The Influence of Pollution on the Shortwave Albedo of Clouds

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ABSTRACT

By increasing droplet concentration and thereby the optical thickness of a cloud, pollution acts to increase the reflectance (albedo) of clouds; by increasing the absorption coefficient it acts to decrease the reflectance. Calculations suggest that the former effect (brightening of the clouds in reflection, hence climatically a cooling effect) dominates for thin to moderately thick clouds, whereas for sufficiently thick clouds the latter effect (climatically a warming effect) can become dominant.

1. Introduction

In the past few years interest has grown in the possibility that pollution can influence the planetary albedo. The SCEP Report (1970) referred briefly to the possible influence of pollution on cloud albedo and inferred that "dirty" clouds would be darker than "clean" clouds formed in uncontaminated air. The writer has pointed out (Twomey, 1974) that increasing pollution generally means increasing cloud nucleus concentrations, hence increasing numbers of cloud drops; this leads to increasing cloud optical thickness and hence for finite cloud thicknesses increasing cloud albedo. The present note will discuss the relative magnitude of these opposing influences on cloud albedo.

2. Optical thickness

Most lower and middle clouds are optically thick. When, for example, the sun's disc cannot be seen from the ground the optical thickness τ of the layer concerned must approach or exceed 10. A cloud of depth h containing $n(r,z)\Delta r$ drops of radius $r \rightarrow r+\Delta r$ per cubic centimeter at height z above cloud base possesses optical thickness τ at wavelength λ, with

$$\tau = \int_0^h k_E dz = \pi \int_0^h \int_0^\infty r^2 Q_E(r/\lambda) n(r,z) dr dz. \quad (1)$$

Here $Q_E(r/\lambda)$, the extinction efficiency, is given by Mie theory and k_E is the extinction coefficient. For solar

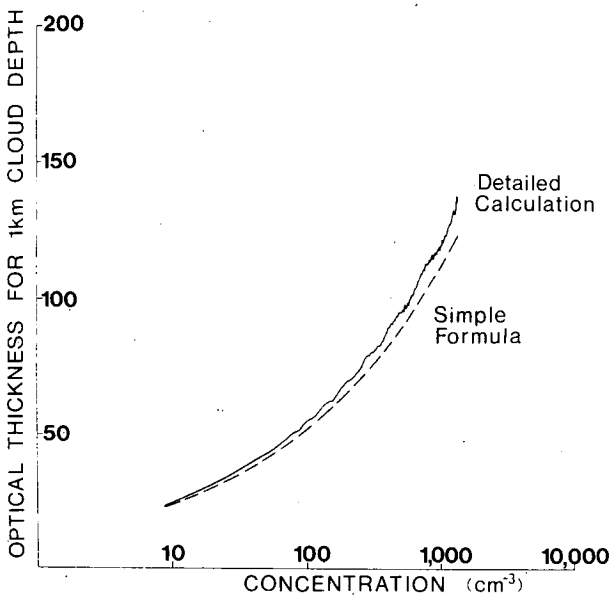

FIG. 1. Comparison of optical thickness calculated by the simple Trabert-type formula (2) and by exact Mie calculations integrated over a distribution of droplet sizes according to (1).

wavelengths the approximation $Q_E \equiv 2$ is quite adequate and for realistic (polydisperse) drop distributions we can eliminate the integration and adopt the simple formula

$$\tau = 2\pi N \bar{r}^2 h, \tag{2}$$

where N is the drop concentration per cubic centimeter and $\bar{r}$ can be any representative mean or model radius. It is convenient and sufficiently accurate to use the volume-mean radius so that the liquid water content W is given by $(4\pi/3)\bar{r}^3 N$. Fig. 1 shows the extent of the approximations involved when (2) is used in place of the detailed calculations of (1). The simple formula is seen to be quite adequate.

Using either formula, one can calculate optical thickness for any depth of cloud as a function of drop concentration. A water content of $\frac{1}{3}$ g m^{-3} [which is typical at least of lower level clouds (see Warner and Squires, 1958)] was adopted to calculate values of extinction coefficient k_E (cm^{-1}) and optical thickness per kilometer of cloud depth t_{km}; the results are given in Table 1.

