On the Relationship between the Aerosol Layer Height a the Mixed Layer Height Determined by Laser Radar an Low-Level Radiosonde Observations

By Sasano Y., A. Shigematsu,* H. Shimizu, N. Takeuchi and M. Okuda

The National Institute for Environmental Studies, Yatabe, Tsukuba, Ibaraki 305 Japan
**The Graduate School of Environmental Sciences, The University of Tsukuba, Niihari-gun, Ibaraki 305 Japan*
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Abstract

The relationship between the height of the stable layer and the height of the aerosol layer nearest to the ground on sunny days was examined using radiosonde and laser radar observations. Aerosol layer heights were determined by the normalized (aerosol) concentration gradient. Good correlation was found between the lowest-level stable layer and the lowest aerosol layer top (correlation coefficient=0.87) and also between the stable layer stability and the vertical gradient of the aerosol concentration at the aerosol layer top (correlation coefficient=0.78).

1. Introduction

The height of the mixed layer is an essential parameter for predicting atmospheric pollution since pollutants emitted near the surface are considered to be transported up to the mixed layer height by turbulent and convective mixing, but not penetrating the stable atmosphere above. The mixed layer height is often determined from the vertical profile of air temperature obtained by the usual radiosonde observations. In this method the mixed layer height is defined as the altitude at which the air temperature profile exhibits an inversion. This definition is based upon the inference that turbulent conversion makes the air temperature profile homogeneous below the stable (inversion) layer. In this situation, the mixing process also distributes pollutants homogeneously below the stable layer. It is then possible that a relationship exists between the structure of the atmospheric temperature profile and the aerosol profile.

In order to determine this relationship, the following problems must be solved. First, does the vertical structure of the pollutant profile correspond to the structure of the temperature profile, that is, the temperature inversion? What relationship exists between the heights of both structures? Is there any relationship between atmospheric stability and the concentration gradient at each height?

Much research (Collis et al., 1964; Viezee and Oblanas, 1969; Spangler and Dirks, 1974; Russell et al., 1964; Coulter, 1979) has been carried out on these problems using laser radars. Most of the research, however, has not resulted in quantitative solutions because only qualitative picture analyses on the structure of the aerosol distribution using a CRT or photographic records have been made.

Recent progress in the computerized digital processing of laser radar signals enables a quantitative and objective analysis (Uthe and Allen, 1975; Endlich et al., 1979; Sasano et al., 1980; Shimizu et al., 1980). Using such digital data processing, the present study is aimed at answering the above questions quantitatively and objectively, introducing some reasonable criteria for determining the aerosol layer height and stable layer height.

2. Data collection

By emitting a laser pulse into the atmosphere and receiving that portion backscattered by suspended aerosols, a laser radar system can detect the spatial distribution of the volume backscatter-

Table 1 List of field observations

Location	Period	Radiosondes	Feature	Symbol
Kujukuri	Sept. 18-19, 1978	10	seashore	△(a) ▲(b)
Sagami	Nov. 9, 1978	1	seashore	●
Kasumigaura	Feb. 18, 1979	1	lakeside	□
Urawa	July 31-Aug. 2, 1979	3	urban	○

(a): point a, (b) point b.

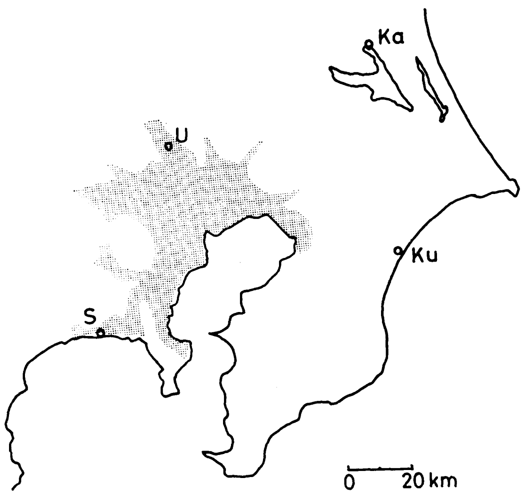

Fig. 1 Field observation sites in Kanto plain: Kujukuri (Ku), Sagami (S), Kasumigaura (Ka) and Urawa (U). The shaded area denotes the urban area.

ing coefficient of aerosols. Since the volume backscattering coefficient is proportional to the integral of the differential backscattering coefficient of individual aerosols with size distribution as a weighting function, the measured volume backscattering coefficient can be converted into the aerosol number density if the size distribution and the optical properties of the aerosols are spatially invariant (Collis and Russel, 1976). In the present study, the size distribution and the optical properties are assumed to be invariant so that the relative aerosol number density can be calculated.

