Chapter 6

ATMOSPHERIC TRANSPORT AND DEPOSITION OF PCBs TO THE ARCTIC REGION

This section contains the results of the assessment of environmental pollution by polychlorinated biphenyls (PCBs) in selected regions of the Russian North for 1996. Levels of concentrations and depositions of PCBs, and contributions to the contamination in these areas made by major emission sources of the Russian Federation and other distant sources within the Northern Hemisphere are estimated. This assessment is carried out on the basis of simulations using the MSCE-POP hemispheric multicompartment model.

Modeling PCB redistribution over the environment is complicated due to of a large number of individual PCB congeners (more than 200), whose fates in the environment differ considerably. This results from the variety of these congeners' physical-chemical properties as well as from the variety of congener compositions of PCB mixtures used in different countries of the Northern Hemisphere. The information needed for model evaluation of transport and environmental accumulation of individual PCB congeners is rather limited. The most thoroughly investigated are the following of 7 PCB congeners: PCB-28, 52, 101, 118, 138, 153 and 180. For these congeners sufficient information on physical-chemical properties and measurement data is available. The information on emissions is at present available for 22 PCB congeners [*Breivik et al*., 2002] including the above mentioned group of 7 congeners. On the other hand, the main interest in PCB assessment is focused on toxic PCB congeners. International toxic equivalency factors are assigned to 12 PCB congeners: PCB-77, 81, 105, 114, 118, 123, 126, 156, 157, 167, 169 and 189. For the toxic congeners, data on emissions are available for only three (PCB-105, 118 and 123). In order to cover a wide spectrum of PCB congeners' behaviour in the environment we have selected PCB-28, 118, 153 and 180 in view of the availability of emission and measurement data. These congeners have different physical-chemical properties and represent light (PCB-28), heavy (PCB-180) and toxic (PCB-118) congeners. A detailed description is given of the main processes of PCB behaviour in the environment using as an example PCB-153. Peculiarities in the behaviour of congeners are exemplified by PCB-28, 118 and 180 (see Annex A).

PCBs continue to be detected in the environment far from areas where they were originally used and despite efforts to restrict their emissions. It is believed that the major reasons for this are their ability to be transported long-range and their high persistence in the environment. Apart from atmospheric and seawater transport these pollutants can undergo a number of deposition/re-emission (multi-hop) cycles, the so-called "grasshopper effect". For proper model description of the re-emission process, long-term accumulations in environmental media should be assessed. On the basis of numerical experiments [*Shatalov et al*., 2000, 2001] it was obtained that a preliminary calculation covering a 25-year period (model spin-up) is sufficient for medium saturation. Thus, for the pollution assessment of the Russian North in 1996 model preliminary calculations were carried out for the period of 1970 to 1995 for each congener considered. The initial conditions for calculations for 1996 were taken from the model spin-up.

Hemispheric annual emission data for the calculation from 1970 to 1996 were adapted from [*Breivik et al.*, 2002] (details in Section 4.2). The emission data is very uncertain, therefore three emission scenarios (Low, Mid and High) are presented in this work. Pilot calculations made by the MSCE-POP model indicated that the results obtained by using the High emission scenario give more reasonable

agreement with observed pollution levels. This suggests that in spite of prohibition on the PCB production, significant emissions could still continue.

The original emission data is given as total values for individual countries. Spatial distribution was made on the basis of population density distribution. Since there is no information about seasonal variations, PCB emissions were uniformly distributed over the year. It seems that the consideration of seasonal emission variations can significantly improve model results.

Apart from pollution level assessment, an analysis of the contributions of major sources to the contamination of the Russian North in 1996 was made. To this end PCB emission sources of the Northern Hemisphere were divided into 17 source groups (Section 4.2). Separate model runs were carried out for the assessment of pollution transport from each source group with the assumption of zero emissions from other sources and with zero initial conditions. These calculations allow us to evaluate the contributions of each emission source to depositions to and concentrations in the Russian North. A special run, with zero emissions and initial conditions obtained during the model spin-up, was performed to evaluate the influence of historical emissions on the contamination of the Russian North in 1996. The difference between pollution levels estimated by calculation on the basis of total emissions and sum of calculation results obtained from separate model runs does not exceed 3% for the considered areas of the Russian North.

The following section contains a general description of modeling results of four selected PCB congeners for the Northern Hemisphere. The verification of computed PCB concentrations in air and precipitation and deposition fluxes is presented in Section 6.2. A detailed description of PCB-153 pollution levels in the Russian North is given in Section 6.3. Similar results for other modeled congeners can be found in Annex A. Section 6.4 is devoted to the analysis of contributions from various emission sources to the contamination of the selected region. Section 6.5 contains information on PCB congener composition in regions of the Russian North.

6.1. General description of modeling results

This section gives calculation results of four model runs for PCB-153, 28, 118 and 180. Long-term trends in accumulation (during model spin-up 1970-95) and distribution between media (atmosphere, soil, seawater and vegetation) on the hemispheric scale for 1996 are described. Special attention is focused on the Arctic.

Redistribution between environmental media

The accumulation process in the environmental media of the whole hemisphere during model spin-up is analysed. The dynamics of the accumulation process for PCB-153 in media along with the emission trend are presented in Figure 6.1. The emissions increase up to 1985 after which time they begin to decrease (Fig. 6.1.a). This leads to an immediate decrease of the content in the atmosphere and vegetation. After 1986, PCB-153 contents in all environmental compartments decrease (Fig. 6.1.b-e). The maximum of soil and seawater concentrations in 1986 testifies to the fact that the processes of degradation in and re-volatilization from these media are comparable with those of depositions and gaseous exchange, that is, that saturation is attained.

However, the rate of content reduction in the media is different. The lowest reduction rate is determined for soil, followed by sea, air and vegetation. Due to large accumulation capacities, low mass exchange rates and the high persistence of PCB-153 in soil and seawater, the rate of decrease

in content in these media is much slower than for emissions. The content decrease in the remaining media lags behind the emission reduction as well. For example, the delay of concentration decrease in air (Fig. 6.1.b) can be explained by re-emission flux from soil, keeping air pollution content. Changes in vegetation content (Fig. 6.1.c) are similar to the atmospheric ones due to high rate of mass exchange flux between these media.

Dynamics of total content and emissions during 1970-96 are given in Figure 6.1.f.

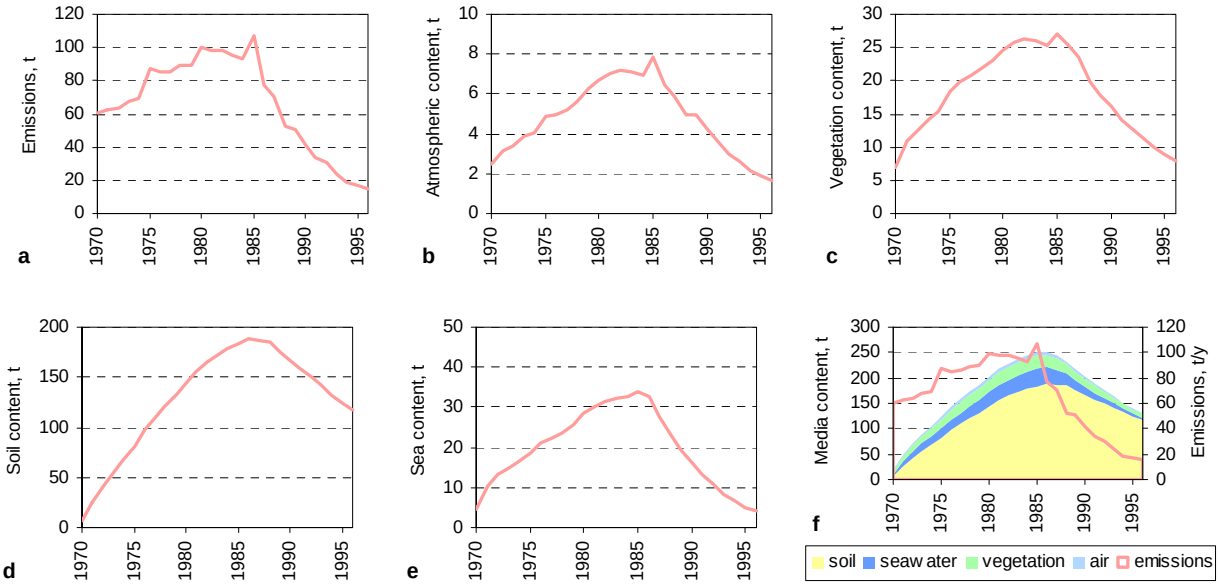

Figure 6.1. *Trends of PCB-153 emissions and content in the Northern Hemisphere during model spin-up*

Trends of medium contents and emissions of PCB-28, 118 and 180 are given in Figure 6.2. These diagrams indicate that medium saturation is also attained for these pollutants. The peculiarity of PCB-28 is that emissions decrease right from 1970 (Fig. 6.2.a). Medium saturation is attained in 1976, followed by a decrease in content. PCB-118 and 180 accumulation (Fig. 6.2.b and Fig. 6.2.c) is similar to that of PCB-153 (Fig. 6.1.f). It should be noted that in comparison with other congeners, PCB-180 soil content decrease after emission reduction is the slowest

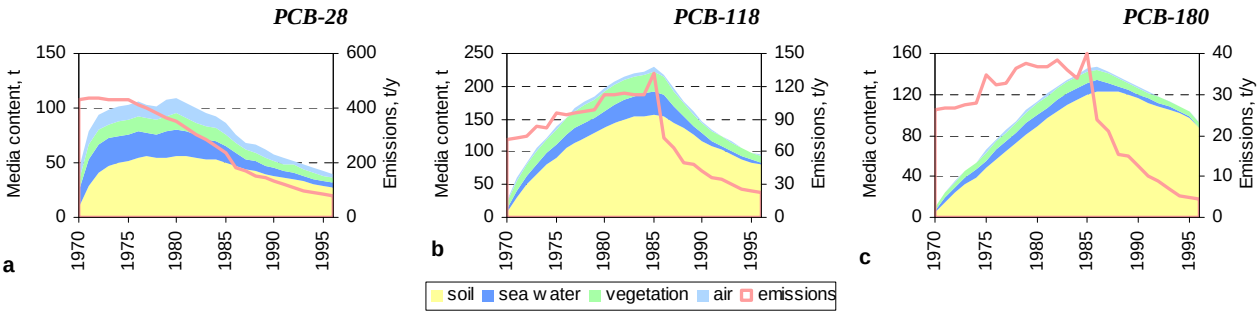

Figure 6.2. *Trends in emissions and accumulation of PCB-28 (a), PCB-118 (b) and PCB-180 (c) in the Northern Hemisphere during model spin-up*

The distribution of considered congeners between environmental compartments in late 1996 due to long-term accumulation is presented in Figure 6.3. As seen from the diagrams, the bulk of PCBs tend to be accumulated in the soil environment. PCB-180 is accumulated in soil to a greater extent than PCB-153, PCB-118, PCB-28. A tangible part of PCB-28 is contained in vegetation, sea and air.

Thus, we can conclude, that for all considered congeners medium saturation is attained. This testifies to the fact that the calculation period is long enough to reasonably describe contamination levels in all environmental compartments. The second conclusion is that soil is the main reservoir for PCBs. According to model assessment, substantial soil content can inflict a noticeable impact on the contamination of the atmosphere and other media against the background of emission reduction due to the re-emission process.

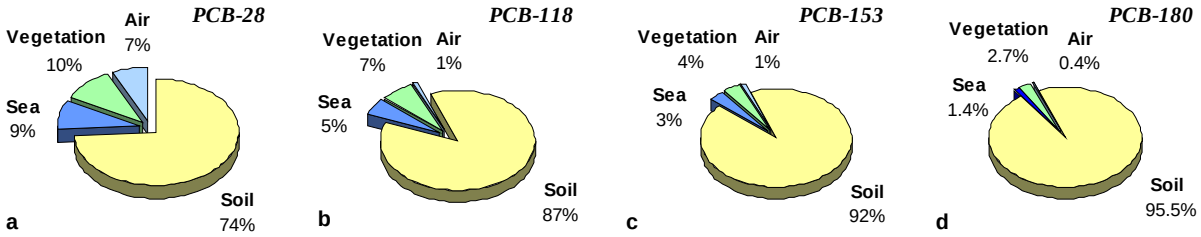

Figure 6.3. *Distribution of PCB congeners between environmental media of the Northern Hemisphere by the end of 1996*

Spatial distribution of contamination

This section is aimed just at a brief description of spatial distribution of PCB contamination over the Northern Hemisphere. We would like to make a note of the contamination levels characteristic of some regions and to describe some peculiarities of PCB spatial distribution. A more detailed description of the contamination in the Arctic and especially in the five selected regions of the Russian North are presented below.

Spatial distribution of PCB-153 depositions and concentrations in environmental media for the whole Northern Hemisphere in 1996 was evaluated. Figure 6.4 displays maps of emissions, concentrations in air, soil, vegetation and seawater, and depositions. As to depositions we consider wet and dry depositions for the particulate phase plus wet deposition of the gaseous phase (so-called “direct” depositions). The importance of this value is connected with the possibility of its comparison with observed data. The gaseous exchange flux between the atmosphere and the underlying surface is evaluated separately due to the importance of the re-emission process. These processes are analysed in Section 6.3.

