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THE ABSORPTION OF NIR SOLAR RADIATION BY PRECIPITATING CLOUDS

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1. INTRODUCTION

For many years it has been assumed in climate models that clouds scatter about 30% of the incident solar radiation while absorbing only about 4% [Kerr, 1995]. However, a number of investigators [*Cess et al.*, 1995; *Ramanathan et al*., 1995; *Pilewskie and Valero*, 1995] have reported that clouds may absorb up to more than 150 W/m^2, which is about four times the absorption of the shortwave flux predicted by current climate models. Subsequent investigations have recently concluded that anomalous absorption is not occurring in the visible region below 1 micron once the multiple absorption processes in the clear sky are properly accounted for; this does not rule out the absorption of short wave NIR by certain types of clouds.

Evans et al. [1995] reported the results of a simple experiment based on a pyranometer and solar cell which indicated that some clouds absorb up to 75 W/m^2 of the solar radiation in the 1 - 3 micron region; hence, the experiment yielded evidence for the approximate spectral region over which the absorption was primarily occurring.

In this paper we present measured solar absorption spectra in the 1 - 4 micron region for clear and overcast sky conditions in order to determine the spectral absorption characteristics that may further elucidate the strong NIR absorption process. Comparison of the resulting cloud transmission spectra with the transmission spectrum of liquid water has provided evidence that the strong absorption of solar radiation by precipitating clouds may be attributed to the presence of large liquid water droplets in the clouds. These measurements were made at Peterborough, Ontario (latitude 44.3 °N) on numerous occasions and at several other locations.

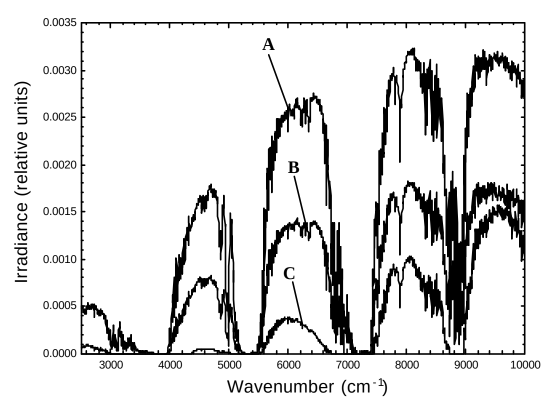
2. EXPERIMENTAL

Spectral measurements of the solar flux in the 1 to 4 micron NIR region were obtained at a resolution of 4 cm^{-1} using a Magna 550 FTS (FTIR spectrometer) and a BOMEM DA8 FTS. This latter instrument incorporated a narrow-band, InSb detector and a quartz beamsplitter. The transmissivity of the beamsplitter was negligible at wavelengths above 3 microns. The solar flux was measured by positioning a diffuse reflector with a magnesium oxide coating at the entrance emission port of the instrument. The measurements were obtained near solar noon so that the solar zenith angle remained approximately invariant over the measurement period. Each spectral measurement required 200 seconds of observing time. This resulted in a root-mean-square signal-to-noise ratio of about 350:1 at 4500 cm^{-1} for clear sky conditions. Accompanying total solar flux measurements of the clear sky were also obtained using a Kipp and Zonen pyranometer (model CM-2). The pyranometer had a wavelength cutoff of 3 microns and it was calibrated using the shortwave calibration factors based on the World Radiometric Reference. A second pyranometer with a glass filter was used to isolate the flux above 900 nm. Transmission spectra of liquid water were derived from the absorption coefficients obtained from water absorption measurements made in the laboratory using the same FTIR spectrometer and quartz cells with pathlengths of 1, 5 and 10 mm.

3. RESULTS AND DISCUSSION

Curve A in Figure 1 shows a solar spectrum in the 1 - 4 micron region obtained for clear sky conditions at 1 p.m. (EST) on April 11, 1995. Curve B represents a spectrum obtained under an extended patch of cloud that filled the field-of-view of the diffuser plate of the spectrometer.

Figure 1: Near-infrared spectra of the clear sky (curve A), of light overcast cloud (curve B) and of very heavy overcast cloud (curve C) obtained on April 11 and 12,



1995 at Peterborough, Ontario.

