Vol.13 No.2 Advances in Atmospheric Sciences May 1996

Influence of Clouds on UV Irradiance at Ground Level and Backscattered Exittance

Wang Pucai (王普才) and *Jacqueline Lenoble*
Laboratoire d'Optique Atmospherique, Universite des Sciences et Technologies de Lille, URA 713 CNRS,
59655 Villeneuve d'Ascq, France

Received July 3, 1995; revised August 24, 1995

ABSTRACT

The influence of various cloud parameters and the interactions with the ground albedo and the solar zenith angle have been studied by means of model simulations. The radiative transfer model suitable for a cloudy atmosphere as well as for a clear atmosphere has been developed on the basis of the Discrete Ordinate Method. This study leads to a general understanding for cloudy atmospheres: in the presence of a uniform cloud, the cloud scattering is dominant to molecular and aerosol scattering, and it is also wavelength–independent; the ratio of transmitted irradiance in a cloudy atmosphere to that in the background clear atmosphere is independent of cloud height and solar zenith angle. That's to say, the radiation downwelling out of a cloud is quite isotropic; it decreases approximately exponentially with the cloud optical depth at a rate related to the ground albedo; the reflected irradiance at the top of the atmosphere is dependent on cloud optical depth as well as on solar zenith angle, but not on ground albedo for clouds of not very thin optical depth.

Key words: Cloud, UV

I. INTRODUCTION

There has been much concern about the possible increase of the ultraviolet radiation reaching the earth's surface because of its negative influence on the biosphere. The influence of ozone on the ultraviolet radiation (UV) has been paid much attention by many scientists since a substantial reduction in the ozone column over Antarctica during the previous decade was reported (Farman et al., 1985). The global scale downward trend in stratospheric ozone concentration was revealed by analysis of NIMBUS 7 TOMS data from 1978 to 1990 (Stolarski et al., 1991). One of the consequences of ozone reduction in the atmosphere is an increase of ultraviolet radiation, especially UV–B (280–320 nm) at the ground level. However, clouds have also a great and complex influence on ultraviolet radiation (Lubin et al., 1991; Tsay et al., 1992). Although global cloud patterns (cover and thickness) are considered to be stable (global cloud cover is approximately 50%), cloud patterns may change markedly on a local scale. The influence of changes of cloudiness may impair the observation of UV changes due to ozone reduction. Therefore, we should also pay much attention to the influence of clouds on ultraviolet radiation.

Worldwide, there are many sites observing ultraviolet radiation at the ground level, for which data are obtained in both clear and cloudy sky conditions. The objective of this work is to help the interpretation of the measurement data, including those collected in the presence of clouds, in order to extract more information on ultraviolet radiation at the ground level.

A UV radiative model for clear atmospheres has been developed by Wang and Lenoble (1994) and used for comparison with measurements obtained during the first campaign of the European Intercomparison of Ultraviolet Spectroradiometers in Panorama, Greece, in July

1991 (Gardiner et al., 1992). The agreement was found within ± 6% without taking account into the angular response correction. We have taken the Discrete Ordinate Method (DOM), realized as Stamnes' code (Stamnes et al., 1988), with twenty flexible layers. Here we extend the model to cloudy atmospheres.

The clouds used in the radiative code are treated as horizontally homogeneous and incorporated into one or several of the background clear atmospheric layers.

We intend to estimate the influence of various parameters of clouds, such as vertical position, optical depth, type, and the interactions between clouds and other parameters, such as ground albedo and solar zenith angle, by model simulations. Although our major interest is the surface irradiance, we have also considered the backscattered exittance, which is of importance for satellite observations and which is obtained from the model, simultaneously with the surface irradiance. We will limit our study in this paper to horizontally uniform clouds, as the non uniform clouds, especially the broken clouds, cannot be handled by a code on plane–parallel geometry.

In Section 2 we present briefly the clear atmosphere model which has been used as a reference to compare the cloudy cases. A large range of cloud models have been considered; they are presented with their radiative characteristics in Section 3. Results are given in Section 4, and some discussions and conclusions are given in Section 5.

II. REFERENCE CLEAR ATMOSPHERE MODEL

A clear atmosphere is defined by the profiles of pressure, temperature, humidity, aerosols, ozone and other trace gases. In the UV spectral region the major processes influencing radiative transfer are the absorption by ozone and the scattering by aerosols and molecules; the absorption by other trace gases is negligible, with an exception for SO_2 in very polluted industrial atmospheres. Water vapor does not absorb in the UV wavelength region, but it has some indirect influence on UV radiation through aerosols, which are related to water vapor.

