Cleaning of the Arctic atmosphere by air transport of pollutants into the midlatitudes

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The spatial distribution of the Arctic air in the midlatitudes has been statistically analyzed. The effect of air transport on cleaning the Arctic atmosphere has been estimated in comparison with the traditionally considered cleaning of the atmosphere by deposition of pollutants onto the surface. The 10-year series of 8-day forward trajectories of air mass transport from three Arctic sites – Franz Josef Land, Severnaya Zemlya, and Wrangel Island – have been studied. The trajectories have been calculated in the State Committee for Hydrology and Meteorology of the Russian Federation at the 850 hPa isobaric surface for every day of one winter month of 1986–1995. In winter, the air transport of pollutants out of the Arctic is the most efficient way of cleaning the Arctic atmosphere. Its equivalent "sedimentation rate" is higher than the dry and wet sedimentation rates for conservative pollutants transported on submicron aerosol particles. The amount of such pollutants transported during one winter month out of the Arctic as a whole is about two times larger than that deposited onto the land surface.

By now the processes of pollution of the Arctic region were studied only from the viewpoint of pollutant transport into this region, although the air transport of pollutants out of the Arctic is one of the most important mechanisms of cleaning the Arctic atmosphere and the Arctic ecosystem as a whole. In the latter case, pollutants are removed from the Arctic, whereas deposition clears the atmosphere, but pollutes other components of the environment (soil, snow, water, etc.). Experimental observations show that air masses arriving in the middle latitudes from the Arctic in winter and spring can carry large amounts of anthropogenic pollutants.[1–3] This is connected with the fact that in the cold half of a year the pollutants carried to the Arctic from industrial regions can stay in the atmosphere up to 10–15 days and mix there, as in a huge reservoir, partially leaving the Arctic region.[4]

In the last five years, analysis of large arrays of air mass trajectories[5] is widely used in solving various climatic problems connected with the distant transport of air masses and substances in the atmosphere. In particular, we studied seasonal regularities in the processes of transport of anthropogenic pollutants into the Arctic just in this way.[4,6–8] On the contrary, in this paper, we undertake an attempt to analyze statistically the frequency and range of spread of the Arctic air into the middle latitudes, as well as to estimate the efficiency of air transport of pollutants from the Arctic as one of the mechanisms of cleaning the Arctic atmosphere.

Air mass trajectories

As was shown in Refs. 4 and 7, in winter and spring the lifetime of a conservative (with respect to chemical reactions) pollutant in the Arctic air exceeds 5 days. Therefore, in this work we have analyzed 8-day forward (outgoing) isobaric (for the 850 hPa isobaric surface) trajectories of air masses from three sites in the Russian Arctic: Franz Josef Land (FJL) 81.1°N, 56.3°E, Severnaya Zemlya (SZ) 79.5°N, 95.4°E, and Wrangel Island (WI) 71.0°N, 178.5°W. The trajectories have been calculated in the State Committee for Hydrology and Meteorology of the Russian Federation for 00:00 GMT with the interval of 6 h for every day of one winter month (since January 11 until February 10) since 1986 until 1995. Thus, the array for each site involved 310 trajectories.

Air mass transport out of 70°N circle

Analysis of the considered trajectories has shown that a significant part of the trajectories – from 50% for the Siberian sector of the Arctic to 60–70% for the North Atlantic and Pacific sectors goes out of the Arctic (in our studies, beyond the 70°N) circle within 8 days, thus determining the direction of transport of the Arctic air mass from the observation sites to the middle latitudes.

Figure 1 shows the distribution of Arctic airflows crossing the 70°N latitude circle. The magnitude of the meridional component of the wind velocity in the case that it is directed to the south (negative values) at the 70°N latitude is also given in the figure. These values have been calculated in Ref. 9 for January from the 30-year long series of meteorological data for the tropospheric layer of 0 to 6 km. It is seen that some of the flows from the Arctic into the middle latitudes are close to the mean Eurasian and Canadian ones. However, the presence of the maximum in the frequency of air outflow from Arctic near 180°E, and not only from Wrangel Island, but also from Severnaya Zemlya, is indicative of powerful meridional air exchange in the lower tropospheric layer (below 1.5 km) in winter at the

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boundary of the Pacific sector of the Arctic. This is also valid, to a lesser degree, for the North Atlantic sector.

