



Persistent Organic Pollutants (POPs) and Polycyclic Aromatic Hydrocarbons (PAHs) in surface sediments from selected fjords, tidal plains and lakes of the North Spitsbergen

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Abstract: The aim of this study was to examine the pollution level of polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) and selected chloroorganic pesticides (HCH isomers, DDT and its metabolites, aldrin, dieldrin, endrin, heptachlor, endosulfan I and II, and methoxychlor) in surface sediments from selected fjords, tidal plains and lakes from the North Svalbard area. The sediments were collected from 34 sampling stations in July 2005. Only endosulfan I and methoxychlor, among selected chloroorganic pesticides, were measured in concentrations near detection limit (LoD) in fourteen sediment samples. The sum of seven PCB congeners varied from <math><0.9</math> to 5.6 ng g⁻¹ d.w. in sediments from fjords and tidal plains and from <math><0.1</math> to 14.6 ng g⁻¹ d.w. in sediments from lakes. The concentrations of analysed PAH compounds in surface sediments from lakes were over ten times higher (Σ_{16} PAHs to 429 ng g⁻¹ d.w.) than in sediments from fjords and tidal plains (Σ_{16} PAHs to 36 ng g⁻¹ d.w.).

Key words: Arctic, Spitsbergen, sediments, PAHs, PCBs, OCPs.

Introduction

Svalbard is situated approximately halfway between the North Cape of Norway and the North Pole and is therefore far away from major sources of pollution.

However previous studies in this region indicate the presence of dangerous pollutants (*e.g.* trace metals, PAHs, PCBs and some pesticides) (Risebrough *et al.* 1976; Tanabe *et al.* 1983; Oehme and Manö 1984; Barrie 1986; De Voogt and Jansson 1993; Wania and Mackay 1993, 1996; Villa *et al.* 2003).

Atmospheric deposition of pollutants on Svalbard has been attributed to long-range sources despite the presence of local mining industries and coal-fired power stations in the Isefjord (Rose *et al.* 2004). It has been postulated that POPs are released into the environment in the northern temperate latitudes and transported to the Arctic via the atmosphere, ocean currents, and riverine inputs (Barie *et al.* 1992, Fellin *et al.* 1996). The significant long-range atmospheric transport of pollutants to Svalbard is thought to originate from the former Soviet Union, Western Europe and North America (Pacyna and Ottar 1985, Pacyna *et al.* 1985, Barrie 1986, Beine *et al.* 1996, Burkow and Kallenborn 2000). The physical and chemical properties that promote long-range atmospheric transport, and, therefore, the presence of POPs in the Arctic environment include low water solubility, the presence in vapour or particle-bound form atmospheric residence times of several days or longer, and high biological and chemical stability. Transport of these compounds around the globe can take the several weeks to a month to occur, whereas transport vertically between the atmospheric boundary layer near the Earth's surface and the upper troposphere occurs on a time scale of a month (Graedel and Crutzen 1993). Additionally, as PAHs associated with airborne particles vary significantly as a function of their emission sources, some PAH concentration ratio has been used to indicate vehicular emission sources (Rogge *et al.* 1993; Khalili *et al.* 1995). Rose *et al.* (2004) suggested that local small industrial point sources of pollution may not be negligible when compared to major source from Europe and America. Particle-bound compounds such as PAH show a clear seasonal trend with values high in winter and low in summer. For organochlorine compounds, the seasonal patterns observed were less clear and average concentrations for some compounds were similar in cold and warm periods (Fellin *et al.* 1996). It is generally assumed, that the degradation of volatile and semi volatile compounds is slower in colder areas compared to warmer ones, since biodegradation and volatilisation processes are known to be temperature dependent. As the temperature decreases, biodegradation slows down, and air/water concentration ratio decreases causing a lower rate of removal by photolysis in air. It has long been recognised that the bottom sediments provide a reliable record of atmospheric deposition to the environment (Oehme and Manö 1984, Rose *et al.* 2004; Głowacki 2007; Ravindra *et al.* 2008; Walker *et al.* 2009).

The aim of this study was to examine the pollution level of PAHs, PCBs and selected organochlorine pesticides (HCH isomers, DDT and its metabolites, aldrin, dieldrin, endrin, heptachlor, endosulfan I and II, and methoxychlor) in surface sediments from selected fjords, tidal planes and lakes from the North Svalbard area.

Material and methods

Study area

The region of the Wijdefjorden, Woodfjorden and Bockfjorden, the tidal plains in Vestfjorden and Bockfjorden and lakes located close to the coasts of Wijdefjorden, Woodfjorden and Bockfjorden were selected as the study area (Fig. 1, Table 1). This area is where mixing of the Atlantic waters with Arctic waters occurs. The different impact of these water masses reach to a place of Wijdefjorden in period of big activity of the West Spitsbergen Current only. For the rest of time this area is under the influence of Arctic water masses. The other fjords are located under the impact of the West Spitsbergen Current over most of the year (Loeng 1991; Haugan 1999; Jones 2001; Løyning 2001; Walczowski and Piechura 2006, 2007).

The sampling stations were labelled with Roman numerals I–III for three fjords and called R for tidal plains and J for lakes. Arabic numerals were used for labelled stations in selected areas.

The Wijdefjorden is the longest (120 km) fjord of Svalbard with variable depth to 246 m. The sampling stations I 1 – I 10 were located in this area. The Woodfjorden with sampling stations III 1, III 2 and III 3 is located in NE Spitsbergen. The



Fig. 1. Location of the Spitsbergen (A) and sampling stations (B).

Table 1
 Characteristics of the study area and surface sediments

Station	Geographical position	Sampling date	Temperature (°C)	Humidity (%)	LOI (%)
Fjords					
I 1	78°54.40' N, 16°24.60' E	22.07.2005	2.7	32.83	4.76
I 2	79°00.40' N, 16°19.10' E	22.07.2005	2.1	40.53	4.96
I 3	79°05.00' N, 16°05.00' E	22.07.2005	3.6	41.19	4.35
I 4	79°10.40' N, 15°49.30' E	22.07.2005	3.3	37.92	4.25
I 5	79°15.00' N, 15°44.00' E	23.07.2005	1.3	38.55	3.88
I 6	79°20.10' N, 15°42.90' E	23.07.2005	2.2	48.59	4.75
I 9	79°38.40' N, 15°45.30' E	24.07.2005	4.6	32.76	1.65
I 10	79°39.90' N, 15°38.00' E	24.07.2005	3.2	43.02	3.21
II 1	79°27.30' N, 13°22.90' E	26.07.2005	3.6	45.74	4.10
III 1	79°18.80' N, 13°53.60' E	26.07.2005	2.8	28.65	2.77
III 2	79°23.60' N, 13°54.00' E	26.07.2005	1.2	37.02	4.14
III 3	79°28.60' N, 13°44.90' E	26.07.2005	4.4	43.58	5.87
Mean (±SD)				39.20 (±5.81)	4.06 (±1.10)
Tidal plains					
R I 2	79°06.08' N, 15°38.64' E	22.07.2005	4.2	25.04	1.82
R I 4	79°06.05' N, 15°39.91' E	22.07.2005	4.6	23.48	1.44
R I 6	79°06.06' N, 15°40.98' E	22.07.2005	4.5	24.37	1.06
R I 7	79°06.05' N, 15°38.42' E	22.07.2005	3.0	25.74	0.85
R II 2	79°26.11' N, 13°23.35' E	22.07.2005	3.2	38.53	2.08
Mean (±SD)				27.43 (±6.26)	1.45 (±0.51)
Lakes					
J I 1	79°06.20' N, 15°37.91' E	23.07.2005	5.0	39.18	4.25
J I 2	79°06.25' N, 15°37.93' E	23.07.2005	4.3	24.51	2.79
J I 3	79°06.34' N, 15°37.91' E	23.07.2005	4.2	25.64	2.24
J II 1	79°38.47' N, 15°38.40' E	23.07.2005	6.6	21.16	0.40
J II 2	79°38.53' N, 15°38.33' E	23.07.2005	0.8	16.54	0.42
J II 3	79°38.45' N, 15°38.93' E	23.07.2005	9.9	24.50	0.95
J III 1	79°40.33' N, 14°15.40' E	27.07.2005	7.8	41.75	14.56
J III 2	79°40.39' N, 14°15.07' E	27.07.2005	8.9	45.69	5.92
J III 3	79°40.90' N, 14°13.38' E	27.07.2005	6.9	67.47	13.68
J III 4	79°40.66' N, 14°12.15' E	27.07.2005	8.6	26.02	4.37
J III 5	79°40.57' N, 14°12.06' E	27.07.2005	9.7	25.71	3.50
J III 6	79°40.53' N, 14°11.92' E	27.07.2005	7.7	28.31	3.36
J IV 1	79°43.58' N, 14°24.12' E	28.07.2005	6.2	n/a	n/a
J V 1	79°48.18' N, 15°40.01' E	29.07.2005	3.2	11.04	3.96
J V 2	79°48.20' N, 15°37.87' E	29.07.2005	7.1	71.88	26.41
J V 3	79°48.14' N, 15°37.56' E	29.07.2005	7.1	39.08	6.24
J VI 1	79°43.11' N, 14°53.12' E	30.07.2005	6.8	12.71	2.78
Mean (±SD)				32.57 (±17.52)	5.99 (±6.81)

