ELEVATED INVERSIONS IN MOSCOW AND AN EVALUATION OF THEIR EFFECT ON THE STATE OF AIR BASIN

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The data on recurrence and heights of elevated inversions in Moscow are derived from continuous acoustic sounding with the acoustic radar "EKhO–1" in 1988–1992. An integral index of a comparative estimate of the effect of elevated inversions on conditions of the admixtures dispersal in the underinversion layer is proposed.

1. INTRODUCTION

Concentrations of contaminants in the atmospheric boundary layer (ABL) are known to be determined by joint action of several factors, which are related to its both dynamic and thermal structure.[1,8] One of these factors is the elevated temperature inversions in ABL. If such an inversion occurs, the mixing layer is bounded by the level of its base (at least, at $\gamma > 0$ in the underinversion layer where $\gamma = -\frac{dT}{dz}$ is the vertical temperature lapse rate with a positive sign down in temperature, which is commonly used in meteorology). If both surface and elevated inversions occur in the ABL simultaneously, i.e., where $\gamma < 0$, the mixing layer height near the ground is sometimes identified as the power of near ground inversion, no matter at what altitude over it the elevated one occurs.[3] However when the near ground inversion is very weak and T increases rapidly in an overlying layer the base of a "barrier" inversion layer can be a real limit of vertical admixture propagation. Thus observations of the elevated inversions in ABL can provide model calculations of pollution levels with important input information. Acoustic radars (sodars) are among the most efficient methods of such observations.

2. TECHNIQUE AND PROCEDURE OF OBSERVATIONS

The Chair of Meteorology and Climatology of the Moscow State University (MSU) and the Institute of Atmospheric Physics have jointly carried out a long–term experiment on continuous acoustic sounding of the lower 800 m air layer over Moscow during 1988–1992. A vertically looking sodar "EKhO–1" was installed at the Meteorological Observatory of the Moscow State University in the region of not compact building up in the southwestern area of Moscow city. Its operating frequency was 1666 Hz, sounding range was 800 m, and duration and power of a sounding pulse were 75 ms and 75 W, respectively. The pulse repetition frequency was 0.1 s^{-1}.

A type of temperature stratification, heights of inversion layers, and height of a mixing layer were determined from a structure of small–scale temperature turbulence on a facsimile records obtained each hour. The method of encoding is described in Ref. 3. The results of sodar observations in Moscow were partially published in Refs. 2, 4–7. A more pronounced blackening at heights of a turbulent layer on a facsimile record was accepted as necessary and sufficient evidence that the elevated inversion exists. Correlation between the sodar images of layers and real inversions is supported by their comparison with simultaneous profiles of T obtained by direct measurement methods.[9,10,12–14] However, some authors[11] believe that the upper boundary of the blackening layer on the record can be lower than the real top of an inversion. Even though the sodar estimates of the top (and, consequently, the power) are somewhat lower, they can be considered unbiased when making relative comparison of different inversions. So, in what follows, the sodar is assumed to be capable of reliably recording the base and top heights and the life time of a turbulent layer which can be highly accurate identified with the elevated temperature inversion. Possible errors in this approach were considered at length in Ref.4.

However, it is possible to accurately measure inversion intensity, i.e., temperature difference at its top and base, using the sodar data. The power of the backscattered acoustic signal detected from regions of inversions in the atmosphere and expressed as a function of degree of facsimile record blackening is proportional to a structure characteristic of the temperature pulsations C_T^2. The structure characteristic is related not only to the potential temperature gradient Θ but also to vertical wind shear, in the field of which the forced differences of Θ from point to point are created.[9]

Nevertheless, one can try to desiribe the value of γ indirectly within the inversion layer. The possibility of determining the degree of ABL stability in terms of the known Paskuil classes from the sodar facsimile records has been tested in Ref. 16. An indirect relation of the blackening level of a facsimile record to the value of γ was also reported in Ref. 12.

