ON CALCULATING THE CHARACTERISTICS OF RADIATION FIELDS IN NUMERICAL MODELS OF ATMOSPHERIC PROCESSES

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The possibility of using a simplified two-flux method to calculate the radiation characteristics in the UV and visible ranges for radiative-convective and photochemical models of the atmosphere is analyzed in this paper. The results of comparing thus technique to the exact Δ-Eddington scheme are presented. It is shown that when calculating the upward and downward radiation fluxes the simplified method saves a considerable amount of computer time, the accuracy of calculations remaining at a satisfactory level (10–15%). This is of particular importance for atmospheric models since the radiation code is frequently addressed during the calculation procedure.

The paper also illustrated the capabilities of this algorithm in its account of the effects of clouds and the respective radiation field transformations, which are very important when modeling the gaseous composition of the atmosphere.

Radiative codes are an extremely important component of modern numerical models simulating different atmospheric physical processes, (e.g., general circulation, radiative models, photochemical models of the gaseous composition of the atmosphere, etc.). Iterative running of such codes in these models, when they are activated at each time step of the calculation procedure, assumes the application of economical numerical algorithms of sufficient accuracy. That is why two-flux schemes for integrating the transfer equation have gain found quite wide use recently. At the same time, such simplified schemes have to be studied in detail to estimate their sensitivity to different perturbing atmospheric factors, such as clouds, the changing ozone and aerosol content, etc., and their accuracy in comparison with more sophisticated algorithms (those of layer addition, the Δ-Eddington approximation, etc.). The latter task is the main purpose of the numerical experiments carried out in the present work.

As the object of such analysis, we chose the two-flux method developed by Isaksen[1] and employed in the most present-day models of the atmospheric photochemistry. The idea of the method is to calculate separately the direct and diffuse radiation fluxes in a plane-parallel atmosphere divided into N layers. The scattering phase function is assumed to be spherical, so that the upward and downward diffuse fluxes may be immediately calculated. On account of the equal probability for photons to be scattered up or down along the propagation path, the recursion relations obtained in Ref. 1 for an arbitrary layer have the following form:

$$\downarrow F_i^d = \downarrow F_{i+1}^d \exp(-\Delta\tau_{i+1/2}) \qquad (1)$$

for the direct downward flux;

$$\downarrow F_i^k = \left[\frac{1}{2} \left(\downarrow F_{i-1}^{k-1} + \uparrow F_i^{k-1} \right) \left(1 - \exp(-\Delta\tau_{i+1/2})\right) + F_{i+1}^k \right] \times$$
$$\times \exp(-\Delta\tau_{i+1/2}) \qquad (2)$$

for the diffuse downward flux;

$$\uparrow F_i^k = \left[\frac{1}{2} \left(\uparrow F_{i-1}^{k-1} + \downarrow F_i^{k-1} \right) \left(1 - \exp(-\Delta\tau_{i-1/2})\right) + \uparrow F_{i-1}^k \right] \times$$
$$\times \exp(-\Delta\tau_{i-1/2}) \qquad (3)$$

for the diffuse upward flux;

$$\uparrow F_i^d = \downarrow F_1^d \, A \exp\left(- \sum_{j=1}^{i-1} \Delta\tau_{j+1/2} \right. \qquad (4)$$

for the direct flux reflected from the Earth's surface. Here τ is the optical depth; A is the albedo of the underlying surface; k is the order of scattering; and $i = 1, \ldots, N$, where N is the number of levels. The method allows one to calculate diffuse radiation fluxes of arbitrary order of scattering. However, as was shown in Ref. 1, account of the first five of such orders is sufficient.

We applied the above-described algorithm to a vertical grid, running from 0 to 50 km grid with a 1 km step at a spectral resolution of $\lambda = 0.005$ μm. The vertical concentration profiles of O_2, O_3, and the extraterrestrial radiation fluxes were taken from Ref. 2. The computation time of the ES-1045 computer needed to solve the monochromatic problem does not exceed 2 sec. The algorithm was realized in the 0.175–0.75 nm spectral range.

For an alternative numerical technique we used the modified Δ-Eddington approximation developed by Joseph, Wiscombe, and Weinman[3] and applied to the radiation-photochemical model constructed at the Main Geophysical Observatory (MGO) (Ref. 4). This particular two-flux approximation is known to provide sufficiently high accuracy in calculating the diffuse radiation fluxes in media with strongly peaked scattering phase functions. However, the time required to solve the monochromatic problem is increased by, at least, an order of magnitude, which is of fundamental importance for calculation regimes in which the radiation code is frequently addressed. To compare these two algorithms, experiments were carried out with a synchronized set of initial data (including the absorption cross section of O_2, O_3, and NO_2, the extraterrestrial flux, etc.) of equal altitudinal and spectral resolutions.

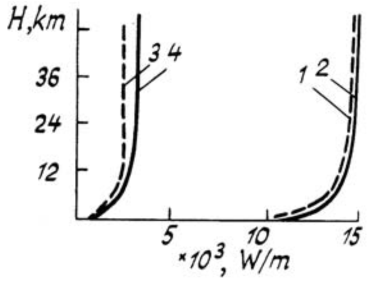

Fig. 1. The total downward (1, 2) and upward (3, 4) radiation fluxes in the range from 0.3125 to 0.75 nm obtained with the help of Ref. 1 (1, 3) and the Δ-Eddington technique (2, 4).

