DETERMINATION OF SPECTRAL OPTICAL CHARACTERISTICS OF CLOUD LAYERS

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Different methods for deriving expressions used for calculation of the characteristics of transmission, reflection, and absorption of radiation by cloud layers taking into account the illumination from below (from the underlying surface) are presented.

In recent years many papers have been devoted to the investigation of the optical characteristics of cloud layers based on theoretical and experimental data. Their generalization and ample bibliography on this subject were given in Refs. (1–3). However, the problem of the investigation of the optical properties of clouds has not yet been completely solved, since new experimental data make it possible to reveal the new peculiarities of this complex phenomenon. As a part of the POLEX–76 and GAREX programs onboard the IL–18 and IL–14 aircraft laboratories the spectral fluxes of short–wave radiation were measured under and above the stratiform clouds located over the ice surface covered with snow. Observations of cloud layers illuminated not only from above but also from below raised some problems of their interpretation and analysis. This paper is devoted to consideration of these questions.

The spectral downwelling $\left(F_1^{\downarrow} \text{ and } F_2^{\downarrow}\right)$ and upwelling $\left(F_1^{\uparrow} \text{ and } F_2^{\uparrow}\right)$ short–wave radiation fluxes above (at height 1) and under (at height 2) the clouds were measured in all previous experimental investigations (see Fig. 1). Then the spectral albedo of the system (A_1) and the surface (A_2) were calculated

$$A_1 = F_1^{\uparrow} / F_1^{\downarrow} \text{ and } A_2 = F_2^{\uparrow} / F_2^{\downarrow} . \tag{1}$$

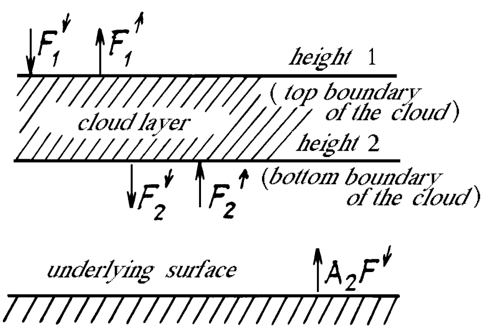

FIG. 1. Radiation fluxes in the atmosphere: incident on the cloud $F_1^{\downarrow}$, reflected from the cloud $F_1^{\uparrow}$, transmitted through the cloud $F_2^{\downarrow}$, illuminated the cloud from below $F_2^{\uparrow}$, and reflected from the surface $A_2F_2^{\uparrow}$ being equal to $F_2^{\uparrow}$.

The spectral balances at the upper and lower heights

$$B_1 = F_1^{\downarrow} - F_1^{\uparrow} \quad \text{and} \quad B_2 = F_2^{\downarrow} - F_2^{\uparrow} . \tag{2}$$

were used for subsequent determination of absolute (b_{12}) and relative (β_{12}) spectral influxes of the radiant energy in the cloud layers

$$b_{12} = B_1 - B_2 \text{ and } \mathrm{b}_{12} = b_{12} / F_1^{\downarrow} . \tag{3}$$

The spectral albedo of the system A_1 was considered as a characteristic of the reflectivity of clouds and the absolute b_{12} and relative β_{12} influxes as a characteristic of their spectral absorption. Sometimes the spectral transmission of the clouds was also calculated

$$T = F_2^{\downarrow} / F_1^{\downarrow} . \tag{4}$$

The given quantities virtually describe the above–indicated characteristics of the cloud layers if the cloud formations are not illuminated (or practically are not illuminated) from below. But, for example, the experimental data given in Ref. 4 were obtained over the surfaces with mean short–wave albedo of the order of 40% (May 29, 1976) and 60% (April 20, 1985). It evidently means that the clouds were illuminated from below.

To take into account this illumination, we may use different approaches, however, we must finally obtain the same results. It seems to be interesting to consider the examples of different methods of solving the problem under consideration.

When determining these parameters of the cloud layers, let us assume the existence of the reversibility properties of the above–indicated quantities, i.e., let us assume that the parameters above the cloud layer will be equal to the corresponding parameters below it.