n/a – data not available

Bockfjorden with station II 1 is a small arm of Woodfjorden. The Vestfjorden (1 km long) with investigated tidal plain and sampling stations R I 2, R I 4, R I 6, R I 7 constitutes the western arm of the Wijdefjorden. The Vestfjorden with the tidal plain is surrounded with the mountain Skirshorg (1318 m a.s.l.). Sediments that have accumulated in the tidal plain area are transported by large rivers running from the glaciers Universitetbreen and Lisbertbreen. The suspended matter carried by the rivers filled up the fjord and created a tidal plain about 2 km long. The second studied tidal plain (station R II 2) was located in the beginning of the Bockfjorden which is an arm of Woodfjorden. The tidal plains were under an influence of different factors originated from land and sea. The Bockfjorden tidal plain is rounded with elevations up to 1200 m a.s.l. with a few smaller glaciers and the big Karlsbreen glacier. The rivers running off from this glacier and many small rivers from the mountain area bring the fine-grounded material sedimented in the tidal plain.

The lakes located in the Svalbard area are an effect of different forms of glacial activity, which effected in morphometric differences and different types of water environments. The present study concerns lakes with different genetic and morphometric properties.

The sampling stations J I 1, J I 2, J I 3 were located in three lakes near the mountain Skirshorg close to the east coast of Vestfjorden. The lakes were small and shallow and filled with water from snow-melt. The hydrological conditions are change from strong discharging in the rain and snow-melt season to no discharge during the dry summer season. The salinity about 11.4 PSU (Practical Salinity Units) might be indicative of incidental sea flows, infiltration and aerosols. The area around lakes was located up the frontal moraine of Yggbreen glacier and almost devoid of vascular plants (green plant having a vascular system: ferns, gymnosperms, angiosperms).

The three sampling stations J II 1, J II 2 and J II 3 were located in the north part of lateral moraine of Nordbreen glacier which is leaking to the Wijdefjorden. The plants around this basin were sparse. The water of very small lake (3 m²) with station J II 1 has low salinity from aerosols and was supplied by snow and ice-melt water, and by rain. The lake with station J II 2 was located in slack ice of the border between moraine and glacier. The lake with J II 3 station was located close to the leaking place of lateral moraine to the sea and had salinity about 0.2 PSU.

The six sampling stations: J III 1, J III 2, J III 3, J III 4, J III 5 and J III 6 were located on the east coast of Woodfjorden (to the North from Mushamn, 57 m a.s.l.) around tundra plant cover. The investigated lakes were supplied by waters from small rivers, e.g. runoff under snow and ice. These lakes have characteristic variable morphometry and size, due to the effect of rain squall or lack of rain (Nowiński 2002). The station J III 1 was located in big (1.2 ha) and deep (3.6 m) lake with permanent outflow to the sea. The sampling station J III 2 was located in smaller lake periodically connected with the lake with station J III 1. The next stations (J III 3, J III 4 and J III 5) were located in a shallow (0.5 ha and 0.1 m) hollow supplied by wa-

ters from the large catchment area. Despite the location close to the sea (150 m), the salinity in waters of these lakes was below detection limit. The lake with sampling station J III 6 was located close to the Wijdefjorden. The salinity about 0.7 PSU might be indicated on incidental sea flows, infiltration and aerosols. The hydrological conditions was changed during the winter and summer seasons.

The sampling station J IV 1 was located in the big lake close to the east coast of the Woodfjorden (Selungane region), 6 km to the North from J III basin. The lake waters with significant suspended matter content were originated from snow-melt, rains and ablation of glacier.

The sampling station J V 1 was located in the next big lake on the east coast of Woodfjorden with genesis and properties similar as J IV 1. The other two stations J V 2 and J V 3 were located close to the area of Woodfjorden. The basin with J V 2 station was the big lake (0.1 ha) supplied by small rivers, with cold desert plants on the coast and outflow to the sea. The station J V 3 was located in the smaller lake, seasonally without outflow.

The sampling station J VI 1 was located in the big, typical fiord's lake on the western side of the Wijdefjorden (close to the Vogtdalen). The water in this lake originated from rivers and glacier. The salinity of water was about 0.4 PSU.

Sample collection

The surface sediment samples (0–5 cm) were collected in the period 23rd–30th July 2005. The samples were taken from 34 sampling stations (Table 1, Fig. 1) with an Ekman grab of dimensions 23 × 23 cm. The water temperature was measured on each sampling station.

Laboratory analysis

Humidity.—The sediment samples were air-dried and the humidity was analysed as mean loss of weight from triplicate measurements (ISO 11464:1994).

Loss of ignition (LOI).—The organic matter content was measured as mean LOI from triplicate samples at a temperature of 550°C for 5 h for all sediment samples.

PCBs and OCPs.—PCBs and OCPs were analysed according to Bremle *et al.* (1995) and Sapota (1997). A subsample of approximately 3–5 g of freeze-dried sediment sample was Soxhlet-extracted with hexane/acetone (1:2 vol.). Prior to the extraction internal standards (PCB 65 and 207) were added to the solvent (Dannerberger and Lerz 1996). The extracts were purified on a column containing two layers of silica gel (with K₂CO₃ and H₂SO₄) and eluted with dichloromethane/hexane (5:95 vol.). Copper powder was added to eliminate the sulphur. The eluate was evaporated and dissolved in isoctane.

PAHs.—PAHs were analysed according to Song *et al.* (2002). A sediment subsample of approximately 1–5 g air-dried at ambient temperature in a clean-air

cabinet was extracted 5 h with dichloromethane in ultrasonic bath. The extracts were evaporated under N₂ gas stream to about 1 cm³ volume and purified on a column containing silica gel and copper powder layers and eluted with dichloromethane. The eluate was concentrated to 1 cm³ volume under N₂ gas stream.

GC analysis

The concentration of selected organochlorine pesticides (HCH isomers, DDT and its metabolites, aldrin, dieldrin, endrin, heptachlor, endosulfan I and II, methoxychlor) and seven PCBs (IUPAC No 28, 52, 101, 118, 138, 153, 180) were analysed by gas chromatograph Agilent Technologies 6890N with electron capture detector (ECD). Sixteen PAH compounds listed by World Health Organisation (naphthalene, acenaphthylene, acenaphthene, fluorene, fluoranthene, anthracene, phenanthrene, pyrene, benzo(a)anthracene, chrysene, benzo(a)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, indeno(1,2,3,cd)pyrene, dibenzo(a,h)anthracene, benzo(g,h,i)perylene) were analysed by GC-MS Hewlett Packard 6890 with mass selective detector 5973.

