ANNUAL VARIATIONS IN ATMOSPHERIC AEROSOL OPTICAL DEPTH TYPICAL OF DIFFERENT CLIMATIC ZONES

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Clear–sky observations of direct solar radiation are used to calculate monthly mean values of the atmospheric aerosol optical depth (τ_{a,λ_0}, $\lambda_0 = 550$ nm) for 155 actinometric stations covering much of the former USSR territory. Six major types of annual behavior of τ_{a,λ_0} are identified, as they are formed due to peculiarities in a regional climate. Ranges of the background τ_{a,λ_0} values variability are estimated for different latitudinal zones, where aerosol emissions from big industrial centers are evaluated.

Among the key problems posed by the climate change is the assessment of the role of aerosol, particularly of anthropogenic aerosol, in regional climate change. To solve such problems, data is needed on seasonal behavior of the atmospheric aerosol turbidity which is governed by the regional climate and underlying surface characteristic of the region. Account of the annual behavior of aerosol optical depth (τ_{a,λ_0}) is important in the analysis of the background τ_{a,λ_0} values at different latitudes, and for estimation of the local industrial sources of pollution. By background atmospheric aerosol optical depths we mean the τ_{a,λ_0} values averaged over the array of data from all stations except industrial cities rather than over the background stations only, as it is usually done. Further complexity comes from the fact that individual aerosol observations are often fragmentary and incomparable and thus fail to display a complete and reliable pattern of spaciotemporal variability of atmospheric aerosol pollutions.

In Ref. 10 it is suggested that this problem be solved using direct solar radiation measurements, routinely made at an actinometric network with a sufficient temporal and global coverage. An important practical application of these data could be the estimate of atmospheric aerosol turbidity, in particular, of the atmospheric aerosol optical depth τ_{a,λ_0} at $\lambda_0 = 550$ nm which is most commonly used in climate models.

This paper presents an analysis of annual behavior of τ_{a,λ_0} and its spatial variation over the former USSR, the τ_{a,λ_0} calculations being made for $n = 1$ using the approximation

$$\tau_{a,\lambda_0} = \frac{\ln S - (0.1886 W^{-0.1830} + (0.8799 W^{-0.0094} - 1)/\sin h_\odot)}{0.8129 W^{-0.0021} - 1 + (0.4347 W^{-0.0321} - 1)/\sin h_\odot},$$

where S is the direct solar radiation as measured with an actinometer, W is the atmospheric humidity, and $h_\odot$ is the solar elevation.[9]

The clear–sky measurements of direct solar radiation, taken at 12:30 solar time and averaged over the period from the beginning of stations' operation and till 1980 have been taken as the initial data. These data have been published in scientific–applied reference books of the USSR climates.[5] Use of averaged data on direct solar radiation and atmospheric himidity[2] in analysis of spatiotemporal variability of τ_{a,λ_0} is well justified in Ref. 10.

A unified technique was used to calculate monthly values of the aerosol optical depth as observed at 12:30 solar time at 155 stations covering much of the former USSR territory, stations included both relatively "clean" zones and those located in big industrial centers. Excluded were the stations of West Siberia, Irkutsk, Amderma, Dikson, and Pevetsk departments since no reference material was available by the time of preparing this paper.

Analysis of monthly values of τ_{a,λ_0} has revealed the presence of different types of annual behavior of aerosol optical depth featuring the predominant atmospheric circulation, seasonal change in the type of air masses, and the state of the underlying surface.

By the type of annual behavior we mean most typical features in the behavior of the many years mean monthly values of τ_{a,λ_0}. Basic criteria used for identifying types of the annual behavior of τ_{a,λ_0} were month or season of occurrence of the principal mode, presence of secondary modes, and annual amplitude of τ_{a,λ_0}.

Based on the results obtained, we have identified six distinct types of annual behavior of atmospheric aerosol optical depth (Figs. 1 and 2).

Type I : the highest values of atmospheric aerosol turbidity with two maxima occur in spring–summer, and the lowest values occur in fall–winter. Such τ_{a,λ_0} variations are characteristic of the most of the European part of Russia, Western Siberia, and Northern Kazakhstan.

First type can be subdivided into three subtypes differing in the positions of the principal and secondary modes (Fig. 1). Subtype Ia has its principal mode in spring, subtype Ib in summer, and the spring and summer modes in subtype Ic are nearly equal in amplitude. For the European part, change from Ia to Ib type occurs, on average, when moving southward, and for the Western Siberia, from Northwest to Southeast; Ic type occurs simultaneously with the predominating Ia type as frequently as with Ib type. Also interesting is that month–to–month change is smoother at higher latitudes, and that for northern stations the spring τ_{a,λ_0} mode typically occurs in May and shifts toward April when moving southward, as caused by changes in the general circulation as well as in the state of the underlying surface, mostly due to shorter snow season. In the southern European part type Ib changes for type II.

