An Introduction to Twomey' Effect

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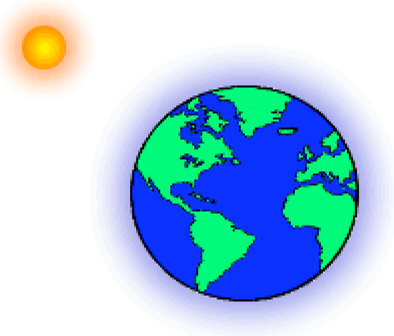
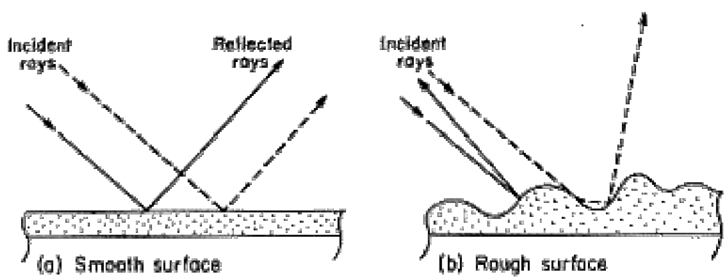
Mauna Loa, Hawaii on a clear day

Mauna Loa, Hawaii on a dusty day

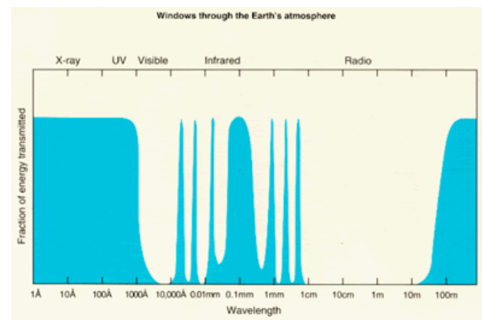
Atmospheric Radiation



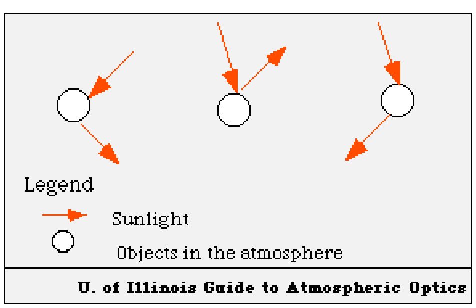
Reflection



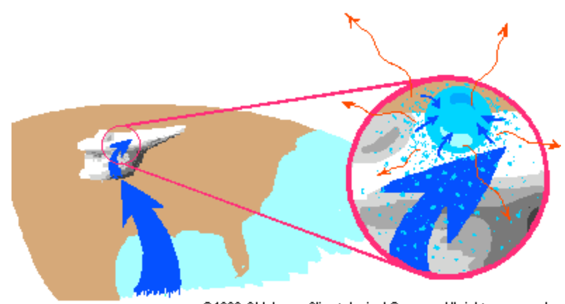
Absorption



Scattering

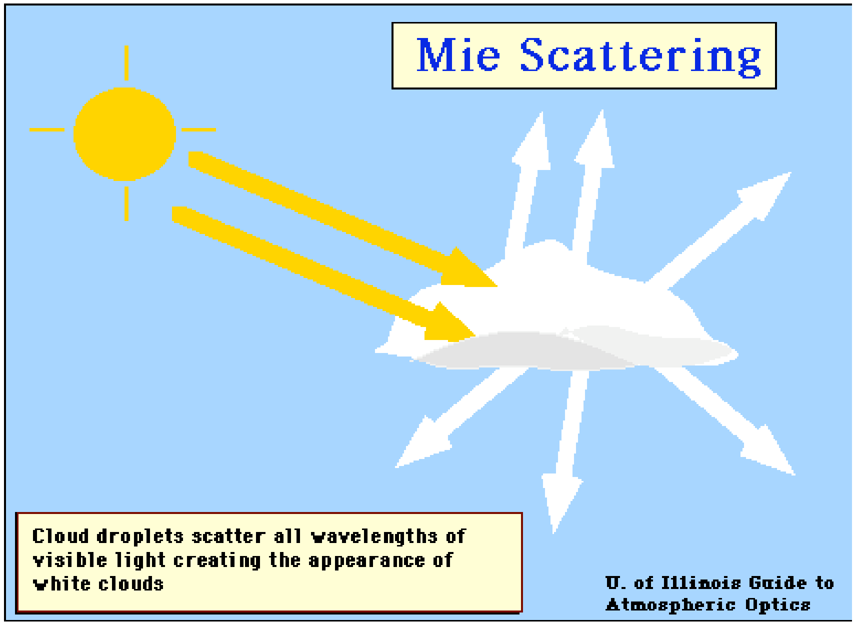


Transmission



Scattering

Rayleigh scattering



Mie scattering

Non-selective scattering.

