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Cirrus Cloud Statistics: Temperatures and Optical Depths

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Measurements of the upwelling infrared radiance at 10.5 μm and 6.5 μm were obtained during the FIRE Cirrus Intensive Field Observations using a radiometer with a 15° cone nadir field-of-view flown on the NASA Ames ER-2. Data is recorded at a frequency of 1 Hertz and the radiometer is continuously calibrated with a liquid nitrogen black-body source, thereby providing a large number of very accurate radiance values during the course of a several hour flight. For this study, we are particularly concerned with the statistical properties of the cirrus deck as deduced from the radiance data. We have focused primarily on the data acquired on 28 October 1986, but also show some data from other flights for comparison purposes.

A histogram of the 10.5 μm brightness temperatures obtained on 28 October between approximately 15:30 and 19:00 GMT is shown in Figure 1. (Brightness temperature is defined as the temperature of a black body that would emit the observed radiance in the same spectral interval.) The distribution shows two distinct peaks. The narrow peak at the higher end represents the range of surface temperatures observed during the flight, with the additional possibility of some observations of very thin cirrus. The broader distribution of colder temperatures represents the distribution of cirrus optical depths ranging from relatively thin to optically thick values. Comparison of cloud heights as deduced from the airborne lidar data (J. Spinhirne, personal communication) and radiosonde profiles (D. Starr, personal communication) show that the actual temperature of the cloud deck was on the order of 235 K. This is quite consistent with the lowest observed brightness temperatures, indicating that the cloud was optically thick in places.

If we neglect any atmospheric emission at 10 μm, we can estimate the cirrus optical depth from the simple relationship:

$$B_E = B_S e^{-\tau} + B_C(1 - e^{-\tau}) + B_S \delta_S - B_C \delta_C.$$

Here B_E is the measured radiance, B_S is the surface emission, B_C is the cloud emission, and τ is the cirrus optical depth. Because ice crystals scatter as well as absorb infrared radiation, correction terms for scatter into the radiometer field of view, δ_S, and for reduced emission from the cloud, δ_C, must be included. These correction terms are calculated with

