Atmospheric stratification revealed by twilight scattering

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ABSTRACT

The uses and limitations of the twilight method of detecting aerosol layers are discussed and an experimental modification capable of checking the reliability of the results is described. The data from several sequences of measurements are shown to give average distributions of stratospheric aerosols in good agreement with those determined by direct sampling.

The stratification revealed by the experiments is very variable. Simultaneous observations at different latitudes show that the aerosol distributions often have the same form over distances of 300 km, but that the degree of similarity decreases rapidly with increasing separations. There are preferred heights for layers showing intense scattering, which on the average, slope upwards towards the equator. Some features show a surprisingly high degree of persistence in time and some curious changes in apparent height.

1. Introduction

The mechanism of air interchange between stratosphere and troposphere is one of the important outstanding problems of meteorology and a considerable effort is currently being devoted to methods of studying it. Use is made of the two co-existing "tracers" of the lower stratosphere—radioactive debris from nuclear explosions, and ozone. The recent improvements in ozone sounding methods have already revealed the complex stratifications that often exist and suggest that a steady-circulation model model is a great over-simplification of the actual mixing processes. Ozone soundings are at present expensive and require complex equipment and are therefore undertaken to a limited extent in spite of their considerable theoretical importance.

The purpose of this paper is to call attention to a possible alternative, or supplementary, method of studying the layering of the atmosphere, and to discuss its limitations, and some of the results obtained with it.

This is the twilight method of detecting aerosol layers described by BIGG (1956). The principle is simple: suppose that we observe a small region of the twilight sky at sunset and that an isolated cloud is in the field of view. As the Sun sinks, the colour of the cloud changes from yellow to orange (or deep red in humid or polluted atmospheres) then quite suddenly fades to grey as the Earth's shadow falls on it. If we measure the rate of change of red light from it, it would show a large maximum at this time. The cloud is thus "detected" by this measurement and its height can be calculated from the height of the Earth's shadow. The same considerations apply to a dust layer on which the Sun sets, but the maximum in the rate of change of red light is not usually so intense.

The relevance of the method to the foregoing discussion arises from JUNGE, CHAGNON & MANSON's (1961) discovery of the existence of a world-wide layer of sulphate particles whose diameters are largely in the size range 0.1 to 1 μ, and whose distribution in height is very similar to that of ozone. If mixing of air from regions either above or below the layer causes it to become inhomogeneous then this can be detected by the light scattering properties during twilight.

The method has been criticised by MEGRELISHVILI (1958) and by VOLZ & GOODY (1960, 1962), and applied to the determination of air densities, their criticism was valid. Applied to the possibility of detecting aerosol layers near the shadow boundary it was not. The argument hinges on whether or not an appreciable discontinuity can exist at the shadow boundary, and with an elaborate sequence of model atmospheres Volz and Goody have shown that at the wavelengths where my measurements were made, no discontinuity would be found. Yet it is immediately clear from a comparison of experiments at wavelengths of 6700 Å with those at 8800 Å, where a discontinuity seems certain on the basis of Volz and Goody's models, that the two give the same answer.

Evidently, the reason is that the model atmospheres chosen were unrealistic. In the widespread anticyclonic conditions which are essential to making such measurements, temperature inversions below 3 km usually limit cloud development and the upward movement of water vapour and aerosols, which create an "artificial horizon". This, then, provides the shadow discontinuity, but because of the smaller refraction of a ray grazing a 3 km layer than of one grazing the Earth, the difference in effective heights of the shadow probe is less than the expected 3 km.

While this also provides an alternative explanation to some of Volz and Goody's own results—near-simultaneous changes in the red and orange, weakly reflected in the green part of the spectrum—it shows a fundamental limitation to the accuracy of the twilight method. If we go to longer wavelengths, where a shadow boundary is to be expected, a partial artificial horizon, by creating two shadow discontinuities may cause all features to appear double. However, one or other of the discontinuities is likely to dominate and their effective separation is likely to be small. The importance of an independent experiment to determine the accuracy of the measurement is obvious.