Let us assume three gradations: 0 – "weak," 1 – "moderate," and 2– "strong" inversions (by analogy with qualitative determination of precipitation intensity degree and solar disk state accepted in meteorology). A zero degree is related to weak light–grey images of layers with indistinct morphology and partly smeared boundaries when the layer is not recorded continuously in time but is intermitted with blank sections on the record. The first degree is typical for the majority of images; it corresponds to equally dark–grey layers with distinct boundaries. The images are necessarily continuous without gaps in the records. The second degree characterizes only well developed bright–black solid layers without halftones and intermediate transitions in color, with distinct boundaries. The examples of facsimile records of elevated inversions of different order of intensity are shown in Fig. 1.

The larger number of gradations can increase errors due to different wind shear with the same value of γ which affects the return signal intensity. Moreover, the record contrast can spontaneously change a little due to the

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instrumentation. Therefore the images of elevated layers are classified not only based on a general background of facsimile record blackening but also based on their morphology and degree of contrast. It is believed that the three gradations are optimal and allow one to extract the most reliable indirect information about the inversion power with a relatively small error in its determination.

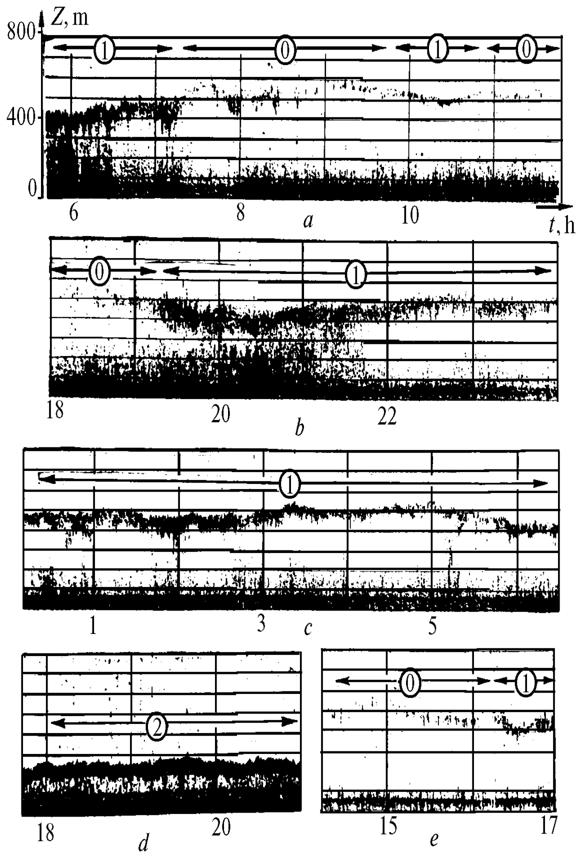

FIG. 1. The sodar recording of elevated inversions of various intensity. a – January 19, 1991 (morning); b – March 20, 1991; c – January 21, 1991; d – November 26, 1991; and, e – January 19, 1991 (day).

Thus, not only the base and top heights were measured but also the inversion power was estimated based on the degree of blackening, the contrast of boundaries, and general morphology of the layer image, every hour from the continuous facsimile record in the presence of an elevated inversion.

3. GENERAL RESULTS OF OBSERVATIONS IN MOSCOW

Table I represents the recurrence interval of inversions based on sodar observations in Moscow during the period between November 1988 and December 1991 and in summer 1992. As is seen no distinct seasonal behavior can be revealed from these data. Only one pronounced maximum is observed late in fall and early in winter when the elevated inversions were recorded two times more frequently than would commonly be the case (to 30% and higher). It is likely created by a joint action of two factors: processes of settling during a cold season at periphery of an extended Siberian pressure maximum (which already exists in November) and long–term above– and undercloud inversions connected with stratified cloudiness and fogs late in fall, especially under thermal advection.[4]

TABLE I. Annual behavior of recurrence of elevated inversions in Moscow based on sodar observations at the Moscow State University in 1988–1992. , given in percents.

