SOME RESULTS OF SOUNDING INDUSTRIAL EMISSIONS USING AN AIRBORNE LIDAR "MAKREL–2M"

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Some results of laser sounding of industrial emissions into the atmosphere of the Far East cities are presented. The plume spreads were tracked at a distance of 22 km from emission sources. They kept a stream character over the entire path. Some peculiarities in spreading of industrial emissions when their height coincides with the upper boundary of temperature inversion were revealed. In this case the plumes were balancing below and above the inversion layer and sometimes the inversion was broken through by convective fluxes.

An unfavourable ecological situation in the majority of industrial centers of the country calls for a comprehensive and objective information on composition, origin, and dynamics of the atmospheric emissions from enterprises active in the area under study. For this reason, in 1989 the aircraft–laboratory "Optik–E" of the Institute of Atmospheric Optics was adapted for conducting ecological observations of the atmosphere over cities.

The contact detectors and remote sounding facilities mounted onboard the AN–30 airplane "Optic–E"[1] make it possible to accomplish complex monitoring of air over cities and the underlying surface.

In this paper we discuss some observational results on the emission plume dynamics obtained by the airborne lidar during complex observations of the Far East cities.

A down–viewing lidar "Makrel–2M" with the receiving telescope of 0.2 m in diameter and pulse energy 50 mJ at the wavelength 532 nm was used for sounding along the flight path. The recording system enabled us to acquire vertical sections of the atmosphere with the resolution 5–100 m along the flight line and 1.5–15 m along the vertical direction.[2]

The lidar power potential provided for the possibility of measuring profiles of the extinction coefficient in optically dense plumes by employing the method of asymptotic accumulation.[3] In the case of less dense formations the method of layer–to–layer reconstruction[3] was used for calculating the extinction coefficient. The lidar ratio was assumed to be constant along the sounding path. The sets of lidar returns recorded for each section of the atmosphere were stored on floppy disks.

In this paper we discuss the results of studies of the emission plume dynamics. In such a formulation of the problem it is admissible to assume, in the first approach, that the backscatter signals are proportional to the aerosol mass concentration. (Our technique for direct estimation of mass concentration is discussed below).

From the entire set of recorded data we have chosen three typical cases which most explicitly demonstrate the efficiency of a lidar in application to studies of dynamic processes which cannot be obtained using other techniques.

Shown in Fig. 1 is the transformation of the emission plume from industrial enterprises of Amursk city (Khabarovsk region) when it propagates along the direction to Komsomol'sk–on–Amur. The scheme of sounding is shown in the lower part of Fig 1*d*: the section a was made from *a* windward side of Amursk at a distance of 2 km from the emission source ($x = -2$ km), a section <u>*b*</u> was made at a distance of 2 km from the source along the wind direction ($x = +2$ km), and a section <u>*c*</u> was made at a distance of 22 km from the source ($x = +22$ km) at the entrance to Komsomol'sk–on–Amur. All sections were made perpendicular to the wind direction from a flight altitude of 250 m. As the data of the thermodynamic system mounted onboard the airplane–laboratory showed, the temperature inversion was observed at the 190–m altitude. Wind velocity was determined using the airplane navigation system during the flight. The data on backscattering signals obtained during the flights (dashed lines *a*, *b*, and *c* in Fig. 1*d*) are presented in Figs. 1*a*, *b*, and *c*, respectively. In these figures, the value of backscattering signals related to the mass concentration $M = 0.01$ mg/m^3 is taken as a unit isogram.

Figure 1*a* shows that the air supplied to Amursk is clear. It should be noted, however, that below the temperature inversion layer there is insignificant increase in the aerosol concentration due to natural processes. The curves of isograms in this layer reflect the action of the underlying surface, the effect of which does not occur above the temperature inversion (the curve near 200 m is more monotonic). There are no emission sources on this side of the town.

As the dashed line *b* in Fig. 1 shows, the plume going out from Amursk is sufficiently dense at a distance of 2 km from the town and involves almost all local emissions. This is concentrated in the 55–190–m layer and its width is 1200 m. At the same time, in the mass concentration field within the plume we observed several streams with different intensities (Fig. 1). The plume is limited from above by the temperature inversion layer (190 m). The absence of disturbances in the unit isogram at the altitudes above the inversion layer is indicative of the fact that the temperature of emissions at such distances from the source is close to that of the ambient air. Shown in Fig. 1*b* is also a secondary, less intense source located at an altitude of 100 m. Near Amursk at an altitude below 50 m there are no sources of aerosol emissions.

