NOTES AND CORRESPONDENCE

Cloud Phase Discrimination by Reflectance Measurements near 1.6 and 2.2 μm

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21 May 1987

1. Introduction

In a recent paper and conference proceedings, the authors (Pilewskie and Twomey, 1986, 1987) discussed and showed experimental results from an instrument which utilized differences in the optical properties of ice and liquid water in the near-infrared to sense remotely the "glaciation" process in growing cumulus congestus clouds. Glaciation of condensed water clouds is important for several reasons: it releases a large amount of latent heat; it is often a precursor to precipitation and a prerequisite for thunderstorm electrification and hail formation; and cloud seeding for precipitation enhancement is based on the premise that clouds are often reluctant to glaciate naturally and can be stimulated by suitable seeding agents. Glaciation does not occur systematically at a predetermined temperature or height, and the incidence of ice at a given temperature level is highly variable (Hallet and Mossop, 1974).

When the results reported in Pilewskie and Twomey (1986) were presented at the AMS Sixth Conference on Atmospheric Radiation in Williamsburg, Virginia some conference members contended that the optical effects which we had attributed to glaciation could be explained by the appearance of large liquid drops; in sufficient numbers, such drops could produce the abrupt decrease in cloud reflectance around 1.6 μm that we had observed and attributed to the appearance of ice particles.

We now have experimental results from an improved version of the instrument, and we believe that these new results identify unambiguously the cause of the decreased reflectance around 1.6 μm; the improved version also extended the instrument's spectral range, so that features due to ice/liquid spectral differences around 2.2 μm could be examined. This note intended to describe briefly these new results.

2. Instrumentation

The detector was changed to a self-cooled lead sulfide photoconductor (Hamamatsu), which provided better signal-to-noise as well as improved spectral range and resolution. (The data system was also improved to provide for faster transmittal and archiving of spectra, but that aspect is hardly material to the present discussion.) As before, spectral discrimination was obtained by a circular variable filter (Optical Coating Laboratory, Inc.), and a signal averager (Princeton Applied Research) enabled individual spectra (acquired at 5 s^{-1}) to be summed to improve their quality.

3. Results

Figure 1 is an example of the spectral change previously attributed by us to glaciation and shows two spectra obtained from the same cloud in 1985. Between 1.55 and 1.75 μm (which is a "window" region for water vapor, in the sense that vapor absorption there is very small and can be neglected), the cloud reflectance (which up to then had shown the spectral behavior exhibited in A) fell to the level indicated in B, and thereafter remained around that latter value. It was that transition from A-type to B-type that we attributed to extensive ice formation (a few ice crystals among many water droplets could not produce an effect of that sort). As shown in Fig. 2, published data on absorption coefficients (Irvine and Pollak, 1968; Hale and Querry, 1973; Warren, 1984) show substantial differences between liquid water and ice in the 1.5–1.75 μm region, with ice absorbing up to 40% or so more strongly near the absorption minimum.

The reflectance of a thick cloud (a high-order, multiple-scattering effect) is dictated primarily by its single-scattering albedo, $\bar{\omega}_0$, which is influenced by both average drop (or particle) size, $\bar{r}$, and absorption coefficient, k. When $k\bar{r}$ is small compared to unity (which it is here), then $1 - \bar{\omega}_0$ is directly proportional to $k\bar{r}$; for optically deep layers, a reflectance which, in the absence of absorption would be unity (or close to it) is reduced below unity in proportion to $(1 - \bar{\omega}_0)^{1/2}$, i.e., $(k\bar{r})^{1/2}$. Thus a reduction in reflectance such as that shown in Fig. 1 could be brought about by either an increase in k (e.g., ice formation) or an increase in $\bar{r}$.

Reflection decreases more than one-half, as occurred in Fig. 1 near 1.6 μm, could be attributed to an approximate fourfold increase in $\bar{r}$, rather than in k. Around 1.6–1.7 μm, absorption in ice is about 14 to 30 cm^{-1} (Warren, 1984), while in the liquid, it is about

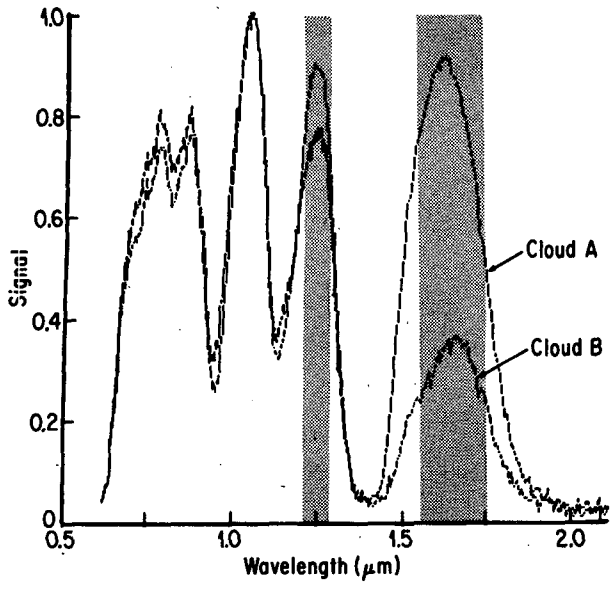

FIG. 1. Two spectra from the same cloud east of Tucson, AZ, on 27 August 1985. The cloud B spectrum was recorded 5 min after that of cloud A. Shaded regions indicate water-vapor absorption windows.

