N91-10474

Cloud Altitude Determinations from Infrared Spectral Radiances

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Abstract

The "CO_2 slicing" method[1,2,3] is generally recognized as the most accurate means of inferring cloud altitude from passive infrared radiance observations. The method is applicable to semi-transparent and broken cloud. During the cirrus-FIRE and COHMEX field experiments, CO_2 channel radiance data suitable for cloud altitude specification were achieved from moderate spectral resolution satellite sounders (NOAA-TOVS[4] and GOES-VAS[5]) and from a High spectral resolution Interferometer Spectrometer (HIS) flown on the NASA U2/ER2 aircraft. Also aboard the ER2 was a down-looking active lidar unit[6,7] capable of providing cloud top pressure verifications with high accuracy (~5 mb). A third instrument[8], the Multispectral Atmospheric Mapping Sensor (MAMS) provided 50 meter resolution infrared "window" data which is used with radiosonde data to verify the heights of middle and low level clouds. In this paper, comparisons of lidar and MAMS/radiosonde "ground truth" cloud heights are made with those determined from: (a) high resolution (0.5 cm^{-1}) HIS spectra, (b) HIS spectra degraded to the moderate resolution (15 cm^{-1}) of the VAS/TOVS instruments, and (c) spectrally averaged HIS radiances for individual pairs of VAS spectral channels. The results show that best results are achieved from high resolution spectra; the RMS difference with the "ground truth" is 23 mb. The RMS differences between the infrared radiance determination and ground truth increase by 35% when the spectral resolution is degraded to the moderate spectral resolution of the VAS/TOVS instruments and by 52% to 183%, depending upon channel combination, when only two spectral channels at VAS/TOVS spectral resolution are used.

1. Introduction

The working equation of the CO_2 slicing method[2] is

$$\frac{I_1(\nu) - I_2(\nu)}{I_1(\nu_o) - I_2(\nu_2)} = \frac{\int_{P_c}^{P_s} \tau(\nu,P)\,\frac{\partial B(\nu, T(p))}{\partial \ln p}\, d\ln p}{\int_{P_c}^{P_s} \tau(\nu_o,P)\,\frac{\partial B(\nu_o, T(p))}{\partial \ln p}\, d\ln p} = C(p_c) \tag{1}$$

where I is an observed spectral radiance at wavenumber (or spectral channel) ν, subscripts 1 and 2 refer to geographically independent fields of view, and the subscript o refers to a reference wavenumber (or spectral channel). It is assumed that the cloud radiates as a "greybody" (i.e., the cloud emissivity is the same for wavenumbers ν and ν_o). $B(\nu,T(p))$ is the Planck radiance corresponding to the temperature T, p is pressure, P_s is surface pressure, and $\tau(\nu,p)$ is the atmospheric transmittance of the atmosphere between the instrument and the pressure p. The cloud top pressure (p_c) which yields the minimum difference between the left-hand side and the right-hand side of Eq. (1) is the cloud pressure estimate. Note that the solution is independent of cloud amount and cloud emissivity.

The CO_2 slicing method assumes that one can find two spatially different radiances due to different cloud amounts and/or cloud emissivity with the cloud emissivity assumed to be independent of spectral wavenumber. In practice, it is attempted to utilize a "clear" air radiance which is representative of the cloudy area of interest together with a cloudy radiance to define the left-hand side of Eq. (1). When using a clear sky reference, the signal-to-noise ratio is maximized and the cloud height need only be constant over a single field of view.