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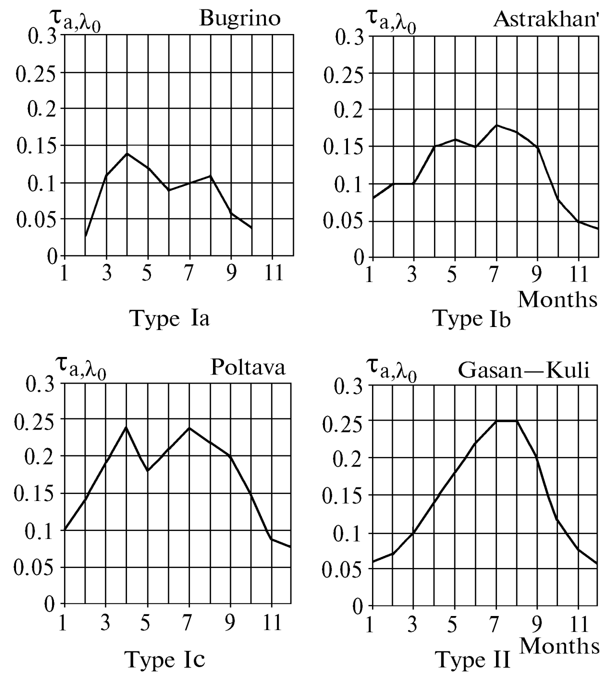

FIG. 1. Types of annual behavior of $\tau_{a,\,\lambda_0}$.

Type II is characterized by a single maximum in summer and a minimum in winter, and is the case for Southern Kazakhstan (Fig. 1). Amplitude of annual behavior of $\tau_{a,\,\lambda_0}$ shows the same tendency of increasing southward, and reaches its maximum (0.15–0.20) for the second type of annual behavior.

Type III of the annual behavior of $\tau_{a,\,\lambda_0}$, with a maximum in winter and minimum in summer, fall, and spring is observed at stations located at closed valleys (Fig. 2). For Erevan, there is a secondary maximum in summer. Character of the type III annual behavior of aerosol optical depth is related to the specific relief, and the winter maximum is further favored by the dominating high pressure fields and associated frequent temperature inversions, leading to accumulation of aerosol in hollows. Also of significance is that the winter season at type III stations is typically snowless.

Type IV of the behavior, with a maximum in spring and minimum in summer, winter, and fall dominates over the Eastern Siberia and Far East (Fig. 2). Enhanced atmospheric pressure is typical here in spring, simultaneously with the onset of snow melting. Similar spring maximum is reported for other geographical locations, such as some stations in the USA and background stations in Europe and Asia.[7] It is interesting that American scientists regard the places with spring maximum of turbidity as most "clean". The atmosphere over stations with the spring maximum in $\tau_{a,\,\lambda_0}$, at the territory under study, is characterized by an enhanced transmission. From Table I we see that the stations in this region have minimum $\tau_{a,\,\lambda_0}$ values. This type of the annual behavior of $\tau_{a,\,\lambda_0}$ is characterized by a moderate annual amplitude of 0.05–0.09.

Type V, which also can be called "monsoon", dominates over Primorskii Krai, and is primarily indicative of the change in the type of air masses, with a maximum atmospheric aerosol turbidity in winter–spring period being caused by dominating continental air masses, while a minimum one in summer and fall by the marine air mass. Type V of the annual behavior of $\tau_{a,\,\lambda_0}$ well agrees with the monsoon behavior of precipitation rate in this region. If these five types of the annual behavior of $\tau_{a,\,\lambda_0}$ are determined by specific relief and regional climates, the sixth type may occur in any region with that or other type of the five types dominating in it.