The values of all analysed substances were expressed in ng g⁻¹ on a dry weight (d.w.) basis. LoD were 0.1 ng g⁻¹ of PCBs and pesticides and 1 ng g⁻¹ of PAHs. Recoveries for all PCB compounds varied between 90–104%. Recoveries for pesticides varied between 75–89% and for PAH compounds 83–116%. Recoveries for lightest compounds (naphthalene, acenaphthylene, acenaphthene, fluorene) were >80% and 90–116% for the rest.

Results and discussion

Generally the concentrations of analysed substances were lower in sediment samples collected in fjords and tidal plains than in lakes. The organic matter and humidity content are given in Table 1. The LOI concentration in sediments from investigated lakes was higher than in other analysed samples. Perhaps it was a result of suspended matter transported by river runoff from mountains and glaciers. The content of LOI in sediments from fjords and tidal planes ranged respectively from 1.65% to 5.87% (mean 4.06% ± 1.10) and from 0.85% to 2.08% (mean 1.45% ± 0.51) (Fig. 2). Similar values of organic matter concentration were found in other Arctic fjords: Kongsfjorden 1–9% (Zaborska *et al.* 2006), Akulliit to 7% and Kuanersuit to 9% (Gilbert *et al.* 2002) and Kangerdluk (Greenland) 6–8% (Gilbert *et al.* 1998). The small content of organic matter in sediments from station I 9 was connected with geological bottom structure of the Wijdefjorden area (Kowalewski *et al.* 1990). Station I 9 was situated on the bottom elevation, which caused organic matter run-off. The inflow of organic matter to the tidal plains located farther from the glacier was smaller. However, the sediments from investigated lakes contained from 0.4% to 26.4% LOI (mean 5.99% ± 6.81) (Fig. 3). The smallest LOI content was indicated in

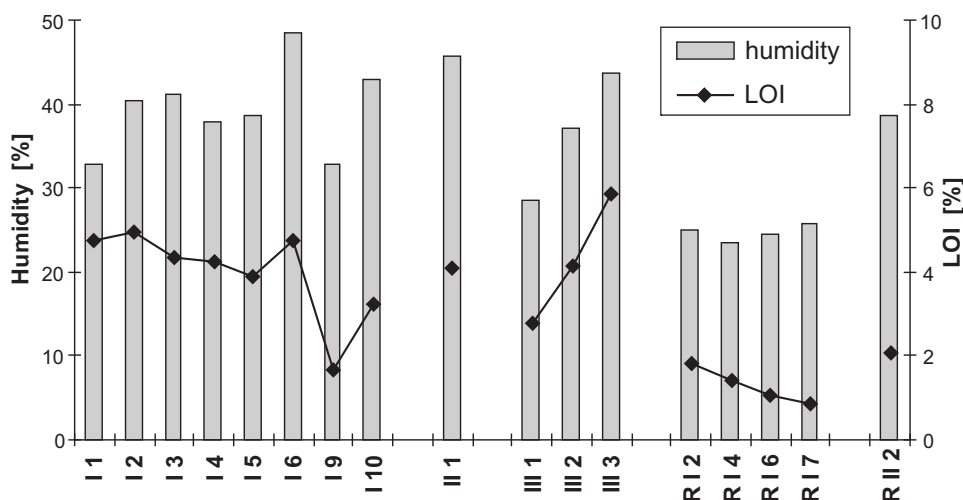


Fig. 2. Humidity and LOI content in sediment samples from investigated fjords and tidal plains.

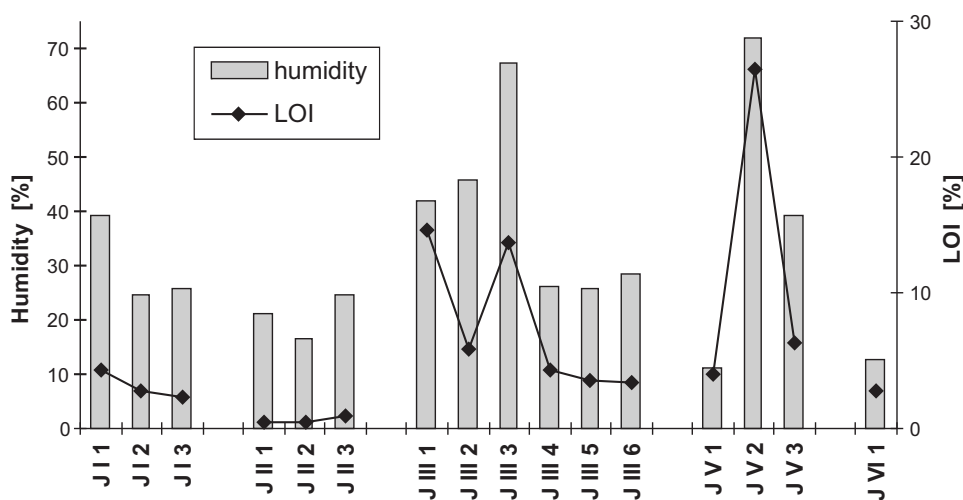


Fig. 3. Humidity and LOI content in sediment samples from investigated lakes.

sediments from sampling stations J II 1, J II 2 and J II 3 located in the north part of lateral moraine of Nordbreen glacier seeping in to the Wijdefjorden.

The concentrations of OCPs, PCBs and PAHs in sediments depend on organic matter content (Lohse 1988, Dannenberger and Lerz 1996, Andruliewicz and Poutanen 2002) and were confirmed by results in this study. In sediments with high concentrations of organic matter the contents of analysed material increased, except in sediments from station I 9, where the sum of sixteen PAHs was 36 ng g^{-1} d.w. and LOI was only 1.6% (Fig. 4).

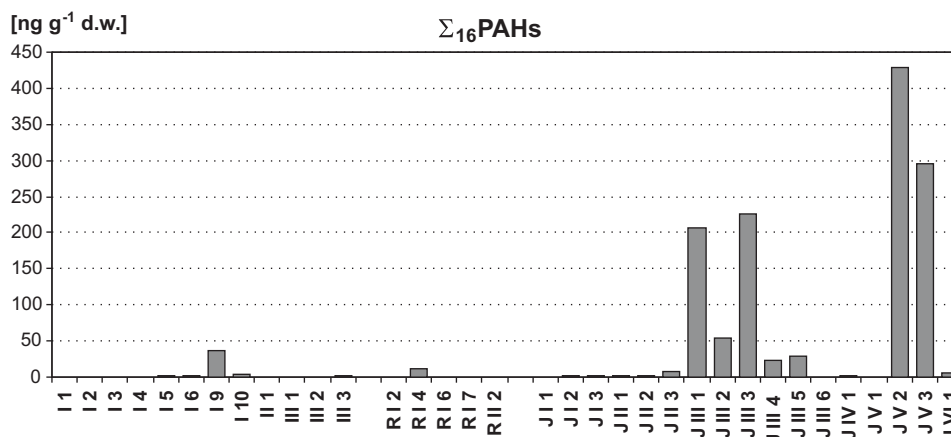


Fig. 4. The content of Σ_{16} PAHs in surface sediments.

