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Cloud-clearing for AIRS radiances using MODIS

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1. INTRODUCTION

The Atmospheric Infrared Sounder (AIRS) on National Aeronautics and Space Administration's Earth Observing System (EOS) Aqua satellite is a high spectral resolution ($\nu / \Delta\nu$ =1200, where ν is the wavenumber and $\Delta\nu$ is full-width half maximum of a channel) infrared (IR) sounder with 2378 channels. AIRS measures radiances in the IR range 3.74-15.4 μm, which can be used to estimate the atmospheric vertical temperature and water vapor profiles from the Earth's surface to an altitude of 40km with a horizontal spatial resolution of 13.5km at nadir. Due to its relatively poor spatial resolution, the chance of an AIRS footprint to be completely clear is less than 10% statistically (Huang and Smith, 2004). One of the important questions is how to effectively perform cloud-clearing (CC) for the AIRS cloudy footprints, while still retaining the single footprint sounding gradient information for numerical weather prediction. Smith *et al.* (2004) combine Moderate Resolution Imaging Spectroradiometer (MODIS) IR clear radiances and AIRS cloudy for CC using the traditional single band N^* approach. In our study, an optimal CC method is developed to retrieve the AIRS clear column radiances by combing the multiband MODIS IR clear radiance observations and the AIRS cloudy radiances on a single footprint basis. The definition of N^* (Smith, 1968) is used as the basis in the optimal MODIS/AIRS CC formulation, while nine IR spectral bands are used simultaneously to determine N^* in our approach. This optimal CC methodology is an extension of the traditional single band CC technique.

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2. MODIS/AIRS COLLOCATION AND AIRS CLOUD MASKING FROM MODIS

AIRS spatial coverage is provided by the scan head assembly, containing a cross-track rotary scan mirror and calibrators. The AIRS spatial distribution is used in the collocation between the MODIS and AIRS measurement, which is the first step for the optimal MODIS/AIRS cloud-clearing. The MODIS pixels with 1-km spatial resolution are collocated within an AIRS footprint. With a set of AIRS earth-located observation, the footprint of each AIRS observation describes a figure that circular at nadir, quasi-ellipsoidal at intermediate scan angles, and ovular at extreme scan angles. The diameter of the AIRS footprint at nadir is approximately 13.5 km. Depending on the angular difference between the AIRS and MODIS slant range vector, a weight (ω) is assigned to each MODIS pixel collocated to AIRS: 1 if the MODIS pixel lies at the center of the AIRS oval, and 0 if at the outer edge. The collocation is modeled correctly and the algorithm provides an accuracy better than 1 km, provided the geometry information from both instruments is accurate.

Once the MODIS pixels are collocated with the AIRS footprints, the cloud properties within the AIRS subpixel can be characterized using the MODIS cloud mask (Li *et al.*, 2003). The cloud mask, cloud phase mask as well as the cloud-layer information mask, can be generated from MODIS products with 1-km spatial resolution (Li *et al.*, 2004). For each AIRS footprint, a clear coverage (0~1) is created by accounting for the percentage of MODIS pixels with confident clear and probably clear within the footprint. The averaged MODIS clear radiance for a given spectral band i with in an AIRS footprint is obtained by

$$R_{M_i}^{clr} = \frac{\sum_{l=1}^{np} \omega_l R_{M_i}^{clr,l}}{\sum_{l=1}^{np} \omega_l}$$

where $R_{M_i}^{clr,l}$ is the radiance of confident clear pixel l, np is the number of confident clear pixels within the AIRS footprint, and ω_l is the weight of pixel l within the AIRS.