The most significant emission sources of PCBs are located in the European and North American regions (Fig. 6.4.a). The areas of highest atmospheric pollution are situated in the same regions (Fig. 6.4.b). Air concentrations in contaminated regions range from 5 to 20 pg/m^3 in America, and reach more than 20 pg/m^3 in Europe. Atmospheric transport from remote sources leads to a relatively large contribution to air contamination levels in the Russian North (1-3 pg/m^3).

The deposition map is presented in Figure 6.4.c. High deposition fluxes – more than 0.5 g/km^2/y occur in Central Europe. Considerable fluxes 0.2-0.5 g/km^2/y occur over most of Europe and the East part of Northern America. The deposition fluxes for the Russian North are in the range of 0.05-0.2 g/km^2/y. There is a clear gradient of deposition reduction from the western to the eastern part of the Russian North. For the Arctic region the typical deposition level is 0.01-0.05 g/km^2/y. A considerable part of the PCBs deposited over the Arctic Ocean are accumulated in the sea ice. The pollutant accumulated in sea ice can be transported with ice over a long distance with a subsequent discharge to the Ocean caused by the melting of ice. Description of the role of sea ice in POP transport is given in Annex E.

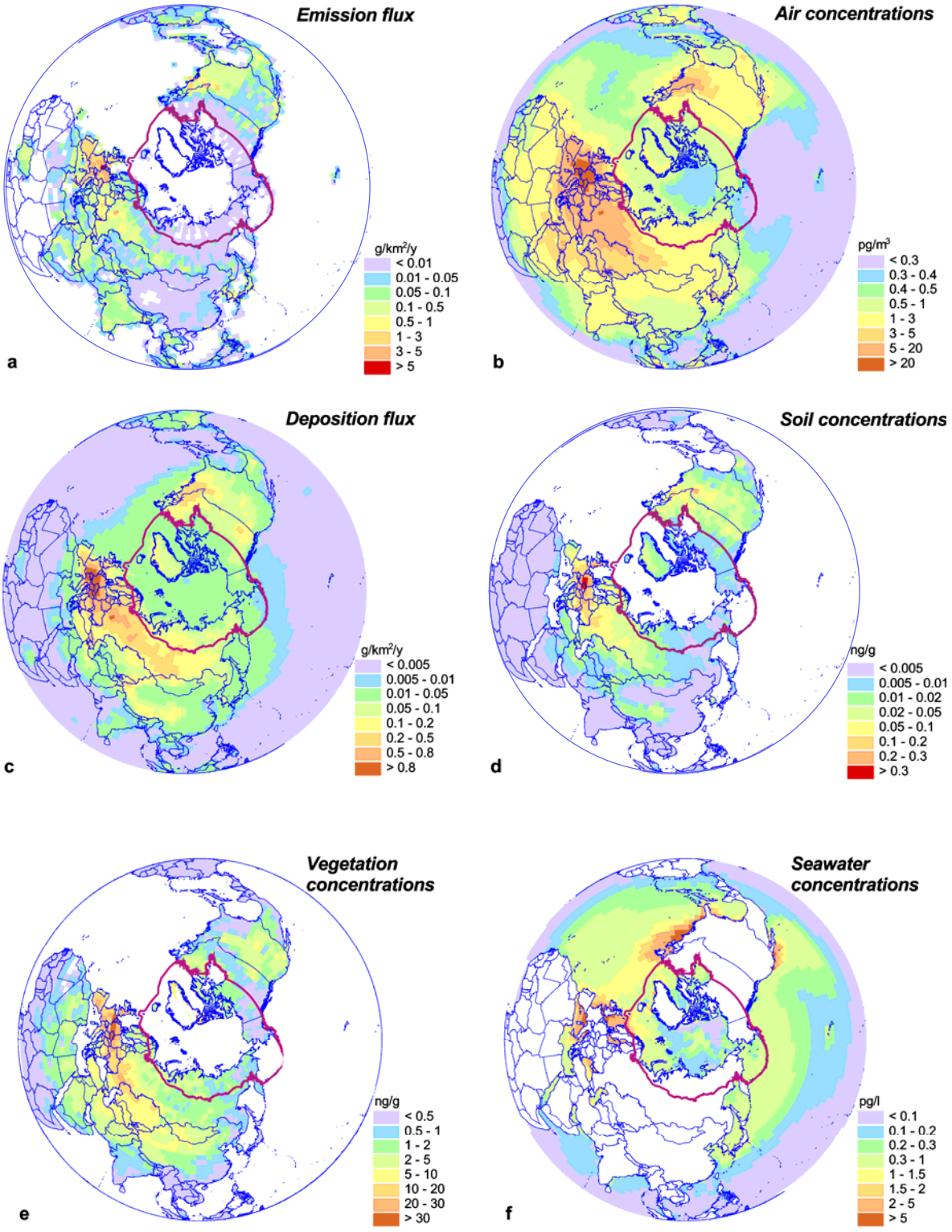

Figure 6.4. *PCB-153 annual emissions, depositions and concentrations in media in the Northern Hemisphere in 1996*

Depositions over land lead to PCB accumulations in soil. Figure 6.4.d presents spatial distribution of averaged concentrations in soil. Averaging is made over the whole depth of the soil calculation domain. Pollutant accumulation in soil is determined by a long-term deposition process. For example, concentrations 0.1-2 ng/g are observed both in regions with high deposition fluxes over Central Europe and in regions with low deposition, in particular, in the UK. This phenomenon is explained by the fact that in the 1970-s the UK PCB emission sources were rather significant, after which their intensity decreased.

The next terrestrial medium is vegetation. Calculated spatial distribution of concentrations in vegetation is presented by Figure 6.4.e. PCBs penetrate to vegetation mainly by the means of gaseous exchange with the atmosphere and dry deposition of the particulate phase. The typical range of concentrations near the main emission sources in the European region is 10-30 ng/g. Throughout most of Asia concentrations in vegetation range from 0.5 to 10 ng/g. The same level is characteristic of Northern America.

Another important medium is seawater. Figure 6.4.f presents the concentration field in this medium. High concentration levels are obtained in the coastal waters not far from main emission sources. For example, the typical range of seawater concentrations in the Mediterranean and Northern seas is 1.2-4 pg/l. In some regions these concentrations can reach 4 pg/l and more.

In the marine environment, pollutant can be transported from one region to another by sea currents. For example, the exchange of water masses between the Atlantic Ocean and the Arctic Ocean occurs in two directions (see Chapter 1). The inflow to the Arctic Ocean takes place along Norwegian and Russian coast, the outflow - along the coast of Greenland. These pathways of pollution transport with seawater are evident in the considered map. Seawater with PCB concentrations of 0.4-1.2 pg/l flow into the Arctic region along the Norwegian and Russian coast and the water masses with concentrations in the range of 0.1-0.4 pg/l flow from the Arctic Ocean to the Northern Atlantic along the coast of Greenland. Seawater pollution in the Arctic Ocean is noticeably affected by sea ice cover, which accumulates and transports a pollutant and hampers the gas exchange between the atmosphere and seawater. A detailed description of the influence of sea currents and ice cover on seawater contamination is given in Annex E.

Similar maps with the spatial distribution of calculated concentrations and depositions for PCB-28, 118 and 180 are given in Annex A.

Contamination of the Arctic region

In this chapter we would like to focus on the contamination of the Arctic region by PCB-153 in 1996. Figure 6.5 shows that relatively high deposition levels (0.1-0.5 g/km^2/y) take place in the west part of the Russian North. Lower levels (0.05-0.1 g/km^2/y) are characteristic of its east part. The deposition range of 0.01–0.1 g/km^2/y is typical for the American North. Depositions over the Arctic Ocean are less than 0.05 g/km^2/y.

The contributions of different regions to PCB-153 depositions to the Arctic are subject to seasonal variations. Below we examine some characteristic features of seasonal variations of contributions made by emission sources in the Americas and North-Western Europe. Figure 6.6 shows seasonal variations of relative contributions of different regions to PCB-153 deposition to the Arctic. As one can see from the diagram the relative contribution of sources from North-Western Europe is the most variable: it changes from about 70% in January to about 25% in May. On the other hand the influence of the Americas is only 5% in January but in May it amounts to 26%, being comparable with the contribution of North-Western Europe.

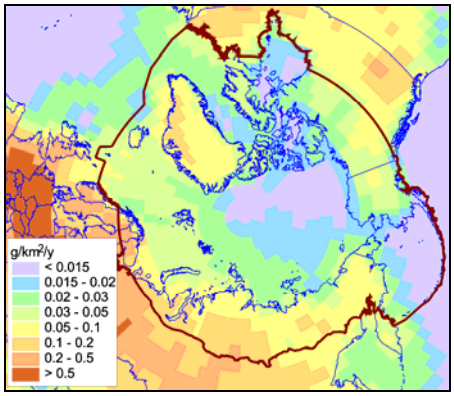

Figure 6.5. *Annual depositions of PCB-153 in the Arctic region*

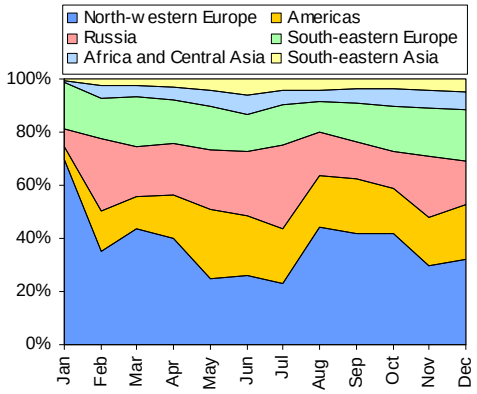

Figure 6.6. *Seasonal variation of relative contributions of different regions to PCB-153 deposition to the Arctic*

These noticeable variations are explained by peculiarities of atmospheric circulation in the Arctic in various seasons and seasonal variations of temperature, precipitation and degradation rates. Seasonal variations of emissions are not considered. To illustrate pathways of atmospheric transport, simulation results of PCB-153 transport from two groups of sources (the Americas and North-Western Europe) for 1996 were examined. In Figure 6.7 (a,b) air concentrations of PCB-153 emitted in the Americas and North-Western Europe in January are shown. The fields of air concentrations originating from the same sources in May are given in Figure 6.7 (c,d).

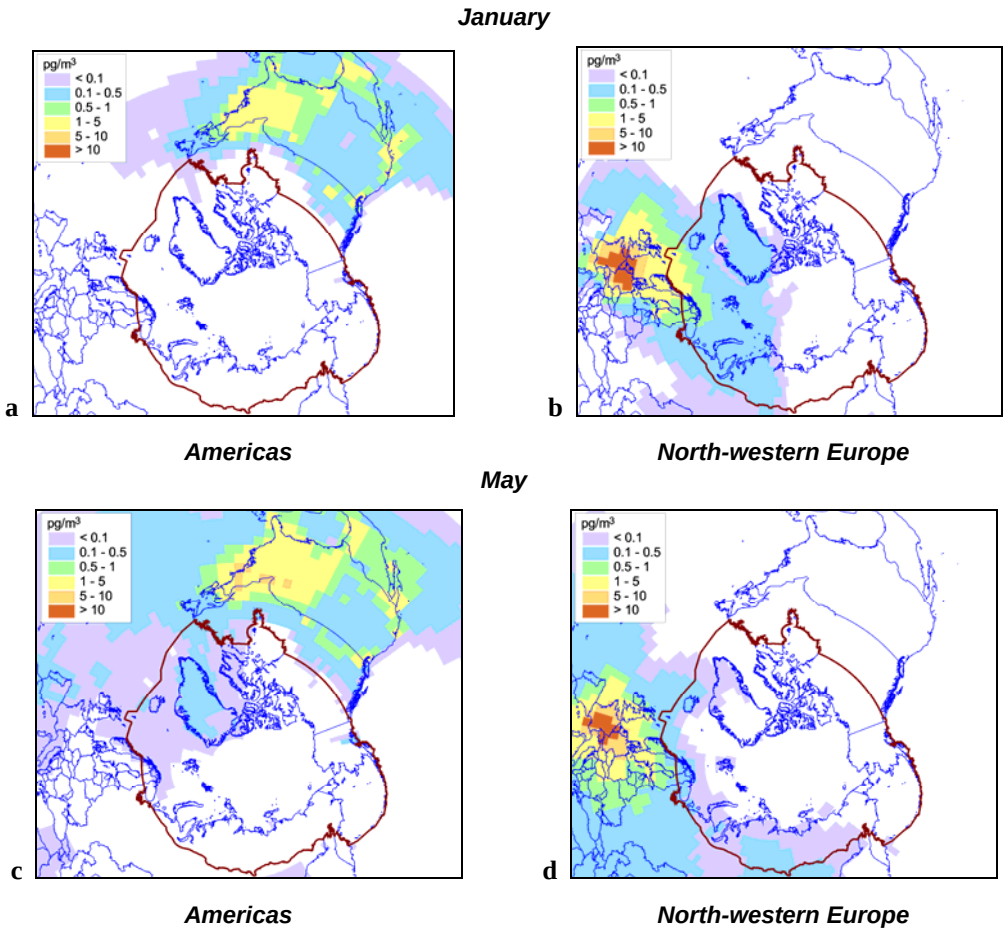

Figure 6.7. *Air concentrations of PCB-153 emitted in Americas and North-western Europe for January and May*

As seen from the maps, PCB-153 from American sources mainly penetrates into the Arctic in May, whereas from European ones - in January. On the whole, the basic contribution to Arctic pollution is made by European emission sources in the cold season. This is in line with the annual pattern of atmospheric circulation in the Arctic region. According to it the mean flow in winter is from Eurasia into the Arctic, and from the Arctic into North America.