A spectrum of very heavy, overcast cloud was obtained at 11:30 a.m. (EST) on April 12, 1995 about 10 minutes before the occurrence of rain. This heavy precipitating cloud spectrum is shown by curve C, and it was measured at approximately the same solar angle as the spectrum of lighter cloud in curve A. The large absorption

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features in the measured clear sky irradiance at 8800, 7200, 5300 and 3500 cm^{-1} are attributed to water vapour. Below 3300 cm^{-1} the thermal emission of the atmosphere becomes a significant component of the spectrum. It has been cancelled out of the spectra in Figure 1.

The corresponding observed cloud transmission spectra for light and heavy clouds are represented in Figure 2 by curves A and B, respectively. In converting to transmission, the cloud spectra have been smoothed to zero in the regions of negligible irradiance and a small absolute offset of 0.001 was added to the clear sky spectrum in order to avoid the artifacts that result when dividing small numbers.

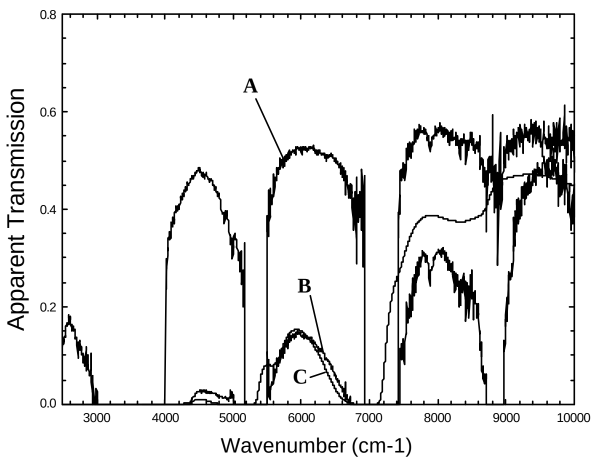
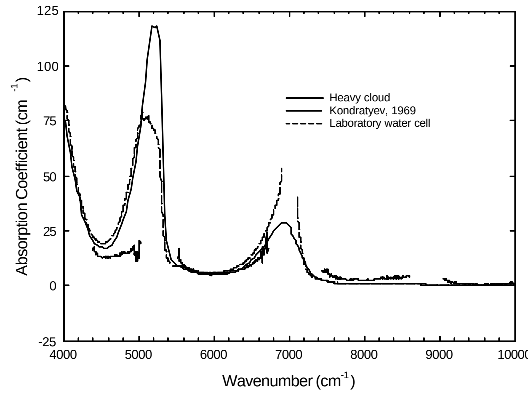


Figure 2: Cloud transmission spectra for light overcast cloud (curve A) and very heavy overcast cloud (curve B). Curve C represents the laboratory absorption spectrum attributed to a 2 mm path of liquid water.

Clearly, there is extra absorption present in the observed heavy cloud transmission curve that is not present in the light cloud spectrum. It is to be expected that water vapour absorption will be similar under the two cloud conditions. Curve C in Figure 2 represents the absorption spectrum of 2 mm of water obtained at a temperature of 18°C in the cell. It has been normalized to the heavy cloud peak transmission of 28% at 9600 cm^{-1}. This result was calculated from the absorption coefficients of water that were measured in quartz cells with pathlengths of 1, 5 and 10 mm. The absorption coefficients were in good agreement with those obtained by Kondratyev [1969]. Comparing the liquid water transmission with that for the heavy cloud in Figure 2 reveals that the decrease in transmission as a function of lower wavenumber in the heavy cloud transmission is consistent with liquid water absorption. That is, large water droplets inside the cloud primarily absorb solar radiation, and the Mie scattering absorption by small droplets is a minor component. The comparison between liquid water absorption and the absorption of radiation occurring in clouds may also be examined from the analysis of the absorption coefficients. Figure 3 illustrates the measured absorption coefficients for the heavy precipitating cloud and pure liquid water.

Figure 3: A comparison of the measured absorption coefficients for heavy cloud and liquid water in a laboratory cell. Also shown for comparison are the absorption coefficients for liquid water as measured by



Kondratyev (1969).

The cloud absorption coefficients have been calculated by dividing the heavy cloud spectrum by the light cloud spectrum in order to approximately account for the Mie scattering which is taking place. These coefficients are compared to those which have been measured for pure liquid water in our laboratory cell; the latter compare favourably with the data of Kondratyev (1969), as shown in Figure 3.