The concentrations of analysed PAH compounds in surface sediments were detected only on five stations from fjords and one station from tidal plains. The contents of Σ_{16} PAHs in sediments from fjords and tidal plains (Σ_{16} PAHs to 36 ng g⁻¹ d.w.) were over ten times lower than in sediments from lakes (Σ_{16} PAHs to 429 ng g⁻¹ d.w.) (Table 2, Figs 4 and 5). The presence of PAHs in analysed sediment samples from lakes was ascertained only in two sampling areas: J III close to Wijdefjorden and J V (Woodfjorden area) (Table 2). In the remaining samples the concentration of PAHs was near detection limits (1 ng g⁻¹ d.w.). Similar ranges of PAH concentrations (to 640 ng g⁻¹ d.w.) were reported by Rose *et al.* (2004) in surface and pre-industrial lake sediments from the west coast of Svalbard. The analytical results show that the high molecular weight PAHs such as fluorine, chrysene, benzo(a)fluoranthene, benzo(a)pyrene, benzo(g,h,i)perylene and indeno(1,2,3,-cd)pyrene, dominate the total fraction, whereas low molecular weight PAHs were found in relatively very low concentrations. Similar results were reported by Fellin *et al.* (1996) for the Ellesmere Island (Arctic) and by Ravindra *et al.* (2008) for the border area between Belgium and France. The authors obtained also high concentrations of that the high molecular weight PAHs. Seasonal and meteorological parameters also play a role in limiting the PAHs concentrations and generally a higher concentration of PAHs in winter season was found. The higher concentration in winter mainly indicates its relation with increased emission from domestic heating and power plants at low temperatures (Fellin *et al.* 1996, Ravindra *et al.* 2008).

The presence of investigated PCB congeners was found in all sediment samples (except sediments from stations J I 1 and J I 2). The sum of seven PCB congeners varied from <0.9 to 5.6 ng g⁻¹ d.w. in sediments from fjords and tidal plains and from <0.1 to 14.6 ng g⁻¹ d.w. in sediments from lakes (Table 3 and 4, Figs. 6 and 7). The PCBs content in sediments from station I 9 was relatively high (3.5 ng g⁻¹ d.w.) among the investigated sediments from fjords and tidal plains. CB 153

Table 2
 The content of PAH compounds in surface sediments from lakes

Compound [ng g ⁻¹ d.w.]	J I 2	J I 3	J II 1	J II 2	J II 3	J III 1	J III 2	J III 3	J III 4	J III 5	J IV 1	J V 2	J V 3	J VI 1
naftthalene	nd	nd	nd	nd	nd	nd	nd	7	nd	nd	nd	4	6	nd
acenaphthylene	1	1	1	1	2	12	4	11	3	4	nd	3	4	nd
acenaphthene	nd	nd	nd	nd	1	3	1	5	1	1	nd	12	13	nd
fenanthrene	nd	nd	nd	nd	nd	1	nd	1	nd	nd	nd	1	14	nd
anthracene	nd	nd	nd	nd	nd	2	1	1	1	1	nd	7	6	nd
fluoranthene	nd	nd	nd	nd	nd	nd	2	1	3	4	1	8	9	1
fluorene	nd	nd	nd	nd	nd	19	6	6	7	5	nd	13	17	nd
pyrene	nd	nd	nd	nd	nd	3	1	6	0	0	nd	7	6	nd
chrysene	nd	nd	nd	nd	1	3	5	4	1	1	1	6	6	nd
benzo(a)anthracene	nd	nd	nd	nd	nd	20	10	3	nd	nd	nd	11	14	nd
benzo(a)fluoranthene	nd	nd	nd	nd	2	4	1	46	2	3	nd	40	67	nd
benzo(k)fluoranthene	nd	nd	nd	nd	1	2	3	10	1	2	nd	18	23	nd
benzo(a)pyrene	nd	nd	nd	nd	nd	38	4	54	2	4	nd	92	28	5
benzo(g,h,i)perylene	nd	nd	nd	nd	nd	74	nd	36	2	3	nd	142	48	nd
indeno(1,2,3,-cd)pyrene	nd	nd	nd	nd	nd	16	11	22	nd	nd	nd	42	20	nd
dibenzo(a,h)anthracene	nd	nd	nd	nd	nd	9	6	13	nd	nd	nd	23	15	nd
$\Sigma_{16} PAHs$	1	1	1	1	7	207	55	226	23	28	2	429	296	6

nd - below the LoD (1 ng g⁻¹)
 Table 3
 The content of PCB compounds in surface sediments from fjords and tidal plains

Compound [ng g ⁻¹ d.w.]	I 1	I 2	I 3	I 4	I 5	I 6	I 9	I 10	II 1	III 1	III 2	III 3	R I 2	R I 4	R I 6	R I 7	R II 2
CB 28	0.4	0.3	nd	nd	nd	nd	nd	nd	0.4	nd	0.4	nd	0.4	0.4	0.4	0.3	0.6
CB 52	0.4	0.7	nd	nd	nd	nd	nd	nd	0.6	nd	0.4	nd	0.9	0.7	1.2	0.9	1.2
CB 101	0.6	0.4	0.8	0.6	0.6	0.5	nd	0.9	0.4	0.3	0.7	nd	0.5	0.5	0.9	0.5	0.7
CB 118	0.6	0.3	0.8	0.8	0.7	0.7	1.1	nd	0.5	0.5	0.9	0.5	nd	0.6	1.1	0.9	1.1
CB 138	0.4	nd	0.7	nd	nd	nd	nd	nd	nd	0.5	1.1	0.5	nd	0.3	nd	nd	nd
CB 153	0.4	nd	1.6	nd	nd	nd	1.4	nd	nd	nd	0.9	0.6	nd	0.8	nd	nd	nd
CB 180	nd	nd	nd	nd	nd	nd	1.1	nd	nd	nd	1.3	nd	nd	nd	nd	nd	nd
$\Sigma_7 PCBs$	2.9	1.7	3.8	1.4	1.3	1.2	3.5	0.9	1.9	1.3	5.6	1.6	1.8	3.5	3.7	2.6	3.6

nd - below the LoD (0.1 ng g⁻¹)

and respectively CB 118, 101 and 52 (Table 3) were identifying in the highest concentrations in sediments from fjords and tidal plains. CB 138 and than CB 118 were dominated (Table 4) in sediments from lakes. The changes in percentage by weight of CB 138 and 153 can be explained by anaerobic process of PCB congeners degradation, which prefers disconnection of chlorine atoms in meta- and para-positions in CB 170, 180 and 187 (Mamantov 1985). CB 101 and 118 are a product of photolysis process of CB 153 (Falandysz 1999). The highest content of PCBs was identified in sediment samples from lakes located on the east part of

