INFLUENCE OF CLOUDS ON THE ABSORPTION OF SHORT-WAVE RADIATION IN THE ATMOSPHERE. PART 2. RATIO OF RADIATIVE FORCINGS AT THE TOP OF THE ATMOSPHERE TO THOSE AT THE UNDERLYING SURFACE

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Two approaches are proposed to determine the ratio r of radiative forcings at the top of the atmosphere (TOA) to that at the underlying surface (short-wave radiation). According to the regression approach to r determination, random cloud geometry has little effect on the ratio of radiative forcings. The other approach assumes that r depends not only on the absorption change due to occurrence of clouds in the clear atmosphere, but also on the associated albedo variations at TOA. For this reason, the r difference between cumulus and stratus clouds, while being small at low surface albedo $A_s \le 0.2$*, may increase by tens of per cent as* A_s *increases for optically thin clouds and (or) small cloud fractions at the solar zenith angle* $\xi_\odot \le 30°$*. After the ratio of radiative forcings is averaged over the entire set of cloud optical and geometrical characteristics, the dependence of r on cloud type becomes much weaker. Also studied in this paper is the question on how accurately does the ratio of radiative forcings represent actual cloud absorption.*

1. INTRODUCTION

Recently the approach based on analysis of the parameter r (the ratio of cloud radiative forcings (CRF) at the surface level (SFC) and at the top of the atmosphere (TOA)) has been widely used (see, e.g., Refs. 1–4) to describe the effect of clouds on the atmospheric absorption of short-wave radiation:

$$r = \frac{CRF_{SFC}}{CRF_{TOA}} = \frac{F^{\rm all}_{SFC} - F^{\rm clr}_{SFC}}{F^{\rm all}_{TOA} - F^{\rm clr}_{TOA}} . \quad (1)$$

Here, F is the total radiative flux at a given atmospheric level; and superscripts “allB and “clrB denote the cloudy and clear-sky variables.

Based on satellite, aircraft, and ground-based measurements, the following r estimates are obtained:

– in the tropics, $r \approx 1.5$ (Refs. 3 and 4);

– at all geographical locations of measurements, $r \approx 1.5$ (Ref. 1);

– in the tropics, r strongly varies, the median being $r \approx 1.4$; $r \approx 1.1$ at mid-latitudes, and $r \le 1$ in polar regions (Ref. 2);

– $r \approx 1.14$ (short-wave radiation) and $r \approx 1.7$ (visible range).[5] Experimental values of r frequently do not coincide with model estimates, according to which $r_{\rm mod} \le 1.1 - 1.2$ (Refs. 1–3).

As proposed in Ref. 1, alternatively the ratio of radiative forcings can be described in terms of the slope s of the linear regression between TOA albedo R_{TOA} and the atmospheric transmittance at the surface level Q_{SFC}:

$$r^{(s)} = -(1 - A_s)/s, \quad (2)$$

where A_s is the surface albedo. According to the field measurement data,[1] $s_{\rm exp} = -0.6$ at $A_s = 0.17$. This is in agreement with Ref. 4, but in odds with Ref. 2, where $s_{\rm exp}$ is found to range from -0.67 to -0.87 for $A_s = 0.15$, the average value being $s_{\rm exp} = -0.77$. Also, Ref. 1 presents the value of the slope of the linear regression between R_{TOA} and Q_{SFC} inferred from some (unfortunately, nowhere described) set of model calculations: at $A_s = 0.17$, $s_{\rm mod} = -0.8$.

These results demonstrate that the ratios of radiative forcings determined by various authors from different sets field measurement data may substantially differ. The causes for the discrepancies are partly explained in Refs. 2 and 6. One more problem to be addressed is that the values of r (Eq. (1)), s, and, consequently of $r^{(s)}$ (Eq. (2)) determined from the experimental data frequently do not coincide with the model calculations. This discrepancy may be in part due to inadequacy of the model of a plane-parallel cloud generally used in calculations.

This work is a logical continuation of the studies performed in Ref. 7. In particular, the same models of broken clouds and the whole atmosphere, as well as the same sets of model results (upward and downward fluxes at 12 atmospheric levels) are used to calculate

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the ratio of radiative forcings within two approaches outlined above. We study how strongly do r, $r^{(s)}$, and s depend on the effects of cloud field random geometry at a varying cloud top height and surface albedo. Also discussed is the utility of the ratio of cloud radiative forcings as a measure of cloud absorption.

Here we adopt the same notations as those used in Ref. 7.

