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ANALYSIS OF CIRRUS OPTICAL PROPERTIES WITH DATA FROM THE NASA ER2 HIGH-RESOLUTION INTERFEROMETER SOUNDER (HIS)

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I. INTRODUCTION

The 8-13 μm spectral region is an important atmospheric window for radiometric studies of the earth's surface and clouds. Most of the earth-atmosphere longwave radiative loss to space occurs in this spectral region. Selective gaseous absorption in this window occurs in the 9.6 μm ozone band with the remaining absorption dominated by the water vapor continuum. Cirrus clouds have a large impact on the transmittance of this atmospheric window region (Platt, 1973; Liou, 1974; Stephens, 1980; Wu, 1984); it is therefore important to understand the interaction of cirrus cloud with the radiation field for climate studies and in the interpretation of satellite radiometric measurements.

The focus of this research was to employ observations of the High-resolution Interferometer Sounder (HIS) made during First ISCCP Regional Experiment (FIRE) to improve our understanding of the radiative properties of cirrus clouds within this window region. Studies were undertaken to investigate the coupling between the microphysical properties of cirrus clouds and their spectral variation within this window region. Extensions of the HIS studies to satellite measurements, with regards to remote sensing and interpretation, were also investigated. This final report summarizes the major findings of this grant. Publications are included in Appendix A.

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II. RESULTS

This grant supported the investigation of three research areas: the variability of cirrus emittance in the infrared window, the inference of cirrus cloud microphysical properties using HIS observations, and the simulation of satellite observations using the HIS data for studying cirrus cloud detection algorithms. The principle findings from these research areas are briefly discussed below.

A. Variability of Cirrus Emittance in the Infrared Window

The study by Ackerman *et al.* (1990) [Appendix A] indicated that the cirrus emissivity in the 8-12 μm spectral region decreases with decreasing wavelength. An example of this spectral dependency is depicted in Fig. 1, in which a set of four (clear, alto-cumulus, and two cirrus) HIS spectral measurements in the 8-13 μm "window" region are shown for 2 November 1986 near Madison, WI. The individual gaseous absorption lines, primarily due to water-vapor, are evident in the clear and alto-cumulus cloud case depicted in Fig. 1. The effect of the water-vapor continuum in the clear spectra is seen as a trend of decreasing equivalent blackbody temperature with increasing wavelength in the 10-13 μm window. The high thick cirrus case also depicts a decreasing trend with a blackbody temperature difference of 5°C between 10 and 12 μm, this change is due to cloud