Clean air over the tropical oceans typically contains about 100 cloud nuclei per cubic centimeter, while over the cooler oceans concentrations can be as little as 10 cm^{-3} or even less; continental concentrations typically run from 500–1000 cm^{-3} and in moderate to heavy pollution values of 5000 cm^{-3} and higher are often measured. The table therefore contains approximately the range of cloud nucleus and cloud drop concentrations in the present atmosphere. The criterion $\tau \gg 1$ which defines "optically thick" is satisfied for a 1 km depth of cloud for all concentrations within that range; a 100 m layer, on the other hand, would be optically thick only in continental to polluted air and would have $\tau \approx 1$ for clean conditions. However, even in extremely clean conditions ($N = 3$–10 cm^{-3}) only a few hundred meters of geometric depth are needed to give a cloud which is optically thick.

TABLE 1. Extinction coefficient k_E and optical thickness t_{km} for a 1 km depth.

	$\bar{r}$ (μm)				
	2	5	10	20	30
N (cm^{-3})	9950	640	80	10	3
k_E (cm^{-1})	0.0025	0.001	0.0005	0.00025	0.00017
t_{km}	250	100	50	25	17

3. Scattering properties of optically thick layers

When optical thickness becomes large, scattering of incoming radiation by a layer becomes relatively uniform, varying smoothly and slowly with angle. It is found that only a few parameters are needed to give the reflection, transmission and absorption quite precisely. These parameters are the optical thickness τ, the single scattering albedo $\bar{\omega}_0$ and the asymmetry factor g (which is the weighted average of the cosine of scattering angle; $g=0$ for any symmetric scattering diagram and $g=1$ for exactly forward scattering). Van de Hulst (1971) has shown that to high accuracy τ, $\bar{\omega}_0$ and g can be collected into two variables so as to further reduce the relevant dependences; in situations of moderate absorption van de Hulst's scaling principle reduces to the use of $\tau(1-g)$ to characterize optical thickness. An increase in drop concentration at constant water content results in smaller drops and hence a decrease in g as well as an increase in τ, so that $\tau(1-g)$ increases somewhat *faster* than τ. In the micron size range with which one is concerned, however, the change in g with size is rather slow; for most purposes its effect is second-order and it is sufficient to consider only the influence of τ. Nevertheless, it is relevant to note that if the effect of g is included, the dependence of reflectance, etc., on drop concentration is somewhat enhanced, rather than diminished.

For optically thick clouds one can therefore consider reflectance S and other optical properties of the layer to be functions of τ and $\bar{\omega}_0$ only. For fixed $\bar{\omega}_0$, S increases monotonically with τ but the rate of increase decreases monotonically with increase in τ; for fixed τ, S evidently decreases with decrease in $\bar{\omega}_0$ (i.e., with increasing absorption). Thus

$$\frac{\partial S}{\partial \tau} \gtrless 0, \quad \frac{\partial S}{\partial \bar{\omega}_0} \gtrless 0,$$

$$\frac{\partial S}{\partial \tau} \underset{\tau \to \infty}{\longrightarrow} 0.$$

If the extent of pollution above a reference "clean" state (at which $\bar{\omega}_0 = 1$, $\tau = \tau_0$, $S = S_0$) is gaged by some

variable x (the precise physical nature of which is irrelevant), then increasing pollution will increase the albedo if dS/dx is positive, i.e., if

$$\frac{\partial S}{\partial \tau}\frac{d\tau}{dx}+\frac{\partial S}{\partial \bar{\omega}_0}\frac{d\bar{\omega}_0}{dx}>0,$$

and vice versa.

The dependence of reflectance and albedo on τ and $\bar{\omega}_0$ may be represented by a set of graphs of S vs τ for a set of constant values of $\bar{\omega}_0$, as illustrated schematically in Fig. 2. With increase in x, S follows a trajectory represented by the broken line in the figure. The increase in τ with increase in the pollution index x will give a component along the curve $S(\tau)$, while a change in $\bar{\omega}_0$ will give a transverse component, which will be downward if $\bar{\omega}_0$ decreases with x.

