NAGW-3150

NASA-CR-204604

Reprinted from the preprint volume of the Seventh Symposium on Global Change Studies, 28 January - 2 February 1996, Atlanta, GA by the American Meteorological Society, Boston, MA

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SOLAR ABSORPTION IN CLOUDY ATMOSPHERES

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1. INTRODUCTION

Water in all three phases absorbs a significant amount of solar energy in the near-infrared at wavenumbers less than about 18,000 cm^{-1}. Vapor absorption is thought to be well quantified (Rothman et al. 1983), at least as far as absorption lines are concerned. There may, however, be some as yet uncertain continuum absorption (Stephens and Tsay 1990). The bulk absorption properties of liquid water are also thought to be reasonably certain (Irvine and Pollack 1968, Hale and Querry 1973, Palmer and Williams 1974, Downing and Williams 1975). Standard Mie theory then provides the single scattering properties of liquid water clouds of a prescribed size distribution (King et al. 1990).

With the above information on vapor and droplet absorption, it is then possible to obtain theoretical estimates of the spectral and band averaged radiative properties of cloud layers and atmospheric columns containing clouds, at least under the assumption that the clouds are plane parallel and homogeneous. However, there is a long history of apparent discrepancies between theoretically obtained cloud radiative properties in the near-infrared and values inferred from measurements (Twomey and Cocks 1982, Stephens and Tsay 1990). Invariably, the measurements have implied that clouds, or cloudy atmospheres, absorb more solar radiation than indicated by computations based on the known properties.

Recent results have piqued renewed interest in this problem. King et al. (1990) have made in situ measurements of the radiation field within thick cloud layers and inferred the single scattering albedos of water clouds in the near-infrared water vapor windows. Their measurements agree quite well with theoretical calculations. It is, therefore, quite surprising that instances of solar absorption well in excess of theory continue to be reported. Cess et al. (1995) analyzed top-of-the-atmosphere and surface broadband shortwave radiation budgets to show that the atmosphere, in the global mean, absorbs 25 Wm^{-2} more solar radiation than is currently modeled based on theory. Ramanathan et al. (1995) have shown that an additional contribution by clouds to atmospheric absorption is necessary to balance the energy budget in the Pacific Ocean warm pool region. Pilewskie and Valero (1995) inferred cloud absorption from identical broad band instruments flown on aircraft flying in a stacked formation above and below cloud layers during TOGA-COARE and CEPEX (both Pacific Ocean experiments). Their conclusion was also that cloudy layers absorb more radiation than is anticipated by theory.

These last three studies have expressed cloudy sky absorption in terms of the cloud radiative forcing of the atmosphere which is the contribution due to the clouds alone (Charlock and Ramanathan 1985) and have all used broadband measurements. Earlier spectral measurements (Twomey and Cocks 1982, Stephens and Platt 1987, Foot 1988) have also led to the conclusion that theoretical reflectances are much higher than observed values in the near-infrared windows where cloud properties dominate column reflectance and absorption. In light of this accumulating evidence that inferred cloud absorption, based on both spectral and broadband measurements, differs significantly from theory, it is perhaps appropriate to revisit the problem of spectral absorption of solar radiation in cloudy atmospheres. The theoretical computations that have been used to compute spectral absorption are discussed in Section 2. Radiative properties relevant to the cloud absorption problem are presented in Section 3 and are placed in the context of radiative forcing in Section 4. Implications for future measuring programs and the effect of horizontal inhomogeneities are discussed in the summary Section 5.

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2. THEORETICAL COMPUTATIONS

Water vapor and liquid do not absorb at visible wavelengths and measurements have shown that there is no indication of an inordinate amount of foreign absorption (aerosols, say) at shorter wavelengths (Twomey and Cocks 1982, Stephens and Platt 1987). In any case, it is unlikely that any foreign matter would be pervasive and present in all clouds at all levels. Interest is therefore focused on the solar near-infrared. In this spectral region, the atmospheric column absorption in the presence of clouds is dictated by a subtle interplay between vapor and liquid absorption and scattering. Although both vapor and liquid absorb at these wavelengths, there are highly transparent windows in the vapor absorption spectrum whereas the liquid absorption is quite smeared out with only local maxima and minima. Moreover, the water vapor band centers are so optically thick that a significant portion of the spectrum can become completely saturated with only modest water vapor path lengths. A result of these characteristics is that column absorption is sensitive to the placement of the cloud in the atmosphere (Chou 1989, Schmetz 1993).