The impact of clouds

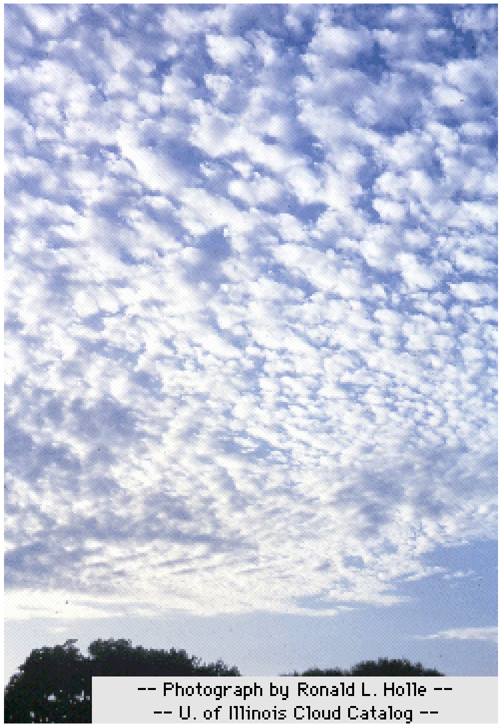
Clouds have two competing influences in the radiation budget:

1) They reflect solar radiation and prevent it from reaching the surface of earth, similar to an umbrella, and preventing the warming of the atmosphere through absorption of the radiation.

2) They absorb the infrared radiation escaping from the surface of the earth and thus trap the warmth in atmosphere, similar to a greenhouse.

Cloud types

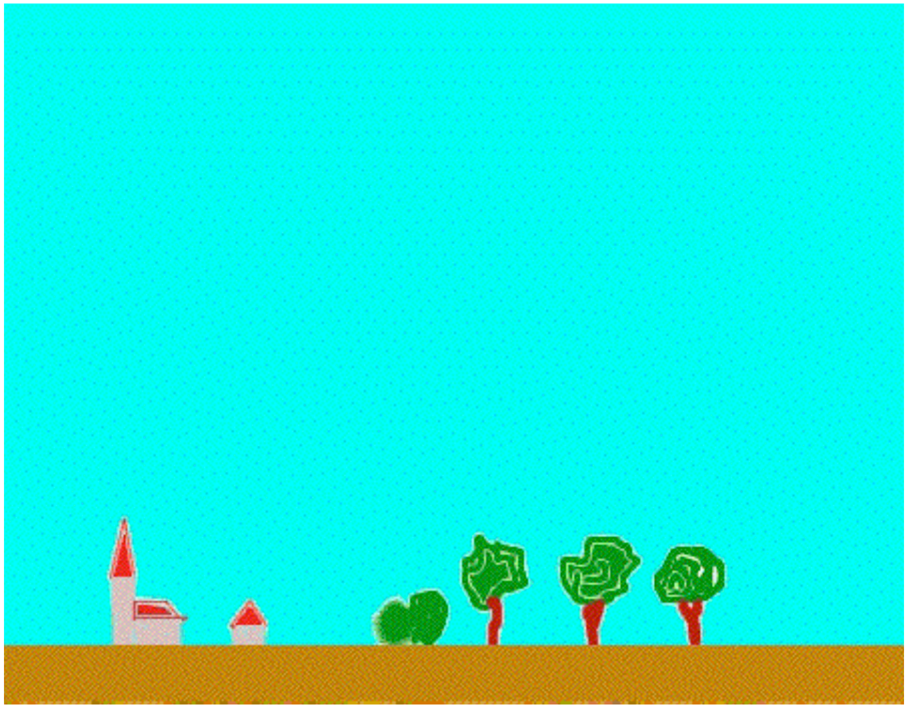
Low cloud



Middle cloud

High cloud

Different impacts of different clouds



Low level clouds: large albedo, weak absorption of infrad radiation-----cooling
Upper level clouds: weak albedo, strong absorption of infrad radiation----warming

