The influence of Norilsk and Ural industry on the environment of different Siberian regions

A.A. Vinogradova, L.O. Maksimenkov, and F.A. Pogarskii

A.M. Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences, Moscow

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Atmospheric transport of heavy metals (Ni, Cu, Pb) over Siberia from two large industrial areas (Norilsk and Ural) is under consideration. The 5-day trajectories of air mass transport for each day of January, April, July, and October, 1981–2000, are analyzed. The model HYSPLIT 4 with reanalysis database NOAA (NCEP/NCAR Reanalysis Data Files) has been applied. The seasonal and long-term variations in average concentrations of anthropogenic heavy metals (from the above sources) in air and precipitations are estimated along with average fluxes of pollutants onto the surface for different regions of Siberia. The obtained results are in agreement with the published data measured at background regions. Long-range atmospheric transport contributes only a negligible portion of pollutants to the environment of the Baikal region as compared with local industrial sources.

Introduction

Model estimations of atmospheric transport of stable anthropogenic ecotoxins is one of the most important aspects in studies of environment. Spatial distribution of pollutants from their sources and their concentration on the underlying surface through the atmospheric channel have a pronounced effect on the natural objects (soils, rivers and other water reservoirs, plants etc.), as well as – via food chains – on animals and humans. Atmospheric transport can cover distances up to 10 thousands of kilometers.[1]

To estimate such mesoscale influence, the information on the emission composition and the potential of their sources is needed. These data, quite limited in number, became available only in recent years.[2,3] Information on elimination of impurities from the atmosphere along the way of their propagation is needed as well. These data are determined from indirect assessments and significantly vary in different climatic zones.[4–6] The extension of the pollution sources and the variety of atmospheric circulation conditions, forming air fluxes of pollutants, cause particular methodical difficulties for investigations. Therefore, calculations with high spatial and time resolution are very laborious and time-consuming.[5,6]

The assumption on a small size of the sources in comparison with the propagation distance and the analysis of long-term (10 years or more) data on the transport of air masses allows one to solve the problem of estimation of mean anthropogenic influences on remote areas via the atmosphere, basing on the methods proposed in Ref. 7. We used this method to estimate the mean concentration of anthropogenic microelements in the atmosphere and their fluxes onto the surface of Russian polar islands (using the analysis of air transport back trajectories),[8] as well as the fluxes to the areas of Russian arctic seas (from the analysis of air transport direct trajectories).[9]

There are several large industrial regions in Russia (Ural, Norilsk region, Kola Peninsula, etc.), which are pollution sources at a global scale and which atmospheric emissions are carried away with air fluxes for long distances. In particular, their "breath" can be felt over Russian arctic seas, in Central Arctic, and even over northern territories of America.[1,10,11] As for Siberia, the most significant sources of anthropogenic pollution here are Norilsk and Ural due to predominance of winds with the western component.

This article is devoted to studies of heavy metals (HM) propagation in the atmosphere from Ural and Norilsk, as well as to the concentration of these impurities on the underlying surface of different Siberian regions. The approach used is based on statistical processing of a big body of information on air transport trajectories. We estimate long-term mean contribution of industrial region-sources to heavy metal pollution of air, precipitation, and surface nature objects, as well as variations of this contribution for the last 20 years of the 20th century.

Initial data and estimation method

Estimations of 5-day trajectories of air mass transport for each day of January, April, July, and October, 1981–2000, became the initial material for studies of the pollution distribution. The sources have the following conventional coordinates: Norilsk

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69°N and 88°E.; Ural was set by two points due to its extension: 53°N and 58°E, as well as 57°N and 61°E. The trajectories were calculated at 925 and 850 hPa isobaric surfaces (start at 00 GMT, a calculation interval of 1 hour), using the HYSPLIT 4 model and the NOAA database (reanalysis of meteorological characteristics fields) (NCEP/NCAR Reanalysis Data Files).[12] Spatial distribution of the trajectory number density and impurity from each source in air was mapped with (1°×1°) grid for every month of 10 years, individually for the 80s and the 90s. The distributions for Ural obtained from two point-sources were averaged in each cell. Effects of these sources were considered as independent and their total influence was estimated through summation in each cell.