Another apparently serious drawback of the twilight method discussed in some detail by Volz and Goody is the ever-present possibility that cloud or other irregularities at the sunset point cause changes in the light which are unrelated to the light scattering properties at the calculated shadow boundary. Fortunately, this is capable of being detected with a small modification to the experimental method, which at the same time allows an estimate of the importance of such factors as variations in lights of the night sky. This is described in Section 3.

2. Theoretical considerations

(*a*) Shadow heights

A formula for the height of the shadow boundary which is a good approximation for small solar depressions has been given by Volz & Goody (1960). An expression which holds for all values of the solar depression was used in this work, and since it does not appear in the literature may be of interest.

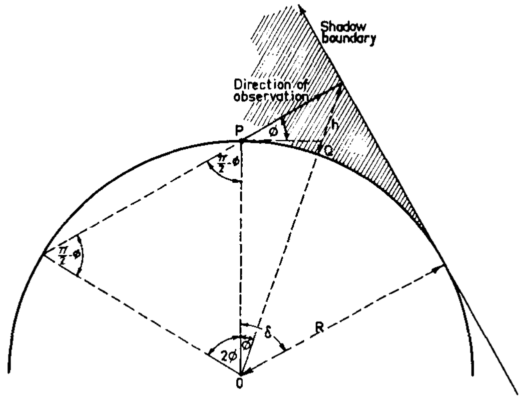

Fig. 1. Calculation of the height of the Earth's shadow.

The relevant geometry is shown in Fig. 1. R is the radius of the Earth, δ the solar depression, ϕ the angle of elevation of the photometer, and h is the height of the shadow boundary.

If the centre of the Earth, O, and the direction, OP, (where P is the point of observation) are taken as the origin of coordinates, the equation of the grazing ray is

$$r = R \sec(\theta - \delta). \tag{1}$$

The equation of the line of observation is

$$r = R \cos \phi \sec(\theta + \phi). \tag{2}$$

These intersect when $\sec(\theta - \delta) = \cos\phi \sec(\theta + \phi)$ which may be shown to be equivalent to

$$\tan\theta = \frac{1 - \cos\delta}{\tan\phi + \sin\delta}. \tag{3}$$

At this point Q, $r = R + h$.

From (1) $$h = R\{\sec(\delta - \theta) - 1\} \tag{4}$$

θ being determined from (3).

Two adjustments must be made: (*a*) The refraction causes a decrease in δ ranging from about 0°.55 at sunset to about 1°.1 for values of δ exceeding a few degrees. (*b*) Unless the photometer follows the Sun in azimuth, the apparent sunset heights will be too low in the later stages of twilight. There is a good case for using an astronomical telescope for following the Sun when quantitative measurements are to be attempted, for the change in scattering angle of $\sim 10°$ during twilight can be very important for particles comparable in size to the wavelength.

In the present measurements, the photometer was allowed to remain at a fixed altitude and the sunset (or sunrise) azimuth; the shadow heights were corrected but no allowance was made for change in scattering angle.

(b) The quantities measured

As explained in the earlier paper, the rate of change of output from a balanced amplifier, in which the balance is changed in small steps, is the quantity measured. It is directly proportional to the proportional rate of change of illumination $1/I\, dI/dt$.

For displaying the results, this is changed to $1/I\, dI/dh$ where h is the shadow height, by multiplying by

$$\frac{d\delta}{dh}\cdot\frac{dt}{d\delta}.$$

The first term is calculated from equation (4), and the second from tables of solar depression for given dates and latitudes, for example, in the Nautical Almanac. The reason for doing this is as follows:

Suppose that we have an idealised atmosphere in which all the scatterers are identical (molecular) and distributed according to the law

$$n = n_0 \exp\left(-h/H\right),$$

where H is the "scale height" and n_0 the concentration at ground level.