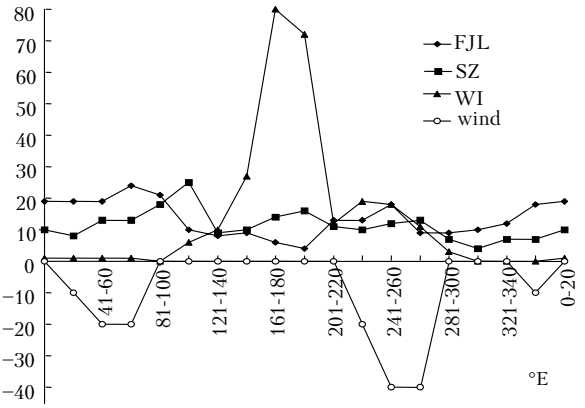
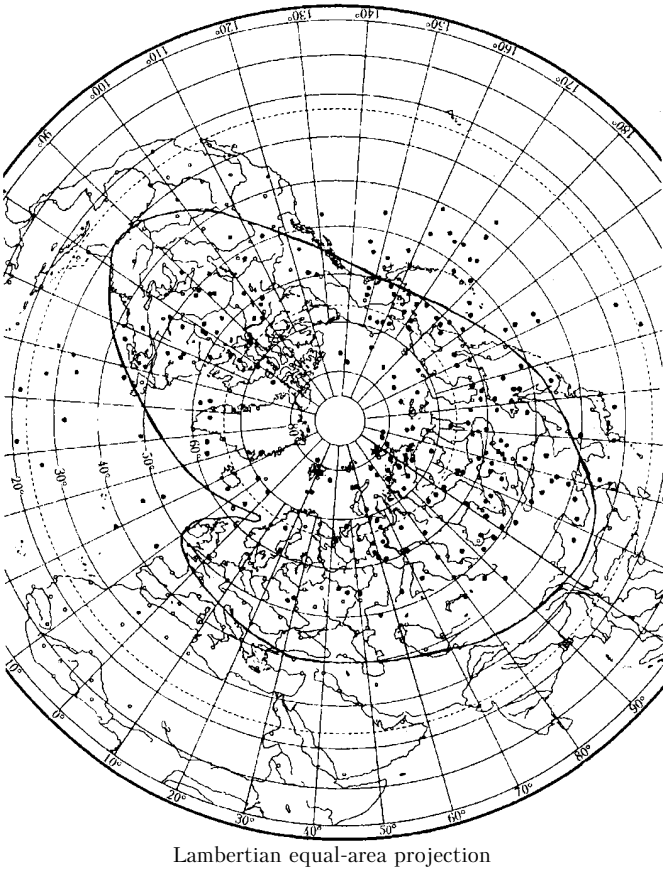


Fig. 1. Frequencies of crossing the 70°N parallel by trajectories starting from the observational sites FJL, SZ, and WI (number of days per month for 10 years). The negative values correspond to the cases that the mean meridional component of the wind velocity at 70°N is directed to the south[9] ($\times -10$ m $\cdot$ s^{-1}).

The considered trajectories cross the 70°N parallel, on the average, within 3 to 5 days after leaving the observational sites. In the cold season, 70–90% pollutants contained in the atmosphere remain in the air for this time [winter values of the sedimentation rate for submicron particles containing anthropogenic microelements were chosen in the range of 0.05–0.07 cm $\cdot$ s^{-1} (Ref. 7)].

How far can the Arctic air move to the south? As an example, Fig. 2 shows the location of the most southern points of all trajectories going from Severnaya Zemlya, whereas Fig. 3 and Table 1 characterize numerically the distributions of the southern points of the trajectories over latitude belts for all the three considered sites. As is seen from Fig. 2, the majority of southern points is located inside the curve showing the mean January position of the Arctic front. Therefore, the Arctic air reaching 50°N and 40°N latitudes in 6–7 days can retain its physical properties, such as low humidity, low temperature, and the inverse altitude dependence of temperature in the surface layer. The latter characteristic affects significantly the conservation of the chemical composition of aerosol (certainly, its components passive with respect to chemical reactions) transported from the Arctic to the middle latitudes.[2,3] In January the surface temperature inversion occurrence in the Arctic is, on the average, 22–25 days[10] and in the rest days the elevated inversion is observed. Under these conditions, pollutants can be transported above the inversion layer. In this case, the pollutant concentration decreases only due to the flow spreading in the horizontal direction, and vertical mixing and deposition of pollutants onto the surface are efficient only at the places of temperature inversion breakdown.