A water path of 2.2 mm was used in the calculation of the cloud coefficients, which gives reasonable agreement with the results for pure liquid water. It should be noted that the breaks which occur at 5200, 7000 and 8800 cm^{-1} in the absorption coefficients from the cloud are due to the presence of water vapour bands which absorb strongly in these regions thus reducing the signal to noise below useable limits in the gap regions. There appears to be a shift of the cloud derived absorption coefficents of about 100 cm^{-1} to higher frequencies. By this process, the absorption spectrum of the strong NIR absorber has been extracted; it turns out to match liquid water. Of interest for the cloud absorption problem is the amount of solar energy absorbed by the heavy cloud. The solar energy available to be absorbed by the liquid water in the heavy cloud can be estimated by calculating the transmitted spectral flux from the product of the transmission through the light cloud and the clear sky solar irradiance. The latter spectrum was derived by calculating the clear sky irradiance from the MODTRAN transmission model [Abreu *et al.*, 1991], incorporating mid-latitude summer atmospheric profiles [Anderson *et al.*, 1986]. The simulated result was scaled by the absolute irradiance of 849 W/m^2 that was measured by the pyranometer for the clear sky conditions on April 11, 1995. Integrating the resultant product over frequency indicated that 136 W/m^2 was transmitted through the light cloud. Hence, evaluating the total radiation that passes through the heavy cloud and then subtracting this flux from the flux transmitted through the light cloud will provide a lower limit of the amount of solar radiation being absorbed by the heavy cloud. This transmitted flux can be estimated from the product of the heavy cloud transmission and available solar radiation beneath the light cloud.

The spectrum of the absorbed flux can be derived from the difference between the transmitted spectral flux for the light cloud and the transmitted spectral flux for the heavy cloud. This absorbed spectrum of energy is depicted by curve A in Figure 4; the integration of curve A over frequency shows that the flux absorbed by the heavy cloud was 80 W/m^2. This can be checked from the transmitted fluxes; the integrated flux transmitted through the light cloud was 136 W/m^2 and the integrated flux transmitted through the heavy cloud was 56 W/m^2. Hence the absorbed flux was 136 - 56 or 80 W/m^2.

Also included in the figure is a modelled result of the liquid water absorption (curve B) at a resolution of 50 cm^{-1} in a 1-km thick stratus cloud with a top altitude of 2 km and an overhead sun [Davies *et al*., 1984]. The model was based on LOWTRAN 5 transmission functions [Kneizys *et al*., 1980] and Monte Carlo simulations of the photon pathlength distributions. The two curves show a similar trend in absorption features as a function of wavelength, except in the 8000-10000 cm^{-1} region where the measured absorption is about twice as large as the modelled result, indicating that liquid water is absorbing more radiation.

The lack of any non-liquid water spectral signatures in the measured absorption result strongly indicates that no other sources of absorption are present. The spectrally integrated liquid water absorption in the 2500-11000 cm^{-1} region was determined to be 80.0 for the observed and 95.5 W/m^2 for the modelled results. The small absorption band located above 10000 cm^{-1} in the modelled result, but missing in the observed result due to the detection limit of the spectrometer, accounts for about 5 W/m^2. The lower limit measurement of 80 W/m^2 is a conservative estimate; an additional 56 W/m^2 is still available for absorption under the heavy cloud in Figure 2, as determined from the integral of the product of the heavy cloud transmission and clear sky irradiance. This amount of radiation being absorbed by the clouds is about 46 W/m^2 greater than the 4% of the incident solar radiation previously attributed to cloud absorption as shown by Kiehl [Kerr, 1995], and is consistent with the anomalous amounts ranging from 25 W/m^2 to over 150 W/m^2 that have been observed from total flux measurements [*Cess et al*., 1995; *Ramanathan et al*., 1995; *Pilewskie and Valero, 1995*].