A set of standard clear atmosphere, NASA (1966, 1976), has been widely used in the simulation of atmospheric processes. They have been incorporated into LOWTRAN 7 code (Kneizys et al., 1988).

We have chosen the midlatitude summer standard atmosphere, including profiles of pressure, temperature, humidity and ozone concentration. The total ozone amount is 332 Dobson units.

The aerosol profile and model are also taken from LOWTRAN 7; they correspond to four altitude regions: the boundary or mixing layer (0–2 km), the upper troposphere (2–10 km), the lower stratosphere (10–30 km), and the upper atmosphere (30–100 km). The rural aerosol profile is used in the mixing layer as well as in the upper troposphere, but with fewer large particles for the latter. This model is applicable to the continental regions which are not directly influenced by the source of aerosols from industrial areas. For the aerosol extinction profile, the optical parameters are determined by Mie code, using their size distribution and assuming spherical particles. The extinction coefficients at 300 nm are approximately 1.8 times their values at the reference wavelength 550 nm. The asymmetry factors of the different aerosol models are very close, around 0.69 in the whole UV spectrum; the aerosols below 10 km are absorptive (single scattering albedo between 0.9 and 0.96) and the aerosols above 10 km are almost non–absorptive.

The extinction profiles of molecules, ozone and aerosols at 300 nm are plotted in Fig. 1. The total atmospheric optical depth as a function of wavelength is presented in Fig. 2, with the separate contributions due to ozone, aerosols and molecules.

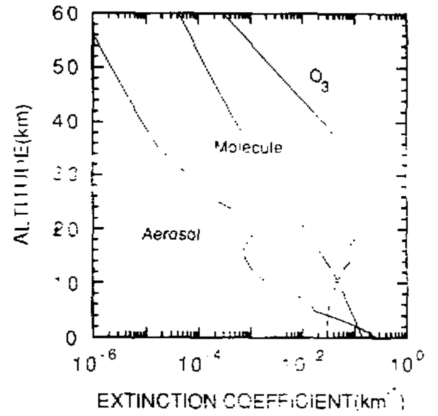

Fig. 1. Extinction profiles of molecules, ozone and aerosols at 300 *nm*.

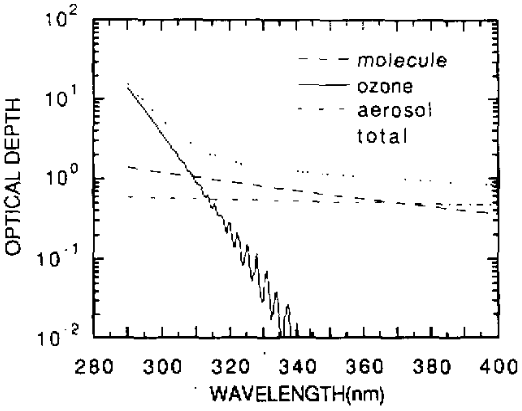

Fig. 2. Optical depths of molecules, ozone and aerosols as function of wavelength.

We must notice that this somewhat arbitrary choice of a reference clear atmosphere model does not impact on our conclusions concerning the cloud influence.

III. CLOUD MODELS

To describe a cloud we should consider the following parameters: (a) cloud type; (b) cloud height, defined by the top and the bottom levels; (c) horizontal extent; (d) phase of water, namely liquid or ice; (e) spatial liquid water density; (f) size distribution of water droplets or ice crystals. We consider here only water clouds with large horizontal extent which can be treated as a plane–parallel homogeneous layers. Ice clouds raise the problem of scattering by crystals, i.e. non–spherical particles, and will be left for a future study.

Here we use some of the cloud models summarized by Silverman et al. (1970) and quoted by Falcone et al. (1979), based on a large number of airborne measurements: Altostratus, Stratus I, Stratus II, Stratus–Stratocumulus, Stratocumulus I, Stratocumulus II, Cumulus, Cumulus–Cumulus congestus, Nimbostratus I, Nimbostratus II. Their size distributions and optical characteristics will be described in Section 3.1 below.