2. INFLUENCE OF STOCHASTIC CLOUD GEOMETRY ON THE RATIO OF RADIATIVE FORCINGS

To study the factors influencing the ratio of radiative forcings, we cast Eq. (1) into a more convenient form. We denote as $\Delta R_{TOA} = R^{\rm all}_{TOA} - R^{\rm clr}_{TOA}$, $\Delta A = A^{\rm all} - A^{\rm clr}$ the changes, caused, in the TOA albedo and clear-sky absorptance, by the presence of clouds. In accordance with Eq. (1), we can write

$$F^{\rm all}_{SFC} - F^{\rm clr}_{SFC} = r\, F^{\rm all}_{TOA} - r\, F^{\rm clr}_{TOA} = -\, r\, \Delta R_{TOA}.$$

On the other hand,

$$F^{\rm all}_{SFC} - F^{\rm clr}_{SFC} = -\, \Delta R_{TOA} - \Delta A.$$

Hence

$$\Delta R_{TOA} + \Delta A = r\, \Delta R_{TOA}$$

and, consequently,

$$r = 1 + \Delta A / \Delta R_{TOA}. \quad (3)$$

From Eq. (3) we readily obtain, for stratus clouds, that

$$r_{St} = r_{pp},$$

where r_{pp} is the ratio of radiative forcings under the overcast conditions ($N = 1$).

It follows from Eq. (3) that the ratio of radiative forcings depends not only on ΔA, but also on ΔR_{TOA}. As surface albedo $A_{\rm s}$ increases for small cloud fractions ($N \approx 0.1$–0.3) and (or) small cloud optical depths ($\tau \approx 5$) and small solar zenith angles ($\xi_\odot \le 30°$), the difference between $R^{\rm all}_{TOA}$ and $R^{\rm clr}_{TOA}$ decreases. This means that an increase in r may be caused not as much by variations in the absorptance ΔA, but by a decrease in ΔR_{TOA} (albedo effect). This is illustrated by Fig. 1, which presents the calculated results on ΔA, ΔR_{TOA} (in relative units), and r in cumulus clouds. We note that for optically thin low-level clouds at $A_{\rm s} = 0.4$, the closeness of $R^{\rm all}_{TOA}$ and $R^{\rm clr}_{TOA}$ values at $\xi_\odot = 0°$ leads to a large relative error of r calculation. So only r values calculated for optically thin low-level clouds at $\xi_\odot \ge 30°$ are presented here.

In Fig. 2, the ratio of radiative forcings for cumulus (r_{Cu}) is plotted versus r value for stratus (r_{St}). Each point (r_{St}, r_{Cu}) on the plot is calculated for the same input model parameters and two different values of the aspect ratio γ: $\gamma \ll 1$ for stratus and $0.5 \le \gamma \le 2$ for cumulus clouds. The calculated results show the following.

At $A_{\rm s} = 0$, for low- and mid-level clouds, (1) - both r_{Cu} and r_{St} do not exceed 1.2; and (2) - r_{Cu} and r_{St} differ a little bit, so that $|r_{Cu} - r_{St}| \le 0.05$ over almost the entire range of the input model parameters.

As surface albedo increases to $A_{\rm s} = 0.4$ the range of r variations widens: (1) - $r_{St} \le 1.5$ for both low- and mid-level clouds; and (2) - $r_{Cu} \le 1.8$ for mid-level clouds and $r_{Cu} \le 2.4$ for low-level clouds. Maximum r values occur for $\xi_\odot = 0°$, as a consequence of the albedo effect.

Ratio of the radiative forcings is a decreasing function of $\xi_\odot$, other model parameters being fixed (and for all $A_{\rm s}$ values) (see Fig. 1). Similar results have been obtained in Ref. 8, which considers the clouds of different phase composition (ice crystals; ice crystals plus water droplets).

At $A_{\rm s} = 0.4$, the difference between r_{Cu} and r_{St} increases, so that r_{Cu} may exceed r_{St} by about a factor of 1.5. The largest difference between r_{Cu} and r_{St} occurs in optically thin clouds and small cloud fractions when $\xi_\odot \le 30°$.

The influence of random cloud geometry on the ratio of radiative forcings was also discussed in Ref. 9, where a single cloud cover case was studied using different model of broken clouds.[10] In Ref. 9, the r growth is related to the increase of absorption due to longer photon mean-free paths in the stochastic cloud fields as compared to that in a horizontally homogeneous cloud layer. In the Poisson model of broken clouds, photon mean-free path is longer in cumulus than in stratus clouds,[11] but this produces no any significant increase in the absorption, as was previously shown in Refs. 7 and 12. As a consequence, ΔA weakly depends on cloud type, and the difference between r_{Cu} and r_{St} is associated mainly with the albedo effect, i.e., ΔR_{TOA} decrease, that is most noticeable in cumulus clouds.

