On the Radiative Interaction in Three-Dimensional Cloud Fields

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Abstract:

The solar radiative interaction among three-dimensional, finite clouds of a cloud field is studied with two analytical models. The input parameters for the cloud field models are given by an analytical model of solar radiative transfer in isolated, finite clouds after DAVIES (1978).

Analysis of an infinitely extended cloud field arranged in chessboard pattern shows the following: at very large cloud separations, the radiative interaction is negligible even considering all clouds within the field. The albedo of an individual cloud in a cloud field increases as the cloud separations decrease. This is caused by the vertical inhomogeneity and anisotropy of the radiation field between clouds. Neglecting this, causes unrealistic results. In the case of oblique sun angles, the mutual shading of clouds can cause a nonmonotonic increase in the albedo.

In addition, the albedo of the entire cloud field (regional albedo) depends on the cloudiness. It can be shown that in many cases the variations of the regional albedo are determined mainly by cloud cover. Therefore, a simple formula, which neglects the radiative interaction and which is often used in circulation models, gives a good approximation of the regional albedo.

Zusammenfassung: Ein Beitrag zur Strahlungsübertragung in dreidimensionalen Wolkenfeldern.

Mit Hilfe zweier analytischer Modelle wird im solaren Spektrum die Strahlungswechselwirkung zwischen drei-dimensionalen, endlichen Wolken eines Wolkenfeldes untersucht. Die Eingabeparameter für die Wolkenfeld-modelle ergeben sich aus einem analytischen Modell nach DAVIES (1978), das die Strahlungsübertragung in einer dreidimensionalen, endlichen Wolke bestimmt.

Die Untersuchung eines schachbrettmusterartig angeordneten, unendlich ausgedehnten Wolkenfeldes zeigt folgendes: Für große Wolkenabstände ist auch bei Berücksichtigung aller Wolken des Feldes die Strahlungs-wechselwirkung vernachlässigbar. Zu geringeren Abständen hin nimmt die Albedo einer einzelnen Wolke in einem Wolkenfeld zu. Dies ist bedingt durch die vertikale Inhomogenität und Anisotropie des Strahlungs-feldes zwischen den Wolken. Eine Vernachlässigung dieser Eigenschaft führt zu unrealistischen Ergebnissen. Bei schrägstehender Sonne kann die gegenseitige Abschattung der Wolken zu einem nichtmonotonen Anstei-gen der Albedo führen.

Die Albedo des gesamten Wolkenfeldes (regionale Albedo) hängt nicht nur von der Strahlungswechselwirkung, sondern auch vom Bedeckungsgrad ab. In vielen Fällen ist die Änderung der regionalen Albedo fast nur durch den Bedeckungsgrad bestimmt, so daß die Vernachlässigung der Strahlungswechselwirkung, die oft in Zirkula-tionsmodellen verwandt wird, eine gute Näherung der regionalen Albedo darstellt.

Résumé: Sur l'interaction radiative dans des champs nuageux tridimensionnels

– On étudie à l'aide de deux modèles analytiques l'interaction radiative dans le spectre solaire, entre des nuages tridimensionnels individuels à l'intérieur d'une population de nuages. Les paramètres de départ pour les modèles de population de nuages sont donnés par un modèle analytique développé par DAVIES (1978) pour le transfert de rayonnement solaire dans des nuages isolés et finis.

L'analyse d'un champ de nuages d'extension infinie, distribué de manière alternante comme sur un échiquier, aboutit aux résultats suivants: pour de très grandes séparations entre nuages, l'interaction radiative est néglige-able, même si l'on tient compte de tous les nuages à l'intérieur du champ. L'albédo d'un nuage individuel à

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l'intérieur d'un champ de nuages s'accroît à mesure que la séparation entre nuages décroît. Ceci est dû à l'inhomogénéité verticale et à l'anisotropie du champ radiatif entre les nuages. Si l'on néglige cet état de choses, on obtient des résultats erronés. Dans des situations de rayons solaires obliques, l'ombre provoquée par des nuages sur leurs voisins peut se traduire par un accroissement de l'albédo.

De surcroît, l'albédo de la population entière de nuages (l'albédo régional) dépend de la couverture nuageuse. On peut démontrer dans de nombreux cas que les variations de l'albédo régional sont fonction surtout de la couverture nuageuse. Par conséquent, une formule simple qui néglige l'interaction radiative et qui est souvent utilisée dans des modèles de circulation, peut donner de bonnes approximations de l'albédo régional.

1 Introduction

In many radiative transfer models, clouds are approximated by infinitely extended, horizontally homogeneous cloud layers. However, in the atmosphere three-dimensional isolated clouds or cloud fields composed of three-dimensional clouds are often observed. Models that have been used to study the radiative transfer within isolated, three-dimensional clouds (e. g. McKEE and COX, 1974; DAVIES, 1978), show that an important fraction of incident energy leaves the side faces of a cloud. Therefore, the radiation budget of a three-dimensional cloud field may be expected to be influenced significantly by multiple reflections between the individual clouds themselves.

The effects on a central cloud by reflection from adjacent clouds were examined by AIDA (1976) with a Monte-Carlo method. Only the central cloud was illuminated by the sun; a fraction of the radiation leaving the sides of the cloud entered the surrounding four clouds and was attenuated and scattered within these clouds. Subsequent scattering of radiation leaving these clouds was neglected. The results of this investigation were confirmed by laboratory observations (McKEE et al., 1980).

