DYNAMICS OF THE ATMOSPHERIC MIXING LAYER AS IT FOLLOWS FROM DATA ON AEROSOL

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Received April 5, 1993

Based on data available from the literature, the concepts of mixing layer and the internal mixing layer are analyzed in this paper. Some specific features of the dynamics of both mixing layers are revealed from data of aircraft sounding of aerosol and interaction between the layers is discussed. A long-term mean annual behavior of the height of mixing layer in the atmosphere over West Siberia is constructed.

Aerosol particles in the air mainly determine its optical properties and energy balance of the atmosphere. Good entrainability of particles causes aerosol to be an excellent tracer of air motions and enables one to study dynamic processes in the atmosphere. It should be noted that the vertical distribution of aerosol in the atmosphere is inhomogeneous. Its major portion is in the lower atmosphere, more precisely, in the mixing layer. However, information about characteristics of this layer is contradictory since the concept itself is ambiguous. Taking into account the fact that the mixing layer height determines to a large extent "capacitance" of the atmosphere with respect to storage of air admixtures, which is very important in determining the pollution potential under specific physico–geographical conditions, it is expeditious to reveal basic characteristics of this layer. This is the subject of the present paper which is based on aircraft measurements of aerosol particle number density carried out during 1981–1988, Refs. 1 and 2.

Let us dwell on definition of "mixing layer" (ML). This concept was introduced by Holzworth in 1964 as an index of atmospheric stability where the temperature lapse rate approaches a dry–adiabatic one or exceeds it.[3] In our national literature the mixing layer is often identified with the atmospheric boundary layer (ABL).[4] The difference between these two layers is briefly described in Ref. 5 where five scales are separated out in ABL, namely, a ground layer, a layer of free convection, a mixing layer, a quasisymmetric upper layer, and an entrainment layer. Since that time the concept "mixing layer" is often used in the scientific literature without proper refinement of it. This can be an internal mixing layer, an atmospheric boundary layer, a level of inversion, and so on. To make this problem clear, we now turn our attention to the results of several papers.

The flights carried out according to the program OECD showed that the major portion of pollutants stays inside the 2–km layer of the atmosphere.[6] Similar results were also obtained during the aircraft measurements in 1980–1982 in the region of the Sea of Japan when studying medium–scale transport due to local circulations.[7] The measurements revealed that the polluted air propagated horizontally over the sea, and it was bounded by 1000–m altitude at night and early morning. At noon and in the evening the pollutions are transported by upward fluxes and breeze up to 3000 m. This data enables one to estimate, in the first approximation, an altitude range of the mixing layer.

The effect of humidity on the ML growth was investigated in Ref. 8. It turned out to tell weakly on the parameter of buoyancy and, correspondingly, on the mixing layer height at the initial stage of its growth. At a later stage, the account of the effect of humidity on buoyancy leads to larger values of the ML height as compared to those obtained with a dry model.

It was shown in Ref. 9 that there is an almost constant profile of specific humidity in the mixing layer since at the stage of development a humid air is transported with convection in the upward direction. The upper boundary of ML is characterized by sharp increase of potential temperature. The phases of fluctuations of specific humidity and potential temperature are opposite. Convection penetrates the upper stable layer as humid cold jets. The upper boundary of ML is a wavy surface which is formed under the action of upward motions. Amplitude of boundary surface vibrations is 100–200 m at 3 to 4 km wavelength.

A nonpassive admixture in the atmosphere changes strongly the dynamics of the mixing layer. The calculational results[10,11] reveal that the aerosol occurring at some level causes formation a stably stratified layer at this altitude which slows down the ML growth. At the same time, above the stably stratified layer the layer with strong instability is formed that accelerates the growth of the ML height in the desctruction of the stable one.

A relatively uniform distribution of meteorological parameters and aerosol inside the mixing layer makes the ML height one of the main parameters when the processes of ML formation are studied.

As of the present time, there are some approaches for determining the ML height. They differ in their methodology, initial information used, etc.