The section (see Fig. 1*c*) made perpendicular to the direction of the emission transport at this altitude is indicative of variations within the plume passed a distance

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of 20 km. On the other hand, the data acquired in this section give more accurate information about characteristics of the air coming to Komsomol'sk–on–Amur from South. As can be seen from Fig. 1, the plume increases by a factor of two and its cross section reaches 2500 m. At the same time, the vertical dimension decreases down to 80–160 m. A balance between the plume "floating up" and the blocking action of the temperature inversion is observed here. And, finally, even though the time of plume transport from Amursk to Komsomol'sk–on–Amur is sufficiently long (about 32 min at wind velocity of 12 m/s) it keeps a stream structure of the primary emission. The aerosol concentration within the plume decreases by a factor of three which is obviously due to its broadening. The plume from the secondary source fixed in section of Fig. 1*b* has not been detected at this distance. It is more likely that this plume is coupled with the basic plume. Noteworthy in Fig. 1*c* is a wide relatively homogeneous region within the isogram 10. Below this region there is the isogram 3. The existence of the region with high aerosol concentration below the plume shows that an intense growth of particles takes place in it due to coagulation and condensation which strengthen their gravitational sedimentation. The "fall–out" of particles is observed in the layer from 130 to 45 m. It is reasonable to assume that sedimented particles reach the surface down a stream. But it is impossible to follow this process since the effluent from plant stacks of Komsomol'sk–on–Amur make their own contribution to aerosol air pollution.