Lambertian equal-area projection

Fig. 2. Geographic location of the most southern points of all the trajectories for SZ (dots). The solid curve shows the mean position of the Arctic front in January.[1]

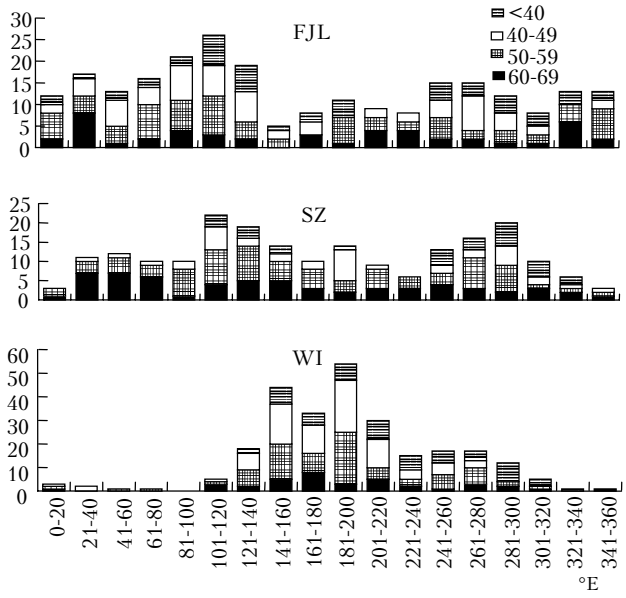


Fig. 3. Distribution of the most southern points of the trajectories going from the observation sites over latitude belts (the numbers correspond to the number of days per month for 10 years).

Table 1. Characteristics of the distribution of the farthest southern points of 8-day trajectories going from different sites in winter season

Longitude, deg	Mean time needed to reach the southern point, in days			Frequency of points falling within latitude belts, in %		
	FJL	SZ	WI	FJL	SZ	WI
60–69	6.8	6.8	5.9	15.5	20.0	11.9
50–59	6.5	6.6	5.7	25.5	25.5	25.8
40–49	7.2	7.3	6.2	21.3	12.6	28.7
< 40	7.2	7.6	7.1	15.5	9.0	18.1

Particular attention should be paid to the frequent transport of the Arctic air (especially, from Wrangel Island) far into the middle latitudes of the Pacific Ocean (Fig. 3). These air masses moving to the south cross the region of the Arctic front (see Fig. 2), where pollutants are efficiently washed out by precipitation onto the ground surface, i.e., into the water of the northern Pacific Ocean. It is just here the physical properties of this air change: the increase of temperature and humidity rapidly transforms this air into the typical marine Pacific air.

Mechanisms of cleaning the Arctic atmosphere

Knowing the peculiarities of the spatial distribution of the trajectories from each site and applying the technique proposed in Ref. 4, we obtain the winter distribution of a conservative pollutant within 8 days after it leaves these sites (Table 2). To calculate these characteristics, we used the parameters of pollutant deposition onto the surface[8] that are based on many-year data on precipitation and cloudiness for winter in the Arctic. Naturally, the distributions given in Table 2 differ somewhat from those given in Ref. 8 for 5-day trajectories, since the fraction of a pollutant deposited onto the surface in the Arctic is directly determined by the time interval, for which it is calculated.

Table 2. Winter distributions of a conservative pollutant within 8 days after leaving different observation sites, in %

Site	Leaves the Arctic, g	Deposits in the Arctic, f	Remains in the Arctic air
FJL	44.6	32.8	22.6
SZ	43.7	16.9	39.4
WI	60.5	17.1	22.4

If the process of atmospheric (horizontal) transport of pollutants from the Arctic is described formally by the exponential time dependence with a fictitious "sedimentation rate," then this rate can be compared with the rates of dry sedimentation onto the surface and sedimentation by precipitation (Fig. 4). It is seen that the most efficient (having the highest rate, all other factors being the same) mechanism of pollutant removal from the Arctic atmosphere in winter is transportation by airflows out of the Arctic region. Only in the North Atlantic sector its "sedimentation rate" is comparable with the rate of dry sedimentation onto the surface. Sedimentation by precipitation is inefficient everywhere in winter.

