Measurements and interpretation of the polarization of radiation emerging from the atmosphere at an altitude of 28 km over south-western New Mexico (USA)

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SUMMARY

The degree of linear polarization of the upward radiation emerging from the atmosphere at an altitude of 28 km was measured over south-western New Mexico (USA) with a balloon-borne photoelectric polarimeter. Measurements were made in four spectral intervals (bandwidth ~ 15 nm) centred on 362, 401, 501 and 599 nm. The objective was to estimate the turbidity factors of simple, homogeneous models of turbid atmospheres from a comparison of the experimental results with computed values of the polarization of the radiation emerging from the top of the model atmospheres. The computations were based on the solution of the radiative transfer problem in a homogeneous turbid atmosphere. The 'doubling' method was used to obtain the solution. It is found that the optimal values of the turbidity factors required to establish good agreement between theory and experiment vary directly as the phase function asymmetry factors associated with the two types of aerosols used in the models. The uncertainty in the interpretation of the polarization data due to the similar effects that the atmospheric aerosols and the unpolarized part of the radiation reflected by the ground have on the polarization of the scattered radiation is briefly discussed.

1. Introduction

It has been proposed that the 'effective' turbidity of the Earth's atmosphere due to aerosols (dust and haze) and the reflective properties of the lower boundary can be determined from a comparison of theoretical computations for model atmospheres with measurements from a space platform of the polarization of the outgoing radiation in the visible and adjacent regions of the spectrum (Sekera 1967). Such a proposal appears reasonable in the light of theoretical investigations of radiative transfer in cloudless models of the Earth's atmosphere with varying degrees of turbidity (Sekera 1956; Coulson 1960; Bulrich 1964; Fraser 1964; Kano 1964). However, the relevance of the information thus obtained is decided by how truly representative the model is of the actual atmosphere.

Proper, unambiguous modelling of the atmosphere is difficult because some of the adjustable model parameters such as the amount and type of aerosols and the unpolarized part of radiation reflected by the lower boundary have similar effects on the outgoing radiation. This difficulty is compounded by the fact that a very limited amount of information, which can be used as the basis for modelling the atmosphere, is available at present about the diversified nature of the atmospheric aerosols (Junge 1963; Penn 1964; Kondratyev, Badinov, Ivlev and Nikolskiy 1969) and about the reflective properties of natural formations such as soils, vegetation and water and snow surfaces which may constitute the lower boundary (Krinov 1947; Ashburn and Weldon 1956).

To investigate some of these difficulties measurements have been made from a high altitude balloon over uniform terrain. Measurements were confined to the principal plane of the sun, i.e. the plane containing the sun and the local nadir (see Fig. 1) to facilitate comparison with theoretical studies. These studies (see, for example, Coulson 1960; Fraser 1964; Kano 1964) have indicated that radiation scattered approximately at right angles to the direction of illumination from the sun exhibits maximum polarization; they also predict the existence of two neutral points on either side of the antisolar point for moderate and high solar elevations, or on the same side of the antisolar point, with one of
they located near the horizon towards the sun, for low solar elevations. It has been suggested that, in addition to the polarization of the scattered radiation, the angular distances of the neutral points from the antisolar point can be used as criteria for judging the turbidity of the atmosphere. However, very few quantitative results which can be used to establish definitive correlation between the positions of the neutral points and the type and extent of atmospheric turbidity are available at present. We shall therefore discuss only the measured and predicted values of polarization of the scattered radiation.

2. Experimental work

The experiment was staged on 28 May 1968 under cloudless skies at the Balloon Research and Test Branch facilities of the Air Force Cambridge Research Laboratories at the Holloman Air Force Base, New Mexico (32°50′N, 106°07′W). The scientific payload consisted of a gain-compensated photoelectric polarimeter and a time-lapse camera with which photographs of the underlying atmosphere and terrain were taken once every minute.

The gain-compensated polarimeter, detailed descriptions of which are available elsewhere (Rao 1970), is shown schematically in Fig. 2. It can accommodate variations of
three to four orders of magnitude in the intensity of the incoming radiation without external commands or controls. This is achieved with the use of a servo-governed high voltage supply. The field of view of the instrument is restricted to a cone of apex angle 3°. The rotating Glan prism acts as the polarization detector and the degree of linear polarization of the incoming radiation is given by the ratio of the difference to the sum of the maximum and minimum values of the sinusoidally varying photosignal. Measurements are made in four spectral intervals isolated by interference filters (bandwidth ~ 15 nm) centred on λ362, 401, 501 and 599 nm. The four colours are sampled in succession every 5 s.

