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A measurement of the albedo of thick cirrus clouds at 3.9 μm

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[1] Cirrus (ice) clouds are often semitransparent (transmittance greater than zero, but less than one), which makes it difficult to measure fundamental cloud properties, such as albedo. This paper explores a way to measure the albedo of thick cirrus clouds (zero transmittance) at 3.9 μm using GOES Imager data. In brief, the 10.7 μm GOES data are used to separate the cirrus clouds into temperature classes. Then the measured 3.9 μm radiance is plotted against the cosine of the solar zenith angle. A theoretical relationship between radiance and solar zenith angle is used to extract the albedo. The result is that thick cirrus clouds have an albedo of 1.08% ± 0.05% at 3.9 μm. The albedo of thick cirrus is a step toward the measurement of the transmittance of thin cirrus. *INDEX TERMS:* 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques

1. Introduction

[2] Unlike stratus (liquid) clouds, cirrus (ice) clouds are often thin: they transmit radiation from below. Satellite measurements at 3.9 μm of stratus clouds [e.g., *Turk et al.*, 1998; *Ellrod*, 1995] have been quite successful and have lead to improved techniques to locate fog and to estimate the effective radius of the cloud drops. Cirrus clouds have not been similarly studied. The purpose of this paper is to explore a method to measure the albedo of cirrus clouds.

2. Theory

[3] Assume that the cirrus cloud is thick (indicated by a superscript *). The radiance measured by the GOES Imager at 3.9 μm is composed of reflected and emitted parts. The emitted part can be approximated as

$$\textit{emitted radiance} = \varepsilon^*_{3.9} B_{3.9}(T_{10.7}) = \left(1 - A^*_{3.9}\right) B_{3.9}(T_{10.7}), \quad (1)$$

where $\varepsilon^*_{3.9}$ is the 3.9 μm emittance, B_λ is the Planck function at wavelength λ, $T_{10.7}$ is the GOES-measured brightness temperature at 10.7 μm, and $A^*_{3.9}$ is the 3.9 μm isotropic albedo. For simplicity, bidirectional effects are ignored in this treatment, and $T_{10.7}$ is assumed to represent the temperature of the cloud. The reflected solar radiation at 3.9 μm can be approximated as [*Kidder et al.*, 1998]

$$\textit{reflected radiance} = \pi^{-1} A^*_{3.9} B_{3.9}(T_{\text{sun}}) \Omega_{\text{sun}} \cos\zeta , \quad (2)$$

where Ω_{sun} is the solid angle of the sun subtended at the earth [6.8×10^{-5} sr $\times (d_{\text{mean}}/d)^2$, where d is the earth-sun distance, and $d_{\text{mean}} = 1.4946 \times 10^{11}$ m is the mean earth-sun distance], ζ is the solar zenith angle, and T_{sun} = 5888 K at 3.9 μm [*Thekaekara*, 1972]. Therefore, the radiance measured by a satellite above a thick, isotropic cloud is the sum of the emitted and reflected terms:

$$L_{3.9} = \pi^{-1} A^*_{3.9} B_{3.9}(T_{\text{sun}}) \Omega_{\text{sun}} \cos\zeta + \left(1 - A^*_{3.9}\right) B_{3.9}(T_{10.7}). \quad (3)$$

For constant $T_{10.7}$ and $A^*_{3.9}$, $L_{3.9}$ varies linearly with $\cos\zeta$. This suggests that if one chooses observations of thick cirrus with a constant $T_{10.7}$ and plots the observed $L_{3.9}$ versus $\cos\zeta$, one should be able to retrieve $A^*_{3.9}$.