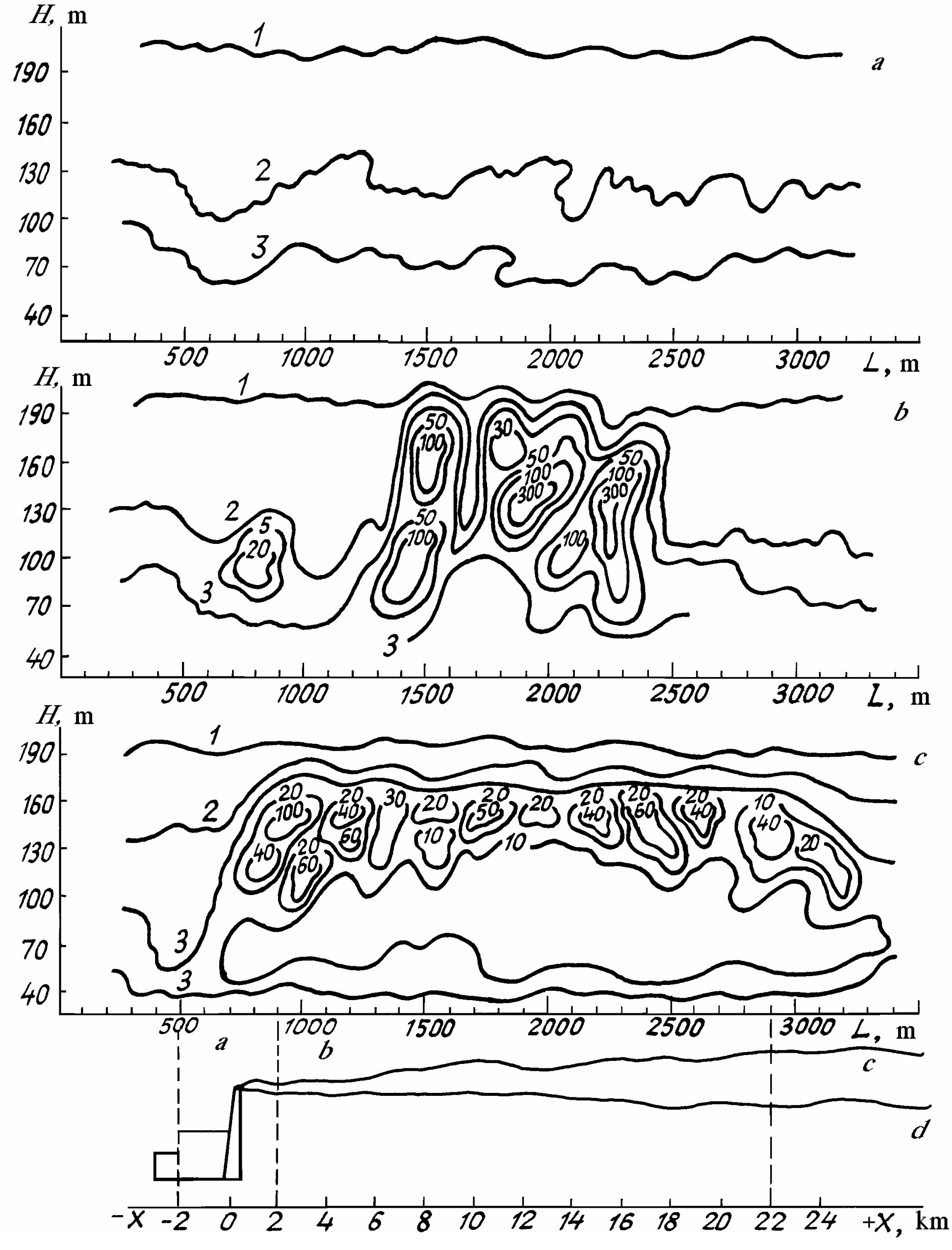

FIG. 1. Vertical distribution of aerosol mass concentration (relative units) near Amursk in December 18, 1990: a) a windword side, b) at 2 km *from the stack edge, c) at* 22 km *from the stack edge, and d) the scheme of sounding.*

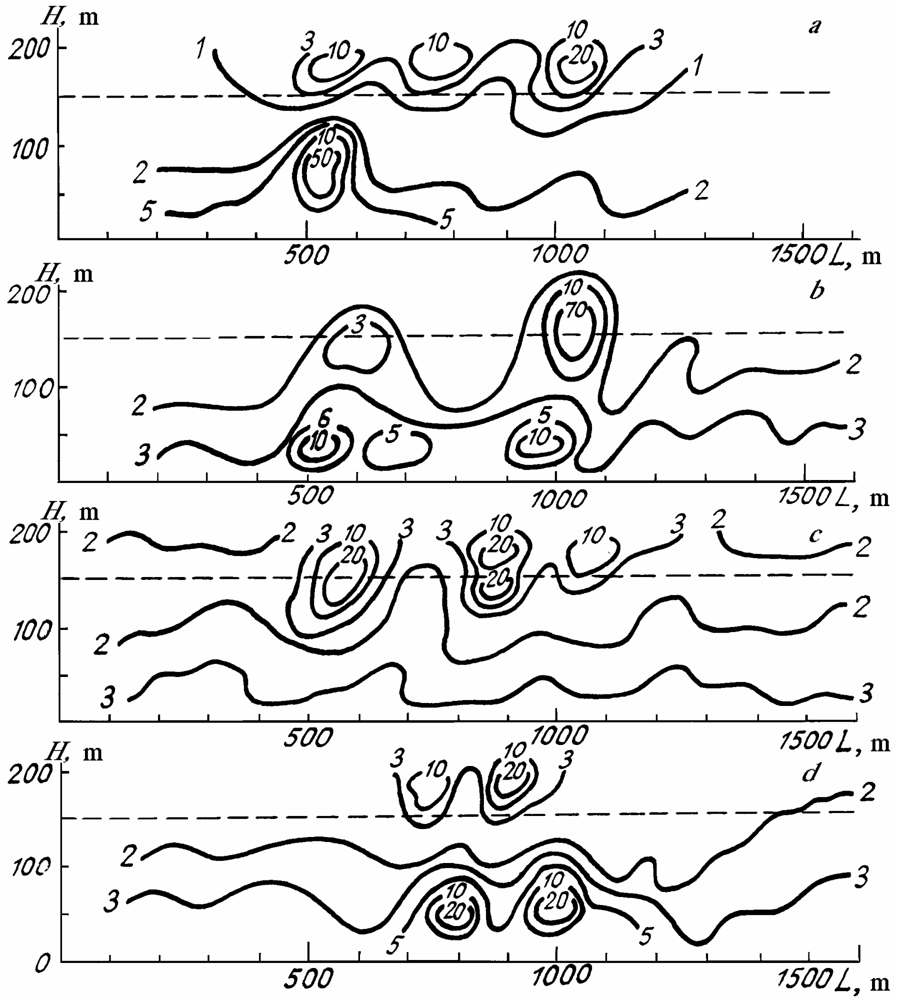

FIG. 2. Vertical section of plumes from the HEPP–1 in Khabarovsk in December 14, 1990: a) 11 h 31 min, *b)* 11 h 39 min, *c)* 11 h 46 min, *and d)* 12 h 27 min *(local time); solid curves are for aerosol mass concentration (relative units) and dashed lines for the level of inversion.*