Optical thickness

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

$Q_E(r/\lambda)$ is the extinction efficiency, is given by Mie theory, nearly eq $Q_E \equiv 2$ 2

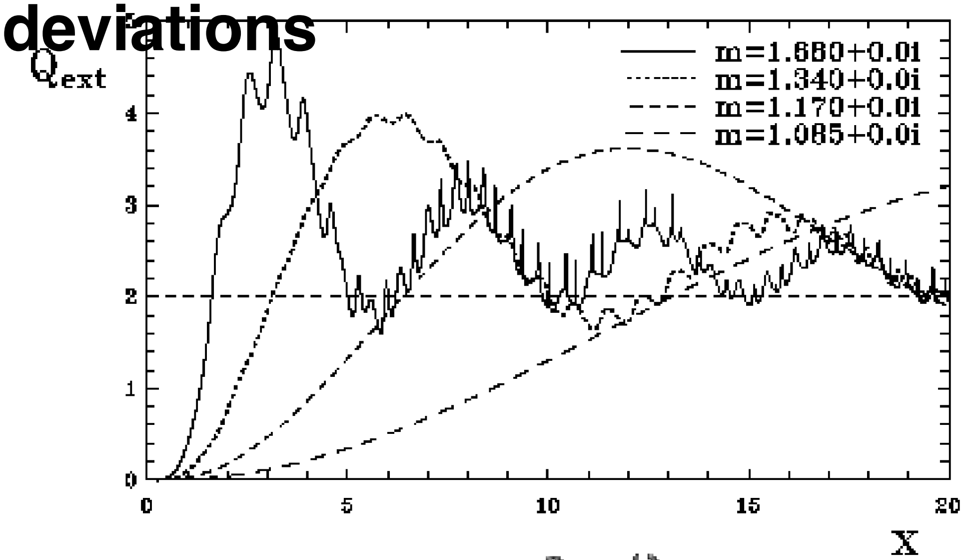
k_E is the extinction efficient

For solar wavelengths and for realistic (polydisperse) drop distributions we can eliminate the integration and adopt the simple formula

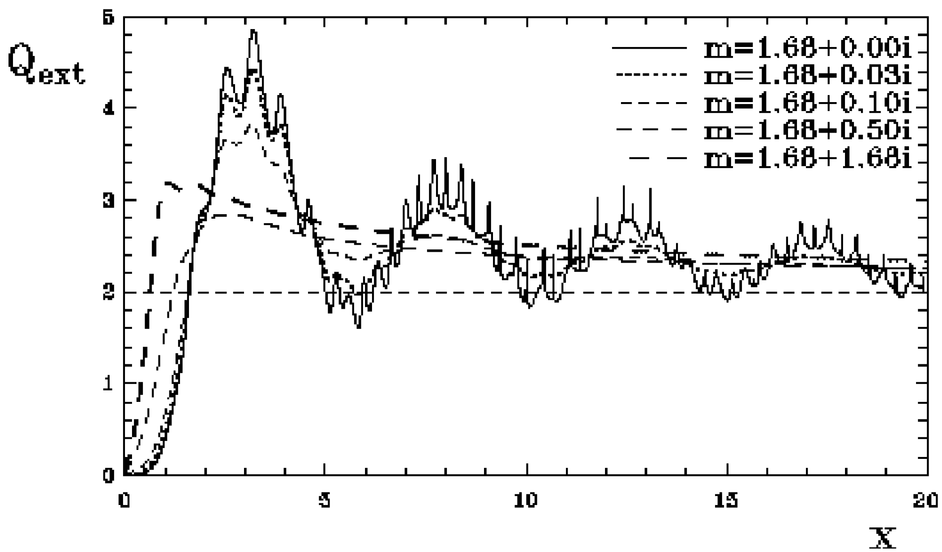
$$\tau = 2\pi N \bar{r}^2 h, \qquad (2)$$

Where N is the drop concentration per cubic centimeter and $\bar{r}$ can be any representative of mean or model radius

Extinction efficiencies: general behaviour and deviations



$$x = 2\pi r/\lambda$$



Size dependence of the extinction efficiency factors for homogeneous spherical particles. The influence of variations of the real part (upper panel) and imaginary part (lower panel) of the refractive index is illustrated.