It will be really so in the case of absence of a sharp vertical inhomogeneity in the cloud layer (of a considerable thickening of the cloud layer from above or from below). It is evident that the resulting inhomogeneities will be smoothed in the process of development and transport of the cloud mass in the atmosphere, and the presence of sharp vertical inhomogeneities in stratus (it is the very case that we mean) is improbable. In addition, let us assume that the above–considered parameters of clouds are independent of the spatial distribution of the intensity of illuminating radiation flux due to relatively a large optical thickness of the cloud layers ($\tau \gg 1$), i.e., their optical parameters from above and from below are equal in spite of the fact that the clouds are illuminated from above by directed solar radiation (at different angles with respect to the cloud surface) and from below by diffuse radiation reflected from the underlying surface. It will be true in the case of complete redistribution of radiation over the directions in

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the process of radiative transfer in the cloud layer. This phenomenon is really observed in clouds with $\tau \geq 10$, as the estimates made by the Monte Carlo method show.

1. THE METHOD OF A SUCCESSIVE SEPARATION AND SUBSEQUENT SUMMATION OF REFLECTED, TRANSMITTED, AND ABSORBED SHORT–WAVE RADIATION FLUXES

Let us consider sequentially all the steps of the transfer of the radiation flux in the cloud layer by the method well known to specialists in analogy with the method which was used for the first time by Stokes in 1862 in calculating the transmission of the collection of milk glasses.[5,6]

a) The incident radiation flux is divided into reflected, absorbed, and transmitted parts (there are no radiation sources in the earth's atmosphere in the short–wave range)

$$F_1^{\downarrow} = A\, F_1^{\downarrow} + K\, F_1^{\downarrow} + \underline{T\, F_1^{\downarrow}}\ . \quad (5)$$

The following designations are introduced here: A is the albedo of the cloud layer (the effective coefficient of reflection of the radiation flux), T is the effective coefficient of transmission of the radiation flux through the clouds, and K is the effective coefficient of real absorption of the radiation flux by clouds. There is an evident relation between these quantities by virtue of the energy conservation law

$$A + T + K \equiv 1\ . \quad (6)$$

Taking Eq. (3) into account, we can write the evident relation for the coefficient K

$$K = \frac{b_{12}}{F_1^{\downarrow} + F_2^{\uparrow}} = \frac{B_1 - B_2}{F_1^{\downarrow} + F_2^{\uparrow}}\ . \quad (7)$$

b) The transmitted part of the incident flux (underlined in Eq. (5)) is divided into the absorbed and reflected from the surface

$$T\, F_1^{\downarrow} = \left(1 - A_2\right) T\, F_1^{\downarrow} + \underline{A_2 T\, F_1^{\downarrow}}\ . \quad (8)$$

c) The part reflected from the surface (underlined in Eq. (8)) is divided into the transmitted, absorbed, and reflected from the clouds

$$A_2 T\, F_1^{\downarrow} = A_2 T^2 F_1^{\downarrow} + K A_2 T\, F_1^{\downarrow} + \underline{A A_2 T\, F_1^{\downarrow}} \quad (9)$$

and so on. As a result, we obtain the formulas for the flux reflected from the cloud layer ($F_1^{\uparrow}$) and for the fluxes absorbed by clouds (F_a) and by the surface (F_{as}):

$$F_1^{\uparrow} = AF_1^{\downarrow} + A_2 T^2 F_1^{\downarrow} + AA_2^2 T^2 F_1^{\downarrow} + A^2 A_2^3 T^2 F_1^{\downarrow} + \ldots =$$

$$= AF_1^{\downarrow} + A_2 T^2 F_1^{\downarrow} \sum_{n=0}^{\infty} \left(AA_2\right)^n =$$

$$= AF_1^{\downarrow} + \left(A_2 T^2 F_1^{\downarrow}\right) / \left(1 - AA_2\right)\ ; \quad (10)$$

$$F_A = KF_1^{\downarrow} + KA_2 TF_1^{\downarrow} + KAA_2^2 TF_1^{\downarrow} + KA^2 A_2^3 TF_1^{\downarrow} + \ldots =$$

$$= KF_1^{\downarrow} + KA_2 TF_1^{\downarrow} \sum_{n=0}^{\infty} \left(AA_2\right)^n = KF_1^{\downarrow} + \frac{KA_2 TF_1^{\downarrow}}{1 - AA_2}\ ; \quad (11)$$

$$F_{as} = (1 - A_2)TF_1^{\downarrow} + (1 - A_2)AA_2 TF_1^{\downarrow} + (1 - A_2)A^2 A_2^2 TF_1^{\downarrow} + \ldots =$$

$$= (1 - A_2)TF_1^{\downarrow} \sum_{n=0}^{\infty} \left(AA_2\right)^n = \frac{(1 - A_2)TF_1^{\downarrow}}{1 - AA_2}\ . \quad (12)$$

It is evident that by virtue of the energy conservation law the identity

$$F_1^{\downarrow} \equiv F_1^{\uparrow} + F_a + F_{as}\ , \quad (13)$$

must be satisfied or, using Eqs. (10), (11) and (12), we obtain

$$F_1^{\downarrow} = AF_1^{\downarrow} + \frac{A_2 T^2 F_1^{\downarrow}}{1 - AA_2} + KF_1^{\downarrow} + \frac{KA_2 TF_1^{\downarrow}}{1 - AA_2} + \frac{\left(1 - A_2\right)TF_1^{\downarrow}}{1 - AA_2}\ . \quad (14)$$

This statement is easy proved using formula (5).

