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CIRRUS DETECTION AND CHARACTERIZATION USING GOES 3.9 µm ALBEDO

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1. INTRODUCTION

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 detect and characterize cirrus clouds using the albedo at 3.9 µm calculated from GOES Imager data.

Section 2 contains the necessary theory, and section 3 shows examples of the resulting imagery. In Section 4 an attempt is made to construct a cloud mask using the GOES 3.9 µm albedo, and it is compared with the MODIS cloud mask. Section 5 contains a discussion of the work.

2. THEORY

As explained in Kidder et al. (1998, 2000), the "fog product" has revolutionized fog and liquid water cloud detection at night. As described by Ellrod (1995), liquid water clouds have a lower emittance (emissivity) at 3.9 µm (GOES channel 2) than at 10.7 µm (channel 4). Whereas the emittance of a "thick" liquid water cloud at 10.7 µm is near 1.0, the emittance at 3.9 µm is near 0.7. The result is that at night, the brightness temperature at 3.9 µm ($T_{3.9}$) is less than that at 10.7 µm ($T_{10.7}$). This difference has been exploited to produce the fog product (or fog-stratus product):

$$\textit{fog product} \equiv T_{10.7} - T_{3.9} \qquad (1)$$

At night, if the difference in brightness temperature is plotted as an image, with light gray-to-white representing positive $T_{10.7} - T_{3.9}$ values and dark gray-to-black representing negative values, then clear areas, whether land or ocean, appear gray; fog or stratus appears white; and thin cirrus appears black.

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When the sun comes up, fog product imagery changes dramatically. Solar radiation at 3.9 µm is not negligible, as it is at 10.7 µm. After sunrise, liquid water clouds (3.9 µm albedo ~0.3) reflect solar radiation to the satellite, and it appears that the clouds warm. $T_{3.9}$ becomes larger than $T_{10.7}$. In the fog product, liquid water clouds turn black due to the reflected solar radiation.

To handle this problem, the "reflectance product" has been developed (Dills et al. 1996). Let $L_{3.9}$ be the measured radiance at 3.9 µm. $L_{3.9}$ is linearly related to the counts returned by the GOES Imager and can be calculated using the equations of Weinreb et al. (1997, 1998) or Hillger (1999). Assume further that $T_{10.7}$ represents the physical temperature of the cloud. Then the Planck function $B_{3.9}(T_{10.7})$ represents the 3.9 µm radiance that the satellite would measure if there were no solar reflection. The difference is the reflectivity product:

$$\textit{reflectivity product} \equiv L_{3.9} - B_{3.9}(T_{10.7}). \qquad (2)$$

It is an estimate of the solar radiance reflected from the surface being observed. When converted into the appropriate gray scale, liquid water clouds appear white, land and ocean appear dark (near zero reflection), and cirrus appears black to gray. Unfortunately, the reflectivity product becomes less useful at night.

Fortunately, it is possible to develop a simple, unified equation which is applicable both day and night. 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

$$\begin{aligned}\textit{emitted radiation} &= \varepsilon_{3.9}\, B_{3.9}(T_{10.7}) \\ &= (1 - A_{3.9})\, B_{3.9}(T_{10.7}), \qquad (3)\end{aligned}$$

where $\varepsilon_{3.9}$ is the 3.9 µm emittance, and $A_{3.9}$ is the 3.9 µm albedo. The reflected radiation starts with the 3.9 µm solar irradiance of the scene, which can be approximated as

$$\textit{solar irradiance} = B_{3.9}(T_{sun})\, \Omega_{sun} \cos\zeta, \qquad (4)$$

where Ω_{sun} is the solid angle of the sun subtended at the earth (6.8×10^{-5} sr), ζ is the solar zenith angle, and T_{sun} = 5888 K at 3.9 µm (Thekaekara 1972). The radiance reflected to the satellite from a particular point or location is the product of the bidirectional reflectance and the solar irradiance. Assuming that the point is an isotropic surface (which scatters radiation uniformly in all directions), the bidirectional reflectance is simply $\pi^{-1} A_{3.9}$ (see Kidder and Vonder Haar 1995, pp. 79-81, for details). Thus, the reflected radiation is

$$\begin{aligned} \textit{reflected radiation} &= \pi^{-1} A_{3.9}\, B_{3.9}(T_{sun})\, \Omega_{sun} \cos\zeta \\ &= A_{3.9}\, L^{*}_{3.9} \cos\zeta \end{aligned} \quad (5)$$

