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Radiative Properties of Cirrus Clouds Inferred from Broadband Measurements During FIRE

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1. Introduction

It is well known that clouds are significant modulators of weather and climate because of their effects on the radiation field and thus on the energy balance of the earth-atmosphere system. As a result, the accurate prediction of weather and climate depends to a significant degree on the accuracy with which cloud-radiation interactions can be described.

It is the purpose of this investigation to report the broadband radiative and microphysical properties of five cirrus cloud systems, as observed from the NCAR Sabreliner during the FIRE first Cirrus IFO, in order to better understand cirrus cloud-radiation interactions. A broadband infrared (BBIR) radiative transfer model is employed to deduce BBIR absorption coefficients in order to assess the impact of the cirrus clouds on infrared radiation. The relationships of these absorption coefficients to temperature and microphysical characterisics are explored.

2. Flight and Data Description

The analysis presented here was conducted for five cirrus systems that were penetrated by the NCAR Sabreliner during the first Cirrus IFO in the fall of 1986. Broadband, infrared (4-50μm) and shortwave (0.3-2.8μm) fluxes were obtained from measurements made by pyrgeometers and pyranometers manufactured by Eppley Laboratories Inc. For a description of these radiometers and calibration procedures, see Albrecht and Cox (1976, 1977) and Smith, Jr., *et al.*, (1988). In addition, the shortwave irradiances were corrected to a horizontal plane and normalized to common time for each flight by taking into account Sabreliner flight information (i.e. pitch, roll, and heading), as well as the sun-earth geometry (Rockwood and Cox 1976; Ackerman and Cox 1981). The microphysics data were obtained from the Particle Measuring System, Inc. (PMS) 2-D probes. These data are described by Heymsfield and Miller (1989). For a description of the Sabreliner data set, see Hein, *et al.*, (1987). A brief description of each of the four flights and the associated synoptic conditions are given in Smith, Jr., and Cox (1989).

3. Broadband Infrared Radiative Transfer Model

In order to assess the impact of the cloud layers on infrared radiation, the broadband (4-50 μm) irradiance data were analysed utilizing a broadband infrared radiative transfer model similar to that described by Cox and Griffith (1979). For clear sky, this model is capable of reproducing broadband divergence values which agree with observations (Albrecht, *et al.*, 1974). This model has been modified to include the effects of clouds and is described in detail by Smith, Jr., and Cox (1989). In this model, the cloud is treated as a greybody where

$$\epsilon_{cld} = 1 - e^{-\tau_{cld}} \quad (1)$$

and

$$\tau_{cld} = \sum_i (K_i \cdot \overline{IWC}_i \cdot \Delta Z_i) = \sum_i \sigma_i \cdot \Delta Z_i \quad . \quad (2)$$

In (5), K_i is the greybody mass absorption coefficient, $\overline{IWC}_i$ is the mean ice water content, σ_i is the broadband absorption coefficient (units m^{-1}) and ΔZ_i is the thickness for the i^{th} cloud layer. Paltridge (1974) and Stephens (1978) have shown that when employing a constant value of K, (5) is a good descriptor of the radiative properties of water clouds. Griffith, *et al.*, (1980) successfully employed this relationship, assuming a constant value of K, to fit irradiance observations of cirrus obtained during GATE, although to date, there is no theoretical basis supporting the assumption that the broadband cloud transmittance through cirrus is an exponential function of optical depth. Therefore, we have adopted (5), but with the assumption that K may be variable through the cirrus layer. This parameterization of cloud emittance permits us to retrieve profiles of K that yield calculated irradiance profiles that precisely match the measured infrared irradiance profiles (Fig. 1) through the cirrus clouds. Vertical profiles of

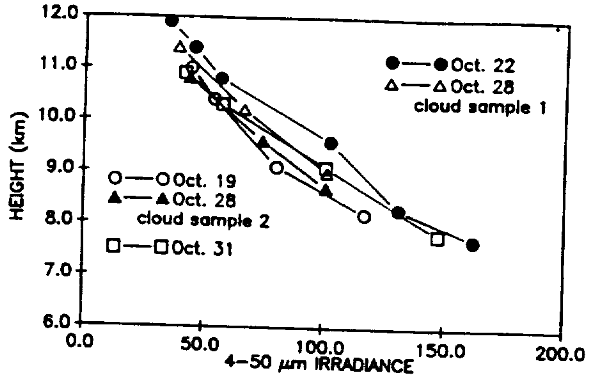

Figure 1.: *Vertical profiles of downwelling 4-50 μm irradiance for five cirrus systems penetrated by the NCAR Sabreliner.*