The description of plume dynamics in terms of backscattering allows one to give a sufficiently comprehensive description of the spatio–temporal structure of the emission spreading. To calculate anthropogenic–influenced contribution of a specific pollutant and to predict ecological situation in the town the weight or gravimetric method is employed by the environmental protection services. The inversion of backscattering coefficients to aerosol mass concentration makes serious problems which are mostly caused by a wide range of lidar ratio variability as a function of microphysical and chemical composition of sounded particles.[4]

The procedure of dual etalon transport was employed to estimate mass concentration based on backscattering signals.

Since the gravimetric method requires certain filter exposition in air flux, a number of particles reasonable for the analysis is collected over a long path at the flight altitude. The aircraft speed must be taken into account.

The operation zone of the lidar is lower than the intaking device in the filter–ventilator by more than 30 m and under strong space–time variation in the particle concentration field it does not allow the lidar returns averaged during this flight to be directly intercompared with the data of gravimetric methods. Therefore at the first stage of our technique we calculated the transition coefficient when passing from gravimetry to the averaged values of scattering coefficients measured with an airborne nephelometer which operated during the flight synchronously with the help of a filter–ventilating device. This procedure was carried out in each town at different altitudes. Then we digitized the averaged values of the lidar return based on the mean values of the scattering coefficient at given altitudes. Our results revealed the error not higher than 20% in mass concentration measurements using the gravimetric method. The certified error in recording (higher than 10%) was determined from the nephelometer signal proportional to the scattering coefficient. The error in recording the backscattering signal was about 25%. Thus the dual etalon transport from the weight method to the lidar one resulted in about 35% estimate error in the lidar aerosol mass concentration data. A systematic nature of the principal error in determining mass concentration should be noted in such a procedure. Therefore, in this paper the plume dynamics is described in arbitrary units of the lidar returns which provides a more detailed representation of a spatio–temporal structure of the phenomenon under study.

The second peculiarity which should be considered here was observed in Khabarovsk when sounding the emission plumes from the heat and electric power plant–1 (HEPP–1) sumultaneously coming from four stacks of equal heights. During the observations the height of the emission plumes was close to the altitude of upper boundary of the temperature inversion recorded at 175 m.

The sounding was carried out from an altitude of 250 m. The airplane flew at a distance of 400–500 m from the stack edge perpendicularly to the wind direction. Seventeen approaches to the HEPP–1 were executed during 2.5 h. Four of the thusly obtained sections are shown in Fig. 2. The most important result presented in Fig. 2 is the observed process of "pulsation" of a vertical structure of plumes (in time and space) at a boundary of the temperature inversion.

As can be seen from Fig. 2*a*, at the starting period of sounding at 11 h 31 min (local time) three of the four plumes were located above the inversion, and one of them was spreading below it at an altitude of about 50 m. In approximately 8 min (Fig. 2*b*) only one plume remained at the level of the inversion, two plumes went down to the ground layer, their cores were observed at altitudes between 20 and 30 m. The fourth plume was splitted into two. One trace was detected at the level of the inversion and the other was in the ground layer. The splitting also affected the concentration of aerosol substance. Seven minutes later (Fig. 2*c*) all four plumes ascended above the inversion or reached its level. Moreover one of the plumes "dived" under the other.

The data in Figs. 2*a*–2*c* reveal that the period of variations in plume heights is of order of several minutes. However, the process of height variations is sufficiently stable in time what is demonstrated by Fig. 2*d* obtained in an hour after the sounding start. Figure 2*d* shows that the plume balance keeps on near the temperature inversion level, two plumes descended down the ground and two plumes spread above the inversion.

In addition to the vertical dynamics of plumes, the variations in concentration of aerosol particles significantly exceeding possible measurement errors can be determined based on the sounding result reprented in Fig. 2. The signals from the plumes vary by a factor of 20. Direct flights of the laboratory–aircraft through the plumes confirm the presence of noticeable variations in particle concentration based both on the results of the photoelectric counter, nephelometer, and gravimetry. The estimates do not reveal any relations between these variations and those in the plume cross section. It is more likely that during the experiment the technological conditions at the HEPP–1 were changed. This is also confirmed by the results of sounding at the HEPP–2 and the HEPP–3 where such variations were not fixed.

