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Estimating thin cloud properties using an improved CO_2 slicing approach

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1. INTRODUCTION

CO_2 slicing has been generally accepted as a useful algorithm for determining cloud top pressure (CTP) and effective cloud amount (ECA) for tropospheric clouds above 600 hPa. A modified CO_2 slicing algorithm was investigated wherein adjustments of both surface emissivity and cloud emissivity ratio are considered. To date, the technique has assumed that the surface emissivity is that of a blackbody in the long wavelength infrared radiances and that the cloud emissivities in spectrally close bands are approximately equal. In the modified CO_2 slicing algorithm, surface emissivity is adjusted according to the surface types and the ratio of cloud emissivities in spectrally close bands is adjusted away from unity according to radiative transfer calculations. The new CO_2 slicing algorithm was examined with MODIS Airborne Simulator (MAS) radiance measurements (King et al. 1996) over thin clouds and validated against Cloud Lidar System (CLS) (Spinhirne and Hart 1990) measurements of the same clouds; it was also applied to GOES Sounder (Menzel et al. 1998) data to study the overall impact on cloud property determinations.

2. MODIFIED CO_2 SLICING ALGOITHM

Infrared radiance measurements used in the CO_2 slicing algorithm are affected by surface emissivity and cloud emissivity considerations. For a specific infrared spectral band, the clear-sky upwelling radiance measured by the satellite within an instrument field-of-view (FOV) can be expressed as

$$R_{clr} = \varepsilon_s B_s \tau_s + \int_{p_s}^{p_0} B(T(p))\,d\tau + (1-\varepsilon_s)\tau_s \int_{p_0}^{p_s} B(T(p))\,d\tau^{\downarrow}$$

where surface emissivity ε_s is typically 0.95 over land and 0.99 over ocean for CO_2 slicing wavelengths.

The ratio of the deviations in cloud produced radiances R and corresponding clear-sky radiances R_{clr} for two spectral bands ν_1 and ν_2 viewing the same FOV are written as

$$\frac{\Delta R(\nu_1)}{\Delta R(\nu_2)} = \frac{R(\nu_1) - R_{clr}(\nu_1)}{R(\nu_2) - R_{clr}(\nu_2)}$$

$$= \frac{N\varepsilon_{c(\nu 1)}\{\int_{p_s}^{p_c} \tau(\nu_1, p) dB(\nu_1, p) + (1-\varepsilon_s)\tau_s(\nu_1)(B_s(\nu_1) - \int_{p_0}^{p_s} B(\nu_1, p) d\tau^{\downarrow}(\nu_1, p))\}}{N\varepsilon_{c(\nu 2)}\{\int_{p_s}^{p_c} \tau(\nu_2, p) dB(\nu_2, p) + (1-\varepsilon_s)\tau_s(\nu_2)(B_s(\nu_2) - \int_{p_0}^{p_s} B(\nu_2, p) d\tau^{\downarrow}(\nu_2, p))\}}$$

$$= \frac{N\varepsilon_{c(\nu 1)}}{N\varepsilon_{c(\nu 2)}} * \frac{RM(\nu_1)}{RM(\nu_2)}$$

When $\left| \Delta R(\nu_1) * RM(\nu_2) - \Delta R(\nu_2) * RM(\nu_1) * \frac{N\varepsilon_{c(\nu 1)}}{N\varepsilon_{c(\nu 2)}} \right|$ is minimum, the CTP has been determined. Given CTP, an ECA is evaluated from the infrared window (IRW) band using

$$ECA = N\varepsilon_{c(w)} = \frac{R(w) - R_{clr}(w)}{R_{bd}(w) - R_{clr}(w)}$$

In a sensitivity study (Zhang 2001), results show that the surface emissivity adjustment places the CO_2 slicing solution for high thin clouds lower in the atmosphere; a 2% surface emissivity change results in a change of about 15 hPa for CTP and a change of 1% for ECA. Furthermore, for high thin clouds (CTP = 300 hPa and ECA = 0.2), a 10% change of cloud emissivity ratio was found to cause about a 35 hPa change in CTP and a 1% change in ECA. Increasing the cloud emissivity ratio places the cloud lower in the atmosphere.

3. VALIDATION OF MODIFIED ALGORITHM

Possible cloud emissivity ratios for MAS bands observing thin high ice clouds were calculated using the Streamer model (Key and Schweiger 1998) wherein longwave ice cloud optical properties are based on Mie calculations using spherical particles at a relatively high spectral resolution. For MAS CO_2 band pairs (including ratios of measurements in spectral bands 14.2/13.7 and 13.7/13.2 microns), they range from 0.9 to 1.13, a few ratios vary from 0.75 to 0.9. For thin clouds, a mean cloud emissivity ratio of 1.05 works best for most of the CO_2 bands in the Streamer calculations.

