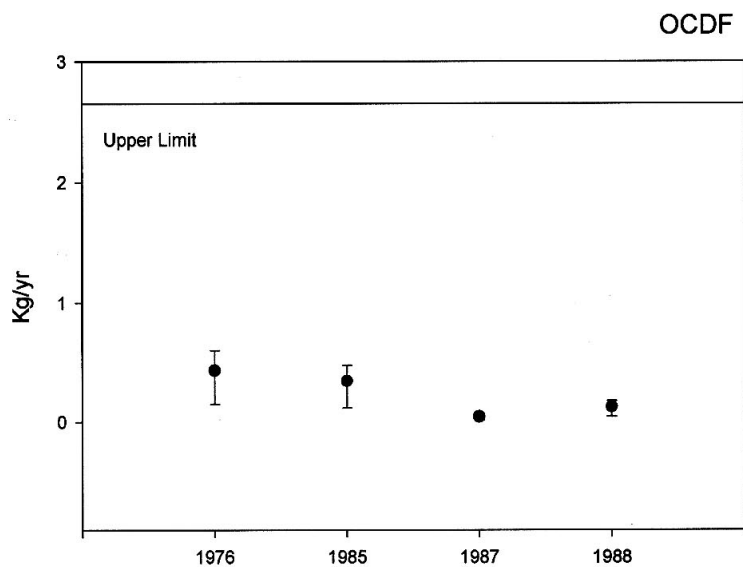
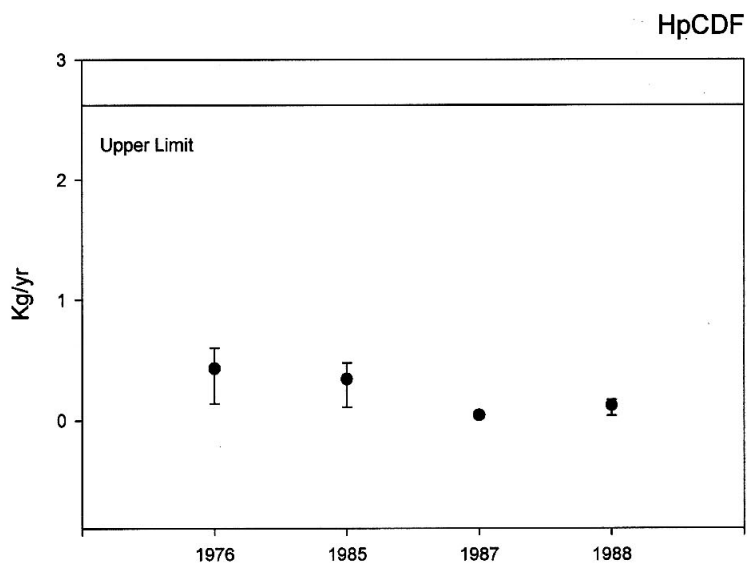