A very thorough investigation of spectral solar absorption was carried out by Davies et al. (1984) who showed the importance of above cloud vapor and the distribution of column absorption among cloud water vapor, cloud droplets, and column vapor. In particular, they showed that for low clouds, vapor absorption within the cloud where scattering is expected to increase the effective path length, is negligible at low wavenumbers due to strong absorption above the cloud and becomes significant at the higher wavenumbers.

Since that study, there have been several calculations of radiative fluxes in cloudy and clear atmospheres under the aegis of the Intercomparison of Radiation Codes in Climate Models (ICRCCM). The shortwave portion of this effort has been summarized in Fouquart et al. (1991). Here we report on an extensive set of near-exact computations carried out for ICRCCM by Ramaswamy and Freidenreich (1991). Two cloud types were used, CS and CL, the main difference being the larger size drops in the CL distribution. The CL clouds are therefore more absorbing than the CS clouds. Optical depths of 1, 10, and 100 were used and two solar zenith angles, 30° and 75.7°. A high cloud layer from 180-200 mb and a low layer from 800-900 mb were inserted in a standard midlatitude summer atmospheric profile (McClatchey et al. 1972). The water vapor mixing ratio was increased to the saturated value in the cloud layers. No other gases apart from water vapor were included. Therefore the effects of O_3, O_2 and CO_2 are not considered. This is not a serious shortcoming since we shall be concentrating on spectral features outside the range of these gases. The surface is assumed to be perfectly absorbing.

3. SPECTRAL COLUMN RADIATIVE HEATING

Although computations for several combinations of cloud type, optical depth, solar zenith angle and cloud location are available, here we will show a selection of results that illustrate the main features of solar near-infrared radiative properties of cloudy columns. The results shown will be for an optical depth of 10. Conclusions drawn from this set are mostly valid for the thinner and thicker cases but exceptions will be noted as warranted.

The analyses of Cess et al. (1995) and Ramanathan et al. (1995) show that the column absorption in the presence of clouds is in excess of theoretical expectations. We will therefore examine column properties and ultimately frame the results in terms of a cloud forcing of the entire atmospheric column.

The total spectral absorption in the atmospheric column for clear skies is dominated by the various near-infrared water vapor bands. The addition of a cloud layer modifies the column heating but in a manner that depends on the cloud properties and more importantly on the location of the cloud layer. Figs. 1(a)-(d) show the incident, clear sky and cloudy sky column absorption for the four cases identified in the

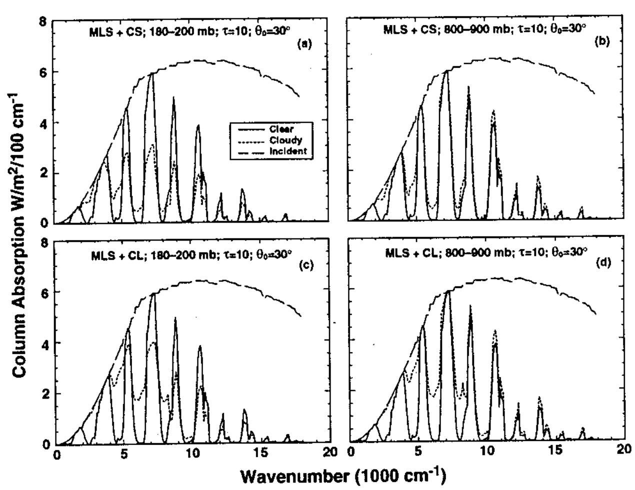

Figure 1. Column absorption for the standard midlatitude summer atmosphere and embedded (a) CS cloud between 180-200 mb, (b) CS cloud between 800-900 mb, (c) CL cloud between 180-200 mb, (d) CL cloud between 800-900 mb. Optical depth is 10.0 for all cases and the solar zenith angle is 30°.

figures. The results are 100 cm^{-1} degraded resolution plots based on the near-exact calculations mentioned previously for an optical depth of 10 and solar zenith angle of 30°. The same incident and clear sky absorption are shown in the four panels. The strong vapor absorption features and well defined windows are evident in the clear sky results. For the mid-latitude summer atmosphere used here, some of the band centers are completely saturated but an important point to note is that the windows are exceedingly transparent, even at the smallest wavenumbers that contain appreciable solar energy. This feature has important implications for the cloud forcing.

