INFLUENCE OF SYNOPTIC CONDITIONS ON THE MIXING LAYER HEIGHT

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The mixing layer height, derived by vertical sodar facsimile chart records, is considered. Some peculiarities of it connected with synoptic situation and type of air masses are investigated during one month in Moscow. The noticeable influence of advective factors on the daily convective mixing layer development is revealed. The simple synoptic situations classification on the basis of temperature advectional effects is proposed.

1. RECORDING MIXING LAYER WITH RADIOSONDES AND SONAR

The concept of a "mixing layer" was introduced by Holzworth,[9] and nowadays it is widely used in calculating the levels of atmospheric pollution.[4,5] However, the experimental technique for detecting the mixing layer based on the data of radiosondes and maximum atmospheric temperature near the ground is incomplete, since mixing the separate air particles due to dynamic turbulence generated by the vertical wind shift in a stable stratified atmosphere is not taken into account. Besides, ordinary radiosondes every so often are not in a position to detect elevated inversions, which prevent upward scattering of the impurities, because of low height resolution. The height of mixing layer (HML) determined in accordance with Ref. 9 evidences solely the largest among its possible values (morning or diurnal) under the condition of sluggishness of processes in the lower atmosphere after radiosonde launching.

More trustworthy and operative estimates of HML can be obtained with acoustic sounding the atmospheric boundary layer. Figure 1 shows examples of an EKhO–1 vertical sodar facsimile chart records obtained in Moscow and represented in the "time–height" coordinates. The sodar operating frequency is 1 666 Hz, the height sounding range is 800 m, sound pulses are repeated every 10 s.

In the case of ground inversion, that is, negative temperature lapse ($\gamma < 0$, where $\gamma^* = -\partial T/\partial z$), the mixing layer is taken to be equal to the upper boundary of its facsimile chart according to the technique described in Ref. 3. If the elevated inversion exists above the ground one (Fig. 1*c*), then the boundary of turbulent layer in the lower part of the record is also identified with HML. In the case of existance of convective ($\gamma \geq \gamma_a$) or weakly stable stratifications ($0 < \gamma < \gamma_a$) below the elevated inversion, HML is determined by the height of the elevated layer base (Figs. 1*a* and *e*). If the stratification is weakly stable and elevated inversions are lacking, HML is considered to be equal to the height of weak disordered images near the Earth's surface. They are created by the sound scattering within the boundary drought–resistant layer, where the increase of potential temperature θ as the height increases occurs in parallel with the wind shift. One can see from Fig. 1*d* that this layer gradually transforms into the ground inversion as the surface is cooled in the evening and γ decreases. To the right of the mark of height *H* indicating HML, the temperature lapse γ becomes already inverse, that is, not only potential temperature θ, but also the normal one *T* increase as height increases.

It is more complicated problem to determine the HML from the sodar records under conditions of free convection being not limited by the upper stable layer within the sounding range. It is well known that the sonar records at such range frequencies the sound scattered only by inhomogeneities of inertial interval of turbulent spectrum. The fluctuations having lesser wave number and relating to energy interval are not manifested on the sodar records. Therefore, the images of vertical structures, so–called "feathers", (Fig. 1*b*) are essentially understated as compared to the true height of upward streams in convective cells. For example, in such cases Maukhan et al.[10] considered the mixing layer to be equal to vertical range of their sodar. M.A. Kallistratova et al.,[3] basing on the results of experimental comparisons by Singal et al.,[11] proposed for the height of "feathers" the correction factor 4.

The sodar technique has some disadvantages. Thus, in the case of rigorously neutral stratification ($\gamma = \gamma_a$) the sound, in practice, is not scattered back and it is impossible to determine the HML from records. Fortunately, such situations with the lack of the facsimile chart records are very rare. For elevated inversion, separated from the drought–resistant layer (Fig. 1*e*) near the ground surface, the mixing layer may be considered in two ways. It is not clear is it equal to the inversion base or the height of area with weak return signal under inversion. Besides, the quadruple height of the "feathers" corresponds only approximately to the level of blocking up stable layer. For concrete geographic conditions the value of such a correction must be refined individually depending on the level of record contrast. Nevertheless, we shall start from the technique proposed in Ref. 3 as the closest to reality. A detailed review of existing technique for determination of HML has been presented by M.S. Pekur.[6]

* Here we use the lapse definition traditional in meteorology, the lapse is positive if meteorological element decreases with height increasing.