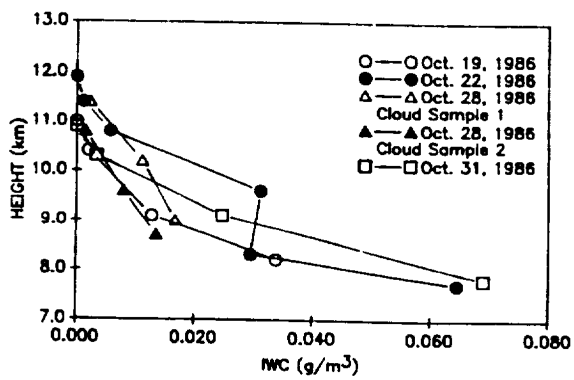

Figure 2: *Vertical profiles of Ice Water Content (IWC) through five cirrus cloud systems.*

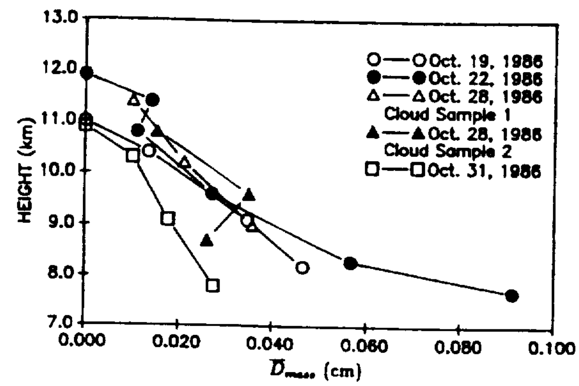

Figure 3: *Vertical profiles of $\overline{D}_{mass}$ (see text for description).*

mean IWC deduced from the 2-D PMS probe measurements are shown in Fig. 2 for the four flights analyzed here. The IWC generally increases with decreasing altitude (increasing temperature) as expected. These values are generally lower than those measured in tropical cirrus systems (i.e. Griffith, *et al.*, 1980) and range from 0.0 in clear regions to about 0.07 near the base of the cirrus cloud sampled on 22 October.

Platt and Harshvardhan (1988), hereafter referred to as PH, discuss the relationship between cirrus cloud absorption and ice water content and provide insight as to why the mass absorption coefficient, K, may not be a constant through a cirrus cloud of variable ice particle size distribution. As in PH, K may be considered as:

$$K = \frac{\sigma}{IWC} \simeq \beta \frac{\overline{Q}_a}{r_e}, \tag{3}$$

where $\overline{Q}_a$ is the "effective absorption efficiency", r_e the "effective radius" for the size distribution and β is a constant which includes the density of ice and an ice particle orientation factor. Theoretical computations of the absorption efficiency Q_a (or extinction efficiency) as a function of size parameter have been carried out by Herman (1962), Pinnick, *et al.*, (1979) and others. For incident energy in the infrared wavelengths, $Q_a \approx c \cdot r_e$ (c is some constant) for size parameters typically found in fogs and stratiform water clouds and thus K is approximately constant. However, for ice clouds where typical ice crystal dimensions are known to be an order of magnitude larger than the water droplet dimensions found in stratiform clouds, the absorption efficiency approaches a value of unity so that K cannot be treated as a constant through cirrus unless r_e remains constant. This is clearly not the case for the cirrus clouds observed during the FIRE first cirrus IFO. Fig. 3 shows the parameter $\overline{D}_{mass}$ varying as a function of height for the five cirrus systems described here where $\overline{D}_{mass}$ is the median mass weighted ice particle dimension as defined by Heymsfield and Miller (1989).

4. Results

In order to deduce the impact of cirrus clouds on infrared radiation, the data sampled in five cirrus systems were analyzed to infer cloud emittances (ϵ_{eld}) and broadband, infrared absorption coefficients (K). The relationship of the absorption coefficients to temperature and microphysical characteristics of the clouds are explored. Because only one aircraft was used, measurements at different levels in the cloud were not made simultaneously. As a result, sampling errors may occur due to the nonsteady state of the cloud field and/or due to the possibility that the flight legs were not flown directly above or below each other. To minimize these errors and in an attempt to set some limits on the observed radiative properties (ϵ_{eld} and K), the downwelling irradiance and IWC data for each flight leg were stratified in the following ways:

MEAN: Average using every measurement along the flight leg to determine a mean value for the cirrus cloud field.

THINNER: Average the lowest 30% of the irradiance measurements and the lowest 30% of the IWC data to represent the optically thinner part of the cloud field.

THICKER: Same as above but for the highest 30% to represent the optically thicker part of the cloud field.