1. *Cloud Droplet Size Distribution*

The droplet size distribution is important to determine the cloud optical characteristics. Water clouds consist of a large number of small spherical water particles, whose diameters may vary from 0.01 to 100 μm. Following Deirmendjian (1969), the cloud droplets size distributions of various water clouds can be represented by a modified gamma distribution

$$n(r) = ar^{\beta}\exp(-br^{\gamma}), \tag{1}$$

where $n(r)$ is the number of particles of radius r; the three distribution parameters, β, b, γ are determined by fitting experimental data; a is related to the total number N_0 of particles per unit volume. Table 1 presents the characteristics of the 10 cloud models.

Table 1. Cloud models. N_0, Number Density; M, Liquid Water Content; β, b, a are Coefficients of Size Distribution in Eq.(1) with $\gamma = 1$ (From Falcone et al., 1979)

Cloud Type	Model number	β	b (μm)	a	N_0 (cm^{-3})	M (g • m^{-3})
Altostratus	1	5	1.11	6.268	400	0.41
Stratus I	2	3	0.667	8.247	250	0.42
Stratus II	3	2	0.6	27.00	250	0.29
St–Sc	4	2	0.75	52.734	250	0.15
Stratocumulus I	5	5	0.8	0.4369	200	0.55
Stratocumulus II	6	2	0.50	9.375	150	0.30
Cumulus	7	3	0.5	2.604	250	1.00
Cu–Cu cong	8	2	0.328	1.4115	80	0.57
Nimbostratus I	9	2	0.425	7.676	200	0.65
Nimbostratus II	10	1	0.333	11.089	100	0.27

2. *Optical Characteristics of the Cloud Models*

The coefficient of extinction, the single scattering albedo, the phase function or phase matrix determined by Mie theory are used to describe the optical characteristics of an individual cloud droplet. The index of refraction of water at UV wavelengths, which is necessary for the treatment by Mie theory, is taken from Hale and Querry (1973). The optical characteristics of a water cloud, which consists of a large number of spherical water droplets, can be obtained by integrating their individual characteristics weighted by their size distribution.

The optical characteristics derived from Mie theory for the 10 clouds are presented in Table 2. The extinction coefficient per unit of liquid water content ($\beta_{ext}(\lambda)/M$) is given at 550 nm, which is often used as a reference wavelength for the visible spectrum and will be used here for comparison between ultraviolet and visible. The single scattering albedo is not given in Table 2 because it is always 1.0 as the liquid water is not absorptive at both visible and UV wavelength. The spectral extinction coefficient ratio, given by $\beta_{ext}(\lambda)/\beta_{ext}(550)$ for six UV wavelengths, is almost independent of the cloud type, and decreases very slightly in the UV range, remaining close to 0.98. The results, together with the non–absorption and approximately the same asymmetry factor results, suggest that the scattering of low and middle altitude uniform clouds is almost wavelength–independent; it also does not depend much on the cloud type.

Table 2. The Optical Characteristics of the Clouds. N, Model Number, β_{ext}, Extinction Coefficient (km^{-1}); $\beta^{*}_{ext} = \beta_{ext}(\lambda) / \beta_{ext}(550\ nm)$; g, Asymmetry Factor

	Wavelength (nm)											
	550		300		325		350		375		400	
N	β_{ext} / M	g	β^{*}_{ext}	g	β^{*}_{ext}	g	β^{*}_{ext}	g	β^{*}_{ext}	g	β^{*}_{ext}	g
1	220.0	.833	.981	.789	.983	.794	.985	.799	.987	.804	.990	.809
2	175.2	.821	.983	.785	.985	.789	.987	.793	.989	.797	.991	.800
3	189.9	.825	.981	.789	.984	.794	.986	.799	.988	.803	.990	.806
4	237.3	.834	.978	.798	.981	.804	.983	.809	.985	.813	.987	.817
5	156.8	.812	.985	.780	.987	.783	.989	.787	.990	.790	.992	.793
6	157.2	.817	.984	.784	.986	.788	.988	.792	.989	.795	.991	.798
7	130.2	.807	.986	.779	.987	.782	.990	.785	.993	.788	.994	.790
8	102.6	.802	.986	.777	.988	.780	.991	.783	.994	.786	.995	.785
9	133.1	.810	.985	.781	.987	.784	.989	.788	.992	.790	.993	.793
10	130.8	.812	.984	.783	.986	.786	.989	.790	.993	.793	.994	.794

The exact phase functions can be obtained from Mie computation for each cloud type and each wavelength. However we have verified that the UV irradiance is not sensitive to the details of the phase function, by comparing the fluxes computed with exact Mie phase function and the Henyey–Greenstein phase function using the same asymmetry factor; they do not differ by more than 0.3%, although these functions are very different. For simplifying the computation of radiative transfer with a large number of wavelengths, the same Mie phase function with the asymmetry factors 0.79 was applied for all cases and all wavelengths.