Then, if each scatterer returns an amount of light ΔI_0 where I_0 is the incident illumination at all heights above the shadow boundary,

$$-\frac{1}{I}\frac{dI}{dh} = \frac{1}{H} - \text{the "inverse scale height"}.$$

In the real atmosphere, the illumination above the shadow boundary is $f(h)\, I_0$ where $f(h)$ is a slowly varying function of height with values between 0 and 1. The quantity $-(1/I\, dI/dh)$ is then equivalent to a smoothed inverse scale height $1/\bar{H}$.

If there is a second type of scatterer (dust) located only in a thin layer according to the law

$$N = N_0\, F(h),$$

where $F(h)$ is appreciable only near h_0, the height of the layer maximum,

$$-\frac{1}{I}\frac{dI}{dh} = \frac{1}{(I_M+I_D)}\cdot\frac{d}{dh}(I_M+I_D),$$

where the subscripts refer to molecular and dust contributions. If $I_D < I_M$ (which will be generally true when a single thin layer is considered) then

$$-\frac{1}{I}\frac{dI}{dh} \doteq -\frac{1}{I_M}\cdot\frac{dI_M}{dh} + \frac{1}{I_M}\cdot\frac{dI_D}{dh}$$

$$\doteq -\frac{1}{H} + \frac{1}{I_M}\cdot N_0 F(h).$$

Thus the dust distribution is superimposed on the inverse scale height. If we take into account the variable illumination above the shadow boundary the dust distribution is barely changed provided the layer is thin, but is superimposed on the smoothed inverse scale height.

The calculation of the degree of modification imposed by various model atmospheres could proceed as in Volz and Goody's work, but would be better examined experimentally, because of the infinite variety of possibilities which the real atmosphere presents.

Bearing in mind that the main purpose of such an experiment is to trace the spatial or temporal extent of inhomogeneities of the stratospheric aerosols, the quantitative uncertainties of the method are relatively unimportant.

(c) Errors caused by an illuminated layer or moonlight

Suppose that, in addition to the varying twilight illumination I, there is a steady background illumination I_0. Then the quantity measured is

$$\frac{1}{(I+I_0)}\cdot\frac{dI}{dh}.$$

The apparent inverse scale height is therefore less than the "true" inverse scale height by the factor $I/(I+I_0)$. Twilight measurements should therefore extend to large enough solar depressions for the steady background to be recorded.

The correction is of the order of 10% at about 60 km and 50% at about 80 km in the absence of appreciable moonlight.

3. The experimental methods

Since the Sun is not a point source, smoothing of the dust distribution occurs even when there is a well-defined shadow boundary. However, this is less than one might expect from the angular diameter of the Sun and a field of view having a vertical extent of ¼° or less is desirable for best resolution. Evidently the greater attenuation of the ray from the Sun's lower, than from its upper limb, reduces its effective diameter.

Several photometers have been used in which the light was collected with either an astronomical telescope or with large mirrors of shorter focal length. The detectors used were photomultipliers (with S-1 spectral response), followed by d.c. amplifiers or Hoffmann silicon photocells in conjunction with a 500 c/s mechanical light interrupter. In each case filters were used which had a short wavelength cut-off at about 0.72 μ, so that only the near infra-red spectrum was used. The peak response occurred between 0.8 and 0.9 μ.

The output from the balanced amplifier was fed to a recorder with a fast chart speed, or to a meter, the time between fixed marks being recorded manually. All the systems used gave comparable results.

(*a*) The oscillating photometer method

If the photometer is oscillated mechanically between two limits the difference signal between the limits contains contributions from three sources.