The laser radar system for the present study is a mobile type and has a Nd:YAG laser (1.06 micron meter, 0.1 J/pulse) and A/D converter and a mini-computer for digital data processing. Details of the system have been reported in Shimizu et al. (1980).

The laser radar data used in the present analysis are the vertical profiles of the aerosol density taken in the daytime (0900 to 1800 JST). Table 1 lists the field observations and Figure 1 shows the observation sites. Observations were carried out at four sites: Kujukuri (Ku), Sagami (S), Kasumigaura (Ka), and Urawa (U), in the Kanto plain, Japan. The Kujukuri and Sagami sites are near the sea, 4 km and 50 m inland from seashore, respectively. The Kasumigaura site is located near a lake. The Urawa site (Sasano et al., 1980) is about 20 km northwest of the Tokyo Bay industrial area and adjacent to the Tokyo metropolitan area.

Of the four sites, continuous operation was done at the Urawa site and periodic data collection was done at the others. The spatial resolution was 3 m. The observation range was 3000 m above the surface. Vertical profiles of the aerosol density were calculated as 10-minute averages with 20 m intervals. The periodically collected data were grouped and averaged over 10 minutes.

During the field observation, fifteen soundings of the air temperature were carried out by low-level radiosondes. The low-level radiosondes were released at the laser radar sites at Urawa and Kasumigaura, at the seashore 1 km east of the laser radar site at Sagami, at the seashore (point a) and 9 km inland from the seashore (point b) at Kujukuri. The ascending rate of the radiosondes was adjusted to a speed of 200 m/min and temperature and pressure signals were received at the ground and recorded by a pen-recorder. The records were read at 50-100 m intervals and at inflection points to calculate the potential temperature profile at 20 m intervals by interpolation. The temperature sensor was a tungsten resistance-thermometer.

The weather was fair during the observation except at Kujukuri where it was cloudy.

3. Method of analysis

Based on a preliminary analysis, a stable layer is defined here as a layer in which the potential temperature gradient is greater than 0.6°C/100 m and the temperature difference between the upper and lower boundaries of the layer is greater than

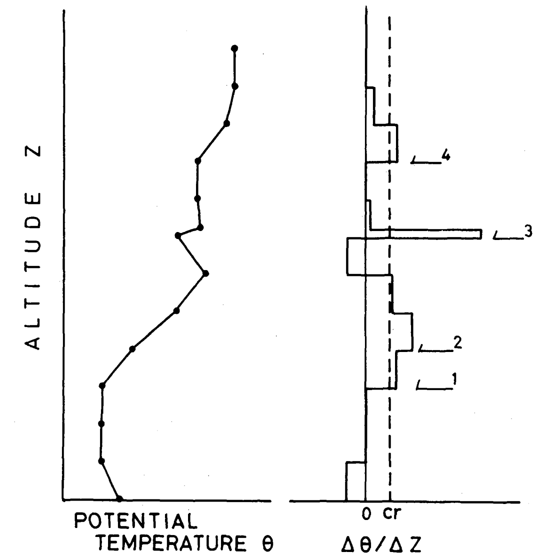

Fig. 2 Schematic diagram of a potential temperature profile and its vertical gradient. The levels (1, 2, 3 and 4) are the bases of the stable layer.

0.6°C. However, when the layer thickness is 20 m, the temperature difference criterion is relaxed 0.4°C. This is shown schematically in Figure 2, where the left-hand side shows the potential temperature profile and the right-hand side shows the corresponding potential temperature gradient. A gradient of 0.6°C/100 m is shown by a dashed line. There are three layers with a gradient greater than 0.6°C/100 m in this figure, which are defined as stable layers. This definition is experimental and different from the usual one in which a stable layer is defined by a positive gradient of potential temperature; it was used because an adiabatic lapse rate rarely occurred and slightly stable conditions were found even in daytime convective conditions as will be shown in Figure 4 later.

The base of the stable layer (BSL) is defined as the level of the lower boundary of the above-defined stable layer (shown by 1, 3 and 4 in Figure 2) and the levels where the potential temperature gradient is greater than at the lower layer (shown by 2). The stability of the stable layer is represented by the potential temperature gradient at the BSL. When there are several BSLs, a stability is assigned for each BSL.

The vertical gradient of the aerosol density is often considered when examining the spatial structure of the aerosol distribution. However, the gradient itself, which contains the dimension of density, is an inappropriate index because aerosol density can be temporally and locally variable. Most research so far (Collis et al., 1964; Viezee and Oblanas, 1969; Spangler and Dirks, 1974; Russell et al., 1974; Coulter, 1979) has examined the pattern displays of the aerosol density distribution by eye with attention paid to sharp gradients of the density profiles, resulting in a lack of objectivity. In the present study, we introduce a normalized concentration gradient (*NCG*) for objective analysis.