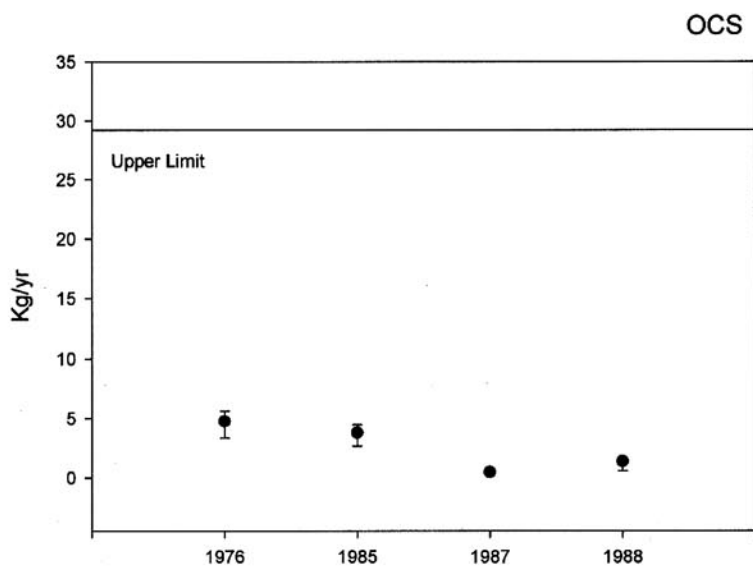
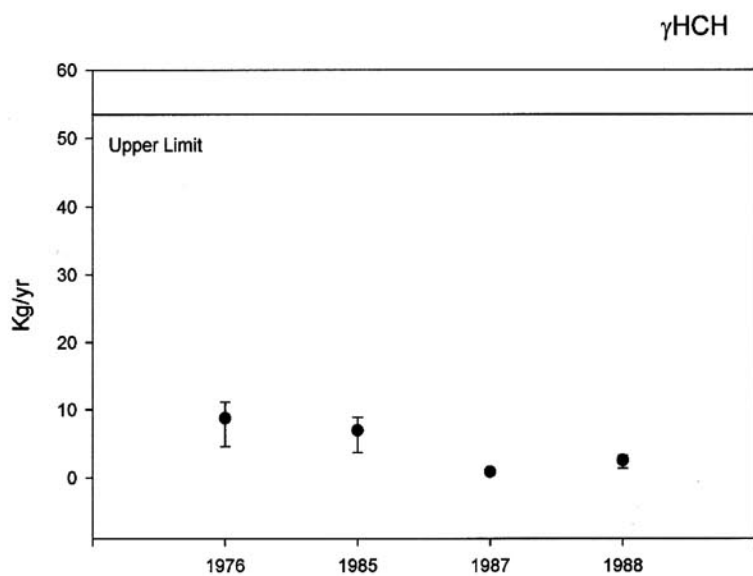
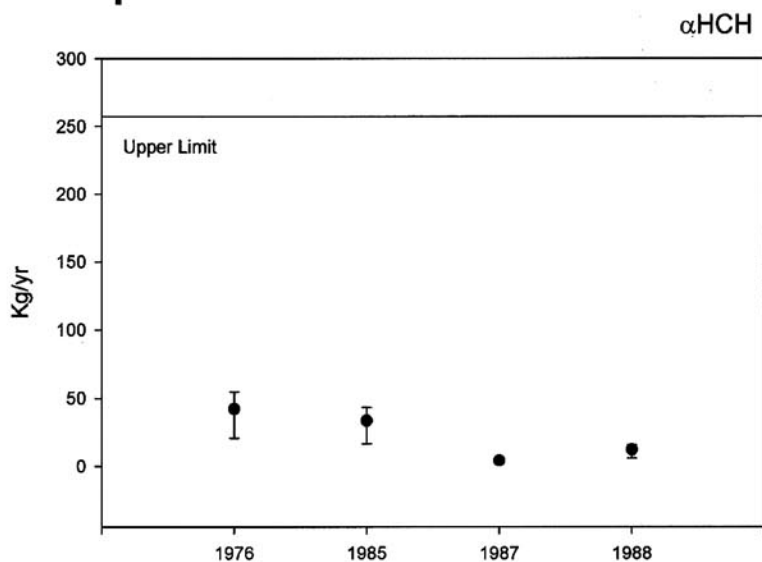


