Cloud-Radiation-Aerosol Experiments at the Institute of Atmospheric Physics, Russia

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Introduction

The Institute of Atmospheric Physics, Russian Academy of Sciences, has carried out several field Cloud-Radiation-Aerosol Experiments in cooperation with other institutions. In 1994 and 1996, local measurements of the optical properties of the near surface aerosol were carried out in parallel with aureole measurements of the aerosol in the atmospheric column. The spectral radiation was measured by a complex of spectrometers. Global radiation was controlled by standard equipment (pyrheliometer, pyronometer, pyrgeometer). A microwave sounder was used for the determination of the liquid water path of clouds and water vapor content. AVHRR (advanced very high-resolution radiometer) data from the National Oceanic and Atmospheric Administration satellite were also used, together with aerological information. Cloud bases were measured by lidar. Microphysical parameters of clouds were retrieved from the aureole and spectral transmittance measurement. In this paper, some results obtained during the experiments are considered.

Measurements and Calculations of Solar and Thermal Downwelling Fluxes

Measurements of the global fluxes of thermal (F) and solar (Q) radiation were carried out with an Eppley Precision Infrared Pyrgeometer and Eppley Precision Pyronometer. The instruments were placed at the tower at a height of 16 m. For measurements of the normal direct-beam solar radiation, a standard actinometer AT-50 was used. The actinometer was mounted on the solar tracking system. Signals were recorded by a Campbell 21x micrologger, connected to a PC. Temperature, relative humidity, and wind speed and direction were measured by a meteorological station also situated at a height of 16 m at the tower. All the data obtained during the experiments were written to the database. Time spacing of the records is equal to 2 min.

The modified radiation codes MODTRAN2 and LOWTRAN7 were used for calculations of the global thermal and shortwave fluxes.

In Figures 1 and 2, examples of the temporal course of the instant values of shortwave and thermal irradiance are shown. It can be seen from Figure 1 that, even for solid cloudiness, the value of Q changes significantly. The main parameter that affects the short-period variations of downwelling fluxes in conditions of solid cloudiness is cloud optical depth τ_{cl}, because all other constituents of the atmosphere do not vary significantly during the period of several hours. In Tarasova and Yarho (1991), estimates of cloud optical depths are obtained from measurements of downward fluxes. For thick clouds, the considerable errors in evaluating τ_{cl} are possibly due to the weak sensitivity of Q to the aerosol optical depth τ_a in cloudy conditions and the strong dependence of the shortwave irradiance in clear sky conditions Q_0 upon τ_a.

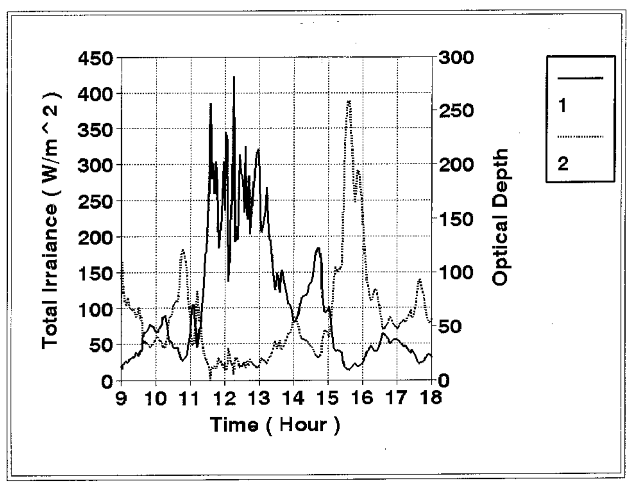

Figure 1. Hemispheric solar irradiance (1) and retrieved cloud optical depth (2). Zvenigorod, September 7, 1996.

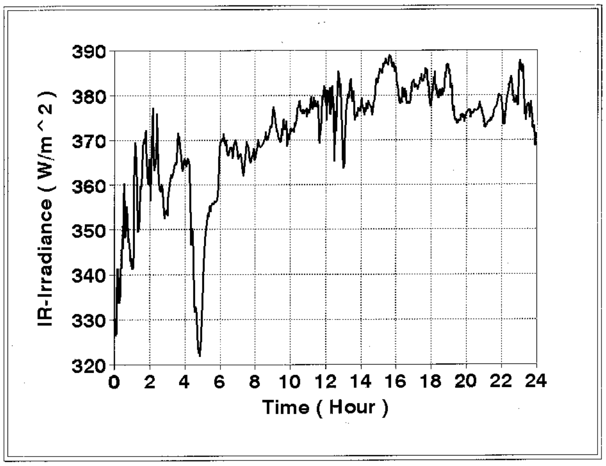

Figure 2. Hemispheric infrared irradiance. Zvenigorod, September 7, 1996.