3. METHODOLOGY AND APPLICATION OF OPTIMAL MODIS/AIRS CLOUD-CLEARING

Detailed optimal cloud-clearing methodology and N^* formulation is described in Li *et al.*, (2005). In this study, the 9 MODIS IR spectral bands 22, 24, 25, 28,30, 31, 32, 33 and 34 are used. These band are in the MODIS IR short-, middle- and longwave regions. MODIS and AIRS data from Hurricane Isabel are used in the study. The AIRS cloud mask is derived from the MODIS cloud mask with 1-km spatial resolution. A fractional coverage (0~1) is derived to represent clear (0) to cloudy (1) for a given AIRS footprint. The AIRS footprints then can be classified as fully cloudy (overcast), partly cloudy, and clear. Only AIRS footprints classified as partly cloudy are used for cloud-clearing. (Figure 2 in paper number P2.1) For comparison, the MODIS cloud phase mask with 1-km spatial resolution is also included (lower right panel). It can be seen that most partly cloudy footprints contain water clouds.

Figure 1 shows the diagram of principle (center) footprint and its 8 surrounding supplementary footprints. The steps of optimal cloud-clearing are as follows.

Step 1) For each partly cloudy AIRS footprint (principle footprint l), find its nearby cloudy footprint in any direction (maximum 8 nearby cloudy footprints) k ($k = 1,2,3,\ldots 8$).

Step 2) For each pair (l, k), calculate $N^*(k)$.

Step 3) Calculate cloud cleared radiance $R_\nu^{cc}(k)$ ($k = 1,2,3,\ldots 8$) through equation (7) in Li *et al.*, (2005).

Step 4) Calculate

$$RES(K) = \sum_i (1/\sigma_i)[(R_{M_i}^{clr} - f_i(R_\nu^{cc}(k))]^2$$

Step 5) Find k_m, which makes $RES(k_m) = \min RES(k)$.

Step 6) Apply quality control to the selected $R_\nu^{cc}(k_m)$ and calculate

$$TBRMS = \sqrt{\frac{1}{I}\sum_i [T_b(R_{M_i}^{clr}) - T_{bi}(f_i(R_\nu^{cc}(k_m)))]^2}$$

where I is the total number of MODIS spectral bands used for quality control (QC), T_{bi} is the function that converts the radiance to BT for MODIS spectral band i. The optimal cloud-clearing is successful only when TBRMS < 0.6 K; otherwise the cloud-clearing for this principle is rejected. The same 9 MODIS IR spectral bands used for N^* determination are also used for the QC.

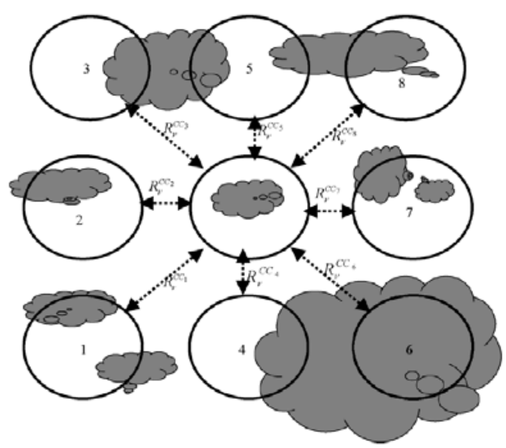

Figure 1. Diagram of the principle footprint and its eight surrounding supplementary footprints in the optimal cloud-clearing procedure.

The optimal cloud-clearing method is applied to all AIRS footprints that are partly cloudy. The optimal cloud-clearing will not be performed if the number of MODIS clear pixels is less than 10% of the total number of MODIS pixels within this partly cloudy AIRS footprint. Figure 2 in paper number P2.1 shows BT images of MODIS band 28 (7.3 μm) convoluted from the AIRS clear footprints (upper left panel) and the one convoluted from AIRS clear plus successful cloud-cleared footprints (upper right panel); the MODIS clear BT observations with 1-km spatial resolution are also shown (lower right panel). It can be seen that cloud-cleared footprints fill many areas where clear AIRS radiances are not available, especially over Florida and Cuba, which illustrates that soundings are achieved over Florida and Cuba and their nearby oceanic areas from AIRS cloudy radiance measurements with help of high spatial resolution of MODIS. In addition, the cloud-cleared radiances are also available over land areas within the states of Alabama and Tennessee. The lower left panel of Figure 2 shows the percentages of clear AIRS footprints, AIRS footprints with optimal cloud-clearing successful (CC-S) (pass the quality control), AIRS footprints with optimal cloud-clearing fail (CC-F), and overcast AIRS footprints (cloud-clearing will not be performed). It can be seen that 22.6% of AIRS footprints (each AIRS granule contains 135 scan lines, each scan line has 90 footprints) are successfully cloud-cleared, or more than 30% of AIRS cloudy footprints are successfully cloud-cleared. Since only partly cloudy footprints are used for cloud-clearing attempts, the success rate is more than 50% in this particular case.