GUBE et al. (1979) determined the radiant flux field of an infinitely extended cloud assembly arranged in a chessboard pattern. The diffusion approximation was applied to the radiative transfer within one cloud. This approximation replaces the actual radiation field by an isotropic one, which is rarely observed.

All the above results demonstrate that the magnitude of the upward component of energy per unit area and time exiting all cloud faces increases as the distance between the clouds decreases. At sufficiently large separations D between clouds of vertical depth Z_0 (i. e. $D/Z_0 \leqslant 2$), the effects of the cloud shape and mutual shading were found to be more important than those due to multiple reflections.

WELCH and ZDUNKOWSKI (1981a, b) have investigated wavelengthdependent parameterizations of the radiative characteristics of a finite cloud. These parameterizations were employed to develop radiative characteristics of fields of noninteracting finite clouds.

In this article we study the physical mechanisms of radiative interaction among clouds considering all effects of multiple reflections and the structure of the radiation field between clouds. We examine the error of an approximation generally used in circulation models: neglection of all multiple reflections.

2 The Finite Analytical Model

The work presented here is based on the „finite analytical model" developed by DAVIES and WEINMAN (1976) and by DAVIES (1978). This model gives an analytical solution of the radiative transfer equation using a finite double cosine transformation, and its results show good agreement with Monte-Carlo calculations even for small optical depth (i. e. $t \approx 10$). The finite analytical model is discussed in detail in DAVIES (1978). Here only the basic ideas will be given.

The monochromatic radiative transfer equation for an externally illuminated, scattering and absorbing cloud is (GOODY, 1964):

$$\frac{1}{\sigma_e}\,\underline{\Omega}\,\nabla\,L = -L + \frac{\widetilde{\omega}}{4\pi}\int p(\underline{\Omega},\Omega')L(\underline{r},\underline{\Omega}')\,d\Omega' + \frac{\widetilde{\omega}}{4\pi}p(\underline{\Omega},\underline{\Omega}_0)F_0(\underline{r},\underline{\Omega}_0) \qquad (1)$$

L   : spectral radiance

$\underline{r}$: space coordinate

$\underline{\Omega}$: unit vector in direction of L

$d\Omega$: solid angle element

σ_e : volume extinction coefficient

$\widetilde{\omega}$: single scattering albedo

p   : scattering phase function

F_0 : solar radiation flux

For calculating radiative fluxes the Delta-Eddington-approximation of the phase function (e. g. JOSEPH et al., 1976) is used.

The model represents an isolated cloud by a cuboid of given dimensions X_0, Y_0, Z_0, within which the optical parameters are constant. The orientation, as shown in Figure 1, is such that the incident solar beam strikes the top and only one side of the cuboid. The solar azimuth angle measured with respect to the x-axis is zero.
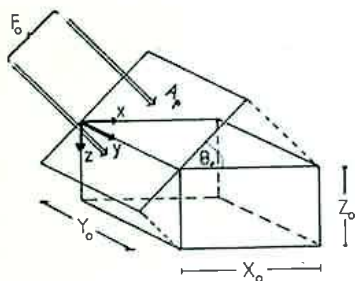
● Figure 1

Cuboidal representation of an isolated cloud

A_p: Area of the cloud projected on the surface normal to the incident solar beam

θ_0: solar zenith angle

● Bild 1

Darstellung einer einzelnen Wolke durch einen Quader

A_p: Senkrecht zur einfallenden solaren Strahlung projizierte Wolkenoberfläche

θ_0: Zenitwinkel der einfallenden solaren Strahlung

In order to remove the x-dependence of the extinction of the direct beam within the cloud, an "equivalent-normal irradiance" approximation is made, which replaces the oblique solar beam by a beam perpendicular to the top face. The z-dependence of the equivalent beam within the cloud is such that the direct beam is weighted by the ratio of real illuminated area at a given depth z to the entire horizontal area of the cloud at the same depth z.

Using the Eddington approximation of the radiance L leads finally to a partial differential equation, which describes the radiative transfer within a cloud of rectangular geometry.

The boundary condition that determines the solution of this differential equation is: For an isolated cloud there is no diffuse radiation incident on the cloud faces.

A finite double cosine transformation leads to a solution.

In order to obtain the relative mean radiant flux emerging from a given cloud face, the relevant radiant flux is integrated over the face in question and then normalized by the incident solar flux.

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3 Cloud Field Models

3.1 Albedo Definition for a Cloud Field

The albedo of a single cloud in a cloud field is defined as the ratio A/B, where A is the mean of upward component of the outward fluxes from all cloud sides over an infinitely extended, horizontal area, and B is the direkt solar flux striking all cloud faces. The albedo of a single cloud in a cloud field depends (besides on given optical parameters) only on the radiative interaction between the clouds and on the albedo of the underlying earth's surface. A second albedo concept, considering also cloud amount, is introduced in Section 3.

In the following the surface albedo is assumed to be zero, which is approximately valid for water. Also the influence of the atmosphere on the radiative interaction is neglected.

3.2 Model I for Large Cloud Separations

From the boundary conditions of the differential equation of the DAVIES-model it can be seen that the radiation exiting the cloud sides is anisotropic. Calculations with the DAVIES-model show that up to twice as much energy is transmitted in the downward direction as in the upward direction.