Typical refractive index m of cloud droplet is:

m=1.333-1.96*10^{-9}i

$$Q_{\mathrm{ext}}^{\mathrm{lim}} = Q_{\mathrm{diff}} + Q_{\mathrm{geom}} = 2.$$

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

$$\tau=2\pi N\bar{r}^2 h, \qquad (2)$$

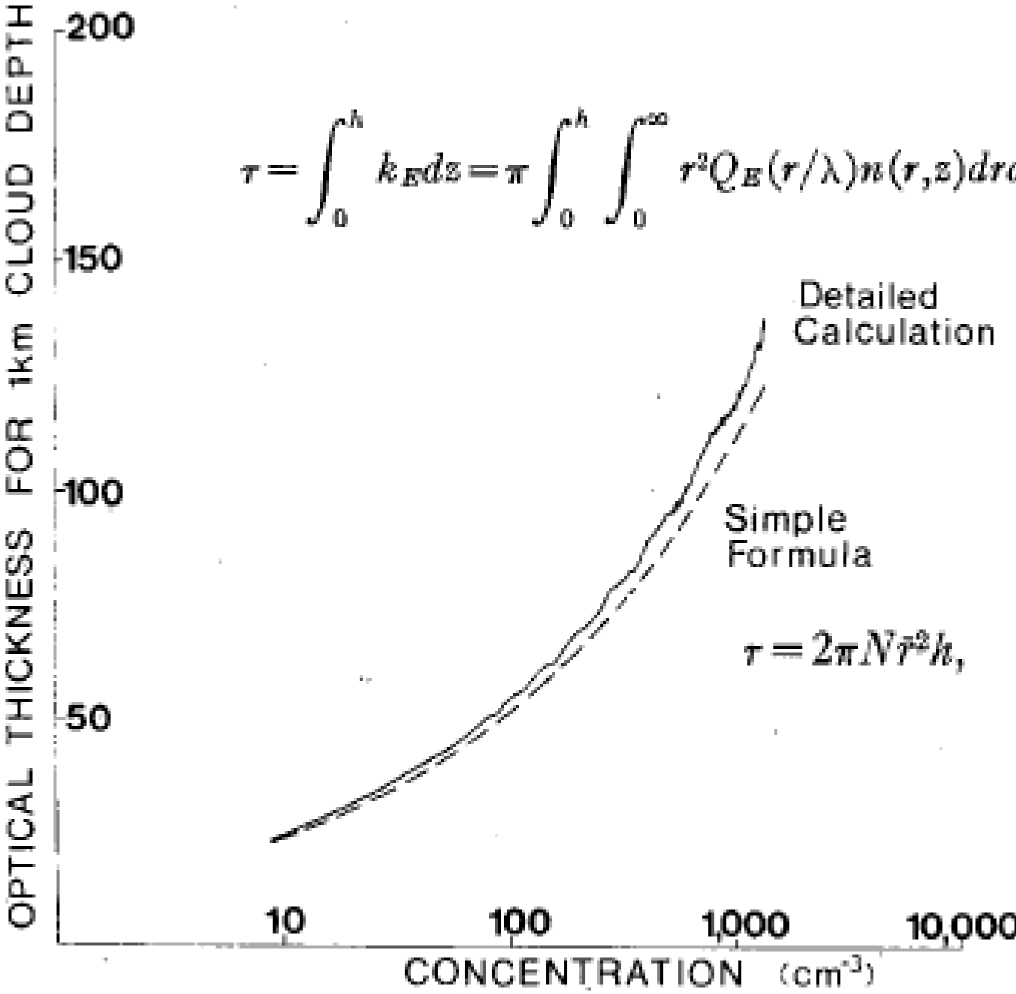


FIG. 1. Comparison of optical thickness calculated by the simple Trabert-type formula (2) and by exact Mie calculations integrated over a distribution of droplet sizes according to (1).

The liquid water content W is given by the volume-mean radius $\bar{r}$

W (in number) $(4\pi/3)\bar{r}^3 N$

= **W** (in mass) ρ_{water} **W** (in number)