Annual contributions of different emission sources to depositions to the Arctic region in 1996 are shown in Figure 6.8. The main group of sources contributing to this region is North-Western Europe (about 40%), which is then followed by Russia (19%), the Americas (17%), South-Eastern Europe (16%). The share of all other sources amounts to 8%.

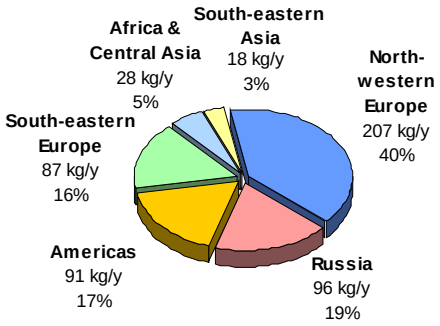

Figure 6.8. *Contributions of different emission sources to PCB-153 deposition to the Arctic region in 1996*

6.2. Comparison of modeling results with measurements

In this section the computed PCB concentrations in air and precipitation and deposition fluxes are verified using the available measurement data. Data for the comparison were taken from several sources including measurements at sites within the AMAP region [*Berg and Hjellbrekke*, 1999], observations of the EMEP monitoring network [*Berg et al.,* 1996, 1997*; Berg and Hjellbrekke*, 1998*; Brorström-Lundén et al.*, 2000], and literature data for 1989-96. This information is primarily concerned with PCB air concentrations. Less data are available on concentrations in precipitation and on deposition fluxes. The verification of model results is made by the comparison of mean annual concentration values. For this purpose, available observations were analysed. A number of studies of PCB concentrations obtained for relatively short periods of duration or otherwise episodic measurement campaigns were not taken into account.

Table 6.1. *Monitoring sites selected for the comparison with model results for PCBs*

Station	Code	Latitude	Longitude
Stórhöfdi	IS91	63° 24'N	20° 17'W
Rörvik	SE2	57° 25'N	11° 56'E
Pallas	FI96	67° 58'N	24° 07'E
Ny Ålesund	NO42	78° 54'N	11° 53'E
Kosetice	CZ3	49° 35'N	15° 05'E
Alert	CA420	82° 28'N	62° 30'W
Tagish	CA1	60° 18'N	134° 16'W
Dunai	RU17	73° 59'N	124° 30'E
Kårvatn	NO39	62° 47'N	8° 53'E
Svanvik	NO47	69° 27'N	30° 02'E
Hazelrigg		54 3'N	2 50'W

Figure 6.9. *Location of monitoring sites selected for the comparison with model results for PCBs*

The locations of the sites are depicted in Figure 6.9. Table 6.1 contains coordinates of these stations. Data on PCB concentrations measured at the EMEP network were available from the following sites: Storhöfdi (IS91), Rörvik (SE2), Pallas (FI96), Ny Ålesund (NO42), and Košetice (CZ3). Measurements of PCB concentrations within the Arctic region were available from Tagish, Dunai, and Alert sites. In addition, data from two Norwegian sites, Karvatn and Svanvik, were used [*Oehme et al.*, 1995]. Observations of PCB concentrations at the semi-rural site Hazelrigg [*Coleman et al.*, 1998] were also used in the comparison. The comparison of mean annual air concentrations of four PCB congeners (PCB 28, 118, 153, and 180) for the period of 1989-96 is presented in Figure 6.10. Most of the computed values of air concentrations (95%) are within a factor of 4 with respect to observed levels. As it can be seen from the figure and Table 6.2, in general the model overestimates atmospheric concentrations of the heavier congeners 180 and 153. For PCB-118 computed concentrations are rather close to measured ones. Computed mean annual air concentrations of PCB-28 are somewhat lower than observed ones. Although the number of sites for the analysis is relatively small, a correlation between observed and computed concentrations can be found. This testifies to the fact that the model reasonably represents spatial distribution of selected PCB congeners in air.

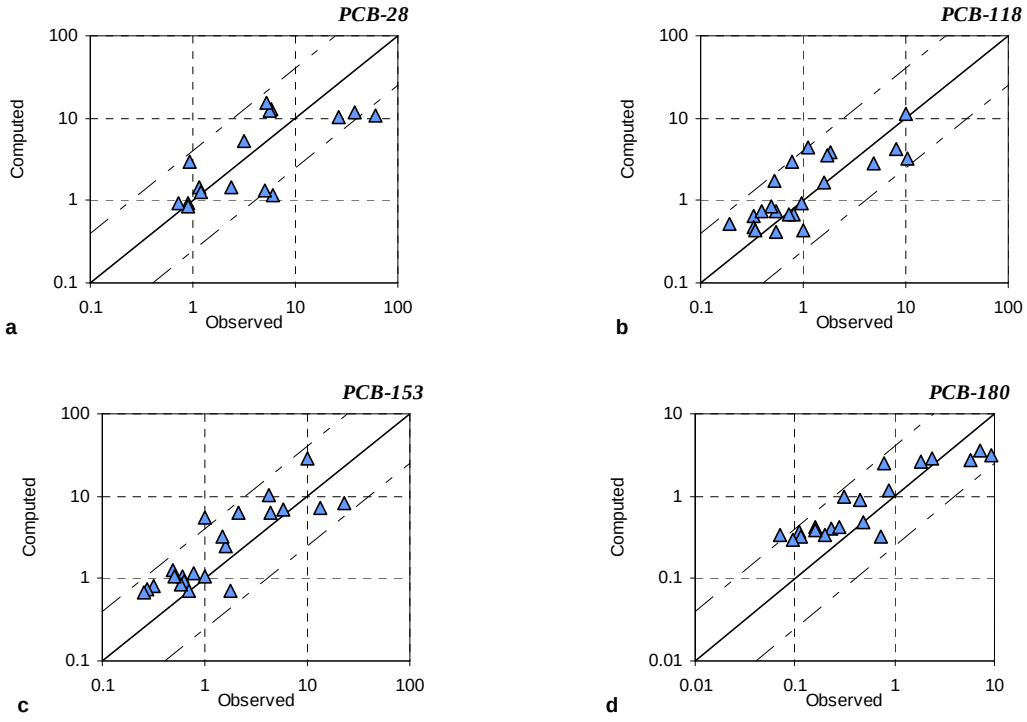

Figure 6.10. *Scatter plots of mean annual concentrations of four PCB congeners in the surface air, pg/m^3. Measured and computed PCB air concentrations are shown using the logarithmic scale. Dashed lines on the diagrams limit the area with agreement between the measured and computed values within a factor of 4*

Table 6.2. *Comparison of measured and computed mean annual air concentrations of four PCB congeners and correlation between measured and computed values*

	Mean observed, pg/m^3	Mean computed, pg/m^3	Mean ratio, Obs/Mod	Correlation
PCB-28	10.27	5.76	1.74	0.5
PCB-118	2.14	2.13	0.98	0.7
PCB-153	3.39	4.34	0.80	0.5
PCB-180	1.58	1.24	0.87	0.8

Next eight figures (Fig. 11.a-h) present more detailed comparison for individual years and sites grouped by two relatively large areas - European and Arctic region.

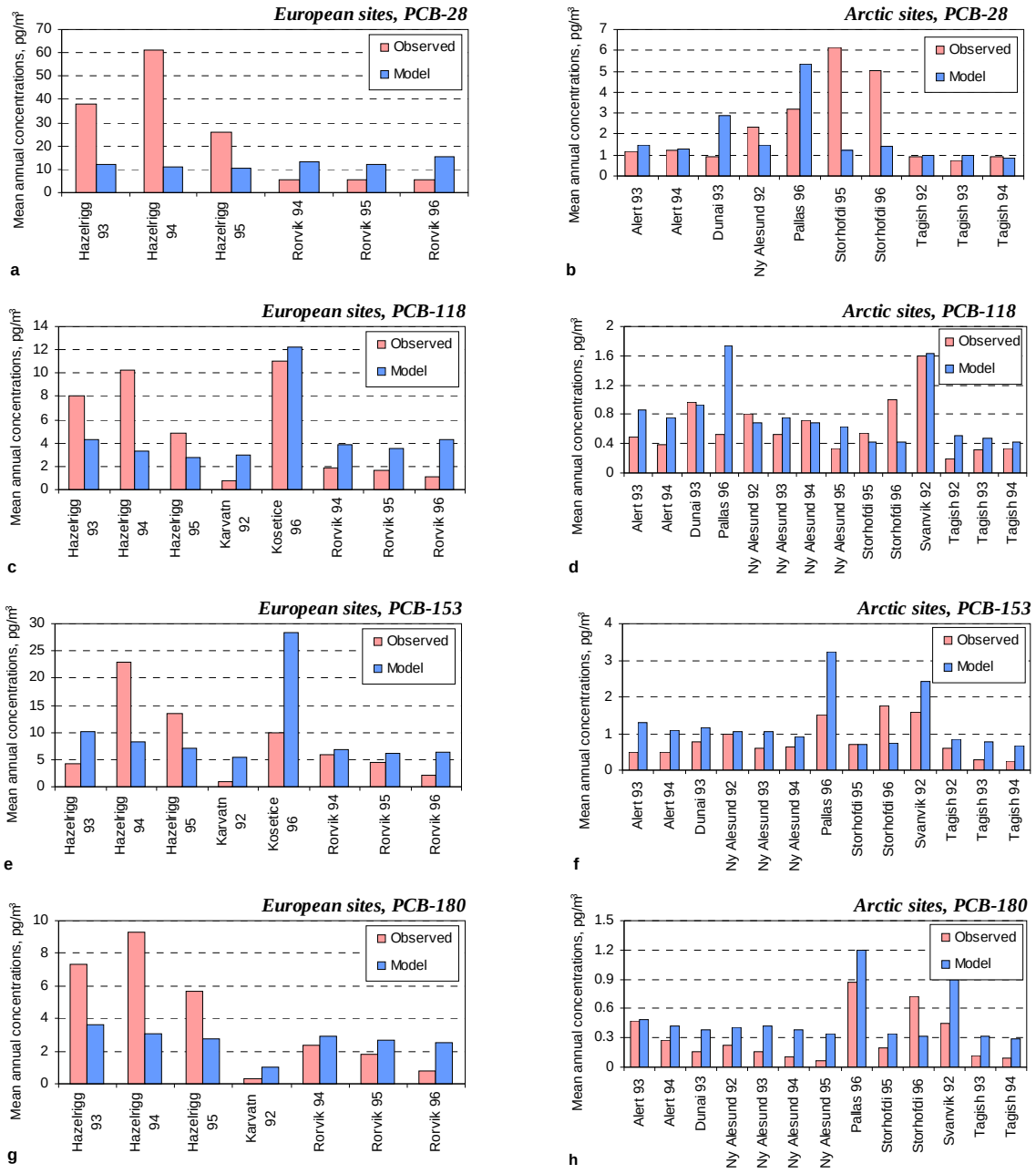

Figure 6.11. *Comparison of mean annual concentrations of four PCB congeners in the surface air of European and the Arctic regions for the period 1989-96, pg/m^3*

The comparison of measured and computed concentration in precipitation of four PCB congeners for site Stórhöfdi in 1995 and 1996 is given in Table 6.3.

The most significant discrepancies were found for Hazelrigg site. This site is located in semi-rural area of the United Kingdom. It is a single semi-rural station for this region (others are urban), therefore it is included into the comparison. Significantly higher levels of measured PCB concentrations at this site in comparison with the computed ones are most likely connected with the proximity of local emission sources.

Table 6.3. *Comparison of computed mean annual PCB concentrations in precipitation for 1995 and 1996 with measurements made at Stórhöfdi (IS91), ng/l*

	Mean observed, 1995	Mean observed, 1996	Mean computed, 1996
PCB-28	0.243	0.160	0.028
PCB-118	0.042	0.037	0.019
PCB-153	0.037	0.070	0.031
PCB-180	0.067	0.041	0.032

Since the values of concentration in precipitation and of deposition flux strongly depend on precipitation amount the comparison of measured and computed values for these parameters should be carried out only for 1996 (meteorology of this year was used in calculation). However, such comparison is complicated by the deficiency of available measurement data for 1996. Therefore, additional measurements for 1995 were used in the comparison. Deposition fluxes include dry and wet particle depositions and wet gas deposition. Data on concentrations in precipitation for 1995-96 were found for Icelandic site Stórhöfdi (IS91) and on deposition fluxes - for Pallas (FI96) and Rorvik (SE2).

The comparison of PCB concentrations in precipitation for this site shows that the computed values of three congeners (118, 153, 180) are quite close to the observed values. The comparison with measurement results of 1996 is better than with that of 1995 because in calculations meteorological parameters of 1996 were used. More significant disagreement is found for PCB-28. The computed value for this congener is significantly lower than measured one. It might be connected with uncertainties in emission data. It may be confirmed by the fact that the computed air concentration for this site is underestimated too (Figure 6.11.b). The second reason for the discrepancy may be the uncertainty connected with parameterization of washout process for this congener. To improve the parameterization of this process more information about simultaneously measured concentrations in air and precipitation are needed.