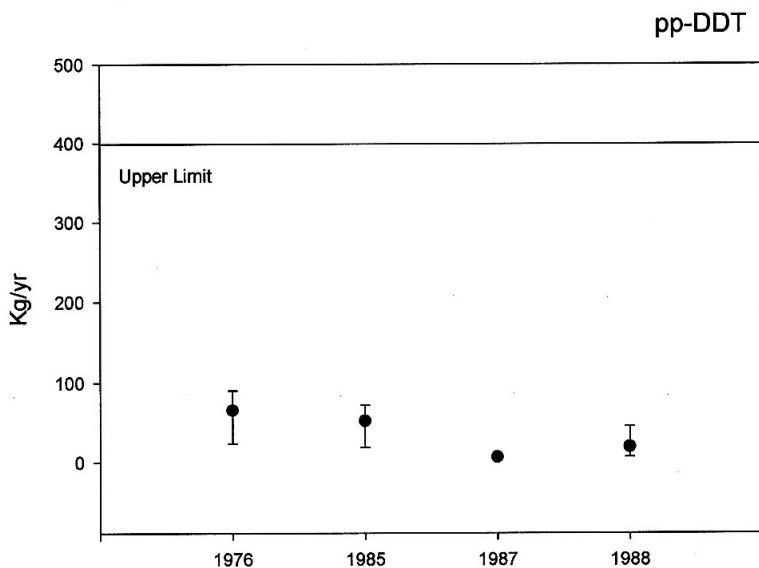
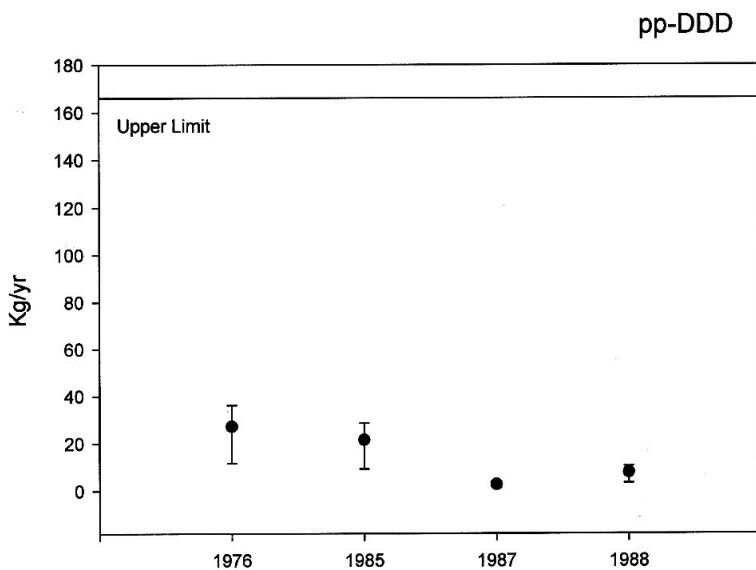
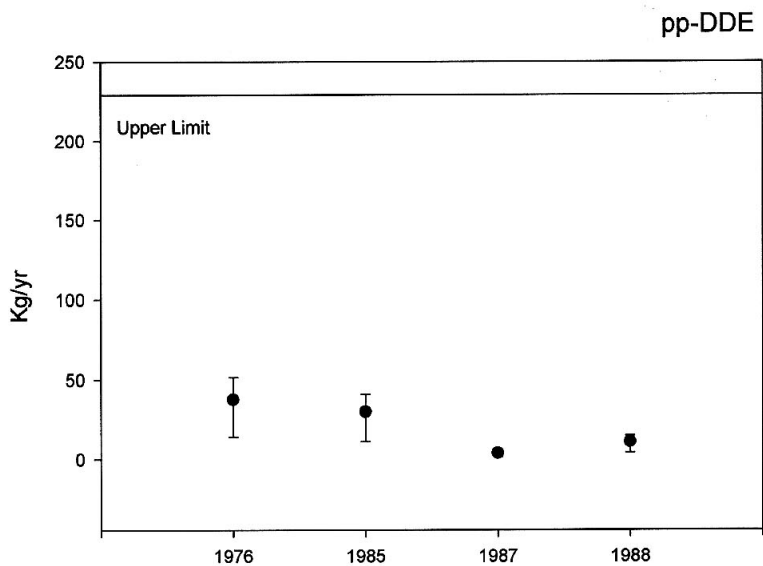


