REMOTE SOUNDING OF THE TEMPERATURE PROFILE AND CLOUD THICKNESS IN CIRRUS CLOUDY ATMOSPHERES FROM NIMBUS VI HIRS CHANNELS

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INTRODUCTION

Investigation on the estimate of cloud properties and temperature field from passive satellite sensing has been extremely limited because of the complexity of the cloud interaction with the radiation field of the atmosphere. This is especially evident for the high, semi-transparent cirrus clouds, consisting of non-spherical ice crystals of various sizes possibly having a preferred orientation in the atmosphere. Cirrus clouds are good indicators of the weather to come and play significant roles in the climate of the earth-atmospheric system. More importantly, from the passive remote sensing point of view, semi-transparent cirrus clouds produce significant interference effects which jeopardize the information content of the atmospheric composition and structure. Since upwelling radiances from the carbon dioxide or water vapor bands contain simultaneous information of the cloud and the temperature field of the atmosphere, it would seem that the temperature profile and certain cirrus cloud information may be derived from a combination of sounding channels. The prime objective of this paper is to explore this idea utilizing the Nimbus VI HIRS (High Resolution Infrared Sounder) channels.

BASIC EQUATIONS FOR REMOTE SOUNDING OF CLOUDY ATMOSPHERES

We consider a complete cirrus cloudy atmosphere in which the upwelling radiance at the top of the atmosphere may be theoretically expressed by [1]

$$I_\nu(\infty) = \frac{\tau_\nu^C(\Delta z)}{\tau_\nu(\Delta z)} \{B_\nu(T_s)\tau_\nu(\infty,0) + \int_0^{z_b} B_\nu[T(z)]d\tau_\nu(\infty,z)\} + \int_{z_b+\Delta z}^{\infty} B_\nu[T(z)]d\tau_\nu(\infty,z), \quad (1)$$

where τ_ν denotes the clear column transmittance in reference to the top of the atmosphere, z_b the cirrus cloud base height, Δz the cloud thickness, $B_\nu(T)$ the Planck function of temperature T, T_s the surface temperature, and the cloud transmissivity $\tau_\nu^C(\Delta z)$ is defined as the ratio of the upwelling radiance at the cloud top to that at the cloud base. When Δz=0, Eq. (1) reduces to the clear column transfer equation. To formulate iteration procedures for the recovery of the temperature profile and cloud parameters simultaneously, we assume that the cirrus base height is a constant and that the cirrus cloud transmissivity is equal to $\exp(-\bar{\beta}_e\Delta z)$, where $\bar{\beta}_e$ is a prescribed mean extinction coefficient for ice particles. For the cloud thickness retrieval, we select a spectral channel in the window region where the effect of water vapor absorption above the cirrus cloud layer can be neglected. The final relaxation equation for the thickness iteration is given by

$$\Delta z^{(n+1)} \approx \Delta z^{(n)} - \ln[\tilde{I}_i / I_i^{(n)}]/\bar{\beta}_e , \quad (2)$$

where $\tilde{I}_i$ represents the observed value, and ν is replaced by the index i.

As for the temperature profile retrieval, a set of sounding channels in the carbon dioxide band is chosen. Basically, we attempt to reconstruct the clear column temperature profile under cirrus cloud conditions. For this purpose, we utilize the principle of approximating the clear column upwelling radiance by the Planck function of the temperature at the weighting function peak developed by Chahine [2]. The sounding channels are classified into two groups according to the height of the weighting function peak with respect to that of the cloud. After some mathematical analyses, the modified temperature relaxation equation can be written as

$$T^{(n+1)}(z_i) = b\nu_i / \ln \{1-[1-\exp(b\nu_i/T^{(n)}(z_i))] I_i^{(n)'} / \tilde{I}_i'\}. \quad (3)$$

