Theoretically determined multiple-scattering effects of dust on Umkehr observations

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SUMMARY

An earlier theoretical treatment by DeLuisi (1967) of the optical effect of dust on Umkehr observations, yielded some differences from dust effects determined by an experimental method. The differences were thought to be due to errors in the observations used to obtain the experimental results, and the primary-scattering restriction imposed on the theoretical calculations. A theoretical investigation was performed recently to assess the effect of multiple-scattering in an atmosphere with dust. The new results are in better agreement with the experimental data and apparently explain nearly all the differences encountered with the theoretical primary-scattering results.

I. INTRODUCTION

The remote sensing observations of the vertical distribution of ozone by the Umkehr technique have contributed to a large body of global data from which have been made numerous scientific contributions (for example Dobson 1968). Many ozone observing stations are presently making Umkehr observations (World Ozone Data Center at Toronto) using the standard Dobson instrument (1957), and these data, as well as past data, no doubt will be useful to the continuing studies of atmospheric ozone.

The ideal inversion system for deducing ozone distributions from the Umkehr observations should include appropriate compensations for all significant optical phenomena contained in the measurement. Unless this is done, error in the deduced ozone distribution can result. Special consideration must be given when attempts are being made to determine small, long-term variations in atmospheric ozone since long-term variations in other optical phenomena affecting well-calibrated Dobson measurements could be the only variants and not the ozone.

An optical phenomenon that does vary in space and time, and is contained in the Dobson measurement, is scattering and absorption by atmospheric dust. DeLuisi (1969) investigated atmospheric dust effects on the Umkehr measurement, using a combined experimental and theoretical approach, and concluded that dust introduced a one-directional bias to the measurement. The magnitude of the bias was mostly dependant on the total dust optical depth and to a lesser extent on the dust size distribution, vertical distribution and refractive index.

In his theoretical calculations of the effects of dust on the Umkehr observation, DeLuisi restricted the problem to primary-scattering in a spherical atmosphere. The experimental and theoretical results were not in total agreement and he concluded that the differences, although not large, were probably due to experimental error, and the primary-scattering restriction. In the present report we describe the results of a recent investigation which is aimed at examining theoretically calculated higher order scattering effects by

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atmospheric dust to determine whether there exist significant differences from those derived from primary-scattering alone.

2. Procedure

The procedure used in the present work follows essentially that used earlier by DeLuisi (1967). An Umkehr curve is calculated for a molecular atmosphere with dust scattering and extinction, and another Umkehr curve is calculated for a purely molecular atmosphere. A standard atmosphere and a single ozone distribution are used for the molecular constituents. The difference between these two curves is the haze effect curve, $\Delta N_A$. Thus

$$\Delta N_A = N_{\text{dust + molec}} - N_{\text{molec}}$$

where $N = 100 \log(I(\lambda')/I(\lambda))$; $I$ stands for the zenith sky intensity, observed from the surface, at wavelengths $\lambda' = 3323 \text{Å}$, $\lambda = 3114 \text{Å}$, and $N$ is measured by the Dobson instrument. The experimental $\Delta N_A$ curve in Fig. 1 was obtained by subtracting theoretically

![Figure 1. Experimental and theoretical haze-effect curves. $\tau$ stands for the average dust optical depth for 9 refractive indices used in the theoretical calculations (after DeLuisi 1969). The circles are results from the present investigation for a dust optical depth of 0.23 and refractive index of 1.55-0.01.](image1)

![Figure 2. Theoretical haze-effect curves for all orders of scattering. The point at the apex of the dashed lines may not be the exact position of the minimum (see text for details). The refractive indices and $\tau$, the total dust optical depth, are given on the figures. Note slight difference in scale from Figs. 1 and 4.](image2)
calculated Umkehr curves, using ozonesonde data, from Umkehr curves measured by the Dobson instrument. The ozonesonde data and Umkehr data were obtained at the same times (Craig et al. 1967). The measured Umkehr curves contain dust effects while the calculated curves do not.