=

A water content of 1/3 gm^{-3} (which is typical at least of lower level clouds) was adopted to calculate values of extinction coefficient k_E (cm^{-1}) and optical thickness per kilometer of cloud depth

$$k_E = 2\pi N\bar{r}^2 \qquad \tau_{km} = 2\pi N\bar{r}^2 h$$

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

Parameters needed to give the extinction

Optical thickness: $\tau_{km} = 2\pi N\bar{r}^2 h$

Single scattering albedo: $\omega_0 = \beta_s / \beta_e$

Asymmetry factor: $g = \dfrac{\int_{-1}^{+1} uP(u)du}{\int_{-1}^{+1} P(u)du}$

Where P(u) is the phase function $u = \cos(\theta)$

$\beta_e = \beta_s + \beta_a$ is the extinction coefficient

$\tau_a = \tau(1 - \omega_0)$ is absorption optical thickness

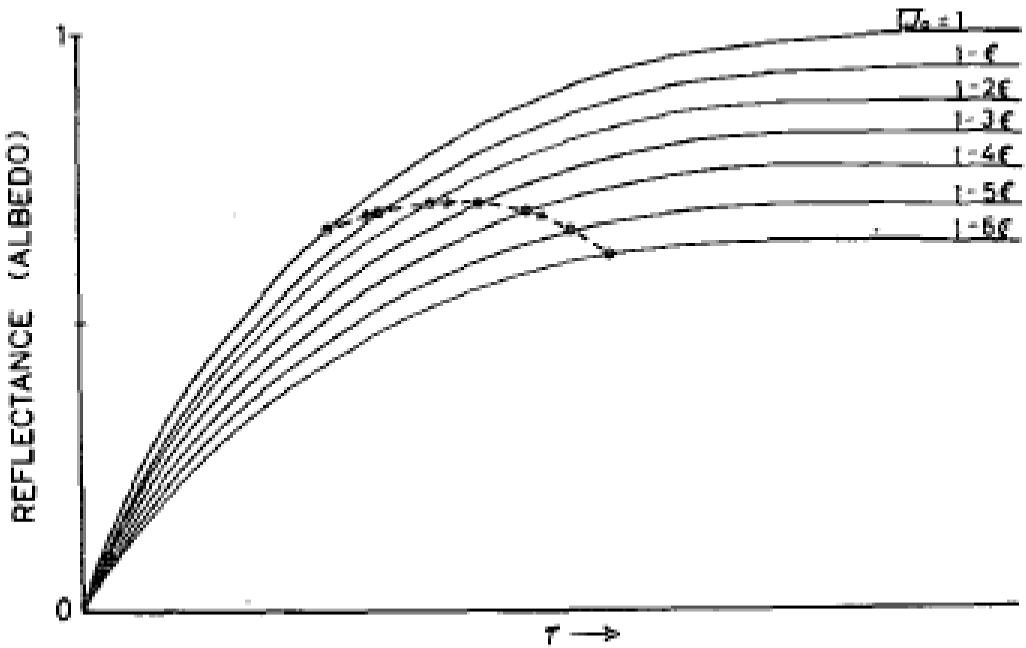


FIG. 2. Schematic diagram showing the variation of reflectance with optical thickness τ for different values of $\bar{\omega}_0$ and the trajectory (dashed curve) of the representative point when increasing pollution increases *both* τ and $1-\bar{\omega}_0$ (or τ_a); ϵ represents the increase in $1-\bar{\omega}_0$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

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

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

$$\frac{\partial S}{\partial \tau} \xrightarrow[\tau \to \infty]{} 0.$$

Increase pollution (pollution index x) will increase the albedo if dS/dx is positive:

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

because:

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

$$\frac{\partial S}{\partial \tau} \xrightarrow[\tau\to\infty]{} 0.$$

so we need to prescrib $d\bar{\omega}_0/dx$ and $d\tau/dx$.

Becaus e: $\tau_a = \tau(1-\omega_0)$

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

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, $d\tilde{\omega}_0/dx$ 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

Typical cloud nuclei concentration

¬Clean air over the tropical oceans 10-100 cm-3

¬Continental concentrations run from 500-1000 cm-3;

¬Moderate to heavy pollution has values >5000 cm^{-3}

The values 0.01 and 0.1 represent a reasonable and an extreme value of τ_a, respectively, for the τ_a absorption km^{-1} depth in continental conditions when $N=1000cm^{-3}$