Month	Time of observations, hrs	%
I	1494	21.0
II	1385	19.7
III	1771	13.5
IV	1856	12.5
V	1959	17.6
VI	1240	18.2
VII	2031	15.2
VIII	1528	14.4
IX	1139	16.0
X	1822	14.5
XI	1696	23.4
XII	1582	25.8

In other remaining seasons the frequency of elevated inversion records did not differ greatly. Reliability of a slightly pronounced minimum in spring and a complementary maximum in summer needs for further verification. It is quite probable that the minimum occurs due to lower occurrence of sinking inversions in early spring, when the elevated inversions caused by morning ascend of the night radiation cooling inversions are yet infrequent. The maximum can obviously reflect more frequent recording of such inversions in the morning in May and June. The seasonal peculiarities of elevated inversions of different origin are analyzed in Ref. 4.

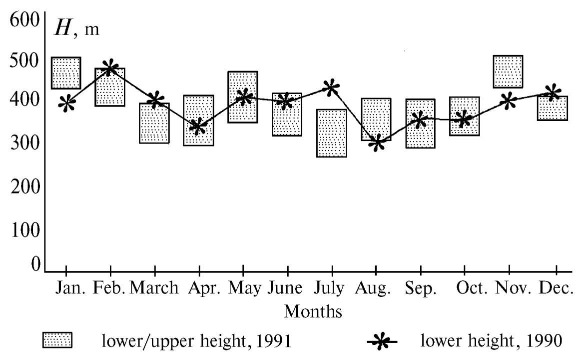

FIG. 2. Annual behavior of mean heights of elevated inversions in Moscow.

Depicted in Fig. 2 is the annual behavior of the lower boundary height of elevated inversions in 1990 and 1991 and of the upper boundary in 1991. There are two weak maxima in early summer and winter. The first maximum can be related to the daytime convection development; the second one can be caused both by frequent sinking inversions during this season at high altitudes and by a general ascend of layers observed simultaneously with near ground inversions since the latter have noticeably larger depth in winter.

4. AN INTEGRAL ESTIMATE OF ECOLOGICAL HAZARD OF ELEVATED INVERSIONS

It is clear that the record of elevated inversions alone is insufficient to determine the extent to which they may be dangerous for the lower atmosphere. In each specific case the conditions of harmful admixture dispersal depend on a number of factors: the inversion base height, its intensity, lifetime as well as on the depth of the inversion layer (i.e., the difference between the inversion top and base heights). The lower is the inversion and the longer is its lifetime, the more probable is the increase of a contaminating specie concentration in the layer under inversion. Of course, here we mean the emissions from low sources, like heavy traffic and low stacks of heat and electric power plants (CO, carbon black, etc.). Concentrations of pollutants from tall stacks whose mouths are higher than the inversion base (e.g., SO_2) can be lowered.[1] At the same time, strictly speaking, the elevated inversion cannot be considered as an absolutely inpenetrable barrier. If having a sufficiently high lifting power, the overheated atmospheric emissions are able to penetrate through a relatively thin inversion layer of low intensity. Hence, the more powerful is this layer and the more rapid is the temperature increase within its limits, the higher is the probability of a dangerous level of pollution near ground.

Synchronous sodar and radiosonde observations allow one to take into account the effect of temperature stratification and mean wind velocity in the layer under iversion (the latter can also be obtained from the results of acoustic sounding with a Doppler three–component sodar). Let the following parameter be introduced for the simplest comparative estimate of the effect of elevated inversions on the air state:

$$K = (t\,h\,(f + 1)/H\,U)\,\exp\,(-\,0.5(\gamma - \gamma_a))\,, \qquad (1)$$

where t is the lifetime of an elevated inversion layer on a facsimile records; h is the layer mean power; H is the base mean height; f is the dimensionless analog of inversion intensity which changes between 0 and 2 according to the above given gradations; U is the mean wind velocity in the layer from the ground up to the inversion base; γ is the lapse rate of the temperature in the ground layer; γ_a is the dry adiabatic temperature lapse rate. Dimensionality of the parameter K is [3600 s^2/m].

With a strictly neutral stratification the power multiplier reduces to unit, in an unstable atmosphere it decreases, and in a stable one it increases. The effects of stratification and horizontal removal factors in the underinversion layer are assumed to be comparable. With the account of this assumption the coefficient – 0.5 was chosen so that the power multiplier varies practically within the order of magnitude (from 0.6 to 5.0 in 56 cases of long–term inversions in 1991). The value of U also varies within the similar limits (from 0.5 to 12.7 m/s for the same events).