The comparison of computed and observed PCB deposition fluxes were made for two sites, Rörvik (SE2) and Pallas (FI96), for 1995 and 1996 (Figure 6.12).

Results of the comparison show that the computed deposition fluxes for these two sites are 3-5 times higher than measured ones for PCB-118, PCB-153, and PCB-180. The same can be noted for the computed air concentrations, which are 2-3 times higher than measured values. For PCB-28 the computed deposition fluxes were in a satisfactory agreement with observed values.

In conclusion it can be noted that the computed concentrations are close to measured PCB concentration levels at several sites located in the Arctic and European regions. Most of computed air concentration values are within a factor of 4 in comparison with measurements. Model air concentrations of four PCB congeners correlate rather well with observed ones.

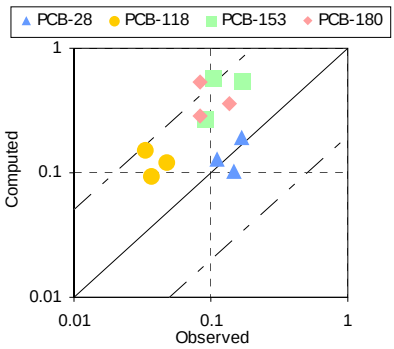

Figure 6.12. *Scatter plot of calculated annual deposition fluxes of four PCB congeners in comparison with measured ones at Rörvik (1995, 1996) and Pallas (1996), g/km^2/y. Observed and computed deposition fluxes are shown using logarithmic scale. Dashed lines limit the area of agreement within a factor of 5 between measured and computed values*

The comparison of concentrations in precipitation and deposition fluxes was limited by the deficiency of available measurements for 1996. Computed concentrations of PCB-118, 153, 180 in precipitation for Stórhöfdi (IS91) are in a good agreement with measured ones. However, the model underestimated observed concentration levels of PCB-28 at this site within a factor of four. Computed deposition fluxes compared to observed ones at Pallas and Rörvik are 3-5 times higher. At the same time model estimates of PCB-28 deposition fluxes agreed rather well with measurements made at these sites.

It should be mentioned that the measurement database for this comparison is rather limited. Therefore for more thorough verification of model results it is necessary to have more measurements in other regions of the Northern Hemisphere.

6.3. Concentration and deposition levels in the Russian North

This section contains information on pollution levels of PCB-153 in the Russian North. Spatial distribution of annual means as well as seasonal variation of contamination is examined for each considered region (Murmansk Oblast, Nenets AO, Yamalo-Nenets AO and Taimyr AO, Sakha Republic and Chukotka AO). Similar information on other congeners (PCB-28, PCB-118, PCB-180) can be found in Annex A.

Deposition fluxes include wet scavenging of the gaseous and particulate phase plus dry depositions of PCB associated with particles. Net gaseous exchange flux between the atmosphere and the underlying surface is considered separately due to the importance of re-emission process for PCBs. Due to a reversible character of gaseous exchange the flux can be directed to the underlying surface (positive value) as well as to the atmosphere (negative value, re-emission).

6.3.1. Spatial distribution

Figures 6.13 and 6.14 display spatial distributions of mean annual air concentrations and annual deposition fluxes of PCB-153 over the selected regions of the Russian North for 1996. There is a clear latitudinal gradient of air concentrations from the western to eastern parts of the Russian North. Relatively high air concentrations (2-4 pg/m^3) take place in Murmansk Oblast, Nenets AO and in the southern part of Yamalo-Nenets and Taimyr AO. Moderate values (1-2 pg/m^3) are characteristic of the northern part of Yamalo-Nenets and Taimyr AO and Sakha Republic. Chukotka AO is characterized by low values (<1 pg/m^3).

Spatial pattern of deposition fluxes is of similar character. Rather high values (> 150 mg/km^2/y) are determined for Murmansk Oblast, Nenets AO and the southern part of Yamalo-Nenets and Taimyr AO as well as for the western part of Sakha Republic. Moderate values (70 - 150 mg/km^2/y) are determined for the northern part of Yamalo-Nenets and Taimyr AO, Sakha Republic and the western part of Chukotka AO. The northern part of the Russian North is characterized by lower values of deposition fluxes (<70 mg/km^2/y).

In addition to the fields of air concentrations and annual deposition fluxes spatial distribution of PCB-153 concentration in seawater within the Arctic region is presented (Fig. 6.15). The highest concentrations in seawater are obtained for coastal waters of Murmansk Oblast (>1.2 pg/l). Moving to the east, seawater concentrations go down, reaching values of 0.2-0.4 pg/l. In some regions of Yamalo-Nenets AO and Taimyr AO, Yakutia and Chukotka AO water concentrations are less than 0.2 pg/l.

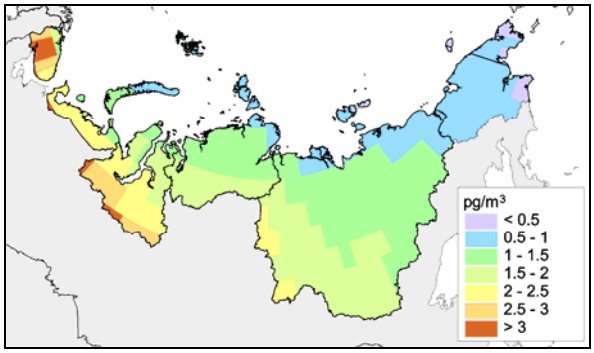

Figure 6.13. *Mean annual air concentrations of PCB-153 in the Russian North, pg/m^3*

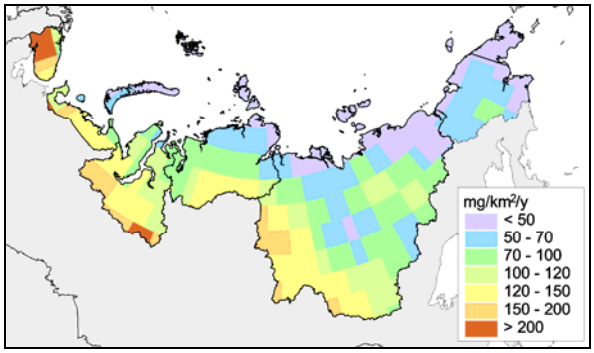

Figure 6.14. *Deposition of PCB-153 in the Russian North calculated for 1996, mg/km^2/y*

Seawater concentration pattern illustrates the inflow of PCB-153 from the North Atlantic with sea currents. It should be mentioned that the results obtained for the marine environment are rather preliminary. At present stage of model development we do not consider the contamination transport by rivers, therefore there is a certain underestimation of PCB concentrations in coastal seawater. In further investigations of the Arctic contamination, the effect of pollutant transported by rivers should be taken into account.

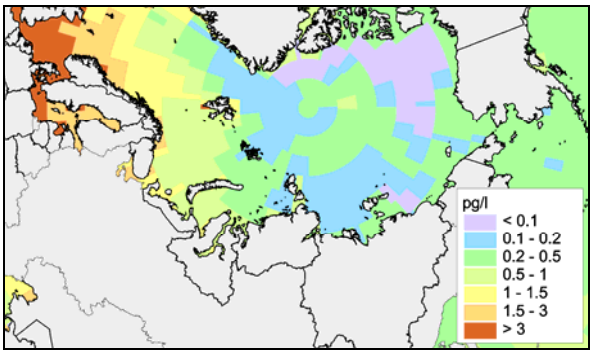

Figure 6.15. *Mean annual PCB-153 seawater concentrations near the Russian North, pg/l*

6.3.2. Annual averages

Mean annual air concentrations, annual deposition and net gaseous exchange fluxes along with their spatial variations for each region are summarized in Table 6.4. It can be seen that air concentrations (sum of gas and particle phases) varies from 0.4 to 4.1 pg/m^3 over the Russian North. Averaged net gaseous flux over the most part of the territory is negative (except for Nenets AO). It means that in these regions the evaporation process prevails over dry gaseous deposition. This is conditioned by large amount of PCBs accumulated in environmental media (mainly in soil) during the period from 1970 to 1995 and essential reduction of air concentrations caused by emission reduction. Annual deposition fluxes vary along the territory of the Russian North more than within an order of magnitude (16 – 373 mg/km^2/y).

Table 6.4. *Annual contamination levels and their spatial variation of the Russian North regions by PCB-153 in 1996*

Region	Air concentration, pg/m^3			Depositions*, mg/km^2/y			Gas exchange, mg/km^2/y		
	Mean	Min	Max	Mean	Min	Max	Mean	Min	Max
Murmansk Oblast	2.6	1.3	4.1	208	70	333	-71	-248	139
Nenets AO	1.7	0.5	3.8	97	27	373	15	-302	100
Yamalo-Nenets AO and Taimyr AO	1.8	0.5	3.3	106	27	216	-44	-167	58
Sakha Republic	1.4	0.4	2.3	89	16	224	-77	-208	14
Chukotka AO	0.7	0.4	1	51	16	74	-34	-64	18

* depositions include wet and dry particle deposition and wet gaseous deposition

Seasonal variations

In this subsection we discuss main tendencies of contamination level variability defined by meteorological parameters (winds, temperature and precipitation). Since emissions are considered to be uniform throughout the year (discussion on this topic is in chapter 4.2.3) the obtained seasonal variations are caused by meteorological and geophysical conditions only (wind speed and direction, temperature, leaf area index, etc.). The main dependencies of seasonal variations of monthly averaged contamination levels are described in detail on the example of Murmansk Oblast. Variations of air concentrations, deposition flux, and net gaseous flux for Murmansk Oblast are presented in Figure 6.16. Variations of temperature and precipitation are also presented for the sake of explanation of characteristic behaviour of contaminant over 1996.

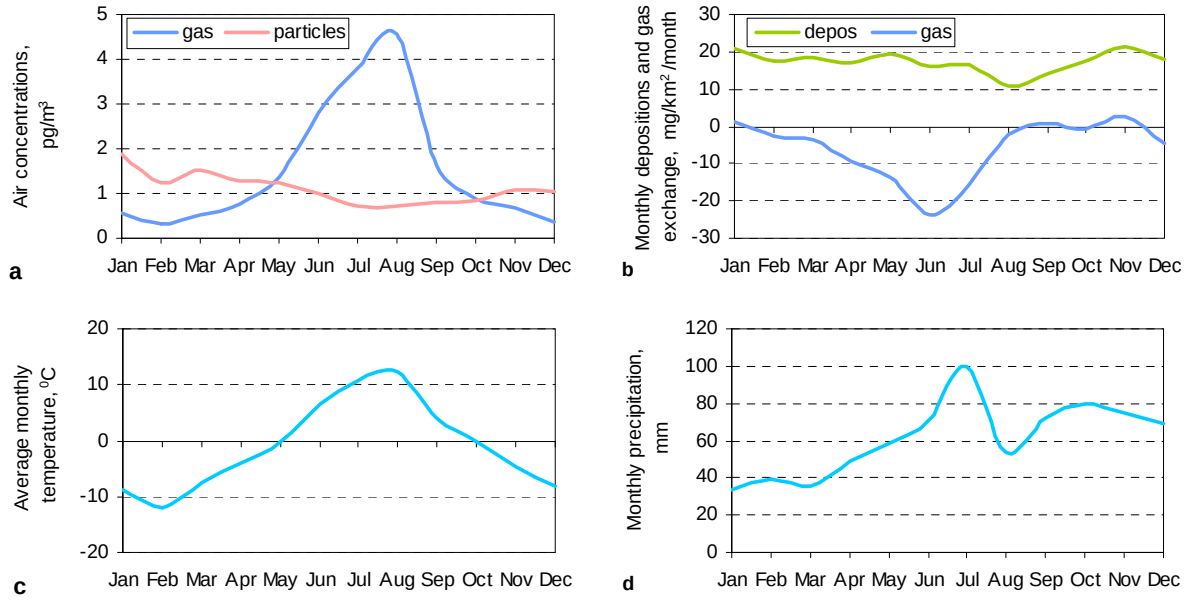

Figure 6.16. *Seasonal variations of PCB-153 contamination levels in Murmansk Oblast for 1996*

Monthly mean air concentrations of the gaseous phase vary within an order of magnitude over the year, reaching the maximum value in August (about 5 pg/m^3). This maximum coincides with the peak temperature. The particulate phase concentrations do not change so drastically and reach their maximum in winter (about 2 pg/m^3). They dominate over the gaseous phase within the cold season. This tendency is explained by the dependence of partitioning between phases on temperature and by the fact that gaseous PCBs are removed more efficiently at low temperatures.

As it was mentioned above, annual depositions include wet gas and particle depositions plus dry particle deposition. The deposition flux ranges from 10 to 22 mg/km^2/month (Fig. 6.16.b). On the whole depositions follow the tendency of the particulate phase concentration within the year. The decrease of deposition flux in August coincides with maximum value of temperature and is explained by temperature dependence of gas/rainwater partitioning coefficient and by lower precipitation amount (Fig. 6.16.d).