3. Data

[4] The data are from the GOES-8 Imager, channels 2 (3.9 μm) and 4 (10.7 μm). Data each half hour from 1615 UTC 10 June 1999 to 1515 UTC 11 June 1999 were used in this study. Figure 1 shows

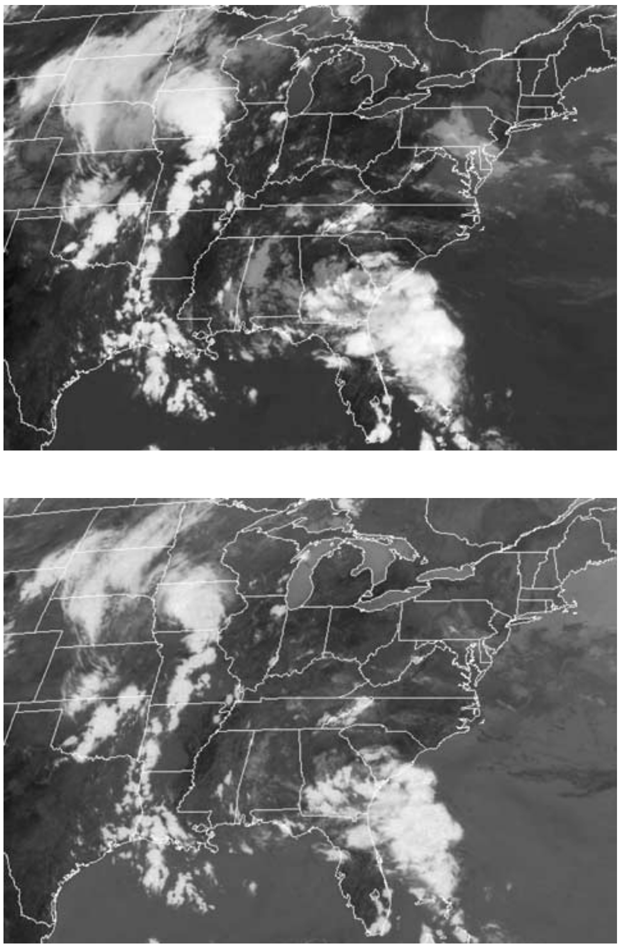

Figure 1. Example of GOES-8 images used in this study: (top) channel 4 (10.7 μm); (bottom) channel 2 (3.9 μm).

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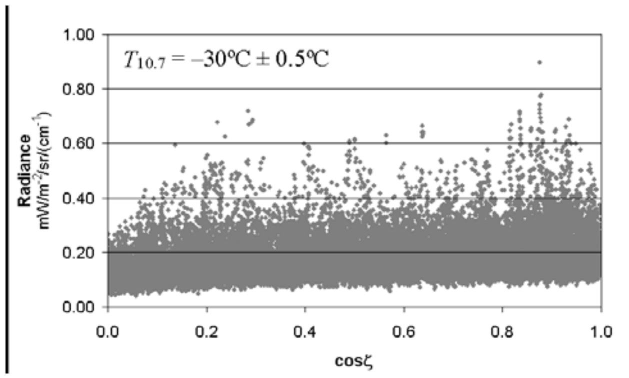

Figure 2. 3.9 μm radiance versus cosζ. Thick clouds are at the bottom edge of the distribution.

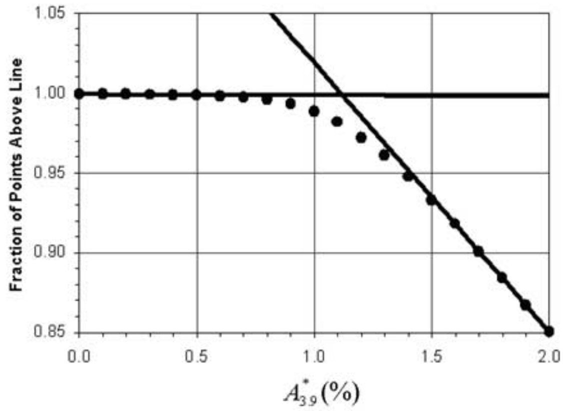

Figure 4. The fraction of points above the radiance-cosζ line for $0 \leq A^*_{3.9} \leq 2\%$ for $T_{10.7} \leq -30°C$. The lines fit the first and last five points in the series. Their intersection is an estimate of the cloud albedo.

the study area and examples of the two channels at 1815 UTC. Raw counts were converted to radiances and brightness temperatures using the calibration equations of *Weinreb et al.* [1998].