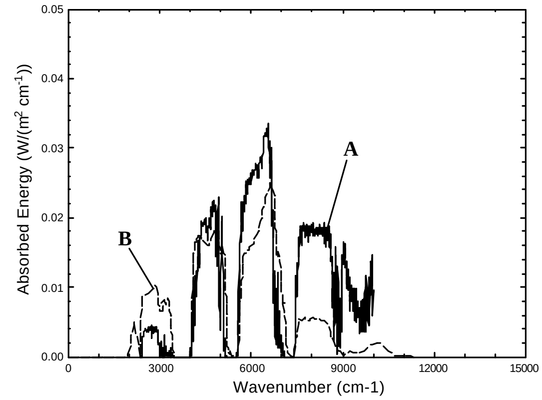


Figure 4: A comparison of the energy absorbed primarily by liquid water in very heavy overcast cloud (curve A) and the modelled result of a liquid water in a 1 km thick stratus cloud at a resolution of 50 cm^{-1} (curve B).

The spectrally integrated liquid water absorption was determined to be 80.0 W/m^2 for the observed and 95.5 W/m^2 for the modelled results [Davies et al., 1984]. Therefore, the magnitude of the absorbed radiation and the consistency between the spectra for pure liquid water and heavy precipitating clouds suggests that the mechanism by which clouds anomalously absorb radiation is through large liquid water droplets in clouds that have approximately a total path of the order of 2 mm. The many scatterings by the sea of small droplets surrounding the large droplets will multiply the number of passes through the large droplets which absorb with the characteristic spectrum of liquid water. The actual size distribution of the droplets is expected to vary with cloud type, and will thereby have a characteristically different liquid water absorption dependence which will affect the quantity of solar radiation absorbed depending on the number of large droplets present.

4. CONCLUSIONS

The implications concerning climate models from the work reported in this paper are highly significant. Our spectral measurements of the spectra of the NIR shortwave flux on clear and precipitating cloudy days have yielded important information on a strong NIR cloud absorption effect. The measured absorption spectrum of the unknown absorber indicates that the absorber is liquid water. On cloudy days with precipitation, the infrared portion of the solar spectrum from 1 to 4 microns is absorbed preferentially by clouds. The amount of solar radiation absorbed by heavy precipitating clouds was estimated to be in excess of 80 W/m^2 or about 46 W/m^2 more than the 4% (35 W/m^2) of the incident solar radiation previously assumed in climate models. A comparison of the measured absorption coefficients for clouds and pure liquid water indicates that liquid water absorption is a primary mechanism by which precipitating heavy clouds anomalously absorb shortwave solar radiation. This implies that most cloud radiation codes are not properly incorporating NIR absorption by liquid water in precipitating clouds including Virga in which rain does not actually reach the ground.

Acknowledgements

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References

Cess, R.D., M.H. Zhang, P. Minnis, L. Corsetti, E.G. Dutton, B.W. Forgan, D.P. Garber, W.L. Gates, J.J. Hack, E.F. Harrison, X. Jing, J.T. Kiehl, C.N. Long, J.-J. Morcrette, G.L. Potter, V. Ramanathan, B. Subasilar, C.H. Whitlock, D.F. Young and Y.Zhou, 1995: Absorption of solar radiation by clouds: Observations versus models, *Science, **267***, 496-499.

Davies, R., W.L. Ridgway and K-E. Kim, 1984: Spectral absorption of solar radiation in cloudy atmospheres: a 20 cm^{-1} model, *J. Atmos. Sci.*, **41**, 2126-2137.

Evans, W.F.J. and E. Puckrin, 1996: Near Infrared Spectral measurements of Liquid Water Absorption by Clouds, *Geophys. Res. Lett*., 23,1941-1944.

Evans, W.F.J., C. Reinhart and E. Puckrin, 1995: A Ground Based Measurement of the Anomalous Cloud Absorption Effect, *Geophys. Res. Lett*., 22,2135-2138.

Kerr, R.A., 1995: Darker clouds promise brighter future for climate models, *Science*, **267**, 454.

Kondratyev, K. Ya., 1969: *Radiation in the Atmosphere*, 912 pp., *Academic Press*, New York.

Pilewskie, P. and F.P.J. Valero, 1995: Direct observations of excess solar absorption by clouds, *Science*, **267**, 1626-1629.

Ramanathan, V., B. Subasilar, G.J. Zhang, W. Conant, R.D. Cess, J.T. Kiehl, H. Grassl and L. Shi, 1995: Warm pool heat budget and shortwave cloud forcing: A missing physics, *Science, **267***, 499-503.