

Spectral characteristics of solar near-infrared absorption in cloudy atmospheres

Harshvardhan,¹ William Ridgway,² V. Ramaswamy,³ S. M. Freidenreich,³ and Michael Batey¹

Abstract. Theoretical and experimentally derived estimates of the atmospheric absorption of solar energy in the presence of clouds have been reported to be at variance for quite a long time. A detailed set of near-monochromatic computations of the reflectance, transmittance, and absorptance of a standard midlatitude atmosphere with embedded water clouds is used to identify spectral features in the solar near-infrared that can be utilized to study this discrepancy. The results are framed in terms of the cloud radiative forcing both at the surface and at the top of the atmosphere, and it is shown that water vapor windows are the most sensitive to variations in cloud optical properties and cloud placement in the vertical. The ratio of the cloud radiative forcing at the surface to that at the top of the atmosphere, R , varies from near zero in the band centers at small wavenumbers for high clouds to ~ 1 in the band centers at larger wavenumbers for low clouds and to values in excess of 2 in the water vapor windows at small wavenumbers. The possibility of using measurements from space with the future Moderate Resolution Imaging Spectroradiometer (MODIS) and simultaneous surface measurements is discussed. It is also shown that horizontal inhomogeneities in the cloud layers do not alter appreciably the estimates of the R factor, but areal mean cloud absorption is lower for an inhomogeneous cloud having the same mean liquid water as the corresponding homogeneous cloud.

1. Introduction

Water in all three phases absorbs a significant amount of solar energy in the near-infrared at wavenumbers less than about $18,000 \text{ cm}^{-1}$. 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 atmo-

spheres, absorb more solar radiation than is 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-atmosphere and surface broadband shortwave radiation budgets to show that the atmosphere, in the global mean, absorbs 25 W m^{-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 broadband instruments flown on aircraft flying in a stacked formation above and below cloud layers during the Tropical Ocean–Global Atmosphere Coupled Ocean–Atmosphere Response Experiment (TOGA COARE) and the Central Equatorial Pacific Experiment (CEPEX) (both Pacific Ocean experiments). They also concluded 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. How-

¹Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, Indiana.

²SM&A Corporation, NASA Goddard Space Flight Center, Greenbelt, Maryland.

³NOAA Geophysical Fluid Dynamics Laboratory, Princeton, New Jersey.

ever, a more recent study of primarily broadband measurements [Francis *et al.*, 1997] has shown that for stratocumulus clouds at several locations, and for cirrus clouds over the Pacific, accepted models of condensed water absorption can explain observations. In light of this continuing debate regarding cloud absorption, based on both spectral and broadband measurements, 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 briefly in section 2 and in much greater detail by Ramaswamy and Freidenreich [1998] (hereinafter referred to as RF98). The thrust of this work, unlike RF98, is to explore remote sensing strategies that might shed light on the question of near-infrared solar absorption in cloudy atmospheres. Section 3 discusses spectral cloud forcing in the near-infrared. The effect of horizontal inhomogeneities is presented in section 4, and implications for future measuring programs are discussed in the summary in section 5.

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. We have therefore chosen to focus 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 owing to strong absorption above the cloud and becomes significant at the higher wavenumbers.

The Davies *et al.* [1984] study used a 20 cm^{-1} model for the spectral properties based on LOWTRAN5 [Kneizys *et al.*, 1980; Robertson *et al.*, 1981] and one cloud type (stratus) inserted as a 1-km-thick layer in a standard atmosphere with its top at 2 km. The detailed spectral results were presented for overhead Sun. Spectrally integrated results were also shown for varying above cloud vapor, increasing the optical thickness of the cloud and using other cloud types. They also showed the effect of solar zenith angle on the spectrally integrated absorption (total and individual contributions of vapor and droplet) and the effect of finite cloud size. 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

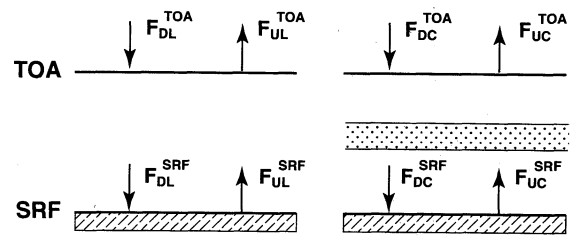


Figure 1. Schematic identifying the various upward and downward fluxes for clear and overcast conditions. Subscripts are identified in section 3.1.

portion of this effort has been summarized by Fouquart *et al.* [1991]. Here we use the results of an extensive set of near-exact computations carried out for ICRCCM by Ramaswamy and Freidenreich [1991] which are presented in RF98, to which the reader is referred for details of the computation method.