Figure 1. Four HIS spectra (clear, altocumulus and two cirrus) over the spectral range 8-13 μm observed during the 28 October 1986. The dotted and dashed lines are theoretical calculations.
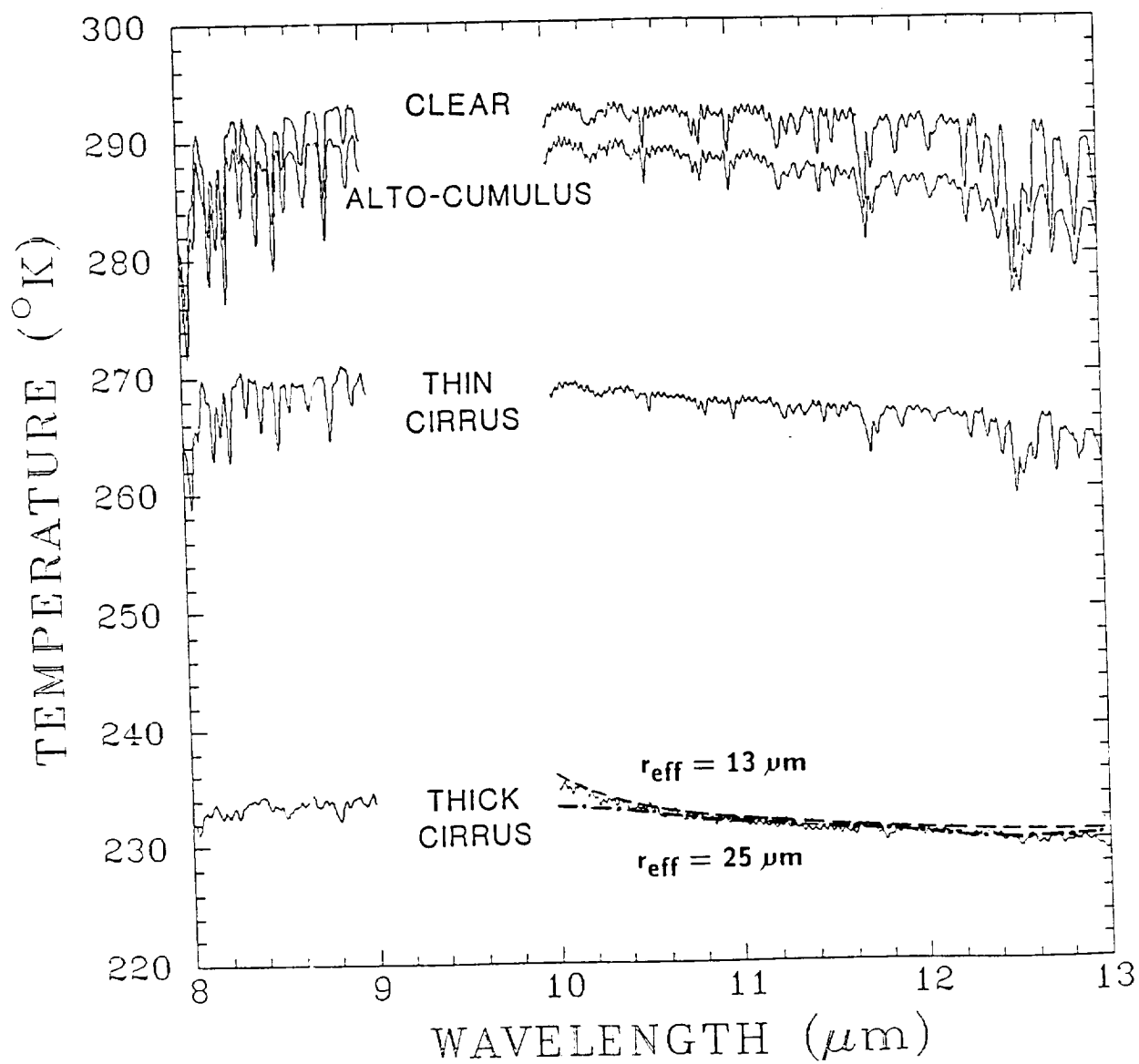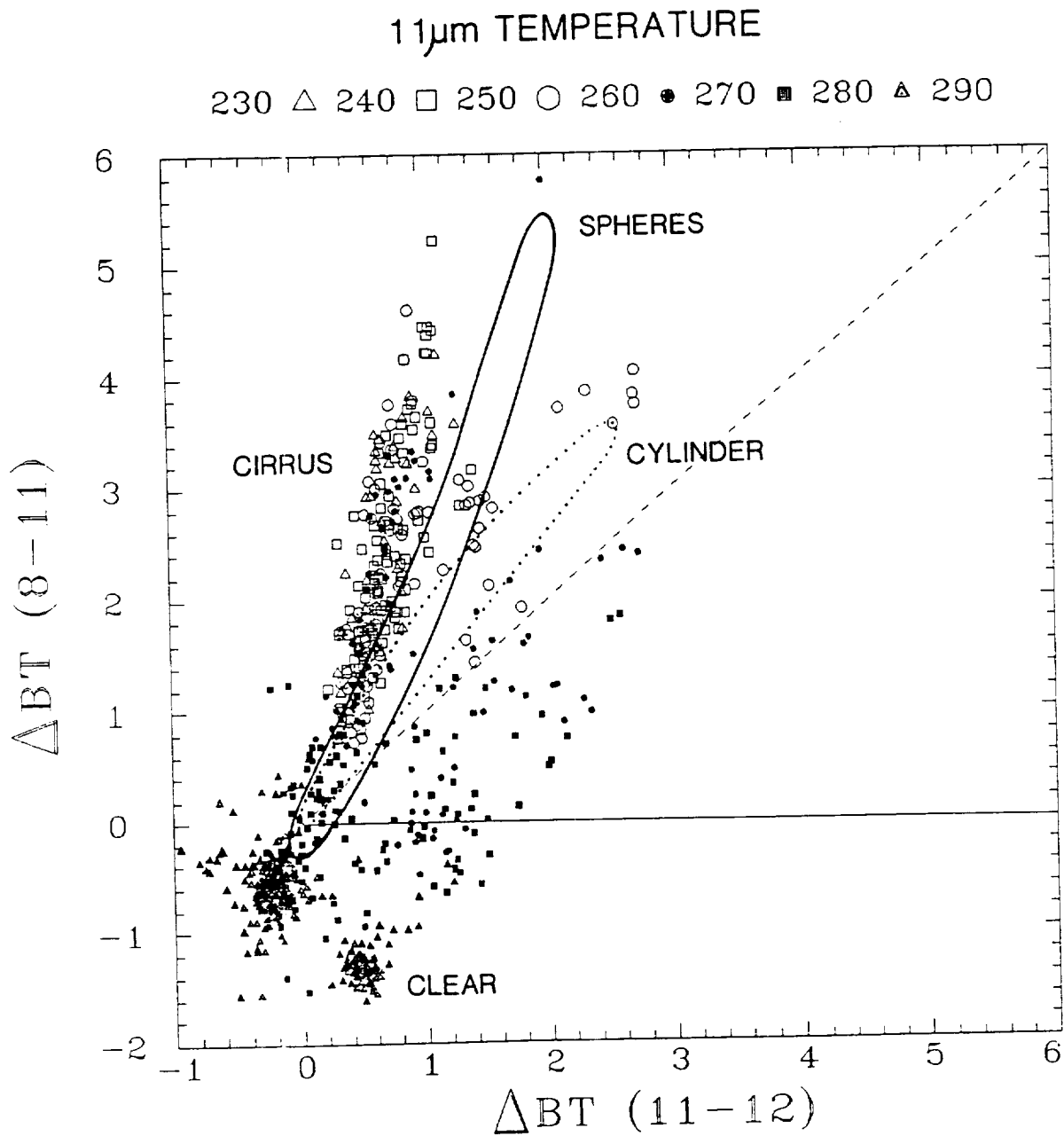
radiative properties and is consistent with the absorption coefficient of ice. This large brightness temperature difference is indicative of the spectral variability of cirrus optical properties in the window region.