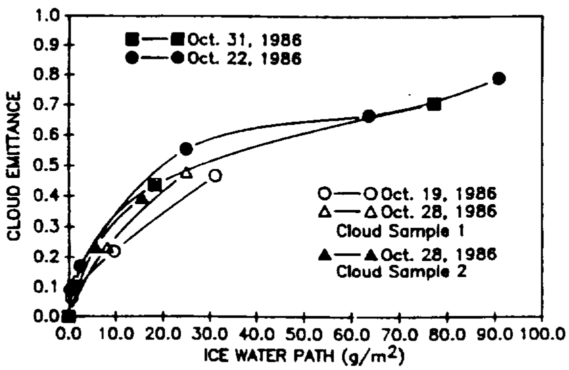

Figure 4: *Model deduced cloud emittance (ϵ_{cld}) for five cirrus cloud systems as a function of ice water path (IWP).*

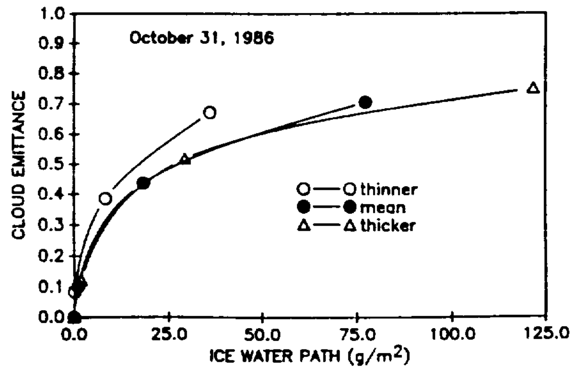

Figure 5: *Model deduced cloud emittance (ϵ_{cld}) for the stratified data of October 31, 1986.*

4.1 Radiative Properties

The model deduced cloud emittances, that is, the emittances due to the cloud ice (water) itself, are shown in Fig. 4 as a function of ice water path (IWP) for the five cirrus clouds for the case using the flight leg means. For the geometrically thinner clouds (19 Oct., 28 Oct.) the emittance approaches about 0.4-0.5 while for the geometrically thicker clouds (22 Oct., 31 Oct.) the emittance approaches 0.7-0.8. This figure suggests that ϵ_{cld} is a similar function of IWP for these 5 cirrus clouds sampled during FIRE.

Fig. 5 depicts the resulting cloud emittances for the stratified irradiance and IWC profiles of 31 October. For the case of 31 October, ϵ_{cld} was about 0.67 for the thinner cloud and 0.75 for the thicker cloud. It is interesting to note that the functional dependencies of the cloud emittance on IWP are similar between the mean and thicker cloud, but not for the thinner cloud. This occurred in the other cirrus cloud systems as well. It is possible that when stratifying the data as described above, the infrared radiative properties of the thinner clouds are being significantly modulated by unmeasured small particles.

Stackhouse (1989) has shown that small particles (d< 50μm) can significantly modulate the transfer of infrared radiation. Furthermore, Prabhakara, *et al.*, (1988) and Ackerman, *et al.*, (1989) have demonstrated that a unique spectral signature which occurs across the infrared window region (8-12 μm) due to cirrus clouds is consistent with radiative transfer calculations for ice particle size distributions with effective radii less than 40 μm. Unfortunately, small particles (d<36 um) were not measured during the FIRE first cirrus IFO and have not been measured anywhere in high altitude cirrus clouds. This shortcoming must be dealt with in the future in order to understand the relationship between small particles and the measured radiative properties of cirrus clouds. Broadband mass absorption coefficients (K in units of m^2/kg) have been deduced and are shown for the five cirrus clouds investigated here and for the different cloud stratifications in Fig. 6 versus the parameter $\overline{D}_{mass}$. Fig. 6 shows the K values retrieved from the mean irradiance and IWC profiles. As expected from the theoretical considerations in Section 3, K is shown to decrease with increasing particle size. The magnitude of K is shown to vary by about two orders from about 0.48 to 0.007. Griffith *et al.*, (1980) deduced K values of 0.096, 0.080 and 0.076 to fit irradiance observations of three cirrus clouds observed during a tropical eastern Atlantic experiment (GATE). Those cirrus systems were anvils very close to deep convection. Paltridge and Platt (1981) deduced a K value of 0.056 to fit irradiance observations of cirrus cloud decks over New Mexico. This investigation is the first which attempts to deduce profiles of K through cirrus clouds. The physical significance of K as it is defined in Eqn. 2 may best be described as a coefficient which relates the IWP to all other microphysical characteristics important to the modulation of the incident irradiance. These other microphysical characteristics probably include, but are not limited to, the effects of small particles, particle orientation and ice crystal habit. The functional dependence of K on the parameter $\overline{D}_{mass}$ shown in Fig. 6 appears to be somewhat dissimilar from one cirrus cloud to the next although the general negative slope is common to all cases. This may indicate that the microphysical properties that the K values characterize in Eqn. 2 are dissimilar from one cirrus cloud to the next. Fig. 7 depicts the retrieved K values for 31 October for the different cloud stratifications. As in the case of the cloud emittance, the functional dependence of K for the mean and thicker stratifications are similar to each other but rather different from that of the thinner clouds. It is likely that the data stratified into the thinner clouds are more effectively characterised by small particles. In other words, the thinner clouds represent data with lower IWC and lower irradiances, however the high values of K that are retrieved from this data indicate the significant effect of some unmeasured microphysical characterisitic (i.e. small particles) on the radiative properties of the cirrus.