The following mean characteristics of environmental pollution were studied: HM concentrations in surface air and in precipitations, HM fluxes onto the underlying surface. The maps of impurities spatial distribution allowed us to estimate these characteristics for any season, as well as for a whole year in any point of West and East Siberia. Considering these months as representative for each season, we estimated seasonal variations of the pollution characteristics, while annual-average and total indices were calculated in assumption of equal length of seasons. Long-term trends in variations of the characteristics were estimated from the comparison of results for the 80s and 90s.

We chose three metals for estimation: lead, nickel, and copper (Pb, Ni, Cu), because they characterize three different emission combinations from the studied sources (Table 1).

Table 1. HM emission in the atmosphere from the sources during the last 20 years of the 20th century

Source	Emission HM, t/year			Years
	Pb	Ni	Cu	
Ural	2000	90	4500	1980s
	1200	30	2000	1990s
Norilsk	100	3000	3500	1980s
	40	1400	2000	1990s

Due to industrial specificity of industry of the analyzed sites, Ural plants emit mainly the lead, while nickel is emitted in the Norilsk region. As for the copper, it is emitted equally by both sources. Table 1 shows annual-average (for ten years) values of lead, copper and nickel emissions, received from the analysis of data for Ural (Sverdlovsk Region and Chelyabinsk) and Norilsk. These data were obtained from Refs. 2 and 3 and similar issues for 1996–2001. It is seen that the emission of these metals in the 90s is two times lower as compared to the 80s.

The method of impurity distribution estimation, in the cases when the mixture is transported in the atmosphere, was similar to that described in Refs. 5, 6, and 8. It was considered that 20% of impurities precipitate near the emission source and other 80% are involved in the process of long-range transport. Vertically, the impurity is distributed uniformly within surface mixing layer, the height of which is determined by the height of surface inversion temperature layer (or the height of low level of raised inversion). In our calculations this height is equal to 1 km. With the increase of the distance from the source the process of impurity exponential decrease in the air flux develops due to impurity precipitation onto the surface with the corresponding rate. Since in the process of long-range transport all the analyzed chemical elements are mainly transported by the aerosol particles of submicron size,[5] the rate of their precipitation onto the underlying surface is considered to be stable along the whole distance from the source. However, all seasonal and spatial variations of impurity precipitation rates should be taken into account.

Since the territory of Siberia includes several climatic zones, in our study we divided it into large (climatic) areas[13,14] (Fig. 1), for calculation of which we used different parameters of aerosol precipitation (Table 2).

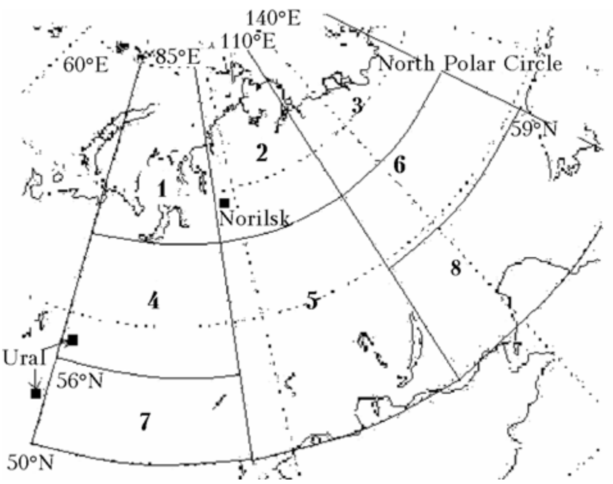

Fig. 1. A conventional division of Siberian territory into 8 climatic areas. The borders (solid lines) correspond to parallels, meridians and the Polar Circle. Black squares are pollution sources.

The values of submicron aerosol dry deposition rate over different underlying surfaces were preset based on data from Refs. 5, 6, 15, and 16, and the values of precipitation rate were calculated from long-term data on the quantity and the aggregative state of precipitations over Siberia[13] with different coefficients of the impurity capture by precipitations (rain, snow). Mean values (used in our calculations) of the characteristics, determining the impurity precipitation on the surface and the portion of impurity, settled with precipitations, for different sites and in seasons, are presented in Table 2.