Figure 3 shows the bias and standard deviation between the MODIS clear BT observations and convoluted AIRS cloud-clearing BTs from all footprints with cloud-clearing successfully performed. Results from traditional single-band N^* cloud-clearing approach and optimal cloud-clearing method are shown in the figure. For optimal cloud-clearing method, the cloud-clearing bias for MODIS bands 22, 23, 25, and 30 through 34 are very small (less than 0.25 K); the bias for bands 24 and 28 are slightly larger but still less than 0.5 K. However, bias for bands 20, 27, 35, and 36 are relatively large (greater than 1.0 K) due to the convolution bias (Tobin *et al.*, 2004) mentioned above. The AIRS popping channels and/or the AIRS channel gap in the spectral region cause the convolution bias. MODIS bands 35 and 36 might also have an SRF calibration bias. Those biases are removable provided that the reliable estimates are available. The standard deviation is very small (less than 0.5 K) for almost all the MODIS IR spectral bands (only band 27 is slightly larger than 0.5 K), which indicates the good agreement between the MODIS clear BT observations and AIRS cloud-cleared BTs. For the traditional single-band N^* cloud-clearing approach, the bias between the MODIS clear BT observations and AIRS cloud-cleared BTs is similar to that from the optimal cloud-clearing method; however, the standard deviations for MODIS shortwave bands 20 through 23 are worse than that of the optimal cloud-clearing method. Traditional single-band approach is better in longwave IR window region (11 μm) than the optimal cloud-clearing method because it uses MODIS 11-μm spectral band for N^* calculation. The two methods have similar performance for the other middle- and longwave spectral bands except for spectral band 32 for which the optimal approach performs better. Although the success rate of cloud-clearing is similar between the two methods, optimal cloud-clearing results are much closer to the MODIS clear observations for MODIS shortwave spectral bands. In the traditional single-band N^* cloud-clearing method, only band 31(11 μm) is used for N^* calculation, and IR shortwave spectral effects might not be fully accounted for in deriving N^*. With the optimal cloud-clearing method, 9 MODIS IR spectral bands are used simultaneously to balance the N^* spectrally, therefore, cloud-clearing results should be optimal when compared with the MODIS clear observations.

Comparing the AIRS cloud-cleared BT spectrum and its nearby clear footprint BT spectrum also helps to evaluate the performance of cloud-clearing (Huang and Smith, 2004). The upper and middle panels of Figure 4 show the bias and standard deviation between the AIRS cloud-cleared BT spectra and their nearby clear footprint BT spectra over water where the atmosphere and surface are assumed homogenous between the two clear adjacent footprints. It can be seen that the standard deviation of AIRS cloud-cleared BTs is less than 1 K for most spectral regions. Part of the standard deviation is due to the atmospheric nonhomogeneity difference between the two adjacent footprints. The lower panel of Figure 4 shows the root mean square difference (RMSD) between the two-adjacent clear AIRS footprint pairs over water of the entire granule. It can be seen that the BT difference can be 1 K in the shortwave spectral region due to the nonuniformity of the atmospheric and surface between the two adjacent clear AIRS footprints. Therefore, the actual standard deviation of the AIRS cloud-cleared BT should be much smaller than that shown in the middle panel of Figure 4.