The horizontal distribution of the radiant flux emerging from a cloud side is nearly homogeneous, while the vertical distribution is distinctly inhomogeneous with a maximum at an optical depth $t \cong 3-4$.

The upward component of the radiation emerging from a cloud side is assumed to be isotropic and is represented by a mean flux $F_{out,z-}$. Also the radiation with a downward component is assumed to be isotropic and is represented by a mean flux $F_{out,z+}$.

As a first step towards modelling the anisotropy and the vertical inhomogeneity of the radiation field between two clouds, the fraction of scattering radiation (from cloud 1) striking the opposite face of the neighbouring cloud (cloud 2) is written by:

$$F_{in,cloud\,2} = (F_{out,z-}\,\frac{\Omega_1}{\pi} + F_{out,z+}\,\frac{\Omega_2}{\pi})_{,cloud\,1} \tag{2}$$

Here Ω_1 and Ω_2 are the two solid angles as seen from a point on the vertical centreline of a cloud side at the depth z_{max} of the maximum radiation flux exiting a cloud side. (See Figure 2). Since model I is valid for large cloud separations, the radiation striking the neighbouring cloud is assumed to be plane parallel and is represented by a mean flux $F_{in,cloud\,2}$.

It is important to note that only the fraction

$$\frac{1}{2}\left(F_{out,z-}\left(\frac{\pi-\Omega_1}{\pi}\right) + F_{out,z+}\left(\frac{\pi-\Omega_2}{\pi}\right)\right)$$

of the radiation leaving a cloud side must be used for calculating the albedo of a cloud field. The residual fraction strikes the neighbouring cloud and only a portion of it may be scattered into the upper hemisphere.
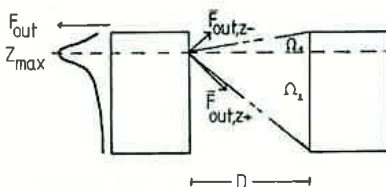
- **Figure 2**
  Solid angles and mean outwelling fluxes in model I

- **Bild 2**
  Schematische Darstellung der Raumwinkel und mittleren Flüsse der aus den Wolkenseiten austretenden Strahlung in Modell I

Neglecting this effect, hereafter referred to as "internal screening", would lead to a larger than realistic estimate of the albedo and the transmission of the cloud field.

With the new input parameter $F_{in,cloud\,2}$ obtained by Equation 2, the emerging flux was again calculated by means of the DAVIES-model. In practice the scattering process was applied only once to one cloud and then the multiple reflection between clouds was computed by use of a geometrical series for each cloud side.

Due to asymmetry of the scattering phase function it is:

$$F_{out,z+} > F_{out,z-}$$

and, therefore, the anisotropy tends to increase the energy being transferred into the lower hemisphere. But since $z_{max} \ll Z_0$, and therefore $\Omega_1 \ll \Omega_2$, most of the radiation being scattered back and forth between clouds descends from the lower hemisphere due to internal screening so that an increase of the albedo is expected. The geometrical effect of different internal screening overcomes the effect of anisotropy.

In Figure 3 the albedo A_f and the transmission T_f of a single cloud in an infinitely extended cloud field in the case of a chessboard cloud pattern is shown. Only the interaction with the next four neighbouring clouds was considered. The solar radiation strikes only the top faces of the clouds with a solar zenith angle $\theta_0 = 0°$. Model I gives qualitatively correct results unless the cloud separations becomes very small.
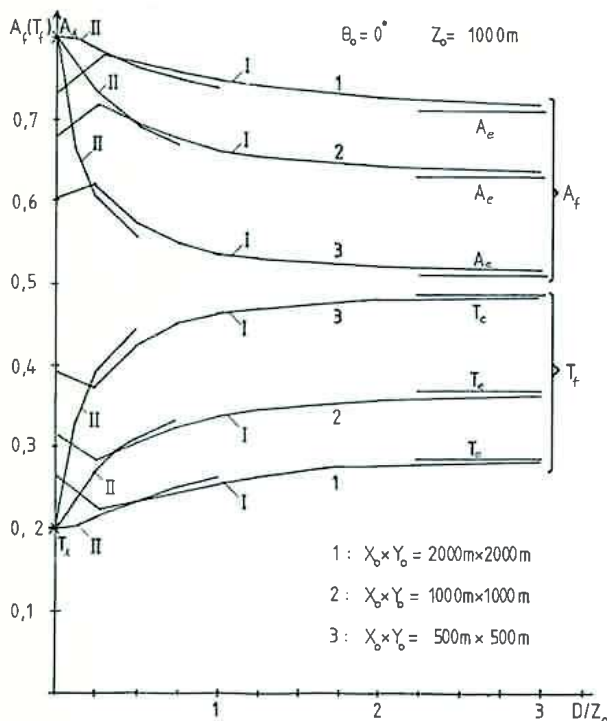
- **Figure 3**

Albedo A_f and transmission T_f of a single cloud in 3 infinitely extended cloud fields with cloud elements of different horizontal X_0, Y_0, but same vertical extent Z_0. The radiative interaction of one cloud with its next four neighbouring clouds was considered. Curve I refers to model I, curve II to model II (See Section 3.3.).

A_e, T_e: Albedo and transmission of the isolated clouds

A_d, T_d: Albedo and transmission of the plane parallel cloud layer.