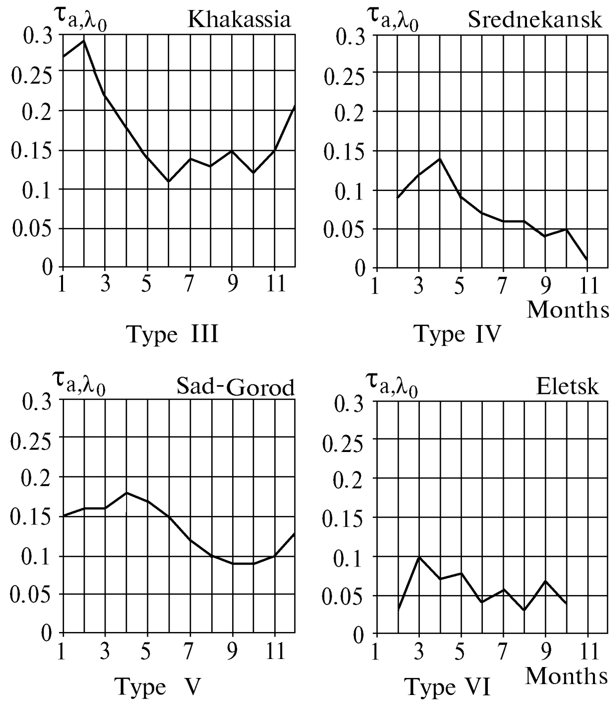

FIG. 2. Types of annual behavior of $\tau_{a,\,\lambda_0}$.

Type VI displays a train of maxima and minima over a year and, as follows from Ref. 7, it is typical of big industrial centers. From the data being analyzed type VI is also observed in relatively "clean" regions, not only at city–stations. On the other hand, certain big industrial cities such as Moscow, Leningrad, Norilsk, and Magadan show the annual behavior of aerosol optical depth typical for the region they are located in.

It is common for European and Asian basins, independent of a season, that the aerosol optical depth increases southward (Fig. 3). Table I presents mean seasonal and statistical characteristics of $\tau_{a,\,\lambda_0}$ at 5–degree latitudinal belts (with averages taken over all $\tau_{a,\,\lambda_0}$, excluding industrial cities).

TABLE I. Variation of atmospheric aerosol optical depth with latitude.

Latitude	Number of cases	Mean	Min.	Max.	A	E	Gradations of the largest occurence
			Winter				
69–60°N (February)	27	0.07	0.02	0.17	0.51	0.08	0.0–0.10
60–55°N	60	0.06	0.01	0.16	0.46	–0.42	0.0–0.10
55–50°N	69	0.11	0.01	0.29	1.21	2.39	0.10–0.15
50–45°N	72	0.11	0.03	0.28	1.07	1.93	0.05–0.15
45–37°N	81	0.11	0.02	0.21	1.08	1.89	0.05–0.02
			Spring				
69–60°N	81	0.11	0.05	0.17	0.01	–0.17	0.05–0.15
60–55°N	60	0.13	0.05	0.17	–0.45	0.27	0.10–0.20
55–50°N	69	0.16	0.06	0.23	0.01	–0.86	0.10–0.20
50–45°N	72	0.15	0.06	0.26	0.27	–1.06	0.10–0.15
45–37°N	81	0.16	0.07	0.23	0.40	–0.01	0.10–0.20
			Summer				
69–60°N	81	0.08	0.02	0.17	0.60	–0.30	0.05–0.10
60–55°N	60	0.13	0.03	0.23	–0.70	1.88	0.10–0.15
55–50°N	69	0.15	0.05	0.28	0.27	–0.62	0.10–0.20
50–45°N	72	0.15	0.04	0.28	0.28	–1.32	0.05–0.10 0.20–0.25
45–37°N	81	0.18	0.08	0.31	0.32	–1.23	0.10–0.15 0.20–0.25
			Fall				
69–60°N (September, October)	54	0.05	0.01	0.12	1.10	1.72	0.0–0.05
60–55°N	60	0.09	0.01	0.17	0.10	–0.56	0.05–0.10
55–50°N	69	0.10	0.03	0.23	0.77	–0.08	0.05–0.10
50–45°N	72	0.10	0.03	0.22	0.71	–0.37	0.05–0.10
45–37°N	81	0.13	0.03	0.26	1.20	–1.00	0..05–0.10

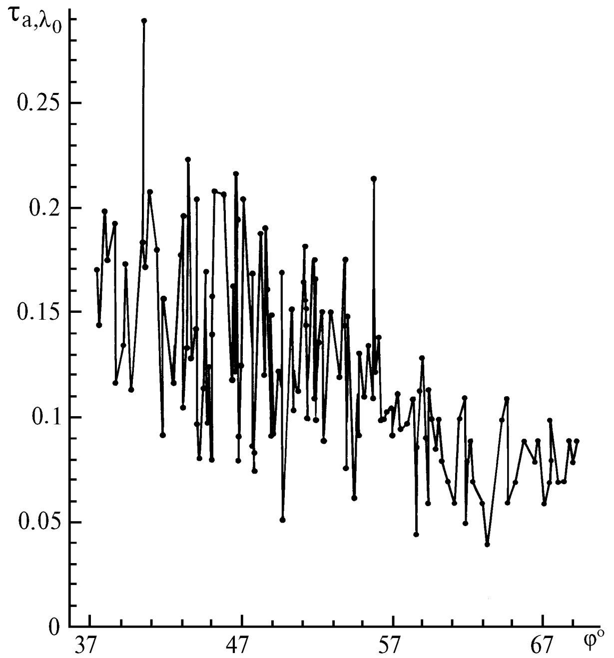

FIG. 3. Change of $\tau_{a,\,\lambda_0}$ with latitude.