In the above discussion, we have considered the ratio of radiative forcings for individual cloud cover cases. To obtain an average r value, it would be ideal to have information on the probabilities of these cloud cover situations.

In the absence of such information, at this research stage we assume that all situations with the cloud cover are equally probable, and the mean ratio $\bar{r}$ of radiative forcings is an average over the entire set of the input model parameters. Assuming that optical and geometrical cloud characteristics to be varying within the ranges indicated in Ref. 7, (introductory section) we obtained the following estimates for $\bar{r}_{Cu}$ and $\bar{r}_{St}$:

– for low-level clouds: at $A_{\rm s} = 0.0$, $\bar{r}_{Cu} = \bar{r}_{St} \approx 1.1 \mp 0.06$; and at $A_{\rm s} = 0.4$, $\bar{r}_{Cu} = 1.34 \mp 0.34$, $\bar{r}_{St} = 1.21 \mp 0.19$;

– for mid-level clouds: at $A_{\rm s} = 0.0$, $\bar{r}_{Cu} = \bar{r}_{St} \approx 0.98 \mp 0.1$; and at $A_{\rm s} = 0.4$, $\bar{r}_{Cu} = 1.07 \mp 0.39$, $\bar{r}_{St} = 0.95 \mp 0.21$.

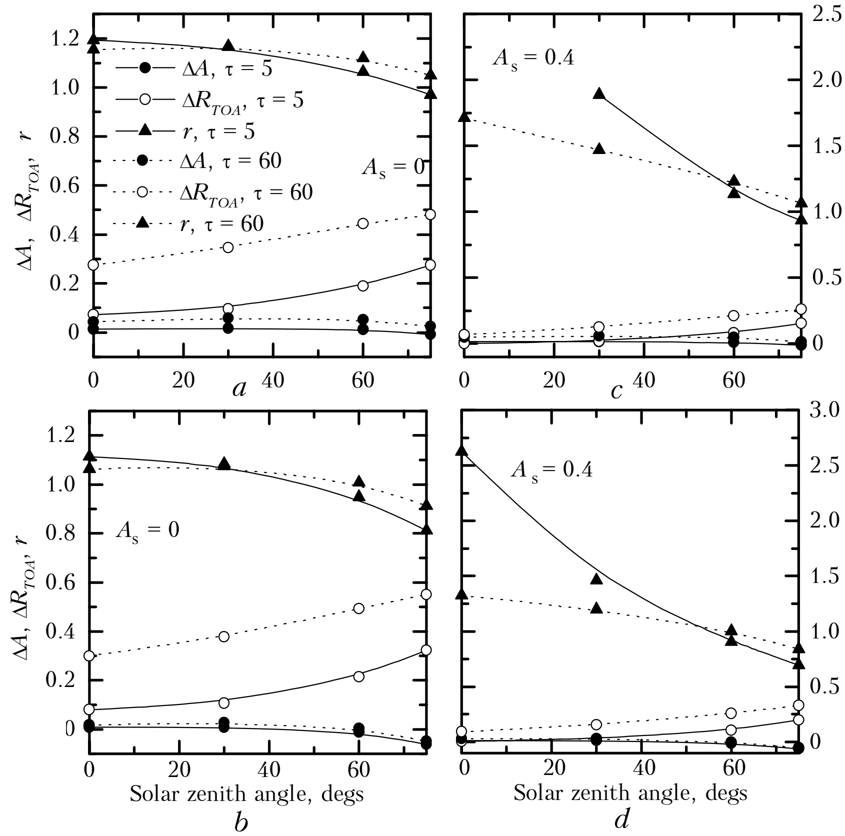

FIG. 1. Variability of ΔA and ΔR_{TOA} and the ratio of radiative forcings r in (a, c) low- and (b, d) mid-level cumulus clouds for $\gamma = 2$, $N = 0.5$, and different values of surface albedo A_s and cloud optical thickness.

