An optimal cloud-clearing method for AIRS radiances using MODIS

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Abstract

The Atmospheric Infrared Sounder (AIRS), onboard NASA's EOA Aqua satellite, provides atmospheric vertical temperature and moisture sounding information with high vertical resolution and accuracy for Numerical Weather Prediction (NWP). Due to its relatively poor spatial resolution (13.5 km at nadir), the chance for an AIRS footprint to be clear is small. However, the Moderate Resolution Imaging Spectroradiometer (MODIS), also onboard Aqua, provides co-located clear radiances at several infrared (IR) spectral broad bands with 1 km spatial resolution within many AIRS cloudy footprints. An optimal cloud-removal or cloud-clearing (CC) algorithm is developed to retrieve the AIRS clear column radiances from the combined MODIS IR clear radiances with high spatial resolution and the AIRS cloudy radiances on a single footprint basis. The AIRS cloud-removed or cloud-cleared radiance spectrum is convoluted to all the MODIS IR spectral bands with spectral response functions (SRFs), and the convoluted brightness temperatures (BTs) are compared with MODIS clear BT observations within all successful cloud-cleared footprints. The bias and the standard deviation between the convoluted BTs and MODIS clear BT observations is less than 0.25 K and 0.5 K, respectively, over both water and land for most MODIS IR spectral bands. The retrieved AIRS soundings from cloud-cleared radiance spectra are compared with the ECMWF analysis and dropsonde data for CC performance evaluation. The AIRS cloud-cleared BT spectrum is also compared with its nearby clear BT spectrum, the difference, accounting the effects due to scene non- uniformity, is reasonable according the analysis. It is found that more than 30% of the AIRS cloudy (partly and overcast) footprints in this study have been successfully cloud-cleared using the optimal cloud-clearing method, revealing the potential application of this method on the operational processing of future GOES-R Hyperspectral Environmental Suite (HES) cloudy radiance measurements when the collocated Advanced Baseline Imager (ABI) IR data is available.

I. Introduction

The Atmospheric Infrared Sounder (AIRS) (http://www-airs.jpl.nasa.gov) (Aumann et al. 2003) on NASA's Earth Observing System (EOS) Aqua satellite is a high spectral resolution ($\nu/\Delta\nu$ = 1200) infrared (IR) sounder with 2378 channels. AIRS measures radiances in the IR region 3.74 – 15.4 µm, which can be used to estimate the vertical profiles of atmospheric temperature and water profiles [2] from the Earth's surface to an altitude of 40 km with a horizontal resolution of 13.5 km at nadir. Due to its relatively poor spatial resolution, the chance for an AIRS footprint to be completely clear is less than 10% statistically [3]. How to get soundings (temperature and moisture vertical profiles) under cloudy skies becomes very important. There are several ways for handling clouds in the sounding retrieval process; one of the most effective ways is to perform cloud-removal or cloud-clearing (CC) on the AIRS cloudy radiance spectrum. The cloud-clearing doesn't require modeling of clouds and is, therefore, a cost-effective method of handling cloudy infrared scenes. For example, use microwave data for AIRS cloud-clearing (Susskind et al. 2003). One of the important questions is how to effectively perform cloud-removal or cloud-clearing for the AIRS cloudy footprints, while still retaining the single footprint sounding gradient information for Numerical Weather Prediction (NWP). Smith et al. (2004) combine Moderate-Resolution Imaging Spectroradiometer IR clear radiances and AIRS cloudy radiances for cloud-clearing using the traditional single band N^* approach. Li et al. (2005) has developed an optimal CC algorithm using multi-band MODIS for N^*. In their approach, the N^* is determined from MODIS IR clear radiances at 9 IR bands along with the AIRS cloudy radiances. Once N^* is determined, the AIRS cloud-cleared radiances (CCRs) can be obtained by simply applying N^* to the cloudy radiances from the two adjacent AIRS footprints. The optimal cloud-clearing methodology is an extension of the traditional single band cloud-clearing technique.