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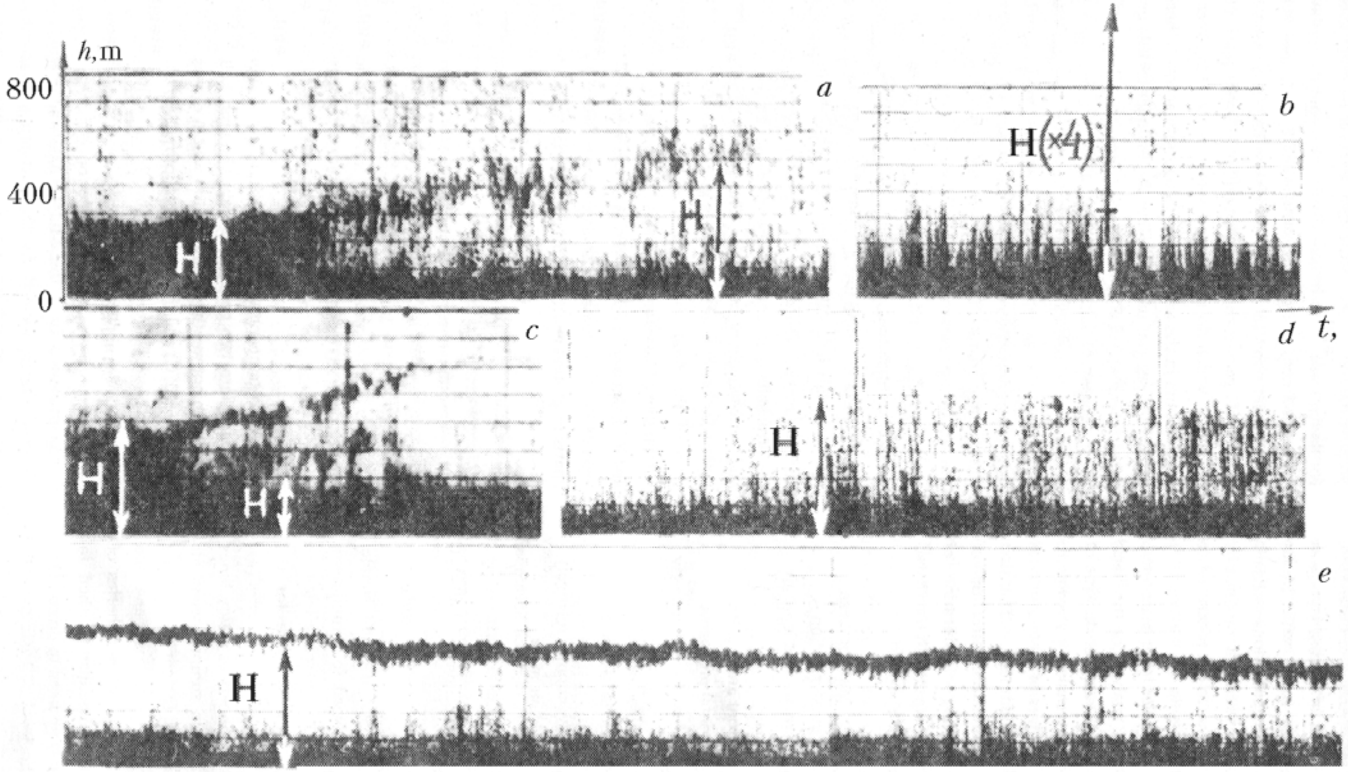

FIG. 1. Determination of the mixing layer height based on sodar facsimile records at different temperature stratification: escape from the Earth of the radiation inversion layer in the morning (a), free convection (b), elevated inversion layers above the surface layer (c), forming of surface inversion from the surface drought–resistant layer (d), and long inversion of subsidence (e).

2. ANALYSIS OF SYNOPTIC CONDITIONS

This paper describes the regularities in HML behavior depending on synoptic conditions. We demonstrate these regularities with example of one summer month. From June, 24 till July, 25, 1991 the "EKhO–1" sonar set operated in Ostankino, the northern part of Moscow. The height of mixing layer was determined from facsimile chart records made with 1 hour intervals. Records, which were made under conditions of heavy and moderate precipitation (in accordance with data obtained by nearest meteorological station (VDNKh)), were not processed to avoid errors connected with acoustic noise.