The insertion of a moderately thick cloud at high altitudes has two effects as seen from Figs. 1(a) and 1(c). The column absorption in the vapor bands is diminished considerably because of the reflection of solar energy at these wavenumbers since solar energy is reflected above the regions of substantial water vapor, this energy is not available for absorption by the vapor bands. Also the absorption in the vapor windows increases since droplets absorb in a continuum manner across the spectrum. When the same cloud is inserted at a low level in the atmosphere, the response is decidedly different. There is still an increase in absorption in the windows of roughly comparable magnitude but there is no compensating decrease in band center absorption. In fact, at the larger wavenumbers in the unsaturated bands, there is an increase in absorption resulting from enhanced within-cloud absorption and also absorption of reflected solar energy by overlying vapor. Comparison of the corresponding CS and CL cases indicates that the primary effect of enhanced droplet absorption is a significant increase in window absorption for both the low and high cloud cases. The absorption in the band center regions is essentially unchanged.

The net effect of placing a cloud layer for the entire near-infrared spectrum, both spectrally and integrated over the 0-18,000 cm^{-1} region is shown in Figs. 2(a)-(b) which are difference plots corresponding to Figs. 1(a)-(d). The quantity plotted is the column spectral cloud radiative forcing for complete overcast. Figs. 2(a) and (b) separately now show the influence of droplet absorption. For the high cloud, positive differences correspond to enhanced window absorption and negative differences to diminished band center absorption. Overall, for the CS cloud, the integrated effect is a reduction of column absorption whereas for the CL cloud there is an increase. For the low cloud, the situation is quite different. There is enhanced absorption in the windows but no corresponding decrease in the band centers. The integrated forcing is positive although the magnitude does depend on the droplet absorption.

4. CLOUD RADIATIVE FORCING

As mentioned earlier, the renewed interest in cloud absorption is driven to some extent by the inferred cloud forcing based on recent analyses (Cess et al. 1995, Ramanathan et al. 1995). Here we present the cloud forcing for overcast conditions, i.e. the difference between clear and overcast net fluxes. The situation is shown schematically in Fig. 3 in which the net downward fluxes at the top of the atmosphere are

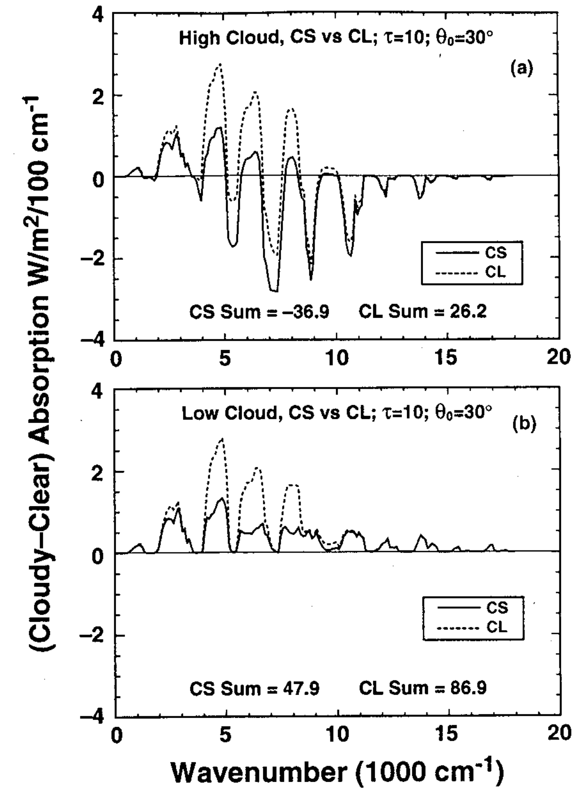

Figure 2. The difference in column absorption between overcast and clear conditions for (a) CS and CL cloud placed between 180-200 mb and (b) CS and CL cloud placed between 800-900 mb. The integrated difference from 0-18,000 cm^{-1} for both CS and CL clouds is also marked on the figure.