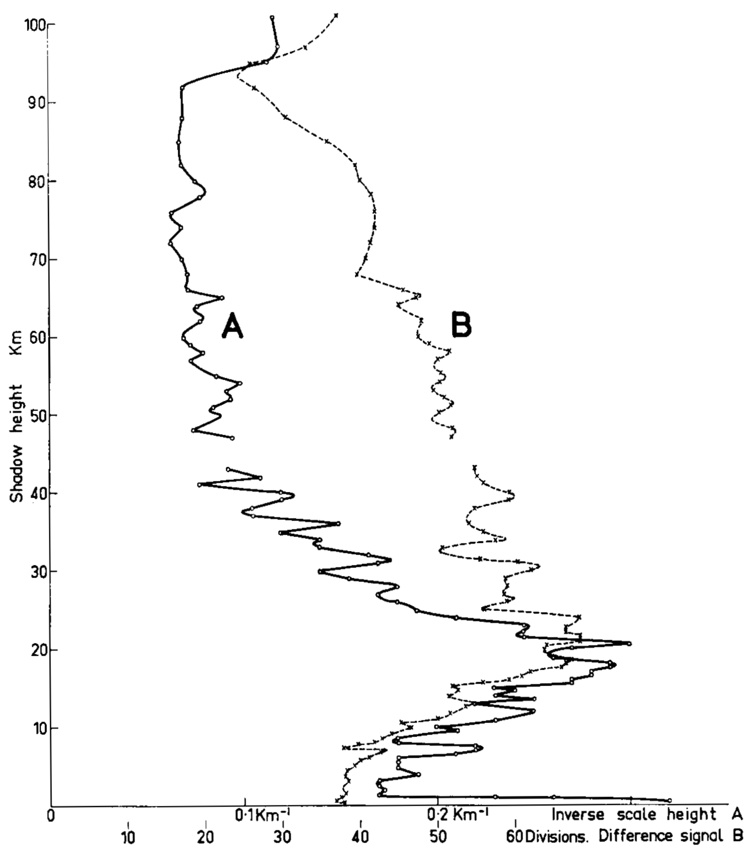

Fig. 2. Comparison of the results of twilight methods (*a*) The proportional rate of change of illumination from a fixed angle of elevation of 20°. (*b*) The difference in illumination between angles of elevation 19° and 20°. Evening twilight 9 July 1961. Wavelength of peak response, 8500 Å.

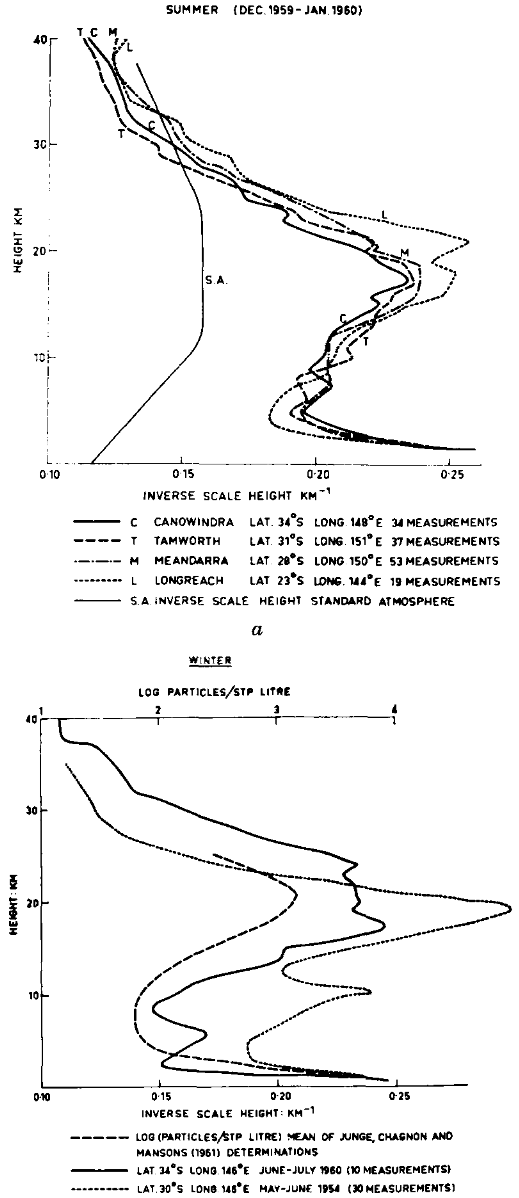

Fig. 3. Average distribution of scatterers.