2. The HIS Instrument

The HIS[9,10] is a Michelson interferometer which measures upwelling radiation (3.5-17.0μm) at high spectral resolution ($\lambda/\Delta\lambda$ > 1000/1). The spectral range of the instrument is partitioned into three bands. Band 1 (9.1-17.0μm or 600-1100 cm^{-1}), band 2 (5.0-9.1μm or 1100-2000 cm^{-1}), and band 3 (3.5-5.0μm or 2000-2800 cm^{-1}). The maximum spectral resolution is 0.28 cm^{-1}. One calibration cycle consists of two cold blackbody views, two hot blackbody views and six earth views followed by two more cold and hot blackbody views. During 1986, the HIS was flown aboard NASA U2/ER2 aircraft at a 65,000 foot altitude during the First ISCCP Regional Experiment (FIRE) and the Cooperative Huntsville Meteorological Experiment (COHMEX). The instrument was nadir viewing during the FIRE and COHMEX aircraft flights.

The high spectral resolution of the HIS in the 700-900 cm^{-1} region makes it ideal for application of the CO_2 slicing method. At a 0.5 cm^{-1} resolution there is available a very large number of spectral "channels". As will be shown, the high resolution enables accurate cloud height estimates. Figure 1a shows a typical radiance spectrum measurement from the HIS in the 600-1100 cm^{-1} region with the spectral bands of the VAS superimposed. Figure 1b shows two CO_2 channel weighting functions for the HIS compared with those for the VAS. The superior vertical resolving power of the HIS is readily apparent and enables more accurate cloud altitude determinations using the CO_2 slicing method.

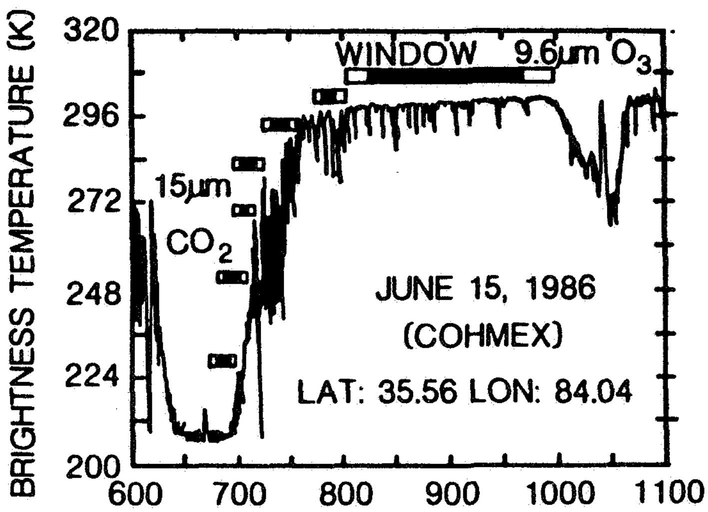

Fig. 1a: HIS long wavelength band spectrum with VAS spectal intervals shown.

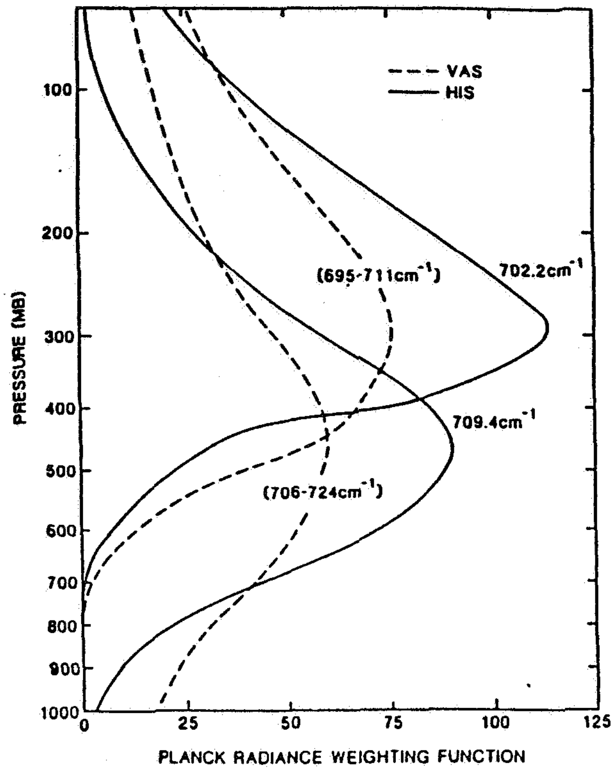

Fig. 1b: Planck radiance weighting functions at HIS and VAS resolutions.