Let us transform Eq. (11) using Eq. (12). Taking into account that $F_{as} = (1 - A_2)F_2^{\downarrow}$ and comparing the right sides of this relation with Eq. (12) we obtain

$$F_2^{\downarrow} = \frac{TF_1^{\downarrow}}{1 - AA_2}\ . \quad (15)$$

Substituting Eq. (15) into Eq. (11), we find

$$F_a = b_{12} = B_1 - B_2 = KF_1^{\downarrow} + KA_2 F_2^{\downarrow}\ , \quad (16)$$

and using Eq. (1) for the albedo A_2, we obtain

$$b_{12} = B_1 - B_2 = KF_1^{\downarrow} + KF_2^{\uparrow} = K\left(F_1^{\downarrow} + F_2^{\uparrow}\right)\ . \quad (17)$$

Relation (17) is the same as Eq. (7), which has been already written. Subsequently we rewrite Eq. (15) taking into account Eq. (1), in the form

$$F_2^{\downarrow} = T\, F_1^{\downarrow} + AF_2^{\uparrow}\ . \quad (18)$$

And, finally, multiplying by TA_2 Eq. (15) and subtracting it from Eq. (10), we obtain $F_1^{\uparrow} = A\, F_1^{\downarrow} + TA_2 F_2^{\downarrow}$. Taking into account Eq. (1), we have

$$F_1^{\uparrow} = A\, F_1^{\downarrow} + TF_2^{\uparrow}\ . \quad (19)$$

Thus, we derive Eq. (17) coinciding with Eq. (7) used for calculation of the coefficient K and two relations (18) and (19) for the coefficient A and T.

2. THE EXACT CALCULATION OF THE RADIATIVE TRANSFER FOR A PLANE ATMOSPHERE MODEL

Before writing the solution of the above–indicated system, let us show that it can be obtained on the basis of the rigourous theory. Practically the sought–after coefficients A and T coincide with the corresponding parameters in solving the radiative transfer equations for the plane atmospheric model with the "black bottom", i.e., in the absence of illumination from below (or the same, for $A_2 = 0$). When $A \neq 0$, we may write

$$F_1^{\uparrow} = \tilde{A}\, F_1^{\downarrow} \text{ and } F_2^{\downarrow} = \tilde{T}\, F_1^{\downarrow}\ . \quad (20)$$

It is well known[7] that $\tilde{A}$ and $\tilde{T}$ are related with A and T by the formulas

$$\tilde{A} = A + \frac{A_2 T^2}{1 - A_2 A} \text{ and } \tilde{T} = \frac{T}{1 - A_2 A} . \quad (21)$$

In this case, using Eqs. (20) and (21) we obtain

$$\left. \begin{aligned} F_2^{\downarrow} &= T\, F_1^{\downarrow} \big/ \left(1 - A_2 A\right) \\ F_1^{\uparrow} &= A\, F_1^{\downarrow} + \frac{A_2 T^2}{1 - A_2 A} F_1^{\downarrow} \end{aligned} \right\} . \quad (22)$$

Using the first equation of system (22) and taking into account definition (1) of the surface albedo A_2, we write

$$F_2^{\uparrow} = A\, F_2^{\downarrow} = \frac{A_2 T}{1 - A_2 A} F_1^{\downarrow} . \quad (23)$$

Finally, substituting Eq. (23) into Eq. (22), we obtain

$$\left. \begin{aligned} F_2^{\downarrow} &= T F_1^{\downarrow} + A F_2^{\uparrow} \\ F_1^{\uparrow} &= A F_1^{\downarrow} + T F_2^{\uparrow} \end{aligned} \right\} ,$$

i.e., the equations completely coinciding with Eqs. (18) and (19).

3. APPLICATION OF THE ENERGY CONSERVATION LAW

Systems of equations (18) and (19) can be written without any calculations on the basis of the energy conservation law. Really, according to the definition of the coefficients A and T, taking into account the energy conservation law, we can write the relations

$$\left. \begin{aligned} F_2^{\downarrow} &= T F_1^{\downarrow} + A F_2^{\uparrow} \\ F_1^{\uparrow} &= A F_1^{\downarrow} + T F_2^{\uparrow} \end{aligned} \right\} , \quad (24)$$

which agree with Eqs. (18) and (19).