where $L^{*}_{3.9}$ is the radiance reflected from a 100% albedo isotropic surface when the sun is directly overhead:

$$L^{*}_{3.9} = \pi^{-1} B_{3.9}(T_{sun})\, \Omega_{sun} \quad (6)$$

Therefore, the radiance measured by the satellite can be written as the sum of the emitted and reflected radiation:

$$L_{3.9} = (1 - A_{3.9})\, B_{3.9}(T_{10.7}) + A_{3.9}\, L^{*}_{3.9} \cos\zeta \quad (7)$$

or, solving for $A_{3.9}$,

$$A_{3.9} = \frac{L_{3.9} - B_{3.9}(T_{10.7})}{L^{*}_{3.9} \cos\zeta - B_{3.9}(T_{10.7})} \quad (8)$$

At night ($\zeta > 90°$) the same equation applies if we simply set $L^{*}_{3.9} = 0$. Note that $A_{3.9}$ is the reflectivity product (Eq. 2) normalized to have a maximum value of 100%.

3. IMAGERY

To construct images of the 3.9 µm albedo, 3.9 µm and 10.7 µm GOES Imager data are processed using Eq. (8). Then 3.9 µm albedos from –30% to +30% are displayed as a gray scale from black to white. Negative albedos result for thin cirrus at night due to transmission of warmer radiances from below the cloud.

Figure 1 shows a nighttime example of 10.7 µm and 3.9 µm brightness temperatures together with the resultant 3.9 µm albedo. Cirrus appears black, liquid water clouds appear white, and other features—land, water, and even snow cover (not shown)—appear gray. Thus the 3.9 µm albedo is an attractive candidate for cloud classification. Note that the 3.9 µm albedo image looks much like a fog product image, but it is normalized, so that thresholds can be set to classify clouds.

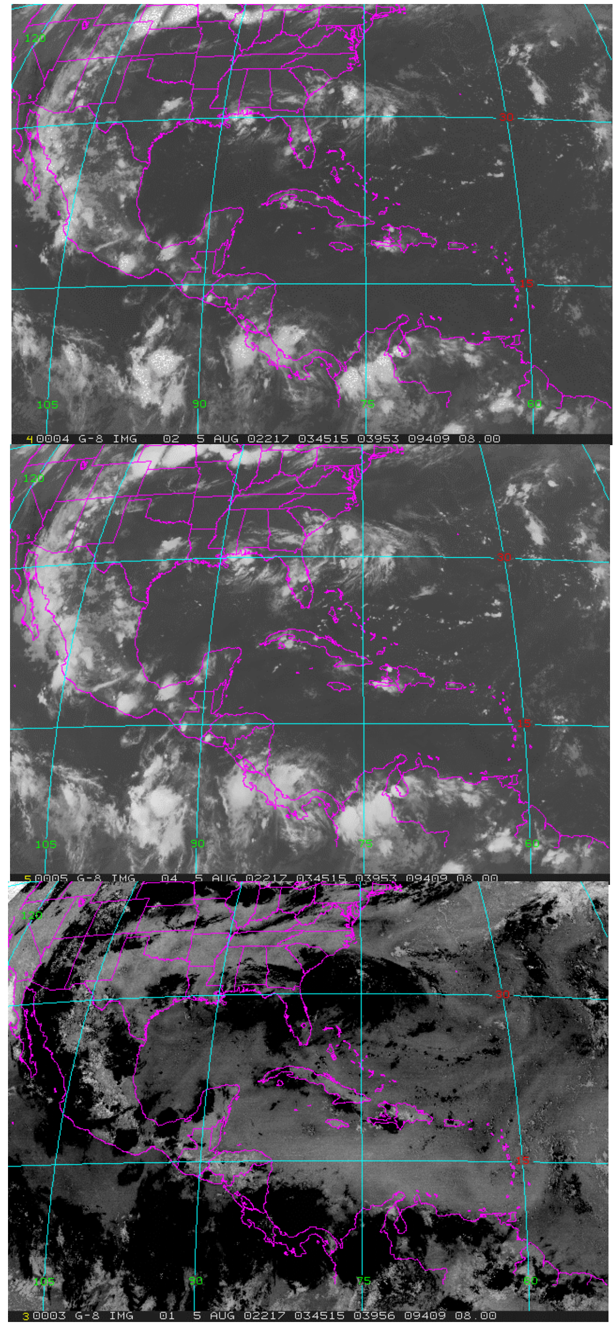

Figure 1. Nighttime example: (top) 3.9 µm image, (middle) 10.7 µm image, (bottom) 3.9 µm albedo.