To further investigate this spectral variability, a method of inferring cirrus cloud spectral emissivity using HIS and lidar data was developed under this grant and applied to data collected during FIRE (Ackerman *et al.*, 1990). The cirrus cloud beam emissivity derived from data collected on October 28, 1986 were primarily limited to between 0.4-0.9 with less than 30% of the cases studied having beam emissivities less than 0.4. Fifty percent of the clouds on this day displayed a difference in the beam emissivity between 10 and 12 μm of greater than ± 0.2 The temperature dependency of the effective beam emissivity on the integrated cloud attenuated backscatter was similar to that observed by Platt and Dilley (1981): for a given emissivity, colder clouds had a smaller attenuated backscatter.

B. Inference of Cirrus Cloud Microphysical Properties

This project demonstrated a technique of detecting cirrus and inferring their optical properties using an 8 μm channel in conjunction with 11 and 12 μm channels. The method is based on the brightness temperature (BT) differences between these channels. The technique is demonstrated in Fig. 2 as a scatter diagram of the BT_8-BT_{11} versus BT_{11}-BT_{12} observations made with the HIS aboard the NASA ER2 during FIRE (November 2, 1986). Each symbol in the figure represents a range in the BT_{11} as noted in the legend. The difference in the brightness temperatures observed in these channels are very useful in detecting the presence of cirrus clouds. The cloud-free regions, determined from lidar observations (Spinhirne and Hart, 1990), have negative differences of BT_8-BT_{11}

Figure 2. HIS observed brightness temperature differences between 8 and 11 μm versus 11 and 12 μm.

11μm TEMPERATURE

230 △ 240 □ 250 ○ 260 ● 270 ▣ 280 △ 290

SPHERES

CIRRUS

CYLINDER

CLEAR

$\triangle$BT (8$-$11)

$\triangle$BT (11$-$12)

due to absorption by water vapor, while cirrus clouds have positive differences owing to the optical properties of ice. The cirrus BT_8-BT_{11} are greater than the BT_{11}-BT_{12} as expected from the theoretical models. For liquid water clouds we expect the BT_8-BT_{11} to be less than the BT_{11}-BT_{12}, and would therefore lie to the right of the dashed line in Fig. 2.

