Study of the Influence of Thin Cirrus Clouds on Satellite Radiances Using Raman Lidar and GOES Data

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Abstract

Hurricane-induced cirrus cloud optical depths (at 351 nm) are presented for the night of August 23, 1998. Optical depths ranged from approximately 0.01 to 0.7 after correcting for multiple scattering, which was estimated to reduce the measured optical depths by up to 20%. The ultraviolet/infrared (UV/IR) cirrus cloud optical depth ratio was estimated based on a comparison of lidar and Geostationary Operational Environmental Satellite (GOES) satellite measurements. Simple radiative transfer model calculations compared with GOES satellite brightness temperatures indicate that satellite radiances are significantly affected by the presence of cirrus clouds if IR optical depths are approximately 0.02 or greater. This has implications for satellite cirrus detection requirements.

Introduction

The third Convection and Moisture Experiment (CAMEX-3) occurred during August-September 1998 and was designed to improve hurricane modeling. Satellite data are an important source of information for these modeling efforts. Accurate measurements of sea-surface temperature and total precipitable water vapor are needed to improve model predictions of hurricane track and intensification. Satellites offer the best chance of providing these data products operationally as inputs to hurricane models. However, it is well known that the presence of cirrus clouds can pose problems for satellite retrievals. This is because thin cirrus clouds, while having small infrared emissivities, can be very cold. Emission from these clouds can cause significant changes in satellite radiances compared to a cloud-free scene. A comparison of Raman lidar cirrus cloud optical depth measurements with retrievals of surface temperature and total precipitable water vapor from GOES-8 has been performed to study the influence of thin cirrus clouds on these satellite retrievals.

The National Aeronautics and Space Administration/Goddard Space Flight Center (NASA/GSFC) scanning Raman lidar (SRL) was stationed on Andros Island in the Bahamas during CAMEX-3 and acquired near daily measurements of water vapor, aerosols, and clouds. SRL measurements of cirrus cloud optical depth during the passage of a hurricane are presented here. Cirrus cloud optical depths were quantified by integrating the equation for aerosol extinction (Ansmann et al. 1992). The influence of multiple scattering on these optical depth measurements was then estimated using the technique of Eloranta (1998) and found to cause a decrease in optical depth of approximately 20%, assuming particle sizes typical for the cold sub-topical cirrus clouds were studied here. Cirrus cloud optical depths measured by the lidar in the ultraviolet region of the spectrum were then translated to optical depths at the 11-micron and 12-micron channel location of the GOES satellite by calculating the IR optical depth from GOES satellite data using the technique described by Wylie et al. (1995). Using these IR optical depth values, the influence of hurricane-induced cirrus clouds on GOES retrievals using the split window technique (Suggs et al. 1998) was studied by comparing radiative transfer model simulations to retrieved surface temperatures and precipitable water.

Hurricane Bonnie Cirrus Clouds

Raman lidar measurements of cirrus cloud backscattering coefficient (km^{-1} sr^{-1}) and optical depth (at 351 nm) acquired at the Andros Island ground on the night of August 23, 1998, are presented in Figure 1. The optical values have been increased by 10% over the lidar-measured values to estimate the influence of multiple scattering. The error in optical depth due to this multiple scattering correction is approximately ±10%. The backscatter coefficient values, being the result of a ratio measurement, have negligible multiple scattering influence (Wandinger 1998). A 10-minute running average of lidar data