3. *Altitude and Optical Thickness of Clouds*

We have seen that all the 10 cloud models can be characterized by a unique set of optical parameters (extinction ratio and asymmetry factor). despite the fact that they have very different size distributions. This is because we are looking for fluxes within a relatively narrow wavelength range rather than for radiance distribution.

The various clouds will therefore differ only by their position (top (Z_t) and bottom (Z_b)) in the model atmosphere and by their total liquid water content M; their optical depth is found as

$$\delta(\lambda) = M\beta^{*}_{ext}(\lambda)(\beta_{ext}(550) / M)(Z_t - Z_b), \tag{2}$$

where $\beta^{*}_{ext}(\lambda)$ and $(\beta_{ext}(550) / M)$ are given in Table 2. The clouds will be located in the different layers of the model between 0.2 and 5.5 km.

IV. RESULTS

In the study of the influence of clouds on UV radiation presented below, the computation for the clear atmosphere model is used as the reference with which the results for the cloudy atmospheres are compared for evaluating the influence of clouds. The ground surface is assumed to reflect according to the Lambert's law.

Clouds are imbedded in the clear atmosphere model and assumed to fill in completely one or several layers of the model. As discussed above, we use only one cloud model characterized by its optical depth and the same phase function. We must keep in mind that an optical depth is related to the geometrical thickness and to the liquid water content of the cloud. For example, a cloud of 0.5 km with an optical depth 36.8 corresponds to a liquid water content of 0.33, 0.42 and 0.56 g • m^{-3} respectively for the altostratus, stratus I and cumulus.

The results presented below are the spectral transmittance and reflectance, and the transmittance and reflectance ratios. The spectral transmittance T and reflectance R are defined respectively as the ratios of irradiances reaching the ground level and reflected out of the atmosphere to the incoming solar irradiance at the top of the atmosphere. We prefer to use them rather than irradiance at the ground or at the top of the atmosphere for avoiding the irregularity and uncertainty of the solar spectrum and, furthermore, for facilitating the comparison processes below. Only when comparing model results with measurements, it is necessary to compute the irradiance in absolute units, for example, W • m^{-2} • nm^{-1}.

The transmittance ratio is defined as

$$T_r(\lambda,\mu_s,\rho_s,\delta_c)=\frac{f_g^{\downarrow,cld}(\lambda,\mu_s,\rho_s,\delta_c)}{f_g^{\downarrow,clr}(\lambda,\mu_s,\rho_s)}=\frac{T^{cld}(\lambda,\mu_s,\rho_s,\delta_c)}{T^{clr}(\lambda,\mu_s,\rho_s)}, \tag{3}$$

where λ is the wavelength, μ_s the cosine of solar zenith angle, ρ_s the ground albedo, δ_c the cloud optical depth, $f_g^{\downarrow,cld}$ and $f_g^{\downarrow,clr}$ are the transmitted irradiances at the ground level in a cloudy atmosphere and in a clear atmosphere, respectively, and T^{cld} and T^{clr} are the corresponding transmittances, defined above.

In the same way, we define the reflectance ratio:

$$R_r(\lambda,\mu_s,\rho_s,\delta_c)=\frac{f_{toa}^{\uparrow,cld}(\lambda,\mu_s,\rho_s,\delta_c)}{f_{toa}^{\uparrow,clr}(\lambda,\mu_s,\rho_s)}=\frac{R^{cld}(\lambda,\mu_s,\rho_s,\delta_c)}{R^{clr}(\lambda,\mu_s,\rho_s)}, \tag{4}$$

where the index *toa* indicates the top of the atmosphere.

The transmittance and reflectance ratios are suitable to evaluate the sensitivity of transmittance or reflectance to cloud parameters, because they separate the effect of ozone from that of cloud parameters.

The transmitted irradiance includes two components, direct and diffuse. Usually, in the presence of clouds, the direct part is close to zero, and the transmitted irradiance is close to the diffuse component, unless the clouds are very thin (for example, $\delta_c < 5$), a case which rarely occurs for low and middle clouds.