Calculations are valid for the optical parameters: $\tilde{\omega} = 1$, $\sigma_e = 0.05$ m, asymmetry factor $g = 0.86$, solar zenith angle $\theta_0 = 0°$.

- **Bild 3**

Albedo A_f und Transmission T_f einer einzelnen Wolke in 3 unendlich ausgedehnten Wolkenfeldern mit Elementen unterschiedlicher horizontaler X_0, Y_0, aber gleicher vertikaler Abmessung Z_0. Die Strahlungswechselwirkung einer Wolke mit ihren 4 nächsten Nachbarwolken wurde berücksichtigt. Kurve I bezieht sich auf Modell I, Kurve II auf Modell II (Siehe Abschnitt 3.3.).

A_e, T_e: Albedo und Transmission einer isolierten Wolke

A_d, T_d: Albedo und Transmission einer planparallelen Wolkenschicht.

Die Rechnungen sind gültig für die optischen Parameter: $\tilde{\omega} = 1$, $\sigma_e = 0.05$ m, Asymmetriefaktor $g = 0.86$, Zenitwinkel der solaren Strahlung $\theta_0 = 0°$.

At sufficiently large distances D between clouds (i. e. $D/Z_0 \geqslant 2$), the radiative interaction is negligible and the albedo A_f and the transmission T_f are determined by the size and shape of the individual clouds. The relative differences $(A_f - A_e)/A_e$ (A_e: albedo of an isolated cloud) are all less than 3 % when $D/Z_0 = 2$. At smaller separations the curves draw closer and the mutual interaction becomes important. The albedo varies more in a cloud field containing smaller cloud elements than in a field with elements of larger horizontal extent but same vertical depth. Moreover the albedo of a single isolated cloud of large horizontal extent is approximately the same as the albedo of the corresponding plane parallel cloud layer (See Table 1).

■ Table 1 Relative difference between the albedo A_e of a single, isolated cloud with quadratic base $X_0 = Y_0$ and the albedo A_d of a plane parallel cloud layer of the same vertical depth Z_0. (Optical parameters: See Figure 3).

■ Tabelle 1 Relativer Unterschied zwischen der Albedo A_e einer einzelnen Wolke mit quadratischer Grundfläche $X_0 = Y_0$ und der Albedo A_d einer planparallelen Wolkendecke von gleicher vertikaler Mächtigkeit Z_0. (Optische Parameter: Siehe Bild 3).

	$(A_d - A_e)/A_d$	
X_0/Z_0	$Z_0 = 1000$ m	$Z_0 = 400$ m
3	7,2 %	8,9 %
5	4,1 %	5,0 %
8	2,2 %	2,8 %
10	1,9 %	2,2 %

Using the assumption of isotropy and homogeneity of the radiation exiting a cloud side, Equation (2) reduces to

$$F_{in,cloud 2} = F_{out,cloud 1} \frac{\Omega_c}{2\pi} \tag{3}$$

$$F_{out,cloud 1} = (F_{out,z+} + F_{out,z-})_{,cloud 1}$$

Ω_c: solid angle as seen from the centre of a cloud side

Equation (3) implies that, because of the homogeneity of the optical parameters within the cloud, the radiation, which strikes a cloud, is scattered in the upper hemisphere of the same amount as in the lower hemisphere. Thus the albedo and the transmission of a single cloud in a cloud field do not vary with the distance between clouds. This means that the assumption of isotropy and homogeneity leads to unrealistic results.

3.3 Model II for Small Cloud Separations

Model I leads to unrealistic results when distances between clouds are very small. This is mainly caused by the inadequate modelling of the vertical inhomogeneity of the emerging radiation. At small cloud separations the radiative interaction between clouds is almost limited to the upper parts of the clouds; this would enhance a scattering of radiation in the upper hemisphere and, therefore, also enhance albedo.

The vertical inhomogeneity of radiant fluxes striking a cloud side can be modelled by changing the boundary conditions of the DAVIES-model. The new boundary conditions are: The radiant flux incident on each point on a cloud side is proportional to the emerging radiant flux from the same point on the opposite side of the neighbouring cloud. The proportionality factor f determines the decrease between emerging and incoming radiant flux. In order to get homogeneous boundary conditions the factor f is assumed to be only a function of the cloud distance and the cloud dimensions. From geometrical reasons f can be defined by:

$$f = \frac{\Omega_1 + \Omega_2}{2\pi} \tag{4}$$

The new boundary conditions are now:

$$F_{diff,in}(0, y, z) = F_{diff,out}(X_0, y, z)\, f_{x=0} \tag{5}$$

$$F_{diff,in}(X_0, y, z) = F_{diff,out}(0, y, z)\, f_{x=X_0}$$

$$F_{diff,in}(x, 0, z) = F_{diff,out}(x, Y_0, z)\, f_{y=0}$$

$$F_{diff,in}(x, Y_0, z) = F_{diff,out}(x, 0, z)\, f_{y=Y_0}$$

$F_{diff,in}(x, y, z)$:   Flux of incoming diffuse radiation at the point (x, y, z) on a cloud side

$F_{diff,out}(x, y, z)$: Flux of outwelling diffuse radiation from a point (x, y, z) on a cloud side

The boundary conditions for $z = 0$ and $z = Z_0$ are the same as those in the DAVIES-model.