By combining collocated MODIS IR clear radiance observations and the AIRS cloudy radiance measurements, the clear column radiances for all AIRS channels can be retrieved by using the optimal cloud-clearing method. In order to make the optimal MODIS/AIRS cloud-clearing effective, two adjacent AIRS cloudy footprints (a pair) will be used to retrieve one AIRS cloud-cleared radiance (CCR) spectrum. For each partly cloudy AIRS footprint (defined as principal footprint in the center of 3 by 3 processing area), another adjacent AIRS cloudy footprint (defined as supplementary footprint) will also be used to form a pair for the optimal MODIS/AIRS cloud-clearing. The CCR spectrum from the pair represents the clear column radiance spectrum of the principal footprint since the quality control (QC) is based on the comparison between the MODIS IR clear brightness temperature (BT) observations and the convoluted AIRS cloud-cleared BT spectrum with MODIS spectral response functions (SRFs) within the principal footprint. Therefore, the principal footprint must be partly cloudy to ensure that MODIS IR clear radiance observations exist, while the supplementary footprint can be either partly cloudy or overcast. Since the 3 by 3 box moves only by single pixel, each cloudy footprint will have a chance to be principal footprint in the cloud-clearing process.

A case from Hurricane Isabel is used for testing the algorithm. The MODIS clear BT observations within all successful cloud-cleared footprints are used for validating the AIRS cloud-cleared BTs convoluted to all the MODIS IR spectral bands with SRFs. The bias and the standard deviation between the convoluted cloud-cleared BTs and the MODIS clear BT observations are calculated; the bias and standard deviation is less than 0.25 K and 0.5 K, respectively, for most MODIS IR spectral bands. Comparing with the traditional single band N^* cloud-cleared BTs, the standard deviation was significantly reduced with optimal cloud-clearing for IR middlewave (water vapor absorption) and shortwave spectral regions, indicating the advantange of the multi-band algorithm over the single-band approach. This is expected since the clear radiance used for the single N^* algorithm comes from the longwave based. The AIRS cloud-cleared BT spectrum is also compared with its nearby clear BT spectrum; the difference is reasonable, considering the effect of scene non-uniformity. It is found that approximately more than 50% of AIRS partly cloudy footprints (or more than 30% of AIRS cloudy footprints including overcast cloudy footprints) in this study can be successfully cloud-cleared using the optimal MODIS/AIRS cloud-clearing method. These positive results reveal the potential application of this method for the operational processing of hyperspectral IR sounder cloudy radiance measurements for atmospheric temperature, moisture and ozone sounding retrieval when IR imager data is available, or real time processing of the MODIS/AIRS data from direct broadcast.

Using MODIS to help AIRS sub-pixel cloud characterization and cloud property retrieval has been investigated (Li et al. 2004a, 2004b, 2005). These techniques that utilize AIRS and MODIS data are also applicable to the processing of data from the future operational Advanced Baseline Imager (ABI) [10] and Hyperspectral Environmental Suite (HES) systems (Gurka and Schmit 2004; Gurka et al. 2004) on the next generation of Geostationary Operational Environmental Satellite (GOES)-R where no microwave sounding measurements are available.

II. MODIS/AIRS collocation and AIRS cloud masking from MODIS

A. *Collocation Between MODIS and AIRS Measurements*
AIRS spatial coverage is provided by the scan head assembly, containing a cross track rotary scan mirror and calibrators. The scan mirror has two speed regimes: During the first 2 seconds it rotates at 49.5 degree/second, generating a scan line with 90 ground footprints, each with a 1.1 degree diameter field-of-view (FOV). During the remaining 0.667 seconds the scan mirror finishes the remaining 261 degrees of a full revolution. The AIRS spatial distribution is used in the collocation between the MODIS and AIRS measurements, 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. Several collocation algorithms have been developed that are based on the scanning geometry of two instruments flown on the same satellite (Nagle 1998; Frey et al. 1995). With a set of AIRS earth-located observations, the footprint of each AIRS observation describes a figure that is 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 vectors, 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 zero if at the outer edge. The collocation is modeled correctly and the algorithm provides an accuracy better than 1 km, provided that the geometry information from both instruments is accurate.