A daytime example of the 3.9 µm albedo is shown in Fig. 2 along with the 0.64 µm albedo and 3.9 and 10.7 µm brightness temperatures. The daytime 3.9 µm albedo is much different in appearance than the nighttime imagery. Land and ocean are still gray, and liquid water clouds are white, but cirrus clouds are gray, not black. Also, there is some reflectance from certain soil types,

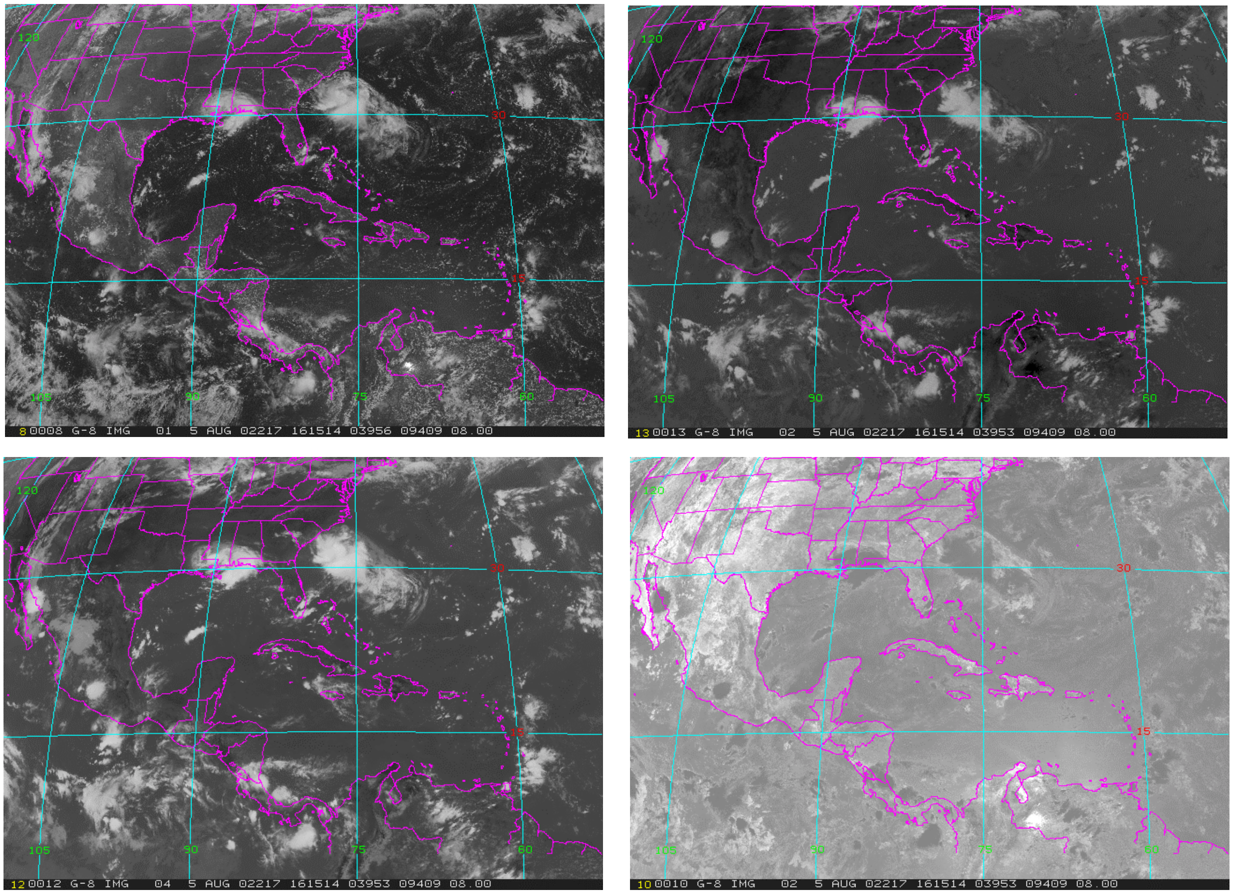

Figure 2. Daytime example: (top left) 0.64 µm albedo, (top right) 3.9 µm image, (bottom left) 10.7 µm image, (bottom right) 3.9 µm albedo.

such as in the western US and northern Mexico, and there is some sun glint, such as in South America.