Implicit in Equation (5) is the assumption of an infinitely extended cloud field with identical cloud elements where the radiative interaction with the next four neighbouring clouds is considered.

The solution of the differential equation of the DAVIES-model with the new boundary conditions (Equation 5) is of the same form as that for a single cloud. Only the eigenvalues are modified.

It can be shown that as the separations between clouds approaches zero, the eigenvalues become zero. This leads to a solution that is the same as the solution for a plane parallel cloud layer. But as the separations become infinitely large, the eigenvalues of the DAVIES-model and model II approach each other.

In Figure 3 the results of models I and II are shown. Both models determine only approximately the distribution of the radiant flux striking a cloud side. At very small separations the distribution of incoming radiation is distinctly vertically inhomogeneous and differs slightly from the distribution of the emerging radiation so that in this case model II can be taken to be valid. At large separations the distribution of incoming radiation is nearly homogeneous and, therefore, model I gives best approximation. Because in many cases curves I and II are nearly parallel when they intersect, a single smooth curve can be found matching curve I and II in the point of intersection. However, in a very few cases (e. g. curve 3 in Figure 3) the single curve must be determined by interpolation between curves I and II in a small range. Different interpolation scemes do not yield large differences in calculating the albedo or the transmission.
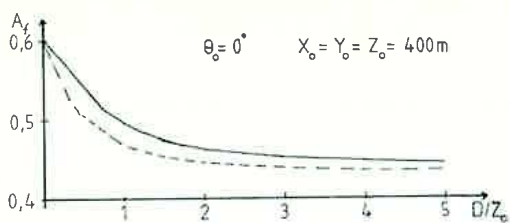
From Figure 3 it can be seen that the radiative interaction between clouds can be described by a simple geometrical model (model I) for sufficiently large distances between clouds (i. e. $D/Z_0 > 0.5$), whereas for small cloud distances the vertical inhomogeneity of the emerging and incoming radiation has to be taken into account explicitly (model II).

3.4   Radiative Interaction with all Clouds

In prevailing calculations only the radiative interaction of one cloud with its next four neighbouring clouds has been considered. The radiative interaction of all clouds with one cloud in an infinitely extended cloud field can be taken into account by changing the limits of integration in the definition of the solid angle $(\Omega_1 + \Omega_2)$, which is

$$(\Omega_1 + \Omega_2) = \int\limits_0^{\pi/2} \int\limits_{\vartheta_1}^{\vartheta_2} \sin\vartheta \, d\vartheta \, d\varphi \tag{6}$$

The integral (Equation 6) is taken over all clouds seen from a point on a cloud side (See also Equation (2) in Section 3.2.). ϑ_1 and ϑ_2 are zenith angles of the upper and lower limit of the neighbouring clouds as seen from one cloud side. These zenith angles are functions of the azimuth angle φ. In the case of cubic cloud elements, Equation (2) can be solved without difficulties because $F_{out,z-}$ and $F_{out,z+}$ are the same for all cloud sides.

● **Bild 4** Albedo A_f einer einzelnen Wolke in einem unendlich ausgedehnten Wolkenfeld. Die Ergebnisse beider Modelle I und II sind berücksichtigt.

Gestrichelt: Die Strahlungswechselwirkung einer Wolke mit ihren 4 nächsten Nachbarwolken ist berücksichtigt.

Ausgezogen: Die Strahlungswechselwirkung aller von einer Wolke gesehenen Nachbarwolken ist berücksichtigt.

Optische Parameter: Siehe Bild 3

Since there are no infinite cloud fields, the results given in Figure 4 may be regarded as an upper limit of the influence of the radiative interaction between clouds. The influence of all clouds of the cloud field on the radiative interaction with a single cloud tends to increase the energy being reflected back and forth and, therefore, tends to increase the albedo also. It is obvious that the radiative interaction may not be neglected in the calculation of the radiation budget of a cloud field when $D/Z_0 \leqslant 5$. However, the maximum relative difference of the albedo values of the lower curve from the upper curve does not exeed 5 %.

3.5   Mutual Shading

If in the case of nonzero solar zenith angle the cloud separation D becomes less than a critical value D_{cr}, then shading of one cloud by a neighbouring cloud will occur (See Figure 5). D_{cr} is given by

$$D_{cr} = Z_0 \tan \theta_0 \qquad (7)$$

The illuminated area Ap of the cloud projected on the surface normal to the incident solar beam decreases to A_p^+. The albedo A_f of a cloud in a cloud field can be written as

$$A_f = \frac{f_1}{f_1 + f_2^+} F_t + \frac{f_2^+}{f_1 + f_2^+} F_s \qquad (8)$$

$$f_2 := \begin{cases} X_0 Y_0 \cos \theta_0 \\ f_2 = Y_0 Z_0 \sin \theta_0 & D > D_{cr} \end{cases}$$

$$f_1 := Y_0 (D \cotan \theta_0) \sin \theta_0 \qquad D \leqslant D_{cr}$$

F_t: sum of the upward component of all mean outgoing fluxes in the case of illumination of the top face of the cloud

F_s: sum of the upward component of all mean outgoing fluxes in the case of illumination of a side face of the cloud