Platt and Harshvardhan (1988) (hereafter referred to as PH) discuss the temperature dependence of cirrus infrared extinction based on data obtained by Platt, *et al.*, (1987) and Heymsfield and Platt (1984). The beam volume absorption coefficients (10-12 μm) deduced from

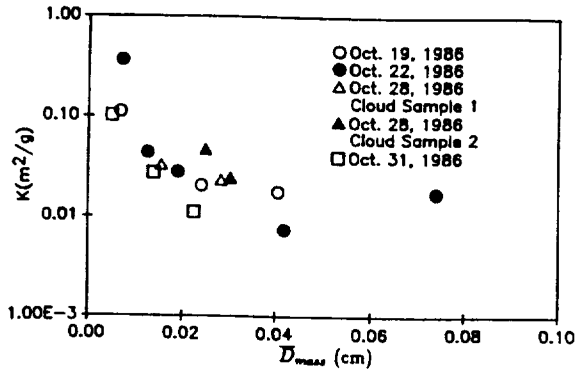

Figure 6: *Mass absorption coefficients (K) as a function of the parameter $\overline{D}_{mass}$ for five cirrus cloud systems.*

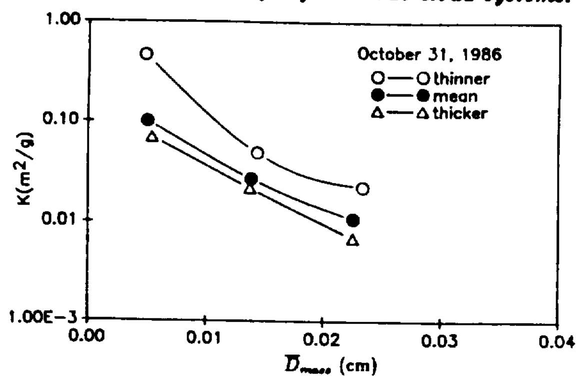

Figure 7: *Mass absorption coefficients (K) as a function of the parameter $\overline{D}_{mass}$ for the stratified data of October 31, 1986.*

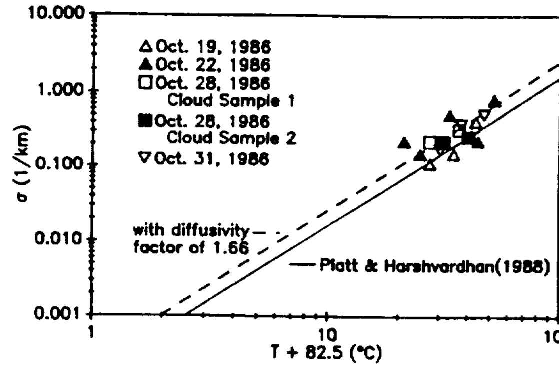

Figure 8: *Broadband absorption coefficients (σ) as a function of temperature. The dashed line is from the data of Platt and Harshvardhan (solid line) multiplied by a diffusivity factor of 1.66.*

these two independent data sets were found to be similar functions of temperature. Broadband volume absorption coefficients (σ) have been computed where

$$\sigma = K \cdot IWC \tag{8}$$

for the five cirrus clouds examined here and for the mean cloud cases. σ is plotted as a function of temperature in Fig. 8 against two regression lines for the data in PH. The solid line fits the beam absorption coefficients as presented in PH while the dashed line fits these same values multiplied by a diffusivity factor of 1.66. The agreement between the σ values and the regression lines from PH is very good. It should be noted that the data of PH were obtained by first deducing a single volume absorption coefficient from ground-based radiometer and lidar observations of a cirrus cloud with some mid-cloud temperature. The absorption coefficients were then averaged for many clouds with similar mid-cloud temperatures. Here, volume absorption coefficients have been determined as a function of depth through cirrus clouds and have been related to the mean temperature of the appropriate layer. The degree with which these two data sets compare may suggest that the bulk infrared properties of cirrus may be adequately parameterized as a function of temperature.

6. Acknowledgements

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