3. Methodology

The first step in the application of the CO_2 slicing method is determining a representative "clear" radiance. "Clear" is in quotes since it refers to the clearest field of view of those corresponding to a geographical sample of radiance spectra. During Project FIRE, a down-looking lidar unit[6,7] was mounted on the NASA U2/ER2 aircraft. This provided a means of locating clear and cloudy regions as well as defining the cloud top pressure "ground truth" with high accuracy (∿5 mb). An average of the largest radiances from among those near the time of interest was chosen as the "clear" reference radiance. Next, differences between the "clear" and cloudy radiances were calculated for each point on the spectrum between 675 and 920 cm^{-1}. The spacing between points was .275 cm^{-1}. The result was normalized by dividing the spatial difference at each point on the spectrum by the value of the spatial difference at a reference wavenumber, chosen to be 899.7 cm^{-1}. This result was compared to the cloud pressure function (the right-hand side of Eq. (1) evaluated from the surface pressure to 50 mb for every point on the spectrum. Atmospheric transmittances were calculated using the line-by-line algorithm "FASCOD"[13] (Clough et al., 1986) while temperature and water vapor profiles were obtained from rawinsonde soundings. (Alternatively, the temperature and water vapor profiles could be obtained by sounding retrieval from the HIS spectra.[12] The value of the cloud pressure function (p_c) for which a minimum difference existed between the left-hand and right-hand sides of Eq. (1) was adopted as the cloud pressure estimate. In this way, a cloud height estimate was obtained for every point on the spectrum.

A reasonable procedure to achieve a single cloud top pressure estimate from a range of frequencies is to form a weighted average over the frequency range. Thus,

$$p_c = \Sigma\, p_c(\nu)\, w^2(\nu) / \Sigma\, w^2(\nu) \tag{2}$$

is used where the weight "w" represents the sensitivity to cloud height and is given by the derivative of the cloud pressure function, $C(P_c)$, with respect to the natural log of pressure (proportional to height). Mathematically,

$$w = \frac{\partial C(p_c)}{\partial \ln p} = C^1(p_c) ,$$

where $C(p_c)$ is defined as the right-hand side of Eq. 1. In our application of Eq. (2), if $w(\nu)$ is not at least one-half the value of the largest $w(\nu)$ within the spectral range used, it is assigned a value of zero.

Figure 2 shows a spectrum of $C^1(p_c)$ for cloud pressures of 300 mb, 500 mb, and 850 mb. The amplitude can be interpreted as the sensitivity of spectral radiance to cloud top pressure variations at these levels. Notice the many sharp peaks along the spectrum. The frequencies of these peaks are ones which should produce the best estimates of the cloud top pressure. Notice that the highest sensitivities are shifted toward larger wavenumbers with lower values of $C(p_c)$ (i.e., higher values of cloud pressure). This is consistent with the fact that in this portion of the 15µm CO_2 absorption band, larger wavenumbers are generally more sensitivity to upwelling radiation from lower levels of the atmosphere. Note the extremely low sensitivity in the opaque region near 720 cm^{-1}. One can see that the highest sensitivities to high clouds (300 mb) are near 710 cm^{-1} and 740 cm with generally lower values elsewhere. It is also apparent that spectral smearing causes a reduction of cloud height sensitivity, particularly for low level clouds.