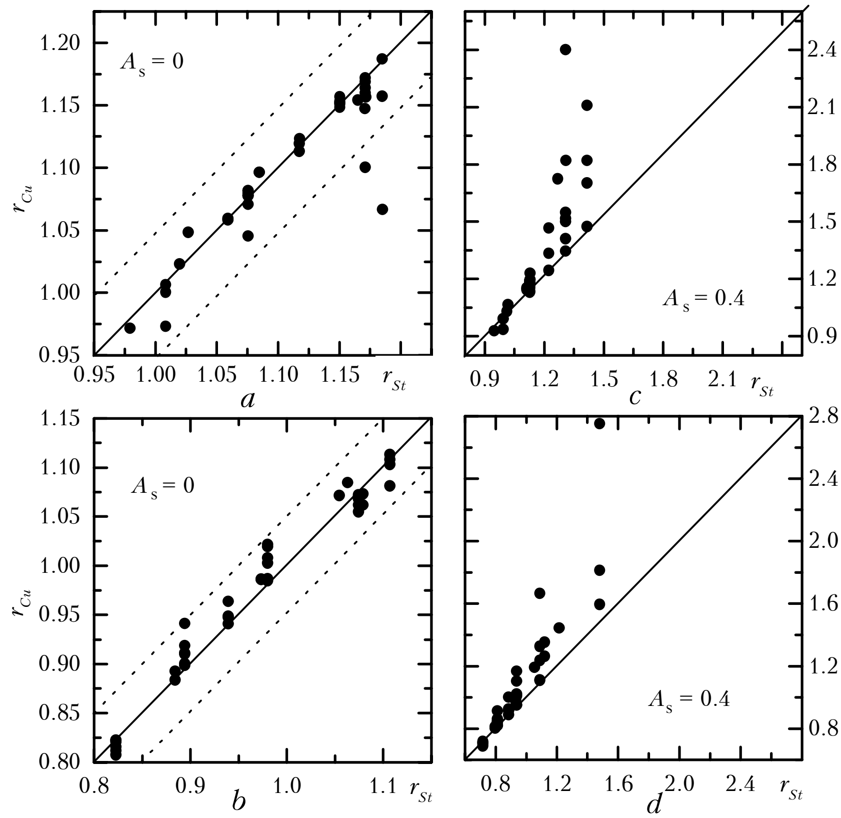

FIG. 2. Ratio of the radiative forcings in (a, c) low- and (b, d) mid-level cumulus and stratus clouds for different values of the surface albedo A_s.

From these results it follows that:

– as cloud top height increases, the ratio of radiative forcings decreases. This is consistent with results presented in Refs. 2 and 3;

– in low-level clouds, $\overline{r}$ is an increasing function of A_s; in mid-level clouds, the dependence of $\overline{r}$ on A_s is determined by cloud type: as A_s grows in the range $0 \le A_s \le 0.4$, $\overline{r}_{Cu}$ increases in cumulus and slightly decreases in stratus;

– at $A_s = 0.0$, the effects of cloud random geometry has little influence on r, so that $\overline{r}_{Cu} = \overline{r}_{St}$ over a wide range of the input model parameters. As surface albedo increases, $\overline{r}_{Cu}$ tends to exceed $\overline{r}_{St}$, however, by insignificant value $\Delta\overline{r} = \overline{r}_{Cu} - \overline{r}_{St}$, e.g., at $A_s=0.4$, $\Delta\overline{r}=0.13$ for both low- and mid-level clouds.

Similar results were obtained in Ref. 2, where the hypothesis is checked on the influence of cloud morphology on the ratio of radiative forcings. (Such a hypothesis has certain grounds: convective clouds in the tropics and mid-latitude stratiform clouds are most strongly influencing the radiation budget at the *TOA* level.) Daily mean ratios of the radiative forcings r calculated for convective and stratiform clouds differ by no more than 0.15.

3. REGRESSION APPROACH TO THE DETERMINATION OF THE RATIO BETWEEN THE RADIATIVE FORCINGS

In this section, we consider the regression approach to determining the ratio between the radiative forcings in terns of the slope s of the linear regression between *TOA* albedo R_{TOA} and the atmospheric transmittance at the surface level Q_{SFC} (Eq. (2)). In this approach, the ratio between the radiative forcings $r^{(s)}$ is a characteristic of a series of observations or a set of calculations (Fig. 3).