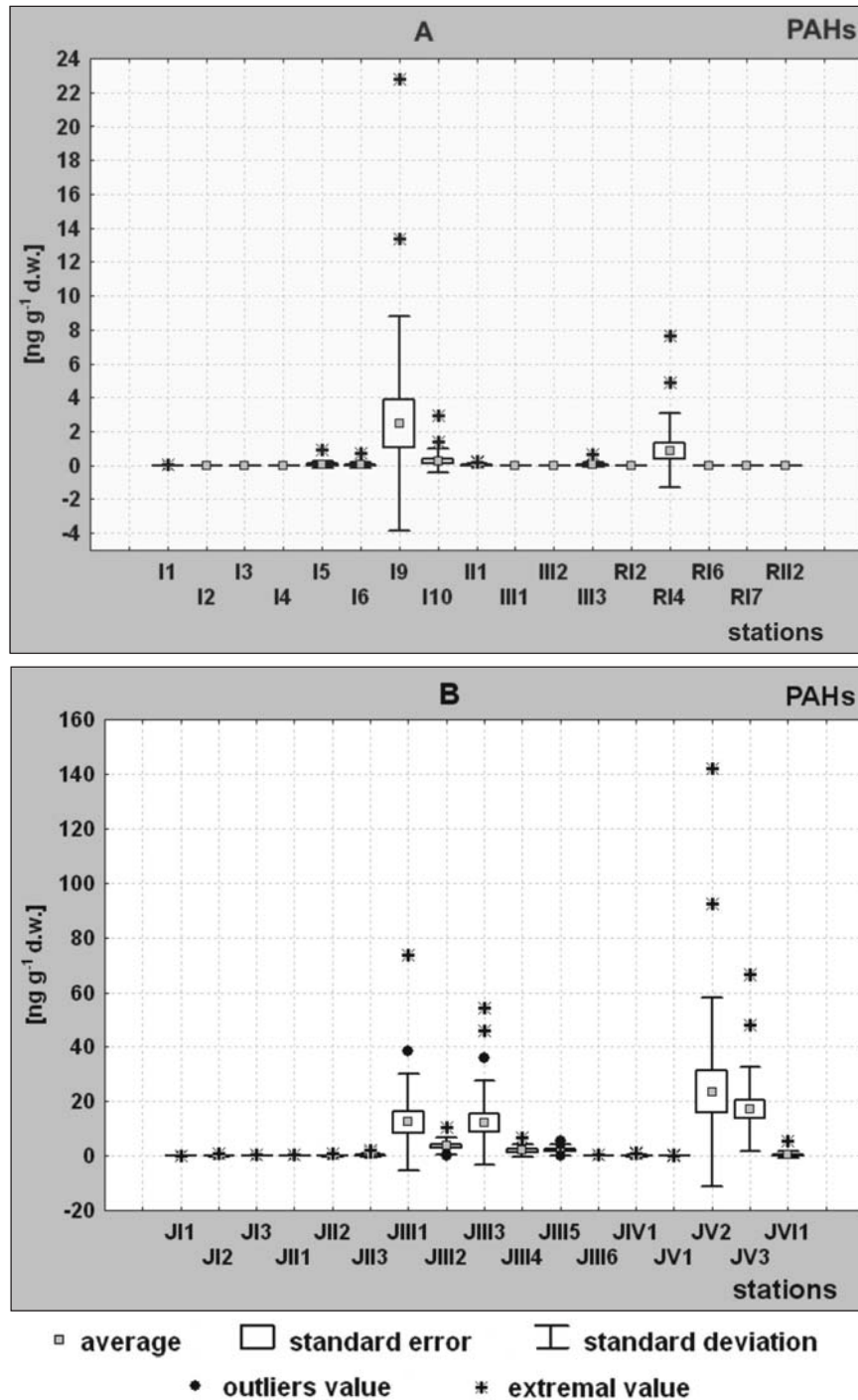


Fig. 5. The statistical analysis of Σ_{16} PAHs concentration in surface sediments from fjords and tidal plains (A), and lakes (B).

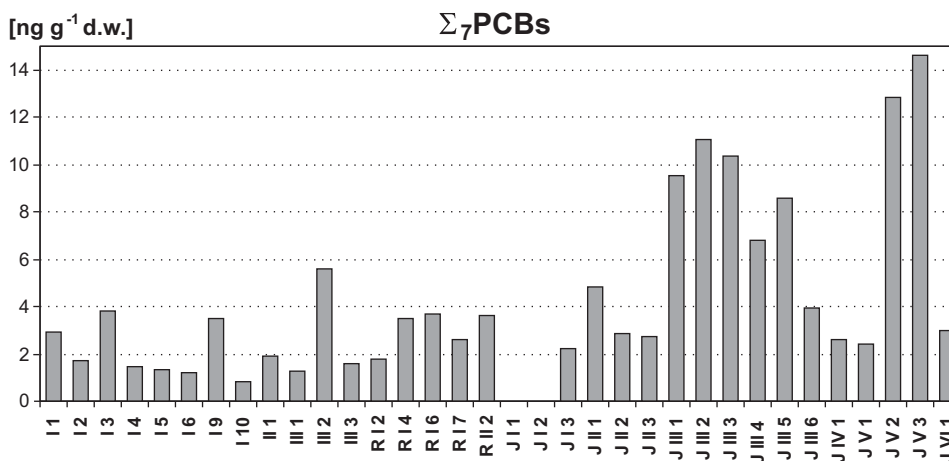
Fig. 6. The content of Σ₇PCBs in surface sediments.

Table 4

The content of PCB compounds in surface sediments from lakes

Compound [ng g ⁻¹ d.w.]	J I 3	J II 1	J II 2	J II 3	J III 1	J III 2	J III 3	J III 4	J III 5	J III 6	J IV 1	J V 1	J V 2	J V 3	J VI 1
CB 28	0.6	0.5	0.4	0.6	0.6	0.5	1.1	0.2	0.3	0.2	0.3	0.3	1.5	0.9	0.1
CB 52	0.4	0.4	0.3	0.5	1.8	0.5	1.0	0.6	0.9	0.7	0.3	0.4	1.5	1.9	0.3
CB 101	0.3	0.5	0.3	0.5	0.6	0.5	0.3	0.4	0.7	0.3	0.1	0.2	1.0	1.3	0.1
CB 118	0.7	1.4	0.4	0.5	0.7	2.3	0.4	1.1	1.2	0.6	0.1	0.5	1.2	1.8	0.0
CB 138	0.3	0.5	0.6	0.7	2.5	4.3	6.8	3.9	4.9	1.5	1.8	1.0	6.5	6.2	2.5
CB 153	nd	0.4	0.5	nd	1.9	1.0	0.6	nd	nd	0.5	nd	nd	1.2	1.0	nd
CB 180	nd	1.1	0.4	nd	1.6	1.9	0.1	0.6	0.6	0.1	nd	nd	nd	1.5	nd
Σ ₇ PCBs	2.3	4.8	2.9	2.7	9.6	11.0	10.4	6.8	8.6	3.9	2.6	2.4	12.8	14.6	3.0

nd - below the LoD (0.1 ng g⁻¹)

Wijdefjorden and Woodfjorden. The highest concentrations of PCBs were indicated in sediments from stations J V 2 and J V 3. Perhaps it was the result of atmospheric transport and deposition (AMAP 2004, Romanov 2004, Vana 2004). Głowacki (2007) suggested that the most of the gas and dust pollutants in the European part of the Arctic have sources in Russia. Rose *et al.* (2004) presented comparable results of PCBs content in surface and pre-industrial lake sediments from west coast of Svalbard ($1.25 \text{ ng g}^{-1} < \Sigma_{10}\text{PCBs} < 13.52 \text{ ng g}^{-1}$). The authors suggested that it is possible that the presence of PCBs in pre-industrial sediments may represent pre-industrial levels of PCBs in the environment (Rose *et al.* 2004). Sanders *et al.* (1992) suggested that small traces of PCBs and PAHs may have been transferred from recent sediments to deeper uncontaminated sediments by mixing, bioturbation, or sampling extruding methods.