The viewing angle difference between the pair of footprints can cause the BT difference (BTD) which should be corrected for cloud-clearing. An alternative way is to use along-track 3 footprints which have the same viewing angles for cloud-clearing. Figure 4 also shows the implement of along-track 3-FOV cloud-clearing in red curve. Based on out study, under the same QC constraint, 3 FOVs cloud-clearing has less bias and standard deviations but lower successful rate that the 9 –FOV cloud-clearing as expected. The CC successful yield from 3-FOV is approximately 5% lower than that from 9-FOV.

4. CONCLUSION AND FUTURE WORK

In this study, optimal cloud-clearing for sounder cloudy radiances using imager IR clear radiances has been successfully demonstrated by using AIRS and MODIS. About 30% of AIRS cloudy footprints (or 50% of the partly cloudy footprints) are successfully cloud-cleared with the help of MODIS high spatial resolution data. In the optimal imager/sounder cloud-clearing, the imager provides a cloud mask for sounder footprints while the multispectral imager IR provides clear radiance observations to synergistically determine N^* and to be used as quality control. The following conclusions can be drawn from this study.

1) Optimal imager/sounder cloud-clearing using multispectral imager IR spectral bands has advantages over the traditional single-band N^* cloud-clearing approach.
2) MODIS IR spectral bands 22, 24, 25, 28, and 30 through 34 are used to determine N^* and quality control; more than 30% cloudy footprints (or more than 50% of partly cloudy footprints) are successfully cloud-cleared with the help of MODIS. The success rate is above 50%.
3) The convoluted AIRS CCRs are compared with MODIS IR clear radiance observations. The bias is less than 0.25 K for most MODIS IR spectral bands, while the standard deviation is less than 0.5 K for almost all the MODIS IR spectral bands.
4) CCRs are compared with their nearby clear AIRS radiances. The standard deviation is within 1 K for most AIRS channels. Part of the standard deviation is due to the natural (atmospheric and surface) variability of the two clear adjacent footprints.

This work is very effective for cloud-clearing the AIRS footprints contaminated by water clouds. The approach could be employed on GOES-R with HES sounder and ABI (e.g., ABI 3.9, 6.15, 7.0, 7.4, 8.5, 9.73, 10.35, 11.2, 12.3, and 13.3 μm bands are critical for HES/ABI cloud-clearing).