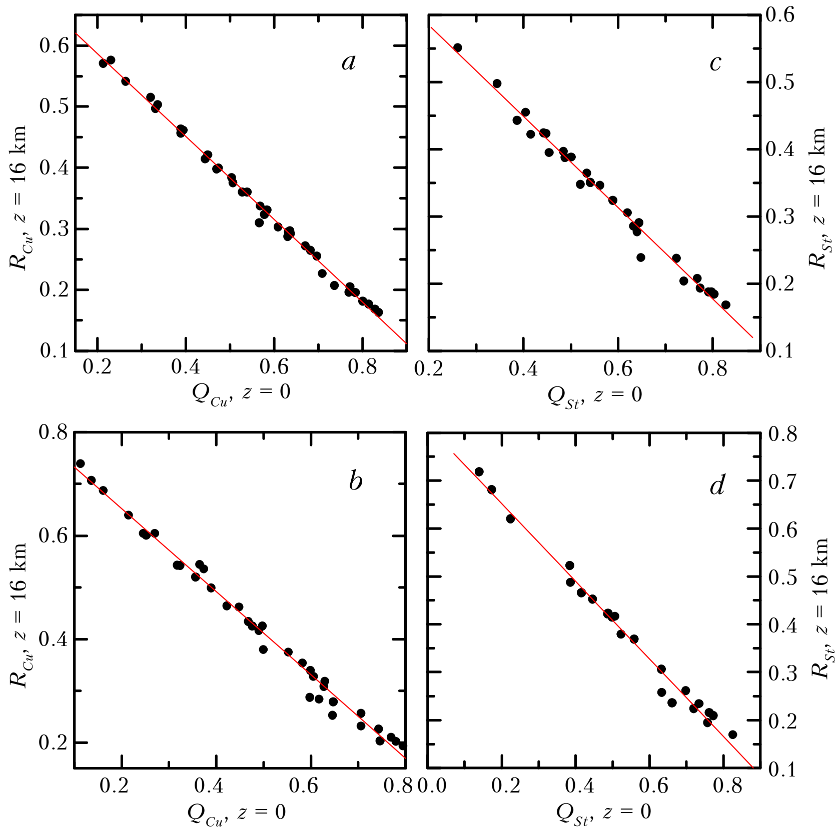

FIG. 3. TOA albedo R_{TOA} versus the atmospheric transmittance at the surface level Q_{SFC} in (a, c) low- and (b, d) mid-level cumulus and stratus clouds at $A_s = 0.2$.

Let us now consider the factors that influence s (and hence $r^{(s)}$). Table I presents s values for low- and mid-level clouds at different A_s.

From these results it follows that:

– $|s|$ increases with increasing cloud top height;. this is consistent with the results presented in Ref. 13;

– $|s|$ decreases with increasing surface albedo in accordance with the model results[2];

– the effects caused by cloud field stochastic geometry have little influence on the slope of the linear regression between R_{TOA} and Q_{SFC} and, consequently, on the ratio of the radiative forcings calculated from Eq. (2).

TABLE I. The slope s of the linear regression between R_{TOA} and Q_{SFC} for low- and mid-level clouds.

Cloud position in the atmosphere	$A_s = 0$		$A_s = 0.2$		$A_s = 0.4$	
	Cu	*St*	*Cu*	*St*	*Cu*	*St*
Low level	−0.87	−0.87	−0.68	−0.68	−0.48	−0.48
Mid-level	−1.0	−0.99	−0.81	−0.81	−0.62	−0.62

4. RATIO BETWEEN THE RADIATIVE FORCINGS AS A MEASURE OF CLOUD ABSORPTION

In the previous sections, we have demonstrated how strongly does the ratio of radiative forcings depend on variations of the cloud top height and surface albedo, as well as on the effects of cloud random geometry. However, the utility of this parameter as a measure of cloud absorption remains unclear.

Researchers have different views on this subject. For instance, Refs. 1 and 8 take r as given by Eq. (3) with the physical meaning which is as follows. If absorption in the cloudy atmosphere $A^{\mathrm{all}}_{\mathrm{atm}}$, coincides with the clear-sky value $A^{\mathrm{clr}}_{\mathrm{atm}}$, i.e., $\Delta A = 0$, then $r = 1$. Otherwise, if $A^{\mathrm{all}}_{\mathrm{atm}} > A^{\mathrm{clr}}_{\mathrm{atm}}$, then $r > 1$, which in other words means that occurrence of clouds increases the atmospheric absorption relative to the clear-sky value. Hence, the ratio between the radiative forcings is thought of as a direct measure of changes in the atmospheric absorption due to clouds. Unlike, Ref. 2 suggests that the ratio between the radiative forcings is affected by many factors more than just the clouds.