Using 10 minute-averaged aerosol density profiles, the *NCG* is defined as

$$NCG(z_i) = -\frac{\Delta C_i}{\Delta z_i C(z_i)} \times 100\%$$

where

$$\Delta C_i = C(z_{i+1}) - C(z_{i-1})$$

$$\Delta z_i = z_{i+1} - z_{i-1}$$

and z_i is the interpolated data level. This normalization procedure excludes the temporal and local changes in the aerosol density and further eliminates the variability in the laser radar system efficiency. Figure 3 is an example of the time-height variation of the *NCG* during a diurnal cycle. In this figure, the darkened areas indicate a large *NCG* value, that is, a sharp gradient in the aerosol density profile. In this example the multiple layer structure exists for a long time.

A preliminary analysis also indicated that the top of the aerosol layer (TAL) can be defined as the height with the maximum $NCG(z)$ within a layer where the $NCG(z)$ has a value greater than 50%/100 m over a 40 m thickness. By this definition, there can exist multiple TALs in one density profile.

Figure 4 shows the potential temperature profiles at the times a to f in Figure 3. The arrows indicate the lowest BSL in each profile. Examining Figure 3 and Figure 4, a high correlation between the heights of the TAL and the BSL is expected.

Whether the existence of a stable layer necessarily accompanies an aerosol layer is, of course, not self-evident, and the top of an aerosol layer is not always capped by a stable layer. For example, the distribution of BSLs and TALs are shown in Figure 5. Here, the aerosol density profile was obtained at the Urawa site from 0950 to 1000 JST on 1 August and the temperature profile was obtained by a low-level radio-

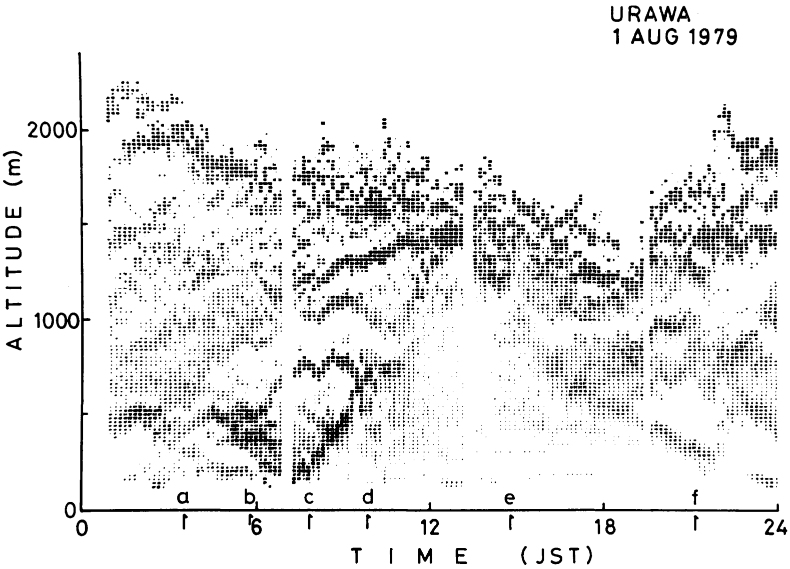

Fig. 3 Time-height variation of the normalized concentration gradient.

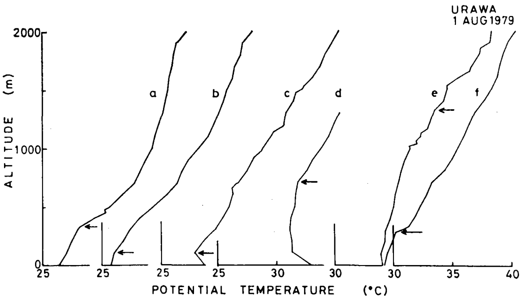

Fig. 4 Potential temperature profiles, a~f correspond to a~f in Fig. 3.