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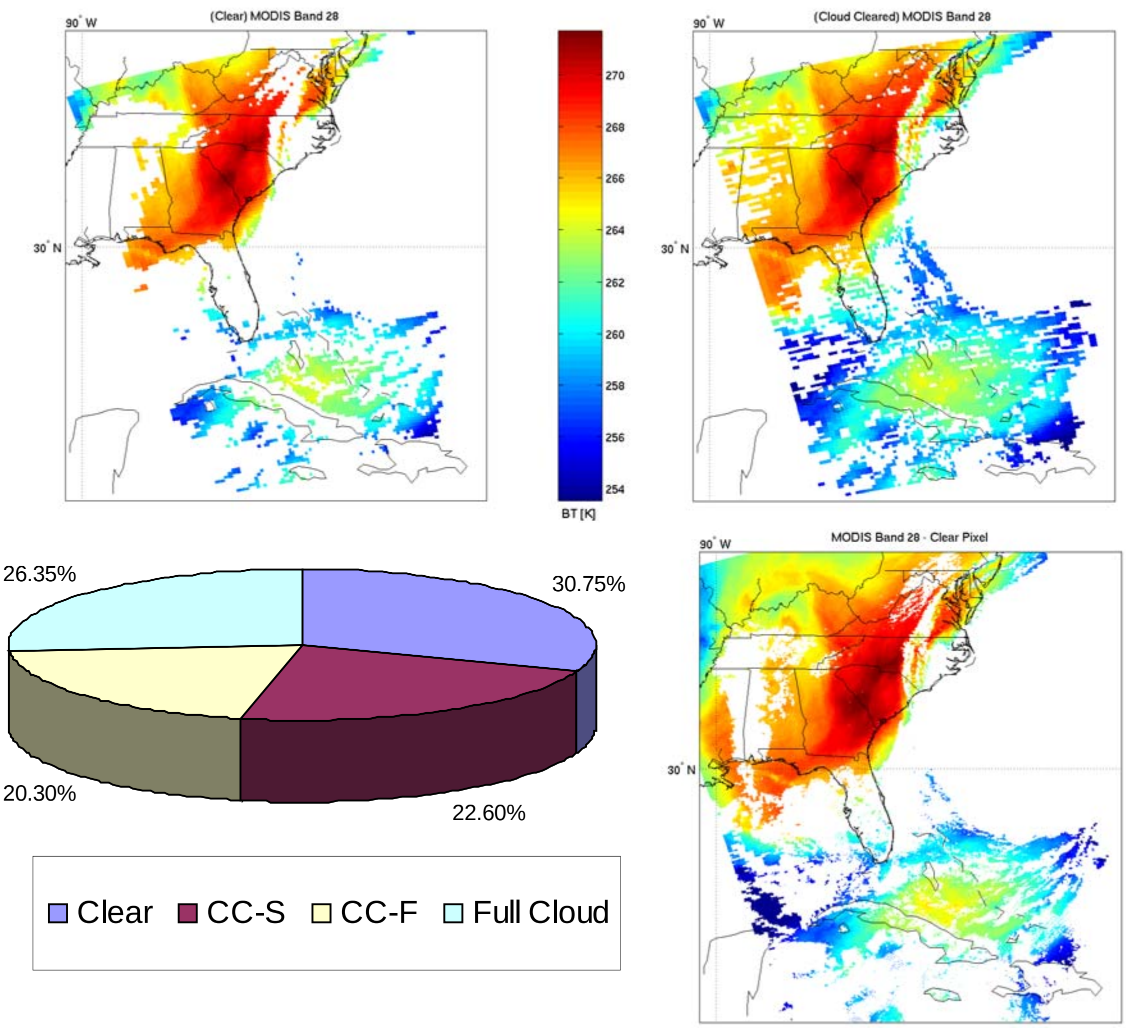

Figure 2 The BT images of MODIS band 28 (7.3 μm) convoluted from the AIRS clear footprints (upper left panel), the one convoluted from AIRS clear plus successful cloud-cleared footprints (upper right panel), the MODIS clear BT observations with 1 km spatial resolution (lower right panel), and the percentages of clear AIRS footprints, AIRS footprints with varitational cloud-clearing successful (CC-S), AIRS footprints with optimal cloud-clearing fail (CC-F), and the overcast AIRS footprints.