MAS and CLS cloud heights of thin cirrus clouds were compared using data taken over Kansas and Oklahoma in the central United States on 16 April 1996. The MAS and CLS images are shown on the web address http://ltpwww.gsfc.nasa.gov/MAS/SUCCESShome.html and http://virl.gsfc.nasa.gov/~success/success.html

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respectively. Figure 1 shows the comparison for single layer cloud observations from the CLS and MAS cloud retrievals for five cloud emissivity ratios (0.95, 1.025, 1.0, 1.05, and 1.075); the same value is used for all CO_2 spectral pair ratios. The distribution of cloud top height difference (CLS – MAS) is shown in 1000m intervals; at an altitude of 10 km in a U.S. standard atmosphere, 500 m corresponds to ~ 20 hPa. The best performance is found for a cloud emissivity ratio of 1.025, with about 60% of the comparisons within 500 m. Thin clouds are found to be very sensitive to the cloud emissivity and the CO_2 slicing technique with the cloud emissivity adjustment improves the agreement with the CLS observations.

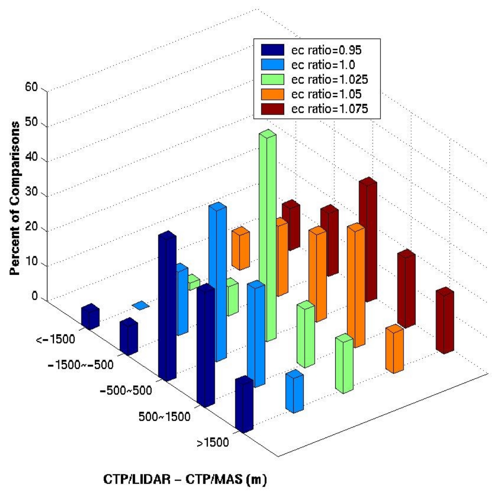

Figure 1: Comparisons of cloud top heights between from CLS and the MAS CO_2 slicing algorithm with different cloud emissivity ratio adjustments [0.95, 1.0 (no adjustment), 1.025, 1.05, and 1.075]. The MAS data is from single layer clouds and cloud top heights are greater than 4000 m on track 14 on April 16, 1996.

4. GOES-8 CASE STUDIES

The modified CO_2 slicing technique was applied to GOES-8 Sounder measurements. Figure 2 shows the scatter plot of CTP from the CO_2 slicing algorithm with non-unity cloud emissivity adjustment versus CTP from the CO_2 slicing algorithm with unity cloud emissivity. The data are from the GOES-8 Sounder on 13:46 UTC Feb. 14, 2001. (a) Comparisons for very thin clouds (ECA < 0.2) show a mean bias of approximately 11 hPa, and RMS (root mean square) difference of approximately 55 hPa. (b) For thin clouds (ECA between 0.2 and 0.5), the mean bias is around 8 hPa, and the RMS difference is approximately 22 hPa. (c) For thick clouds (ECA between 0.5 and 0.95), the mean bias is around 5 hPa, and the RMS difference is approximately 12 hPa. (d) For all cloud types, the mean bias is around 5 hPa, and the RMS difference is approximately 20 hPa. The associated ECA mean bias is 0.64% and RMS difference is 2%, approximately.

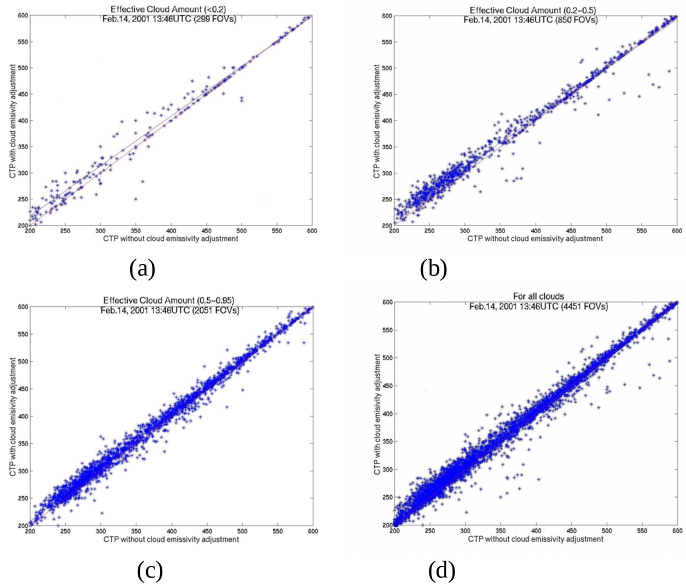

Figure 2: The scatter plot of GOES CTP using modified (y-axis) and original (x-axis) CO_2 slicing algorithm.

5. SUMMARY

The modified CO_2 slicing algorithm is found to be relatively insensitive to surface emissivity; there is a small effect on the cloud properties for thin cirrus and no effect for thick clouds. Adjusting the cloud emissivity ratio to 1.025 improves the cloud height product for high thin clouds and produces little change for thick and opaque clouds. For very thin clouds, the bias of differences is about 10 to 20 hPa and RMS difference is approximately 50 hPa; for thin clouds, there is about 10 hPa bias and RMS difference is approximately 30 hPa. The modified CO_2 slicing algorithm places the clouds lower in the troposphere.

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