$$F_{NL}^{TOA} = F_{DL}^{TOA} - F_{UL}^{TOA} \qquad (1)$$

for clear sky conditions and

$$F_{NC}^{TOA} = F_{DC}^{TOA} - F_{UC}^{TOA} \qquad (2)$$

for overcast conditions where suffixes U, D and N stand for upward, downward and net fluxes respectively and suffixes L and C stand for clear and overcast conditions. The cloud forcing at TOA is then

$$CF^{TOA} = F_{NC}^{TOA} - F_{NL}^{TOA} \qquad (3)$$

There is a corresponding set of relations for the surface quantities. As our calculations are for zero surface albedo and the downward flux at the top is the insolation, it follows that

$$CF^{TOA} = - F_{UC}^{TOA} \quad (4)$$

and

$$CF^{SRF} = F_{DC}^{SRF} - F_{DL}^{SRF} \quad (5)$$

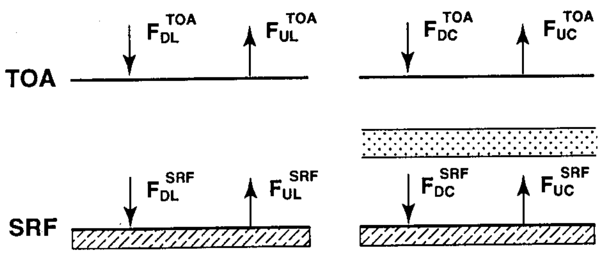

Figure 3. Schematic identifying the various upward and downward fluxes for clear and overcast conditions.

CF^{SRF} is then simply the change in transmittance to the surface with the addition of the cloud layer and F_{UC}^{TOA} is the flux reflected to space by the cloud (recall that the surface is non-reflecting). Both CF^{TOA} and CF^{SRF} are negative. It may also be shown that

$$CF^{SRF} = CF^{TOA} + A_L - A_C \quad (6)$$

where A_L and A_C are, respectively, clear sky and cloudy sky column absorption shown in Figs. 1(a)-(d). When cloudy sky atmospheric absorption exceeds the clear sky value, CF^{SRF} is more negative than CF^{TOA} and when the cloudy sky absorption is less than the clear sky value, CF^{SRF} is less negative. When $CF^{SRF} = CF^{TOA}$, the presence of the cloud layer does not alter the column absorption.

Figs. 4(a)-(d) show the surface and TOA forcing for overcast conditions. Comparison of Figs. 4(a) and 4(b) for high and low clouds, respectively shows the extreme sensitivity of CF^{TOA} to cloud height. The surface forcing is much less sensitive. The spectral response is quite different in the vapor windows and the band centers.

For high clouds, there is a substantial forcing at the top of the atmosphere in the band center region as well as the windows, i.e., the reflection by the cloud layer affects the entire spectrum. The surface forcing in the windows is more negative as a result of droplet absorption. However, in the band centers, the surface forcing is less negative implying a decrease in column absorption. This is because energy that would have been absorbed in the lower troposphere is now reflected back to space.

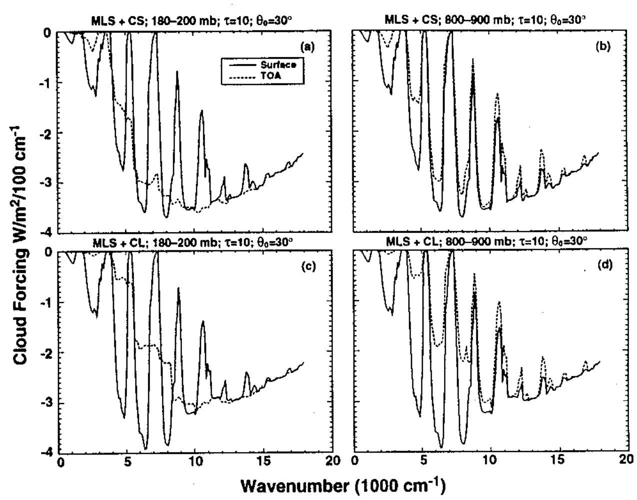

Figure 4. Spectral cloud forcing for overcast conditions at both the surface (solid) and top-of-the-atmosphere (dashed). The cloud conditions are as in Fig. 1.