5 to 6 cm^{-1} (Irvine and Pollak, 1968; Hale and Querry, 1973). That, of course, was the point raised at the Williamsburg conference.

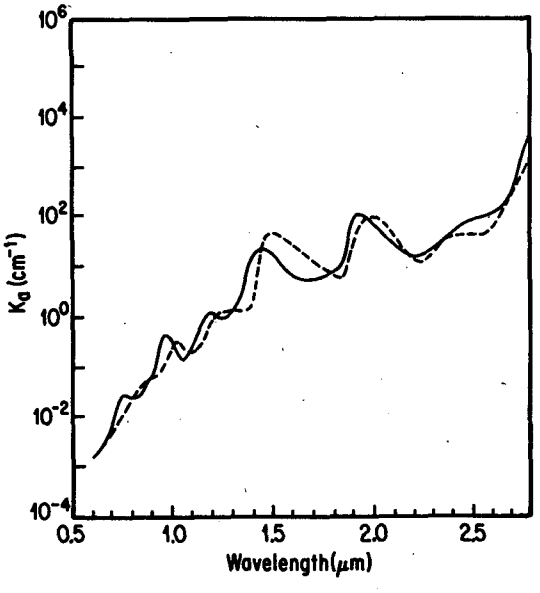

FIG. 2. Bulk absorption coefficients for water (solid curve) and ice (dashed).

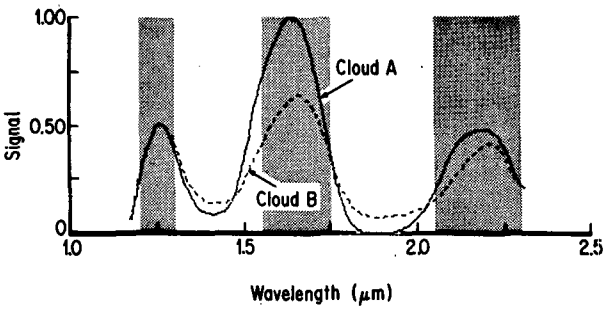

FIG. 3. Two spectra from the same cloud to the northeast of Tucson on 8 August 1986, obtained with the modified spectroradiometer. The cloud B spectrum was recorded 7 min after that of cloud A. Again, shaded regions indicate water-vapor absorption windows.

Figure 2 shows that the wavelengths of absorption minima and maxima also differ between water and ice, the latter being almost 0.1 μm longer than the former. There is, in fact, a suggestion of this wavelength shift in Fig. 1, but it is not very convincing. However, our 1986 results, with the newer version of the instrument, show the shift very clearly and consistently. Figure 3 shows similar spectra from summer 1986; these demonstrate also very clearly that when reflectance near 1.6 μm fell, the peak shifted towards longer wavelengths by about 0.1 μm, which cannot be explained by any change in size alone. The reduction of the signal level around 2.2 μm was also accompanied by a shift of the local maximum in this region. These newer experimental results unambiguously point to glaciation (i.e., a fairly sudden change from predominantly liquid phase to predominantly solid phase) as causing large changes in reflectance around 1.6 μm and 2.2 μm.

REFERENCES

Hale, G. M., and M. R. Querry, 1973: Optical constants of water in the 200 nm to 200 m wavelength region. *Appl. Opt.*, **12**, 555–563.

Hallett, J., and S. C. Mossop, 1974: Production of secondary ice particles during the riming process. *Nature*, **249**, 26–28.

Irvine, S. M., and J. B. Pollack, 1968: Infrared properties of water and ice spheres. *Icarus*, **8**, 324–360.

Pilewskie, P., and S. Twomey, 1986: Cloud spectral reflectance in the near-infrared. Extended Abstracts, *Sixth Conf. on Atmospheric Radiation*, Williamsburg, Amer. Meteor. Soc., 63–65.

——, and ——, 1987: Discrimination of ice from water in clouds by optical remote sensing. *Atmos. Research*, (in press).

Warren, S. G., 1984: Optical constants of ice from the ultraviolet to the microwave. *Appl. Opt.*, **23**, 1206–1224.