An envelope of results from model calculations, assuming a distribution of spherical ice particles, is depicted in Fig. 2 by the solid line. From theoretical calculations it was found that the large BT differences observed by the HIS are associated with cirrus particle size distributions which have a small effective radius. The magnitude of the BT differences is also related to the ice water path (e.g., very thin clouds are similar to clear sky values). A method of determining the cloud effective radii from the HIS measurements was demonstrated by Ackerman *et al.* (1990) (Appendix A).

Differences between theoretical calculations and observations are seen in Fig. 2 at the larger BT_8-BT_{11} differences. This difference may be attributed to particle shape. The effect of particle shape is demonstrated in the figure by the dashed line which is the envelop for a cirrus cloud consisting of small ice crystals of cylindrical shape. We plan to continue investigating the relationship between particle shape and the spectral observations in the 8-12 μm window.


C.   Satellite Remote Sensing of Cirrus

One of the objectives of the FIRE was to provide verification and improve satellite cloud retrieval techniques (Cox *et al.*, 1987). The 10-12 μm band is a standard spectral region for meteorological satellite observations and has been used extensively for applications in the remote sensing of clouds and of the earth's surface. Bi-spectral measurements in the 10 to 12 μm region have been developed for remotely sensing the presence of cirrus clouds and their optical properties (e.g.,

Inoue, 1985; Prabhakara *et al.*, 1988). A drawback of a bi-spectral technique at these wavelengths is that the brightness temperature generally decreases between 10 and 12 μm, whether viewing a cloud or a clear region.

The 8, 11 and 12 μm three channel technique was demonstrated above with the HIS data. The HIRS/2 on board the NOAA-9 satellite has an 8.2 and an 11.1 μm channel, while the AVHRR channels 4 and 5 provide 11 and 12 μm observations. The HIRS/2 and AVHRR channels have a much broader spectral bandwidth than that of the HIS three channel technique demonstrated in Fig. 2. An advantage of the HIS observations is that they can be integrated over the bandpass and spectral response function of narrow band instruments to simulate measurements made from satellites. This allows one to study the capabilities of the HIRS/2 and AVHRR combined observations for cirrus cloud studies. Figure 3 is the brightness temperature difference between these simulated HIRS/2 and AVHRR channels from HIS observations made on November 2, 1986. The pattern depicted in Fig. 3 is similar to that of Fig. 2 in which optimum wavelengths for cirrus cloud detection were selected. The broader spectral channels of the HIRS/2 and AVHRR primarily result in a change in the threshold for cirrus cloud detection. For example, clear regions in Fig. 3 have BT_8-BT_{11} of less than -2°C as opposed to the 0°C threshold of Fig. 2. Collocated observations from the HIRS/2 and AVHRR on the NOAA-9 therefore provide a potential data set to study the radiative properties of cirrus clouds using the three channel technique developed under this grant. We are presently expanding the software to apply the three channel technique to collocated HIRS/2 and AVHRR observations.