Two cloud types were used, CS and CL, the main difference being the larger size drops in the CL distribution. The single scattering drop co-albedo of the two cloud models is shown in Figure 1c of RF98. Computations were made for clouds of varying optical depths placed in selected layers of standard atmospheres with varying incident solar zenith angles. The water vapor mixing ratio was increased to the saturated value in the cloud layers. No gases other than water vapor were included. Therefore the effects of O_3 , O_2 and CO_2 are not considered. This will affect the quantitative results somewhat but not alter the main conclusions regarding cloud forcing and the choice of spectral bands for making atmospheric measurements. The spectral reflectance, surface transmittance, and column absorptance from 0 to $18,000 \text{ cm}^{-1}$ for several cases have been presented in RF98. Here we frame the results in terms of the spectral nature of the effects and measurement strategies.

3. Cloud Radiative Forcing

3.1. Spectral Forcing

As was 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]. Although cloud forcing has traditionally implied the total radiative effect of clouds, recent work has introduced the concept of spectral cloud forcing [Lubin *et al.*, 1996]. 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 Figure 1 in, which the net downward fluxes at the top of the atmosphere (TOA) are

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

for clear sky conditions and

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

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

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

There is a corresponding set of relations for the surface (SRF) quantities. The calculations presented here are for zero surface

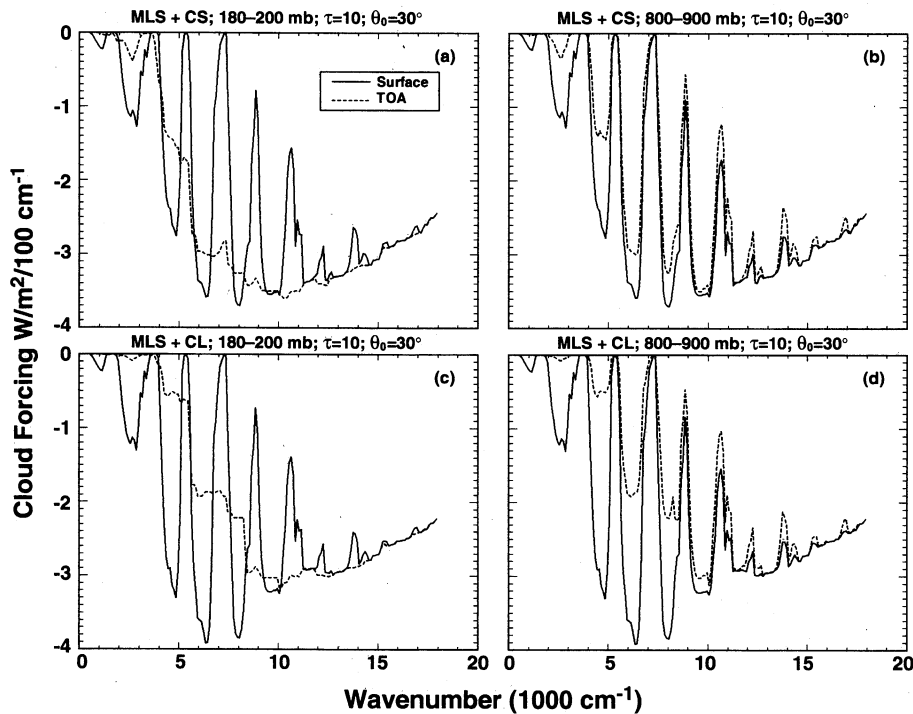


Figure 2. Spectral cloud forcing for overcast conditions at both the surface (solid) and the top of the atmosphere (dashed). (a) CS cloud between 180 and 200 mbar. (b) CS cloud between 800 and 900 mbar. (c) CL cloud between 180 and 200 mbar. (d) CL cloud between 800 and 900 mbar. Optical depth is 10.0 for all cases, and the solar zenith angle is 30° . MLS is the standard midlatitude summer atmosphere.