For low clouds, the forcing is primarily confined to the windows and the region of weak absorption at wavenumbers larger than 12,000 cm^{-1}. In the windows, as for high clouds, the surface forcing is more negative and this is also true for the band centers of the weaker bands. In these spectral regions, there is droplet absorption and enhanced vapor absorption through the increase in path length within the cloud and the absorption of reflected energy by vapor above the cloud. The strong band centers are saturated so both the surface and TOA forcing are essentially zero. This is a major difference between high and low clouds. Whereas for high clouds there is a reduction in column absorption in the band centers, this is not so for low clouds, and in all spectral regions, the surface forcing is more negative than the TOA forcing.

The relative magnitudes of CF^{SRF} and CF^{TOA} are best illustrated by presenting the ratio

$$R = CF^{SRF}/CF^{TOA}. \quad (7)$$

Cess et al. (1995) have used the spectrally integrated value of R to examine cloud absorption. Here we present the spectral variation of R in Figs. 5(a)-(d). From Eq. (6) it is evident that R = 1.0 implies no change in column absorption with the addition of a cloud layer. Values of R > 1.0 indicate an increase in atmospheric absorption and R < 1.0 indicates a loss. Also marked on the plots is the spectrally integrated value of R integrated from 0-18,000 cm^{-1}. The integrated value is not directly comparable to the values quoted in Cess et al. (1995) since it does not include the effect of ozone absorption at larger wavenumbers. However, it does indicate the change in column absorption in the near-infrared.

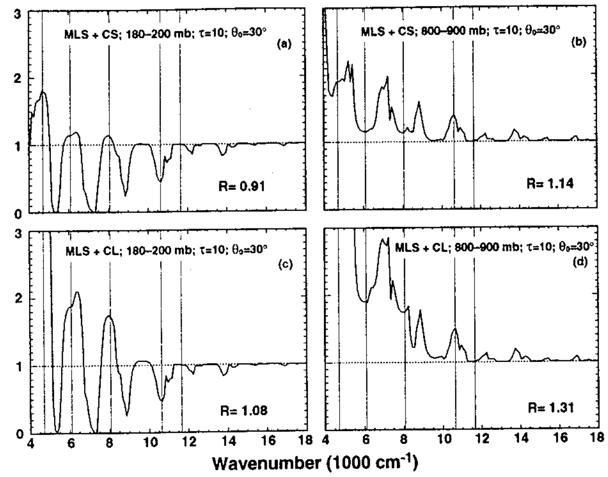

Figure 5. Ratio of the cloud forcing at the surface and top-of-the-atmosphere. MODIS channels are marked for reference. The cloud conditions are as in Fig. 1. The cloud forcing ratio integrated from 0-18,000 cm^{-1} is also marked on the figures.

The influence of cloud height is now dramatically evident. For high clouds, R is much less than 1.0 in the band centers and somewhat greater than 1.0 in the window regions. It is close to 1.0 at wavenumbers larger than 12,000 cm^{-1} where droplet absorption is quite modest. The spectrally integrated value shows this compensation and the net effect is close to 1.0 implying little change in column absorption in the presence of the cloud layer.

On the other hand, for low clouds, $R \geq 1.0$ throughout the spectrum and the integrated value of the ratio exceeds 1.0. For the more absorbing cloud, this ratio is of the same order of magnitude as that presented by Cess et al. (1995) and Ramanathan et al. (1995). The significance of the spectral nature of R for measurement programs will be discussed in the next section.