This tendency is most apparent for European part, not only due to the change in physical and geographycal climatic conditions, but also to a more dense population of industrial regions to the south.

As an example, we present a profile of $\tau_{a,\,\lambda_0}$ along 33°E, comprising points between 30.1°E and 35.2°E. For all seasons, $\tau_{a,\,\lambda_0}$ significantly changes as inverse of the latitude, with the correlation coefficient of –0.81, –0.84, –0.88, and –0.72 for April, July, October, and January, respectively.

Same tendency toward $\tau_{a,\,\lambda_0}$ decrease poleward is clear for points located between 60°E and 65°E, but with a significant dependence being observed in summer only. Irrespective of season $\tau_{a,\,\lambda_0}$ profile is lower in Central and Northern Kazakhstan, with maxima in Central Ural, contaminated by many industrial plants, and Central Asia, dominated by air masses rich in natural aerosol. In the eastern part of the country, around 133°E, the increase of $\tau_{a,\,\lambda_0}$ southward is significant in all seasons except for spring (April). The latter fact is presumably because $\tau_{a,\,\lambda_0}$ reaches maximum over much of this region in spring.

The latitudinally general trend in $\tau_{a,\,\lambda_0}$ to decrease eastward is seasonally obscured since $\tau_{a,\,\lambda_0}$ behaves differently with season at different longitudes (Table II). To isolate such an obscurity, we have considered the longitudinal behavior of $\tau_{a,\,\lambda_0}$ at 5–degree latitudinal belts, excluding stations in big industrial centers.

For high latitudes (69–60°N), the inversely proportional behavior of $\tau_{a,\,\lambda_0}$ with longitude is significant only in summer, and then it weakens and disappears in spring. The longitudinal behavior of $\tau_{a,\,\lambda_0}$ in spring is distinctly bimodal: one peak, over European part, is due to both natural conditions and enhanced industrial loading, and the second one, over Eastern part, is just the seasonal maximum in annual behavior of $\tau_{a,\,\lambda_0}$. Between 60° and 55°N, the latitudinally decreasing turbidity is less pronounced, becoming even increasing in winter, due to high–pressure fields dominating over central and eastern basins. Similar winter behavior is seen in 55–50°N and 50–45°N belts, and is most pronounced from 45°N southward, while in winter and fall a significant inverse scaling of τ_{a, λ_0} with longitude is well fitted by a power function. In winter τ_{a, λ_0} is extremely low in Kazakhstan and Western Siberia, while increasing in Primorskii Krai where just a seasonal maximum of τ_{a, λ_0} occurs at that time.

TABLE II. Variation of atmospheric aerosol optical depth with longitude.

Longitude	Number of cases	Mean	Modal	Min.	Max.
		January			
33°E	16	0.06	0.05	0.01	0.12
63°E	11	0.07	0.06	0.02	0.11
133°E	8	0.11	0.11	0.07	0.17
		April			
33°E	19	0.15	0.12	0.11	0.23
63°E	12	0.14	0.15	0.07	0.21
133°E	10	0.15	0.13	0.12	0.19
		July			
33°E	19	0.17	0.12	0.11	0.28
63°E	12	0.13	0.14	0.06	0.24
133°E	10	0.10	0.12	0.06	0.13
		October			
33°E	19	0.09	0.06	0.02	0.17
63°E	12	0.09	0.10	0.04	0.20
133°E	10	0.07	0.08	0.05	0.11

The aerosol optical depths given in Table I can be considered as background values for latitudinal zones under consideration. Since the analysis of aerosol pollution of the atmosphere over cities is made in comparison with the background τ_{a, λ_0} values, it is also important to allow for the longitudinal behavior of τ_{a, λ_0}. It would be most reasonable to determine background τ_{a, λ_0} from the mean values at "clean" stations for each of the above types of the annual behavior of τ_{a, λ_0}, but only three longitudinal ranges, < 60°, 60–120°, and > 120°, were used because some of the types had poor statistics. From Table III we see significantly different behavior of τ_{a, λ_0} at different locations.

However, the observed latitudinal and longitudinal regularities in the atmospheric aerosol optical depth suffer abrupt change at industrial cities.