Table 2. The characteristics defining the HM precipitation from the atmosphere onto the underlying surface in different seasons at separated sites of Siberia (Fig. 1)

Month	Site number							
	1	2	3	4	5	6	7	8
	Precipitation quantity, mm/month							
January	15	15	15	20	15	10	10	5
April	20	15	20	25	20	20	15	10
July	70	50	50	80	80	80	60	100
October	60	30	30	60	50	50	30	20
	Precipitation rate, cm/s							
January	0.10	0.09	0.09	0.14	0.15	0.13	0.14	0.11
April	0.16	0.12	0.12	0.26	0.39	0.38	0.34	0.27
July	0.96	0.73	0.73	1.74	1.74	1.10	1.32	1.34
October	0.36	0.17	0.18	0.84	0.72	0.70	0.70	0.37
	The portion of impurity settled with precipitations, %							
January	18	7	7	16	19	15	28	9
April	24	15	19	38	59	61	51	44
July	84	79	79	89	89	84	88	87
October	64	34	33	82	81	83	83	62

The results of model estimations

The process of atmospheric circulation over the northern part of Eurasia noticeably changed during the last 20 years of the 20th century. In the framework of our task, this means that provided the trivial regularity of decreasing air pollution with the distance from the source holds, changes in impurity distribution were not uniform over Siberia and alternated at individual sites in different months. Besides, the emission from the sources decreased in that period (see Table 1). Let us consider how these variations in average anthropogenic loads influence nature object of different sites.

The comparison between the influence of atmospheric circulation change on pollution of different sites of Siberia caused by the analyzed sources and the effect of emission reduction is shown in Fig. 2. The estimates were made using the values of annual flux density of the impurity brought from each source onto the surface. It is seen that in the 90s, as compared to the previous decade, the pollution decreased almost on the whole territory under study. On the greater part of Central Siberia this occurred not only due to the reduced emission from the sources, but also due to changes in atmospheric processes. In the regions, being more remote from the sources, the environment pollution attenuation from Ural and Norilsk is not significant, because it is partially (in some sites even totally) compensated by changes in processes of the atmospheric circulation.

It is evident that spatial and seasonal variations of the calculated characteristics of the environmental pollution from two industrial regions are rather significant at different Siberian sites.

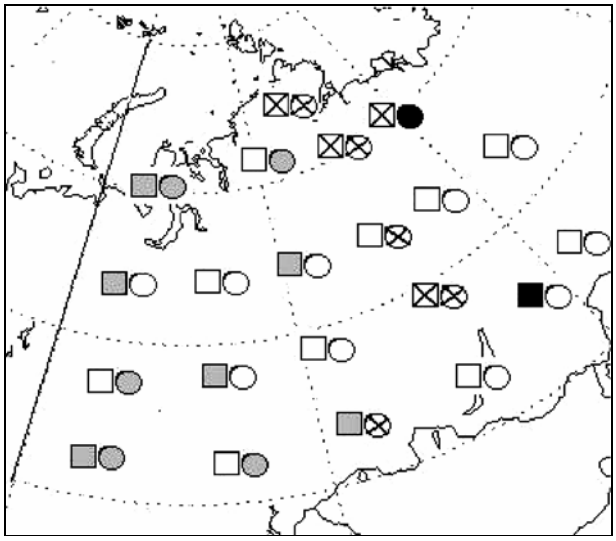

Fig. 2. The effect of atmospheric circulation change (in the 90s as compared to the 80s) on the pollution of different Siberian sites by Norilsk (squares) and Ural (circles) in comparison with the effect of the emission reduction: white signs denote the absence of the influence, grey ones – additional reducing, crossed ones – increasing without compensation of the emission effect, black ones – compensation of the emission reduction.

Table 3 shows mean (for 1990s) concentrations of Pb, Ni, and Cu in the ground air in different months for 12 background (not urban) regions close to or at the area of different geographical objects.