B. *AIRS Cloud Masking Using MODIS*

Once the MODIS pixels are collocated with the AIRS fooprints, the cloud properties within the AIRS sub-pixel can be characterized using the MODIS cloud mask, cloud phase mask (King et al. 2003; Platnick et al. 2003), and the MODIS classification mask (Li et al. 2003). The AIRS cloud mask, cloud phase mask, as well the cloud-layer information mask can be generated from MODIS products with 1 km spatial resolution (Li et al. 2004a). 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 (Ackerman et al. 1998) within the footprint. Only confident clear MODIS pixels within the AIRS footprint are averaged for optimal MODIS/AIRS cloud-clearing; the averaged MODIS clear radiance for a given spectral band i within an AIRS footprint is obtained by

$$R_{M_i}^{clr} = \sum_{l=1}^{np} \omega_l R_{M_i}^{clr,l} / \sum_{l=1}^{np} \omega_l ,$$
(1)

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 footprint as described in section II.A.

III. Methodology of optimal MODIS/AIRS cloud-clearing

Given that R_ν^1 and R_ν^2 are the AIRS cloudy radiance spectra as a function of wavenumber ν from two adjacent footprints (footprint 1 is the principal, while footprint 2 is the supplementary), assume that the two adjacent footprints have (a) the same atmospheric temperature and moisture profiles, (b) the same surface skin temperatures and surface IR emissivity spectrum, (c) the same cloud-top height, while the only difference is the effective cloud emissivity ($N\varepsilon_c$, the product of the cloud emissivity, ε_c, and the fractional cloud coverage, N). The cloudy radiance spectra of the two adjacent footprints can be expressed as

$$R_\nu^1 = (1 - N\varepsilon_{vc}^1)R_\nu^{clr} + N^1\varepsilon_{vc}^1 R_\nu^{ovc} ,$$
(2)

$$R_\nu^2 = (1 - N\varepsilon_{vc}^2)R_\nu^{clr} + N^2\varepsilon_{vc}^2 R_\nu^{ovc} ,$$
(3)

where subscript c denotes the cloud, and R_ν^{clr} and R_ν^{ovc} are the clear and overcast column radiance spectra, respectively, for both footprints 1 and 2. Rewrite Eq.(1) and Eq.(2) as

$$R_\nu^1 - R_\nu^{clr} = N^1\varepsilon_{vc}^1 (R_\nu^{ovc} - R_\nu^{clr}) ,$$
(4)

$$R_\nu^2 - R_\nu^{clr} = N^2\varepsilon_{vc}^2 (R_\nu^{ovc} - R_\nu^{clr}) .$$
(5)

From Eq.(4) and Eq.(5), we have

$$\frac{R_\nu^1 - R_\nu^{clr}}{R_\nu^2 - R_\nu^{clr}} = \frac{N^1 \varepsilon_{vc}^1}{N^2 \varepsilon_{vc}^2} = N^* \qquad (6)$$

Eq.(6) defines N^* (Smith 1968), which is independent of wavenumber assuming $\varepsilon_{vc}^1 = \varepsilon_{vc}^2$ (i.e., the cloud properties are the same for footprints 1 and 2). If N^* is known or estimated, then the AIRS CCR spectrum R_ν^{cc} can be retrieved by

$$R_\nu^{cc} = \frac{R_\nu^1 - R_\nu^2 N^*}{1 - N^*} \qquad (7)$$

The key question is how to determine N^*. In order to determine N^*, one needs to know the clear radiance at a certain wavenumber with good accuracy. Smith et al. (2004) used the MODIS IR window spectral band (band 31, 11 μm) clear radiance together with the convoluted AIRS cloudy radiances with MODIS 11 μm SRF within the two adjacent footprints to determine N^*, that is

$$N^* = \frac{f_{31}(R_\nu^1) - R_{M_{31}}^{clr}}{f_{31}(R_\nu^2) - R_{M_{31}}^{clr}} \quad , \qquad (8)$$

where f_i is the SRF for MODIS IR band i, and $R_{M_i}^{clr}$ is the averaged observed clear radiance for MODIS IR spectral band i for the two adjacent AIRS footprints (see Eq.(1)). Once N^* is determined by Eq. (8), the AIRS clear column radiance spectrum for this footprint pair then can be retrieved (see Eq.(7)). Eq.(8) is the traditional way to estimate N^* using a single IR window spectral band.