A biaxial solar pointing control (Greeb 1965) capable of pointing accuracies in excess of 5 min of arc both in elevation and azimuth was used to keep the polarimeter in the principal plane of the sun. The polarimeter was programmed to sample the diffusely reflected radiation in discrete steps of 2°54' over a 180° arc in the two quadrants on either side of the local nadir. The 180° scan was completed in a little less than 7 min and the direction of scan was automatically reversed when the limit on either side was reached. A conventional frequency modulated telemetry unit transmitted the polarimeter data and the solar azimuth and elevation to the ground station.

The helium-filled balloon, with a ceiling altitude displacement of $5.6 \times 10^4$ m$^3$, carried a total payload of 290 kg. It was launched at 0551 MDT (Mountain Daylight Time). The ceiling altitude of 28 km was attained at 0800 MDT. It remained at altitude till 1000 MDT when it had travelled a distance of 90 km westward of the launch site.

3. Results

(a) Experimental work

Optical and radar tracking established that the balloon trajectory lay over the semi-arid regions of south-western New Mexico. No clouds could be detected in any of the photographs taken with the time-lapse camera. The underlying terrain appeared flat and uniform with the exception of the San Andres mountains. This was confirmed by an examination of large-scale topographical maps furnished by the US Geological Survey. A mean elevation of 1,350 m above sea level was assigned to this flat, uniform terrain and used as the datum level to compute the molecular optical thickness of the model atmosphere.

Geological data showed that the soil belonged to the family of 'orthids' — a mixture of clay, loam, soil and gypsum (white) sands (Gerlach 1970). The sparse vegetation belonged to the family of 'shrubsteppe'. This description was the basis for the choice of the possible values of spectral albedo or diffuse reflectance of the ground used in the theoretical computations and shown in Fig. 3.

Two sets of measured values of the degree of linear polarization of the diffusely reflected radiation, corresponding to two different values of the solar zenith distance $\theta_0$, are shown in Fig. 4(a) and (b). The condition for the selection of the data points shown in the diagrams was that there should be no skewness in the middle portion of the corresponding polarization traces. This accounts for the paucity of data points in the region of very low polarization on either side of the antisolar point. The accuracy of the measurements has been conservatively estimated to be ±10 per cent.

(b) Computational work

We have computed the polarization of the radiation emerging from the top of a very simple model of a homogeneous turbid atmosphere in which the number mixing ratio of the aerosols is constant throughout the atmosphere. The following assumptions are also made:

(i) The plane-parallel, purely scattering atmosphere is illuminated at the top with unpolarized, parallel radiation from the sun. The molecular and aerosol components scatter radiation according to the Rayleigh and Mie laws respectively; the state of polarization of the incident radiation remains unaltered on scattering by the aerosols.
Figure 3. Wavelength dependence of the diffuse reflectance of the ground. Values assumed in the present work are indicated by open squares and represent the ratios of the outward normal flux of radiation to the inward normal flux of radiation incident on the ground. The albedo measurements of Ashburn and Weldon (1956) and the bi-directional reflectance measurements of Krnov (1947) are shown for comparison.

(ii) The ground reflects radiation according to the Lambert law; the reflected radiation is unpolarized and isotropically distributed in the outward hemisphere independently of the state of polarization and angle of incidence of the incident radiation.

The variable model parameters are the spectral albedo or diffuse reflectance, $A$, of the ground, the characteristic phase functions of the aerosols and the turbidity factor $T = (\tau_N + \tau_A)/\tau_R$ where $\tau_N$ and $\tau_A$ are respectively the normal molecular (Rayleigh) and aerosol optical thicknesses of the turbid atmosphere for radiation of wavelength $\lambda$. We consider here, first, the very elementary aspect of inversion of the polarization data – the determination of $T$ and hence $\tau_A$.

Two types of polydisperse aerosols with different size distributions, refractive indices and phase functions have been considered. The first is Deirmendjian's model $L$ water haze (Deirmendjian 1969). The particle size distribution is given by a modified gamma distribution of the form $n(r) = 4.9757 \times 10^6 \times r^2 \exp(-15 \times 1186r^{1/2})$ where $n(r)$ is the partial concentration of haze particles per unit volume per unit increment of radius $r$ which lies between the limiting values of 0.005 and 2.9 $\mu$m. The second type corresponds to dust particles with a refractive index of 1.5 and a size distribution governed by the Junge power law $dN/d\log r = cr^{-4}$ where $N$ is the total concentration of particles of radius smaller than $r$ and $c$ is a constant (Junge 1963). We have used the phase function computations of de Bary, Braun and Bullrich (1965) for this type of dust particle. The particle radius varies between the limiting values of 0.04 and 3.0 $\mu$m.