Kuznetsova[12] determines the ML height by altitude of the layer with positive energy of instability whose lower boundary is the underlying surface. A level of intersection of the state curve with the curve of vertical distribution of air temperature is taken as a ML height on an aerogram. It is also pointed out in Ref. 12 that the account of the turbulence coefficient is of particular importance in the mixing layer. The performed comparison revealed the following relation between the ML heights determined using the method described and the turbulence coefficient[13]:

under unstable stratification H_{ML} exceeds explicitly the height H_c found from the turbulence coefficient (H_{ML} = 2000 m and H_c = 1000 m);

under neutral stratification H_{ML} = 2000 m, and H_c does not have a pronounced boundary.

Vertical profiles of number density were measured at a tower in Beijing. The height H_{ML} was found to be 1.41 km from the measured values using the formula $N_z = N_0 \exp(-z/H)$.

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The estimates of H_{ML} which varied between 0.8 and 2 km remaining equal, on the average, 1.01 km were obtained in Ref. 15. Here the formula[14] was used too.

In Ref. 16 the lidar measurements in the mixing layer were carried out. The following equation was employed:

$$\frac{\mathrm{d}\, H_{ML}}{\mathrm{d}\, t} - \overline{w} = \frac{A_F\, \sigma_w}{\left[A_T + \frac{g}{T_0}\frac{\Delta\theta_h}{\sigma_w^2} - \frac{A_P\,(\Delta U)^2}{\sigma^2\, w}\right]},$$

where $\overline{w}$ is the mean vertical velocity at the upper boundary of the mixing layer; $\sigma_w^3 = w_*^3 + (A_s/A_F)\, V_*^3$; $A_F = 1 - \alpha_1$, $A_s = 2(C_D^{-1/2} - \alpha_2)$, $A_p = 1 - \alpha_3$, $A_T = 2\alpha_T$; and α_1, α_2, α_3, and α_T are constants.

Under convective conditions they obtained $A_F = 0.22 + 0.08\, A_T + 0.09\, A_T^2 - 0.03\, A_T^3$ for $0.0 < A_T < 2.0$. Under mechanical turbulence $A_s = 7.5$ and $A_p = 1$ with the same A_F and A_T.

The mixing layer height was proposed to be found from the conventionally measured meteorological parameters [17]

$$H_{ML} = [2P_0/\rho\, C_p\, \alpha\, U_0]^{1/2},$$

where P_0 is the total flux of heat; ρ is the air density; C_p is the specific heat capacity of air; α is the difference between dry–adiabatic and true gradient of temperature; and, U_0 is the wind velocity.

The difference between the boundary and mixing layers set the scientists searching for the other methods of determining the ML height.

In Ref. 18 the ML height is obtained from the condition

$$H = M/Q(0),$$

where $M = \int_0^\infty Q(z)\, \mathrm{d}z$ is the mass of admixture in a vertical column of an unit cross section, and $Q(z)$ and $Q(0)$ are concentrations at an altitude z and near the Earth's surface, respectively.

It was assumed during realization of the OECD program that in the idealized situation in the mixing layer $Q(z)$ is constant and the rms deviation of height $\sigma_H = H_{ML}\sqrt{3}$, then[19]

$$H_{ML} = \frac{\sigma_H}{\sqrt{3}} = \sqrt{\frac{\int_0^\infty z^2\, Q(z)\, \mathrm{d}z \;/\; \int_0^z Q(z)\, \mathrm{d}z}{3}}.$$

Here integration is made to the altitude z where $Q(z) = 0$ or $Q(z)$ becomes close to a background one.

Such a variety of methods causes one to look for a more optimal and reliable approach to determining the mixing layer height.

We infer from the analysis of aerosol vertical distribution made based on the aircraft measurements that for climatic purposes it is possible to find the ML height from destruction of correlations in the lower troposphere. The coefficients of correlation between aerosol particle number density at different altitudes for three months are depicted in Fig. 1.