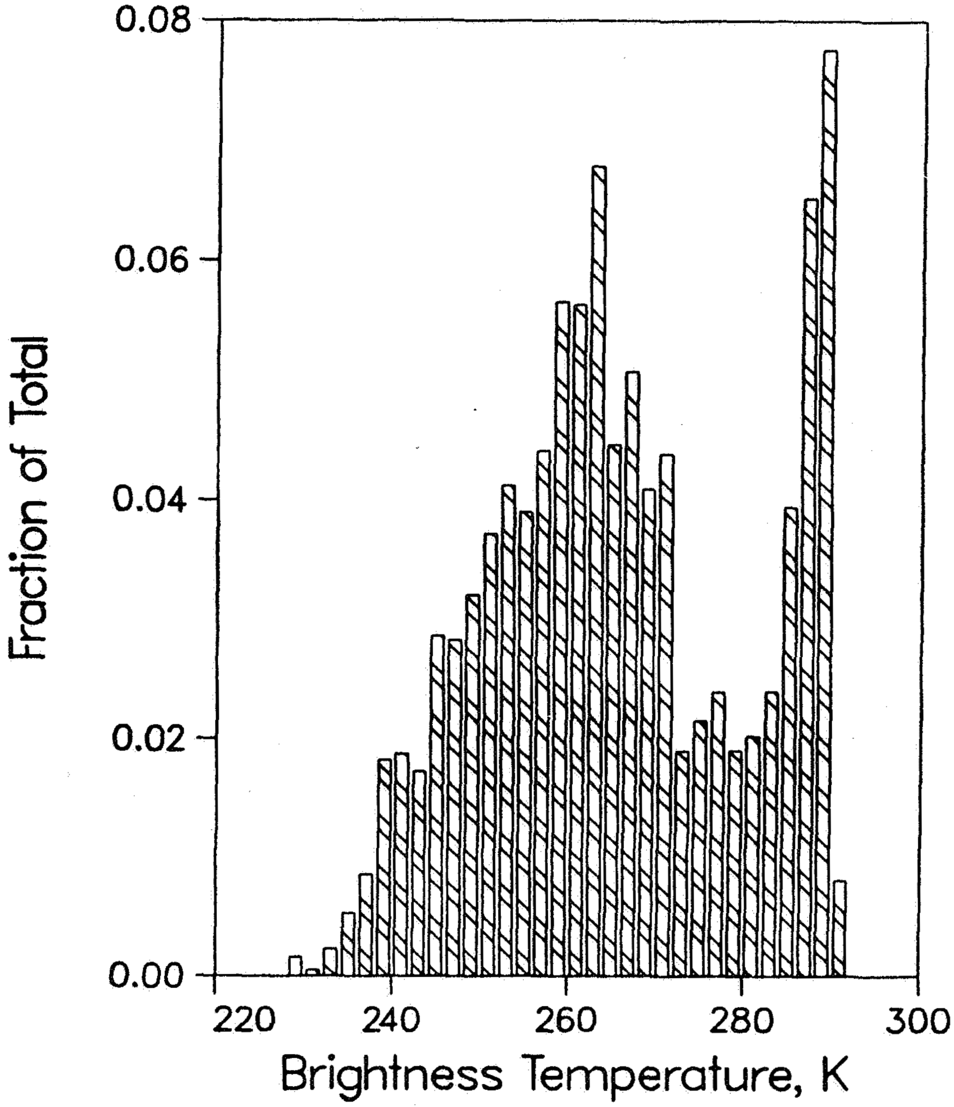

Figure 1: Histogram of 10.5 μm brightness temperatures (in degrees Kelvin) obtained on 28 October, 1986. The bars represent 2K temperature increments and the vertical axis is the fraction of the total observations falling into the given bin.

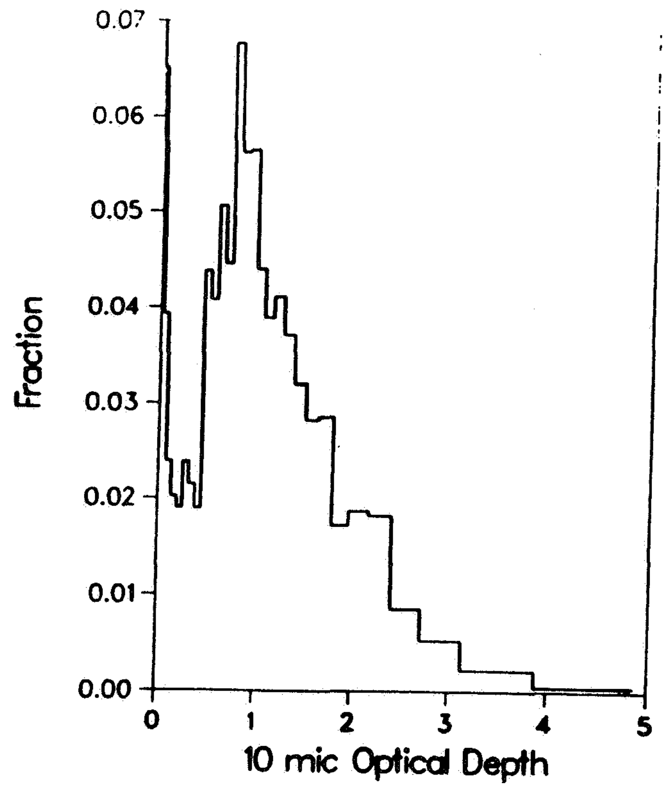

Figure 2: Cirrus 10 μm optical depth inferred from the observed brightness temperature distribution. The vertical axis is the fraction of total observations falling into the given bin.

a simple radiance model incorporating a two-stream source term. A trial value of τ is calculated assuming no scatter and the equation is then solved iteratively and converges in a few iterations.

The results of the optical depth inversion process applied to the distribution in Figure 1 is shown in Figure 2. Here we have assumed that the actual cloud temperature is given by the lowest observed brightness temperature and the actual surface temperature by the highest observed temperature. The latter assumption produces the probably spurious peak of very low optical depths seen in Figure 2. The broad distribution of optical depths appears to be approximately log-normal in shape with a geometric mean of about 0.9. The inversion process is uncertain at large optical depths (since the $e^{-\tau}$ terms tend to 0), so we truncate the distribution at optical depths of about 5.

Given a distribution of optical depths, the atmospheric temperature profile, and the location of the cirrus layer, we can then compute the infrared exchange and atmospheric heating rates. We have used a multi-spectral, two-stream code to compute the broad-band infrared heating rates in the cirrus layer as a function of optical depth. The results of these calculations are compared to the upwelling infrared flux measurements obtained from the ER-2.

Finally, we have carried out similiar analyses for the entire 6.5 μm data record and for sub-sections of the 28 October flight, as well as for some of the other cirrus IFO flights. We show that the distributions of brightness temperature and optical depth vary with time and synoptic situation.