(i) The difference in scattering angles in the two directions.

(ii) The different contribution to scattering caused by the partial shadow area above the shadow boundary.

(iii) The aerosols illuminated in one direction but shadowed in the other.

The first two components vary only very slowly, while the third varies according to the amount of dust between h and $h+dh$, the shadow boundaries in the directions ϕ and $\phi+d\phi$.

A graph of the difference signal against time, or shadow height, then produces a partially independent assessment of the dust concentration. The chief virtue of the method is that it allows various spurious influences to be detected

Suppose, for example, that a cloud intervenes at the sunset point. There is a sudden jump in the shadow height, causing a maximum in $1/I\ dI/dh$ which is unrelated to the dust content at h. However, it affects the illumination in the direction ϕ and $\phi+d\phi$ simultaneously so that the difference signal does not show a marked discontinuity. Hence one can detect the presence of clouds or other irregularities at the sunset point.

A relatively common occurrence is for dust layers to become aligned in billows. Whether these are shadowed or illuminated, their passage across the field of view of the photometer causes fluctuations in the rate of change of light which may be misinterpreted as stratifications in the vertical. Since the fluctuations in light are not simultaneous in the two directions, changes in the difference signal occur at slightly different times to the changes in $1/I\ dI/dh$.

The same considerations hold for fluctuations in the light of the night sky and the correlation between the two measurements is a good indication of their reliability. Figure 2 shows how in an apparently perfect twilight, the changes in $1/I\ dI/dh$ do not always agree well with those of the difference signal. Below 25 km there is only one serious discrepancy (the "layer" at 4 km does not exist in the difference signal), but above it $1/dI\ I/dh$ shows a number of uncorroborated fluctuations as well as some which appear to be substantiated.

From several comparisons of this sort, it seems that below about 30 km the methods generally agree very well, but the agreement at greater heights is somewhat variable. We will consider, therefore, the results from below about 30 km in more detail here.

4. Results

(a) The average distribution of scatterers

The average values of the inverse scale heights found in different sequences of observations at various sites are shown in Fig. 3a, b. In the