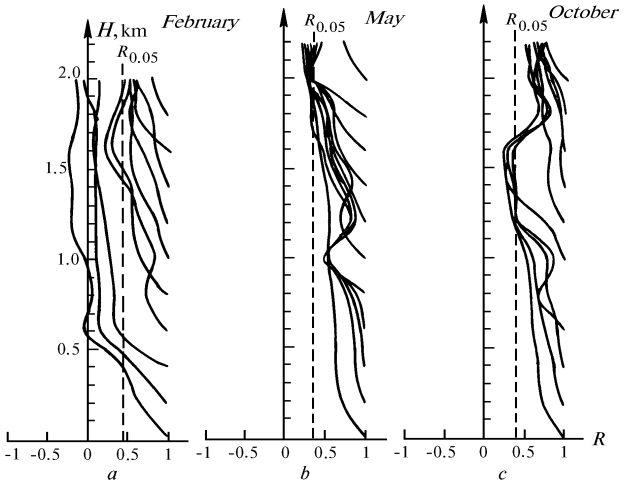

FIG. 1. Correlation between vertical variations in aerosol particle number density over West Siberia: a – in February, b – in May, and c – in October.

From Fig. 1 it is apparent that the February variation in aerosol concentration near the Earth's surface correlates with that occurring in the upper layers only to the 0.4–km altitude. In May (Fig. 1*b*) the layer in which aerosol variations are interconnected increases its height to 1.8 km. In October (Fig. 1*c*) the ML height decreases and becomes 1.1 km. Verification of these conclusions based on single ascents data in the same months shows that the results depicted in Fig. 1 reflect mean characteristics for each of them. On some individual days the ML height can be 30% larger or smaller than the mean climatic one.

The approach proposed allowed us to construct for the first time the mean long–term annual behavior of the mixing layer height over West Siberia which is represented with a solid line in Fig. 2. The marks denote H_{ML} for individual years.

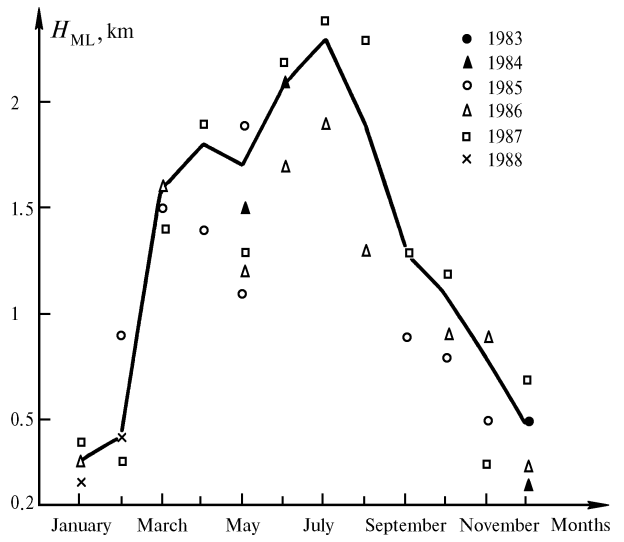

FIG. 2. Mean long–term annual behavior of the mixing layer height over West Siberia; marks depict monthly thickness of the mixing layer in individual years.

As seen in Fig. 2, the annual behavior of the ML height differs substantially from that of aerosol concentration due to turbulence intensity which has its

maximum in summer.[20] In this case, the ML height is maximum in July and minimum in January. It should be noted that the ML height equals 0.3 km in January. This is, in fact, the height of the internal mixing layer which exists inside ML permanently. This will be discussed in the following.

The secondary maximum in April should be noted. This can be explained by peculiarities of dynamics of the atmosphere over West Siberia. This maximum was found earlier in such circulation characteristics as altitude frontal zones and jet streams.[21,22] The point is that a planetary altitude frontal zone moves irregularly from south to north over West Siberia in spring and the May minimum reflects reconstruction of the thermobaric field.

The spread of values of the ML height in individual months shown with marks illustrates variations in the mean ML height in individual years. The spread is seen to attain 60% of the mean long–term magnitude.

Later, a concept of the internal mixing layer (IML) appeared based on the analysis of measurement results.[5] In this layer, the vertical mixing occurs nearly adiabatically and distribution of many of the characteristics is uniform with altitude. The level at which the concervative characteristics uniformly distributed in IML undergo abrupt change is identified with the IML height. In the morning, owing the continuous generation of turbulence due to solar radiation, IML increases. As this takes place, the air from upper layers is involved and rapidly mixed within IML. Thus, two basic mechanisms play the main role in evolution of the diurnal IML: entrainment and turbulent mixing.