More preferable to use for an estimation of τ_{cl} is the ratio C_Q of the irradiance Q in cloudy conditions to Q_0 (Tarasova and Chubarova 1994). Use of the parameter C_Q eliminates the uncertainties that are due to the dependence of Q upon the solar zenith angle, variations of optical characteristics of cloudless atmosphere, and systematic measurement errors. Clear sky irradiance Q_0 can be parameterized as a power function of the solar zenith angle μ_0 (Tarasova et al. 1992):

$$Q_0 = a\mu_0^{\ b} \qquad (1)$$

Parameters a and b depend upon the integral atmospheric transparency P_2, corresponding to the solar zenith angle 60°. The periods of the experiments in 1996 and especially in 1994 were characterized by small aerosol loading in the atmosphere with $P_2 \approx 0.8$. The regression analysis of the data set of the instant values of Q_0 measured in 1994 and 1996 gave the following values: a = 6.99, b = -1.22. Tarasova and Chubarova (1994) suggested formulas for estimating the optical depth of the low and middle extended clouds from the measurements of the solar radiation. For rather thin clouds $(\tau_{cl} < 20)$, it can be expressed as:

$$C_Q = (a_1 + b_1\mu_0)\exp((c_1 + d_1\cos\mu_0)\tau_{cl}) \qquad (2)$$

and for $\tau_{cl} > 20$

$$C_Q = (a_2 + b_2\mu_0)\exp(\ln\tau_{cl}(c_2 + d_2\cos\mu_0)) \qquad (3)$$

with different numerical values of coefficients in two ranges of $\tau_{cl}(20 < \tau_{cl} < 50$ and $50 < \tau_{cl} < 100)$. Variations of cloud optical depth retrieved using Equations (2) and (3) are also shown in Figure 1.

The measurements and calculations were used to evaluate a cloud amount for clouds with different optical depth. An example of the temporal course of the cloud amount and the distribution of the optical depth is presented in Figure 3.

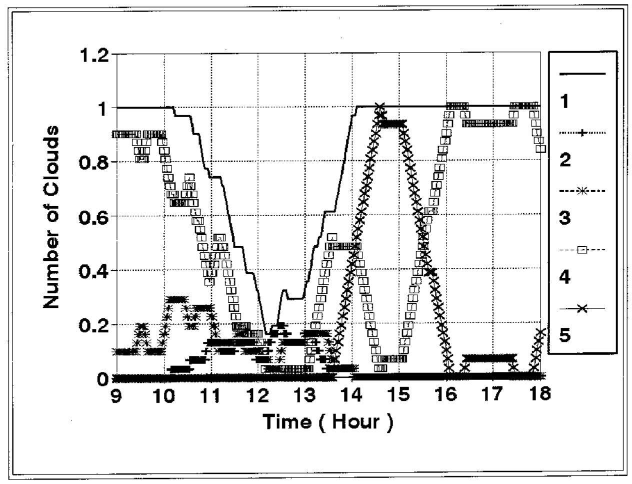

Figure 3. Duirnal course of the cloud amount for different cloud optical depths. 1 - total; 2 - τ_{cl} < 5; 3 - 5 < τ_{cl} < 10; 4 - 10 < τ_{cl} < 20; and 5 - τ_{cl} > 20. Zvenigorod, September 27, 1996.

Cloud Radiative Forcing from Experimental Measurements in the Case of Stratus Clouds

For solar radiation, cloud radiative forcing (CRF) can be expressed as:

$$C_s(z) = Q(z)_{cloud} - Q(z)_{clear} \qquad (4)$$

Here Q(z) is the radiative balance $Q(z) = Q\downarrow(z) - Q\uparrow(z)$ in cloudy $(Q(z)_{cloud})$ or clear $(Q(z)_{clear})$ conditions. $Q\downarrow(z)$ is the downward flux of the integral solar radiation at the level z, $Q\uparrow(z)$ is the corresponding upward flux. In this present study, as in Ramanathan et al. (1995), we consider both thermal and solar radiation. In this case, a combination of balances is represented as follows:

$$C*(z) = C_s(z) + C_L(z) \quad (5)$$

where $C_L(z) = F(z)_{cloud} - F(z)_{clear}$. The balance $F = F\downarrow - F\uparrow$ is determined in cloudy and clear conditions. $F\downarrow(z), -F\uparrow(z)$ are the fluxes of downward and upward integral thermal radiation. The quantities $C^*(z)$, $C_s(z)$ and $C_L(z)$ are determined not only for the whole atmosphere $(0,\infty)$, but also above clouds (z_t, ∞), into the cloud (z_l, z_t), and under cloud layers $(0, z_l)$.