The ‘doubling’ technique (Van de Hulst and Grossman 1968; Hansen 1971; Hovenier 1971) was used to determine the linear polarization of the radiation diffusely reflected by an atmosphere of total optical thickness $\tau = \tau_N + \tau_A$. The computational technique is such that the diffuse reflection and transmission matrices for an atmosphere of optical thickness $2\kappa$ can be determined if they are known for an atmosphere of optical thickness $\kappa$. The initial value of $\kappa$ is chosen to be sufficiently small to allow the consideration of only primary or single scattering of radiation, under which circumstances the diffuse reflection and transmission matrices can be replaced with the phase matrix for single scattering; in the present case this is given by $P^d(\theta) = (\tau_N P^r_N(\theta) + \tau_A P^r_A(\theta))/\tau^d$ where $P^r_N(\theta)$ and $P^r_A(\theta)$ are respectively the molecular (Rayleigh) and aerosol phase matrices and $\theta$ is the scattering angle. The ‘doubling’ is continued until the desired total optical thickness is reached. We have used an initial layer of optical thickness $2 \times 10^{-5} \tau^d$. The adequacy of the computational scheme, which takes into account primary and higher orders of scattering, was tested by
computing the polarization of the outgoing radiation in a pure molecular atmosphere and in a pure aerosol atmosphere characterized by a modified Henyey-Greenstein phase function and then comparing the results with those obtained earlier by Coulson, Dave and Sekera (1960) for a molecular atmosphere and by Hovenier (1971) for an aerosol atmosphere. There was reasonable agreement in both cases. For the molecular atmosphere, maximum relative discrepancy between the two sets of computations was about 1-5 per cent when the degree of polarization was about 5 per cent. All the computations were performed on an IBM 360/91 computer using double precision arithmetic.

The parameter $T$ was varied, while maintaining the albedo $A$ at the values shown in Fig. 3, until good correspondence was established between measured and computed values of polarization. The results are shown in Fig. 4(a) and (b) together with the results for a pure molecular atmosphere of optical thickness $\tau_0$ bounded by an identical Lambert ground. The computations for the molecular atmosphere were based on the earlier work of Coulson, Dave and Sekera (1960).

4. Discussion

The fact that relatively lower turbidity factors and consequently lower aerosol optical thicknesses are required to establish correspondence between theory and experiment in the case of the dust particles as opposed to the water haze may be attributed to the fact that the
dust particles scatter more radiation in the lateral directions than does the water haze, thereby contributing more to multiple scattering and resultant depolarization of radiation. A measure of this scattering in the lateral directions is the closeness to zero of the phase function asymmetry factor \( <\cos \theta > = \frac{1}{\pi} \int \cos \theta d (\cos \theta) \) where \( P_{1}(\theta) \) is the first term of the leading diagonal of the aerosol phase matrix in the Stokes representation of polarized radiation (Hovenier 1971), \( \theta \) being the scattering angle. It has a value around 0.79 for the water haze in the spectral region of interest; it decreases to about 0.53 for the dust particles. The optimal values of the turbidity factors for the two types of aerosol are found to vary directly as the phase function asymmetry factors.

We have also examined the dependence of the polarization of the scattered radiation on the turbidity factor in the model atmosphere containing the water haze. The results, corresponding to turbidity factors which differed from the optimum values by \( \pm 25 \) per cent (of the latter), are shown in Table 1. We feel that the changes in polarization, \( \Delta P \), should only be considered as indicative of a trend since the degree of maximum polarization was determined by graphical interpolation. Relatively smaller changes are noticed in the spectral interval centred on \( \lambda 599 \) nm compared to the others. This may be partly due to the
TABLE 1. DEPENDENCE OF THE DEGREE OF MAXIMUM POLARIZATION, $P_{\text{max}}$, ON THE TURBIDITY FACTOR, $T$, IN THE HOMOGENEOUS TURBID ATMOSPHERE CONTAINING WATER HAZE