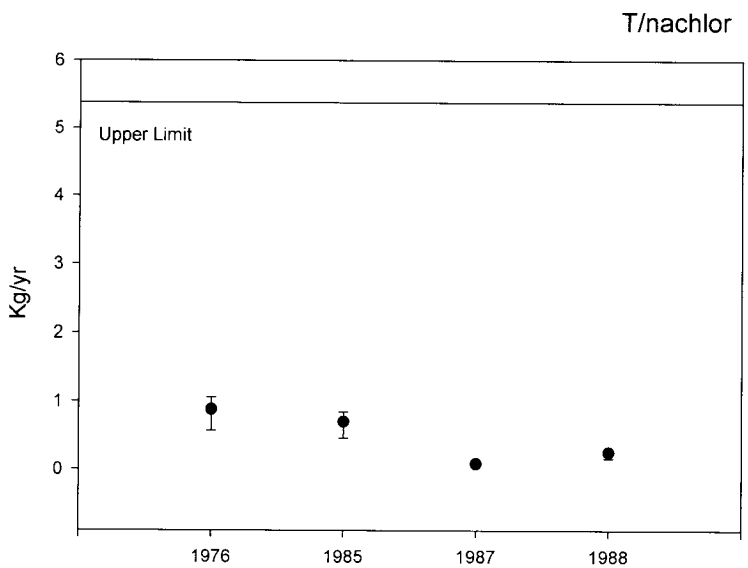
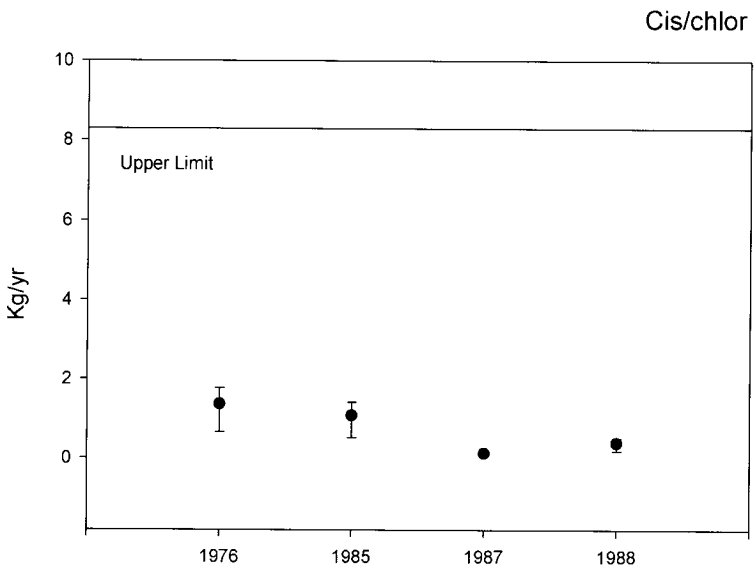
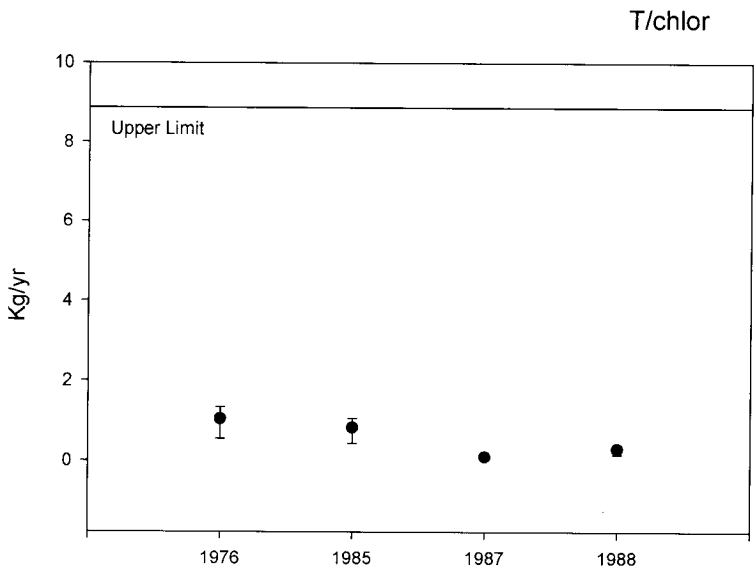