It should be noted here that the $A_{3.9}$ product is not useful near sunrise and sunset. Because $L^*_{3.9}$ is large in comparison to $B_{3.9}(T_{10.7})$, the denominator of Eq. 8 goes through zero near the terminator, which causes anomalies in the imagery.

The day versus night behavior of $A_{3.9}$ can be explained with the aid of a simple model. Suppose that we have a cloud with temperature T_{cld} overlying a black surface with temperature T_{sfc}. Suppose further that transmittance of the cloud at both 3.9 and 10.7 µm is τ. Then we can model the measured quantities as:

$$T_{10.7} = B^{-1}_{10.7}[(1-\tau)\, B_{10.7}(T_{cld}) + \tau\, B_{10.7}(T_{sfc})] \quad (9)$$

$$L_{3.9} = A^*_{3.9}\,(1-\tau)\, L^*_{3.9} \cos\zeta + (1 - A^*_{3.9})\,(1-\tau)\, B_{3.9}(T_{cld}) + \tau\, B_{3.9}(T_{sfc}), \quad (10)$$

where B^{-1} is the inverse of the Planck function, and $A^*_{3.9}$ is the albedo of a thick cloud (τ = 0) at 3.9 µm. The three terms in Eq. 10 are, respectively, the reflected radiance, the radiance emitted by the cloud, and the surface radiance transmitted through the cloud.

We choose $A^*_{3.9}$ to be 0.3 for stratus clouds (Ellrod 1995) and 0.01 for cirrus clouds (Kidder 2002). We also choose T_{cld} to be –20°C for the cirrus cloud and +10°C for the stratus cloud. T_{sfc} is chosen to be +15°C. Nighttime conditions are simulated by setting $L^*_{3.9}$ = 0. Figure 3 shows a plot of $A_{3.9}$, calculated with Eq. 8.

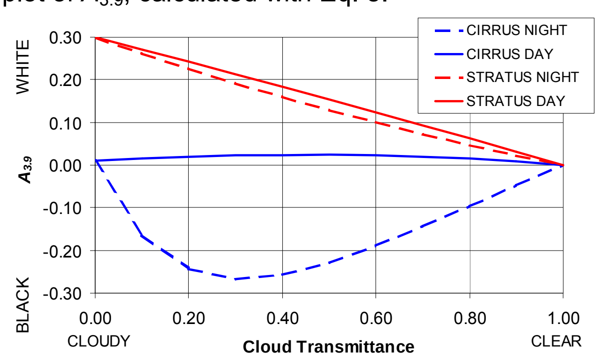

Figure 3. $A_{3.9}$ calculated for transmissive stratus and cirrus clouds. See text for model details.

Due to the facts that (1) most cirrus clouds are “thin” ($\tau < 0$), (2) that they are cold with respect to the underlying surface, and (3) 3.9 µm radiance is more sensitive to within-pixel temperature variance than is 10.7 µm radiance, the model explains why cirrus is black at night and almost uniform gray during the day. It also explains why the warmer and more reflective stratus is white changing to gray as the transmittance decreases. The model and the imagery together suggest that $A_{3.9}$ could be a useful tool for cirrus and status detection at night and for stratus detection during the day.

4. CLOUD DETECTION

One strategy for deriving a cloud detection algorithm is to calibrate it using different data. The Moderate-resolution Imaging Spectroradiometer (MODIS) flies on NASA’s Terra and Aqua satellites. It has 36 channels, and a plethora of products are derived from its data. One such product is the MODIS cloud mask (Ackerman et al. 1997). MODIS cloud mask data were acquired for the GOES images show in Figs. 1 and 2. Figure 4 shows the cloud mask for the nighttime case.

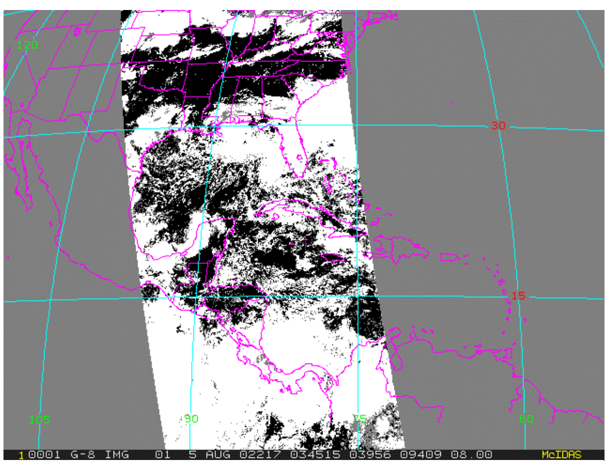

Figure 4. MODIS cloud mask corresponding to Fig. 1. White indicates cloud, black indicates clear, and gray indicates uncertain classification or not observed.

