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Measurements and calculations of cloud radiative forcing on the base of the Moscow Region Experiment 1994

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RESUMEN

Ejemplos de medidas y cálculos son usados para la evaluación de influencia de las nubes sobre el intercambio de radiación de calor en toda la atmósfera, dentro de las nubes, debajo y encima de las capas nubosas. Se muestra que toda la atmósfera es calentada aproximadamente por radiación tanto como las propias nubes.

ABSTRACT

Examples of measurements and calculations are used for evaluation of the clouds influence on the radiative heat exchange in the whole atmosphere, into the clouds, under and above cloud layers. It is shown that the atmosphere on the whole is heated by radiation approximately as much as the clouds themselves.

1. Introduction

The international science community engaged in radiative heat exchange, clouds physics and climate modelling, has been considered the Cloud Radiative Forcing (CRF) from the 1950s with more and more attention at present.

In Cess *et al.* (1995) CRF has been evaluated only for the solar radiation by means of the radiative balance expression:

$$C_s(z) = Q(z)_{cloud} - Q(z)_{clear} \tag{1}$$

Here the balance $Q(z) = Q\downarrow(z) - Q\uparrow(z)$ in the 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 case CRF or C_s (z) the difference of the solar radiation balances between the cloudy and cloudless conditions. It is considered in Cess *et al.* (1995) only for $z = 0$ and $z = \infty$, and is evaluated on the base of satellite and ground level measurements. The opinion of these authors is that theoretical models underestimate the absorption of solar radiation in the atmospheric thickness, that 0 is:

$$\Delta C_s = C_s(\infty) - C_s(0) \qquad (2)$$

not less than by 25-30 W/m^2 and give the ratio $R = C_s(0)/C_s(\infty) \cong 1$, instead of $R = 1, 5$, "needed for the closure of the energy budget''. (Cess *et al.*, 1995).

2. Theoretical models of the radiative transfer in cloudy atmosphere

Reliability of such opinion about theoretical models we have verified on base of Fomin *et al.* (1994) paper that presents solar integral fluxes calculations with line by line method in the range 0.3-5.0 µm. The model parameters are solar constant 1367 W/m^2, albedo of the surface 0.2, zenith angle of the sun 30°. The error of these calculations is about 0.1%.

We used it for obtaining $C_s(0)$, $C_s(\infty)$, ΔC_s, R in case of clouds:

1. ST liquid water content Wc = 0,3 g/m^3, lower boundary level z_L = 0,5 km, upper boundary z_{up} = 1,0 km, optical thickness $\tau = 31.8$.
2. As, Wc = 0,15 g/m^3, z_L = 4,0 km, z_{up} = 5,0 km, $\tau = 31.8$.

Aerosol extinction coefficient is 0.1 km^{-1} in the layer 0-2 km and 0.0025 km^{-1} in $2 \le z \le 12$ km. The results are given in the Table 1.

Table 1. Radiative balances and absorption according the theoretical model Fomin *et al.* (1994)

Form of cloud	$C_s(0)$W/m^2	$C_s(\infty)$W/m^2	C_sW/m^2	R
St	-515.4	-483.0	32.4	1.07
AS	-515.5	-479.8	35.7	1.07

It is seen that, at least with respect to the values of R Cess *et al.* (1995) they are almost right.

3. Cloud radiative forcing for experimental measurements in the case of stratus clouds

In our paper as in Ramanathan *et al.* (1995) we consider besides solar radiation also the thermal one. In this case combination of balances is represented as follows:

$$C^*(z) = C_s(z) + C_L(z) \qquad (3)$$

where

$$CL(z) = F(z)_{cloud} - F(z)_{clear} \qquad (4)$$

The balance $F = F\downarrow - F\uparrow$ is determined in cloudy (F_{cloud}) and clear (F_{clear}) conditions.

$F\downarrow(z)$, $F\uparrow(z)$ are fluxes of downward and upward integral thermal radiation. The quantities $C^*(z)$, $C_s(z)wC_L(z)$ are determined not only for the whole atmosphere, but also for the above cloud, cloud and undercloud layers. The data of the 1994 year, June month experiment on the Zvenigorod Scientific Station of the Institute of Atmospheric Physics, Russian Academy of Sciences, are used.