The values of the introduced parameter K were calculated for continuous elevated inversions with duration longer than 5 hrs based on 11–months observations in 1991. Altogether there were 56 such cases recorded with the MSU sodar during this period.

The value of t is the duration (in hours) of continuous observation of a single elevated inversion on a facsimile record. The values of h, H, and f were obtained by averaging the corresponding hourly mean values. The values of U and γ were calculated from the radiosonde results obtained at the nearest radiosonde station of the Central Aerological Observatory (Dolgoprudnyi, 25 km far from Moscow). The value of γ was determined in the layer from the control values near the ground and up to 100 m, i.e. the first level of counts. If an inversion occurred between the periods of radiosounding, then we used the data of one or two nearest launchings with the account for diurnal behavior of γ in the lower layer.

Based on the results of K calculations for inversions of duration ≥ 5 h its smallest value was 0.1 and the largest one was 12.4 in 1991. Thus the parameter K varies between two orders of magnitude. Mathematical expectation of K for sampling of 56 cases was 1.9 and only in 14 cases it was larger than 1.9. Examples of calculations are given in Table II.

TABLE II. Examples of calculations of estimating the effect of elevated inversions on conditions of the admixtures dispersal (parameter K), 1991.

Date	h, m	t, h	$(f + 1)$	H, m	U, m/s	K, 3600 s^2/m
18–19/I	43	37	1.6	459	4.9	1.0
7/III	44	6	1.3	183	1.0	9.4
11/III	176	5	2.6	150	3.,7	5.0
7–8/V	88	10	1.6	384	2.8	1.3
11/VI	112	5	1.4	276	2.0	0.9
18/VI	82	15	1.4	418	3.5	2.5
30/VIII	96	7	1.6	451	6.5	0.4
20–21/IX	70	19	1.6	240	1.3	8.2
6/X	84	14	1.5	425	2.4	1.2
5/XI	106	9	1.7	620	12.7	0.3
14/XI	56	5	1.6	570	11.1	0.1
17/XI	95	9	1.7	258	0.5	12.4
25–28/XI	49	77	1.9	446	4.8	3.7
29/XI	40	5	1.0	340	2.8	0.2

As is seen, the extremely long elevated inversions, in contrast to a common opinion, are not always dangerous from the view point of conditions of an admixture dispersal. Thus the inversion observed in November 1991 with the largest lifetime (77 h) resulted from deposition of a vast anticyclone at its periphery and subsequent development of stratified cloudiness under its base. It had a small value K = 3.7. At the same time the inversion with a far shorter lifetime (9 h.) on the same month which could be related to dynamic and radiative processes at the edge of a cloud cover turned out to be much more dangerous: K = 12.4.

It should also be noted that the majority of cases with the large K values took place in a cold season. According to our results this parameter did not exceed 2.5 in summer.

Summing up what has been said above it should be noted that the proposed parameter is only an approximate comparative estimate of a possible level of pollution created by emissions from sources under an elevated inversion layer. It can be used for analyzing the conditions of admixture dispersal in the lower atmosphere when the simplest sodar observations are complemented with radiosounding with a sufficiently high vertical resolution.

5. CONCLUSIONS

1) The data of continuous acoustic sounding of the lower 800 m layer over Moscow in 1988–1992 do not reveal any annual behavior of both the frequency of occurrence and heights of the elevated temperature inversions which, in fact, is very complicated. Such inversions were recorded most often in November and December; they were somewhat higher in winter and summer and relatively lower in spring and fall.

2) The base height of elevated inversions in Moscow varies in a month an average from 300 to 450 m.

3) Classification of facsimile records of elevated inversion images which indirectly characterizes the inversion intensity has been proposed. Based on this classification we introduced the parameter of the generalized estimate of the effect of elevated inversions on the state of air basin. Its values vary within wide limits what demonstrates substantially different effects of elevated inversions on conditions of the admixtures dispersal in the atmosphere.

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