Using actinometric data from the majority of stations, data have been obtained on aerosol pollution of cities of various industrial loadings, as well as data for nearly "clean" stations, in different climatic zones (total of 20 pairs), with which it is possible to assess the aerosol pollution of cities in different climatic zones. The aerosol loading of the air above towns and "clean" stations was bound to differ by as much as 25 to 50%.

In absolute τ_{a, λ_0} values, most "dirty" are southern cities with the annual behavior of the second or third types, among which there are Odessa (average annually $\tau_{a, \lambda_0} = 0.22$), Alma–Ata (0.22), and Fergana (0.29). Among the midlatitude cities with high τ_{a, λ_0} values is Moscow (0.21); and most "clean" cities of fourth and fifth types of annual behavior are Yakutsk (0.08), Khabarovsk (0.12), and Arkhangel'sk (0.11). It is important that even towns with low absolute values of τ_{a, λ_0} show substantial enhancement over "clean" stations: Arkhangel'sk from Umba by 27%, Yakutsk from Chernyshevsk by 25%, and Leningrad from Voeykovo by 31%. Primorskii Krai, Vladivostok, and Timiryazevsk have close values of aerosol turbidity. Aerosol optical depth rapidly decreases away from a town. Annually mean τ_{a, λ_0} value for 1972–1976 in Moscow is 27% higher than that for Podmoskovnaya located 30 km south–west, and 58% greater than that for Krasnovidovo 100 km to the west. Towns substantially affect adjacent suburbs, so that Podmoskovnaya station, for example, has the same annually mean τ_{a, λ_0} as a middle–size industrial city at that same latitudinal belt.[10]

TABLE III. Variation of background τ_{a, λ_0} values with latitude and longitude.

Latitude	Longitude	Number of cases	Winter	Spring	Summer	Fall
	<60°	27	0.07 (9)	0.11	0.11	0.05
69–60°	60–120°	21	0.03	0.11	0.07	0.04
	>120°	33	0.03	0.11	0.05	0.03
	<60°	36	0.05	0.13	0.14	0.08
60–55°	60–120°	15	0.09	0.14	0.13	0.09
	>120°	6	0.04	0.08	0.04	0.03
	<60°	36	0.10	0.17	0.20	0.12
55–50°	60–120°	18	0.14	0.15	0.12	0.09
	>120°	12	0.09	0.12	0.09	0.07
	<60°	39	0.12	0.18	0.21	0.13
50–45°	60–120°	24	0.09	0.14	0.08	0.07
	>120°	9	0.10	0.14	0.08	0.07
	<60°	31	0.09	0.15	0.19	0.14
45–37°	60–120°	23	0.12	0.17	0.22	0.16
	>120°	13	0.13	0.17	0.19	0.13

Thus, large, within pair, differences in τ_{a, λ_0} may be due to large separations. For instance, large (> 60%) difference between Krasnodar and Pyatigorsk is just because of the Pyatigorsk being a clean mountain station with the τ_{a, λ_0} values that are below the background ones in all seasons (Table III). Also, Alma–Ata was compared against Balkhash whose annually mean τ_{a, λ_0} is quite different from that in Alma–Ata, thus giving a 64% difference in τ_{a, λ_0}. Thus, for a more reliable estimate of the industrial pollution it is necessary to compare aerosol depth over towns against the specific regional background value (Table III). The largest deviation from regional background is in Moscow: a factor of 2 to 3 in winter and 1.5 to 2 in summer. In Alma–Ata, winter τ_{a, λ_0} values are also two times greater than the background, while the summer values are normally lower since the annual behavior of τ_{a, λ_0} in Alma–Ata (of third type) is out of the phase with the regional one.

So, the results presented explicitly show the importance of all characteristics of regional climate and relief, and not only the average τ_{a, λ_0} values, for estimating correctly the impact of industrial emissions upon the atmospheric aerosol turbidity.

The dynamic of atmospheric pollution is best traceable with many–year data of τ_{a, λ_0} variability available. Such a study was performed for seven stations with different industrial loadings and different climatology, as well as for Moscow and Podmoskovnaya using a 30–year intercomparison[1,10]; the results reveal the presence of a significant trend in $\tau_{a,\,\lambda_0}$ in industrial cities, and recent increase of the role of anthropogenic factors in aerosol loading of the atmosphere.

However, values of the annual and spatial behavior of aerosol pollutants, as obtained using average $\tau_{a,\,\lambda_0}$ values, agree well with data from Refs. 3, 4, 6, 7, 8, and 11, what favors the use of the technique proposed.

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