To put Fig. 2 on a quantitative basis, one needs to prescribe $d\bar{\omega}_0/dx$ and $d\tau/dx$. Since $(1-\bar{\omega}_0)\tau$ equals the absorption optical thickness τ_a it follows that

$$\frac{1}{1-\bar{\omega}_0}\frac{d\bar{\omega}_0}{dx}=\frac{1}{\tau}\frac{d\tau}{dx}-\frac{1}{\tau_a}\frac{d\tau_a}{dx}.$$

Necessarily $\tau_a \leqslant \tau$ (and in any real cloud context $\tau_a \ll \tau$), so if absorption optical thickness τ_a increases with increasing pollution, $d\bar{\omega}_0/dx$ tends eventually to become negative. The simplest assumption which can be made (other than the assumption that scattering is conservative) is to take N and τ_a each to be directly proportional to x. This assumption amounts to assuming that all components in the aerosol increase together and in the same proportion, so that the increase in cloud nuclei and in aerosol absorption are proportional.[1] If W is to be maintained constant, independent of x, the total optical thickness τ, which is dominated by scattering, must then increase as $N^{\frac{1}{3}}$ or $x^{\frac{1}{3}}$. Thus $\tau^{-1}d\tau/dx = \frac{1}{3}\tau_a^{-1}d\tau_a/dx$.

Measurements of cloud nucleus concentration (Twomey and Wojchiechowski, 1969) suggest that $N\sim 10^3$ cm^{-3} is typical of the continental aerosol; measurements by de Luisi *et al.* (1976) suggest a value of around 0.05 for the absorption optical thickness for the entire atmospheric column, the aerosol scale height being of the order of 2 km. The latter measurements were made in geographical areas (Blythe, Calif., and Big Spring, Tex.) in which cloud nucleus concentrations around 1000 cm^{-3} could be expected with some confidence. The values 0.01 and 0.1 were therefore selected to bracket the measurements of de Luisi *et al.* and would roughly represent a reasonable value and an extreme value, respectively, for the absorption t_a per kilometer depth in continental conditions when N is $\sim$1000 cm^{-3}. The arbitrary measure of pollution x can conveniently be defined to be unity when N is 1000 cm^{-3}; if a perfectly clean atmosphere is taken to have $N=25$ cm^{-3}, the following formulas ensue for the variation with x of N and t_a:

$$\left.\begin{aligned} N &= 25+975x \ [\text{cm}^{-3}] \\ \text{Moderate absorption } t_a &= 0.01x \ [\text{km}^{-1}] \\ \text{Heavy absorption } t_a &= 0.1x \ [\text{km}^{-1}] \end{aligned}\right\}.$$

The clean value $N=25$ cm^{-3} was selected to give a representative starting point, but which starting point was used is of little consequence beyond its illustrative value. $N=25$ cm^{-3} is typical of very clean polar maritime air and in the present context all increases above this level are assumed to be occasioned by contamination which adds absorbing particles in the same proportion.

With the above assumptions, computations can be made for the variation with pollution index x of reflectance, albedo, etc. In Fig. 3 we have plotted trajectories (dashed curves) for moderate and heavy absorption for a thin (250 m) cloud layer (initial point A), a cloud layer 1 km thick (initial point B) and a thick (4 km) layer (initial point C). The quantity plotted was the spherical albedo A_s, which eliminates geometric variables and gives a reasonably representative global value of albedo. [It represents the fraction of incident radiation reflected by a sphere covered by a layer of the prescribed properties; for a reflection function $S(\mu,\mu_0)$ which relates intensity in the emergent μ direction to intensity in the incident μ_0 direction, the spherical albedo is given by