albedo and the downward flux at the top is the insolation. Therefore it follows that

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

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

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 nonreflecting). 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 clear sky and cloudy sky column absorption, respectively (shown, for instance, in Figure 6 of RF98). Where 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.

Figures 2a to d show the surface and TOA forcing for overcast conditions. The computations are for a CS cloud (Figures 2a and 2b) and a CL cloud (Figures 2c and 2d) inserted at two different levels in a standard midlatitude summer atmosphere [McClatchey *et al.*, 1972]. The cloud optical depth is 10.0, and the solar zenith angle is 30° . Comparison of Figures 2a and 2b, for high and low clouds, respectively, shows the extreme sensitivity of CF^{TOA} to cloud height. The surface forcing is much less sensitive. An exhaustive explanation is provided in RF98 and will not be repeated here. 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.

For low clouds the forcing is primarily confined to the windows and the region of weak absorption at wavenumbers larger than $12,000 \text{ cm}^{-1}$. 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 Figures 3a to 3d in a manner similar to Lubin *et al.* [1996]. Superimposed on the plot are the location of five selected channels on the Moderate-Resolution Imaging Spec-

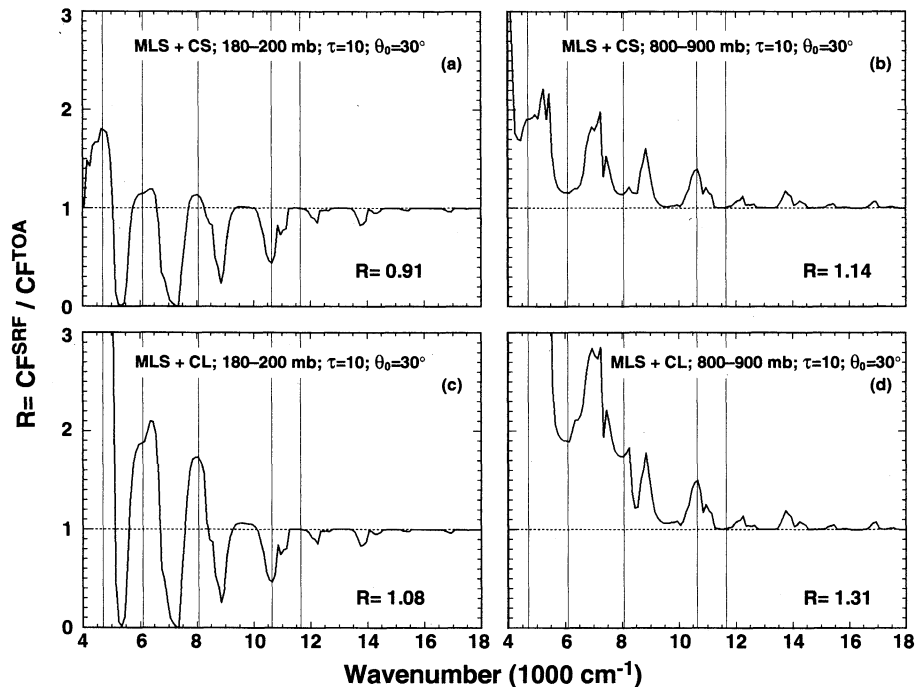


Figure 3. Ratio of the cloud forcing at the surface and top of the atmosphere. MODIS channels are marked for reference. The cloud conditions are as in Figure 2. The cloud forcing ratio integrated from 0 to 18,000 cm^{-1} is also marked on the figures.

troradiometer (MODIS) instrument planned for an Earth Observing System satellite launch in 1998 [King *et al.*, 1992]. A discussion on this aspect follows in section 5. From (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 to 18,000 cm^{-1} . The integrated value is not directly comparable to the values quoted by 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. A much more thorough discussion of the variation of the spectrally integrated ratio R is given by Li and Moreau [1996]. They present values from simulations as well as measurements from satellites and selected ground stations. Here we focus on the spectral variation only.