The integrated effect of the spectral forcing results in a forcing through the atmospheric column that changes the heating rate profile. For high clouds, the reflection of energy high in the atmosphere results in a uniform depletion of absorbed energy below the cloud. There is, of course, additional absorption within the cloud layer. The degree of compensation is given by the integrated value of R. If $R < 1.0$, the increase in cloud layer absorption is less than the decreased absorption below the cloud layer as is the case for the high CS cloud of optical depth 10.0. When the zenith angle is greater, reflection is enhanced, and the net effect is a sharper decrease in column absorption. For instance, when the zenith angle is increased to 75.7°, the integrated R factor for the high CS cloud is 0.76 compared to $R = 0.91$ for a zenith angle of 30°.

When the cloud layer is placed low in the atmosphere, there is not only significant absorption within the cloud but also an enhancement in the vapor absorption above the cloud. This is the absorption of reflected energy at wavenumbers that still carry sufficient energy down to the level of the cloud and in which there is some vapor absorption. These are the weaker water vapor bands at larger wavenumbers. There is a depletion in below cloud absorption but the integrated effect is one of enhanced column absorption as evident from the value of R.

The effect of increased droplet absorption is felt only within the cloud. The heating rate of the cloud layer itself increases with an increase in droplet absorption. This results in a greater overall absorption and a higher value of R.

5. DISCUSSION

The results presented here suggest that a program directed towards the measurement of spectral cloud radiative forcing could help resolve some of the uncertainty in cloud absorption. Of course, these results are for horizontally homogeneous plane parallel clouds and so there will still be a degree of ambiguity in any analysis of measurements.

Near-infrared reflectance measurements have been made over clouds by Twomey and Cocks (1982), Stephens and Platt (1987), Foot (1988) and others. Reflectance measurements in the vapor windows were found to be inconsistent with plane parallel theory when the relative reflectance at several channels was considered (Twomey and Cocks 1982). They pointed to reduced reflectance or, by inference, increased absorption when compared to theory. However, King et al. (1990) have shown that window single scattering albedos of water cloud droplets agree with single scattering theory. The prevalent explanation for the discrepancy has been that plane parallel theory should not be expected to work for the typically inhomogeneous and structured clouds over which measurements were made. But the analysis of Cess et al. (1995) is still intriguing because it suggests that the integrated broad band absorption of cloudy columns exceeds theoretical estimates. The field of view of the measurements is quite extensive (several kilometers), so the implication is that areal mean absorption is in excess of theory.

One way to resolve the ambiguity to some extent is to consider simultaneous reflectance and transmission measurements such as by stacked aircraft flying above and below a cloud deck. These have recently been made by Pilewskie and Valero (1995) who again find cloud layers absorbing more than the theoretically expected broad band value. However, they do find that the discrepancy is least when clouds are more homogeneous. If such work is extended to encompass spectral measurements, then it may be possible to isolate the source of the discrepancy. In a similar experiment, Hayasaka et al. (1995) were able to make measurements of total solar (0.3-3.0 μm) and near-infrared (0.7-

3.0 μm) radiation separately. They also found excess absorption in the near-infrared but also unrealistic radiative properties. They attributed this to reflection from cloud sides and other geometrical effects, and, in fact were able to correct for these effects by ratioing visible and near-infrared measurements using the method of Ackerman and Cox (1981). A similar study by Rawlins (1989) for a field of broken clouds showed that areal mean absorption for such inhomogeneous cloud layers ranges from the clear sky value to the expected layered cloud value.

If the spectral cloud radiative forcing can be estimated by surface and TOA measurements, the sensitivity of the cloud forcing and the spectral ratio, R, shown in Figs. 5(a)-(d) can be compared with theory. Possible measurement programs in the future could involve MODIS being developed for the Earth Observing System (King et al. 1992). The R factor plot shown here (Fig. 5) also includes five selected channels from MODIS which is a 36 channel instrument. There is the potential for measuring R in the windows and band centers using channels such as shown here. For purposes of illustration, we have chosen four window channels centered at 4695, 6098, 8065 and 11,655 cm^{-1} and one channel centered on a vapor band at 10,638 cm^{-1}. The spectral R factor and column absorption can be estimated by simultaneous TOA and surface measurements. This would essentially parallel the Cess et al. (1995) effort but will be more informative since spectral quantities will be measured.