Since clear areas appear gray in the nighttime $A_{3.9}$ imagery, with cirrus being darker and stratus being lighter, it makes sense to study clear areas. Histograms (one for land and the other for ocean) of $A_{3.9}$ were calculated for points (black) that were classified as clear by the MODIS cloud mask. (Note that the MODIS cloud mask algorithm uses 3.9 µm data, but it does not use the 3.9 µm albedo.) If anything, the MODIS cloud mask algorithm appears to be too aggressive in assigning clouds, so the points classified as clear are very likely to be so. Figure 5 shows these histograms.

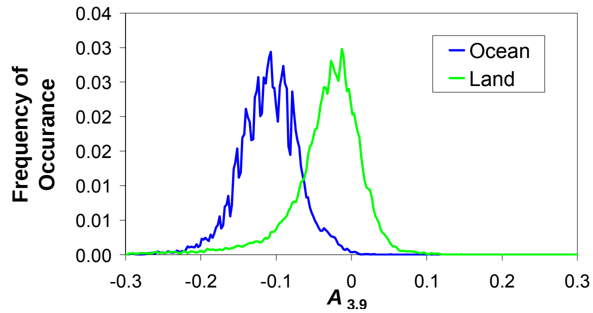

Figure 5. Histograms of $A_{3.9}$ over land and ocean. Over land the mean is –0.032 and the standard deviation is 0.049. Over ocean the mean is -0.110 and the standard deviation is 0.040.

With the mean and standard deviation of the clear 3.9 µm albedos, one can set thresholds for a cloud mask. After some experimentation, it was decided that 2.5 standard deviations would suffice as a threshold for cloud. That is, if $A_{3.9}$ is greater than 2.5 standard deviations above the clear mean, it is classified as stratus. If it is more than 2.5 standard deviations below the clear mean, it is classified as cirrus. Otherwise, it is classified as clear. Table 1 shows these thresholds.

Table 1
Nighttime $A_{3.9}$ Cloud Thresholds

	Land	Ocean
Cirrus	< – 0.154	< – 0.209
Stratus	> 0.089	>– 0.011

Figure 6 shows the results of applying these thresholds to the GOES data. In this figure black is cirrus, white is stratus, and gray is clear. It is to be compared with Figs. 1 and 4. In general, the $A_{3.9}$ cloud mask does a good job at locating the cirrus, and not too bad a job at locating the stratus—what little stratus there is in the image.

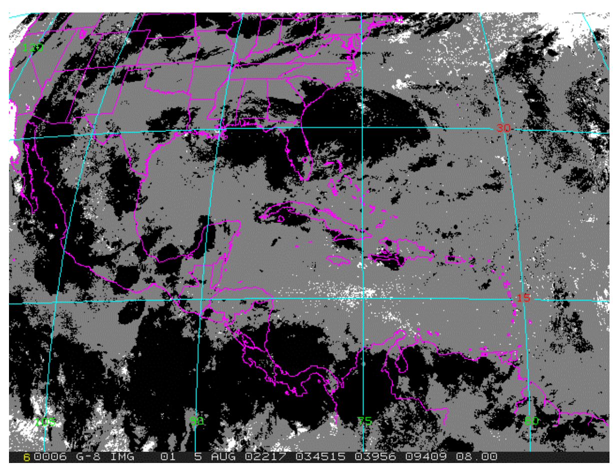

Figure 6. GOES $A_{3.9}$ nighttime cloud mask. Black is cirrus, white is stratus, and gray is clear.

5. DISCUSSION

Many things remain to be done. As explained above, the A3.9 product appears radically different during daylight hours. Given that clouds can be detected quite well using visible and window infrared data, the 3.9 µm albedo may not be as useful during the day as it appears to be at night. However, it might have some ability to augment the VIS and IR data in classification of clouds. In particular, it may be able to locate liquid water clouds, although this is already done using 3.9 µm imagery.

Finally, at night, at least, it may be possible to apply the equations above to retrieve transmittance of cirrus clouds. This effort would entail removing the competing signal of varying backgrounds.

Acknowledgments

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