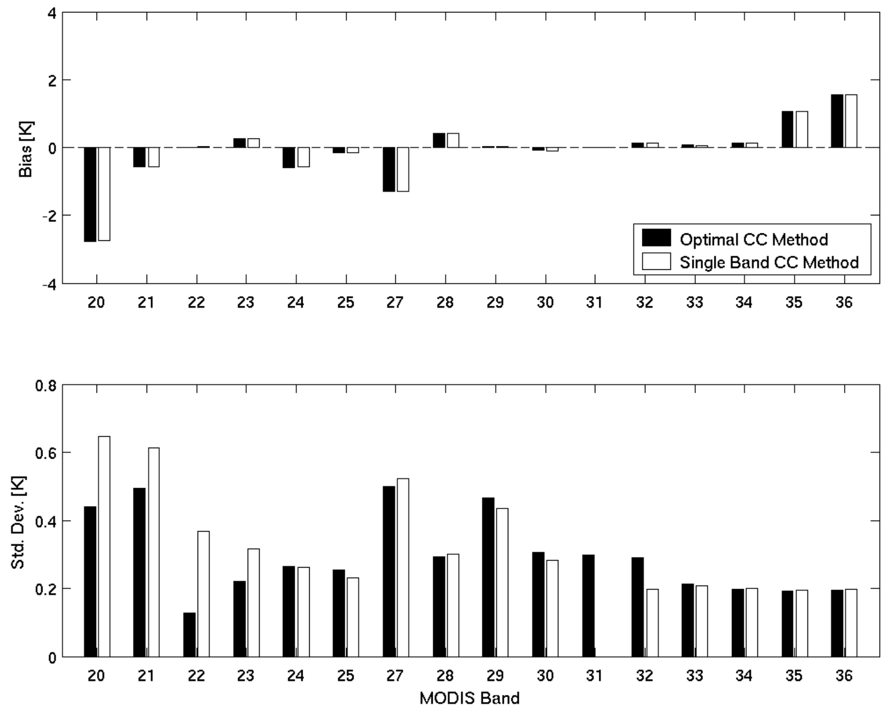

Figure 3 Bias and standard deviation between the MODIS clear BT observations and convolved AIRS cloud-clearing BTs from all footprints with both the optimal cloud-clearing and the single-band N^* cloud-clearing successful.

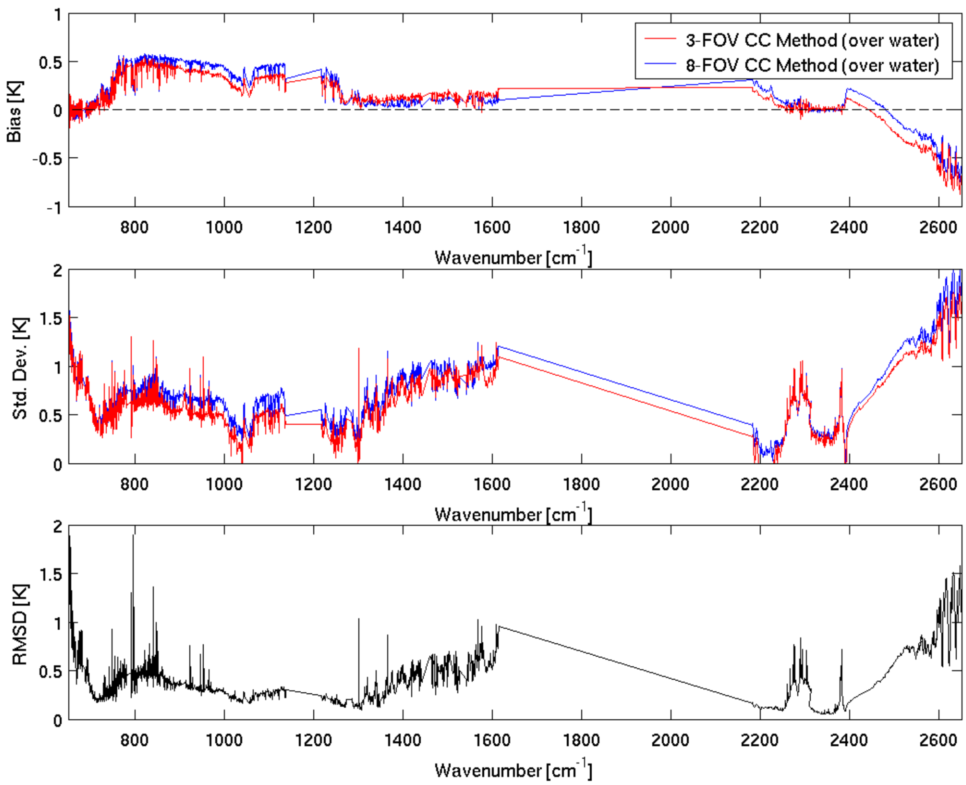

Figure 4. (Upper panel) Bias and (middle panel) standard deviation between the AIRS cloud-cleared BT spectra and their nearby clear footprint BT spectra along with the RMSD between the two-adjacent clear AIRS footprint pairs over the water of the granule.