The behaviour of net gaseous flux is somewhat more complicated (Fig. 6.16.b). Its value varies from 3 to –24 mg/km^2/month over the year. In the cold period gaseous phase concentrations of the underlying surface are rather low therefore the flux is positive. This means that PCBs mainly deposit to the underlying surface from the atmosphere. During warm season re-emission process takes place.

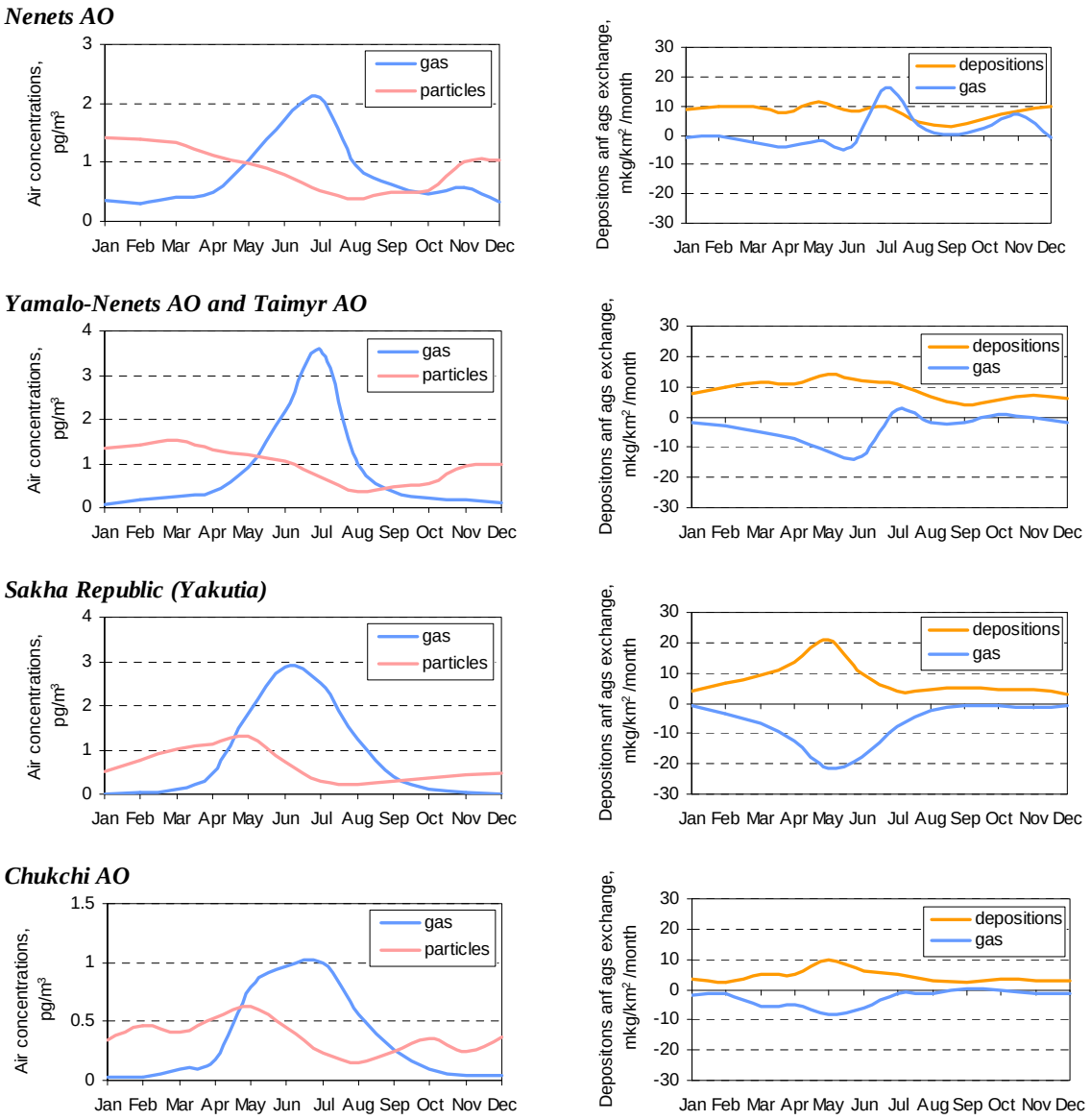

Figure 6.17. *Seasonal variations of PCB-153 contamination levels in regions of the Russian North for 1996*

Calculated seasonal variations of PCB-153 pollution levels in other regions of the Russian North are demonstrated by plots in Figure 6.17 along with variations of temperature and precipitation (Fig. 6.18). General tendencies can be explained in the same way as in the case of Murmansk Oblast. As a special feature we can indicate positive values of the gaseous flux in summer time in Nenets AO, Yamalo-Nenets AO, and Taimyr AO.

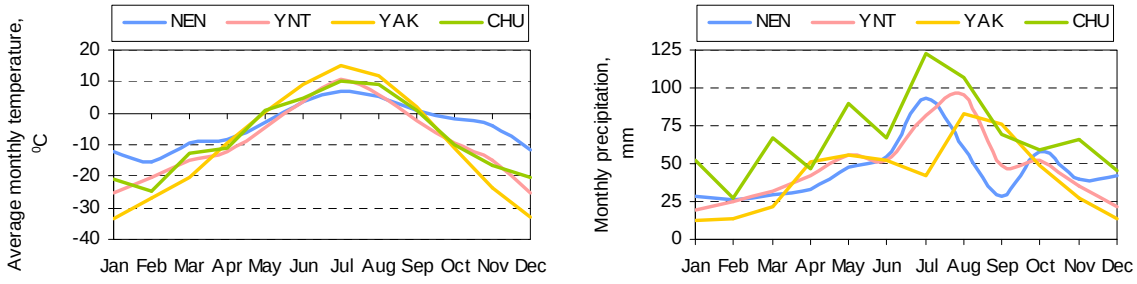

Figure 6.18. *Seasonal variations of temperature and precipitation in regions of the Russian North for 1996*

The above described pollution levels are caused by both emissions of the considered year and re-emission from environmental media (soil mainly). The influence of this last process amounts to 30-80% depending on the congener and region. Taking into account that re-emissions cannot be controlled by any political decisions we focus on the influence of emissions of 1996.

6.4. Source-receptor relationships

This section contains information on contributions from different emission sources of the Northern Hemisphere to PCB contamination of the Russian North (selected 5 region-receptors) in 1996. Contamination in regions-receptors is formed both by emissions of the considered year (1996) and by amount of pollutant accumulated in the environment during the period preceding the reference year (1990 – 1995). Calculations show that large fraction of concentrations in soil and seawater over regions of the Russian North are formed by PCBs earlier accumulated in environmental media. Keeping in mind that the historical emission cannot be controlled by any political decisions we shall pay the main attention to deposition from anthropogenic sources.

The Northern Hemisphere is divided into 6 large source-regions – Russia, the Americas, North-western Europe, South-eastern Europe, South-eastern Asia, Africa and Central Asia (Fig.6.19.a, see also Section 4.2). For more detailed examination of influence of Russian sources on the contamination of the Russian North, Russia is subdivided into 12 individual source regions, 5 of them are located in the Russian North and are at the same time considered as the regions-receptors (Fig. 6.19.b, Table 6.5).

Figure 6.20.a displays contributions of different source groups to the overall Northern Hemisphere emissions. Figure 6.20.b presents values of emissions from different regions of Russia. As above, we consider an example of PCB-153. Information on other congeners is collected in Annex A. The most significant emission sources in the Northern Hemisphere are located in North-western Europe (about 4.4 t/y, 30%), then come South-eastern Europe, America, Africa and Central Asia (Fig.6.20.a). Russian emissions take the fifth place. Due to proximity to regions under investigation, it is important to consider Russian emissions in detail (Fig.6.20.b). It should be noted, that total own emissions of 5 regions-receptors of the Russian North (MUR, NEN, YNT, YAK, CHU) are rather low. Therefore PCB contamination of Russian North is mainly formed due to the long-range transport from other regions with substantial emission levels.

Table 6.5. *Russian emission sources and their codes. The first 5 sources are also receptors in the Russian North*

	Code		Russian sources
Sources	Receptors	MUR	Murmansk Oblast
		NEN	Nenets AO
		YNT	Yamalo-Nenets AO and Taimyr AO
		YAK	Sakha Republic (Yakutia)
		CHU	Chukotka AO
		NRT	Northern region
		NWK	North-western region and Kaliningrad Oblast
		CVV	Central and Volga-Viatsky regions
		CVN	Central-Chernozem, Volga, and North-Caucasian regions
		URL	Ural region
		WSB	West-Siberian region
		ESB	East-Siberian and Far-Eastern regions

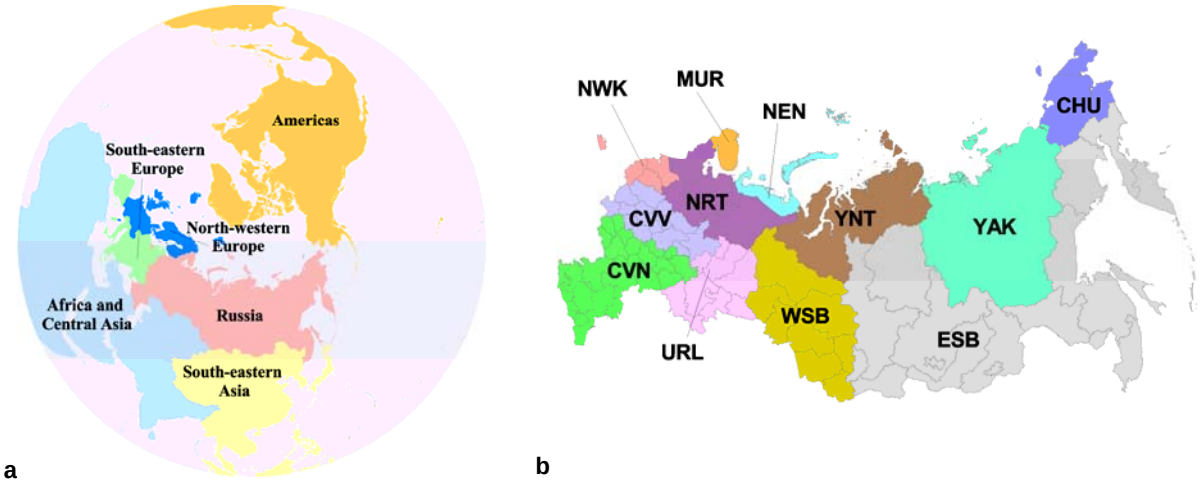

Figure 6.19. *Splitting emission sources into groups, (a) – rough scheme, (b) – specification of Russian sources*

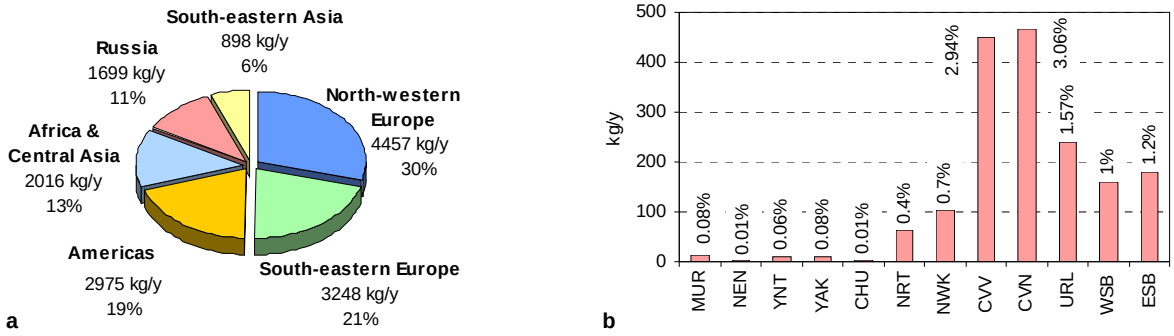

Figure 6.20. *Contributions of different emission source groups of PCB-153 to the hemispheric emissions in 1996: source-regions in the Northern Hemisphere (a), detailed splitting of Russian sources (b)*

Murmansk Oblast. Here we consider the contributions of various emission sources to depositions and concentrations in Murmansk Oblast in 1996. Contributions of emission sources of the Northern Hemisphere and Russia to depositions to Murmansk Oblast are illustrated by Figure 6.21 a – b. As seen the largest contribution is made by Russian sources (44%), although their emission fraction is only 11% (Fig.6.21.a). Then come more significant, but remote emission sources, namely North-western Europe (35%) and South-eastern Europe (14%). The minor influence of sources located in the Americas, Africa and Central Asia and South-eastern Asia (in sum 7%) can be explained by their significant remoteness from Murmansk Oblast.

Russian contribution to depositions to Murmansk Oblast is formed mainly by own Murmansk sources (about 22%) in spite of a small fraction of Murmansk Oblast in total Russian emissions (Fig.6.21.b).

Contributions of different emission sources to air and soil concentrations are given in Figures 6.21.c and 6.21.d. As seen from the figures, these contributions are almost the same as for depositions. For example, Russian contributions to depositions and concentrations in air and soil are from 44% to 47%, respectively. Similar situation is observed also for other regions.

Inputs of different emission sources to deposition are subject to seasonal variations determined by meteorological conditions (wind speed and direction, precipitation amount and temperature). Figure 6.22 displays seasonal variations of contributions of main source groups to deposition to this region in absolute (a) and relative (b) values for 1996.