Equation (8) was derived with the assumption that the radiation striking f_2^+ is uniformly distributed so that the flux $F_0^+ = F_0 f_2^+ / f_2$ strikes the entire cloud side in question. This approximation is valid for the cases $D > D_{cr}$ (due to $f_2^+ = f_2$), $D \cong D_{cr}$ (due to $f_2^+ \cong f_2$) and $D \cong 0$ (due to $f_2^+ \cong 0$). The approximation is also valid for small solar zenith angles, since $f_2^+ F_0 \ll f_1 F_0$. If $D_{cr} \cong 0$, then the approximation is assumed to be valid over the entire range of cloud separations. For the other cases $D < D_{cr}$ we assume the
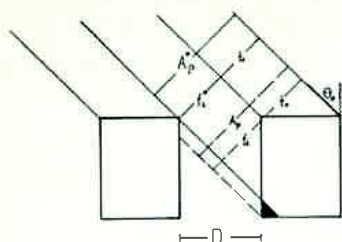
following: The solar radiation, which strikes a portion of a cloud side, spreads out in a small range within the cloud. For calculating the radiation budget, it may be equivalent to investigate the radiation, which is scattered from direct radiation spreading out in a small range within the cloud, or the radiation, which is scattered from a less amount of direct radiation spreading out within the entire cloud. The approximation does not apply to the case of narrow, deep clouds with a large horizontally optical depth.

3.5.1   Albedo of an Isolated Cloud in the Case of Nonzero Solar Zenith Angles

The albedo A_e of an isolated, single cloud can be written in a form analogous to Equation (8) with $f_2^+ = f_2$ and F_t, F_s being modified by considering that there is no radiative interaction.

By differentiation of Equation (8) with respect to θ_0, the behaviour of the albedo A_e or A_f, respectively, can be explained.

The increase or decrease of A_e with increasing solar zenith angle depends on the magnitude of the difference $(F_s - F_t)$. If $(F_s - F_t)$ is of order 0.1 and negative, for instance in the case of optically thick cubic or flat clouds, then A_e decreases with increasing θ_0 (curve A in Figure 6). In the case of optically thin clouds, $(F_s - F_t)$ is of order 0.1 but positive and A_e increases (curve C in Figure 6). If $(F_s - F_t)$ is small and of either sign, then a non monotonic increase or decrease of A_e will be observed (curve B in Figure 6).

Curve A : 1000 × 1000 × 1000
B : 400 × 400 × 400
C : 200 × 200 × 200
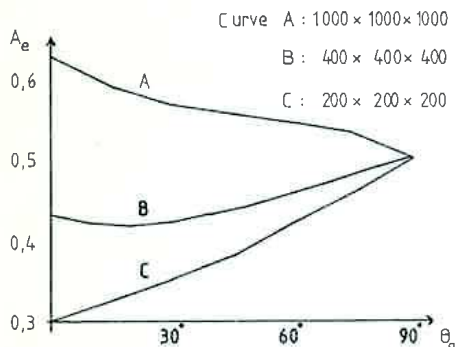
● Figure 6

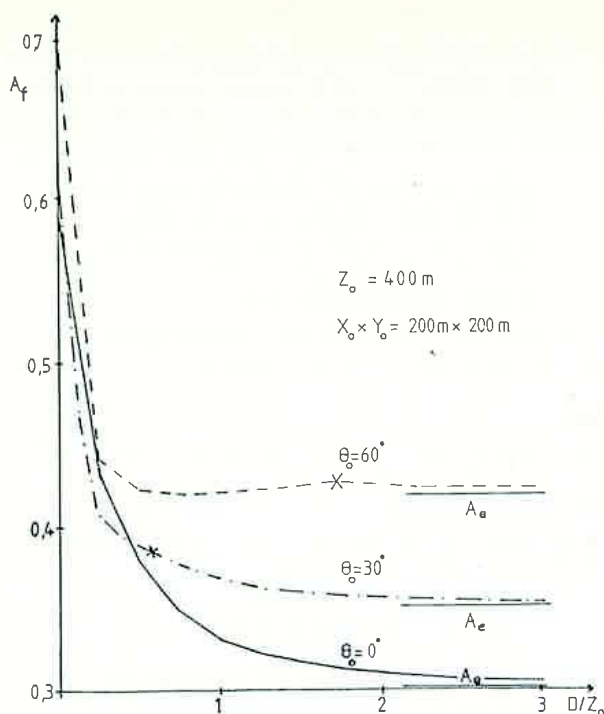Albedo of an isolated, single cloud as a function of the solar zenith angle. Curves A, B, C refer to different cloud sizes.

● Bild 6

Albedo einer isolierten Wolke als Funktion des Sonnen-zenitwinkels. Die Kurven A, B, C beziehen sich auf ver-schiedene Wolkenabmessungen.

3.5.2   Albedo of a Cloud in a Cloud Field in the Case of Nonzero Solar Zenith Angles

In Figure 7 A_f as a function of θ_0 is shown. The curves demonstrate a similiar behaviour as in the case of $\theta_0 = 0^\circ$ (section 3.3.). From Equation (8) it can be seen that the variation of A_f with θ_0 is determined by the sign of $(F_s - F_t)$. Furthermore if $(F_s - F_t)$ is larger than zero, then a non monotonic increase of A_f with decreasing cloud separations D is possible (See curve $\theta_0 = 60^\circ$ in Figure 7). Thus in a few cases, when the radiation input on a cloud side face becomes more important than that on the cloud top face (e. g. narrow, deep clouds), the mutual shading can overcome the radiative interaction and cause decreasing albedo. At very small cloud separations the radiative interaction is always a larger effect than that from mutual shading.