According to the data of Tables 2 and 3 we can estimate mean HM flows onto the surface and their content in precipitations for these sites (they are not presented for brevity sake). Seasonal trend of the considered pollution indices is formed for each site as a result of individual combination of atmospheric

Table 3. Mean concentrations (for 1990s) of lead, nickel, and copper in the ground air of background regions close to or at the area of different geographical objects of Siberia in different months, ng/m^3

Site	Pb				Ni				Cu			
	Month											
	I	IV	VII	X	I	IV	VII	X	I	IV	VII	X
Tiksi	0.04	0.02	0.01	0.12	1.36	0.68	0.20	1.36	2.2	1.1	0.3	2.3
Yamal Peninsula	0.81	0.27	0.04	0.40	2.59	8.58	0.86	3.44	4.9	12.3	1.3	5.4
Norilsk	1.28	0.83	0.50	1.03	34.33	25.75	17.16	25.75	49.5	36.9	24.5	37.3
Taimyr Peninsula	0.39	0.30	0.03	0.39	10.46	10.46	1.05	10.46	15.1	14.9	1.5	15.1
Hanty-Mansiysk	1.57	0.96	0.82	0.84	0.19	0.61	0.31	0.75	2.8	2.4	1.8	2.4
Tura	0.63	0.48	0.02	0.67	4.40	5.86	0.73	5.86	7.1	8.9	1.0	9.2
Sverdlovsk Region	15.72	9.46	3.41	11.27	0.39	1.09	0.15	0.53	26.2	16.9	5.8	19.1
Tomsk Region	3.15	1.85	0.64	3.69	0.20	0.53	0.26	0.70	5.4	3.8	1.4	7.0
Omsk	6.73	5.39	4.49	8.97	0.17	0.24	0.11	0.22	11.2	9.1	7.5	15.0
Barnaul	1.57	1.57	0.45	2.69	0.04	0.20	0.06	0.17	2.6	2.8	0.8	4.6
Lake Baikal	0.18	0.07	0.00	0.28	0.03	0.73	0.00	0.53	0.3	1.1	0.0	1.2
Yakutsk	0.05	0.01	0.00	0.09	0.67	0.27	0.00	0.67	1.0	0.4	0.0	1.1

transport factors and parameters of impurity precipitation. The summer minimum of impurity atmospheric concentration in all sites is connected with the conditions favorable for atmospheric refinement (great rainfall and high rates of impurity settling, see Table 2). In spring and autumn, maxima of the impurity flux onto the surface and their content in precipitations are often formed due to great amount of precipitations (most often liquid) and quite high impurity content in the air in this period (at precipitation rates lower than maximum).

Annual-average HM fluxes onto the surface of the analyzed Siberian sites are shown in Fig. 3.

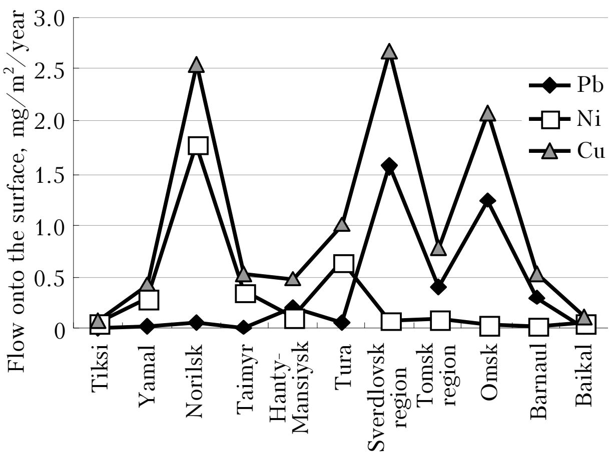

Fig. 3. Mean annual HM flow from the atmosphere onto the surface in different background sites of Siberia near the indicated objects.

These data allow estimation of the contribution of the atmospheric channel (only from two sources) to environmental pollution of some site, as well as a qualitative comparison of roles of the analyzed elements in this pollution (taking into account the fact that copper emission from both sources is identical in the 90s, see Table 1). It is evident that the areas closest to the sources are more polluted. In the most eastern sites (Baikal) the effect of Norilsk is higher than of Ural (Fig. 4).