The N^* value determined from a single MODIS spectral band, using different MODIS IR window spectral bands, may result in different cloud-cleared spectra. The results are also highly dependent on the quality control (QC) for the single band N^* cloud-clearing. In order to obtain an optimal N^* value and make the cloud-clearing result dependent on an objective quality control criterion based on all MODIS spectral bands, an optimal cloud-clearing methodology is developed. In the optimal MODIS/AIRS cloud-clearing, the definition of N^* in Eq.(6) is still adopted. However, the N^* value is determined by simultaneously minimizing the differences between the MODIS IR clear radiance observations and the convoluted AIRS CCR spectrum with SRFs for all 9 MODIS IR spectral bands within footprint 1 (the principal footprint).

The cost function for the optimal cloud-clearing is defined as

$$J(N^*) = \sum_i \frac{1}{\sigma_i^2}[(R_{M_i}^{clr} - f_i(R_\nu^{cc})]^2 \qquad . \qquad (9)$$

Since the CCR spectrum, R_ν^{cc}, is a function of N^* (see Eq.(7)), Eq.(9) becomes

$$J(N^*) = \sum_i \frac{1}{\sigma_i^2}[(R_{M_i}^{clr} - f_i(\frac{R_\nu^1 - R_\nu^2 N^*}{1 - N^*})]^2 , \qquad (10)$$

where σ_i is the radiance detector noise (NEdR) for MODIS band i. Given that the SRF f_i is a linear operator for MODIS IR spectral band, Eq.(10) becomes

$$J(N^*) = \sum_i \frac{1}{\sigma_i^2} [(R_{M_i}^{clr} - \frac{1}{1-N^*} f_i(R_\nu^1) + \frac{N^*}{1-N^*} f_i(R_\nu^2)]^2 \qquad . \quad (11)$$

Therefore, the first order derivative of $J(N^*)$ with respect to N^* can be derived from Eq.(11) as

$$\frac{\partial J(N^*)}{\partial N^*} = \frac{2}{(1-N^*)} \sum_i \frac{1}{\sigma_i^2} [R_{M_i}^{clr} - \frac{1}{1-N^*} f_i(R_\nu^1) + \frac{N^*}{1-N^*} f_i(R_\nu^2)][f_i(R_\nu^1) - f_i(R_\nu^2)]$$

$$(12)$$

The solution of N^* should minimize the cost function $J(N^*)$; therefore,

$$\frac{\partial J(N^*)}{\partial N^*} = 0 \qquad . \qquad\qquad\qquad (13)$$

N^* then can be analytically solved from Eq.(13) as

$$N^* = \frac{\sum_i \frac{1}{\sigma_i^2} [f_i(R_\nu^1) - R_{M_i}^{clr}][f_i(R_\nu^1) - f_i(R_\nu^2)]}{\sum_i \frac{1}{\sigma_i^2} [f_i(R_\nu^2) - R_{M_i}^{clr}][f_i(R_\nu^1) - f_i(R_\nu^2)]} \qquad . \qquad (14)$$

Once N^* is determined by Eq.(14), the cloud-cleared AIRS radiance spectrum, arbitrarily located at the location of the principal footprint, can be retrieved by applying N^* to Eq. (7). In this study, the 9 MODIS IR spectral bands 22, 24, 25, 28, 30, 31, 32, 33, and 34 are used. Note that MODIS IR spectral bands 20, 23 and 27 are not used due to the convolution error introduced by the spectral gaps in the AIRS measurements, MODIS IR spectral band 21 is not used due to the large detector noise, while MODIS IR spectral IR bands 35 and 36 are not used due to their SRF calibration error (Tobin et al. 2004).