The downward fluxes were measured only at the ground level. Into the thickness of the atmosphere and on its upper boundary $z = \infty$, all fluxes and balances were calculated. For calculations of $Q\downarrow(0)$, we used the experimental data of heights of the lower and upper cloud boundaries, liquid water, and water vapor contents in the whole atmospheric column; the optical thickness of clouds; and the profile of water vapor content. The aerosol influence was neglected because aerosol loading was very small during the period of the experiment.

For thermal radiation the measured and calculated fluxes are in good agreement because the input parameters (z_l, temperature and humidity under the cloud) are measured rather precisely. To get such agreement in the case of solar radiation was difficult because of a number of very changeable cloud parameters. We used the mean for the hour values of $Q\downarrow^{meas}(0)$, which is not in bad agreement with $Q\downarrow^{calc}(0)$.

In Table 1, the values of C_s, C_L, C^* for levels $z = 0, z_l, z_t$ and ∞ (the upper boundary of the atmosphere) are given. Finally, in Table 1, we present the absorption of solar $\Delta C_s\ (z_i, z_j)$, thermal $\Delta C_L(z_i, z_j)$ and summary $\Delta C^*(z_i, z_j)$ radiation in the layers $(0, z_l), (z_l, z_t), (z_t, \infty)$ and in the whole thickness of the atmosphere - $(0, \infty)$. In general,

$$\Delta C = C(z_{i+1}) - C(z_i) \quad (6)$$

where $C = C_s, C_L, C*$.

In all cases, compared with cloudless atmosphere, the solar radiation always cools and thermally heats the under-cloud layer. Above the cloud, into it, and in the whole thickness of the atmosphere, the situation is opposite. On the whole (see ΔC^*), the clouds and the whole atmosphere are heated. Most interesting is the phenomenon that heating of the clouds and of the whole atmosphere is of the same order of magnitude.

Table 1. Radiative balances and absorption.

Date time	Z km	(z_i, z_j)	C_s W/m²	C_L W/m²	C* W/m²	ΔC_s W/m²	ΔC_L W/m²	ΔC^* W/m²
07.06.94	0	$(0, z_l)$	- 514.6	76.8	-437.8	-3.3	5.0	1.7
16.34	0.2 (z_i)	(z_l, z_t)	- 517.9	81.8	-436.1	111.8	-27.7	84.1
	6.5 (z_t)	(z_t, ∞)	- 406.1	54.1	-352.0	0.7	-6.6	-5.9
	∞	$(0, \infty)$	- 405.4	47.5	-357.9	109.2	-29.3	79.9
20.06.94	0	$(0, z_l)$	- 393.3	76.8	-316.5	-15.6	22.0	6.4
17.34	1.435 (z_l)	(z_l, z_t)	- 408.9	98.8	-310.1	92.5	-67.3	25.2
	2.8 (z_t)	(z_t, ∞)	- 316.4	31.5	-284.9	4.8	-5.1	-0.3
	∞	$(0, \infty)$	- 311.6	26.4	-285.2	81.7	-50.4	31.3
22.06.04	0	$(0, z_l)$	- 207.3	39.3	-168.0	-15.7	23.9	8.2
17.04	3.105 (z_l)	(z_l, z_t)	- 223.0	63.2	-159.8	59.9	-38.4	21.5
	3.8 (z_t)	(z_t, ∞)	- 163.1	24.8	-138.3	2.9	-3.8	-0.9
	∞	$(0, \infty)$	- 160.2	21.0	-139.2	47.1	-18.3	28.8
24.06.94	0	$(0, z_l)$	- 419.5	88.5	-331.0	-16.0	18.3	2.3
17.12	1.11 (z_l)	(z_l, z_t)	- 435.5	106.8	-328.7	104.6	-79.3	25.3
	2.0 (z_t)	(z_t, ∞)	- 330.9	27.5	-303.4	5.9	-7.5	-1.6
	∞	$(0, \infty)$	- 325.0	20.0	-305.0	94.5	-68.5	26.0

Retrieval of the Microphysical Parameters of Semi-transparent Clouds from Solar Aureole Measurements

Aureole phase functions D( ) were measured during the experiment with a modified multifilter sunphotometer (Isakov 1994). The effective wavelengths of the filters are 460, 540, 620, 820, 1170, and 1550 nm. The spectral dependencies of the phase functions at one scattering angle were recorded for about 1 sec. One series of measurements for three scattering angles, = 1.2°, 1.65°, 2.2°, lasted about 10 sec. The instrument was calibrated by diffuse scatterer with the albedo close to unity. The systematic error of the calibration in absolute units (sr^{-1}) does not exceed 15%. The uncertainty in the spectral course of phase functions is about 5%.