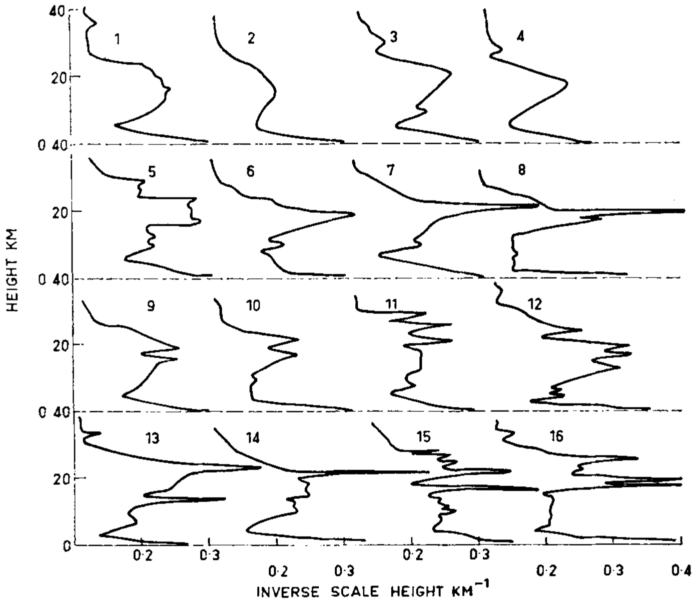

FIG. 4. Particular height distributions of apparent inverse scale heights in twilight experiments.
Deep layer showing little structure: 1. Canowindra 21 Jan. 1961 p.m.; 2. Tamworth 7 Dec. 1960 p.m.; 3. Meandarra 21 Jan. 1961 p.m.; 4. Longreach 9 Dec. 1960 p.m.;
Single well-defined layer: 5. Meandarra 10 Jan. 1961 a.m.; 6. Canowindra 17 Jan. 1961 a.m.; 7. Longreach 2 Jan. 1961 p.m.; 8. Tamworth 8 Jan. 1961 p.m.
Multiple layers: 9. Canowindra 4 Jan. 1961 p.m.; 10. Tamworth 7 Jan. 1961 a.m.; 11. Tamworth 13 Jan. 1961 p.m.; 12. Meandarra 23 Jan. 1961 p.m.
Intense, very shallow layers: 13. Yenda 29 June 1960 a.m.; 14. Tamworth 22 Jan. 1961 a.m.; 15. Meandarra 20 Jan. 1961 a.m.; 16. Meandarra 14 Jan. 1961 a.m.

latter they are compared with the concentrations of particles larger than about 0.1 μ found by Chagnon, Junge and Manson by direct sampling. The mean curves suggest that the twilight method yields a reasonable qualitative picture of the dust distributions and confirms the conclusion that the sulphate layer is widespread and relatively constant in its particle concentration, when an average over a long period is considered.

(*b*) INDIVIDUAL DISTRIBUTIONS

The frequency with which different types of distribution are found is of greater theoretical interest. Selected examples showing the range of distributions are shown in Fig. 4. Mildly stratified cases, such as 1 to 4 in this diagram constituted about one-third of the total observations, but for the remaining two-thirds it is clear that a measurement of particle concentration, or other related parameter, at a discrete height may be quite unrepresentative of concentrations at nearby heights. Evidently the sulphate layer, while maintaining an average constancy is highly variable on a short term basis.

The types of stratification in this figure are very similar to the stratifications of ozone revealed by soundings using Regener chemiluminescent or Brewer electro-chemical methods. It would be very desirable to carry out simultaneous measurements with an ozone sonde and twilight probe to study the amount of agreement obtained.

(*c*) HORIZONTAL EXTENT OF STRATIFICATIONS

A simultaneous set of experiments at the four sites listed on Fig. 3*a* yielded some information on the horizontal extent of particular dust distributions. Slightly more than half those observed simultaneously at neighbouring sites, whose separation was about 350 km, were nearly identical. Less than one third of those observed at sites separated by 700 km were closely similar. Evidently 350 km is the common order of the horizontal extent of a specific

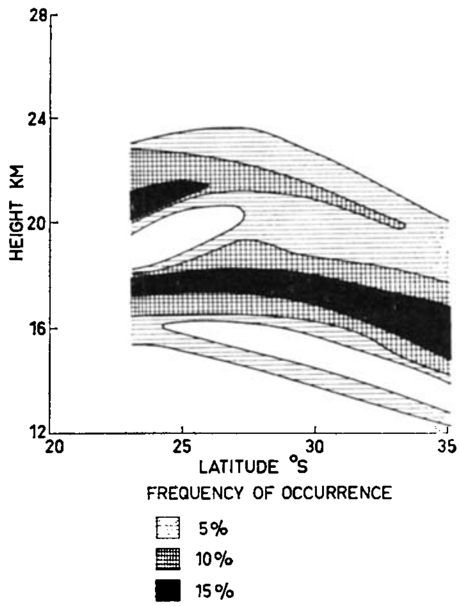

FIG. 5. Preferred positions of dominant layers.

type of mixing in the stratosphere at these sites in midsummer.

This suggests that transient and localized air interchanges, rather than a widespread steady circulation, are responsible for the inhomogeneities.

(*d*) PREFERRED HEIGHTS OF LAYERS

A further result from these simultaneous observations is derived from a consideration of the height of the dominant peak in each individual distribution (or two dominant peaks, if two were of comparable size). Arranged by 1 km intervals, their relative frequencies as a function of latitude are given in Fig. 5.

The lowest preferred height, which slopes upwards towards the equator, can probably be identified with the mean tropopause, which is rendered visible by the aerosols which tend to accumulate there in times of strong tropospheric mixing, or by the formation of very thin cirrus.