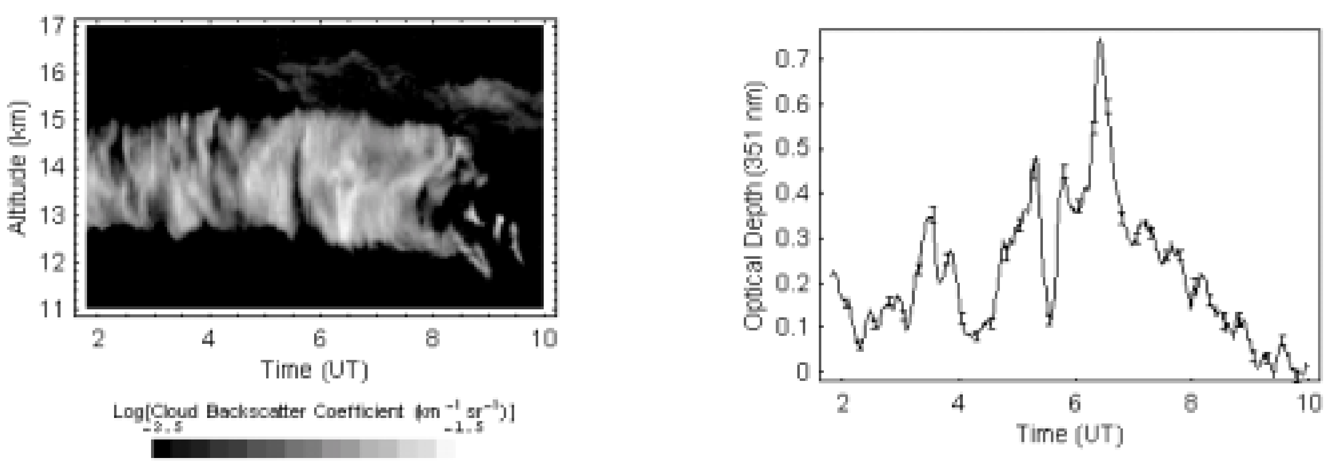

Figure 1. Cloud backscatter coefficient and optical depth at 351 nm as measured by the SRL on the night of August 23, 1998, at Andros Island, Bahamas. The optical depth values have been increased 10% over those measured to account for the effects of multiple scattering.

has been used for the optical depth calculations, while the backscatter coefficient measurements are presented shown using 1-minute resolution. The optical depth error is calculated using Poisson statistics.

The measurements of August 23 provided a convenient dataset to test the sensitivity of satellite retrievals to the presence of cirrus clouds because of the range of optical depths covered. On this night, the measured optical depth at 351 nm ranged from a minimum of approximately 0.01 to a maximum of approximately 0.7. The lidar cloud backscatter coefficient ranged from approximately 3 x 10^{-4} to 3 x 10^{-2} km^{-1} sr^{-1}.

In order to estimate the radiative effects of these cirrus clouds, a simple radiative transfer model, which accounts for surface emissivity, surface temperature, cloud emissivity, and cloud temperature was used. The model equation is

$$R_{sat} = (1 - e_c) e_s P(L_{sat}, T_s) + e_c P(L_{sat}, TBar_c)$$

Here, R_{sat} is the predicted satellite radiance (W/m^{-2} sr^{-1} $micron^{-1}$), e_c is the cirrus cloud emissivity calculated from e_c = 1-exp[-Tau_c] where Tau_c is the cirrus infrared optical depth, e_s is the surface emissivity, P is the Planck function, L_{sat} is the wavelength of the satellite instrument channel, T_s is the surface-radiating temperature, and $TBar_c$ is the mean cirrus cloud radiating temperature. The first term in the equation for R_{sat} is the surface contribution to the satellite radiance and the second term is the contribution due to the cirrus cloud. The satellite effective brightness temperature T_{sat} is then obtained numerically from the Planck function using the value of R_{sat} determined from the equation. Averaging over the GOES 11-micron and 12-micron channel filter widths is required since the index of refraction of ice varies significantly in this region of the spectrum (Warren 1984).

The purpose of this equation is not to yield highly accurate values of satellite radiance but rather to study the influence of varying cirrus optical depths on those radiances. Toward that end, the values used in the equation were: e_s = 0.95, T_s = 302 K obtained from GOES during a cloud-clear period, $TBar_c$ = 214 K obtained from radiosonde measurement.