4.4 Chlorinated pesticides







5 Discussion

Sediment is transported from shallow Siberian shelves by the transpolar ice drift towards the Fram Strait. Korsnes and Pavlova (2000) predict that ice formed in the Kara Sea can reach the Barents Sea region within 2 years (on average) with a 51% probability. Through the melting of ice, sediment is released back into the marine environment. Previous estimates of the total amount of sediment exported by sea ice through Fram Strait varies widely from 7 – 150 million tons (Wollenburg, 1993). Sediment distributions in ice indicate that sediment usually accumulates at the surface as patches or as surface layers on the ice (Nuernberg et al., 1993). The highest concentrations of sediment can usually be found on the surface of multi-year ice with observed values in the central Arctic ranging from 10 mg/l to 56 000 mg/l. Due to uncertainty in the amount of sediment that is actually transported by sea ice, estimates of contaminant transport with particles in sea ice also vary widely. The present study represents a significant advancement in the understanding of this phenomenon because the results are based on a mechanistic model used to predict the amount of sediment incorporated into sea ice during different years. The model results were then coupled together with actual data on sea ice fluxes and contaminant concentrations.

It is obvious from Table 2 that contaminant uptake during ice formation is sensitive to the amount of sediment injected into the ice during the freezing process. Comparing the four different years, sediment incorporation ranged from a low of 5.8 in 1987 to a high of 58 in 1976, or a factor of 10. Naturally, contaminant fluxes also vary among the different years in association with the variability in sediment uptake by sea ice. However, it is apparent that even with this variability, the fluxes are considerably smaller than would be predicted based on the worst-case scenario (theoretical limit). The worst-case scenario represents the unrealistic condition that during all storm events the maximum amount of sediment is always incorporated into sea ice. This assumption is unrealistic because wind forced mixing which entrains sediments into ice is highly intermittent in both time and space.

For most contaminants in the Arctic, data do not exist with which to compare the results derived in the present study. However, some work has been carried out on radionuclides. After Russian authorities announced that solid and liquid nuclear waste was dumped into the Kara Sea beginning in the mid-1960's (Yablakov, 1993), there has been considerable interest in the study of sea ice as a transport medium for radioactive sediments. Alternative approaches were used to obtain some idea of the importance of this transport mechanism.

One such approach is to estimate sea ice export using a 3-D model of the Arctic. For example, estimates of sea ice flux from a region similar to the one used in the present study have been derived using the U.S. Office of Naval Research Laboratory model (PIPS 2.0) (Preller and Cheng, 1999). Flux determinations of 167 km³/yr and 209 km³/yr were derived and these are similar to the values determined by the analysis of Korsnes and Pavlova (2000) based on actual sea ice drift patterns. Using assumptions on the sediment load of the ice, it is then possible to estimate the magnitude of this pathway for the transport of radionuclides. The authors of the IAEA - IASAP Modelling and Assessment Working Group used a sediment load of 3 kg/m³ and a Cs-137 concentration of 60 Bq/kg to derive an estimate of 24 x 10¹² Bq/yr from the Kara Sea. This result is of course highly dependent on the values chosen for the sediment load in ice and the concentration of radionuclides on the sediment. Assuming a sediment load of 3 kg/m³ and an ice flux of 167 km³/yr, the corresponding sediment flux is 552 million tons. This flux is much larger than the fluxes estimated by the model procedure of Smesrud (2000) even for the worst-case scenario (355 million tons).

Even considering this very large sediment flux, the transport of radionuclides by seawater is still much greater than transport by sediment-laden sea ice. The authors of the IAEA – IASAP Modelling and Assessment Working Group estimate that if all the ice transported through the Fram Strait originates in the Kara Sea, approximately 4×10^{14} Bq/yr Cs-137 would be transported by ice. For the same scenario, transport by seawater would be 4×10^{17} Bq/yr. A similar conclusion was derived by Dethleff et al. (2000) for the flaw lead located along the Novaya Zemlya coastline.