The downward fluxes were measured only at the ground. Into the thickness of the and on its upper boundary ($z = \infty$) all fluxes and balances were calculated. As input parameters for calculations the following measurements data were used: heights of the lower (z_L) and upper (z_{up}) cloud boundaries, cloud liquid water content (Wc) optical thickness of the clouds (τ), albedo of the surface (A). Vertical profiles of temperature, humidity and pressure through the whole atmosphere were also measured. The aerosol influence was neglected because it was small at time of the experiment.

Solar integral fluxes were calculated by δ-Eddington approximation (Liou, 1992) Thermal fluxes were calculated on basis of integral transmission functions (Gorchakova, 1994).

Tabla 2. Comparison of the calculated (calc) and measured (meas) fluxes of the thermal and solar radiation at ground. ξ- the solar zenith angle.

Date Time	07.06.9 16.34	20.06.94 17.34	22.06.94 17.04	24.06.94 17.12
$\cos(\xi)$ z_L, km z_{up}, km τ Wc, kg/m^2	0.682 0.2 6.5 50 0.2	0.582 1.4 2.8 27 0.1	0.639 3.1 3.8 5 0.004	0.624 1.1 2 25 .1
$F\downarrow^{meas}$ W/m^2	385.6	361.8	325.6	349.2
$F\downarrow^{calc}$ W/m^2	383.3	361.3	334.9	345.3
$Q\downarrow^{meas}$ (0)W/m^2 momentary mean for 10 min for 30 min for 1h	105.4 105.3 105.3 104.6	114.3 118.5 119.5 131	492.2 489.4 434.7 476.6	248.5 256.1 203.4 168.6
$Q\downarrow^{calc}(0)$ W/m^2	107.6	144.3	457	171.9

In Table 2 we compare the calculated and measured fluxes of integral solar ($Q\downarrow(0)$) and thermal ($F\downarrow(0)$) radiation coming to the surface. Cases of solid clouds were chosen. For calculation of $Q\downarrow(0)$ we used the experimental data of heights of the lower and upper cloud boundaries, liquid water and water vapour content into it, the optical thickness of the cloud and the profile of water vapour content. For calculation of $F_L(0)$ we used the experimental data of cloud lower boundaries and the profile of the temperature and water vapour under the cloud.

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

In Table 3 are given the values of balances for the solar $Q(z)$ and thermal $F(z)$ parts of them. Also the corresponding values C_s, C_L, C^*, for levels: $z = 0, z_L, z_{up}$, and ∞- that is the upper boundary of the atmosphere. Parameter R is also given.

Table 3. Radiative balances of solar and thermal ranges for cloudy (Q_{cloud}, F_{cloud}) and clear (Q_{clear}, F_{clear}) skies and the whole balances C_s, C_L, C^*) on the levels $z = 0$, z_L, z_{up} and ∞ .

Date Time	z km	Q^{cloud} W/m^2	Q^{clear} W/m^2	C_s W/m^2	R	F^{cloud} W/m^2	F^{clear} W/m^2	C_L W/m^2	C* W/m2
07.06.94 16.34	0	88.7	603.3	-514.6		-10.2	-87	76.8	-437.8
	0.2(z_L)	89	606.9	-517.9		-13.9	-95.7	81.8	-436.1
	6.5(Z_{up})	276.7	682.8	-406.1	1.27	-128.9	-183	54.1	-352
	∝	326.5	731.9	-405.4		-198.1	-245.6	47.5	-357.9
20.06.94 17.34	0	118.3	511.6	-393.3		-25.1	-101.9	76.8	-316.5
	1.43(z_L)	120.9	529.8	-408.9		-24.4	-123.2	98.8	-310.1
	2.8(z_{up})	238.5	554.9	-316.4	1.26	-115.4	-146.9	31.5	-284.9
	∝	305.7	617.3	-311.6		-220	-246.4	26.4	-285.2
22.06.94 17.04	0	367.1	574.4	-207.3		-84.5	-123.8	39.3	-168
	3.1 (z_L)	394.9	617.9	-223.5		-107.5	-170.7	63.2	-160.4
	3.8(z_{up})	466.5	629.6	-163.1	1.29	-157.5	-182.3	24.8	-138.3
	∝	519.8	680	-160.2		-244.1	-265.1	21	-139.2
24.06.94 17.12	0	140.5	560	-419.5		-19.1	-107.6	88.5	-331
	1.11(z_L)	143.8	579.3	-435.5		-21.7	-128.5	106.8	-328.7
	2(z_{up})	268.4	599.3	-330.9	1.29	-113.6	-141.1	27.5	-303.4
	∝	335.2	660.2	-325		-227	247	20	-305

The values of R are larger ($R \cong 1.3$) as compared with the theoretical model (Table 1). But they do not achieve the given in Cess *et al.* (1995) value R = 1.5. Finally in Table 4 we present 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 outstanding layers: $(0, z_L)$, (z_L, z_{up}), $(z_{up}, \propto)$, and in the whole thickness of the atmosphere -$(0,\infty)$.