TABLE I. Sensitivity of the radiative changes in the atmospheric total ozone.

H, km	Doubling (upper row) and halving (lover row) of the ozone content		
	For the downward flux	For the upward flux	For temperature
	$\Delta = \frac{\downarrow F_\varphi - \downarrow F^*}{\downarrow F_\varphi} 100\%$	$\Delta = \frac{\uparrow F_\varphi - \uparrow F^*}{\uparrow F_\varphi} 100\%$	$\Delta = \frac{T_\varphi - T^*}{T_\varphi} 100\%$
0	–3.5	–3.0	0
	1.6	1.2	0
10	-3.4	-3.1	0.04
	1.5	1.3	0.04
20	-2.5	-3.3	0.12
	1.3	1.8	0.8
30	-1.3	-3.3	0.3
	0.5	2.4	-0.19
40	-0.6	–3.7	0.3
	0.3	2.8	-0.2
50	-0.3	-3.8	1
	0.2	2.9	-1.2

RESULTS OF NUMERICAL EXPERIMENTS

The total upward and downward radiation fluxes (direct plus scattered) are shown in Fig. 1. The results were obtained for the spectral range of 0.3125–0.750 μm both by the technique described in Ref. 1 and by the Δ-Eddington technique. As can be seen from the figure, the differences are insignificant for the downward flux and are more noticeable for the upward radiation flux above 15 km. However, even in this case the maximum discrepancy does not exceed 10–15%. Apparently such close agreement between the values should allow one to use the simpler algorithm given in Ref. 1 to calculate the stratospheric vertical profiles of the equilibrium temperature, thus saving much computer time. The temperature profiles obtained by coupling the simplified algorithm with the IR code of the MGO radiative-convective model[4] are presented in Fig. 2. (The MGO model uses the Δ-Eddington approach to calculate heating rates in the UV and visible ranges).

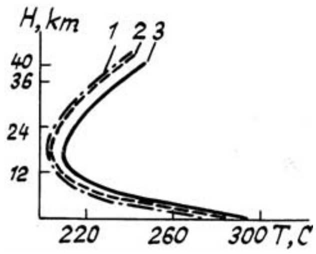

Fig. 2. The vertical temperature profiles obtained in the framework radiative-convective model (RCM) as compared with the standard profile: 1 – RCM, a simplified algorithm; 2 – RCM, Δ-Eddington technique; 3 – the standard atmosphere, USA, 1962, 45° of the north latitude, July.

The purpose of the next group of numerical experiments is to illustrate that the sensitivity to variations in the absorption optical depth is practically identical. Quantitative estimates of the response of the radiation scheme given in Ref. 1 to doubling and halving of the total ozone in the atmosphere are presented in Table I.

Thus it is possible to recommend the more economic algorithm[1] for use in radiative codes in numerical models of the atmosphere of climatic type. Another important application of the two-flux approximation[1] is in calculating the photochemical dissociation constants for trace gas components in photochemical atmospheric models where this method has found wide recognition due to the economy of its use. At the same time, in the calculation of the photodissociation constants

$$J^A(z) = \int_{\Delta\lambda} P_\lambda(z)\, q_\lambda^A\, \sigma_\lambda^A\, d\lambda, \qquad (5)$$

where $J(z)$ is the rate of photochemical dissociation of gas A at level z in the atmosphere, $P_\lambda(z)$ is the monochromatic radiation flux at the level z, q_λ^A is the quantum efficiency of the reaction, q_λ^A is the absorption cross section of gas A at the wavelength λ, and $\Delta\lambda$ is the spectral range of photochemical dissociation for gas A, some peculiarities arise at the troposphere levels where the effects of cloudiness have to be accounted for. However, no attempts of adapting the algorithm in Ref. 1 to cloudy conditions have so far been undertaken (at least no references to them exist in the current literature). Such an attempt in the framework of the present study was undertaken on the basis of a parametrization suggested in Ref. 5.

A cloudiness parametrization scheme that describes a homogeneous layer 1 km thick is shown in Fig. 3.

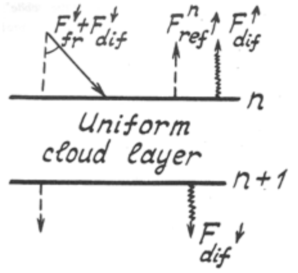

FIG. 3. Cloudiness parametrization scheme.

The reflected part of the direct and the diffuse downward fluxes is added to the diffuse upward flux at the top level of the cloud:

$$F_r^n\uparrow = A_{cl}\left[2\cos\theta\cdot F_d^n\downarrow + F_{dif}^n\downarrow\right], \tag{6}$$

where A_{cl} is the cloudiness albedo.