4. Cloud Height Verification Results

HIS determinations of cloud height were obtained from U2/ER2 flights on November 2, 1986 (a FIRE flight), July 5, 1986 (a COHMEX flight), and June 15, 1986 (a COHMEX flight). The November 2 flights were above widespread CIRRUS over north central Wisconsin. The July 5 flight was above middle and upper tropospheric altocumulus clouds associated with a warm front over New England. The June 15 flight was over boundary layer cumulus cloud over northern Alabama and central Tennessee. The November 2 cirrus cloud height verifications were achieved using the ER2 lidar, which is believed to provide cloud top altitudes to an accuracy of 100 meters. The July 5 and June 15, middle and low level cumulus cloud verifications were achieved using time coincident window channel radiance data from the 50 meter resolution MAMS instrument and nearby radiosonde temperature and moisture profiles. A complete description of the "ground truth" cloud height data used to verify the "CO_2 slicing" determinations for these three days can be found in the thesis of Frey.[14]

Table I shows the RMS differences between the "CO_2 slicing" determinations and the ground truth for three categories of cloud height. Scatter diagrams of the results are shown in Fig. 3. As can be seen from Fig. 3, a large part of the RMS difference is due to a systematic tendency for the

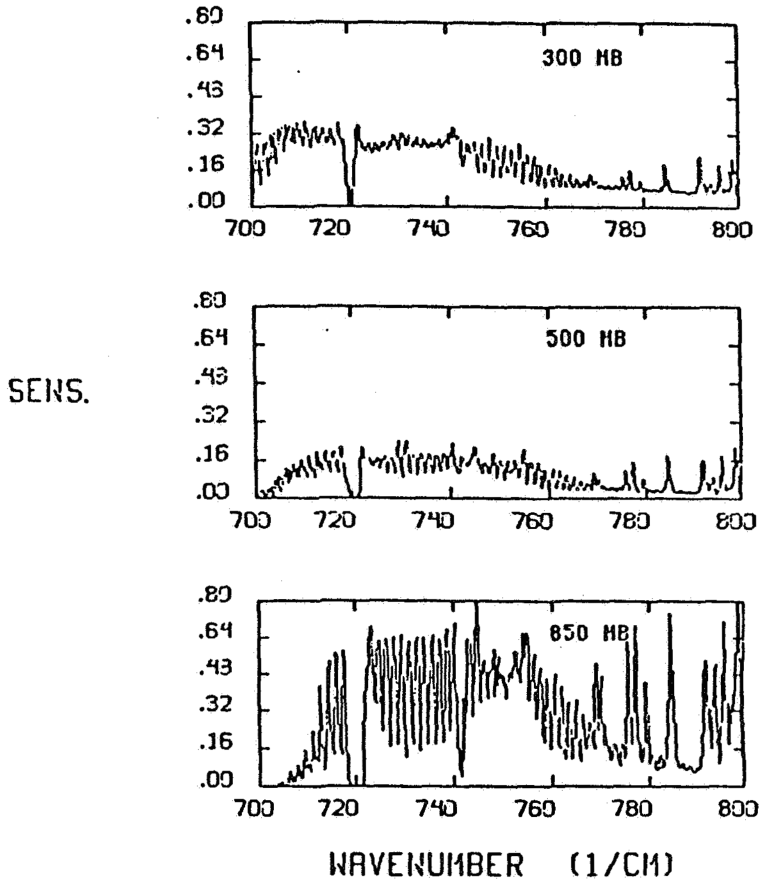

Fig. 2: Sensitivities of spectral radiance to variations of cloud top pressure.

infrared cloud pressures to be higher (low heights) than the ground truth. This tendency which is seen to be spectral resolution dependent is due to the semi-transparency of the cloud.[2] Referring to Table I, the most accurate results are achieved when the determinations are based upon high resolution HIS spectra. The discrepancies increased by 35% when the HIS spectral resolution is degraded to that of the VAS/TOVS sounding instruments. When the determinations are made using pairs of infrared spectral channels pertaining to the VAS, as opposed to using the continuous spectrum, the discrepancies increase by as much as 183%, depending upon the channel combination used. In general, best results for VAS channel combinations are achieved when a "window" channel is used as a reference; the discrepancy in this case is less than a factor of two poorer than that achieved with high resolution HIS spectra.