The influence of cloud height on the spectrally integrated ratio R was presented by Chou *et al.* [1995]. The spectral variation shown here illustrates the details that result in the net effect. 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. This points out the pivotal role of cloud reflection in the water vapor band centers. The presence of some high cloud will tend to decrease the integrated value of R . For the more absorbing cloud, the ratio R 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 section 5.

3.2. Integrated Atmospheric Forcing

The integrated effect of the spectral forcing results in a forcing through the atmospheric column that changes the heating rate profile. Figures 4a to 4d show the clear and cloudy heating rate profiles. Again, the sensitivity to cloud height is very evident. 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. Although an example is not shown here, 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 with $R = 0.91$ 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

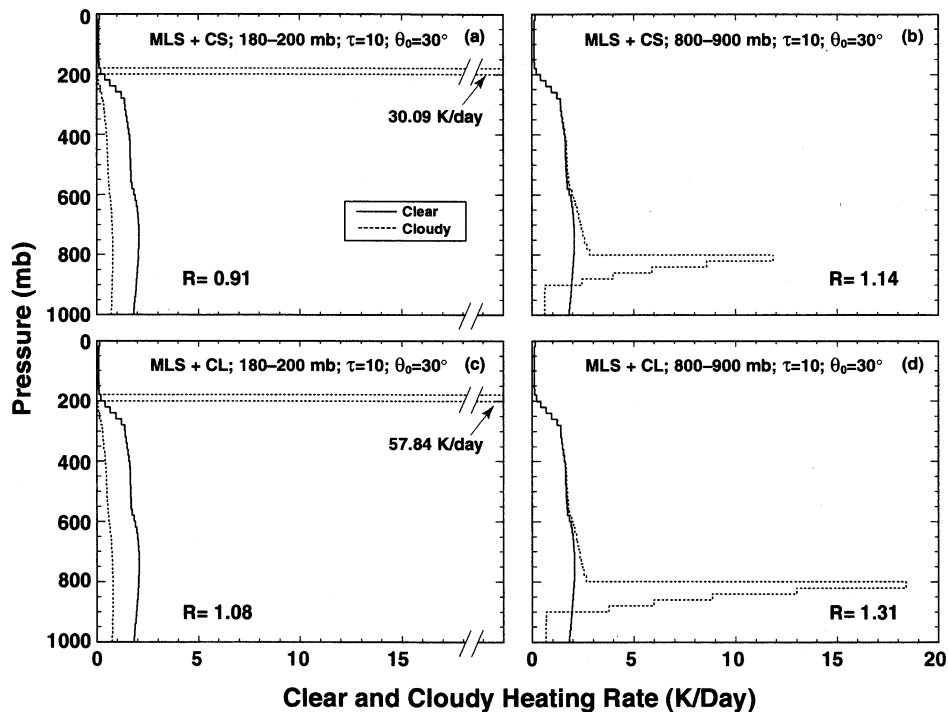


Figure 4. Heating rate profiles for clear (solid) and cloudy (dashed) conditions for the four cloud conditions given in Figure 2. The cloud forcing ratio integrated from 0 to $18,000\text{ cm}^{-1}$ is also marked on the figures.

with an increase in droplet absorption. This results in a greater overall absorption and a higher value of R .

4. Cloud Inhomogeneity

It is very difficult to isolate cloud inhomogeneities as the source of any 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 Figure 5 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 subportions until a two-dimensional, inhomogeneous distribution of liquid water is obtained which has statistical properties similar to observed stratus in the First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment (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 absorption as the cloud layer becomes more inhomogeneous.

The results can be framed in terms of the cloud forcing ratio R , defined by (7). Table 1 shows the values of R_N , $N = 1, 2, \dots, 32$, 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 (one 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.