For clarifying the complicated interaction between the cloud parameters and the surface and solar parameters, we present below first the effects of ground albedo and solar zenith angle, then effects of cloud height and cloud thickness. The results are exclusively given by the radiative transfer code with a 20–layer atmospheric model and with a spectral resolution of 0.5 nm.

Figs. 3 and 4 present an example of calculated transmittance and reflectance for a cloud layer of optical depth of 36.8 situated at 1.5–2 km and for albedoes 0.05, 0.3 and 0.8. Usually, a cloud layer significantly reduces the transmitted UV radiation at the ground and greatly augments the reflected UV radiation at the top of the atmosphere. A high ground albedo augments slightly the transmittance for a clear atmosphere, but strongly the transmittance in the presence of clouds, because of the multiple reflectances of light between the ground and the cloud layer. A high ground albedo affects the reflectance little in a cloudy atmosphere, which is not true for a clear atmosphere. The cloud layer, as a lower limit, blocks largely the contribution of light reflected by the ground and scattered in the atmosphere below the cloud

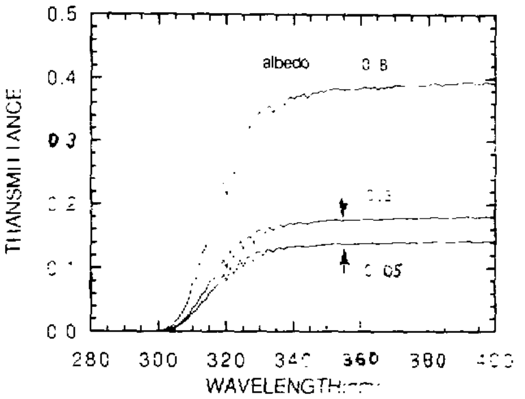

Fig.3. Transmittance in the cloudy atmosphere for different ground albedoes with solar zenith angle 45° and cloud optical depth 36.8.

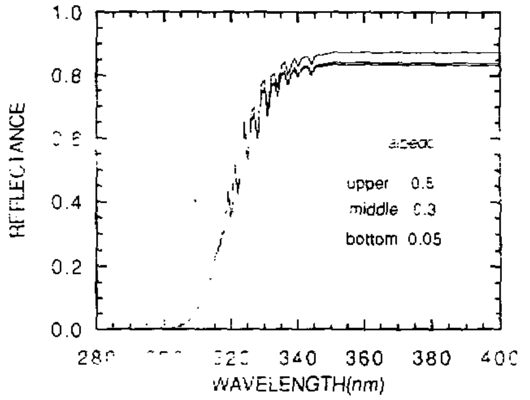

Fig.4. Reflectance in the cloudy atmosphere for different ground albedoes with solar zenith angle 45° and cloud optical depth 36.8.

layer. Clouds and ground albedo have no important effects on reflectance for wavelength less than 300 nm because of the strong absorption by ozone, which makes most of the reflectances come from the high atmosphere layers. Furthermore, clouds neutralize the wavelength–dependency between 340–400 nm, which is important for a clear atmosphere, as the scattering of clouds is dominant and wavelength–independent.

The effects of solar zenith angle on transmittance and the reflectance are shown in Figs. 5 and 6, which present the transmittance and reflectance ratios. Three solar zenith angles, 45°, 60° and 75° have been selected. The same cloud layer between 1.5–2 km of optical depth of 36.8 and the ground albedo of 0.05 are used. Fig. 5 shows that the transmittance ratio is almost independent of solar zenith angle. This is because photons entering a sufficiently thick

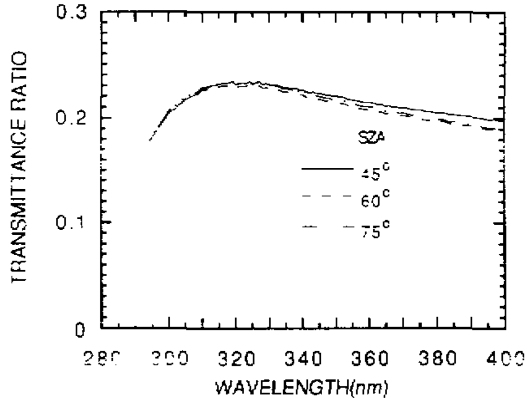

Fig. 5 Transmittance ratios for different solar zenith angles ($\rho_g = 0.05$, $\delta_c = 36.8$).