4. Results

[5] Figure 2 shows a plot of $L_{3.9}$ versus cosζ for $T_{10.7}$ within ±0.5°C of −30°C. The vertical distribution of the data clearly shows that many cirrus clouds are semitransparent. Radiation from the warmer atmosphere below the cirrus is transmitted to the satellite and increases the measured radiance. The lower edge of the data distribution, which is where one would expect the thicker clouds to be plotted, is quite uniform (apart from the ±2 counts noise in the GOES Imager data) and linear, as predicted by Equation (3).

[6] Figure 3 is similar to Figure 2; $L_{3.9}$ is plotted versus cosζ for $T_{10.7}$ within ±0.5°C of −20°C, −30°C, and −40°C. Warmer values were avoided so that liquid water clouds could be excluded. Colder values were not analyzed because the GOES Imager 3.9 μm data become noisy at temperatures below −40°C. Only the lower

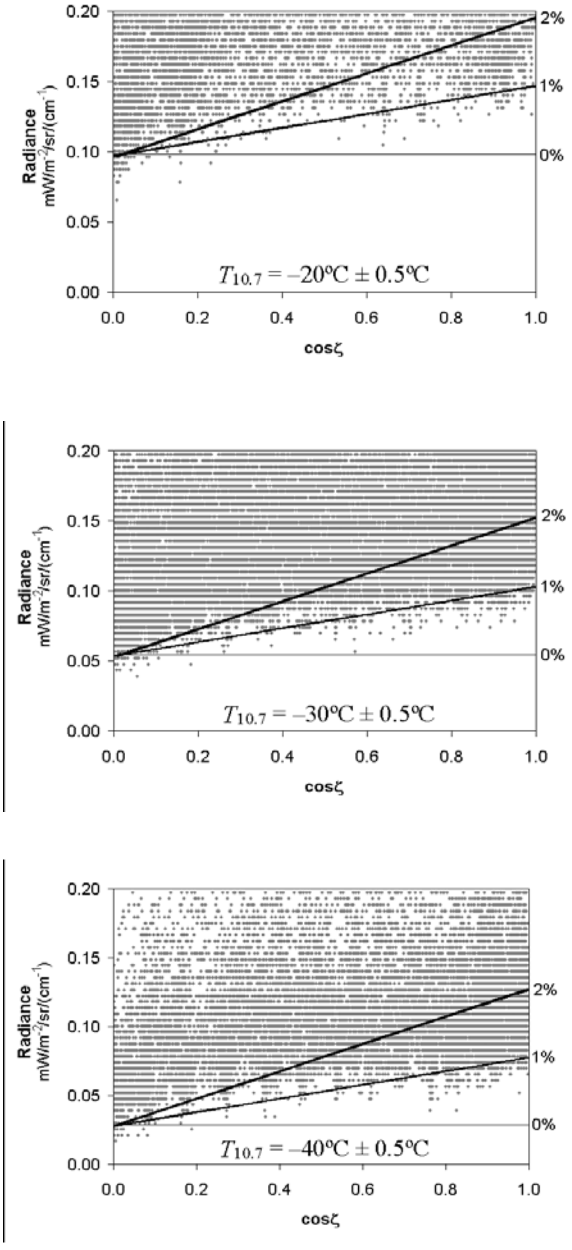

Figure 3. Radiance versus cosζ for three values of $T_{10.7}$. Equation (3) with different values of $A^*_{3.9}$ is plotted on the figures.

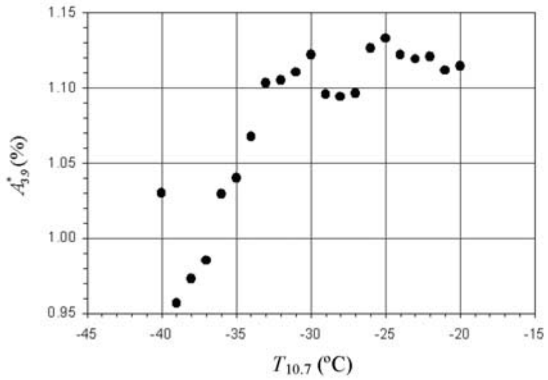

Figure 5. $A^*_{3.9}$ calculated at 1°C intervals of $T_{10.7}$ from −40°C to −20°C by the slope method pictured in Figure 4.

portion of the data distribution is shown. Equation (3), with several values of $A^*_{3.9}$, is plotted on the graphs. By inspection, $A^*_{3.9}$ is consistently near 1%.