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Albedo</th>
<th>$\tau_R$</th>
<th>$T$</th>
<th>$P_{\text{max}}$ (%)</th>
<th>$\Delta P^*$ (%)</th>
<th>$\theta_o = 49^\circ$00'</th>
<th>$P_{\text{max}}$ (%)</th>
<th>$\Delta P^*$ (%)</th>
<th>$\theta_o = 66^\circ$00'</th>
</tr>
</thead>
<tbody>
<tr>
<td>362</td>
<td>0.075</td>
<td>0.478</td>
<td>2.40</td>
<td>31.0</td>
<td>19.3</td>
<td>35.0</td>
<td>20.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.20*</td>
<td>26.0</td>
<td>0</td>
<td>29.0</td>
<td>20.0</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>4.00</td>
<td>21.0</td>
<td>-19.3</td>
<td>24.0</td>
<td>-17.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>401</td>
<td>0.125</td>
<td>0.306</td>
<td>3.15</td>
<td>26.0</td>
<td>18.2</td>
<td>30.0</td>
<td>20.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4.20*</td>
<td>22.0</td>
<td>0</td>
<td>25.0</td>
<td>6.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>501</td>
<td>0.150</td>
<td>0.122</td>
<td>3.75</td>
<td>19.0</td>
<td>15.2</td>
<td>22.5</td>
<td>12.5</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>5.00*</td>
<td>16.5</td>
<td>0</td>
<td>20.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>599</td>
<td>0.175</td>
<td>0.058</td>
<td>4.12</td>
<td>12.0</td>
<td>-12.1</td>
<td>17.5</td>
<td>-12.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5.50*</td>
<td>11.0</td>
<td>0</td>
<td>12.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6.87</td>
<td>10.0</td>
<td>-9.1</td>
<td>11.5</td>
<td>-8.0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*The quantity $\Delta P$ denotes the percentage deviation of $P_{\text{max}}$ computed at some value of $T$ from $P_{\text{max}}$ at the optimum value of $T$ indicated with an asterisk in the Table.

increased importance assumed by the radiation reflected by the Lambert ground in determining the polarization of the emergent radiation of longer wavelengths, for it is observed that increasing the albedo of the ground from 0.175 to 0.200 at the wavelength of 599 nm while maintaining the turbidity factor at 5.5 resulted in decreases in the degree of maximum polarization comparable to those caused by increasing the turbidity factor from 5.5 to 6.87 while the albedo was maintained at 0.175.

This raises questions as regards the validity of the assumption that the ground is a Lambert reflector, for under this assumption considerable amounts of unpolarized radiation are added to what would prevail in a planetary atmosphere with a perfectly absorbing ground, thereby causing further depolarization. This is very relevant since radiation reflected by natural formations has been observed to be partially polarized and anisotropically distributed in the outward hemisphere (Chen and Rao 1968). However, even if the proper reflection matrix characteristic of the ground is incorporated into the equation of transfer, there will still be some residual ambiguity as regards the relative importance of the roles played by the unpolarized part of radiation reflected by the ground and the atmospheric aerosols in determining the polarization of the emergent radiation.

This ambiguity is again noticed if we attempt to judge the appropriateness of the turbidity factors by adopting the criterion that the aerosol particle concentrations derived from the volume scattering coefficients at two different wavelengths should be comparable. We shall consider the case of the turbid atmosphere with the water haze in order to be able to make use of readily available computations. The volume scattering coefficient $\beta_A^V$ is given by $\tau_A^V/\tau_H$ where $\tau_H$ is the scale height of the homogeneous molecular atmosphere and $\tau_A^V = (T - 1)\tau_R$. The values of $T$ and subsequently those of $\beta_A^V$ were estimated at the wavelengths of 450 nm and 700 nm on the assumption that the turbidity factor was a smoothly varying function of wavelength. The values of $\beta_A^V$ thus deduced were compared with the values tabulated by Deirmendjian (1969) for a known particle concentration. In the present case, computations at the wavelength of 450 nm yielded a particle concentration around 190 cm$^{-3}$ whereas those at the wavelength of 700 nm yielded a value around 52 cm$^{-3}$. Agreement between the two values could have been brought about either by increasing the albedo and decreasing the turbidity factor at the shorter wavelength, or by decreasing the albedo and increasing the turbidity factor at the longer wavelength.

It is obvious that the homogeneous model of the turbid atmosphere is an over-
simplification of the actual situation in so far as the vertical distribution of the atmospheric aerosols is involved. We used this very simple model mainly because the 'doubling' technique could easily be used to solve the radiative transfer problem and also because we wished to examine how complicated would be the elementary act of retrieval of the aerosol optical thickness from the polarization data even with a very simple model. It is, however, our belief that a more realistic representation of the vertical distribution of the aerosols may only alter the values of the turbidity factor and ground albedo and may not remove the ambiguity caused by the similar effects the two have on the outgoing radiation. Also the very limited amount of information available about the aerosols is too variegated to permit its use as a basis for modelling their spatial distribution.

It is thus felt that even to be able to learn about the gross features of the atmosphere-ground system from graphical inversion of the polarization data, very extensive knowledge of the optical and physical properties of representative types of naturally occurring aerosols and of natural formations which may constitute the lower boundary is required in order that suitable constraints may be imposed on the range of variability of model parameters. It is this interrelationship between what we wish to retrieve from an interpretation of the polarization data and what is required to facilitate such interpretations that will ultimately limit the scope of this indirect method of learning about the atmosphere-ground system. Inclusion of details pertinent to the real atmosphere such as the departure from optical homogeneity of the aerosols and their true absorption and horizontal inhomogeneities due to the presence of clouds will add to the complexity of the problem.

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