Figs. 2 and 3 present theoretical values of $\Delta N_A$ for a mean mid-latitude ozone distribution having a total vertical column depth of 0.3 cm STP. A vertical distribution of dust concentration similar to Elterman's (1965) is employed. The ozone absorption and Rayleigh scattering coefficients are for the Dobson instrument C-wavelength pair (Dobson 1957).

The method for calculating the zenith sky intensities for a vertically inhomogeneous molecular atmosphere including dust is described by Herman and Browning (1965). Although the Umkehr observation is nearly continuous and normally spans a range of solar zenith angles from 60° to 90°, the present calculations are restricted to specific solar zenith angles that are dictated by the numerical calculation procedures employed in the multiple-scattering programs.

The dust optical characteristics were calculated using Mie theory for complex refractive indices of 1.33–0.0i, 1.55–0.01i and 1.55–0.1i. The first two indices are assumed to be most representative of a reasonable range of natural atmospheric dust characteristics (Volz 1954; Eiden 1966; Fisher 1970; Fisher and Hänel 1972). The third index has a much higher absorption term which could represent the case for an atmosphere severely polluted by industrial effluents (Bergstrom 1972).

The size distribution function used for the dust scattering calculations for spherical particles is log normal, and produces a nearly neutral extinction cross-section with wavelength over the range of visible wavelengths. From a practical standpoint, the dust extinction cross-sections are considered not to vary with wavelength. The variation of extinction cross-section with wavelength has little effect on the results (DeLuisi 1967).

In order to determine the dust extinction optical depth dependence of the haze effect we chose optical depths of 0.15 as the case for a relatively clear atmosphere and 0.35 as the case for a more turbid atmosphere (Elterman 1970; Herman et al. 1971; DeLuisi 1974).
3. Results and Discussion

Fig. 1 shows experimental and theoretical primary-scattering haze effect curves from DeLuisi (1969). These curves were adjusted to equal zero at a zenith angle of 60° to eliminate an unknown instrumental constant. It is clear that primary scattering cannot account for the curvature between zenith angles 60° and 80°, as well as the very rapid rise beyond 80° that prevails in the experimental haze-effect curve.

Fig. 2 shows the newly calculated curves which include multiple scattering by dust. These curves are for a dust optical depth of 0.15 and refractive indices as shown. Fig. 3 shows curves calculated in the same way, but for a dust optical depth of 0.35. It is obvious that there is a noteworthy improvement over single scattering in the match between these $\Delta N_A$ curves and the experimental curve shown in Fig. 1. (Note that the scales of Figs. 2 and 3 are slightly different from those of Figs. 1 and 4.) Similar to the single scattering case, as the dust optical depth is increased, the magnitudes of the haze effect curves likewise increase. The minimum point connected by dashed lines near 80° solar zenith angle in the multiple-scattering curves have been determined by increasing the angular resolution of the numerical calculation scheme, but the exact point of the minimum was not isolated because of the greatly increased computer time that would be needed.

There are two distinct and contrasting differences that are revealed in a comparison of the primary scattering with the multiple-scattering results. Unlike the trends in the single-scattering curves shown in Fig. 4, the multiple-scattering results show a tendency to increase

![Figure 4. Primary scattering haze-effect curves for dust optical depth 0.30. Refractive indices are given on each curve. (After DeLuisi 1969.)](image)
	he magnitudes of the minima as the imaginary term (causing absorption) in the refractive index is increased, (see Figs. 2 and 3). The second contrasting difference which is almost entirely attributable to higher order scattering is the sharper upturn of the haze effect curves beyond 80°. If the haze-effect curves in Figs. 2 and 3 are adjusted to zero at 60° it is seen that some of them are positive at large solar zenith angles. Both refractive index and optical depth have an influence on this characteristic. According to DeLuisi (1967) the individual experimental haze-effect curves used in constructing the composite curve in Fig. 1 displayed variable features like those for refractive indices between 1.33–0.0i and 1.55–0.01i in Figs. 2 and 3, but it was not possible to ascertain whether the variations were real or due to measurement error of the vertical ozone distribution. When thin clouds pass overhead during an Umkehr observation, the reading on the dial is noted to increase. Mateer (1964) discusses an unpublished study of this effect made by Hans U. Dütsch. The
effect is consistent with the haze effect curves for dust that does not absorb \((m = 1.33 - 0.0i)\), essentially equivalent to a low-level cloud in our calculations.