Now consider the relationships between ΔA and r calculated from Eq. (1) for cumulus and stratus clouds at $A_s = 0$ (Fig. 4). Obviously, these parameters are not uniquely related. For instance, two cloud cover cases, case A (with $\xi_{\odot} = 0$, $N = 0.5$, $\gamma = 2$, and $\tau = 5$) and case B (with $\xi_{\odot} = 75°$, $N = 0.5$, $\gamma = 2$, and $\tau = 30$), while both having $\Delta A \approx 1\%$, differ in r value: $r = 1.19$ and $r = 1.02$ (points A and B in Fig. 4=). This difference is caused by the fact that $\Delta R_{TOA} = 0.072$ in case the A, and $\Delta R_{TOA} = 0.442$ in the case B.

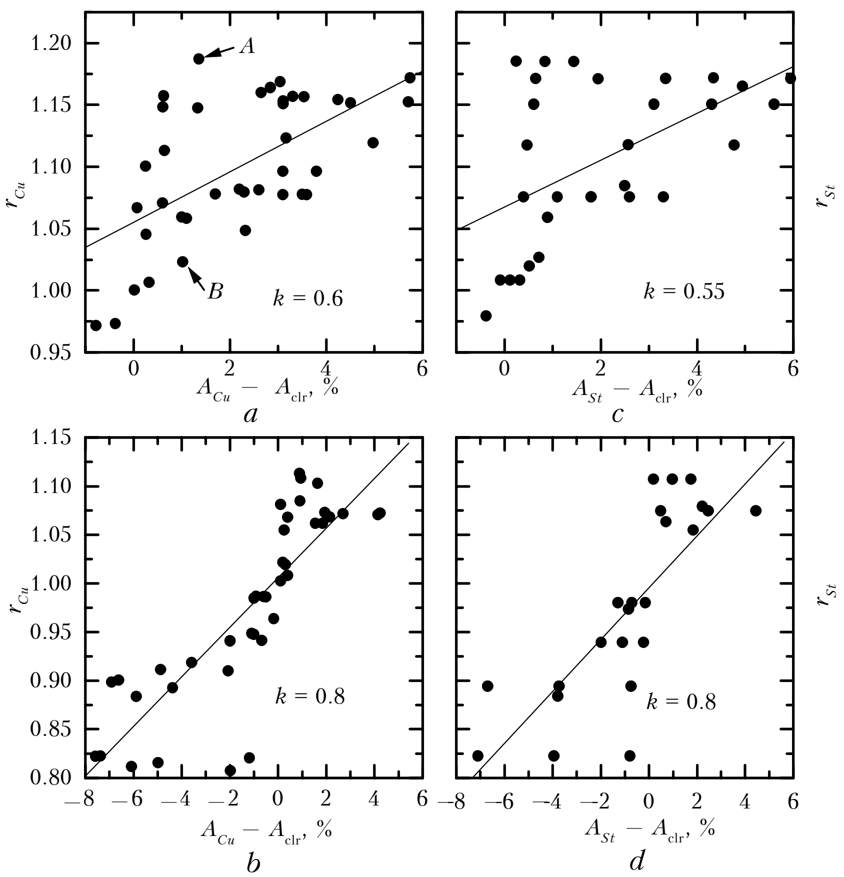

FIG. 4. Ratio between the radiative forcings versus absorption variability ΔA in (a, c) low- and (b, d) mid-level cumulus and stratus clouds at $A_s = 0$.

At $A_s = 0$, the coefficients of linear correlation k between ΔA and r are:

– $k^{\mathrm{low},\,Cu} \approx k^{\mathrm{low},St} \approx 0.6$ for the low level;

– $k^{\mathrm{mid},Cu} \approx k^{\mathrm{mid},St} \approx 0.8$ for the upper level.

If cases of cloud cover, where r increases due to the albedo effect, are omitted, then for low-level clouds the correlation coefficient between r and ΔA increases:

$k^{low,Cu} \approx k^{low,St} \approx 0.7$. (For the mid-level clouds this increase is less significant.) As A_s increases, the linear correlation coefficients decrease, especially for cumulus clouds; and at $A_s = 0.4$ they are:

– $k^{low,Cu} = 0.4$, $k^{low,St} = 0.5$ at the low level;
– $k^{mid,Cu} = 0.6$, $k^{mid,St} = 0.7$ at the high level.