5. Discussion

The results presented here suggest that a program directed toward 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.

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 been made by *Pilewskie and Valero* [1995], who again find cloud layers absorbing more than the theoretically expected broadband value. However, they do find that the discrepancy is least when clouds are most 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 ($0.3\text{--}3.0\ \mu\text{m}$) and near-infrared ($0.7\text{--}3.0\ \mu\text{m}$) 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

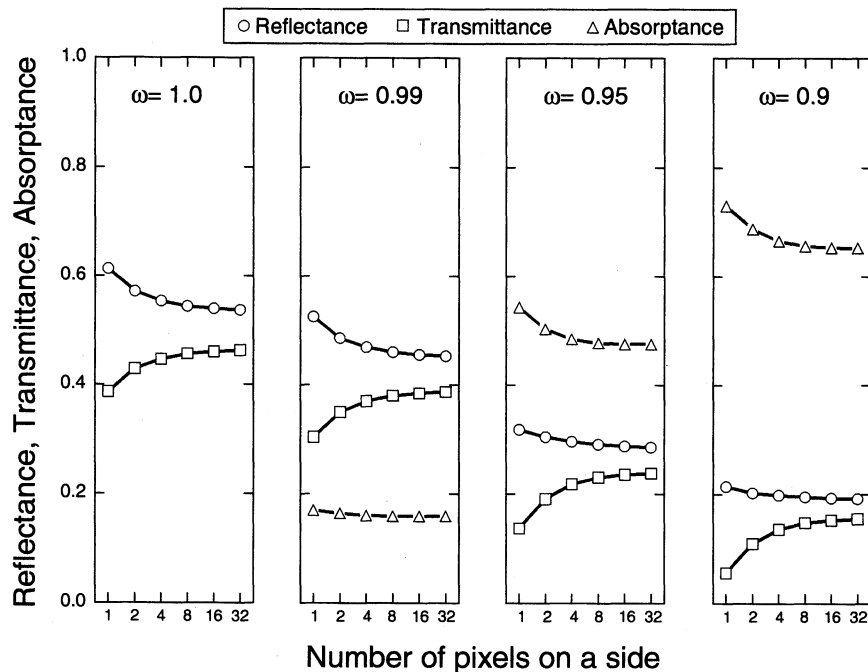


Figure 5. Areal mean transmission, reflection, and absorption for three different single-scattering albedos ω , for a two-dimensional cascade model of cloud inhomogeneity. Mean optical depth is 10.0, and solar zenith angle is 60° . Each cascade creates two unequal optical depths in adjacent cells in each horizontal dimension.

showed that areal mean absorption for such inhomogeneous cloud layers ranges from the clear sky value to the expected layered cloud value. The more recent study by *Francis et al.* [1997] for stratocumulus clouds shows results closer to plane-parallel theory. There are also vertical inhomogeneities in clouds but *Ramaswamy and Li* [1996] found little effect on the column absorption.

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 Figure 3 can be compared with theory. Possible measurement programs in the future could involve the 36-channel MODIS instrument being developed for the Earth Observing System [*King et al.*, 1992]. The reflectance, transmittance, and R factor plots shown here also include five selected channels from MODIS. 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 Figure 3 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. Although the results presented here cannot address the difficult problem of cloud inhomogeneity, they point to the spectral regions which should be targeted for an investigation of the cloud absorption issue.

Acknowledgments. This study was supported by NASA grant NAG5-3992 and ONR contract N00014-96-1-G916.

References

- Ackerman, S. A., and S. K. Cox, Aircraft observations of the shortwave fractional absorptance of non-homogeneous clouds, *J. Appl. Meteorol.*, 20, 1510–1515, 1981.
- Cahalan, R. F., W. Ridgway, W. J. Wiscombe, T. L. Bell, and J. B. Snider, The albedo of fractal stratocumulus clouds, *J. Atmos. Sci.*, 51, 2434–2455, 1994.
- Cess, R. D., et al., Absorption of solar radiation by clouds: Observations versus models, *Science*, 267, 496–499, 1995.
- Charlock, T. P., and V. Ramanathan, The albedo field and cloud radiative forcing produced by a general circulation model with internally generated cloud optics, *J. Atmos. Sci.*, 42, 1408–1429, 1985.
- Chou, M.-D., On the estimation of surface radiation using satellite data, *Theor. Appl. Clim.*, 40, 25–36, 1989.
- Chou, M.-D., A. Arking, J. Otterman, and W. L. Ridgway, The effect of clouds on atmospheric absorption of solar radiation, *Geophys. Res. Lett.*, 22, 1885–1888, 1995.