Figure 3. HIRS/2 simulated brightness temperature differences between 8.2 and 11.1 μm versus the HIS simulated AVHRR difference between 11 and 12 μm.
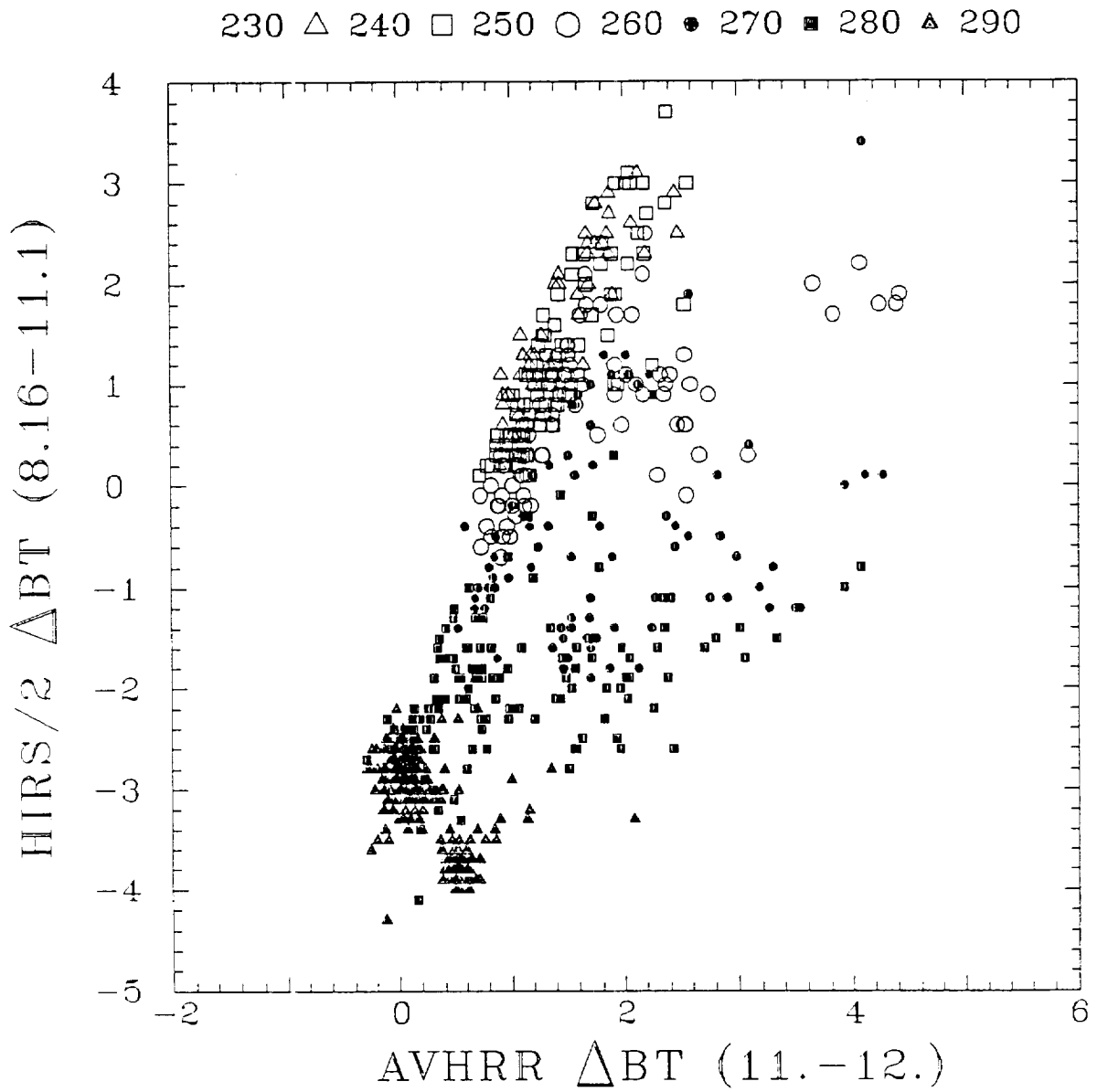
III. CONCLUDING REMARKS

The major findings of the research grant can be summarized as follows:

♦ The HIS observations depict spectral variations in equivalent blackbody temperature in the window region of greater than 5°C for a given cirrus cloud.

♦ A method of inferring cirrus cloud spectral emissivity using HIS and lidar data was developed and applied to data collected during FIRE.

♦ The brightness temperature differences between 8 and 11 μm are useful parameters for detecting the presence of cirrus clouds. For narrow spectral observations of the HIS this difference is negative for clear regions and positive for cirrus clouds. For the broader spectral bandpass of the HIRS/2, brightness temperature differences greater than -2°C are indicative of cirrus.

♦ Theoretical calculations indicate that the magnitude of the spectral variation in brightness temperature is related to the particle size. The smaller particles are associated with the larger brightness temperature differences.

♦ The magnitude of the brightness temperature differences are also related to the particle shape. Calculations assuming spherical particles are in better agreement with the majority of HIS observations than similar calculations assuming cylindrical particles.

♦ Collocated HIRS/2 and AVHRR NOAA-9 observations provide a potentially useful data set for developing and applying a cirrus cloud retrieval method from observations at 8,11 and 12 μm.

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