When considering synoptic processes at least two approaches are possible: on the basis of analysis of the baric topography charts or on the basis of determination of the type of predominant air mass. The second approach makes it possible to trace the nature of the weather and the ranges of meteorological values which are typical for the given conditions. The first approach makes it possible to determine the direction of changing these conditions. The following classification of synoptic situations can be proposed in accordance with the "baric" approach.

Types of situations	Main process
1. Small–lapse baric field in the col, in the center of anticyclone, spur or on the axis of the ridge	Transformation, formation of local air mass
2. Center of cyclone, secondary cyclone or the region of the narrow gully axis	Front area, active frontal processes
3 (a). West or north periphery of anticyclone or ridge. (b). Forepart of cyclone, east or north periphery of narrow gully	Advection of relatively warm air mass
4 (a). East or south periphery of anticyclone or ridge. (b). Back area of cyclone, west or south periphery of narrow gully	Advection of relatively cold air mass
5. Warm sector of cyclone	Advection of relatively warm air mass

The above–mentioned scheme is descriptive and simple, and the number of taxonomic units is reduced to a minimum. The basis for this scheme are synoptic processes related to specific parts of baric relief. They form the base for the integration of allied shapes connected with common process (for example, back area of cyclones and east periphery of anticyclones and spurs). It should be noted that it is in summer when air masses are fastly transformed above the land, the correctness of a one–to–one correspondence between the situations and the advection nature is beyond question. Adjacent peripheries of neighboring baric formations are sometimes distinguished in isobar curvature.[7] In our opinion, there is no need to do so. Our task is to reveal the differences at the level of basic synoptic processes. From this point of view there is no any pronounced boundary between the subtypes (a) and (b) since the case at hand is the advection with common sign. Therefore we shall use only 5 main types without separating them in more detail.

In most cases the separation of them is not difficult. The boundaries of type 5 are the warm and cold fronts, those of types 3 and 4 are fronts and lines of zero advection on the axes of ridges. They are usually localized in time within 2 to 3 hours. The boundary of type 1 is slightly subjective. To determine it we propose the following criteria: zero value of barometric tendency (or its decrease down to 0.2–0.3 GPa per 3 hours); calm or very weak wind near the ground surface (≤ 2 m/s); low velocity of geostrophic wind (about 10–15 m/s) at 850 GPa; and, the low values of geostrophic component of temperature advection $(\partial T/\partial t)_a$, which do not exceed some tenths of degrees Celsius per 12 hours in the same area. Taking into account these values as a whole, we can usually define the boundaries of a given type with an accuracy of some hours.

Analysis of air masses was made on the basis of their geographic classification. Initially the type of mass was considered to be appropriate to an assumed source of its origination determined from the return paths of air particles on the synoptic charts. Then to refine the identification of the type the following parameters were used: average daily T_{ad}, maximum T_{max}, and minimum T_{min} temperatures of air, °C; pseudopotential temperature θ_{ps}, °C; water vapor pressure e, GPa; absolute humidity a, g/m^3; specific humidity q, g/kg; humidity deficit d, GPa; least daily relative humidity f_{min}, %; visibility D, km; dimensionless index of aerosol optical depth of the atmosphere τ; and, condensation system, i.e., type of clouds and atmospheric phenomena. The ranges of values, which are typical for various air masses, are given in Refs. 1, 2, and 8. The time of the final change of mass type due to advection or completion of transformation was determined by variations of T_{ad} and θ_{ps} from day to day as well as by the values of $(\partial T/\partial t)_a$ at the level of 850 GPa. Synoptic analysis was performed on the basis of charts of ground analysis, ring ones for European territory of the former USSR and high–altitude ones (AT_{850} and AT_{500}) as well as on the basis of the observations material obtained at Meteorological Observatory of the Moscow State University and the radiosonde observations performed at Central Aerological Observatory (CAO). The values of τ are amiablely presented by G.M. Abakumova.