Table 1. 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

- Davies, R., W. L. Ridgway, and K.-E. Kim, Spectral absorption of solar radiation in cloudy atmospheres: A 20 cm^{-1} model, *J. Atmos. Sci.*, *41*, 2126–2137, 1984.
- Downing, H. D., and D. Williams, Optical constants of water in the infrared, *J. Geophys. Res.*, *80*, 1656–1661, 1975.
- Foot, J. S., Some observations of the optical properties of clouds, I, Stratocumulus, *Q. J. R. Meteorol. Soc.*, *114*, 129–144, 1988.
- Fouquart, Y., B. Bonnel, and V. Ramaswamy, Intercomparing short-wave radiation codes for climate studies, *J. Geophys. Res.*, *96*, 8955–8968, 1991.
- Francis, P. N., J. P. Taylor, P. Hignett, and A. Slingo, On the question of enhanced absorption of solar radiation by clouds, *Q. J. R. Meteorol. Soc.*, *123*, 419–434, 1997.
- Hale, G. M., and M. R. Querry, Optical constants of water in the 200 nm–200 μm wavelength region, *Appl. Opt.*, *12*, 555–562, 1973.
- Hayasaka, T., N. Kikuchi, and M. Tanaka, Absorption of solar radiation by stratocumulus clouds: Aircraft measurements and theoretical calculations, *J. Appl. Meteorol.*, *34*, 1047–1055, 1995.
- Irvine, W. M., and J. B. Pollack, Infrared optical properties of water and ice spheres, *Icarus*, *8*, 324–360, 1968.
- King, M. D., L. F. Radke, and P. V. Hobbs, Determination of the spectral absorption of solar radiation by marine stratocumulus clouds from airborne measurements within clouds, *J. Atmos. Sci.*, *47*, 894–907, 1990.
- King, M. D., Y. J. Kaufman, W. P. Menzel, and D. Tanré, Remote sensing of cloud, aerosol, and water vapor properties from the Moderate Resolution Imaging Spectrometer (MODIS). *IEEE Trans. Geos. Remote Sens.*, *30*, 2–27, 1992.
- Kneizys, F. X., E. P. Shettle, W. O. Gallery, J. H. Chetwynd, Jr., L. W. Abreu, J. E. A. Selby, R. W. Fenn, and R. A. McClatchey, Atmospheric transmittance/radiance: Computer code LOWTRAN 5, *Tech. Rep. AFGL-TR-80-0067*, 233 pp., Air Force Geophys. Lab., Hanscom Air Force Base, Mass., 1980.
- Li, Z., and L. Moreau, Alteration of atmospheric solar absorption by clouds: simulation and observation, *J. Appl. Meteorol.*, *35*, 653–670, 1996.
- Lubin, D., J.-P. Chen, P. Pilewskie, V. Ramanathan, and F. P. J. Valero, Microphysical examination of excess cloud absorption in the tropical atmosphere, *J. Geophys. Res.*, *101*, 16,961–16,962, 1996.
- Marshak, A., A. Davis, W. Wiscombe, and G. Titov, The verisimilitude of the independent pixel approximation used in cloud remote sensing, *Remote Sens. Environ.*, *52*, 71–78, 1995.
- McClatchey, R. A., R. W. Fenn, J. E. A. Shelby, F. E. Voltz, and J. S. Garing, Optical properties of the atmosphere, *Rep. AFCRL-72-0497*, 110 pp., Hanscom Air Force Base, Bedford, Mass., 1972.
- Palmer, K. F., and D. Williams, Optical properties of water in the near-infrared, *J. Opt. Soc. Amer.*, *64*, 1107, 1974.
- Pilewskie, P., and F. P. J. Valero, Direct observations of excess solar absorption by clouds, *Science*, *267*, 1626–1629, 1995.
