The role of atmospheric aerosols in the pollution of the Arctic Ocean and its seas

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The contribution of atmospheric aerosols to the content of four trace elements (nickel, lead, zinc, and cadmium) in the Arctic Ocean and its seas has been evaluated. It is shown that this contribution compares well with the contribution coming from river suspension (after passing through marginal filters) of inflowing rivers. In the water of the Kara Sea, Laptev Sea, and East-Siberian Sea, the atmospheric contribution of lead and cadmium is 15–17% of the contribution from river waters, and for the whole ocean, these contributions are about the same. In waters of Chukchi Sea the content of lead and cadmium is determined to a greater extent by vertical air flows, whose contribution is several times greater than the contribution from river run-off.

Introduction

The atmosphere (along with the hydrosphere) is one of the channels through which the matter and energy are transported from midlatitudes to the Arctic. The main body of the mater influx is formed by the natural components of terrigenous or marine origin. However, in the industrial age the content of gases and aerosols of the anthropogenic origin in the Arctic atmosphere sharply increased.[1] When deposited from the atmosphere on the water and ice of the Arctic Ocean (AO) and other natural objects in the Arctic, the atmospheric aerosols (including their anthropogenic components) can affect the ecological systems of the region.

Climatic and natural peculiarities of the Arctic are of the type that many objects of the environment accumulate pollutants during many years. As a result, the anthropogenic pollution of the regional nature increases with time. Up to now, the effect of aerosol substances on the water suspension composition and bottom deposits of the Arctic Ocean was underestimated. However, in Ref. 2 it was shown that the water suspension composition of the Arctic Ocean was formed by three main sources, i.e., by river discharge, atmospheric aerosols, and melting ice. The contributions coming from these sources are quite comparable.

In places of seasonal marine ice melting, in polynias and meltwater pools where in spring the life is activated close to the water surface, the aerosols, including the anthropogenic ones, are involved in biochemical processes, being the constituents of microseaweeds, and are the first links in the food web of animals and human beings. Under conditions of rigorous cold climate of Arctic with short summer many animals and plants develop slowly and are long-lived, accumulating heavy metals and other contaminants entering the animals and plants during many years. The investigations under Arctic Monitoring Assessment Program (AMAP)[3] have shown that some types of vegetation (mosses, lichens, muchrooms), and animals (ringed seals, seals, partridges, caribou deer) in the Arctic region contain increased amounts of heavy metals. These objects are incorporated into the ration of food of animals and human beings in the Arctic and can have a negative effect on their vital activity.[1,3] As a result, even at relatively low pollution levels of atmospheric and water objects of the Arctic, the content of anthropogenic components in plants and animals, consumed as food, can be much higher.

Thus, the problem of determining the pollutant flows from the atmosphere to the underlying surface in the Arctic is an urgent task not only for geophysicists and oceanographers but also for geographers, biologists, and specialists in ecology.

Assessments of heavy metal fluxes from the atmosphere

For our assessments, we have chosen four microelements of the anthropogenic origin that are present in the Arctic atmosphere on aerosol particles of submicron size. These are heavy metals – nickel (Ni), lead (Pb), zinc (Zn), and cadmium (Cd), which are of high priority for the study[1] because of their negative impact on the environment, animals, and human beings.

Vertical fluxes of these microelements on the Arctic Ocean surface were estimated based on data[4,5] on the mean concentrations of microelements in the Arctic atmosphere during one year and their mean fallouts per unit surface in the Russian Arctic. These results were obtained by analyzing the long-term

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series of daily paths of air mass transfer and model estimates of atmospheric transfer and sedimentation on the surface of anthropogenic aerosol contaminants in the Arctic regions of Russia.

Table 1 shows the mean fluxes of microelements per year and per unit area in the Russian Arctic as compared with the same data for other regions.

The calculated amounts of the elements, which fall out per one year on the surface of Russian seas and on the entire territory of the Arctic Ocean, are given in Table 2. It should be noted that the values of the microelement fluxes on the underlying surface were obtained in Ref. 5 in such a way that they characterize only their anthropogenic part.

Note that annual fluxes for the Arctic Ocean are in a good agreement with the estimates,[6] made using two different assumptions on the amount of precipitation on the territory of the Arctic Ocean. It is interesting to note that these amounts are also close to the estimates given in Ref. 7 of the anthropogenic contribution to the annual accumulation of the same microelements in the bottom sediment on a comparatively small territory of the Gulf of Finland of the Baltic Sea.

To gain greater insight into how essential is the aerosol contribution to the water composition of the Arctic Ocean, we shall compare the aerosol contribution with that of the river run-off.