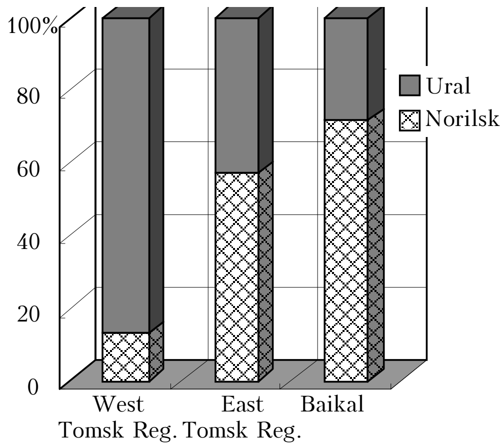

Fig. 4. The change in share of the sources in surface pollution in the 90s when moving from the West to the East (by copper fluxes onto the surface from each source with identical emission).

Comparison with measurements

Unfortunately, measurements of atmospheric aerosol composition (and elemental composition) or the HM content in different surface nature objects were conducted irregularly and only at several sites of the great area of Siberia (mostly in towns and their surroundings).[17] Therefore, the materials for comparison of our results are very scarce and episodic from the point of view of 10-year averaging. The presented comparison results are our rough model estimations, not claiming to be verified.

The comparison between our HM concentration estimates near Norilsk and measurements from Ref. 18 shows their good agreement (Fig. 5). We use maximal and minimal HM concentrations measured in urban conditions off industrial smoke trails and near cities.

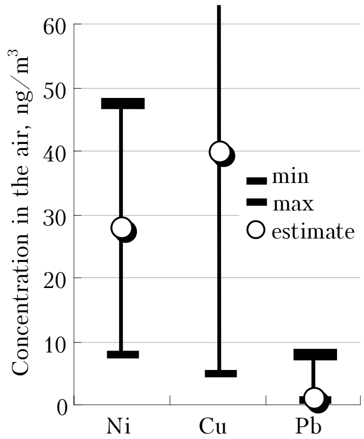

Fig. 5. The comparison of our HM concentration estimates in spring near Norilsk with experimental data (maximal and minimal values are taken from Ref. 18).

The appearance of our estimates in such a wide value range indicates only the agreement in the orders of magnitude. The data of Table 4 show a more accurate agreement of our estimates with experimental values.

Table 4. HM concentrations in ground air of Siberian sites in 1990s according to our estimates and the data of other researchers

Site	Season, year	Concentration in air, ng/m^3			Reference
		Pb	Ni	Cu	
North of West Siberia	winter, 1999	–	10	–	19
	summer, 1999	–	2	4	
	winter, 90s	–	5.6	–	this work
	summer, 90s	–	2.1	3.3	this work
Mondy station, Baikal region	1990–1997	0.2	–	0.3	20
	1991–1999	0.13	–	0.66	this work

Here we have HM atmospheric concentrations obtained from measurements in background sites in the north of West Siberia[19] and at the background Mondy station in the Baikal region.[20] It is clear that our estimates give a more adequate description of the HM pollution of the surface air at the background areas located far from local and regional industrial centers.

Underline that the analyzed sources (Ural and Norilsk) for Baikal region define only background pollution levels. The actual level of environment pollution is formed by the local sources,[20] the contribution of which exceeds the contribution of long-term transport by the order of magnitude. As for the pollution of Baikal water, the long-term atmospheric transport supplies less than 3% of total annual pollution with HM, the remainder is supplied by the water of the falling rivers.[17]

The comparison of the mean HM fluxes onto the underlying surface with the content of the same metals in soils in southern sites of Central Siberia is shown in Fig. 6.