The dynamics of relation between ML and IML is investigated at length in Ref. 23, though the interpretation of the results is simplified. The authors showed that the profiles of aerosol extinction can be schematically represented as a three–layer distribution. The first layer of elevated turbidity H_1 is adjacent to the underlying surface, and it coincides with IML. The second layer H_2 is characterized by constant backscattering coefficients in the interval $H_2 - H_1$, and it represents ML. Above the H_2 level the backscattering coefficients decrease sharply and remain constant with the value which is specific for the free atmosphere.[24]

The height H_1 is approximately constant in all seasons and equal to 0.2 ... 0.4 km. The height H_2 has a pronounced seasonal dependence: in fall it is 1.2 ... 1.7 km, in spring –1.5 ... 2.5 km, and in summer –2.0 ... 3.5 km. In winter when the ML height is small it is possible to assume $H_1 = H_2$, i.e., $H_{ML} = H_{IML}$.

The lidar sounding of IML made in Ref. 25 allowed the refinement of its temporal characteristics. The internal mixing layer attains its maximum height at about 1 p.m. Its height in the morning is 200 m. It reaches 400 m by 11 a.m. The rate of height growth changes from 100 to 300 m/hr between 8 and 12 a.m.

Common to both these layers [mixing (boundary) and internal] is that they are limited from above by inversion, isothermy, or a layer with stable stratification. This results in displacing of concepts of internal and boundary or external mixing layers though they differ not only in height but also in their nature of formation. The dynamics of the internal mixing layer is determined by a diurnal behavior of meteorological elements, and it does not depend on a season. Its height is within 200 to 400 m. The internal mixing layer can disappear completely after midday or under developed convection.[26,27] The boundary mixing layer height changes during a year from 200 m in winter to some kilometers in summer and does not depend on day time. The internal ML being inside the boundary layer specifies the aerosol and other admixtures content in this layer.

Let us illustrate what has been said above with examples of vertical distribution of aerosol particle number density which are depicted in Figs. 3 and 4.

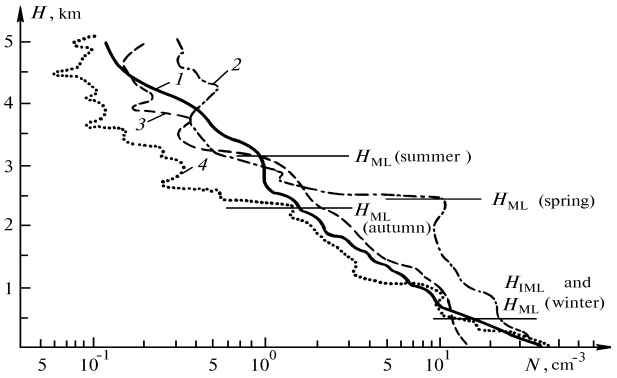

FIG. 3. Mean long–term profiles of number densities over West Siberia in different seasons; 1) winter (n = 208); 2) spring (n = 85); 3) summer (n = 52); and , 4) fall (n = 67).

As seen in Fig. 3 the boundary, or external, mixing layer H_{ML} is clearly seen on vertical profiles of aerosol concentration in any season, except winter, and its height varies during a year. The height H_{IML} remains constant during a year. In winter when H_{ML} and H_{IML} practically coincide it is impossible to separate the layers.

Figure 4 illustrates a mean long–term diurnal behavior. The main variations in aerosol concentration occur in the lower 400–m air layer which is adjacent to the underlying surface that is determined by height of the internal mixing layer. The height H_{IML} has a sufficiently pronounced behavior. It is maximum at noon and in the evening. At night H_{IML} decreases, and attains its maximum in the morning when intensity of turbulence is insignificant.