Figure 1 shows the MODIS SRFs overlayed with an AIRS BT spectrum. Since AIRS does not have an 8.5 μm spectral region channel, MODIS band 29 is excluded in the determination of N^*. The advantage of Eq.(14) is that the multiple MODIS spectral bands are weighted in the N^* calculation. There are two weighting factors, the detector noise accounts for the observation error in the N^* calculation, while the radiance contrast between the two adjacent footprints accounts for the cloud height effect in the N^* calculation. For example, if the pair contains low clouds, the MODIS middle and upper level bands 33 and 34 will have less weight because $f_i(R_\nu^1) - f_i(R_\nu^2)$ is small; however, when the pair contains high clouds, bands 33 and 34 will influence the N^* calculation. Besides the cloud height effect, cloud fraction is another factor contributing to the spectral weighting that maximizes the information content of the optimal cloud-clearing approach.

IV. Application of optimal MODIS/AIRS cloud-clearing

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 or fields-of-view (FOVs) then can be classified as fully cloudy (overcast), partly cloudy, and clear. Only AIRS footprints classified as partly

cloudy are used for cloud-clearing. The upper left panel of Figure 2 shows the AIRS BT image of channel 560 (833.206 cm^{-1}) on 17 September 2003 (AIRS granule 184); the presence of cold clouds is indicated by the blue (cold) colors. The lower left panel shows the AIRS coverage of clear, partly cloudy and overcast cloudy footprints derived from the MODIS cloud mask with 1 km spatial resolution (see upper right panel).   For comparison, the MODIS cloud phase mask with 1 km spatial resolution is also included (see lower right panel). It can be seen that most partly cloudy footprints contain water clouds. Note that the color bars have different definitions in the four panels.

Figure 3 shows the diagram of the principal (center) footprint and its 8 surrounding supplementary footprints. The steps of optimal cloud-clearing are:
Step 1: For each partly cloudy AIRS footprint (principal footprint l), find its nearby cloudy footprint in any direction (maximum eight nearby cloudy footprints) k ($k =1, 2, 3, …, 8$);
Step 2: For each pair (l,k), calculate $N^{*}(k)$, ($k =1, 2, 3, …, 8$) using Eq.(14);
Step 3: Calculate $R_{v}^{cc}(k)$ ($k =1, 2, 3, …, 8$) from Eq. (7)

Step 4: Calculate $RES(k) = \sum_{i} \frac{1}{\sigma_{i}} [(R_{M_{i}}^{clr} - f_{i}(R_{v}^{cc}(k))]^{2}$

Step 5: Find k_{m}, that makes $RES(k_{m}) = \min RES(k)$.

Step 6: Apply quality control to the selected $R_{v}^{cc}(k_{m})$, and calculate

$$TBRMS = \sqrt{\frac{1}{I} \sum_{i} [T_{b}(R_{M_{i}}^{clr}) - T_{bi}(f_{i}(R_{v}^{cc}(k_{m})))]^{2}} \quad , \tag{15}$$

where I is the total number of MODIS spectral bands used for 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 $TBRMS < 0.5$ K, otherwise the cloud-clearing for this principal footprint is rejected. The same 9 MODIS IR spectral bands used for N* determination (see Eq.(14)) are also used also for the QC.

The CCR radiance spectrum $R_{v}^{cc}(k_{m})$ is the final clear column radiance spectrum for the cloudy footprint l (the principal footprint). The footprint index l starts from the first footprint to the last footprint of the AIRS granule. In order to make accurate CCRs, quality control must be applied to $R_{v}^{cc}(k_{m})$. If the root mean square (RMS) difference between the MODIS IR clear BT observations and convoluted AIRS cloud-cleared BTs (from $R_{v}^{cc}(k_{m})$) with MODIS SRFs within the principal footprint is greater than 0.5 K (as defined in Eq.(15)), the CCR spectrum is then rejected.

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 4 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 CCRs are also available over land areas within the states of Alabama and Tennessee. The lower left panel of Figure 4 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.

The traditional single band N^* cloud-clearing method is also applied; MODIS spectral band 31 (11 μm) is used for N^* determination while the 9 MODIS IR spectral bands 22, 24, 25, 28, 30, 31, 32, 33, and 34 are used for quality control and a similar success rate of optimal cloud-clearing is achieved. Figure 5 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 [19] 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 N^* approach is better in lowgwave IR window region (11μm) 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. W. L. Smith (personal communication) suggested using two N^*s in cloud-clearing (e.g., one N^* from MODIS spectral bands 22, 24, and 25 for AIRS IR shortwave, while the other N^* from MODIS spectral bands 28, 30, 31, 32, 33, and 34 for AIRS IR middlewave and longwave). Two N^*s should minimize the effects of co-registration errors and perform better than one N^*.