In Eq. (3) b is a constant. For the weighting functions whose peaks are above or within the cloud layer, the modified radiance ratio is defined by

$$\frac{\tilde{I}_i + [1-\exp(-\bar{\beta}_e \Delta z^{(n+1)})/\tau_i]\alpha_i^*}{I_i^{(n)} + [1-\exp(-\bar{\beta}_e \Delta z^{(n)})/\tau_i]\alpha_i^*} = \frac{\tilde{I}_i'}{I_i^{(n)'}} = \frac{B_i[T^{(n+1)}(z_i)]}{B_i[T^{(n)}(z_i)]} , \quad (4)$$

where α_i^* represents the radiance contribution from the surface to the cloud base. If the weighting functions whose peaks are below the cloud, the modified radiance ratio is given by

$$\frac{(\tilde{I}_i - \gamma_i^*)\tau_i \exp(\bar{\beta}_e \Delta z^{(n+1)}) + \gamma_i^*}{(I_i^{(n)} - \gamma_i^*)\tau_i \exp(\bar{\beta}_e \Delta z^{(n)}) + \gamma_i^*} = \frac{\tilde{I}_i'}{I_i^{(n)'}} = \frac{B_i[T^{(n+1)}(z_i)]}{B_i[T^{(n)}(z_i)]} , \quad (5)$$

where γ_i^* denotes the radiance contribution from the cloud top to the top of the atmosphere.

NUMERICAL EXPERIMENTS USING NIMBUS VI HIRS CHANNELS

The Nimbus VI HIRS instrument is a third generation infrared radiation sounder. It consists of 16 channels in the infrared. In this investigation, we employed seven long wave channels in the 15 μm CO_2 band (channels 1-7) for the temperature retrieval and the window channel at 11 μm (channel 8) for the thickness iteration. The cirrus cloud base height z_b was fixed at 400 mb and the mean extinction cross section of ice particles β_{ext} was assumed to be 1 km^{-1}. The procedures for numerical iterations involving temperature retrieval used here were based largely on those proposed by Chahine [3] and Smith [4]. These procedures included the establishment of the convergence criterion and the selection of weighted scaling factors for temperature iterations. A third order orthogonal polynomial was further adopted to smooth the recovered temperature profile. Various cloud thicknesses were inserted in the atmosphere to evaluate the expected upwelling radiance. Mid-latitude summer climatological humidity and temperature profiles were used in the preliminary simulation study.

The resulting thickness retrievals for cirrus thicknesses of 0.5 and 1 km with maximum random errors ranging from 0 to 4 radiance units added to the expected upwelling radiances are shown in Table 1. For a maximum random error of 4%, the deviation from the true thickness is about 0.1 km regardless of the original thickness. A number of numerical experiments show that errors of the recovered thickness appear to be independent of the thickness used. Figures 1 and 2 show the retrieved temperature and temperature error profiles when a synthetic 0.5 and 1 km cirrus whose bases are located at 400 mb are present. The mean temperature errors evaluated from each

TABLE 1 Cirrus Thickness Estimate for Various Random Errors

Δz(km)	Max. Random Error RMS Random Error	0 0	2 1.27	4 2.54
0.5	Δz(km)	0.475	0.416	0.402
1	Δz(km)	0.974	0.917	0.902

50 mb interval are about 1.3°, 1.4° and 1.8°K for the 0.5 km case and about 1.3°, 1.5° and 1.9°K for the 1 km case involving random errors of 0, 2 and 4%, respectively. The retrieved clear column temperature profile not shown here also reveals similar errors.

A number of known cirrus cloudy cases have been chosen to perform the retrieval exercises utilizing the available HIRS radiance data during August 22-25, 1975 when the HIRS instrument was working correctly. Two cases on August 25 are presented here for representative illustration purposes. The NOAA 4 IR picture and synoptic conditions associated with this day have been described by Feddes and Liou [5] in conjunction with the mapping of the ice and water contents over the cloudy areas. The two cases selected were Omaha, Nebraska and Green Bay, Wisconsin where high cirrus only and cirrus with lower precipitating clouds were present, respectively. Figure 3 shows the recovered temperature profile and cirrus thickness for the Omaha case. Initial guess used the middle latitude summer climatological water vapor and temperature profiles. Two available radiosonde temperature soundings at 12Z on August 25 and 00Z on August 26 are also plotted for comparison purposes. A strong diurnal variation of the surface temperature is noted. The recovered temperature profile in general compares well with observed soundings up to the tropopause. The retrieved cloud thickness is about 0.95 km using an extinction coefficient of 1 km^{-1}. This value also agrees well with that derived by Feddes and Liou [5] using a combination of HIRS channels. Figure 4 shows the retrieval results for the Green Bay case. The recovered temperature profile reveals unsatisfactory fluctuation probably caused by the presence of a low cloud deck. The 0.45 km cirrus thickness derived in this illustration seems reasonable in comparison with that derived by Feddes and Liou.