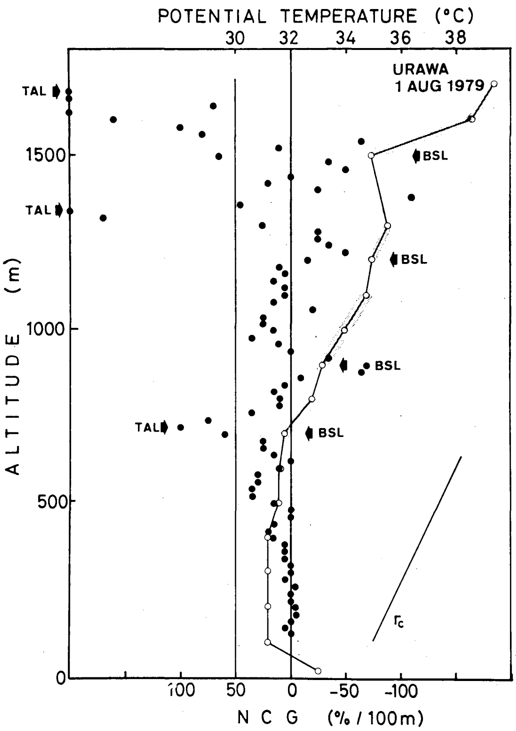

Fig. 5 An example of the distribution of the bases of the stable layer and tops of the aerosol layer. Γc means a criterion for a stable layer.

sonde release at 0950. The dots show the *NCG* distribution and the solid curve through the open circles the potential temperature profile. Arrows pointing to the right indicate the TALs and arrows pointing to the left indicate the BSLs. In the situation shown in Figure 5, it is rather difficult to determine by physical reasoning which BSL and which TAL are related among the many-layered structure. To overcome this difficulty, we adopted a corresponding rule based on the assumption that the height of each BSL must be equal to or close to the height of the TAL. Consequently, a correspondence is established between the BSL and TAL with the smallest height difference for each BSL in a pair of profiles of aerosol density and potential temperature.

4. Results and discussion

The earth's surface, heated by solar radiation, produces a mixed layer in the atmosphere whose height is defined by the level of the lowest stable layer during the sunny daytime. Figure 6 shows the relationship between the heights of the top of the aerosol layer (TAL) nearest to the surface and of the corresponding base of the stable layers (BSL). In this figure the solid lines through the symbols indicate one stable layer and the BSLs included in it, which means that the TAL nearest to the ground may not correspond to the lowest BSL but to the second or third higher BSL although they are within one stable layer. In the two cases shown by the dashed lines the TALs correspond not to the lowest stable layers but to the third BSLs from the ground.

The vertical distribution of aerosols would have layered structures when (1) the observation site is near the aerosol sources and mixing is inadequate, (2) there are differences in the vertical mixing ability, (3) a multi-layer structure in the wind field exists, for example. Especially in the case of a stable layer aloft, the vertical mixing is reduced forming a mixed layer on a sunny day, resulting in a marked structure in the aerosol distribution. Frequently, air currents at different altitudes have different characteristics and directions. At the interface of these different air masses, there may be a vertical aerosol concentration structure as well as a vertical temperature structure. These make one expect that there exists a relationship between the structure of the stable layer and of the aerosol layer.

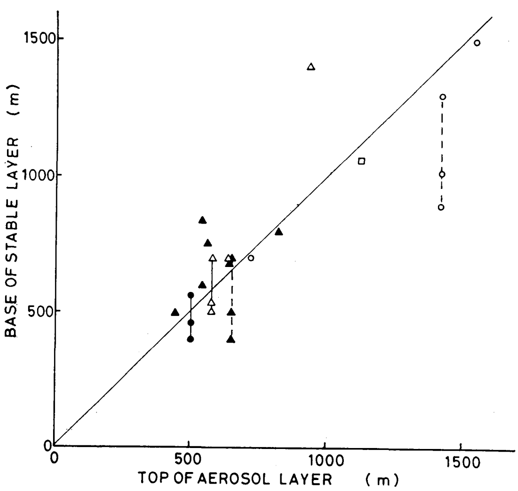

Fig. 6 Relationship between the heights of the tops of aerosol layer and bases of stable layer. [For symbols, see Table 1.]

In fact, Figure 6 shows the close relationship which exists between the heights of the lowest-level TALs and the stable layer nearest to the surface (13 out of 15 cases) and indicates the possibility of determining the mixed layer height by laser radar observation of the aerosol distribution. The correlation coefficient for linear regression is 0.87 (11 out of 15 cases excluding the solid and dotted line cases). Consequently, Figure 3 shows that the top of the mixing layer found at 200 m at 0800 JST rose to 1,200 m by 1200 JST, indicating the development of the mixed layer.