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

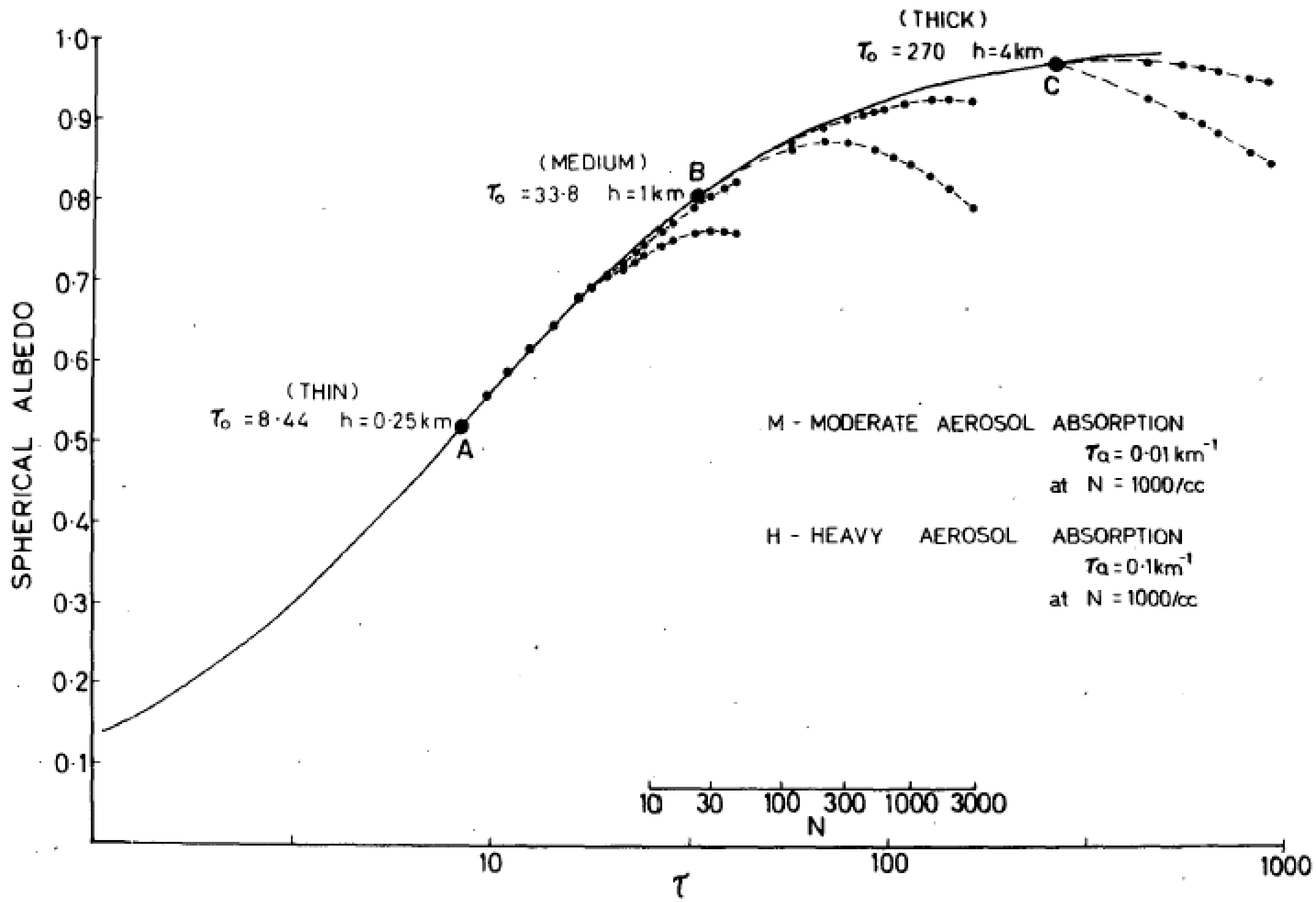


FIG. 3. Numerically computed trajectories corresponding to the schematic curves in Fig. 2, for the change of spherical albedo with increasing pollution for thin, moderate and thick clouds.

Spherical (or global) albedo: As= $2\int_0^1 \int_0^1 \mu S(\mu,\mu_0) d\mu d\mu_0.]$