During the experiment in September -October 1996, more than 150 realizations of D( ) for cirrus clouds with optical depth from 0.1 to 1.3, 30 for cloud types Cc and Ac with τ_{cl} = 0.5 - 1.5, and 8 for condensation trails were registered.

Spectral-angular dependencies of D( ) were inverted to the cloud particle size distributions in the radius range r = 0.3 - 80 µm. The iterative technique of retrieving the size distribution from aureole measurements (Twitty 1975) was adopted to the measurement data set. The r.m.s. deviation between measured and recalculated optical characteristics was about 10%.

In case of cirrus clouds, a narrow mode of the volume size distribution dV(r)/dr occurs with modal radius r ≈ 25 µm. Retrieved volume size distributions for cirrus clouds are shown in Figure 4. The first and second curves (left axis) are obtained on different days, but refer to the close values of the optical depth (0.3). The third curve corresponds to the greater value of τ_{cl} and was obtained from measurements on the same day as the second. Volume size distributions for quasi-homogenous field of Ac clouds are shown in Figure 5. In this case, for a 15-min period, the variations in the shape of the size distribution were much less than particle concentration. The radius corresponding to the maximum of the volume distribution was equal to 5 µm. On the whole, the maximum of the volume distribution for Ac and Cc clouds varied from 2 to 5 µm. In condensation trails, the shape of the size distribution depended upon the "age" of the trails— bimodal distribution with modes at 3 and 10 µm converted in time into a distribution with single mode at 10 µm.

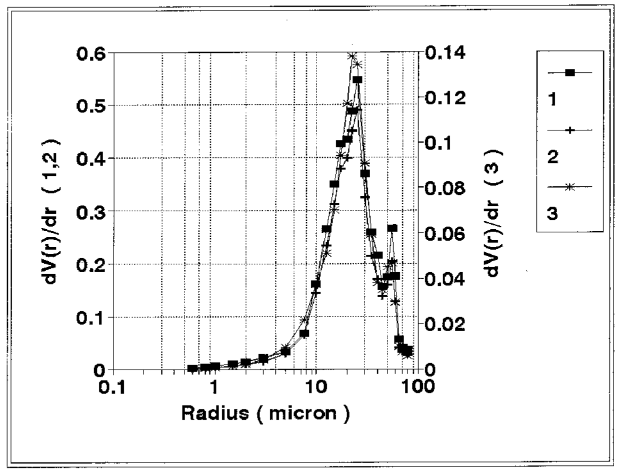

Figure 4. Volume size distributions retrieved from aureole measurements in cirrus clouds. 1-October 5; 2,3-September 30, 1996, Zvenigorod.

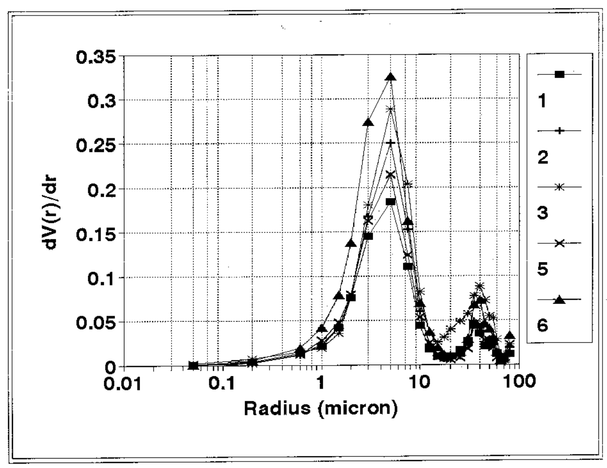

Figure 5. Volume size distributions retrieved from aureole measurements in altocumulus clouds. Zenigorod, October 29, 1996. 1-12h.46m.; 2-12h.48m.; 3-12h.50m.; 4-12h.56m.; 5-12h.58m. local time.

Acknowledgments

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