Figure 6 shows the scatterplot between the MODIS IR clear BT observations and the convoluted AIRS cloud-cleared BTs with the traditional single band N^* cloud-clearing approach and the optimal cloud-clearing method for MODIS spectral bands 22 (upper left), 25 (upper right), 27 (lower left) and 32 (lower right). Approximately 2400 AIRS partly cloudy footprints are included in the plot. It can be seen that the optimal cloud-clearing method creates less scatter and has a larger correlation with MODIS IR clear observations for MODIS IR spectral band 22 (3.95 μm).

Comparing the AIRS cloud-cleared BT spectrum and its nearby clear footprint BT spectrum also helps to evaluate the performance of cloud-clearing [3]. The upper and middle panels of Figure 7 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 non-homogeneity difference between the two adjacent footprints. The lower panel of Figure 7 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 non-uniformity 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 7. Figure 8 shows the MODIS cloud mask with 1 km spatial resolution superimposed to the AIRS footprints from a small area over Florida (see the box on the upper left panel of Figure 2), the footprints indicated by arrows are the principal and its supplementary cloudy footprints used for optimal cloud-clearing, and its nearby clear footprint for comparison. The lower panel of Figure 8 shows the optimal cloud-cleared BT spectrum (red line) from the two adjacent cloudy BT spectra (black and green lines), as well as the nearby clear BT spectrum (blue line) (lower panel). It can be seen that the optimal cloud-cleared AIRS BTs are much warmer than those of the two adjacent cloudy footprints, indicating the successful removal of cloud effects in the optimal cloud-clearing. The cloud-cleared BT spectrum is also reasonably close to its nearby clear BT spectrum, differences in window region might be caused by the non-uniformity of surface skin temperature in the two footprints.

V. Discussions

Unlike using AMSU in AIRS cloud-clearing, an algorithm for AIRS cloud-clearing using MODIS data is developed. Since both the imager and sounder measure radiances at the same IR spectral regions, a direct relationship between an imager IR radiance and a sounder IR radiance spectrum for a given imager spectral band provides unique advantages for imager/sounder cloud-clearing. The advantages of imager/sounder cloud-clearing are: (1) it is easy to find imager clear pixels within the sounder footprint which is critical for the N^* calculation and the quality control on CCRs; (2) cloud-clearing can be achieved on a single footprint basis (hence maintaining the spatial gradient information); and (3) imager IR clear radiances provide tropospheric atmospheric information that enhances the effectiveness of cloud-clearing for IR sounder cloudy radiances. However, there are also limitations: (1) the cloud-clearing can only be done with partly cloudy footprints, (2) N^* has to be constant for the whole IR spectrum, and (3) the surface and the atmospheric profile must be homogeneous within the pair of two adjacent footprints. The cloud-clearing might fail when one of the above physical assumptions fails. For example, in the presence of ice clouds, the cloud-clearing might give spectrally inconsistent results due to N^* not being constant in the IR spectral region. In addition, when the radiance contrasts in the IR window region is too small, N^* tends to be 1 and the cloud-clearing can amplify noise rather than remove the cloud effects on the measurements.   However, all these failures will be filtered by the quality control procedure (see Eq.(15)). The quality control is very important to assure that the final CCRs representing the clear part of the principal footprint fit the MODIS IR clear radiance observations in all IR spectral regions simultaneously.