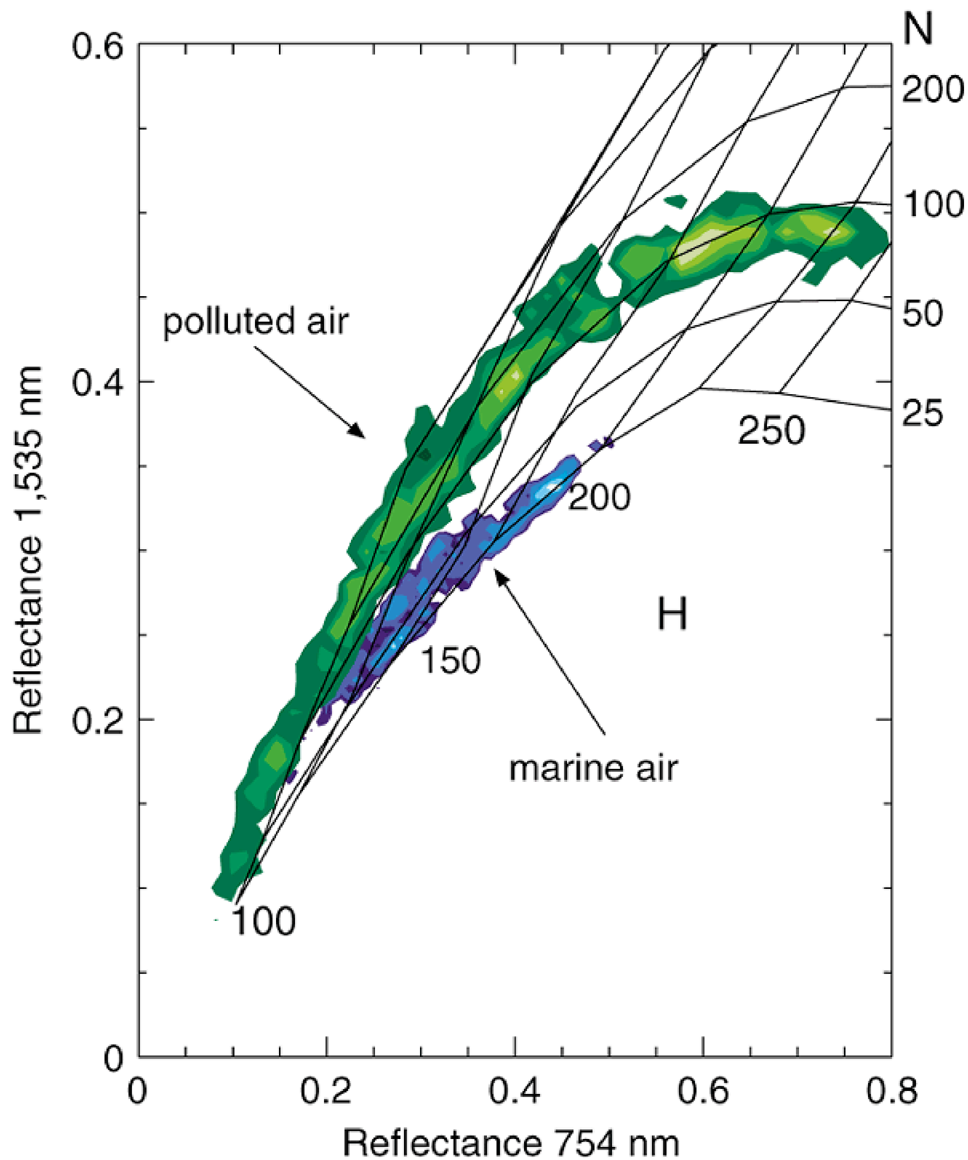
Spherical albedo eliminates geometric variables and gives a reasonably representative global value of albedo, It represents the fraction of incident radiation reflected by a sphere covered by a layer of the prescribed properties.

According to *Liou*, spherical albedo can be calculated as:

$$\bar{r} = \frac{f^{\uparrow}(0)}{\pi a^2 F^*} = 2\int_0^1 r(\mu_0)\mu_0 d\mu_0$$

$$r(\mu_0) = \frac{F_{dif}^{\uparrow}(0)}{\mu_0 F^*} = \frac{1}{\pi}\int_0^{2\pi}\int_0^1 R(\mu,\Phi;\mu_0,\Phi_0)\mu d\mu d\Phi$$