Assessment procedure of heavy metal inflows arriving with the river suspension

At present only poor data can be found in the literature on the influxes and composition of undissolved matter coming to the Arctic Ocean with the river run-offs. However, these investigations are being rapidly developed at present. The most comprehensive and reliable results have been collected and generalized in Refs. 8 and 9.

In estimating the contribution of river run-off we took into account the fact that only smaller part of river suspension came to the open sea (ocean) through the so-called marginal filter.[10,11] The transformations of river water composition in such filters occur due to a complex of physical, chemical, and biological phenomena as well as due to interactions taking place at mixing the fresh and marine water close to the river outlets. These processes lead to an efficient sedimentation of suspended particles and products of their biotransformation on the bottom territory within first tens of thousands of square kilometers close to the river outlet. According to our assessments made using the data from Ref. 9 about 11%, on the average, of the mass of each of the anthropogenic microelements considered, coming with the run-offs of the northern rivers of Russia, pass through the filter and form the water composition of the corresponding seas and the Arctic Ocean as a whole.

The content of microelements in the suspension of rivers flowing to every sea was calculated based on data from Ref. 9 on the annual mean flows of river water and on the composition of suspended mater of the river water. Since Ref. 9 presents data on the suspension composition of only some rivers, we used in our estimations for the Kara Sea the averaged values for two rivers (Ob' and Yenisei), for the Laptev Sea three rivers (Lena, Yana, and Khatanga) were taken into account and in the rest three cases six rivers (all the above-listed plus Kolyma River).

Table 1. Annual fluxes of some microelements per unit area in the Russian Arctic, and over seas in other regions, $\mu g \cdot m^{-2} \cdot year^{-1}$ ($g \cdot km^{-2} \cdot year^{-1}$)

Region	Ni	Pb	Zn	Cd	Comments
Mean estimates for the Russian Arctic (Ref. 5)	5.7	16	9.8	0.5	Anthropogenic part, 1986–1995
The Greenland Sea (Ref. 14)	65	60	–	1.5	Experimental measurements, 1995–1997
The Mediterranean Sea (Ref. 15):					
Corsica Island	430	880	4600	550	
French coast	1600	30000	100000	1600	
The Baltic Sea (Ref. 16)	–	1600	–	70	Model estimates, 1991–1995

Table 2. Annual mean fluxes of the anthropogenic microelements on the surface of Arctic Ocean and its seas, ton/year

Territory	Area (Ref. 17), 10^6 km^2	Ni	Pb	Zn	Cd
The Barents Sea	1.42	8.5	31	18.5	0.68
The Kara Sea	0.88	5.3	14	9.2	0.39
The Laptev Sea	0.66	3.6	8.2	5.1	0.23
The East-Siberian Sea	0.91	5.4	11	8.1	0.36
The Chukchi Sea	0.59	3.4	9.5	5.8	0.30
The Arctic Ocean	13.2	75	210	130	6.6

Comparison of heavy-metal fluxes coming to the Arctic Ocean and its seas from the atmosphere and rivers

In comparing the contributions of atmospheric fluxes and river run-off, we took into account that some fraction of the water area of each sea is occupied by the outlet zones (marginal filters) of rivers entering this sea. The fraction value depends on the rate of river flow, sea salinity, and other factors.[12] In this connection, it was assumed that the fractional areas of the marginal filters of rivers entering the Kara Sea, Laptev Sea, East-Siberian Sea, Chukchi Sea and the entire Arctic Ocean are 10, 10, 5, 2, and 3%, respectively. The flows of heavy metals from the atmosphere were calculated based on the remaining sea water area beyond the limits of filter zones.

Figures 1 and 2 show the ratio between the vertical (from the atmosphere) and horizontal (river run-offs) influxes of heavy metals studied for each of the above seas and for the entire ocean. It is seen from these figures that the relative contribution of aerosol to the content of lead and cadmium to the water area of all the seas and ocean as a whole is much higher than for two other elements, and the above contribution is comparable with that from river run-off. In this case it should be noted that we assessed only the anthropogenic part of microelements, contained in aerosol of the arctic atmosphere, and, hence, the anthropogenic part of flows of these elements falling out on the surface of the Arctic Ocean and its seas. Real mean flows of heavy metals falling on the surface may be much higher (due to the contributions of natural origin, which sources may be volcanoes, forest fires, sea surface, and so on). As a result, for other elements the atmospheric contributions to the sea water composition may appear to be comparable with the contribution from river run-offs.