Certain factors will also affect the cloud-clearing results. The operational MODIS cloud mask with 1 km spatial resolution used for determining the MODIS clear IR radiances within the principal footprint is critical for the success of the cloud-clearing. Only confident clear MODIS pixels should be selected to determine the MODIS IR clear radiances. The daytime MODIS cloud mask should be more accurate than the nighttime mask because of the use of visible (VIS) and near IR (NIR) bands. MODIS/AIRS collocation is also very important to assure the success of the cloud-clearing; mis-collocated MODIS clear pixels with the AIRS footprint may result in additional cloud-clearing errors.   A reliable algorithm is necessary to provide good imager/sounder collocation. The time difference between the imager and sounder is an issue in cloud-clearing.   Since MODIS and AIRS are in the same spacecraft, the time difference between MODIS and AIRS for a given AIRS footprint is small enough to assure the same clouds and atmospheric measurements are observed. The convolution error due to the AIRS spectral gaps or bad channels that are excluded in the calculation is another error source for MODIS/AIRS cloud-clearing. Tobin et al. [19], [20] have estimated the bias due to the AIRS spectral gaps or bad channels; they found that window region bands 22, 31 and 32 have less bias, longwave CO_2 bands 33 throught 36 have mean biases increasing to 1 K for band 36, and water vapor bands 28 and 27 have mean biases of 0.48 and 1.05 K respectively.   Those biases have not been taken into account yet when applying MODIS SRFs. The SRF and gap issues could be mitigated if a forward model for both instruments is used [20]. There are also other sources of error for MODIS/AIRS

cloud-clearing such as MODIS and AIRS calibration errors that need to be considered when interpolating and using the MODIS/AIRS CCRs.

VI. Conclusions and future work

In this paper, 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 multi-spectral 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). Future work will focus on cloud-clearing for footprints with mutli-layer clouds. For example, employing multi-layer cloud-clearing approach developed by Susskind et al. [2] and using MODIS clear observations for high spatial resolution cloud-clearing could be of great potential