$$2\int_0^1\int_0^1 \mu S(\mu,\mu_0)d\mu d\mu_0.]$$

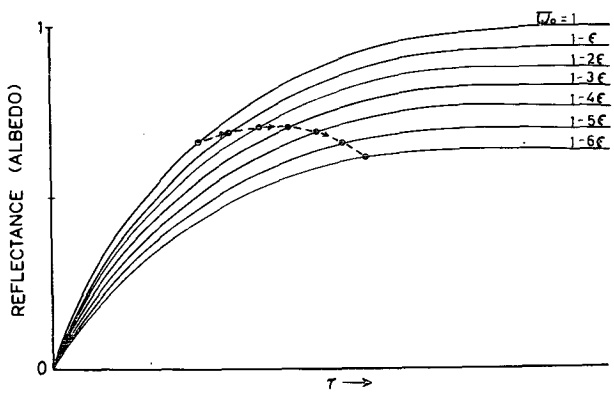

FIG. 2. Schematic diagram showing the variation of reflectance with optical thickness τ for different values of $\bar{\omega}_0$ and the trajectory (dashed curve) of the representative point when increasing pollution increases *both* τ and $1-\bar{\omega}_0$ (or τ_a); ϵ represents the increase in $1-\bar{\omega}_0$ from curve to curve.

[1] One is also assuming tacitly that absorption is not greatly modified when a cloud forms; that will be the case if, for example, absorption is by particles which remain unchanged after cloud formation. The results of Prishivalko and Astafyeva (1974), and unpublished computations in this laboratory, suggest that even if drops form and grow around insoluble absorbing particles the overall absorption is not profoundly changed (the change being typically no more than 50%, and not necessarily an increase).