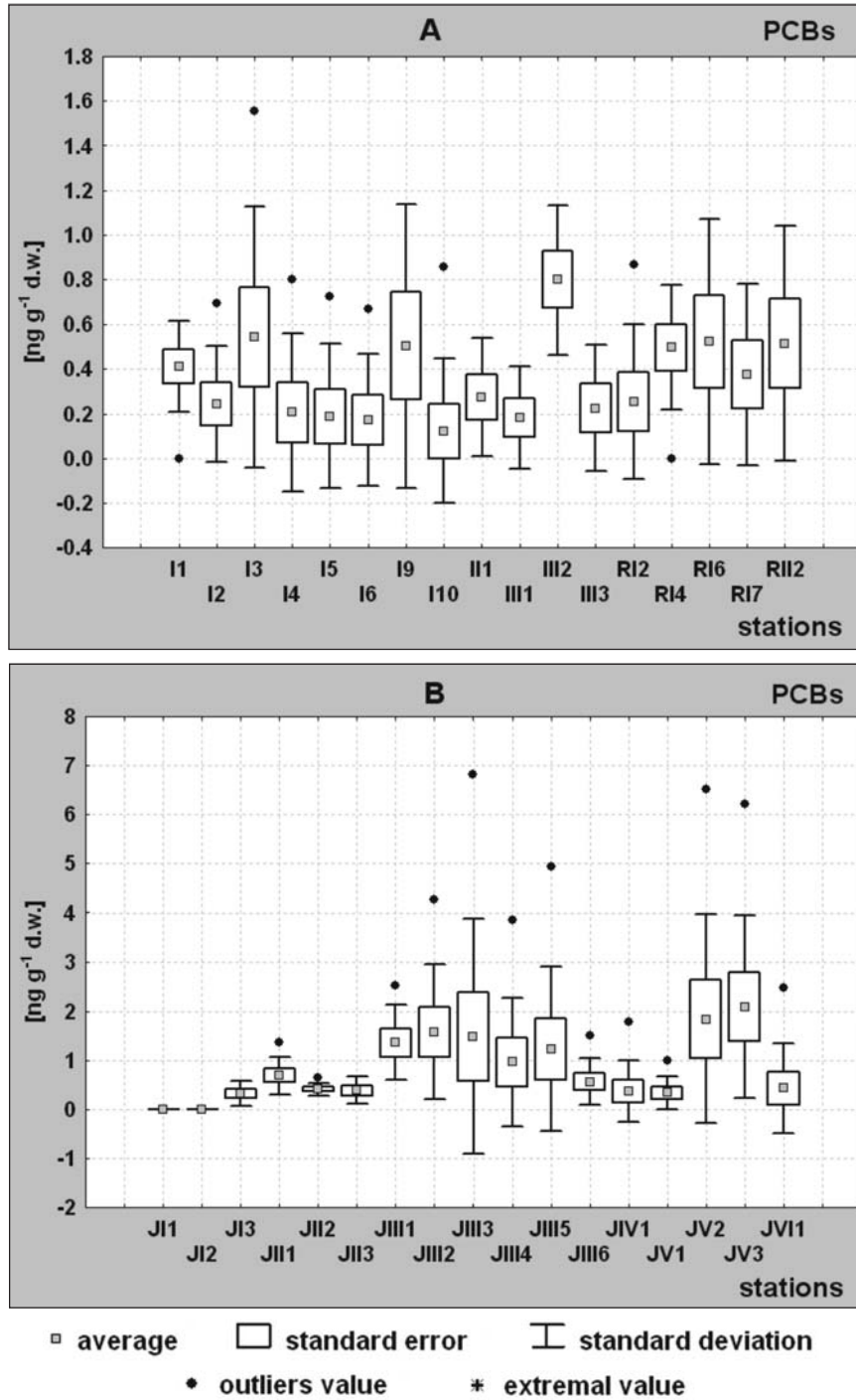
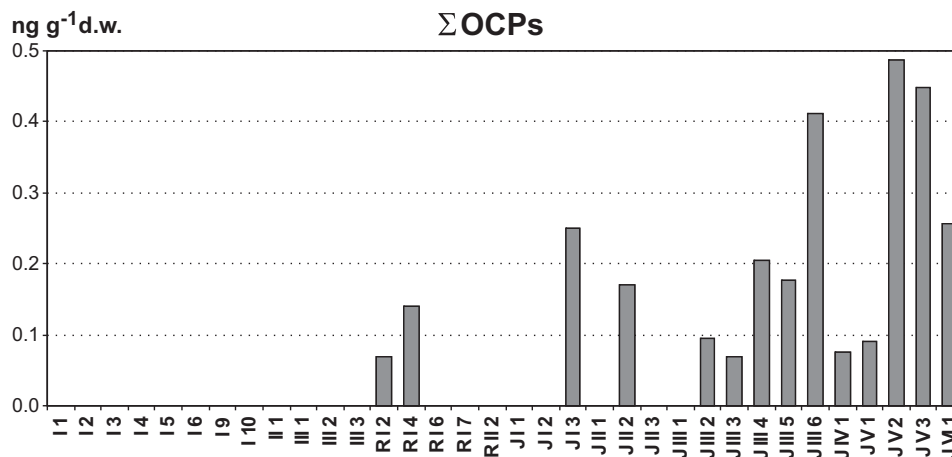


Fig. 7. The statistical analysis of Σ_7 PCBs concentration in surface sediments from fjords and tidal plains (A), and lakes (B).

Fig. 8. The content of Σ OCPs in surface sediments.

Both PCBs and PAHs ratio data of heavy and light compounds (Table 5) were comparable with results of similar latitudes (78°50' to 79°40' N) of west Svalbard (Rose *et al.* 2004). These ratios show the decreases with latitudes. The PCBs data show a linear decrease with latitude whilst the PAHs data show an exponential decrease (Rose *et al.* 2004). The ratio of CB 153 : CB 28 ascertained in this study was 0–3.3 and respectively 1.4–1.9 of west Svalbard, fluoranthene:fluorene 0–0.8, chrysene:fluorene 0–1 and respectively 1–1.2 and 1.7 for west Svalbard. The ratio of heavy: light PAHs in sediments from fjords and tidal plains was not available. The ratio of CB 153 : CB 28 in sediments from tidal plains was 0–2. The ratio for fjords was ascertained on four stations (I 1, I 2, II 1 and III 2) and was amounted 0–2.6.

Among the selected OCPs in analysed sediment samples were ascertained only trace concentrations of endosulphan I and methoxychlor. These pesticides were present in two samples from tidal plans (stations R I 2 and R I 4) and twelve sediment samples from lakes. The concentrations of pesticides ranged from 0.1 to 0.4 ng g⁻¹ d.w. (Figs 8 and 9). Fellin *et al.* (1996) have evaluated that the seasonal patterns for organochlorine compounds were less clear than for PAHs and average concentrations for some compounds were similar in cold and warm periods.

Table 5

Ratios of heavy: light PCBs and PAHs compounds in sediments from lakes

	J I 3	J II 1	J II 2	J II 3	J III 1	J III 2	J III 3	J III 4	J III 5	J III 6	J IV 1	J V 1	J V 2	J V 3	J VI 1
CB 153:CB 28	0	0.8	1.2	0	3.3	1.9	0.5	0	0	2.8	0	0	0.8	1.2	0
fluoranthene:fluorene	n/a	n/a	n/a	n/a	0	0.3	0.2	0.4	0.8	n/a	n/a	n/a	0.6	0.5	n/a
chrysene:fluorene	n/a	n/a	n/a	n/a	0.2	0.1	1.0	0	0	n/a	n/a	n/a	0.5	0.4	n/a