In all cases as compared with unclouded atmosphere the solar radiation almost cools and thermal heat the under cloud layer. Above the cloud, into it and in the whole thickness of the atmosphere the situation is the opposite. As it is indicated in Cess *et al.* (1995) the values of $\Delta C_s(0,\infty)$ are essential larger then in the case of theoretical model (Table 1)

Table 4.

Date Time	Z km	(z_i, z_j)	ΔC_s W/m^2	ΔC_L W/m^2	ΔC^* W/m^2
07.06.94 16.34	0	(0, z_l)	-3.3	5.0	1.7
	0.2 (z_l)	(z_l, z_{up})	111.8	-27.7	84.1
	6.5(z_{up})	(z_{up},∝)	0.7	-6.6	- 5.9
	∝	(0, ∝)	109.2	-29.3	79.0
20.06.94 17.34	0	(0, z_l)	-15.6	22	6.4
	1.435(z_l)	(z_l, z_{up})	92.5	-67.3	25.2
	2.8(z_{up})	(z_{up},∝)	4.8	-5.1	-0.3
	∝	(0, ∝)	81.7	-50.4	31.3
22.06.94 17.04	0	(0, z_l)	-16.2	23.9	7.6
	3.105 (z_l)	(z_l, z_{up})	60.4	-38.4	21.1
	3.8(z_{up})	(z_{up},∝)	2.9	-3.8	-0.9
	∝	(0, ∝)	47.1	-18.3	28.8
24.06.94 17.12	0	(0, z_l)	-16	18.3	2.3
	1.11 (z_l)	(z_l, z_{up})	104.6	-79.7	25.3
	2(z_{up})	(z_{up},∝)	5.9	-7.5	- 1.6
	∝	(0,∝)	94.5	-68.5	26

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 are of the same order of magnitude.

So in the whole cloudy atmosphere the effect of the clouds is the main factor which determines the radiative heat exchange.

4. Cloud radiative forcing for cirrus clouds

In addition we present data of calculations for solar and thermal radiation balances and absorption (Table 5) in cases of cirrus clouds. It is based on data of the experiment on Zvenigorod Station in 1987 year (Gorchakova and Tarasova, 1989).

Optical thickness of the clouds, the levels of their boundaries and water vapour content m_v were measured. The calculations of solar radiation fluxes were performed for spherical droplets large as compared with the wave length of solar radiation. Lognormal distribution of particles by sizes parameters were used with dispersion $\sigma^2 = 0.1$, median radius is 10 μm. The mean cosine of the phase function is 0.9, albedo of the single scattering is 0.9, albedo of the surface is 0.2. Table 5 presents 3 cases of calculation C^*, C_s and C_L for $z = 0$ and $\propto$ and $\Delta C_s(0, \propto)$, $\Delta C_L(0, \propto)$, $\Delta C^*(0, \propto)$.

Table 5. The balances and absorption got in cases of cirrus clouds 1987 Zvenigorod station experiment.

Date Time	τ	m_v g/cm^2	z	C_S W/m^2	C_L W/m^2	C^* W/m^2	ΔC_S W/m^2 (0,∝)	ΔC_L W/m^2 (0, ∝)	ΔC^* W/m^2 (0,∝)
19.05.87 17.30 - 18.00	0.33	1.3	0	-15	12	-3	3	18	21
			∝	-12	30	18			
20.05.87 11.30 - 12.00	0.17	1.9	0	-8	6	-2	4	14	18
			∝	-4	20	16			
22.05.87 13.30 - 14.00	0.46	2.8	0	-17	11	-6	7	18	25
			∝	-10	29	19			

It is naturally that all quantities are much lesser then in case of lower level clouds (Tables 3, 4). But the resulting effect, that is the $\Delta C^*(0, \propto)$ turn out to be almost of the same order of magnitude.

Undoubtely, we need new measurements and calculations for clouds of all kinds. Of course the represented results are preliminary ones. We hope to get more exact results with taking into account aerosol and in the more interesting case of broken clouds.

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