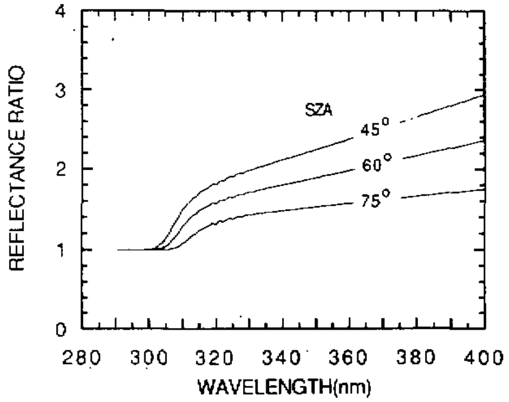

Fig. 6. Reflectance ratios for different solar zenith angles ($\rho_g = 0.05$, $\delta_c = 36.8$).

cloud layer loose soon the memory of their original incident direction. So, we have between the transmittance in a cloudy atmosphere $T^{cld}(\mu_s)$ and in the background clear atmosphere T^{clr} the approximate relationship:

$$T^{cld}(\mu_s) = T^{clr}(\mu_s) \cdot T^c, \tag{5}$$

where μ_s is the cosine of solar zenith angle, and T^c is the transmittance ratio of the cloud layer, independent of the solar zenith angle.

The reflectance ratio is larger for small zenith angles; it decreases towards the short wavelengths when the molecular scattering contribution increases and it tends to 1 in the region of strong absorption.

The effects on transmittance and reflectance of the cloud height have been tested. A cloud of optical depth 36.8 is successively placed between 0.16–0.66, 1.5–2, 3–3.5 and 5–5.5 km. A solar zenith angle of 45° and a ground albedo of 0.05 are used. The test results show that both the transmittance and the reflectance ratios are almost insensitive to cloud height.

This is because the light scattering by clouds is dominant to that of molecules and of aerosols. So, cloud layers with the same optical depth, have the same influence whatever is their altitude. But we should point out that we have limited our study to lower and middle clouds (with altitude < 5.5 km).

The effects on transmittance and reflectance of the cloud optical depth are presented in Figs. 7 and 8. The clouds are located between 1.5–2 km with different optical depths from 5 to 80. The solar zenith angle of 45° and the ground albedo of 0.05 are assumed again. The figures show that the transmittance ratio decreases as expected with the increase of the cloud optical depth and it depends only weakly on wavelength, as cloud scattering is essentially wavelength–independent; the reflectance increases with the cloud optical depth as well as with wavelength, but it remains 1 below 302 nm because the absorption by ozone above cloud layers is dominant.

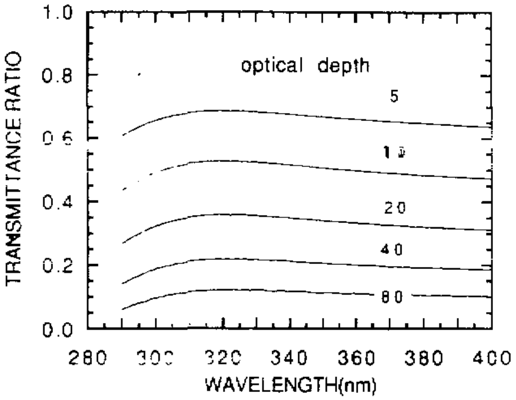

Fig. 7. Transmittance ratios for different cloud optical depths (θ_s = 45°, ρ_s = 0.05).

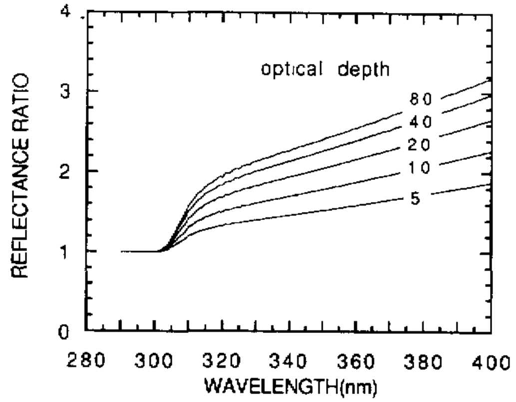

Fig. 8. Reflectance ratios for different cloud optical depths (θ_s = 45°, ρ_s = 0.05).