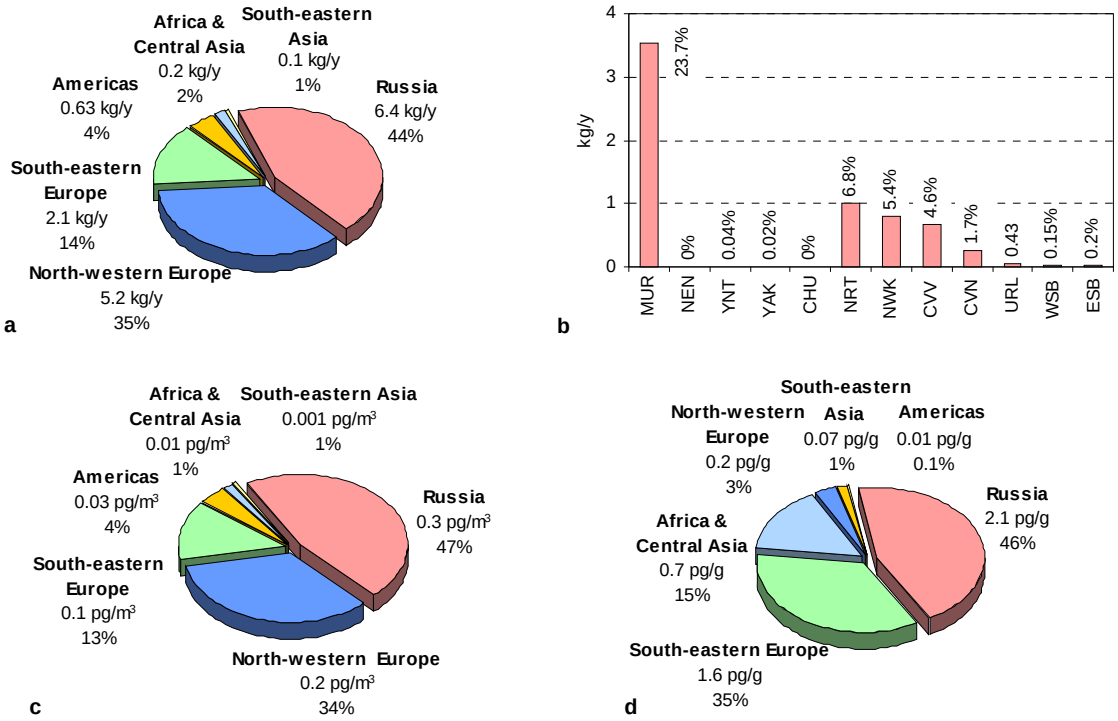

Figure 6.21. *Contributions of different emission sources to PCB-153 depositions (a - source-regions in the Northern Hemisphere, b - detailed splitting of Russian sources), and concentrations in air (c) and in soil (d) of Murmansk Oblast in 1996*

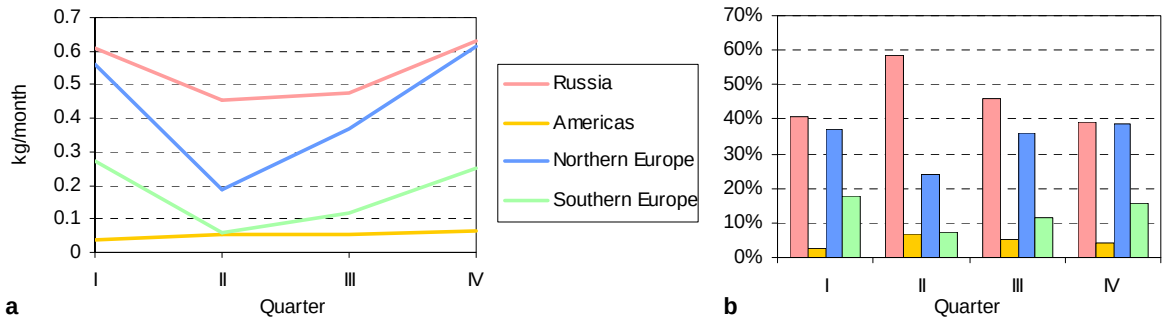

Figure 6.22. *Seasonal variations of contributions of different emission sources to PCB-153 depositions to Murmansk Oblast (I-IV quarters of 1996)*

As it was shown above, the main contributions to depositions are made by Russia and North-western Europe (Fig.6.22). The depositions are higher in the cold season, than in the warm one (Fig.6.22.a). This can be explained by the fact that at high temperature the particulate fraction of PCB decreases, leading to the decrease of depositions (the second quarter). Rates of decrease for various sources are different. For example in the second quarter the decrease of depositions from North-western Europe sources is stronger than that from Russian sources. This leads to the decrease of the fraction of North-western Europe sources in the second quarter among others (Fig.6.22.b). It happens because north-west winds are rare in this period and because of a large transport distance from North-western Europe to Murmansk Oblast. In the third quarter total depositions increase. Due to prevailing north-west winds in the cold period, the contribution to depositions from sources of North-western Europe increase and its fraction becomes equal to that of Russian sources.

Nenets Autonomous Okrug. The contributions of different source groups to the pollution of Nenets AO are similar to that of Murmansk Oblast. Contributions of Russia and North-western Europe are slightly lower (41 and 31%), but contributions of South-eastern Europe and America are slightly higher (18% and 6%) in comparison with Murmansk Oblast (Fig.6.23.a). The structure of Russian contribution to depositions to this region is principally different from that for Murmansk Oblast. The main contributions (15%) are made by Central and Volga-Viatsky regions and (10%) by the Northern region (Fig.6.23.b). The contribution of local sources for this region is negligible. Therefore, the long-range transport plays a leading role in the contamination of Nenets AO since basic contributions to pollution of this region is made by remote sources.

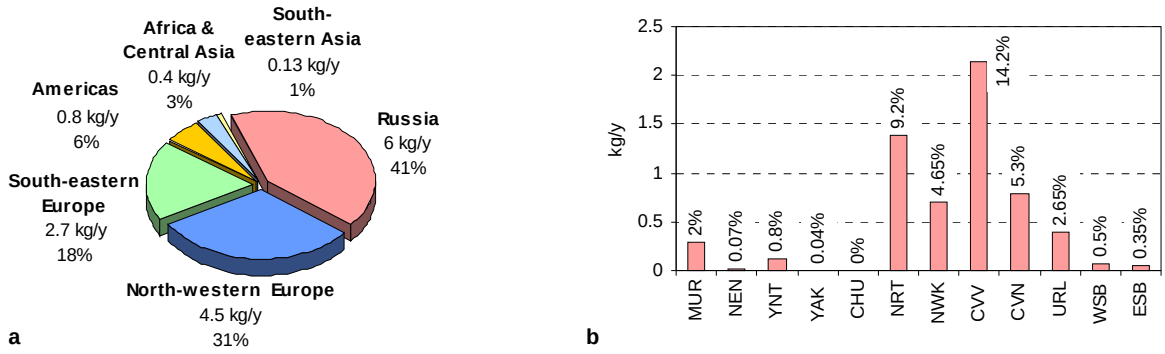

Figure 6.23. *Contributions of different emission sources to PCB-153 depositions to Nenets AO in 1996. (a) – from source-regions in the Northern Hemisphere , (b) - detailed splitting of Russian contribution*

Seasonal variations of contributions of main source groups to deposition to Nenets AO in absolute (a) and relative (b) values in 1996 are displayed in Figure 6.24.

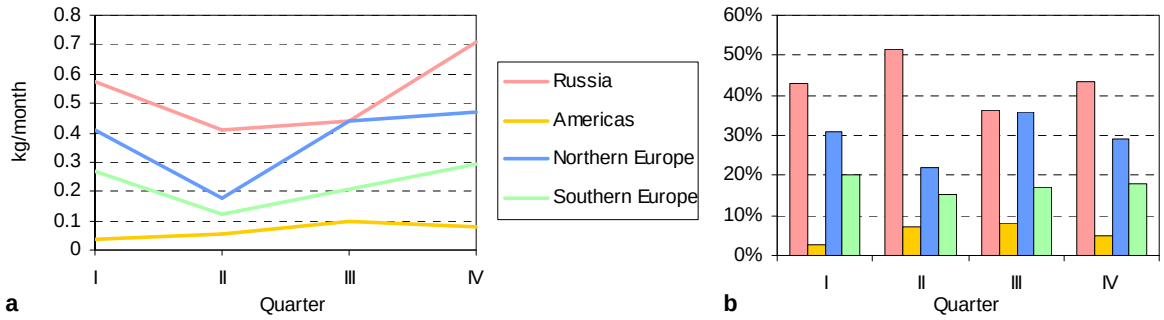

Figure 6.24. *Seasonal variations of contributions of different emission sources to PCB-153 depositions to Nenets AO (I-IV quarters of 1996)*

The main contributions to depositions to the region are made by North-western Europe, South-eastern Europe and Russia. The situation is quite similar to that of Murmansk Oblast - the depositions decrease in the warm period (the second quarter) and increase in the cold period (Fig. 6.24.a). The rates of decrease for various sources are different. For example in the second quarter the decrease of depositions from North-western Europe source is stronger than that of Russian sources. This leads to the decrease of the fraction of North-western European sources in the second quarter in comparison with others (Fig. 6.24.b). The reason for that is just the same as for Murmansk Oblast.

Yamalo-Nenets and Taimyr Autonomous Okrugs. For this region substantial contribution to the depositions is made by Russian (47%), North-western (26%) and South-eastern (16%) European emission sources (Fig. 6.25.a). The largest contribution of Russian sources is obtained from Central and Volga-Viatsky regions (12%). Then come the contribution of internal emission sources of the considered region (9%).

Seasonal variations of contributions of main source groups to deposition to Yamalo-Nenets AO and Taimyr AO in absolute (a) and relative (b) values for 1996 are shown in Figure 6.26.

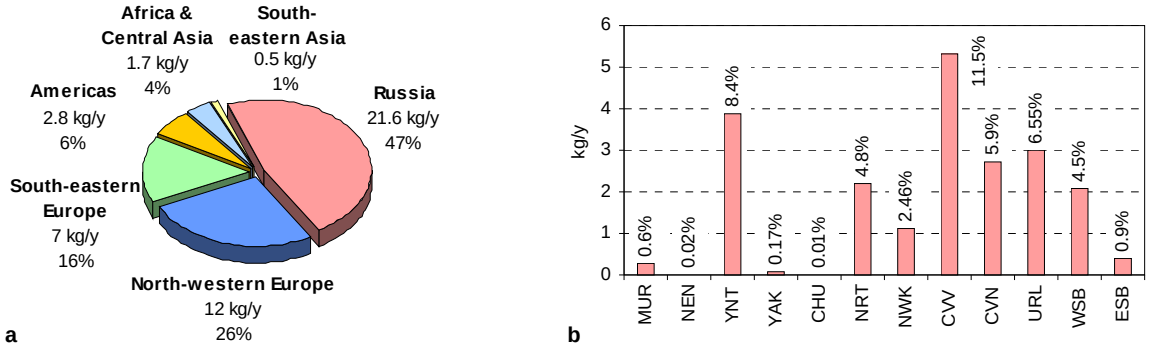

Figure 6.25. *Contributions of different emission sources to PCB-153 depositions to Yamalo-Nenets and Taimyr AO in 1996. (a) – from source-regions in the Northern Hemisphere , (b) - detailed splitting of Russian contribution*

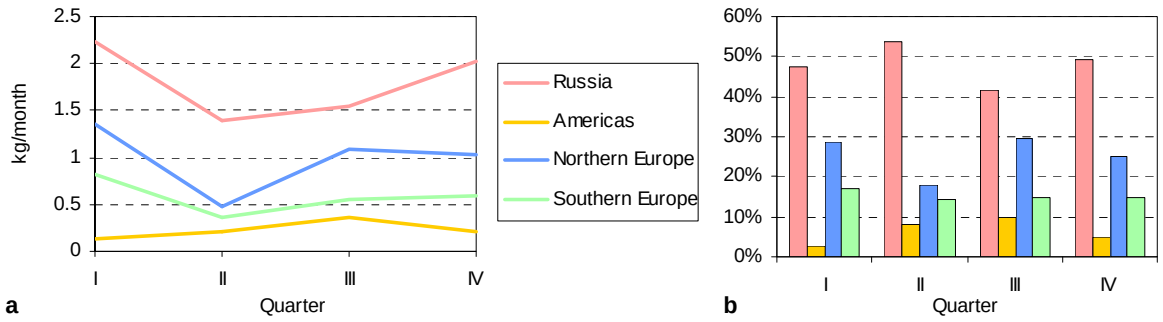

Figure 6.26. *Seasonal variations of contributions of different emission sources to PCB-153 depositions to Yamalo-Nenets AO and Taimyr AO (I-IV quarters of 1996)*

Seasonal variations of contributions of different emission sources to PCB-153 depositions are the same as in Nenets AO. Depositions decrease from the first to the second quarter and then go up. The rate of increase of depositions from North-western Europe sources is higher in comparison with those of Russian ones. There is a difference for the fourth quarter, when depositions from North-western Europe remain less than depositions from Russia. This can be explained by the fact that the considered region is located to the east from Nenets AO. Therefore southern and south-western winds transport of the pollutant from Russian sources in considerable amounts.