Dethleff et al. (2000) estimated the entrainment and export of particle-bound radionuclides with newly formed lead-ice for the western Kara Sea (Novaya Zemlya). They compared their estimate with the uptake and transport of dissolved radionuclides by dense-water formed subsequent to ice extraction. A best estimate was made using sedimentological and radiochemical data from the western Kara Sea as well as a maximum estimate based on a simulated scenario of releases from a Novaya Zemlya Bay (release = 1×10^{15} Bq Cs-137 and 1×10^{13} Bq Pu-239,240). For the best case scenario, the fluxes of radionuclides attached to sea ice sediments were 2.90×10^9 Bq (Cs-137) and 5.1×10^8 Bq (Pu-239,240). For the maximum estimate, the export of ice-particle bound Cs-137 and Pu-239,240 from the western Kara Sea is 6.4 and 1.6×10^{13} Bq/yr respectively. For the western Kara Sea, these authors concluded that even for the maximum estimate, the values are very small especially when compared with the transport of radionuclides with dense water rejected in the flaw lead area (9×10^{14} Bq Cs-137 and 6.75×10^{12} Bq Pu-239,240).

The present study provides new estimates of contaminant fluxes via sediment-laden sea ice for specific years based on realistic contaminant concentrations in Arctic sediments, sediment concentrations in sea ice, and sea ice fluxes into the Eurasian Basin from the Kara Sea. This represents an improvement over earlier attempts to estimate the amount of sediment incorporated into ice based on measured concentrations in very few samples. The results however, do confirm the conclusion of earlier attempts to quantify this transport process. While sea ice sediment is an efficient transport mechanism of Arctic contaminants, the quantities of sediment and associated contaminants carried by sea ice are small.

6 Summary

Sea ice transport of sediment is thought to be a highly efficient mechanism for transporting contaminants from Arctic marginal seas into the interior ocean. The shallow waters of the marginal seas are a key region where this process takes place because contaminants are commonly found in nearshore waters and the physical/chemical mechanisms responsible for contaminant entrainment are most active in turbid coastal waters. The amount of contaminants transported by this mechanism is dependent upon the amount of sediment incorporated into the ice. Yet the uptake of contaminated sediments during the formation of frazil ice is a highly intermittent process. Based on this assessment of realistic conditions during several different years, the fluxes of important heavy metals, radionuclides and persistent organic pollutants have been quantified. Contaminant fluxes associated with the process of frazil ice formation in the Kara sea are much smaller than worst-case estimates based on the assumption of continuous incorporation of sediment in sea ice during all storm events. For example, fluxes of the radionuclide Cs-137 determined for the years 1976, 1985, 1987 and 1988 are 2%-16% of the worst-case scenario value of 8.3×10^{12} Bq/yr. Based on these results, the amount of sediment and contaminants incorporated into sea ice is lower than previously thought.

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9 Appendix I

A written questionnaire was given to experts to provide information on (1) contaminant effects for humans and marine organisms and (2) applications of contaminants as tracers in models of contaminant transport and biological effects. The project was conducted within the Norwegian Ministry of the Environment and Ministry of Foreign Affairs Program, "Transport and Fate of Contaminants in the Northern Seas."

The table gives a summary of priority contaminants considering (1) contaminant effects for humans and marine organisms. The important abiotic subcompartments (atmosphere, sediment, water) for each contaminant are indicated in **boldface** type. Important biotic subcompartments (F=fish, I=invertebrates, M=mammals, B=birds) are identified in parentheses next to the contaminant name.