In two cases (indicated by dotted lines in Figure 6), there exists another stable layer below the lowest TALs. This seems to oppose the results described above; however, this may only be a problem in data processing. Since the vertical profile of the aerosol distribution was obtained as a 10-minute average any sharp gradients would be smoothed out and marked structures would disappear. This is shown in Figure 7 as an example. Figure 7 shows the time variation of the vertical profile of the aerosol distribution. A profile was calculated every 4 sec and showed a sharp gradient initially at about 300 m, de-

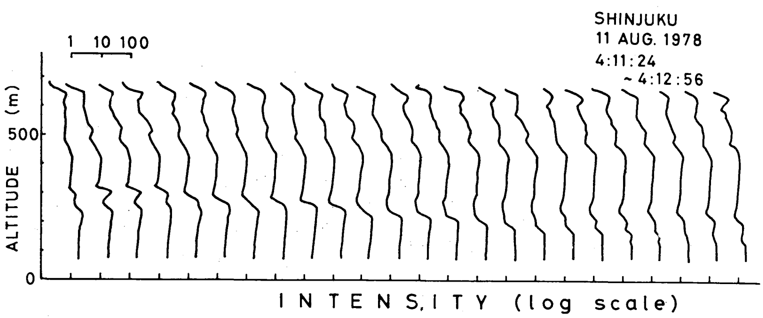

Fig. 7 An example of rapid changes in vertical structure of the aerosol distribution.

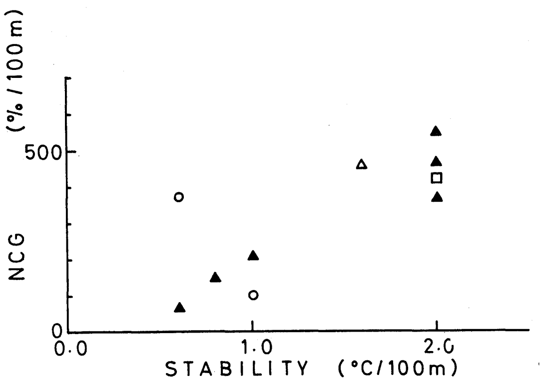

Fig. 8 Relationship between the stability of the stable layers and the normalized concentration gradient at the tops of the aerosol layer. [For symbols, see Table 1.]

creasing by 100 m over 90 sec. Time-averaging would make the profile smooth. If continuous data can be obtained and stored individually, numerical pattern recognition techniques make it possible to distinguish the aerosol layer as a temporally and spatially continuous structure (Endlich et al., 1979). However, air temperature was measured by radiosondes which detected the local and instantaneous temperature at each level. Thus, on occasion, a small-scale structure of the temperature field was detected. These methodological differences can cause difficulties in correspondence. Following Hicks et al. (1977) who uses sodar observation, an unambiguous single layer should be analyzed; however, there were few cases which had an unambiguous single layer in each profile in our observations.

Recently, Coulter (1979) reported the analysis of the relationship between the mixed layer heights obtained by sodar, laser radar and radiosonde observations, in which the mixed layer height was objectively determined through visual inspection of the vertical time sections which display the relative aerosol concentration as a function of height. His definition of mixed layer height by potential temperature profile was the level at which the potential temperature gradient changed from zero to positive. His results shows that the mixed layer heights determined by laser radar were consistently 100~200 m higher than the mixed layer heights determined by potential temperature profile. This could be explained by the different definition of mixed layer height by potential temperature profile.

In Figure 8, the relationship between the stability of the stable layers and the normalized concentration gradient (*NCG*) of the TALs for the corresponding BSL-TAL data found in Figure 6 (except those data connected by solid and dotted lines and one data point which shows extremely large deviation) is shown. Obviously, there is a positive correlation between them (correlation coefficient = 0.78) though the number of samples is small. This positive correlation suggests the role of the stable layer in vertical mixing.

In this paper, we proposed a new definition of the base of the stable layer, which correlates well with the top of the aerosol layer determined from laser radar observations.

To summarize, —when considering the mixed layer structure in the daytime (15 cases), the lowest-level stable layer generally corresponded to the lowest aerosol layer top (13 out of 15), —there is a positive correlation between the stable layer stability and the vertical gradient of the aerosol concentration (*NCG*) at the aerosol layer top.

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低層ゾンデとレーザーレーダー観測から決定された安定層高度とエアロゾル層高度の関係

笹野泰弘・重松明夫*・清水　浩・竹内延夫・奥田典夫

環境庁国立公害研究所

晴れた日中の安定層の高さとエアロゾル層の高さとの関係について，低層ゾンデとレーザーレーダー観測に基づいて調べた。エアロゾル層の高さは正規化したエアロゾル濃度鉛直勾配から決定した。最も低高度の安定層とエアロゾル層の上端高度との間に良い相関（相関係数0.87）が認められる。また，安定層安定度とエアロゾル層上端の濃度勾配との間に相関（相関係数0.78）が認められる。

* 筑波大学環境科学