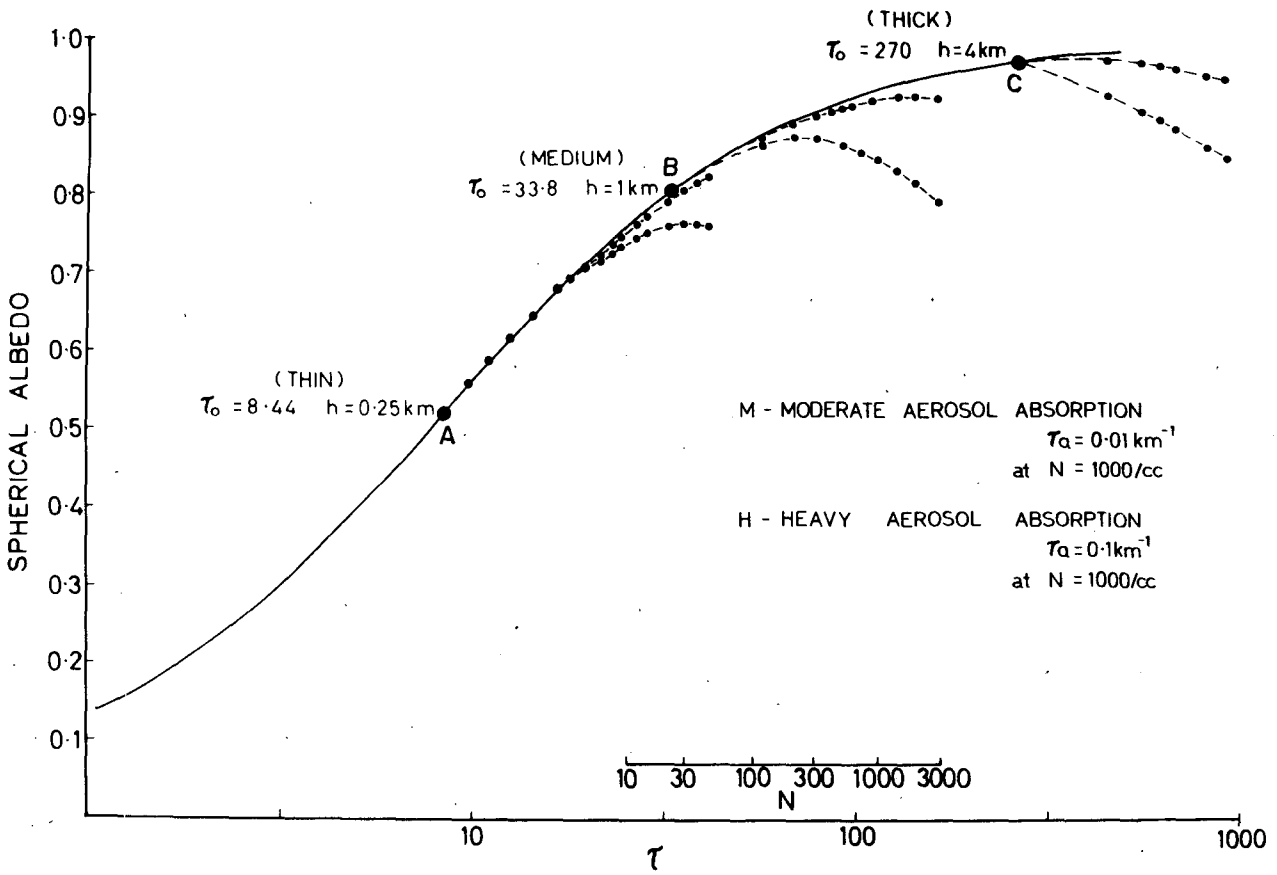

FIG. 3. Numerically computed trajectories corresponding to the schematic curves in Fig. 2, for the change of spherical albedo with increasing pollution for thin, moderate and thick clouds.

The solid curve in Fig. 3 represents the conservative ($\bar{\omega}_0 = 1$) value of A_s; if pollution did not increase absorption at all, trajectories of A_s vs x would lie on this curve, since then only τ would change with increasing pollution. The starting point for each pair of curves corresponds to $x=0$, i.e., conservative scattering and $N=25$ cm^{-3}. Fig. 3 shows that for all but the thickest clouds, the brightening influence of increasing τ outweighs the darkening influence of increasing τ_a, even though the latter increases in proportion to N while τ increases as $N^{\frac{1}{3}}$. One clearly would have had to postulate a much more rapid increase of τ_a relative to N to obtain a different result. It would be routine to carry out similar calculations for other assumed relationships between N and τ_a but no useful purpose would seem to be served by such computations. Measurements to determine how the relevant quantities N and τ_a vary in pollution are clearly what are required.

4. Conclusions

Pollution may increase or decrease the brightness of clouds depending on the optical thickness of the clouds and the way in which cloud nucleus concentration varies with absorption optical thickness. Plausible assumptions concerning the latter lead to results which suggest that in all but the thickest clouds the pollution increases the albedo. Since most of the earth's cloud cover is in the form of clouds which are not very thick this result suggests that the planetary albedo also will increase with increase of pollution.

REFERENCES

De Luisi, J. J., P. M. Furukawa, D. A. Gillette, B. G. Schuster, R. J. Charlson, W. M. Porch, R. W. Fegley, B. M. Herman, R. A. Rabinoff, J. T. Twitty and J. A. Weinman, 1976: Results of a comprehensive atmospheric aerosol-radiation experiment in the southwestern United States. Part I: Size distribution, extinction optical depth and vertical profiles of aerosols suspended in the atmosphere. *J. Appl. Meteor.*, **15**, 441–454.

Prishivalko, A. P., and L. G. Astafyeva, 1974: Absorption, scattering and extinction of light by water-coated atmospheric particles. *Izv. Atmos. Oceanic Phys.*, **10**, 815–818.

SCEP (Study of Critical Environmental Problems) 1970: *Mass Impact on the Global Environment.* The MIT Press, 319 pp.

Twomey, S., 1974: Pollution and the planetary albedo. *Atmos. Environ.*, **8**, 1251–1256.

——, and T. A. Wojchiechowski, 1969: The geographic variation of cloud nuclei. *J. Atmos. Sci.*, **26**, 684–688.

Van de Hulst, H. C., 1971: Some problems of anisotropic scattering in planetary atmospheres. *Planetary Atmospherés* (IAU Symposium No. 40) C. Sagan *et al.*, Eds., Reidel, 177–185.

Warner, J., and P. Squires, 1958: Liquid water content and the adiabatic model of cumulus development. *Tellus*, **10**, 390–394.