TABLE II. Ratio between the radiative forcings calculated using different approaches to their determination (Eqs. (1) and (2)) and mean variations of the atmospheric absorption $\Delta\bar{A}$.

r, $r^{(s)}$, ΔA	Low-level				Mid-level			
	$A_s = 0$		$A_s = 0.4$		$A_s = 0$		$A_s = 0.4$	
	Cu	*St*	*Cu*	*St*	*Cu*	*St*	*Cu*	*St*
Eq. (1) $\bar{r}$	1.1 ∓ 0.06	1.1 ∓ 0.06	1.34 ∓ 0.34	1.21 ∓ 0.19	0.98 ∓ 0.1	0.98 ∓ 0.1	1.07 ∓ 0.39	0.95 ∓ 0.21
Eq. (1) $r^{(s)}$	1.15	1.15	1.25	1.25	1	1	0.97	0.97
$\Delta\bar{A}$, %	2.21	2.12	2.34	1.94	– 1.17	– 0.95	– 1.1	– 1.3

Thus, one of the reasons for relatively weak correlation between r and ΔA in some cloud cases is the albedo effect.

Let us now discuss the question on how exactly *the mean value of the radiative forcings* quantifies *the mean change in the absorption* when passing from clear-sky to cloudy conditions ($\Delta\bar{A}$). To do this, we will compare $\bar{r}$ (Eq. (1)), $r^{(s)}$ (Eq. (2)), and $\Delta\bar{A}$ (Table II). This would also enable us to estimate how adequate are the approaches to determination of the cloud radiative forcings discussed above when describing changes in the atmospheric absorption.

From the results presented in Table II it follows that $\Delta\bar{A}$ is primarily determined by the cloud top height, and it only weakly depends on the cloud type and surface albedo. For the low-level clouds, $\Delta\bar{A} > 0$, that is, occurrence of low-level clouds, on average, increases the atmospheric absorption relative to that under clear-sky conditions. Conversely, an increase in the cloud top height to $H^t_{cl} = 7$ km leads to a reverse effect.

How closely do $r^{(s)}$ and $\bar{r}$ reflect these dependences? The ratio between the radiative forcings determined within the regression approach from Eq. (2) matches quite closely the mean variations of the absorption. In particular, (1) $r^{(s)}$ does not depend on the cloud type; and (2) $r^{(s)}$ value is quite certainly related to the cloud top height: $r^{(s)} > 1$ for low- and $r^{(s)} \le 1$ for mid-level clouds.

The average $\bar{r}$ calculated from Eq. (1) qualitatively and quantitatively coincides with $r^{(s)}$ for stratus clouds. Good agreement between $\bar{r}$ and $r^{(s)}$ also takes place for cumulus clouds at $A_s = 0.0$. This means that, in these cases, $\bar{r}$, as well as $r^{(s)}$, reasonably well describes the mean variability of the absorption $\Delta\bar{A}$. As A_s grows, $\bar{r}$ becomes more sensitive to cloud type, and at $A_s = 0.4$ the inequality $\bar{r} > r^{(s)}$ holds true for cumulus clouds. However, the inequalities $\bar{r} > 1$ and $r^{(s)} > 1$ hold for low-level clouds, for the mid-level clouds the situation is quite opposite, that means that $r^{(s)} < 1 < \bar{r}$ in that case. Note that $\Delta\bar{A}_{Cu} < 0$ in this case; so the use of Eq. (1) to calculate *CRF* can lead to an erroneous conclusion that, on the average, mid-level cumulus favor an increase in the atmospheric absorption compared to that under clear-sky conditions. However in reality, it is most likely, that increased $\bar{r}$ value is just the consequence of the albedo effect. It is expected that the omission of cloud cases where albedo effect is most pronounced can bring $\bar{r}$ and $r^{(s)}$ into closer agreement and, thereby, establish unambiguous relation between the mean radiative forcing and mean variability of the atmospheric absorption.

5. CONCLUSION

In this paper, two approaches have been used to study the ratio between the radiative forcings in the short-wave spectral range. It is shown that when Eq. (1) is used to calculate r, the ratio between the radiative forcings for individual cloud cases depends not only on the absorption variability $\Delta A = A^{all} - A^{clr}$, but also on the variations of TOA albedo $\Delta R_{TOA} = R^{all}_{TOA} - R^{clr}_{TOA}$. In this regard, an increase in r may be caused not so much by the increase in ΔA, but by the albedo effect to a greater extent, i.e., by ΔR_{TOA} decrease due to A_s increase at $\xi_\odot \le 30°$ and small cloud fractions and (or) small cloud optical thickness. This leads to the fact that r and ΔA are not uniquely related, and the coefficient of linear correlation between those is ≈ 0.6 for the low- and ≈0.8 for the mid-level clouds at $A_s = 0.0$ and even smaller for larger A_s.