[7] To obtain a more precise estimate of the albedo, the following reasoning was pursued. If there really is a sharp bottom edge in the data, and if Equation (3) fits the edge, as one decreases $A^*_{3.9}$ from 2%, the fraction of points which lie above the line should fall until the edge is found, then the fraction should fall more slowly because the only points below the line are caused by instrument noise. The value of $A^*_{3.9}$ at which the slope changes most rapidly is an estimate of the true albedo of the cloud. Figure 4 shows the fraction of points above the line for $A^*_{3.9}$ between 0% and 2% in 0.1% intervals (dots) and for $T_{10.7} = -30°\text{C} \pm 0.5°\text{C}$. At other temperatures, the plots are similar, except that the slope of the right-most portion of the curve changes. An estimate of $A^*_{3.9}$ can be calculated by fitting lines to the five points on the far left and the five points on the far right. Their intersection marks the location where the slope is changing most rapidly. This calculation was performed for $T_{10.7}$ between $-20°$C and $-40°$C in 1°C steps (Figure 5). The resulting albedos ranged from 0.96% to 1.13% with a mean of 1.08% and a standard deviation of 0.05%. There is a slight indication that the albedo decreases at lower temperatures, but more work needs to be done to assess this possibility.

[8] Although it is difficult to measure the albedo of cirrus clouds, scattering calculations have been possible for many years. For comparison, *Hunt* [1973] calculated the albedo of ice clouds at 3.8 μm for two different particle size distributions to be 2.13% and 0.61%. *Welch et al.* [1980] calculated the 3.3 μm albedo of 3 km thick cirrus clouds with overhead sun to be between 0.1% and 0.7%.

5. Discussion

[9] Most cirrus clouds are not opaque; they transmit radiation from below. In fact, the transmittance of the cloud ($\tau_{3.9}$) is the parameter which one would like to find. Cirrus cloud transmittance is important for electro-optical applications and for climate, especially in separating water vapor signals from cloud signals.

[10] The measured radiance of a thin cirrus cloud can be modeled as

$$L_{3.9} = \pi^{-1} A_{3.9} B_{3.9}(T_{\text{sun}}) \Omega_{\text{sun}} \cos\zeta + \varepsilon_{3.9} B_{3.9}(T_{\text{cloud}}) + \tau_{3.9} L_{3.9}^{\text{cloudbase}}, \tag{4}$$

where T_{cloud} is the cloud temperature and $L_{3.9}^{\text{cloudbase}}$ is the upwelling radiance from below the cloud. Equation (4) has five unknown quantities: $A_{3.9}$, $\varepsilon_{3.9}$, $\tau_{3.9}$, T_{cloud}, and $L_{3.9}^{\text{cloudbase}}$.

[11] With the value of $A^*_{3.9}$ measured in this work, the albedo of a thin cirrus cloud can be approximated as

$$A_{3.9} = A^*_{3.9}(1 - \tau_{3.9}), \tag{5}$$

and the emittance as

$$\varepsilon_{3.9} = \varepsilon^*_{3.9}(1 - \tau_{3.9}) = \left(1 - A^*_{3.9}\right)(1 - \tau_{3.9}). \tag{6}$$

Substituting equations (5) and (6) in equation (4) yields

$$L_{3.9} = \pi^{-1} A^*_{3.9}(1 - \tau_{3.9}) B_{3.9}(T_{\text{sun}}) \Omega_{\text{sun}} \cos\zeta + \left(1 - A^*_{3.9}\right)(1 - \tau_{3.9}) B_{3.9}(T_{\text{cloud}}) + \tau_{3.9} L_{3.9}^{\text{cloudbase}}, \tag{7}$$

which has three unknown quantities: $\tau_{3.9}$, T_{cloud}, and $L_{3.9}^{\text{cloudbase}}$. Thus, the work reported in this paper reduces from five to three the number of unknowns in the radiance equation and is a step toward determining the transmittance of cirrus clouds.

[12] **Acknowledgments.** This research is supported by the DoD Center for Geosciences/Atmospheric Research at Colorado State University under Army Research Laboratory Cooperative Agreement DAAL01-98-2-0078.

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