n/a – data not available

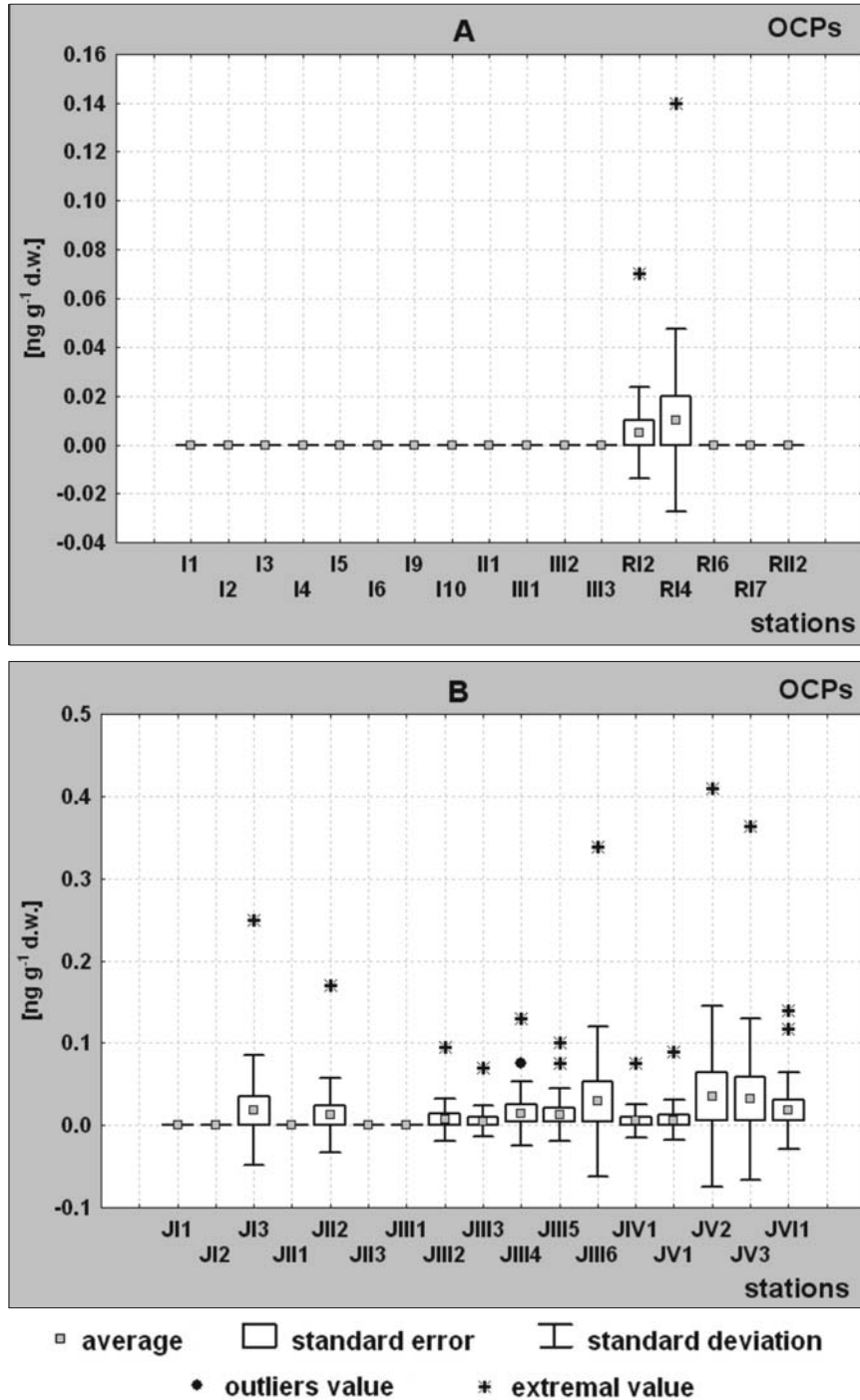


Fig. 9. The statistical analysis of Σ OCPs concentration in surface sediments from fjords and tidal plains (A), and lakes (B).

Conclusions

Since the late 1960s detectable concentrations of POPs have been discovered in many environmental matrices (air, water, sediments and biota) in the Antarctic and Arctic (Sladen *et al.* 1966; Risebrough *et al.* 1976; Tanabe and Tatsukawa 1980; Muir *et al.* 1995; MacDonald *et al.* 2000; AMAP 2004). In this study the concentrations of analysed substances (PAHs, PCBs and OCPs) were lower in sediment samples from fjords and tidal plains than from lakes. The LOI concentrations in sediments collected in lakes were higher than in other samples. The concentrations of analysed PAHs in surface sediments from fjords and tidal plains were over ten times lower than in sediment samples from investigated lakes. The presence of PCB congeners were detected in all sediment samples (except stations J I 1 and J I 2). Only trace concentrations of endosulphan I and methoxychlor were detected among the selected OCPs in sediments. The higher concentrations of LOI in surface sediments from lakes were mostly connected with organic matter inflow in this area. The high concentrations of PAHs, PCBs and OCPs were obtained in sediments with high concentrations of organic matter. The distribution pattern of obtained POPs concentrations suggested important role of long-range atmospheric transport of these pollutants to Svalbard. The analytical results show that the high molecular weight PAHs such as fluorine, chrysene, benzo(a)fluoranthene, benzo(a)pyrene, benzo(g,h,i)perylene and indeno(1,2,3-cd)pyrene, dominate the total fraction, whereas low molecular weight PAHs were found in relatively very low concentrations.

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References

- AMAP 2004. Persistent Organic Pollutants in the Arctic. *Arctic Monitoring and Assessment Programme (AMAP)*, Oslo: 309 pp.
- ANDRULEWICZ E. and POUTANEN E.-L. 2002. Organic contaminants. *In: Environment of the Baltic Sea area 1994–1998. Baltic Sea Environment Proceedings 82B*: 126–128.
- BARRIE L.A. 1986. Arctic air pollution: an overview of current knowledge. *Atmospheric Environment* 20: 643–663.
- BARRIE L.A., GREGOR D., HARGRAVE B., LAKE R., MUIR D., SHEARER R., TRACEY B. and BIDELMAN T. 1992. Arctic contaminants: sources, occurrence and pathways. *Science of the Total Environment* 122: 1–74.
- BEINE H.J., ENGARDT M., JAFFE D.A., HOV Ø., HOLMÉN K. and STORDAL F. 1996. Measurements of NO_x and aerosol particles at the Ny-Ålesund Zeppelin mountain station on Svalbard: influence of regional and local pollution sources. *Atmospheric Environment* 30: 1067–1079.
- BREMLE G., OKLA L. and LARSSON P. 1995. Uptake of PCBs in fish in a contaminated river system: bioconcentration factors in the field. *Environmental Science and Technology* 29 (8): 2010–2015.
- BURKOW I.C. and KALLENBORN R. 2000. Sources and transport of persistent pollutants to the Arctic. *Toxicology Letters* 112–113: 87–92.