Currently, there is the opportunity to use the MODIS Airborne Simulator (MAS) which is a scanning spectrometer flown on a NASA ER-2 (Platnick et al. 1994). This instrument mimics MODIS in that it carries similar channels. Corresponding transmission measurements at the surface need to be made at the same near-infrared frequencies. The results presented in Figs. 5(a)-(d) could act as a guide for interpreting the cloud forcing. For example, the difference in forcing ratio, R, between windows and band centers could be exploited.

It will still be very difficult to isolate cloud inhomogeneities as the source of the absorption discrepancy. However, Davies et al. (1984) and Stephens (1988a,b) have shown that inhomogeneities and finite cloud effects reduce absorption and not increase it, as is required to explain the discrepancy. In the presence of inhomogeneities, the transmission increases at the expense of both reflectance and absorption. This is illustrated in Fig. 6 for a geometrically plane parallel but inhomogeneous cascade model of a stratocumulus cloud (Cahalan et al. 1994, Marshak et al. 1995). In this model, a homogeneous cloud is divided into two in each horizontal dimension and a fraction of liquid water moved from one side to the other while conserving total liquid water. This process is carried out for the sub-portions until a two-dimensional inhomogeneous distribution of liquid water is obtained which has statistical properties similar to observed stratus in FIRE (Cahalan et al. 1994). The geometrical thickness of the cloud is uniform and the domain is cyclic so there are no edge effects. The computations shown were carried out using the Monte Carlo method for a mean optical depth of 10.0 and solar zenith angle of 60°. Four single scattering albedos are presented encompassing the range encountered in the solar near-infrared. Note that the areal mean transmittance increases at the expense of both reflectance and absorptance as the cloud layer becomes more inhomogeneous.

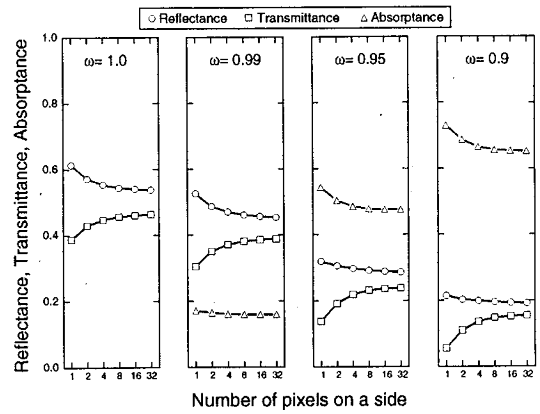

Figure 6. Areal mean transmission, reflection and absorption for three different single scattering albedos, ω, for a two-dimensional cascade model of cloud inhomogeneity. The mean optical depth is 10.0 and solar zenith angle is 60°. Each cascade creates two unequal optical depths in adjacent cells in each horizontal dimension.

The results can be framed in terms of the cloud forcing ratio, R, defined by Eq. (7). Table 1 shows the values of R_N, N = 1,2,...32, for different values of the single scattering albedo, ω, where N is the number of pixels on a side. R_1 corresponds to the forcing ratio for the homogeneous case (1 pixel on a side). It is evident that for this simple model, in which there are no edge effects, the R factor for areal mean radiative forcing is not appreciably affected by the degree of inhomogeneity. There is actually a tendency for R to decrease somewhat for the more absorbing cases.

Table 1. The ratio of the cloud radiative forcing at the surface to that at the top of the atmosphere.

ω	R_1	R_2	R_4	R_8	R_{16}	R_{32}
1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.995	1.17	1.17	1.17	1.18	1.18	1.18
0.99	1.32	1.34	1.34	1.35	1.35	1.35
0.95	2.70	2.65	2.63	2.64	2.65	2.66
0.9	4.40	4.38	4.34	4.35	4.38	4.39
0.8	8.81	8.59	8.52	8.54	8.58	8.62

Although the results presented here cannot address the difficult problem of cloud inhomogeneity, it points to the spectral regions which should be targeted for an investigation of the cloud absorption issue.

Acknowledgements: This study was supported by NASA grant NAGW-3150 and ONR contract N00014-92-K-6001.

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