As also follows from Figs. 1 and 2, the water composition of the Chukchi Sea are formed, in great part, by atmospheric flows coming to the surface. Undoubtedly, for this region of the Arctic Ocean it is necessary to take into account the contribution of the matter carrying by Bering Sea flows from the Pacific Ocean. In this connection of great interest in the analysis of water composition and bottom sediments of the Chukchi Sea as compared with the other northern seas of Russia.

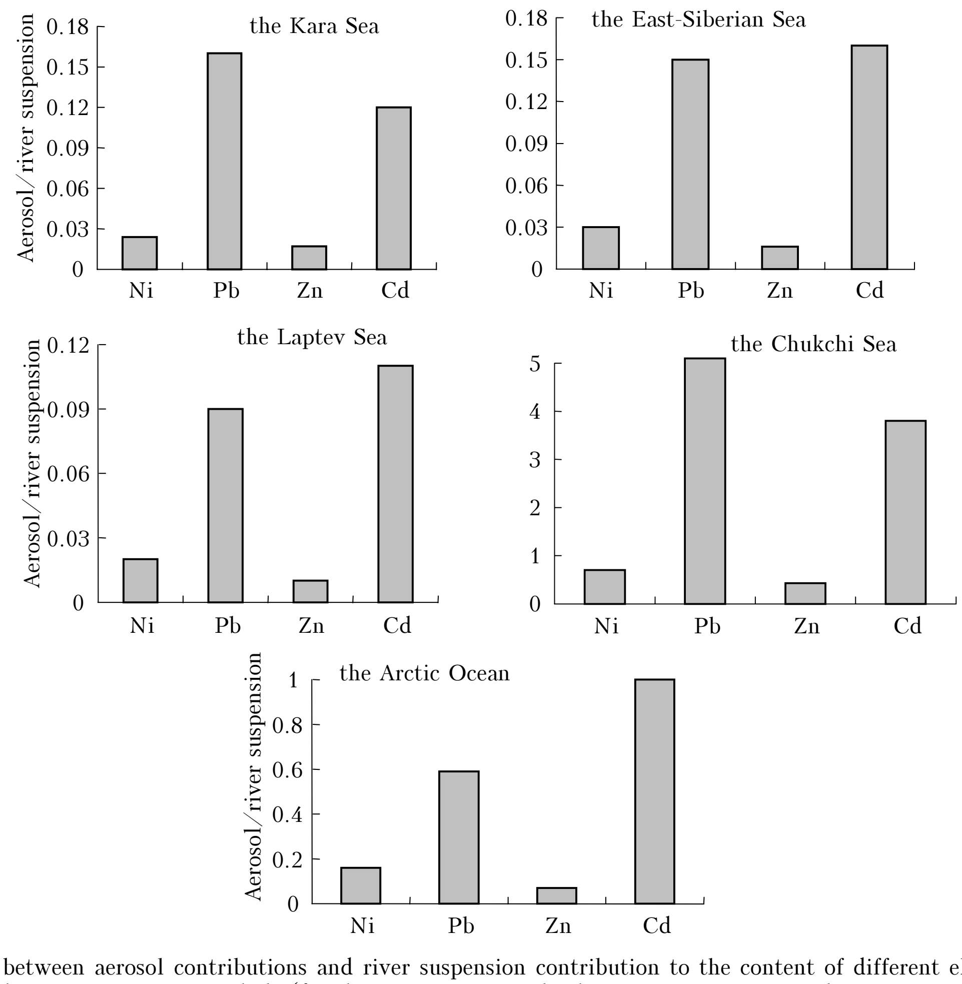

Fig. 1. The ratio between aerosol contributions and river suspension contribution to the content of different elements in the sea water and in the Arctic Ocean as a whole (for the Arctic Ocean only the Eurasian rivers are taken into account).