		<i>Atmosphere</i>	<i>Sediment</i>	<i>Water</i>	<i>Biota</i>
Radionuclides		Cs-137 I-131	Cs-137 Pu-239,240	Cs-137 Sr-90	Cs-137 (F) Po-210 (F)
Heavy Metals		Cd Hg Pb (As,Se)	Cd Hg Pb	Cd Hg Pb	Cd (I,M) Hg (F) Pb (M) (As,Se) (M)
Organics	C. U. P.	-	-	-	-
	C. P.	Tox C/Tchlor C/Tachlor Ox-chlor	C/Tchlor C/Tachlor Ox-chlor	dieldrin endrin a-HCH b-HCH	-
	I. P.	HCB PCB PCDD/Fs	PCDD/Fs nPCB PCB7	HCB PCB TCB	PCDD/Fs NPCB PCB7

C. U. P. = current use pesticides

C. P. = chlorinated pesticides

I.P. = industrial products

10 Appendix II

	Component	Group	Material
Heavy Metals			
Cd			Sediment in ice, Kara Shelf
Hg			Bottom Sediments-Kara Shelf
Pb			Sediment in ice, Kara Shelf
Radionuclides			
Cs-137			Bottom Sediments-Kara Shelf
Pu-239			Bottom Sediments-Kara Shelf
POPs-Industrial Products			
PCB 8	pentachlorbenzene	chlorobenzenes	Bottom Sediments-Kara Shelf
PCB 11	pentachlorbenzene	chlorobenzenes	Bottom Sediments-Kara Shelf
PCB28	pentachlorbenzene	chlorobenzenes	Bottom Sediments-Svalbard
PCB52	pentachlorbenzene	chlorobenzenes	Bottom Sediments-Svalbard
PCB101	pentachlorbenzene	chlorobenzenes	Bottom Sediments-Svalbard
PCB118	pentachlorbenzene	chlorobenzenes	Bottom Sediments-Svalbard
PCB153	pentachlorbenzene	chlorobenzenes	Bottom Sediments-Svalbard
PCB180	pentachlorbenzene	chlorobenzenes	Bottom Sediments-Svalbard
5-CB	pentachlorbenzene	chlorobenzenes	Bottom Sediments-Kara Shelf
HCB	hexachlorbenzene	chlorobenzenes	Bottom Sediments-Kara Shelf
TCDD	Tetrachlorodibenzo-p-dioxin	Polychlorinated dibenzo-p-dioxins	Arctic marine sediments
PnCDD	Pentachlorodibenzo-p-dioxin	Polychlorinated dibenzo-p-dioxins	Arctic marine sediments
HXCDD	Hexachlorodibenzo-p-dioxin	Polychlorinated dibenzo-p-dioxins	Arctic marine sediments
HpCDD	Heptachlorodibenzo-p-dioxin	Polychlorinated dibenzo-p-dioxins	Arctic marine sediments
OCDD	Octachlorodibenzo-p-dioxin	Polychlorinated dibenzo-p-dioxins	Arctic marine sediments
TCDF	Tetrachlorodibenzofuran	Polychlorinated dibenzofurans	Arctic marine sediments
PnCDF	Pentachlorodibenzofuran	Polychlorinated dibenzofurans	Arctic marine sediments
HXCDF	Hexachlorodibenzofuran	Polychlorinated dibenzofurans	Arctic marine sediments
HpCDF	Heptachlorodibenzofuran	Polychlorinated dibenzofurans	Arctic marine sediments
OCDF	Octachlorodibenzofuran	Polychlorinated dibenzofurans	Arctic marine sediments
PCDD/Fs	2,3,7,8-substituted tetra-to octachloro dibenzo-p-dioxins and dibenzofurans	PCDD/Fs	Arctic marine sediments
Chlorinated Pesticides			
α HCH	α HCH	Hexachlorocyclohexane	Bottom Sediments-Kara Shelf
γ HCH	γ HCH	Hexachlorocyclohexane	Bottom Sediments-Kara Shelf
OCS	oxchlordane	chlordanes	Bottom Sediments-Kara Shelf
pp-DDE	4,4'-DDE	DDT	Bottom Sediments-Kara Shelf
pp-DDD	4,4'-DDD	DDT	Bottom Sediments-Kara Shelf
pp-DDT	4,4'-DDT	DDT	Bottom Sediments-Kara Shelf
Trans-chlor	γ -chlordane	chlordanes	Bottom Sediments-Svalbard
Cis-chlor	α -chlordane	chlordanes	Bottom Sediments-Svalbard
Trans-nonachlor	γ -nonachlor	chlordanes	Bottom Sediments-Svalbard
Cis-nonachlor	α -nonachlor	chlordanes	Bottom Sediments-Svalbard