It can be seen from Figs. 2 and 3 that as the dust optical depth is increased an increasing curvature begins to appear in the haze-effect curves between 60° and 80°. The curvature is more pronounced for the curves with absorbing aerosols. It is also seen that at all zenith angles, the curves for no absorption and high absorption have shifted apart considerably. (In the analysis of Umkehr measurements for ozone distribution this is of no consequence because the measurements are adjusted to 0 at a zenith angle of 60°.) Neither of these features could be adequately reproduced by primary-scattering calculations (see Figs. 1 and 4). It has been noted above that the multiple-scattering calculations, at this time, cannot be used to resolve a reversal in a small angular range such as the second reversal near 88° in the experimental curve. The slight second reversals that appear in the theoretical primary-scattering curves in Fig. 1 are a consequence of placing a dust layer at 20km similar to Elterman's profile. It remains as a problem for future research to determine whether the second reversal in the experimental curve is real, an artifact of experimental error, or possibly a combination of both factors.

Judging from the appearance of the multiple-scattering haze effect curves in Figs. 2 and 3 it would appear that the experimental curve would be consistent with a dust optical depth of 0.23 for a dust refractive index of 1.55 - 0.01i. Fig. 1 shows a fit to the experimental curve. The dust optical depth deduced from fitting the theoretical curves to the experimental data is remarkably close to the average annual turbidity reported by Flowers et al. (1969) near Tallahassee, Florida, where the measurements were made for the experimental curve in Fig. 1. It should be noted, however, that there is an increasing uncertainty in the accuracy of the experimental curve proceeding beyond 80° because of errors contained in the data used by DeLuisi.

![Figure 5](image)

Figure 5. Comparison of the resulting ozone distributions as obtained from dust adjusted (broken line block distribution) and unadjusted (solid line block distribution) averaged set of Umkehr observations. The dust adjustment is the experimental curve of Fig. 1. The smooth curve represents the average of simultaneous balloon observations of the vertical ozone distribution. Omega is the total ozone. (After DeLuisi 1969.)
(a) Consequence to the Umkehr observation

Using the experimental curve shown in Fig. 1 as a correction to an Umkehr curve, DeLuisi (1969) concluded that the correction tended to increase the ozone concentration at the level of the principal maximum and decrease the concentrations below 15km in the vertical distribution profile derived from the inversion system used by the World Ozone Data Center at Toronto, Canada (see Fig. 5). Since the multiple scattering haze-effect falls almost exactly upon the experimental haze effect curve we would expect the same redistribution of ozone as shown in Fig. 5 for corrected Umkehr observations. If the haze-effect curve becomes positive near 90° it would have the effect of reducing the amount of ozone in the levels near 30km and above given in the Umkehr evaluation system. In turn, this would tend to bring Umkehr results in slightly better agreement with direct observations of ozone distribution near 30km (Bojkov 1966; Craig et al. 1967). Should more refined correction techniques be desired, it will be necessary to have some knowledge of the refractive indices of dust, perhaps as they vary with season and location.

4. Conclusion

It has been shown by use of theoretical calculations of radiative transfer for a vertically inhomogeneous atmosphere that multiple-scattering produces deviations from the haze-effect curve calculated on the basis of primary-scattering only. These deviations tend to bring the theoretically calculated curves into better agreement with experimental results, but there is introduced a greater complexity in the haze effect curve itself, especially with changes in the refractive index of the dust. With multiple-scattering, the haze-effect increases with increasing absorption by dust; a result directly opposite to that for primary scattering.

If the Umkehr curve is adjusted so that θ = 0 at a solar zenith angle of 60° then according to the multiple-scattering calculations, haze decreases the N-value between 60° and 85°, but depending on the refractive index of the dust, the N-value either can be increased or decreased beyond about 85°. Primary scattering calculations produce a decrease in the N-value at all solar zenith angles.

Limitations in the numerical procedures used in the multiple-scattering calculations did not permit adequate solar zenith angle resolution to verify the experimental results beyond 87°.

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