Thus, summarizing the above discussed three methods of the derivation of system (24), it should be noted that:

a) the method of a successive separation and subsequent summation of the components of radiation fluxes makes it possible to illustrate the physical processes, which take place in the considered short–wave radiative transfer in the cloud layer as well as to formulate the assumptions about the properties of the layer, which must be introduced, but this method occurs to be very cumbersome;

b) in Section 2 we used only the final results (Eq. (21)) of the exact calculation of the short–wave radiative transfer for the plane atmospheric model. To obtain them, we must make definite transformations. It should be noted that relations (21) were obtained in solving the problem, which does not completely coincide with the problem considered in this paper, so the applicability of them for solving the problem under consideration becomes evident due to the complete coincidence of final relations;

c) relations (24) are written at once, without derivations, as a consequence of the energy conservation law. The specialists in radiative transfer theory often neglect a two–flux consideration, calling it "a two–flux approximation" and assuming it in all cases as the approximate method; it was convincingly shown above that it is a mistake.

4. RELATIONS FOR THE COEFFICIENT A, T, AND K.

Solving the above–written system for A and T, we obtain.

$$A = \frac{F_1^{\downarrow} F_1^{\uparrow} - F_2^{\downarrow} F_2^{\uparrow}}{\left(F_1^{\downarrow}\right)^2 - \left(F_2^{\uparrow}\right)^2} , \quad (25)$$

$$T = \frac{F_1^{\downarrow} F_2^{\downarrow} - F_1^{\uparrow} F_2^{\uparrow}}{\left(F_1^{\downarrow}\right)^2 - \left(F_2^{\uparrow}\right)^2} . \quad (26)$$

Let us note the other possible form of relations for A and T. Let us first consider the conservative radiative transfer ($K \equiv 0$). In this case $T_0 = 1 - A_0$ and from Eq. (24) we obtain

$$\Delta F^{\uparrow} = F_1^{\uparrow} - F_2^{\uparrow} = A_0 \,(F_1^{\downarrow} - F_2^{\uparrow}) ,$$

$$\Delta F^{\downarrow} = F_1^{\downarrow} - F_2^{\downarrow} = A_0 \,(F_1^{\downarrow} - F_2^{\uparrow}) . \quad (27)$$

Here the subscript "0" refers to the case of the conservative radiative transfer. The difference between equations (27) gives the trivial identity for the case under consideration. $\Delta F^{\uparrow} - \Delta F^{\downarrow} = B_1 - B_2 \equiv 0$.

To find A_0 we can use any equation, since they are identical ($\Delta F^{\downarrow} \equiv \Delta F^{\uparrow}$ in the case of the conservative radiative transfer); however, in order to decrease the random of error in calculation of A_0 (measurements of all four fluxes are assumed to be independent), it is better to find it after summation of the above–written relations

$$A_0 = \frac{1}{2} \frac{\Delta F^{\downarrow} + \Delta F^{\uparrow}}{F_1^{\downarrow} - F_2^{\uparrow}} . \quad (28)$$

In general ($K \neq 0$), substituting Eq. (6) into Eq. (20), after simple transformations we obtain

$$\Delta F^{\uparrow} = A \left(F_1^{\downarrow} - F_2^{\uparrow}\right) - K F_2^{\uparrow} ;$$

$$\Delta F^{\downarrow} = A \left(F_1^{\downarrow} - F_2^{\uparrow}\right) + K F_1^{\downarrow} . \quad (29)$$

Subtracting these equations we obtain already known relation (7). Summing them (as it was made above), we find

$$A = \frac{1}{2} \frac{\Delta F^{\downarrow} + \Delta F^{\uparrow} - K\left(F_1^{\downarrow} - F_2^{\uparrow}\right)}{F_1^{\downarrow} - F_2^{\uparrow}} = A_0 - \frac{K}{2} . \quad (30)$$

Relation (30) can be easy understood from the physical point of view.

For practical calculations of K, A, and T (without computer) it is more convenient to use the last formulas in the following order: a) we find K from Eq. (7), b) we find A from Eqs. (28) and (30), and c) we find $T = 1 - K - A$. Next paper of this journal describes the application of the obtained relations for the interpretation and analysis of the concrete experimental data. The author sincerely thanks Dr. A.K. Kolesov for the helpful discussions of this paper.

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