In summary, the retrieval program developed here appears to be working successfully for single cirrus cloud layers based on numerous case studies using the real HIRS data. However, it is unsatisfactory for the temperature retrieval when low clouds are present. Thus, in order to derive realistic temperature profiles it would seem that a separate sounding program for clouds may first be required. On the basis of the cloud field determination, we may classify cloudy conditions into various groups such as cirrus alone, cirrus with low nonprecipitating clouds, cirrus with precipitating clouds, etc. Sounding techniques may then be explored for each specific cloudy case to investigate the feasibility of the temperature profile inference.

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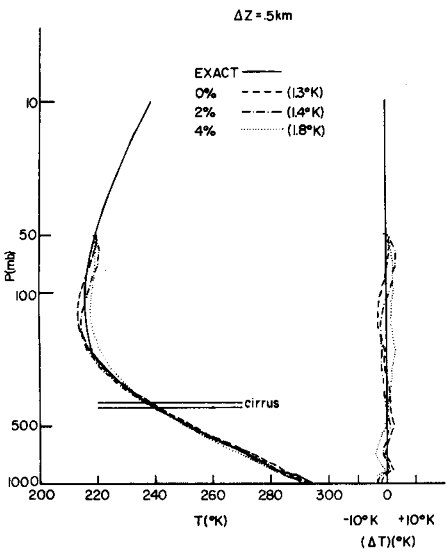

Fig. 1. Synthetic temperature profile retrieval involving a 0.5 km cirrus.

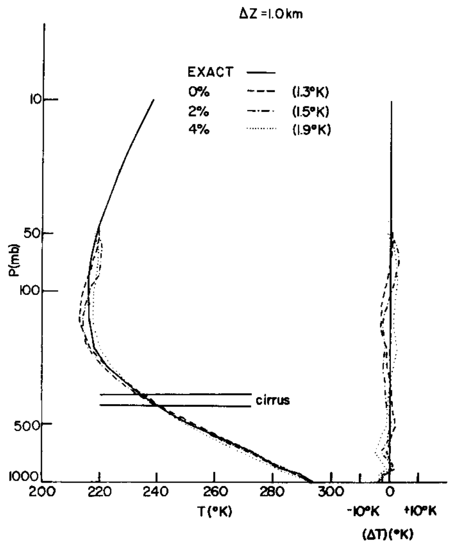

Fig. 2. Synthetic temperature profile retrieval involving a 1 km cirrus.

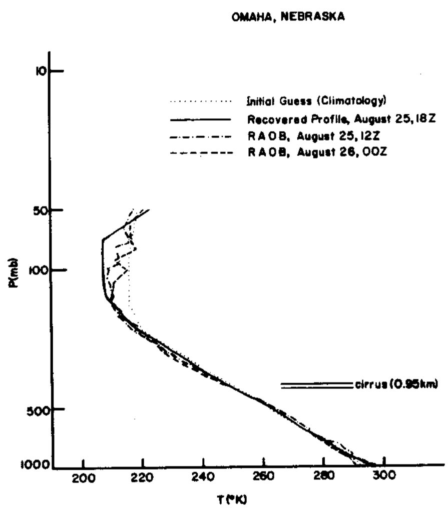

Fig. 3. Temperature profile and cirrus cloud thickness retrieval for a single cirrus layer (Omaha, NB) from HIRS radiances on August 25, 1975, 18 Z.

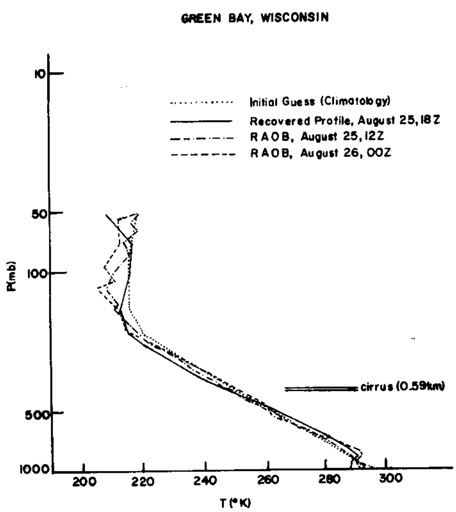

Fig. 4. Temperature profile and cirrus cloud thickness retrieval for cirrus with a low precipitating clouds (Green Bay, WI) from HIRS radiances on August 25, 1975, 18 Z.