The unreflected part of the radiation reaches the cloud bottom as a diffuse component only:

$$F_0^{n+1}\downarrow = (1 - A_{cl})(2\cos\theta\cdot F_d\downarrow + F_{dif}^n\downarrow] \tag{7}$$

(It is assumed that no photon absorption takes place in the cloud). The total downward diffuse flux in the first layer below the cloud consists of radiation transmitted through the cloud, plus the part of the upward diffuse flux reflected downward from the cloud bottom:

$$F_{dif}^{n+1}\downarrow = F_0^{n+1}\downarrow + A_{cl}\times F_{dif}^{n+1}\uparrow \tag{8}$$

Thus, only one parameter, the albedo, which characterizes the optical properties of the cloud, enters into relations (6-8). In the numerical experiments it was set equal to 0.8 following Ref. 5.

Figure 4 presents the results of a calculation of the relative change of the total radiation flux between the altitudes 0 and 5 km (i.e., above and below the cloud layer stretching from 2 to 3 km). These are compared at the results from Ref. 5, where the above parametrizatIon of cloudiness was incorporated into Luther's radiation scheme.[6]

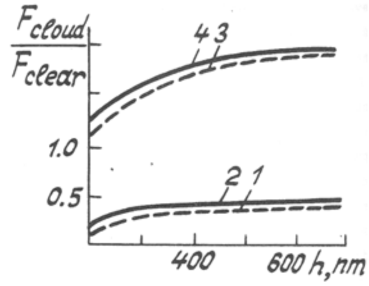

FIG. 4. Spectral dependence of the ratio of the radiation fluxes in a cloudy and a clear atmosphere: zenith angle $\theta = 60°$, $A_{cl} = 0.8$, $A = 0$; 1) subcloud layer, $z = 0$. calculated results; 2) same, according to Ref. 5; 3) cloud top layer, $z = 10$ km, calculated results; 4) same, according to Ref. 5.

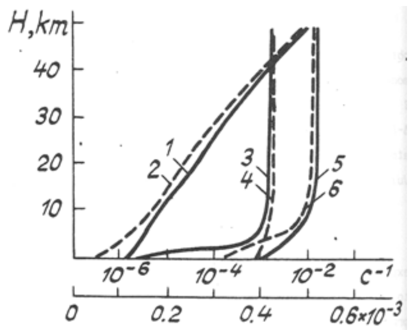

FIG. 5. Calculated vertical profiles of the reaction rate constants (9–11) in a clear sky in a cloudy one (see text): $A = 0$, $A_{cl} = 0,8$, $\theta = 60°$, z_{cl} = 2-3 km; 1) clear sky (9); 2) cloudiness accounted for (reaction (9)); 3) clear sky (react ion(10)); 4) cloudiness accounted for (reaction (10)); 5) clear sky (reaction (11); 6) cloudiness accounted for (reaction (11)).

Figure 5 shows the computed vertical profiles of the rate constants for the following photochemical dissociation processes, which are of fundamental importance for atmospheric photochemistry:

$$O_3 + h\nu \longrightarrow O_2 + O(^1D)\ (\lambda < 200\ \text{nm}); \tag{9}$$

$$O_3 + h\nu \longrightarrow O_2 + O(^3P)\ (\Delta\lambda = 200\text{-}700\ \text{nm}); \tag{10}$$

$$NO_2 + h\nu \longrightarrow NO + O\ (\lambda < 400\ \text{nm}). \tag{11}$$

The fact that the rates of reactions (9)–(11) calculated for cloudy and clear sky conditions differ by severalfold, emphasizes the necessity of accounting for cloud effects when simulating photochemical processes in the lower troposphere. The influence of cloudiness on the intensity of photodissociation in the upper troposphere is much weaker, as shown by Fig. 6, which gives the ratio between the rates of reactions (9) and (11) as a function of the zenith angle under cloudy and clear sky conditions at an altitude of 10 km.

Similar data from Ref. 5 are presented for comparison purposes.

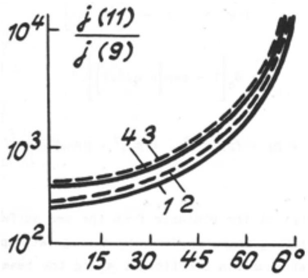

FIG. 6. The ratio of photochemical dissociat ion reaction rates $j_{(11)}/j_{(9)}$ as a function of solar zenith angle: altitude 10 km; clear sky and cloudy; $A_{cl} = 0.8$; 1) clear sky, calculated results; 2) same according to Ref. 5; 3) cloudiness accounted for; 4) same according to Ref. 5.

Summarizing the foregoing arguments, the following recommendations can be made for calculating the radiative characteristics in the modeling of various atmospheric processes:

– The two-flux scheme[1] can be used to calculate the characteristics of the radiative and thermal atmospheric regime in the UV and visible spectral ranges;

– The recommended scheme provides sufficient accuracy as compared to more sophisticated algorithms, at a considerable saving of computation time;

– The considered algorithm allows one to take account of the effect of cloudiness on the tropospheric radiation fields. The calculations based on it testify to the necessity of taking cloud effects into account when calculating the photodissociation constants in the lower atmosphere, in agreement- with the conclusions of Ref. 5.

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