Sakha Republic (Yakutia). Contributions to depositions to Sakha Republic from sources of the Northern Hemisphere are presented in Figure 6.27.a. As for other regions the major contribution to depositions is made by Russia (38%). Then come North-western Europe (23%) and South-eastern Europe (16%). Contributions from American sources to the pollution of this region become tangible (contrary to the above considered regions) and comparable with that of local sources – about 11%.

As to Russian emission sources (Fig. 6.27.b), the main contribution is made by own sources of Yakutia (11%). Then come CVV, CVN, URL, WSB, ESB with contributions from 4% to 6%.

Seasonal variations of contributions of main source groups to deposition to Sakha Republic in absolute (a) and relative (b) values in 1996 are displayed in Figure 6.28.

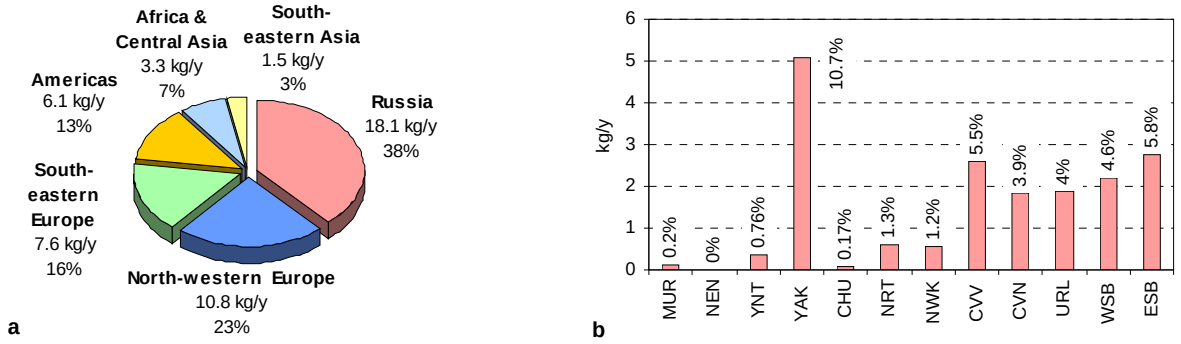

Figure 6.27. *Contributions of different emission sources to PCB-153 depositions to Sakha Republic (Yakutia) in 1996. (a) – from source-regions in the Northern Hemisphere, (b) - detailed splitting of Russian contribution*

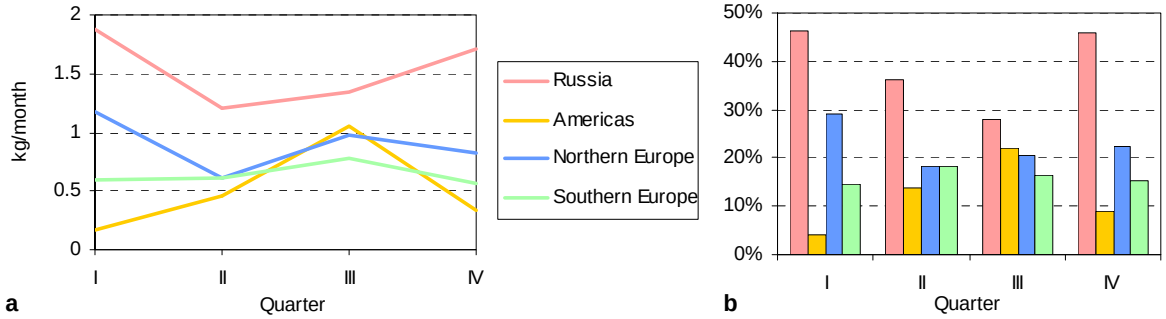

Figure 6.28. *Seasonal variations of contributions of different emission sources to PCB-153 depositions to Sakha Republic (I-IV quarters of 1996)*

The main difference of seasonal variations in this region in comparison with previous ones is that contributions from American sources in this region became more significant. Due to meteorological conditions contributions of these sources are growing from the first to the third quarters and drop down in the fourth quarter. Fast increase of contributions from American sources leads to the increase of their relative input and at the same time to the decrease of relative input from North-western European and Russian sources in this region in the second and the third quarters.

Chukotka Autonomous Okrug. For this region considerable contributions to depositions are made by Russian (25%), North-western (22%) and South-eastern (19%) European emission sources (Fig. 6.29.a). In comparison with Yakutia, the contribution from the Americas increased up to 17%, that is explained by specific geographical location and meteorological features of this region.

Contributions to depositions from Russian sources are presented in Figure 6.29.b. The main contribution is made by emissions of Chukotka AO itself (8%), then come East-Siberian and Far-Eastern regions (5%).

Seasonal variations of contributions of main source groups to deposition to Chukotka AO in absolute (a) and relative (b) values in 1996 are displayed in Figure 6.30.

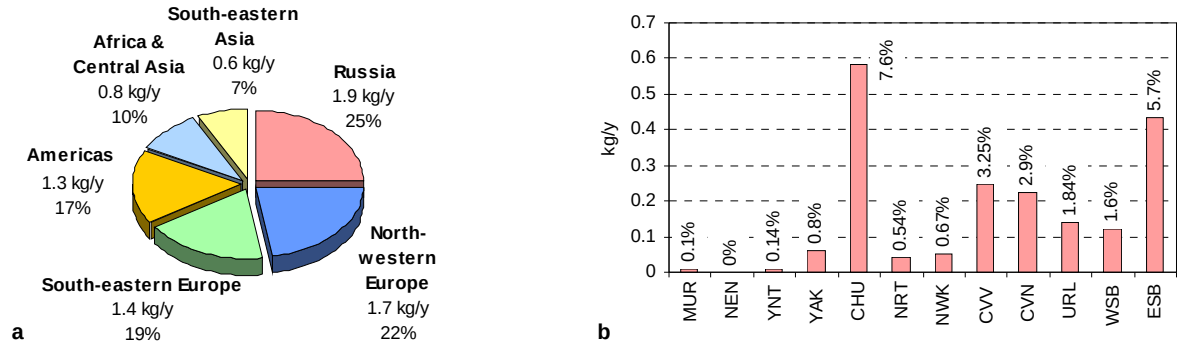

Figure 6.29. *Contributions of different emission sources to PCB-153 depositions to Chukotka AO in 1996. (a) – from source-regions in the Northern Hemisphere, (b) - detailed splitting of Russian contribution*

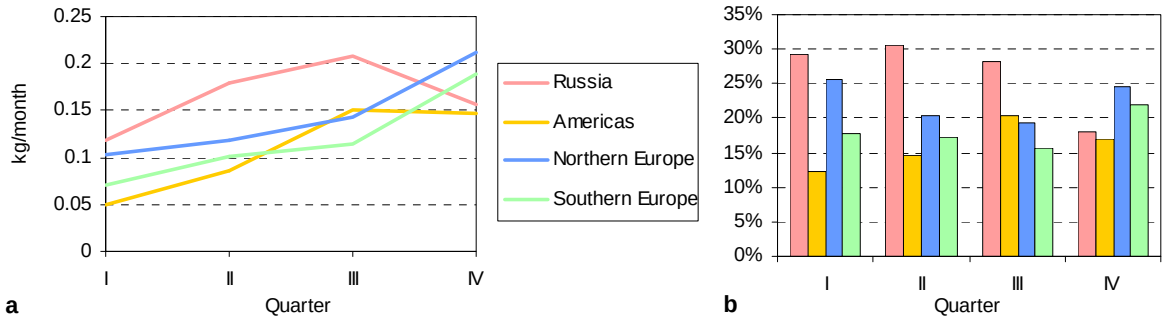

Figure 6.30. *Seasonal variations of contributions of different emission sources to PCB-153 depositions to Chukotka AO (I-IV quarters of 1996)*

Increase of depositions from the considered emission sources takes place for the period from the first to the fourth quarters (Fig. 6.29.a). There is an exception for Russian sources, which decrease beginning from the third quarter. Further increase of contributions from American sources with respect to those of North-western and South-eastern Europe determine the character of seasonal variations of relative inputs of different source groups in the region. These inputs from Russian sources are greater in the second and the third quarters. On the contrary relative inputs North-western and South-eastern Europe sources are maximum in the first and the fourth quarters.

Thus, from the analysis of contributions of different emission sources to PCB contamination of the selected regions of the Russian North the following results were obtained:

- contributions of different emission sources to the formation of air and soil concentrations are similar to their contributions to deposition formation.
- major contribution to PCB-153 pollution of the Russian North is made by Russian emission sources, then come North-western and South-eastern Europe, and the Americas.
- among Russian sources the strongest influence on the pollution of the considered regions is made by its own emissions. This is true for Murmansk Oblast, Sakha Republic and Chukotka AO. Nenets AO and Yamalo-Nenets AO and Taimyr AO are influenced mainly by Central and Volga-Viatsky regions.

6.5. Congener composition analysis

Simulations of long-range transport and accumulation of four PCB congeners (PCB-28, PCB-118, PCB-153 and PCB-180) make it possible to compare the peculiarities of environmental behaviour of different PCB congeners during their long-range transport. In particular, changing of PCB congener composition in air during their transport is of particular interest. Clearly, this analysis is of preliminary character and the results may be changed in the course of further refinement of PCB physical-chemical properties and emission data.

The diagrams of Figure 6.31 present PCB congener composition (in this section we consider congener composition of the mixture of 4 selected PCB congeners) in air of different regions-receptors of the Russian North in comparison with that of emissions. Figure 6.31.a displays the congener composition formed by all emission sources of the Northern Hemisphere during the period from 1970 to 1996.

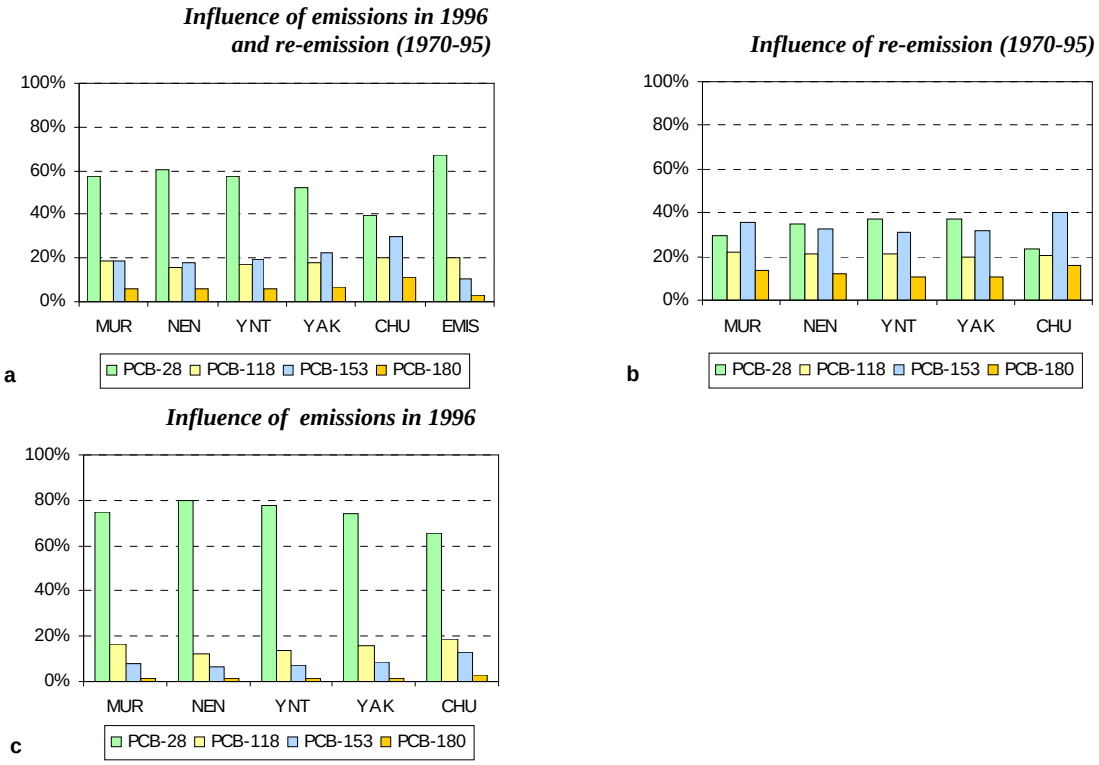

Figure 6.31. *PCB congener composition in air of different regions-receptors of the Russian North in 1996*

For all regions-receptors, the fraction of PCB-28 is highest and PCB-180 is lowest, in compliance with their fraction in emissions (last column in Fig. 6.31.a). The other congeners are in the intermediate position. It should be noted that the congener composition of four selected PCB congeners vary from region to region. This congener composition for 1996 may be split into two parts: formed by re-emission process caused by PCB accumulations in media during the period from 1970-95 (Fig. 6.31.b) and formed by emission in 1996 (Fig. 6.31.c). In the first case we consider results of the model run for 1996 with zero emission and initial concentrations obtained from model spin-up (1970-95). In the second case the results of the model run with zero initial concentrations in all the media and emission of 1996 are considered.

The most contribution to the congener composition due to re-emission is made by PCB-28 and PCB-153 (Fig. 6.31.b). Considering the congener composition caused only by emissions of 1996 (Fig. 6.31.c), it should be noted that PCB composition in air in general follows that of emissions, being different for individual regions.