3. PECULIARITIES OF THE WEATHER AT THE PERIOD OF OBSERVATIONS

As to temperature regime, the month under study can be separated into two periods, namely, the first half of month till July 3 with hot weather (temperature was in excess of the normal one by 8–10°C) and the second half of month with cool weather (T_{ad} was 1–2°C below than the mean value). From the standpoint of synoptic situation the first week (till June 30) was characterized by a predominance of continental tropical air (CTA) incoming from the Middle Asia and Kazakhstan, with Moscow region located in the western and south–western periphery of anticyclone (type 3). Then during four days the observation point was in the region of the axis of a large ridge, being a prolongation of the Azores pressure maximum. The baric field was diffuse, practically with zero values of $(\partial T/\partial t)_a$ both near the ground and at the altitudes (Fig. 2*a*, type 1). In this case the area of continental tropical air was rapidly transformed to the area of continental moderate air (CMA) of tropical origin. It should be noted that under conditions of high insolation in the middle of summer such a transformation even at the Moscow latitude has not been finally completed since the shaped local air mass occupied, in accordance with the values of the majority of parameters, the intermediate position between the continental tropical air and continental moderate air of tropical origin in the classification of main geographic types.

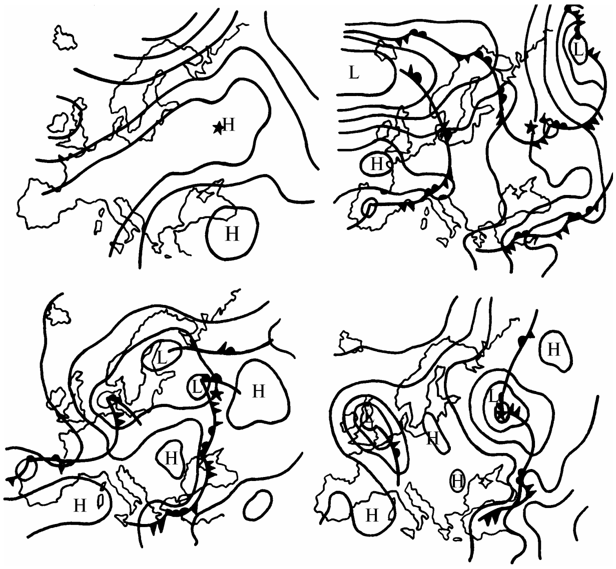

FIG. 2. Fragments of synoptic charts: July 1, 1991, at 12.00, AT_{850} (a); *July 9, 1991, at* 12.00, *ground analysis (b); July 19, 1991 at* 12.00, *ground analysis (c); and, July 24, 1991 at* 12.00, *ground analysis (d). Moscow is shown by an asterisk.*

Beginning on July 4, almost continuous advection of cold occurred initially in the eastern periphery of stationary blocking anticyclone over the Scandinavia, then under conditions of the restored west air–mass transport, which was especially intense from 16 till 23 July (Fig. 2*c*, type 5). During all this time the periodic intrusions of the sea air (moderate one (SMA), typically, and arctic air (SAA) from the northern sector of the Atlantic Ocean from July 5 to July 6) occurred. Each regular portion of the sea moderate air in the rear of atlantic cyclones (with the advection decrease) evolved rapidly over the heated continent into the local air mass. Besides, on July 9 and 10 the ultrapolar entry of continental arctic air (CAA) happened in the Arctic front. The arctic air was partially transformed in temperature regime (Fig. 2*b*, type 4). During the last two days of observations (July 24 and 25) Moscow fell in the center of the wave regenerating to the cyclone in the Polar front (Fig. 2*d*, type 2). Thus, this month was characterized by a wide range of weather conditions. At the same time, the characteristics of meteorological values, apart from the first hot days were close to conventional ones for the middle of summer.

It should be noted that averaging the baric situation and the nature of air mass over 24 hours is so rough because of dynamics of atmospheric processes. We illustrate this situation by the example of one day. The axis of the pressure ridge was detected above Moscow approximately at midnight on July 19. An observation point appeared in the front part of the next cyclone with center in the north–west of the European territory of the former USSR, the type 4 changed into type 3. The east component appeared in the south wind. At about 7–9 o'clock the diffuse warm front pronounced only in cirrus and altostratus cloudiness was observed. Then Moscow fell into the warm sector (Fig. 2*c*), in the southern air mass flows. At 16–17 o'clock the cold front, clearly defined in pressure behavior, passed accompanied by shower and wind turn. In the evening the observation point fell into the rear of cyclone, type 5 changed into type 4.