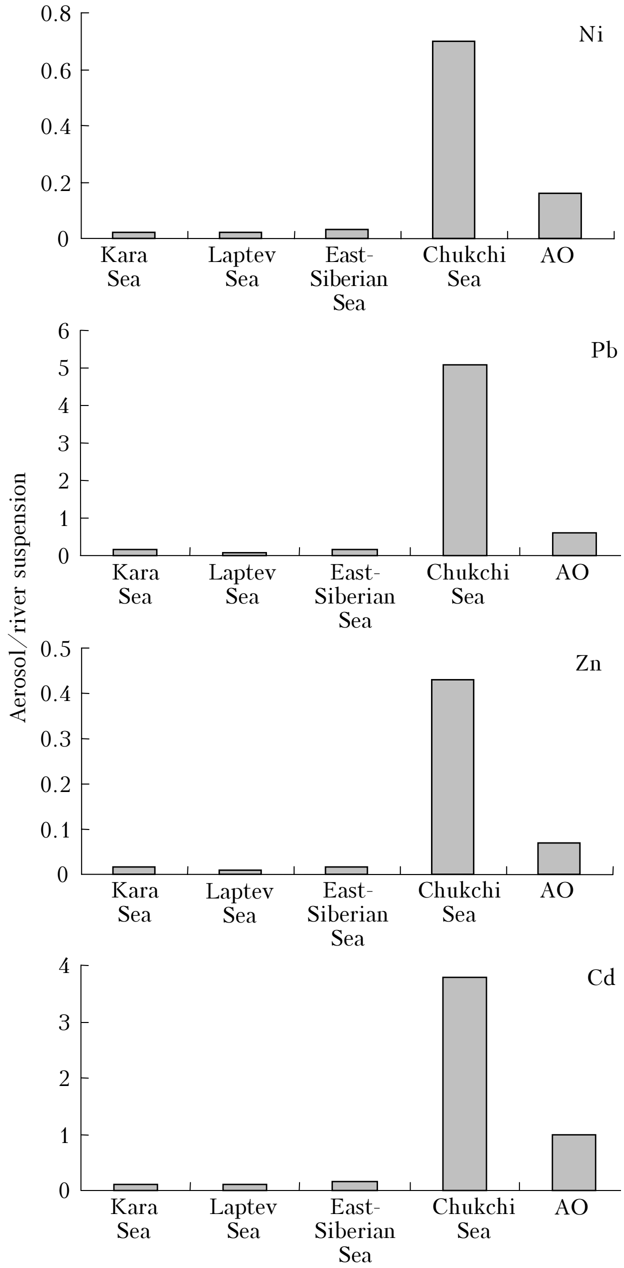

Fig. 2. The ratio between the contributions of aerosol and river suspension to the content of each element in the water of different seas and the entire Arctic Ocean (for the Arctic Ocean only the Eurasian rivers are taken into account).

It should be noted that we did not compare the contributions of atmospheric aerosols and rivers flowing into the Barents Sea. The reason is that the rivers with small volume of discharge affect its water composition to a lesser degree than the Chukchi Sea water area.[9] But the contribution of Atlantic Currents (and, primarily the Gulf Stream) to the formation of water composition of the Barents Sea can be governing factor. Unfortunately, we did not manage to find the quantitative data on the composition of water of the Atlantic Ocean flowing into the Barents Sea.

It is well to bear in mind that different elements are to be found in water in different chemical compounds and, as a result, the elements enter not only into the composition of suspension but also in the solution. Consequently, a comparison of the aerosol contribution with the river effluent gives an incomplete and sometimes improper idea about the relationship of the contributions of the atmosphere and rivers to the sea water composition. As an example we consider Fig. 3. It is evident that the substances containing nickel are largely dissolved in water whereas the lead practically the entire is contained in the suspension.

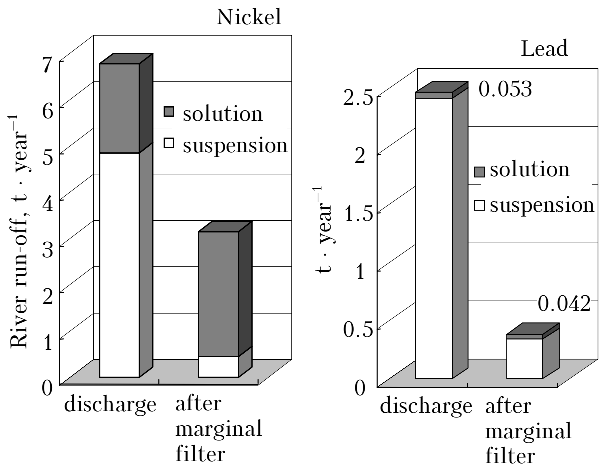

Fig. 3. The content of nickel and lead in a dissolved form and in suspension before and after the marginal filters of the Eurasian rivers flowing to the Arctic Ocean (based on data from Ref. 9).

Passing through the marginal filters the major part (up to 85–97%) of river suspension is deposited and thus taken out from the composition of sea water whereas in the solute form the content of specific microelement varied not so strong and can not only decrease (lead) but even increase (nickel). Therefore, for elements contained mainly in the river suspension (this is not only lead but also zinc and cadmium[9]), general regularities taken from Figs. 1 and 2 in the beginning of this section can be qualitatively extended to the ratios of contributions to the water composition of seas and the Arctic Ocean due to atmospheric aerosol and rivers as a whole. However, for nickel this is not the case: the ratios given in Figs. 1 and 2 for nickel relate only to the contributions from atmospheric aerosol and undissolved matter of river water.