Fig. 9 shows the transmittance ratio as a function of cloud optical depth at 340 nm for 3 different ground albedoes 0.05, 0.3 and 0.8 with a fixed solar zenith angle of 45° and a cloud height of 1.5–2 km, as we have seen the transmittance ratio is almost insensitive to the cloud height and to the solar zenith angle (Fig. 5). The transmittance ratio decreases approximately exponentially with the cloud optical depth at rates related to the ground albedo. A similar result at 345 nm with a ground albedo of 0.4 and a solar zenith angle of 60° has been obtained by Lubin and Frederick (1991) when they studied the ultraviolet radiation environment of the Antarctic peninsula. The reflectance ratios as a function of cloud optical depth at 340 nm for the same cases as in Fig. 9 are shown in Fig. 10. The reflectance ratio is also almost independent of the cloud height, but it depends on the solar zenith angle (Fig. 6). Fig. 10 shows that reflectance is sensitive to the cloud optical depth when ground albedo is low but not when it is high.

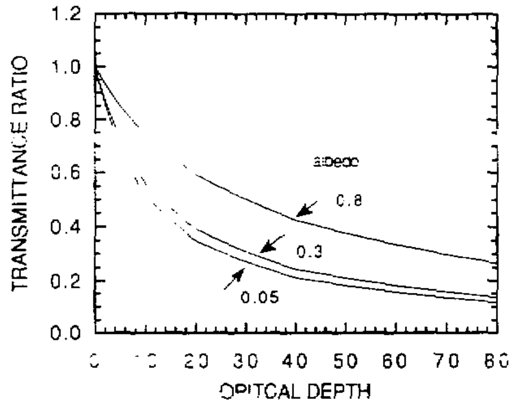

Fig. 9. Transmittance ratios at 340 nm as function of cloud optical depth for different ground albedoes with solar zenith angle 45°.

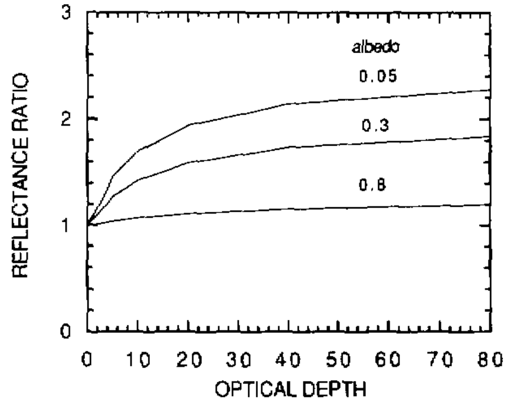

Fig. 10. Reflectance ratios at 340 nm as function of cloud optical depth for different ground albedoes with solar zenith angle 45°.

V. CONCLUSIONS AND DISCUSSIONS

We have so far studied the influence on UV radiation of low and middle extended clouds. High clouds, as cirrus, consist of large crystal particles; their scattering characteristics can no more be obtained by Mie theory; their optical depth is much smaller, and they are often semi–transparent. They will be considered in a further study. Another problem is the thin stratospheric clouds (PSCs) located at the level of the ozone layer and which play an important role in the ozone chemistry.

The assumption of homogeneous clouds made in the study for the adaptation of plane–parallel theory is insufficient to describe real clouds, whose forms are irregular, usually broken. The influence of the inhomogeneous and broken clouds on UV radiation would be very complicated. For example, clouds reduces generally the transmitted UV radiation at the ground level, but some broken clouds maybe augment it by some percents.

We have studied here the influence of the various parameters of the cloudy atmosphere, including ground albedo, cloud height, cloud optical depth and solar zenith angle. Although transmittance in both cloudy and clear atmospheres is evidently strongly dependent on wavelength, the ratio of transmittance in a cloudy atmosphere to that in a clear atmosphere is only weakly dependent on wavelength, this is essentially determined by wavelength–independent cloud scattering. The transmittance ratio is almost insensitive to cloud height as the cloud scattering is dominant to the molecular and the aerosol scattering. The transmittance ratio is also independent of the solar zenith angle, this is the result of the high efficiency of cloud scattering. The transmittance ratio decreases approximately exponentially with the cloud optical depth at a rate related to ground albedo. The reflectance for the cloudy atmosphere is almost independent of the ground albedo, but the reflectance ratio depends on this ground albedo. It decreases with the cloud optical depth for a low ground albedo, but is almost constant for a very high ground albedo.

This work has been supported by the Commission of European Communities (Contract No. STEP0076). The authors are indebted to K. Stamnes and his colleagues for providing a DOM radiation code.

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