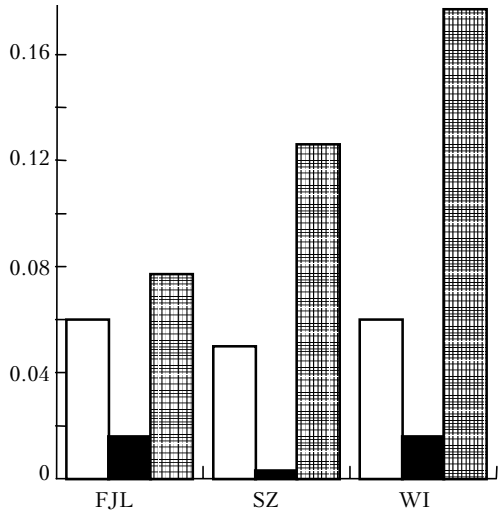


Fig. 4. Comparison of the rates of sedimentation for three mechanisms of cleaning the Arctic atmosphere at the three observation sites ($cm \cdot s^{-1}$): dry sedimentation (□), sedimentation by precipitation (■), atmospheric transport (▦).

Note that the average (over the three sites) percentages of the rates for the three cleaning mechanisms agree, accurate to 1–2%, with the corresponding winter values calculated for 5-day trajectories[8] (if we believe that there are no other mechanisms for removal of pollutants from the Arctic atmosphere).

Efficiency of pollutant transport from the Arctic as a whole

In the cold season, air masses and pollutants actively mix in the Arctic atmosphere.[4,7,8] Therefore, for rough estimates we can assume that the Arctic atmosphere in winter is completely mixed. Then the concentration of some pollutant C is constant all over the territory inside the 70°N circle, as well as on its boundary. The mean height of the mixing layer H is also assumed the same all over the Arctic territory. Then, the mean amount of the pollutant D deposited during a month onto the Arctic surface can be estimated by the equation

$$D = (N/8)\, C\, H\, S\, f, \qquad (1)$$

where f is the pollutant fraction deposited onto the Arctic surface during 8 days, $S = 2.3 \cdot 10^{13}$ m^2 is the area bounded by the 70°N parallel. Analogously, substituting the pollutant fraction g leaving the Arctic for 8 days for f in Eq. (1), we can estimate the mean amount, G, of this pollutant leaving the Arctic with air masses. Averaging the values of f and g from Table 2 over the three considered sites and assuming that the obtained values roughly characterize the corresponding processes at any point of the Arctic region and are applicable to the Arctic as a whole, we can estimate the mean ratio of the resulting values as $G : D = 2.2$.

The relative contribution of the mechanism of horizontal transport of pollutants by airflows to the process of air cleaning at any point of the Arctic region depends on the location of the considered site. In particular, high values of the "sedimentation rate" for this mechanism on Wrangel Island (see Fig. 4) are likely connected with the fact that this site is situated farther to the south than the two others, and it is, as was noticed earlier, in the zone of active air exchange between the Arctic and the middle latitudes. To the contrary, for those Arctic regions, where this air exchange is weak, the efficiency of the considered cleaning mechanism can be lower than that for the sites under study. Therefore, to estimate numerically the outgoing flows from the Arctic as a whole, let us try to use the results obtained in Ref. 9 for the entire Arctic region.

The mean flow of the pollutant transported from the Arctic by air masses can be estimated if the mean distributions of the pollutant concentration $C(l)$ and the height of the mixing layer $H(l)$ along the 70°N parallel are known, as well as the mean velocity of air motion in the southern direction $V(l)$. Then, the amount of the pollutant G_0 going out for the time t to the south through an imaginary wall of height H at 70°N can be calculated by the equation

$$G_0 = t \int [C(l)\, H(l)\, V(l)]\, \mathrm{d}l, \qquad (2)$$

where $\mathrm{d}l$ is a linear element of an arc along the 70°N parallel, and the integral is taken along the entire parallel. Simplify the calculations assuming that air masses and pollutants in the Arctic in winter are completely mixed. Factoring the constants C and H in Eq. (2) out of the integral sign, we obtain

$$G_0 = t\, C\, H \int V(l)\, \mathrm{d}l. \qquad (3)$$

Comparing Eqs. (1) and (3), we can see that in such rough estimates the ratio between the contributions of the deposition processes and transport outside the Arctic is independent of a specific pollutant and the mean height of the mixing layer. Substituting $V(l)$ from Ref. 9 (see Fig. 1) and taking t equal to one month, we obtain that the ratio between the contributions of the horizontal transport estimated by Eq. (3) and the vertical deposition estimated by Eq. (1) is $G_0 : D = 2$. If the values of D calculated in Ref. 8 from 5-day trajectories are used, then we have $G_0 : D = 1.6$.