As can be seen from the aforementioned data, the near–ground temperature inversions to an essential degree determine the peculiarities in spreading and dynamics of plumes and stimulate accumulation of suspended substances in the ground layer of the atmosphere. It is generally believed that the temperature inversion makes insurmountable barrier for emissions from sources located below their upper boundary.[5] However, there are several papers describing penetration of pollutants through the inversion layer.[6,7] During the aircraft sounding we have succeeded in recording an especially pronounced event of aerosol particle penetrations through the inversion layer.

This case is shown in Fig. 3. Sounding was carried out in December 17, 1990 over Komsomol'sk–on–Amur at an altitude of 300 m in a day after air mass exchange. As was shown in Ref. 8, the aerosol conditions could not be established during a day. Therefore the mass concentration in the section has low quantities. During the experiment there were two inversions over the town which were well observed on the vertical profile of temperature in the right part of Fig. 3 taken with the airborne thermodynamic system before reaching the sounding path.

Figure 3 contains only a fragment of the vertical section accomplished over the entire town with extension of more than 20 km. As can be seen from the figure, the near–ground inversion with the upper boundary at about 90 m really contributes to accumulation of aerosols, the isograms are close to each other. At the same time, at a distance of 1400 m there are two aerosol out breaks through the inversion layer, one of which reaches the base of the second (upper) inversion layer. All in all nine such outbreaks were detected along the 20 km path, the distance between them varied from 1400 to 2400 m.

Unfortunately, because of the lack of detailed information about the spatial distribution of the vertical temperature profile we could not determine unambiguously a mechanism of the emission breaking through the blocking inversion layer. This is due to local overheating of the emission or there are some other dynamic factors.

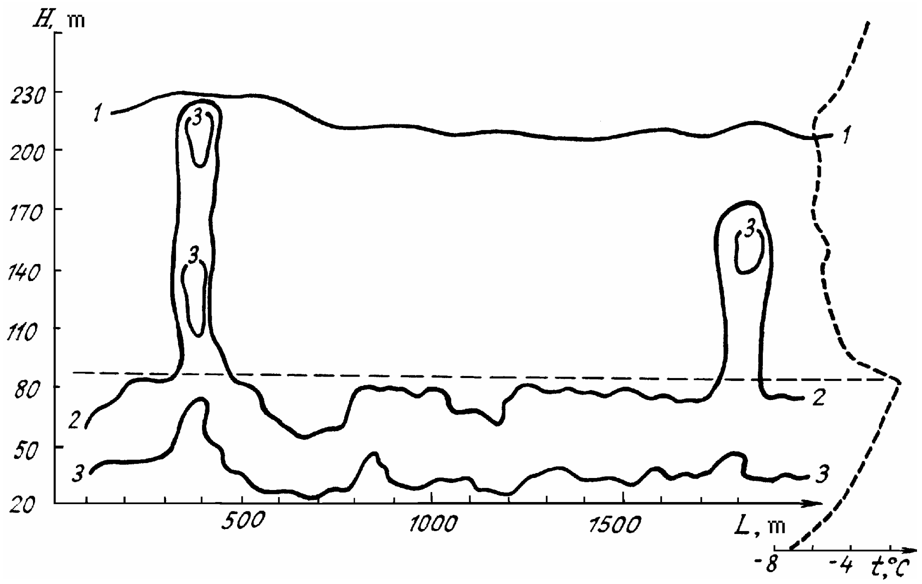

FIG. 3. Vertical section of aerosol mass concentration (relative units) are shown by solid lines and vertical distribution of air temperature – dashed lines over Komsomol'sk–on–Amur in December 17, 1990.

In conclusion t should be noted that in this paper we gave only some results of the work, which illustrate most explicitly the advantages of remote methods for sounding in conjunction with the contact ones combined in an aircraft–laboratory complex. We should emphasize that at least two of the three aforementioned results cannot be obtained using the other methods. In our first publication devoted to this problem we would like to acknowledge the chairman of the Khabarovsk Regional Environmental Protection Committee A.A. Kolenchenko, the members of the regional and town committees in Khabarovsk and Komsomol'sk–on–Amur who are the initiators and supporters of these works.

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