11 Appendix III

Nomenclature

$f(x)$ = Beta -Pert probability distribution

α_1 = variable in Beta-Pert function $f(x)$

α_2 = variable in Beta-Pert function $f(x)$

μ = mean of parameter values used in Beta-Pert function $f(x)$

σ^2 = variance of parameter values used in Beta-Pert function $f(x)$

minimum = minimum value of probability distribution

maximum = maximum value of probability distribution

mostlikely = most likely value of probability distribution

x = value of Beta-Pert function

$B(\alpha_1, \alpha_2)$ = function used to calculate Beta-Pert function $f(x)$

t = variable used to calculate $B(\alpha_1, \alpha_2)$

There are few data available to calculate a probability distribution function for contaminant concentrations in sediments from the Kara shelf and adjacent areas. As an alternative we constructed probability distribution functions for each parameter using the Beta-Pert function. Parameter values used to establish a Beta-Pert distribution $f(x)$ are the minimum, maximum and most likely values. Whereby the functional parameters (α_1, α_2) are given by,

$$\alpha_1 = \frac{(\mu - \text{minimum})(2 * \text{mostlikely} - \text{minimum} - \text{maximum})}{(\text{mostlikely} - \mu)(\text{maximum} - \text{minimum})} \quad (2)$$

$$\alpha_2 = \alpha_1 \frac{\text{maximum} - \mu}{\mu - \text{minimum}} \quad (3).$$

The mean and variance of the parameter values used to define the Beta-Pert distribution are defined as,

$$\mu = \frac{\text{minimum} + 4 * \text{mostlikely} + \text{maximum}}{6} \quad (4)$$

$$\sigma^2 = \frac{\text{maximum} - \text{minimum}}{6}^2 \quad (5).$$

The Beta-Pert function is then given by,

$$f(x) = \frac{x^{\alpha_1-1} (1-x)^{\alpha_2-1}}{B(\alpha_1, \alpha_2)}, 0 \leq x \leq 1 \quad (6)$$

$$B(\alpha_1, \alpha_2) = \int_0^1 t^{\alpha_1-1} (1-t)^{\alpha_2-1} dt \quad (7)$$

with mean,

$$\frac{\alpha_1}{(\alpha_1 + \alpha_2)} \quad (8)$$

mode,

$$\begin{aligned} & \frac{\alpha_1 - 1}{(\alpha_1 + \alpha_2 - 2)}, \alpha_1 > 1, \alpha_2 > 1 \\ & 0, 1, \alpha_1 < 1, \alpha_2 < 1 \\ & 0, \alpha_1 < 1, \alpha_2 \geq 1, \text{ or } \alpha_1 = 1, \alpha_2 > 1 . \\ & 1, \alpha_1 \geq 1, \alpha_2 < 1, \text{ or } \alpha_1 > 1, \alpha_2 = 1 \\ & \text{value} = \text{undefined}, \alpha_1 = 1, \alpha_2 = 1 \end{aligned} \quad (9)$$

and variance,

$$\frac{\alpha_1 \alpha_2}{(\alpha_1 + \alpha_2)^2 (\alpha_1 + \alpha_2 + 1)} . \quad (10)$$

The mean of the Beta-Pert distribution (Eq. 8) which is defined for the range 0-1, corresponds to the mean (Eq. 4) defined by the minimum and maximum parameter values. And similarly, the mode of the Beta-Pert distribution (Eq. 9), corresponds to the most likely parameter value. The values created by the Beta-Pert function are easily converted to values defined by the initial range of parameter values as,

$$\text{minimum} + [f(x) * (\text{maximum} - \text{minimum})] \quad (11)$$