Table I. RMS differences (mb) between cloud top pressure estimates from HIS and simulated VAS data with lidar and MAMS/radiosonde ground truth.

Method	RMS Error (mb) High Cloud (N=30)	Middle Cloud (N=6)	Low Cloud (N=16)	All Clouds[3] (N=52)
HIS at high resolution	26	13	26	23
HIS at VAS/TOVS resolution	31	14	42	31
VAS Channels[1] (simulated from HIS, window channel reference)				
3/8	46	18	NA	35
4/8	49	20	NA	37
5/8[2]	34	31	44	37
VAS Channels[1] (simulated from HIS, near channel reference)				
3/4	45	54	NA	50
3/5[2]	48	17	NA	36
4/5	54	74	NA	65

[1]The half bandwidth spectral limits of VAS channels are: (1) Channel 3, 695-711 cm^{-1}; (2) Channel 4, 706-724 cm^{-1}; (3) Channel 5, 742-758 cm^{-1}; and, (4) Channel 8, 822-960 cm^{-1}.
[2]Considered to be the "optimum" channel combination.
[3]Computed from the average of the error variance for each height category.

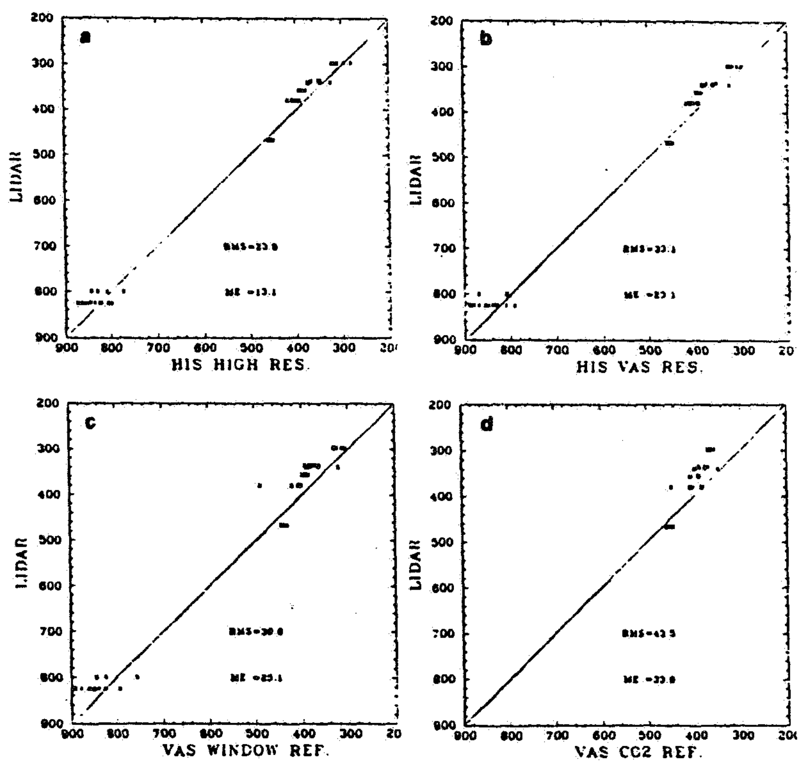

Fig. 3: Scatter diagrams of ground truth (lidar) versus CO_2 slicing infrared cloud pressure heights (mb) for (a) HIS high resolution spectra, (b) moderate (VAS) resolution spectra, (c) VAS channels using a window channel (8) as a reference, and (d) VAS channels using a CO_2 channel (5) as a reference.

Acknowledgments

We wish to thank Henry Revercomb, Harold M. Woolf, H. B. Howell, and H.-L. Huang for their assistance with the HIS data processing required for this research. We gratefully acknowledge Jim Spinhirne for providing the lidar data used to verify the radiometric cloud height determinations. Our thanks to Laura Beckett and Steve Ackerman for their help in the preparation of this manuscript. This research was supported by NASA under contract NAS1-18272.

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