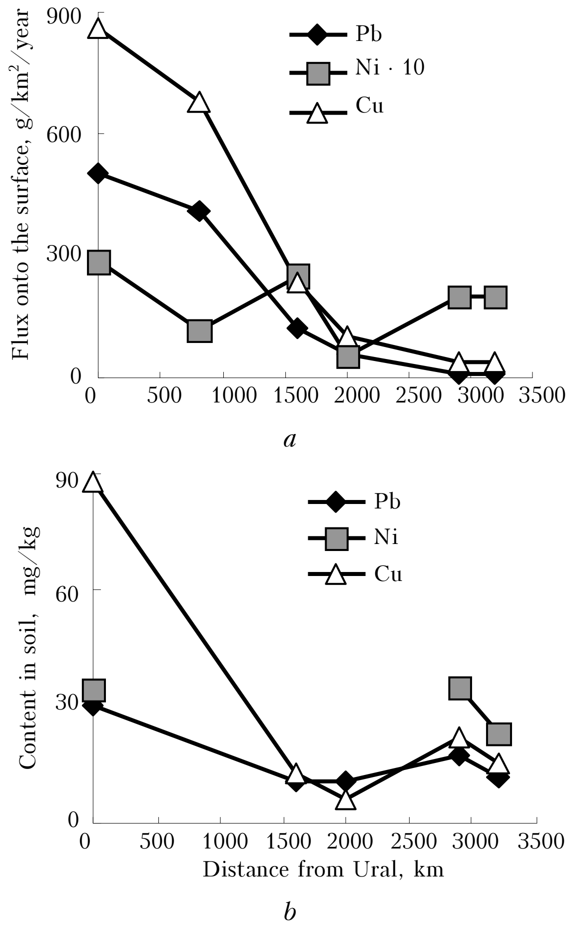

Fig. 6. The comparison of Pb, Ni, Cu fluxes from the atmosphere onto the underlying surface (*a*) with the content of these very metals in soils (*b*)[17,21] at several sites of the southern part of Siberia and Ural: Sverdlovsk, Omsk, and Tomsk Regions, Novokuznetsk, Irkutsk, and Baikal.

Note that Central Siberia is a region with developed industry, characterized by an increased level of atmospheric pollution in cities.[17,21] The HM content in soils (Fig. 6*b*) situated not very far from Ural (up to 2000 km) is roughly proportional to average HM fluxes from the atmosphere onto the surface (Fig. 6*a*). As for the greater distances, the emissions from Ural hardly influence HM content in soils and apparently the pollution is mainly conditioned by the closest industrial centers (Novokuznetsk, Irkutsk, etc.)

It is interesting to compare the estimates of mean HM fluxes from the atmosphere onto the surface with our results according to the content of these elements in peat samples from the Bakchar bog located in the north-western part of the Tomsk Region.[22] Peat is a well preserved depository medium, the composition of which is formed during a long period of time and is the result of natural time averaging. However, we should note that HM migration between natural media is a very complicated process with chemical interactions and transformations playing an important role. Therefore, we compare only ratios of fluxes onto the surface in the 90s and the 80s for each metal. Our estimates are the following: Pb (0.7), Ni (0.4), and Cu (0.5); the estimations of authors of Ref. 22 are: Pb (0.7), Ni (0.7), and Cu (1.3). Thus, the results qualitatively coincide for lead and nickel. As for the copper, the estimates do not coincide even qualitatively. This can be due to different reasons, which discussion is beyond the scope of this work.

Conclusion

We received quantitative estimates of mean concentrations of three heavy metals (Pb, Ni, Cu) brought in the atmosphere from two large industrial regions (Norilsk and Ural) in surface air of different Siberian sites and in different seasons in the end of the 20th century. We also determined the parameter values, which determine the elimination of these impurities from the atmosphere. These parameters allow us to estimate mean content of these metals in precipitations and their mean fluxes onto the underlying surface.

In the 90s the pollution of Siberian natural objects by Ural and Norilsk plants decreased as compared to the 80s. Long-term pollution of natural environment in different Siberian sites under the influence of changes in the atmospheric circulation processes is well comparable with the effect of reduction of emissions in the end of the 20th century. The cumulative effect is different for different places, seasons and impurities.

The content of anthropogenic impurities in air and in precipitations in the Baikal region is almost completely determined by the emission of local and regional sources. As for the lake waters, this content is determined by the pollution of the falling rivers. During a year long-range atmospheric transport of the emissions from Norilsk and Ural regions supplies a copper flux onto the lake surface, which is less than several percent from the flux brought with river waters.

The received quantitative estimates of mean HM distribution from two large industrial regions in air over Siberian territory most adequately describe the actual atmospheric concentrations of these elements at background (far from industrial centers) sites. These results can be used for estimation of anthropogenic influence on nature objects in regions difficult to access.

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