The two higher preferred positions may represent a real bifurcation of the sulphate layer,

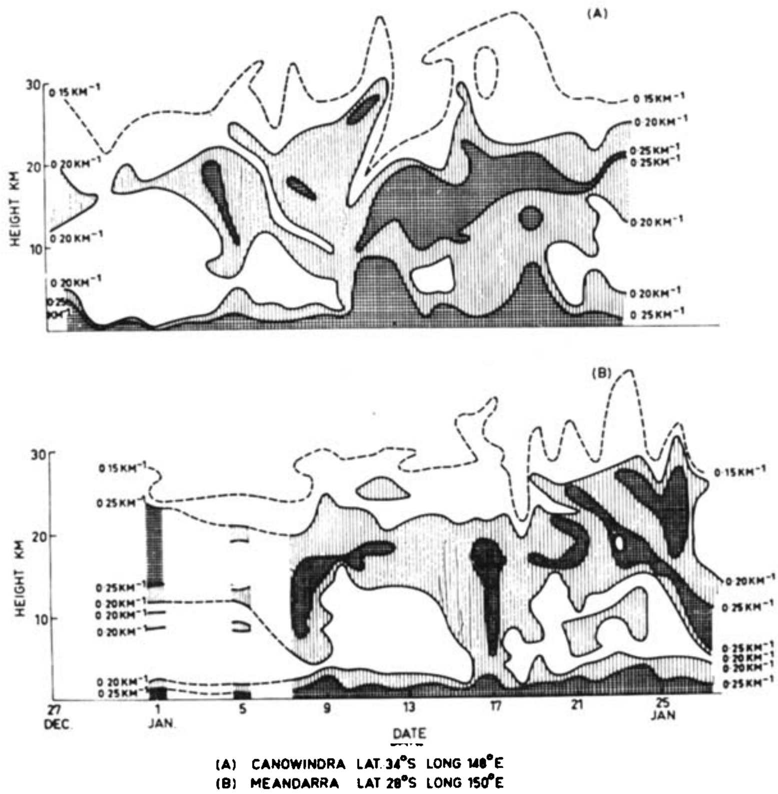

FIG. 6. Time-height contours of equal light scattering.

for 9 and 10 in Fig. 3 were relatively common types. There is the possibility, however, that the presence of an artificial horizon could on some occasions have produced this apparent double layer from a single-peaked distribution.

(*e*) PERSISTENCE OF STRATIFICATIONS

During the simultaneous experiments referred to above, some unusually long sequences of cloudless twilights were obtained due to very stable weather conditions, and the degree of persistence of stratifications which these reveal is shown by the contour diagrams of Fig. 6.

The apparent slow and regular motions of some of the features is interesting but difficult to explain. It must always be remembered that the weather conditions under which such long unbroken sequences of fine weather are obtained are far from usual.

The increased scattering of the lower atmosphere on some occasions is possibly related to the passage of very weak fronts, sufficiently intense to increase either the particle concentration or the humidity in the troposphere without promoting obscuring cloud.

5. Conclusions

The results given here are sufficient to indicate that with relatively simple equipment, the twilight method is capable of revealing qualitatively the stratification of the atmosphere using the 15–25 km sulphate layer as a tracer. The theoretical limitations to a quantitative measurement are severe, but for some purposes, such as verifying or extending ozone soundings may be unimportant. The inaccuracies of the method become greater with increasing shadow height since the lights of the night sky and inhomogeneities of the lower atmosphere cause larger proportional changes.

There are several ways in which the results could be extended or verified. One is by measuring other co-existing tracers, but a better experiment would be to use the same tracer—but probe it with a searchlight beam at night. For comparable results, a spaced transmitter and receiver giving the light received from forward scattering would have to be used.

Another experiment, which has been tried in conjunction with these observations, is direct photography of dust layers from balloons. So far it has not been possible to obtain sufficient coincidences between cloudless twilights and balloon launchings for an adequate comparison of the methods. It has been found, however, that the 15–25 km region is considerably stratified on occasions and that clear layers in a dusty medium are as common as excessively dusty layers.

6. Acknowledgements

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