- DANNENBERGER D. and LERZ A. 1996. Polychlorinated biphenyls (PCB) and Organochlorine Pesticides in Sediments of the Baltic and Coastal Waters of Mecklenburg-Vorpommern. *German Journal of Hydrography* 48 (1): 5–26.
- DE VOOGT P. and JANSSON B. 1993. Vertical and long range transport of persistent organics in the atmosphere. *Reviews of Environmental Contamination and Toxicology* 132: 1–27.
- FALANDYSZ J. 1999. Foteliza [in:] Polichlorowane bifenylo (PCBs) w środowisku: chemia, analiza, toksyczność, stężenia i ocena ryzyka. Fundacja Rozwoju Uniwersytetu Gdańskiego, Gdańsk: 46–50.
- FELLIN P., BARRIE L.A., DOUGHERTY D., TOOM D., MUIR D., GRIFT N., LOCKHART L. and BILLECK B. 1996. Air monitoring in the Arctic: results for selected persistent organic pollutants for 1992. *Environmental Toxicology and Chemistry* 15 (3): 253–261.
- GILBERT R., NIELSEN N., DESLOGES J.R. and RASCH M. 1998. Contrasting glaciomarine sedimentary environments of two arctic fjords on Disko, West Greenland. *Marine Geology* 147: 63–83.
- GILBERT R., NIELSEN N., MÖLLER H., DESLOGES J.R. and RASCH M. 2002. Glaciomarine sedimentation in Kangerdulk (Disko Fjord), West Greenland, in response to a surging glacier. *Marine Geology* 191: 1–18.
- GŁOWACKI P. 2007. Role of physical and chemical processes in the internal structure formation and mass circulation of Spitsbergen glaciers. *Publications of the Institute of Geophysics Polish Academy of Sciences, Monographic Volume M-30* (400): 9–13.
- GRAEDEL T.E. and CRUTZEN P. 1993. *Atmospheric Change: An Earth System Perspective*. W.H. Freeman, New York, NY: 446 pp.
- HAUGAN P.M. 1999. Structure and heat content of the West Spitsbergen Current. *Polar Research* 18: 183–188.
- ISO 11464:1994(E). Soil quality – Pretreatment of samples for physico-chemical analyses. *Technical Committee ISO/TC 190, Subcommittee SC 3*: 1–18.
- JONES E.P. 2001. Circulation in the Arctic Ocean. *Polar Research* 20: 139–146.
- KHALILI N.R., SCHEFF P.A. and HOLSEN T.M. 1995. PAH source fingerprints for coke ovens, diesel and gasoline engines, highway tunnels, and wood combustion emissions. *Atmospheric Environment* 29: 533–542.
- KOWALEWSKI W., RUDOWSKI S. and ZALEWSKI M. 1990. Seismoacoustic studies within Wijdefjorden, Spitsbergen. *Polish Polar Research* 11 (3–4): 287–300.
- LOENG H. 1991. Features of the physical oceanographic conditions of the Barents Sea. *Polar Research* 10: 5–18.
- LOHSE J. 1988. Distribution of organochlorine pollutants in North sea sediment. *Mitteilungen aus dem Geologisch-Palaeontologischen Institut der Universitaet Hamburg* 65.
- LØYNING T.B. 2001. Hydrography in the north-western Barents Sea, July–August 1996. *Polar Research* 20: 1–11.
- MACDONALD R.W., BARRIE L.A., BIDLEMAN T.F., DIAMOND M.L., GREGOR D.J., SEMKIN R.G., STRACHAN W.M.J., LI Y.F., WANIA F., ALAEE M., ALEXEEV L.B., BACKUS S.M., BAILY R., BEWERS J.M., GOBEIL C., HALSALL C.J., HARNER T., HOFF J.T., JANTUNEN L.M.M., LOCKHART W.L., MACKAY D., MUIR D.C.G., PUDYKIEWICZ J., REIMER K.J., SMITH J.N., STERN G.A., SCHREDER W.H., WAGEMANN R. and YUNKER M.B. 2000. Canadian Arctic chemical contaminants metal model, organochlorine polycyclic aromatic hydrocarbons pathways, radionuclides temporal trends. *Science of the Total Environment* 254 (2–3): 93–234.
- MAMANTOV A. 1985. The photolysis of polychlorinated biphenyls may proceed via carbenes. *Chemosphere* 14: 901–904.
- MUIR D.C.G., GRIFT N.P., LOCKHART W.L., WILKINSON P., BILLECK B.N. and BRUNSKILL G.J. 1995. Spatial trends and historical profiles of organochlorine pesticides in Arctic lake sediments. *Science of the Total Environment* 160/161: 447–457.
- NOWIŃSKI K. 2002. Physicolimnological features of chosen reservoirs in the area of Hornsund (south-west Spitsbergen). *Limnological Review* 2: 285–294.
- OEHME M. and MANÖ S. 1984. The long-range transport of organic pollutants to the Arctic. *Arctic Fres. Z. Analytical Chemistry* 319: 141–146.

- PACYNA J.M. and OTTAR B. 1985. Transport and chemical composition of the summer aerosol in the Norwegian Arctic. *Atmospheric Environment* 19: 857–865.
- PACYNA J.M., OTTAR B., TOMZA U. and MAENHAUT W. 1985. Long-range transport of trace elements to Ny-Ålesund, Spitsbergen. *Atmospheric Environment* 19: 2109–2120.
- RAVINDRA K., WAUTERS E. and VAN GRIEKEN R. 2008. Variation in particulate PAHs levels and their relation with the transboundary movement of the air masses. *Science of the Total Environment* 396: 100–110.
- RISEBROUGH R.W., WALKER W., SCHMIDT T.T., DE LAPPE B.W.E. and CONNORS C.W. 1976. Transfer of chlorinated biphenyls to Antarctica. *Nature* 264: 738–739.
- ROGGE W.F., HILDEMAN L.M., MAZUREK M.A., CASS G.R. and SIMONEIT B.R.T. 1993. Sources of fine organic aerosol: 2. Nonycatalyst and catalyst-equipped automobiles and heavy-duty diesel trucks. *Environmental Science and Technology* 27: 636–651.
- ROMANOV V.F. 2004. Northern hemispheric air circulation. In: S. Skreslet (ed.) *Jan Mayen Island in Scientific Focus*, NATO Science Series, IV. *Earth and Environmental Sciences* 45, Kluwer Academic Publishers, Dordrecht: 55–66.
- ROSE N.L., ROSE C.L., BOYLE J.F. and APPLEBY P.G. 2004. Lake-sediment evidence for local and remote sources of atmospherically deposited pollutants on Svalbard. *Journal of Paleolimnology* 31: 499–513.
- SANDERS G., JONES K.C., HAMILTON-TAYLOR J. and DÖRR H. 1992. Historical inputs of polychlorinated biphenyls and other organochlorines to a dated lacustrine sediment core in rural England. *Environmental Science and Technology* 26: 394–396.
- SLADEN W.J.L., MENZIE C.M. and REICHEL W.L. 1966. DDT residues in Adele penguins and a crab-eater seal from Antarctica: Ecological implications. *Nature* 210: 670–673.
- SAPOTA G. 1997. Chlorinated hydrocarbons in sediments from the Vistula Lagoon. *Oceanological Studies* (2–3): 61–69.
- SONG Y.F., JING X., FLEISCHMANN and WILKE B.M. 2002. Comparative study of extraction methods for the determination of PAHs from contaminated soils and sediments. *Chemosphere* 48: 993–1001.
- TANABE S. and TATSUKAWA R. 1980. Chlorinated hydrocarbons in the North Pacific and Indian Oceans. *Journal of the Oceanographical Society of Japan* 36: 217–226.
- TANABE S., TANAKA H. and TATSUKAWA R. 1983. PCBs and chlorinated hydrocarbon pesticides in the Antarctic atmosphere and hydrosphere. *Chemosphere* 12: 277–288.
- VANA M. 2004. Natural and anthropogenic aerosols in Arctic areas. In: S. Skreslet (ed.) *Jan Mayen Island in Scientific Focus*. NATO Science Series, IV. *Earth and Environmental Sciences*, 45, Kluwer Academic Publishers, Dordrecht: 67–77.
- VILLA S., VIGHI M., MAGGI V., FINIZIO A. and BOLZACCHINI E. 2003. Historical trends of organochlorine pesticides in an Alpine Glacier. *Journal of Atmospheric Chemistry* 46: 295–311.
- WALCZOWSKI W. and PIECHURA J. 2006. New evidence of warming propagating toward the Arctic Ocean. *Geophysical Research Letters* 33, L12601 DOI: 10.1029/2006GLO25872.
- WALCZOWSKI W. and PIECHURA J. 2007. Pathways of the Greenland Sea warming. *Geophysical Research Letters* 34, L10608 DOI: 10.1029/2007GLO29974.
- WALKER T.R., CRITTENDEN P.D., DAUVALTER V.A., JONES V., KUHR Y. P., LOSKUTOVA O., MOKKOLA K., NIKULA A., PATOVA E., PONOMAREV V.I., PYSTINA T., RÄTTI O., SOLOVIEVA N., STENINA A., VIRTANEN T. and YOUNG S.D. 2009. Multiple indicators of human impacts on the environment in the Pechora Basin, north-eastern European Russia. *Ecological Indicators* 9: 765–779.
- WANIA F. and MACKAY D. 1993. Global fractionation and cold condensation of low volatility organochlorine compounds in polar regions. *Ambio* 22 (1): 10–18.
- WANIA F. and MACKAY D. 1996. Tracking the distribution of persistent organic pollutants. *Environmental Science and Technology/News* 30: 390–396.
- ZABORSKA A., PAPUCI C. and PEMPKOWIAK J. 2006. Some Sediment Characteristics and Sedimentation rates in an Arctic Fjord (Kongsfjorden, Svalbard). *Środkowo-Pomorskie Towarzystwo Naukowe Ochrony Środowiska* 8: 79–97.

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