In order to use the lidar-measured optical depths for IR radiative transfer calculations, the optical depths must be translated to the IR. The ratio of visible (532 nm from a Nd:YAG laser) to IR cirrus optical depth has been shown to vary between approximately 1.6 and 2.4 (Wylie et al. 1995; DeSlover 1999). This ratio depends on particle size and, due to the changing values of the index of refraction of ice, the exact spectral locations that are being compared. These studies have indicated that the values for 11 microns typically are larger than the values for 12 microns.

To study the ratio of UV/IR cirrus optical depths, the same approach described in Wylie et al. (1995) was used. The mean values for the ratio of optical depths calculated using this technique were 1.6 ± 0.6 at 11 microns and 1.4 ± 0.5 at 12 microns. These ratios were then used to convert the lidar-derived optical depths to the IR. These IR optical depths were then used in the model to simulate satellite radiances.

The left panel in Figure 2 shows the brightness temperatures calculated from the model for both the 11-micron and 12-micron GOES channels (long dash and dot-dot-dash lines, respectively). Also plotted are the actual GOES 11-micron and 12-micron channel brightness temperatures (closed boxes and triangles) and the retrieved skin surface temperature using the split-window physical retrieval technique (Suggs 1998) (open diamonds). No cloud screening was performed in these retrievals. Therefore, the GOES brightness temperatures and the subsequent retrievals have the effects of cloud-contamination implicitly in them. The corresponding precipitable water retrievals using the split-window technique are shown on the right in Figure 2. In this plot, the lidar-derived total precipitable water (TPW) and the cirrus optical depth measurements (adjusted to the IR) are also shown. The lidar measurements indicate that the TPW changed relatively little during the measurement period.

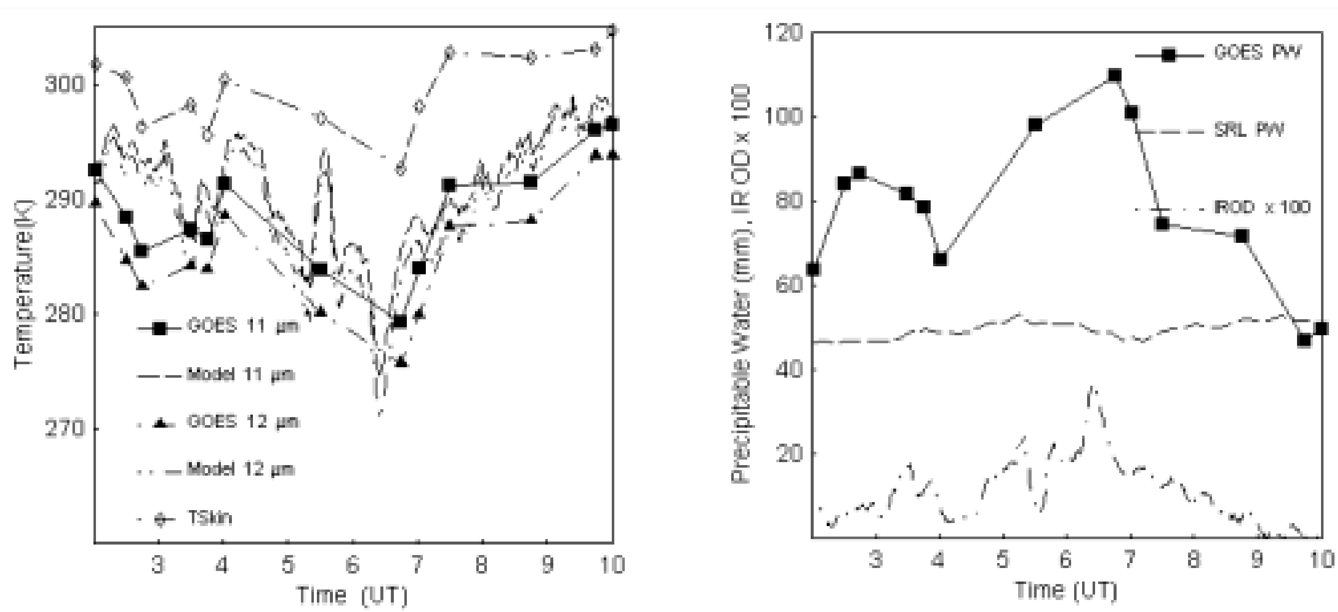

Figure 2. On the left is a comparison of GOES 11-micron and 12-micron channel brightness temperatures and model calculations for the satellite pixel containing the lidar site. Also plotted are the retrieved skin surface temperatures using the split-window technique. The model assumes constant surface and cloud temperatures. On the right is a comparison of retrieved precipitable water from GOES for the same satellite pixel. The SRL measurements of precipitable water and cirrus cloud IR optical depth are also shown.