- Platnick, S., M. D. King, G. T. Arnold, J. Cooper, L. E. Gumley, and S.-C. Tsay, Status and calibration of the MODIS airborne simulator for Earth remote sensing applications, *Proc. SPIE Int. Soc. Opt. Eng.*, *2317*, 91–101, 1994.
- Ramanathan, V., B. Subasilar, G. J. Zhang, W. Conant, R. D. Cess, J. T. Kiehl, H. Grassl, and L. Shi, Warm pool heat budget and shortwave cloud forcing: A missing physics?, *Science*, *267*, 499–503, 1995.
- Ramaswamy, V., and S. M. Freidenreich, Solar radiative line-by-line determination of water vapor absorption and water cloud extinction in inhomogeneous atmospheres, *J. Geophys. Res.*, *96*, 9133–9157, 1991.
- Ramaswamy, V., and S. M. Freidenreich, A high-spectral-resolution study of the near-infrared solar flux disposition in clear and overcast atmospheres, *J. Geophys. Res.*, *103*, 23,255–23,273, 1998.
- Ramaswamy, V., and J. Li, A line-by-line investigation of solar radiative effects in vertically inhomogeneous low clouds, *Q. J. R. Meteorol. Soc.*, *122*, 1873–1890, 1996.
- Rawlins, F., Aircraft measurements of the solar absorption of broken cloud fields: A case study, *Q. J. R. Meteorol. Soc.*, *115*, 365–382, 1989.
- Robertson, D. C., L. S. Bernstein, R. Haines, J. Wunderlich, and L. Vega, 5-cm^{-1} band model option to LOWTRAN 5, *Appl. Opt.*, *20*, 3218–3226, 1981.
- Rothman, L. S., R. R. Gamache, A. Barbe, A. Goldman, J. R. Gillis, L. R. Brown, R. A. Toth, J. M. Flaud, and C. Camy-Pérot, AFGL atmospheric absorption line parameter compilations: 1982 edition, *Appl. Opt.*, *22*, 2247–2256, 1983.
- Schmetz, J., Relationship between solar net radiative fluxes at the top of the atmosphere and at the surface, *J. Atmos. Sci.*, *50*, 1122–1132, 1993.
- Stephens, G. L., Radiative transfer through arbitrarily shaped optical media, I, A general method of solution, *J. Atmos. Sci.*, *45*, 1818–1836, 1988a.
- Stephens, G. L., Radiative transfer through arbitrarily shaped optical media, II, Group theory and simple closures, *J. Atmos. Sci.*, *45*, 1837–1848, 1988b.
- Stephens, G. L., and C. M. R. Platt, Aircraft observations of the radiative and microphysical properties of stratocumulus and cumulus cloud fields, *J. Clim. Appl. Meteorol.*, *26*, 1243–1269, 1987.
- Stephens, G. L., and S.-C. Tsay, On the cloud absorption anomaly, *Q. J. R. Meteorol. Soc.*, *116*, 671–704, 1990.
- Twomey, S., Computations of the absorption of solar radiation by clouds, *J. Atmos. Sci.*, *33*, 1087–1091, 1976.
- Twomey, S., and T. Cocks, Spectral reflectance of clouds in the near-infrared: Comparison of measurements and calculations, *J. Meteorol. Soc. Jpn.*, *60*, 583–592, 1982.

M. Batey and Harshvardhan, Department of Earth and Atmospheric Sciences, Purdue University, West Lafayette, IN 17907-1397. (harsh@purdue.edu)

S. M. Freidenreich and V. Ramaswamy, NOAA Geophysical Fluid Dynamics Laboratory, Princeton University, P.O. Box 308, Princeton, NJ 08542.

W. Ridgway, Code 913, NASA Goddard Space Flight Center, Greenbelt, MD 20771.

(Received August 6, 1998; accepted August 30, 1998.)