In accordance with the synoptic situation the air mass changed twice during a day. At night the sea moderate air was observed, gradually displaced by the continental air. Till 10 o'clock the type of mass was intermediate between the sea moderate air and the continental moderate air. From 10 till 16 o'clock a relatively warm continental moderate air was observed. The warm sector was filled by the above–mentioned air. Over this period the water vapor pressure e increased sharply from 13.1–13.5 up to 18.1 GPa; a increased from 10.3–10.5 up to 13.7 g/m^3; and, q increased from 8.5 up to 11.5 g/kg. Short time of predominance of this mass is explained by the vicinity of Moscow to the point of cyclone occlusion. The relatively warm air was manifested by the values of $(\partial T/\partial t)_a$, namely: + 4.2°C/12 h by night and 4.1°C/12 h by day. Beginning with 17–18 h the cold front was followed by the sea air mass from the Northern Atlantics. The value e decreased again down to 12.5–13.0 GPa, the value a decreased down to 9.4–9.9 g/m^3, and q decreased down to 7.9–8.2 g/kg. The change of mass type manifested itself in the transmittance regime. In the morning the visibility D was 15–25 km in the front part of cyclone; by day it decreased down to 10 km that was indicative of the primordially tropical nature of mass in the warm sector; and, in the evening in the rear area visibility again increased up to 50 km, i.e., up to the value typical for the air of arctic origin.

Thus, both the baric situation (3b → 5 → 4b) and the type of mass changed twice during a day. Therefore, the temporal limits, when analyzing the circulation conditions, were determined everywhere accurate to 2–4 h. HMS was then calculated over the entire period of sodar observations except for some controversial hours when changing the type of baric situation. As to air masses, data processing was performed for the periods when the values of most of the indices corresponded to one certain type of mass.

4. SYNOPTIC REGULARITIES OF THE HEIGHT OF MIXING LAYER

Daily behavior of HML in various situations is given in Fig. 3*a*, and under conditions of predominance of different air masses the daily variation of HML is given in Fig. 3*b*. The average heights of mixing layer in both aspects of investigation are presented in the Table I. As a whole, over one month HML was 480 m. It should be noted that the sodar data obtained over separate hours at apparent sufficient sample size have no statistical intraseries independence in real situations. Therefore, along with the number of hours the total number of complete and incomplete days with one type of mass is given in the Table I. The Table I shows how frequently this situation or the type of air mass were noted continuously. It can be seen from Fig. 3 that by night HML slightly changes. To put it otherwise the powers of surface inversions and other stable structures are noticeably connected with none of the factors under study. All the differences between the types are created mainly over daytime with free convection in the boundary layer. They are the result of the influence of advection on the height of ascending currents in convection cells and the time of existence of cell circulation. This influence is due to advective variations of the difference T between the underlying surface and the adjacent air layer.

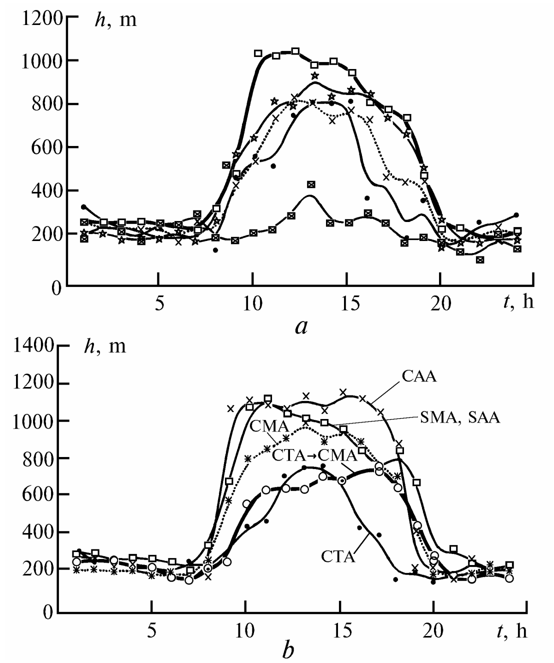

FIG. 3. Daily behavior of the HML under various synoptic conditions (a) and under conditions of various air masses (b).