There are several points that can be made from this figure. Despite the sampling issues relating to the comparison of 10-minute averages of lidar data and 10-km satellite pixels, these simple model calculations capture the main features observed in the satellite brightness temperatures. A comparison of the results using the pixel just to the east of the lidar site yielded very similar results to those shown indicating that the constant surface temperature assumption in the model retrievals is reasonable. That being the case, another point is that the changing cirrus cloud optical depth is the dominant factor causing fluctuations in the satellite brightness temperatures and TPW. It is clear from Figure 2 that the cirrus-induced errors in the retrieval of TPW are larger than and in opposite direction to those in skin temperature. Increases in cirrus optical depth depress the retrieved surface temperature and elevate the retrieved TPW. A simple explanation for this effect can be obtained by considering the adjustments in the derived values of surface temperature or precipitable water required to account for the change in radiance due to the presence of cirrus. Because of the T^4 dependence of blackbody radiant energy, small reductions in retrieved surface temperature can explain the reduced brightness temperatures of a cirrus-cloud-contaminated scene. However, large increases in precipitable water are required to bring about comparable reductions in brightness temperatures since the precipitable water is concentrated near the surface and is characterized by a radiating temperature that contrasts with the surface temperature much less than do cirrus cloud temperatures.

In Figure 2, the influence of cirrus clouds on the satellite radiance is seen to last until approximately 0900 Universal Time (UT) as indicated by the general slope in the model predictions toward higher brightness temperatures. Taking 0900 UT as an estimate of the first time during the measurement period when the satellite brightness temperatures were uninfluenced by the presence of cirrus, the IR optical depth threshold above which the presence of cirrus significantly influences GOES satellite brightness temperatures is estimated to be 0.02. It is interesting to note here that the optical depth limit for visual detection of cirrus clouds has been set at 0.03 (Sassen and Cho 1992). It is reasonable to expect that a cirrus cloud that cannot be seen by the naked eye might also have little radiative impact on satellite measurements.

This threshold can be compared to the results of Wylie and Menzel (1989) where, in their study of VAS [VISSR (visible and infrared spin-scan radiometer) atmospheric sounder] data, they concluded that 50% of the clouds with IR optical depths of 0.1 or less went undetected. If this statistic is representative of the current state of cloud detection algorithms, it seems likely that the probability of undetected cirrus significantly influencing satellite data is high.

Summary and Conclusions

The influence of thin cirrus clouds on satellite radiances has been studied here. After converting the lidar-derived UV optical depths to IR optical depths based on a comparison of SRL optical depth and GOES brightness temperatures, the predictions of satellite brightness temperatures from a simple radiative transfer model were compared with actual GOES brightness temperatures. These predictions indicated that satellite radiances are noticeably affected for cirrus optical depths above approximately 0.02. Larger errors were induced in the retrieved precipitable water than in the retrieved skin temperatures.

An important conclusion of this effort is that satellite retrieval algorithms must be able to detect the presence of cirrus clouds with IR optical depths as small as 0.02 in order to avoid significant influences on satellite radiances and thus potential errors in retrievals. Improved satellite measurement strategies such as the 1.375-micron cirrus channel of the moderate resolution imaging spectroradiometer (MODIS) instrument (http://modarch.gsfc.nasa.gov/MODIS/) on the recently launched Terra satellite are needed to improve satellite sensitivity to cirrus. Studies similar to that performed here are needed to determine the effectiveness of these new approaches to cirrus detection from satellite.

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