It is found that, at $A_s \le 0.2$, the ratio between the radiative forcings weakly depends on the cloud type ($|r_{Cu} - r_{St}| \le 0.1$); however, as A_s increases, the range of r values becomes wider, so that r_{Cu} and r_{St} may differ by as much as tens of per cent. The ratio between the radiative forcings decreases with increasing cloud top height. When averaged over the entire set of optical and geometrical cloud characteristics (under assumption that all cloud cases are equally probable), r dependence on the cloud type weakens, so that $|\bar{r}_{Cu} - \bar{r}_{St}| \approx 0.15$ at $A_s = 0.4$. Thus, while the effects caused by random cloud geometry are essential in calculations using Eq. (1), on the average, it is insufficiently strong to suggest that model calculations of r disagree with the experimental estimates due to the neglect of the stochastic structure of actual clouds.

Another approach to the determination of the ratio between the radiative forcings is to estimate the slope of the linear regression between albedo R_{TOA} and the transmittance Q_{SFC}, and to calculate $r^{(s)}$ from Eq. (2). When $0.0 \le A_s \le 0.4$, $r^{(s)}$ is inversely proportional to the cloud top height and only weakly depends on cloud type.

It is shown that $\bar{r}$ and $r^{(s)}$ quite closely coincide, at any A_S in stratus and at $A_s \le 0.2$ in cumulus. In these cases, $\bar{r}$ and $r^{(s)}$ provide for a qualitatively correct description of the mean change in atmospheric absorption $\Delta\bar{A}$ due to the cloud occurrence in the clear-sky atmosphere: $\bar{r} > 1$ and $r^{(s)} > 1$ values corresponds, on the average, to an increase in the atmospheric absorption $\Delta\bar{A} > 0$, whereas $\bar{r} \le 1$ and $r^{(s)} \le 1$ values are associated with $\Delta\bar{A} \approx -1\%$, an indication of a slight decrease (or constancy, in view of the smallness of $\Delta\bar{A}$) of the atmospheric absorption below the clear-sky value due to the cloud occurrence. At $A_s = 0.4$ $\bar{r}$ and $r^{(s)}$ in mid-level cumulus are related by the inequality $r^{(s)} < 1 < \bar{r}$, whereas $\Delta\bar{A} \approx -1\%$. The $\bar{r}$ value, overestimated due to the albedo effect at the cloud top level, incorrectly describes the mean variability of the atmospheric absorption. The ratio between the radiative forcings is thus unacceptable as an unambiguous measure of the short-wave absorption by clouds and, hence, the discrepancy between theoretical and experimental r values cannot be directly related to the anomalous cloud absorption problem.

REFERENCES

1. R.D. Cess, M.H. Zhang, P. Minnis, et al., Science **267**, 496–499 (1995).
2. Z. Li, H.W. Barker, and L. Moreau, Nature **376**, 486–490 (1995).
3. V. Ramanathan, B. Subasilar, G. Zhang, et al., Science **267**, 499–503 (1995).
4. P. Pilewskie and F. Valero, Science **267**, 1626–1629 (1995).
5. K.Ya. Kondratiev, V.I. Binenko, and I.N. Mel'nikova, Meteorol. Gidrol., No. 2, 14–23 (1996).
6. G.L. Stephens, R.D. Cess, M.H. Zhang, P. Pilewskie, and F. Valero, Science **271**, 1131–1136 (1996).
7. T.B. Zhuravleva, Atmos. Oceanic Opt. **11**, No. 8, 730–736 (1998).
8. D. Lubin, J.-P. Chen, P. Pilewskie, V. Ramanathan, and F. Valero, J. Geophys. Res. **101**, No. D12, 16961–16972 (1996).
9. R.N. Byrne, R. Somerville, and B. Subasilar, J. Atmos. Sci. **53**, No. 6, 878–886 (1996).
10. F. Malvagi, R.N. Byrne, G.C. Pomraning, and R. Somerville, J. Atmos. Sci. **50**, 2146–2158 (1993).
11. G.A. Titov, Izv. Ros. Akad. Nauk, Fiz. Atmos. Okeana **20**, No. 5, 1372–1378 (1984).
12. G.A. Titov and T.B. Zhuravleva, Atmos Oceanic Opt. **8**, No. 10, 767–771 (1995).
13. J.Schmetz, J. Atmos. Sci. **50**, No. 8, 1122–1132 (1993).