As would be expected, the mixing layer is weaker in the front part of cyclones and in their warm sectors with heat advection, it was 390 and 420 m, respectively. Note that the conditions of these types differ slightly. This result reflects a known characteristic feature of summer, namely, the lack of essential temperature contrasts in the region of warm front over the heated continent. The mixing layer is the largest in the rear area with cold advection, it was 540 m. The centers of anticyclones and the col, where the advective changes of T are negligible have intermediate value of height (470 m). The most unfavourable conditions for vertical scattering of admixtures, from the standpoint of thermal structure, are observed in the areas of stationary fronts, in the troughs and depressions, the height of mixing layer was 240 m. Here, usually at continuous low clouds and frequent rainfall, the convection is not developed practically. Although the convection is a basic mechanism providing the scattering of admixtures over daytime. The regularities are pronounced in the second aspect of the analysis as well. The arrangement of the air mass types in a series in HML increasing order coincides with successive variation of their temperature effect with reference to the surface. The least mixing layer of 360 m corresponds to the warmest air (continental tropical one). For the transition mass type from continental tropical to continental moderate air the HML increases up to 410 m, it becomes higher under conditions of local air mass of sea origin being thermally neutral relative to the surface (490 m). HML increases up to 580 m in cold atlantic air (in the sea moderate air and in the sea arctic air). Finally, for a short period of predominance of continental arctic air the largest value of HML was 590 m. Figure 3*b* shows that the HML increase occurs due to direct amplification of convection in the middle of the day and also due to time extension of its action during the day transition time. Transformation of tropical air to continental air manifests itself mainly in the action of the second factor, that is, in the increase of recurrence of superadiabatic γ in the morning and in the evening.

TABLE I. Height of mixing layer under various synoptic conditions, June–July 1991.

Types of synoptic situations	2	3	5	1	4
Number of hours	40	49	88	181	298
Number of complete and incomplete days	4	4	9	12	19
Number of cases	2	3	4	5	6
Average HML, m	240	390	420	470	540
Types of air masses	CTA	CTA → CMA	CMA from SMA	SMA, SAA	CAA
Number of hours	99	66	157	120	26
Number of complete and incomplete days	6	4	11	8	2
Number of cases	2	1	6	4	1
Average HML, m	360	410	490	580	590

Summarizing aforesaid we may conclude that the colder the air relative to the surface, the larger height of mixing layer during the day and the height changes faster in the transition time of the day. Specific ranges of HML values for various situations of baric field and types of air mass should be refined. However, the general regularities obtained in the present paper for the summer period are objective and reliable.

REFERENCES

1. B.P. Alisov, *Climatic Areas and the USSR Regions* (Geografgiz, Moscow, 1947), 210 pp.

2. A.S. Zverev, *Synoptical Meteorology* (Gidrometeoizdat, Leningrad, 1977), 712 pp.

3. M.A. Kallistratova, M.S. Pecur, I.V. Petenko, and N.S. Time, "*Technique of remote measurement of the mixing layer parameters with a Doppler acoustic locator (sodar)*", Preprint No. 1, Institute of Atmospheric Physics of the Russian Academy of Sciences, Moscow (1991), pp. 77–94.

4. *Climatic Characteristics of Conditions of Propagation of Admixtures in the Atmosphere. Handbook* (Gidrometeoizdat, Leningrad, 1983), 328 pp.

5. G.E. Landsberg, *Climate of a City* (Gidrometeoizdat, Leningrad, 1983), 246 pp.

6. M.S. Pekur, "*Determination of parameters of the mixing layer height using the sodar facsimile chart records (review)*", Preprint No. 7, Institute of Atmospheric Physics of the Russian Academy of Sciences, Moscow (1990), pp. 15–30.

7. L.P. Son'kin, Tr. Gl. Geofiz. Obs., No. 172, 79–85 (1965).

8. S.P. Khromov, *Principles of Synoptical Meteorology* (Gidrometeoizdat, Leningrad, 1948), 696 pp.

9. G.C. Holzworth, Monthly Weather Rev. **92**, No. 5, 235–242 (1964).

10. R.A. Maughan, A.M. Spanton, and M.L. Williams, Atmos. Environment **16**, No. 5, 1209–1218 (1982).

11. S. Singal, B. Gera, and S. Aggarwal, J. Sci. and Industr. Research **43**, September, 469–488 (1984).