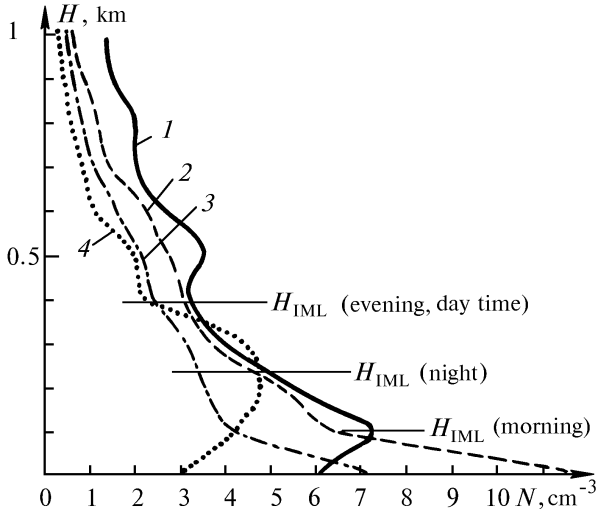

FIG. 4. Mean long–term diurnal behavior of aerosol particle number density over West Siberia in the mixing layer: 1) morning; 2) day time; 3) evening; and , 4) night.

The existence of the internal mixing layer inside the basic ML affects the ML characteristics. Let us illustrate this by Fig. 5 where peculiarities of filling of the basic mixing layer with aerosol after air mass exchange are depicted. This figure was published in Ref. 28 but without proper interpretation. In the figure curves *1–5* represent profiles of aerosol particle number density from 12th to 16th of May, 1984; curves *1′–5′* are the corresponding profiles of air temperature. Curves *1* and *1′* were obtained during the aircraft measurements of the atmosphere on May 12, 1984 when a moderate warm air mass was located over the region. At night of 12th to 13th of May a cold arctic front passed through the measurement site, and the region was found to be inside the arctic air mass. In this case, the aerosol particle number density decreased by a factor of 5–7 in the entire layer, and the air temperature in the boundary layer dropped by 15°C. Curves *2–5* and *2′–5′* were obtained in the arctic air mass.

It is seen from Fig. 5 that if one separates out the internal mixing layer (H_{IML}), then the aerosol generated in the ground layer, after exchange of air mass, does not propagate over the entire basic mixing layer, but it is stored inside IML. And only when aerosol concentration in IML reaches the value commensurate with that observed in the old air mass (curves *4* and *1*), the particle transport into the basic mixing layer comes into action (curve *5*). Thus, the existence of the internal layer results the filling of the basic mixing layer to follow the two–stage course. At the first stage there occurs storage of admixture inside IML. After this admixture attains its critical value the second stage of ML filling starts.

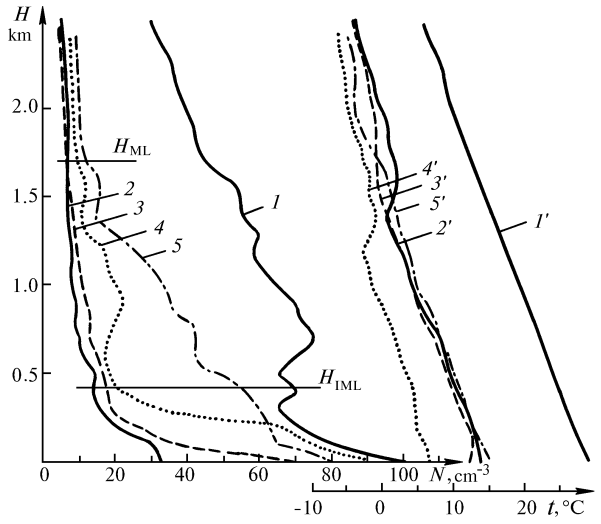

FIG. 5. Transformation of vertical profile of aerosol particle number density (1–5) and air temperature (1′–5′) near Tomsk: 1) May 12, 1984 (17.30 local time); 2) May 13 (15.30); 3) May 13 (22.30); 4) May 15 (17.00); and, 5) May 16 (18.20).

Under the conditions of well heated air, as it was shown in Ref. 28 by the example of Kazakhstan during summer period, the internal mixing layer has no time in day to form. In this case the filling of the basic mixing layer starts immediately after exchange of air mass (Fig. 4 from Ref. 28) over the entire basic mixing layer.

It is possible to summarize by saying that the use of aerosol data allows revealing of the peculiarities of the atmospheric mixing layer formation and dynamics of its development, including the internal one, the knowledge of which is needed both for climatic estimates and calculations of the atmospheric pollution potential.

ACKNOWLEDGMENTS

This work was supported in part by USA Government Department Grant No. R25.

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