Thus, different estimates give very close results, and this suggests that the contribution of the process of horizontal cleaning of the atmosphere (transport outside the region) for the Arctic in winter is roughly twice as large as the contribution of vertical cleaning (deposition on the surface). This estimate must be valid (to the accuracy, with which the spatial extrapolation of the results obtained at three sites in the Russian Arctic to the entire territory of the Arctic region is valid) for all chemically conservative pollutants transported in winter in northern latitudes by submicron aerosol particles, for which the sedimentation rate ranges from 0.05 to 0.07 cm $\cdot$ s^{-1}.

Numerical estimates

As an example of such a pollutant, let us consider lead, as a typical anthropogenic chemical element. As was shown in Ref. 8, it is just for this element that our estimates of the many-year mean concentration and its seasonal behavior in the Russian Arctic are in the closest agreement with the experimental many-year values of these characteristics in the atmosphere of the Canadian Arctic. This justifies the assumption on the constant concentration of the pollutant all over the Arctic territory. Take the value of 2 ng $\cdot$ m^{-3} as the winter lead concentration all over the Arctic territory[8] and the mean height of the mixing layer $H = 1$ km (these values agree well with the experimental observations[10]). Then, from Eq. (1) we have that about 40 t lead is deposited onto the surface for one month in the Arctic. Taking into account the mean ratio between f and g from Table 2, we can estimate the amount of lead transported by air masses for a month as $G = 88$ t. On the other hand, from Eq. (3) we have that about 78 t of lead is removed from the Arctic by air masses in January (the amount transported to Canada is roughly twice as large as that transported to Eurasia). To maintain this balance, no less than 120–150 t lead must come from the middle latitudes to the Arctic for one winter month. These amounts are quite real. For example, according to Ref. 11, the amount of lead coming to the Arctic in January 1980 can be estimated at about 200 t.

Conclusions

In winter the Arctic air masses and pollutants transported by them can penetrate deep into the middle latitudes (up to 50°N and 40°N latitudes) coming over the continents inside the Arctic front (and thus retaining their properties) and crossing the Arctic front over the Pacific and Atlantic Oceans, where pollutants are washed-out by precipitation onto the sea surface and the physical properties of an air mass change.

Transportation of anthropogenic pollutants by air masses from the Arctic region is considered, for the first time, as one of the mechanisms of cleaning the Arctic atmosphere, and the efficiency of this process is estimated in comparison with the pollutant sedimentation onto the surface. It is shown that in the considered sites the equivalent sedimentation process would have the higher rate than the winter processes of dry and wet sedimentation for pollutants transported by submicron aerosol particles. As a result, in winter the contribution of horizontal transport of pollutants to cleaning the Arctic atmosphere as a whole is roughly twice as large as the contribution of deposition onto the surface.

Acknowledgments

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References

1. G.E. Shaw, Atmos. Environ. **22**, No. 10, 2239–2248 (1988).
2. K.A. Rahn, D.H. Lowenthal, and J.M. Harris, Atmos. Environ. **23**, No. 11, 2597–2607 (1989).
3. T.G. Adiks, Izv. Ros. Akad. Nauk, Ser. Fiz. Atmos. Okeana **34**, No. 3, 337–344 (1998).
4. A.A. Vinogradova and T.Ya. Ponomareva, Izv. Ros. Akad. Nauk, Ser. Fiz. Atmos. Okeana **36**, No. 3, 357–365 (2000).
5. A. Stohl, Atmos. Environ. **32**, No. 6, 947–966 (1998).
6. A.A. Vinogradova, Atmos. Environ, **34**, No. 29–30, 5151–5160 (2000).
7. A.A. Vinogradova and T.Ya. Ponomareva, Dokl. Ros. Akad. Nauk **376**, No. 5, 671–674 (2001).
8. A.A. Vinogradova and T.Ya. Ponomareva, Izv. Ros. Akad. Nauk, Ser. Fiz. Atmos. Okeana (2001), in press.
9. L.P. Burova and N.I. Luk'yanchikova, Tr. AANII (Gidrometeoizdat, St. Petersburg, 1998), Vol. 439, pp. 111–123.
10. A.P. Nagurnyi and A.A. Timerev, Dokl. Ros. Akad. Nauk, **319**, No. 5, 1110–1113 (1991).
11. F.A. Akeredolu, L.A. Barrie, M.P. Olson, et al., Atmos. Environ. **28**, No. 8, 1557–1572 (1994).

0235-6880/01/06–07 458-05 $02.00