Thus, one of the most important factors, influencing PCB congener composition in air, is congener composition of emissions. To demonstrate the role of physical-chemical properties and atmospheric transport in the formation of PCB congener composition, it is interesting to exclude the emission factor from the consideration. To this end we normalized air congener compositions to their emissions and show results in Figure 6.32. By this normalization we have obtained PCB congener composition in air under the assumption that emissions of all four congeners equal one another. The congener composition caused by re-emission processes (Fig. 6.32.a) is normalized by total emissions from 1970-95, and the congener composition caused by emissions of 1996 (Fig. 6.32.b) is normalized by emissions of this year.

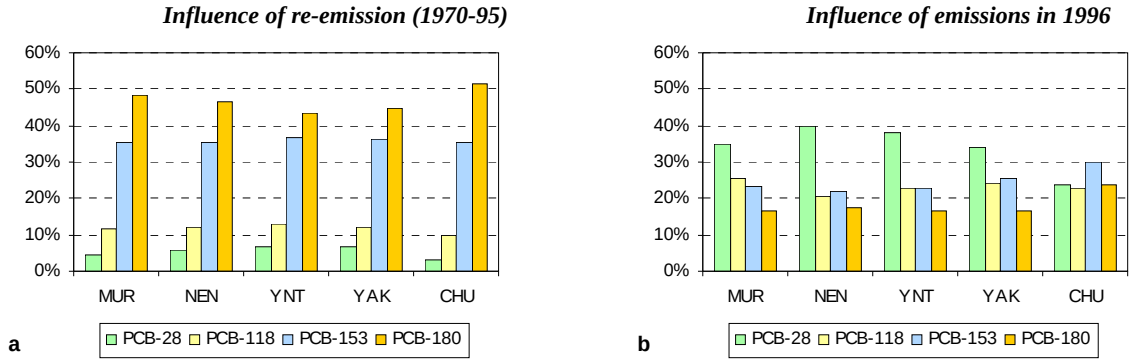

Figure 6.32. *PCB congener composition in air of different regions-receptors in 1996 (equal emission totals)*

From Figure 6.32.a it is clearly seen, that the heavier congener is the greater re-emission influences on air pollution. This may be explained by higher degradation half-life in soil for heavy congeners and higher soil capacity for them. As to emissions of 1996, Figure 6.32.b demonstrates that fraction of PCB-28 is higher than fractions of other congeners for all regions-receptors excluding Chukotka AO.

Simple normalization to emissions keeps the uncertainty of different congener composition of emission sources located in different countries. To get over this uncertainty it is interesting to consider the congener composition of air concentrations transported from a single emission source with equal fractions of each congener. More reliable estimates may be obtained if we consider one region-source and regions-receptors located in increasing distance. This experiment is shown in Figure 6.33, where normalized emissions only from Murmansk Oblast are considered. As seen from the diagram, there are certain variations in congener composition of PCB mixture transported from Murmansk Oblast to

five regions-receptors. However, these differences are less significant than those caused by different congener composition of different emission sources.

Thus, in the atmosphere of the Russian North PCB-28 dominates, then come PCB-118, 153 and PCB-180. For different regions-receptors, the composition of PCB mixture is different. The main factor affecting the air congener composition is emissions.

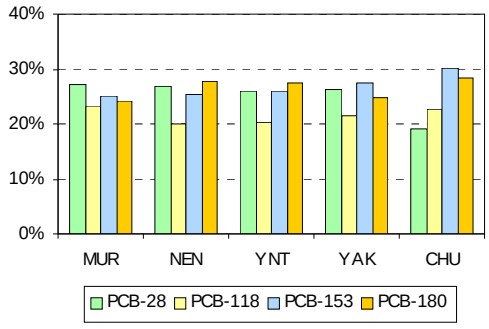

Figure 6.33. *PCB congener composition in air of different regions-receptors in 1996 caused by Murmansk emission sources (equal emission totals)*

6.6. Evaluation of deposition of total PCB mixture to the Russian North

The aim of this section is to give a rough estimate of total deposition of the whole PCB mixture to five regions-receptors of the Russian North and to the Arctic as a whole. To do that the fractions of four selected congeners (PCB-28, 118, 153 and 180) in total 1996 emissions of 22 congeners included in the emission inventory by [*Breivik et al.,* 2002] from different source groups were calculated in accordance with the cited work (Table 6.6).

Table 6.6. *Relative contributions (%) of selected four congeners to total emission of 22 PCB congeners for different source groups (according to [Breivik et al., 2002])*

Source group	PCB-28	PCB-118	PCB-153	PCB-180
Russia	13.8	4.5	1.1	0.2
America	11.2	2.9	2.1	0.8
North-Western Europe	11.0	2.9	4.1	1.2
South-Eastern Europe	12.6	3.4	2.6	0.7
Africa and Central Asia	12.3	3.4	2.6	0.7
South-Eastern Asia	10.5	3.9	2.6	0.7

Using these data four estimates of total deposition of the mixture of 22 PCB congeners to regions-receptors and to the Arctic were performed under the assumption that all PCB emissions consists totally of one of the four considered congeners (PCB-28, PCB-118, PCB-153 or PCB-180). The results of evaluation are summarized in Table 6.7.

Table 6.7. *Annual deposition of the mixture of 22 PCB congeners to five regions-receptors and to the Arctic estimated on the basis of physical-chemical properties of four selected congeners*

Regions-receptors	Deposition of mixture of 22 PCB congeners (tonnes) evaluated via properties of				Range (%)
	PCB-28	PCB-118	PCB-153	PCB-180	
Murmansk Oblast	0.78	0.84	0.82	0.84	7
Nenets AO	0.90	0.82	0.80	0.66	38
Yamalo-Nenets AO and Taimyr AO	2.3	2.4	2.6	2.6	14
Republic of Sakha	1.8	2.2	2.6	2.6	46
Chukotka AO	0.19	0.30	0.38	0.39	109
Arctic region	19.7	19.1	23.0	22.2	20

Clearly, such estimates disregard differences of physical-chemical properties of different PCB congeners assigning properties of one of the congeners to the whole mixture. This leads to essential differences in obtained estimates, which can reach factor 2 in some regions of the Russian North (Chukotka AO). For the Arctic as a whole the range of the obtained estimates is about 20%.

Relatively small difference between estimates obtained by properties of different congeners can be explained by the fact that at high content of light congeners in the Arctic air, their deposition velocities are essentially lower than for heavy congeners. The combined effect of these two opposite-directed factors leads to close values of depositions evaluated on the basis of properties of different congeners. These considerations show that averages of deposition values calculated with the help of properties of four selected congeners can serve as an estimate of depositions of the mixture of 22 PCB congeners to different regions-receptors within a factor of two.

The evaluation of total depositions of 22 PCB congeners to regions-receptors can be done in different ways. First, one can assume that all emissions of 22 PCB congeners are distributed between four considered congeners in equal fractions (25% scenario). Then the estimate of total deposition will be arithmetical mean of estimates obtained by properties of each four congeners. Further, one can assume that all emissions of 22 PCBs are distributed between four congeners according to their fractions in total emissions (4 congener scenario). Finally, all emissions of 22 PCB congeners can be divided into four groups (di+trichlorinated PCBs, tetra+pentachlorinated PCBs, hexachlorinated PCBs and hepta+octachlorinated PCBs). It is supposed that these groups are transported with properties of PCB-28, 118, 153 and 180, respectively (4 group scenario). The results of all three estimates are presented in Table 6.8.

Table 6.8. *Estimated annual deposition of the mixture of 22 PCB congeners to five regions-receptors and to the Arctic, tonnes*

Regions-receptors	25% scenario	4 congener scenario	4 group scenario
Murmansk Oblast	0.82	0.79	0.80
Nenets AO	0.80	0.87	0.87
Yamalo-Nenets AO and Taimyr AO	2.5	2.36	2.37
Republic of Sakha	2.3	2.01	1.99
Chukotka AO	0.31	0.24	0.23
Arctic region	21.0	20.1	20.0

All these estimates are close enough to one another.

Further, according to estimates of the work [*Breivik et al.,* 2002], the share of considered there 22 PCB congeners *in the production of total PCB mixture* amounts is about 43%. If we assume (clearly, this assumption is a very rough one) that the share of these 22 congeners *in PCB emissions* is also close to 50%, we can evaluate annual deposition of total PCB mixture to five regions-receptors and to the Arctic (Table 6.9). These values are obtained using 4 group scenario from Table 6.8. The obtained estimate of total PCB deposition to the Arctic (40 tonnes) agrees well with the estimate by R.W. Macdonald with co-authors [Macdonald et all., 1999] (45 tonnes).

Table 6.9. *Estimated depositions of total PCB mixture to selected regions, tonnes*

	Murmansk Oblast	Nenets AO	Yamalo-Nenets AO and Taimyr AO	Republic of Sakha	Chukotka AO	Arctic region
Annual deposition of PCB mixture	1.6	1.7	4.8	4.0	0.46	40

6.7. Concluding remarks

As a result of the model assessment of PCB pollution levels and contributions of main emission sources, the following conclusions were made:

1. Model evaluation gives spatial distribution of depositions and concentrations in air, soil, seawater and vegetation for PCB-28, 118, 153, and 180 for 1996. For model verification, air concentrations were compared with measurements. The comparison demonstrated that for all considered congeners about 95% of results are within a factor of 4.
2. Air concentrations of PCB-153 in the Russian North in 1996 vary from 0.7 to 2.6 pg/m^3, the depositions - from 0.05 to 0.21 g/km^2/y. The pollution level decreases, concurrent with the distance from main emission sources from Murmansk Oblast to Chukotka AO. The pattern for the other congeners is similar.
3. As to emissions of 1996, source-receptor analysis shows that the highest contributions to pollution of the Russian Arctic are made by Russian and North-western and South-eastern Europe emission sources. Among Russian sources for the regions of Murmansk Oblast, Yakutia and Chukotka AO, the highest contributions are made by their own local sources. For Nenets AO, and Yamalo-Nenets AO and Taimyr AO, a considerable contribution is made by the Central and Volga-Viatsky regions.
4. Seasonal variations of air contamination of the Russian North are substantial and different for each region-receptor. The influence of region-sources on receptors depends on the season and may be explained by the character of atmospheric transport.
5. Investigation of congener composition in the air of the Russian North reveals that PCB-28 dominates, followed by PCB-118, 153 and 180. For different region-receptors, the composition of the PCB mixture is slightly different. The main factor affecting the air congener composition is emissions.
6. Rough estimation of the contamination of the Russian North by the total PCB mixture has been done on the basis of four congener transport simulations taking into account the fractions of these congeners in the entire PCB mixture.

References

Baart A., J.Berdowski, J.van Jaarsveld and K.Wulffraat [1995] Calculation of atmospheric deposition of contaminants on the North Sea. TNO-MEP-R 95/138, Delft, The Netherlands.

Berg T., and Hjellbrekke A.-G. [1998]. Heavy metals and POPs within the ECE region. Supplementary data for 1989-1996. EMEP/CCC-Report 7/98, 103 p.

Berg T., and Hjellbrekke A.-G. [1999]. AMAP Datareport: Atmospheric Subprogramme. NILU, OR-16-99, 100 p.

Berg T., Hjellbrekke A.-G. and N. Ritter [1997]. Heavy metals and POPs within the ECE region. Additional data. EMEP/CCC-Report 9/97, 79 p.

Berg T., Hjellbrekke A.-G., and Skjelmoen J.E. [1996]. Heavy metals and POPs within the ECE region. EMEP/CCC-Report 8/96, 187 p.

Breivik K., A. Sweetman, J. Pacyna and K. Jones. [2002] Towards a global historical emission inventory for selected PCB congeners – a mass balance approach 2. Emissions. *The Science of the Total Environment*. In press.

Coleman P. J., Donovan B.J., Campbell G.W., Watterson J.D., Jones K.C., Lee R.G.M., Peters A.J. [1998] Results from the Toxic Organic Micropollutants (TOMPS) network: 1991 to 1997. AEAT-2167, Issue 2.

Brorström-Lundén E., E.Junedal, H.Wingfors and S.Juntto [2000] Measurements of the Atmospheric Concentrations and the Deposition Fluxes of Persistent Organic pollutants (POPs) at the Swedish West Coast and in the northern Fennoscandia.

Macdonald R.W., T.F., Bidleman, D.C.G., Muir, L.M. Jantunen and T. Harner [1999] Arctic Mass Budgets - a look at HCH, toxaphene and PCBs, Annex 14., In Modelling and Sources: A Workshop on Techniques and Associated Uncertainties in Quantifying the Origin and Long-Range Transport of Contaminants to the Arctic. AMAP Report 99:4.

Oehme M., J.Haugen and M.Schlabach [1995] Ambient air levels of persistent orgamochlorines in spring 1992 at Spitsbergen and the Norwegian mainland: comparison with 1984 result and quality control measures. *The Science of Total Environment*, v.160/161, pp.139-152.

Shatalov V. and A.Malanichev, [2000], Investigation and assessment of POP transboundary transport and accumulation in different media, Part I and II, EMEP Report 4/2000.

Shatalov V., A.Malanichev, N.Vulykh, T.Berg and S.Manø [2001] Assessment of POP transport and accumulation in the environment. EMEP Report 4/2001, Moscow.