Figure 7

Albedo A_f of a cloud in a cloud field as a function of the relative distance D/Z_0 and the solar zenith angles θ_0. The radiative interaction of one cloud only with its next four neighbouring clouds was considered.

A_e: Albedo of an isolated cloud
x: Cloud separation D_{cr}, at which mutual shading occurs

The results of model II and I are combined into a single curve. Optical parameters: See Figure 3

Bild 7

Albedo A_f einer Wolke in einem Wolkenfeld als Funktion des relativen Abstandes D/Z_0 und des Sonnenzenitwinkels θ_0. Die Strahlungswechselwirkung einer Wolke nur mit ihren vier nächsten Nachbarwolken wurde berücksichtigt.

A_e: Albedo einer isolierten Wolke
x: Wolkenabstand D_{cr}, bei dem die gegenseitige Abschattung eintritt.

Die Ergebnisse von Modell II und I sind in einer Kurve dargestellt. Optische Parameter: Siehe Bild 3

3.6   Regional Albedo

The albedo of the entire cloud field or "regional albedo" is defined as the ratio A/B, where A is the mean of upward component of the outward fluxes from all cloud sides over an infinitely extended, horizontal area, and B is the solar flux striking the infinitely horizontal area. The regional albedo of a single cloud or of a cloud field with infinite separations between clouds is equal to the surface albedo, because the mean flux from the clouds is negligible compared with the incident solar flux.

The difference between the two albedo concepts, the regional albedo and the albedo of a single cloud in a cloud field, is the reference area of the incident solar radiation. When the surface albedo is assumed to be zero, the albedo A_f of a single cloud in a cloud field depends only on the radiative interaction, while the regional albedo A_r depends also on the cloud cover. In the case of a chessbord cloud pattern of an infinitely extended cloud field, A_r and A_f are related by:

$$A_r = A_f \frac{X_0 Y_0 \cos\theta_0 + Z Y_0 \sin\theta_0}{(X_0 + D_x)(Y_0 + D_y)} \tag{9}$$

D_x, D_y: distance between clouds in x-, y-direction

$$Z = \begin{cases} D_x \cotan\theta_0 & D_x < D_{cr} \quad \text{(in case of shading)} \\ Z_0 & D_x \geqslant D_{cr} \quad \text{(in case of no shading)} \end{cases}$$

At zero separation A_r and A_f join together, while at very large separations A_r vanishes.

In some general circulation models (e. g. MANABE and WETHERALD, 1975) an approximation A_r of the regional albedo A_r is used. The approximation is given by:

$$\overline{A_r} = n A_d \tag{10}$$

where n is the cloud cover, and A_d is the albedo of a one-dimensional cloud layer.
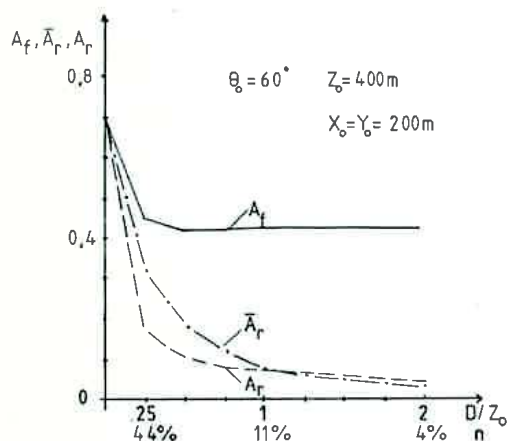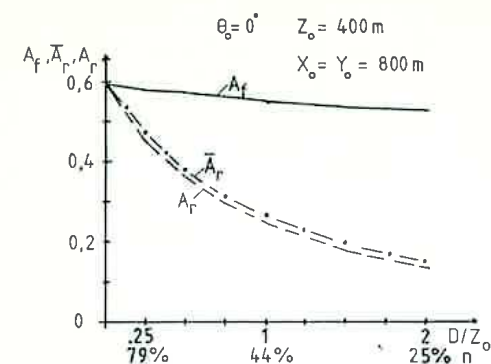
- **Figure 8**

  Different albedo concepts for infinitely extended cloud fields as functions of the relative distance D/Z_0 or percentage cloudiness for two cloud fields with different cloud elements and different solar zenith angles.

  ———: Albedo A_f of a single cloud in the cloud field considering the radiative interaction only

  – – –: Albedo A_r of the cloud field considering radiative interaction and cloud cover

  –.–.–: A simple approximation of A_r

  The curves contain the combined results of model I and II. Optical parameters: See Figure 3

- **Bild 8**

  Verschiedene Albedokonzepte für unendlich ausgedehnte Wolkenfelder als Funktion des relativen Abstandes D/Z_0 oder des prozentualen Bedeckungsgrades n für zwei Wolkenfelder mit unterschiedlichen Wolkenelementen und Sonnenzenitwinkeln.