Aerosol impact on the surface of the Arctic Ocean

Figure 4 shows how the flow of heavy metals from the atmosphere to the surface in different regions of the Russian Arctic is formed during one year.

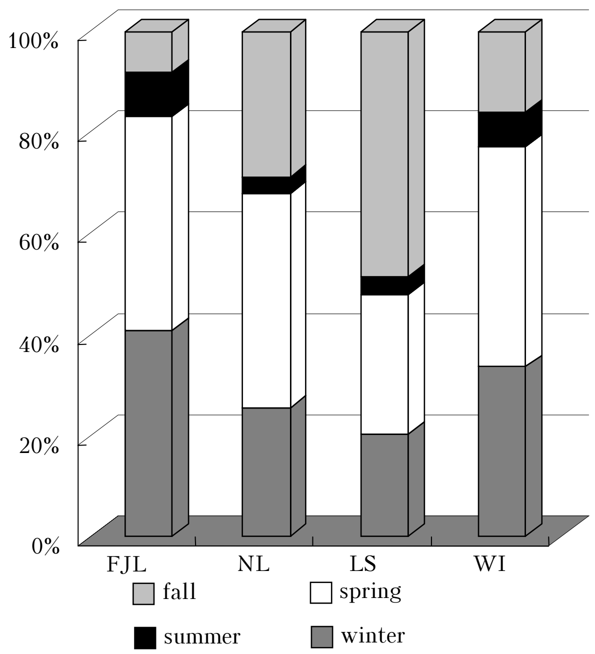

Fig. 4. The formation of microelement flux from the atmosphere to the surface during four seasons (3 months each) in the region of the Franz Josef Land (FJL), the Northern Land (NL), the Laptev Sea (LS), and the Wrangel Island (WI).

The amount of deposited matter is determined by seasonal variations of its content in the atmosphere and by the amount of precipitation. It is evident that the maximum precipitation occur in winter and in spring when the heavy metal concentrations are large in the arctic atmosphere, and in the regions far removed from the Atlantic and Pacific oceans, even during the fall when after summer the content of impurities in the atmosphere is increased and precipitation rate also grows. Thus the effect of atmospheric aerosols and atmospheric contaminants on the Arctic environment is concerned, it is necessary to take into account that the most part of this material falls on the ice and not on the water surface of the Arctic Ocean and its seas.

Having redistributed in the ice thickness as a result of melting of the snow and ice, anthropogenic aerosols are accumulated in the pack ice and spread within the limits of the entire ocean at circumpolar ice wandering from the Russian shore to the Trahin channel.[12] There melting of ice occurs and the ice releases impurities into the water of the northern part of the Atlantic Ocean. The period of such a cycle is from 2 to 15 years, during which the pack ice accumulates and redistributes the anthropogenic pollutants in the Arctic region.

Finally, upon entering the waters of the Arctic Ocean, the atmospheric aerosol is involved in the formation of their composition and, to a certain degree, the composition of bottom sediments. Processes proceeding with the suspension since its entering the sea water until binding in bottom sediments, are very diverse – from biochemical transformation by plankton and benthos to the mechanical sedimentation of products of this conversion and the suspension particles themselves.[10,11] The process of sedimentation is also affected by the streams, sea disturbance (for off-shore zones), depth, bottom relief, and many other climatic and geographic factors.[13] As a result, the rate of sedimentation and the quality of bottom sediments in different parts of the Arctic Ocean and in its seas can strongly differ. Accordingly, the impacts of sedimentation of aerosol pollutants from the atmosphere onto the surface in different parts of the Arctic Ocean are found to be different.

Conclusions

The atmosphere is one of the channels through which the matter, including that of anthropogenic origin, comes to waters of the Arctic Ocean. The role of atmospheric aerosols in the pollution of the Arctic environment is of great variety. Falling to the underlying surface, the anthropogenic aerosol components, in particular, heavy metals become part of sea water, vegetation, soils, and animals affecting different ecological systems of the region.

The contribution of atmospheric aerosols to the water composition of the Arctic Ocean and its seas can be compared with the contribution of river suspension (after passing through the marginal filters), especially for such anthropogenic microelements as lead and cadmium.

In the water of the Kara Sea, Laptev Sea, and East-Siberian Sea the atmospheric contribution of these elements is about 15–17% of the contribution coming from the river run-offs and for the entire ocean these contributions are almost the same. In Chukchi Sea water the content of lead and cadmium is determined, to a great extent, by the air vertical flows, which contribution is several times higher than that from the river run-offs. The variety and the importance of physical processes, chemical and biological transformations, in which aerosols were involved falling on the surface of the Arctic Ocean, call for further thorough studies of these phenomena.

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