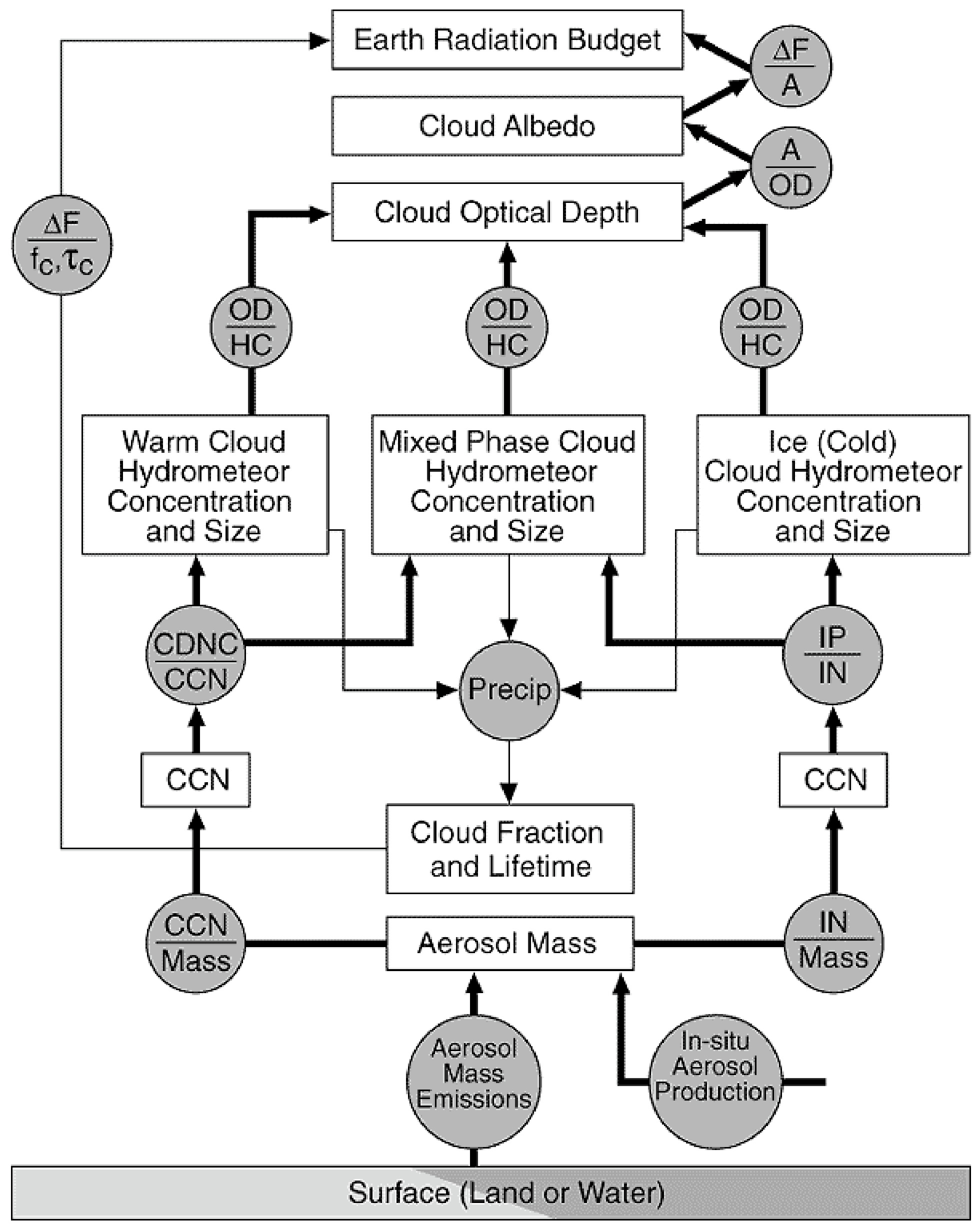
$$R(\mu,\Phi;\mu_0,\Phi_0) = \pi I_r(0;\mu,\Phi)/(\mu_0 F^*)$$



Frequency distributions of the reflectances at 1,535 nm versus reflectances at 754 nm determined during the ACE-2 experiment. Isolines of geometrical thickness (H) and droplet number concentration (N) demonstrate the higher reflectance in polluted cloud if normalised by a similar geometrical thickness (Brenguier et al. 2000).

Indirect Forcing of Aerosols

Flow chart showing the processes linking aerosol emissions or production with changes in cloud optical depth and radiative forcing. Bars indicate functional dependence of the quantity on top of the bar to that under the bar. Symbols: CCN (Cloud conden-sation nuclei); CDNC (Cloud droplet number concentration); IN (Ice nuclei); IP (Ice particles); OD (Optical depth); HC (Hydrometeor concentration); A (Albedo); fc (Cloud fraction); Dc (Cloud optical depth); tc (Radiative forcing).



conclusio
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¬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.

¬In all but the thickest clouds the pollution increases the albedo. Since most of the earth’s cloud cover is not very thick this result suggest that the planetary albedo also will increase with increase of pollution.