  ———: Albedo A_f einer einzelnen Wolke in einem Wolkenfeld unter Berücksichtigung nur der Strahlungswechselwirkung

  – – –: Albedo A_r eines Wolkenfeldes unter Berücksichtigung der Strahlungswechselwirkung und des Bedeckungsgrades

  –.–.–: Eine einfache Näherung für A_r

  Die Kurven enthalten die Ergebnisse von Modell I und II. Optische Parameter: Siehe Bild 3

In Figure 8 the albedo A_r, A_f and $\overline{A}_r$ are shown as functions of D/Z_0. If the solar zenith angle is zero, then the approximation $\overline{A}_r$ overestimates the regional albedo. The difference between $\overline{A}_r$ and A_r is less for cloud fields with flat elements than for fields with elements of smaller horizontal extent. In the case of oblique sun angles a more complex behaviour is observed. The results indicate that the difference between the regional albedo A_r considering the radiative interaction and the simple approximation $\overline{A}_r$ is small in all relevant cases of non absorbing clouds. Because the absorption of solar radiation due to water vapour in the clouds and in the atmosphere reduces the radiation being scattered between clouds, the radiative interaction is expected to be negligible in calculating the radiation budget integrated over the solar spectrum.

4   Summary and Conclusion

Two models were developed to investigate the radiative interaction among clouds. In model I the radiation transmitted from one cloud into a neighbouring cloud is assumed to be plane parallel, and the vertical inhomogeneity and the anisotropy of the outgoing radiation from a cloud side is modelled by simple approximations. The multiple reflection is calculated by use of a geometrical series with parameters obtained by the DAVIES-model, which gives an approximate, analytical solution of the radiative transfer in a cuboid. Because of the simple modelling of the vertical inhomogeneity of the radiation between the clouds, model I gives poor results when the cloud separations become too small. A second model considers the inhomogeneity explicitly by changing the boundary conditions of the DAVIES-model. Model I was found to be a good approximation for large cloud separations, model II for very small cloud separations.

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At sufficiently large distances D between clouds of a vertical depth Z_0 (i. e. $D/Z_0 > 2$) radiative interaction is negligible and the albedo of a single cloud in a cloud field is determined by the properties of the individual cloud. As the distances between clouds decrease the albedo increases (in few cases the increase is up to 100 %) and the transmission decreases (up to 50 %). This can be explained by the effect of internal screening, which is different for the upper and lower hemisphere due to the anisotropy of the radiation emerging from a cloud side. At very small distances (i. e. $D/Z_0 < 0.5$) the vertical inhomogeneity of the outgoing radiation must be taken into account. This inhomogeneity tends to limit the radiative interaction among the upper parts of the clouds and causes a strong increase in the albedo. It can be shown that calculations neglecting the effects of inhomogeneity and anisotropy lead to unrealistic results.

In the cases of oblique sun angles, the mutual shading of the clouds reduces the solar radiation input. If variation of the radiation input into a cloud side becomes more important than that into the cloud top (e. g. narrow, deep clouds), then the mutual shading will compensate the radiative interaction and will cause a nonmonotonic increase of the albedo as the cloud separations decrease.

A comparision of the total albedo of the entire cloud field considering radiative interaction and cloud cover with the simple approximation $\overline{A_r} = A_d$, often used in general circulation models, shows no large differences for nonabsorbing clouds. This leads to the hypothesis that for calculating an albedo integrated over the entire solar spectrum, the radiative interaction could be small or even negligible.

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References

AIDA, M., 1976: Scattering of solar radiation as a function of cloud dimensions and orientation. J. Quant. Spectrosc. Radiat. Transfer 17, 303–311.

DAVIES, R. and WEINMAN, J. A., 1976: Results from two models of three-dimensional transfer of solar radiation in finite clouds. Proceedings on the symposium on radiation in the atmosphere, Garmisch-Patenkirchen, FRG, 19–28 Aug. 1976, Editor H.-J. Bolle, 214–216.

DAVIES, R., 1978: The effect of finite geometry on the three-dimensional transfer of solar irradiance in clouds. J. Atmos. Sci. 35, 1712–1725.

GOODY, R. M., 1964: Atmospheric Radiation I (Theoretical Basis), Oxford University Press.

GUBE, M., SCHMETZ, J. and RASCHKE, E., 1979: Solar radiative transfer in a cloud field. Beitr. Phys. Atmosph. 53, 24–34.

JOSEPH, J. H., WISCOMBE, W. J. and WEINMAN, J. A., 1976: The Delta-Eddington approximation for radiative flux transfer. J. Atmos. Sci. 33, 2452–2459.

MANABE, S. and WETHERALD, R. T., 1975: The effects of doubling the CO_2 concentration on the climate of a general circulation model. J. Atmos. Sci. 32, 3–15.

McKEE, T. B. and COX, S. K., 1974: Scattering of visible radiation by finite clouds. J. Atmos. Sci. 31, 1885–1892.

McKEE, T. B., DeMARIA, M. and KUENNING, J. A., 1980: Verfication of a Monte Carlo model of scattering in finite clouds by laboratory and field observations. I.R.S. symposium 11–16 Aug. 1980. Volume of extended abstracts, 465–467.

WELCH, R. M. and ZDUNKOWSKI, W. G., 1981a: The radiative characteristics of noninteracting cumulus cloud fields, Part I: Parameterization of finite clouds. Beitr. Phys. Atmosph. 54, 258–273.

WELCH, R. M. and ZDUNKOWSKI, W. G., 1981b: The radiative characteristics of noninteracting cumulus cloud fields, Part II: Calculations for cloud fields. Beitr. Phys. Atmosph. 54, 274–286.