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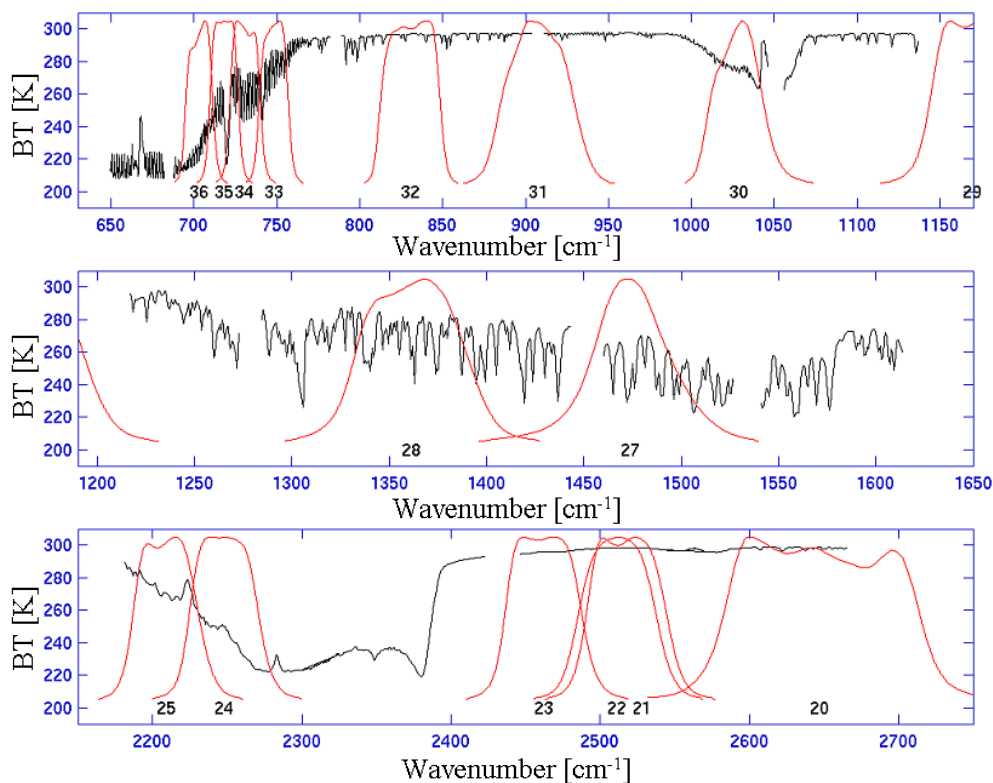
Figure 1. The MODIS SRFs overlayed with an AIRS BT spectrum. The units of the abscissa and ordinate are wavenumber and brightness temperature, respectively.
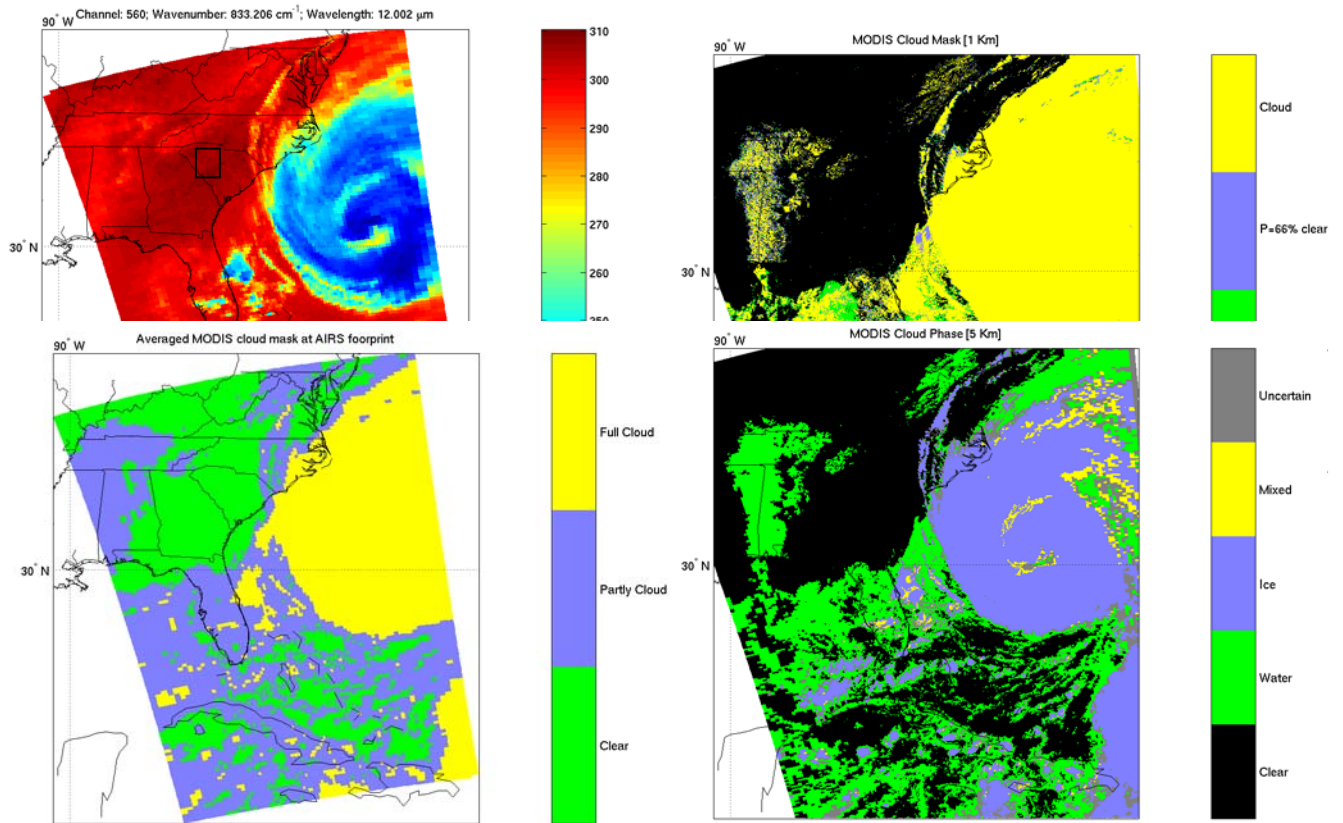
Figure 2. The AIRS BT image of channel 560 (833.206 cm^{-1}, approximately 12 μm) on 17 September 2003 (upper left panel), the MODIS cloud mask with 1 km spatial resolution (upper right panel), the AIRS coverage of clear, partly cloudy and overcast cloudy footprints (lower left panel), and the MODIS cloud phase mask with 1 km spatial resolution (lower right panel).
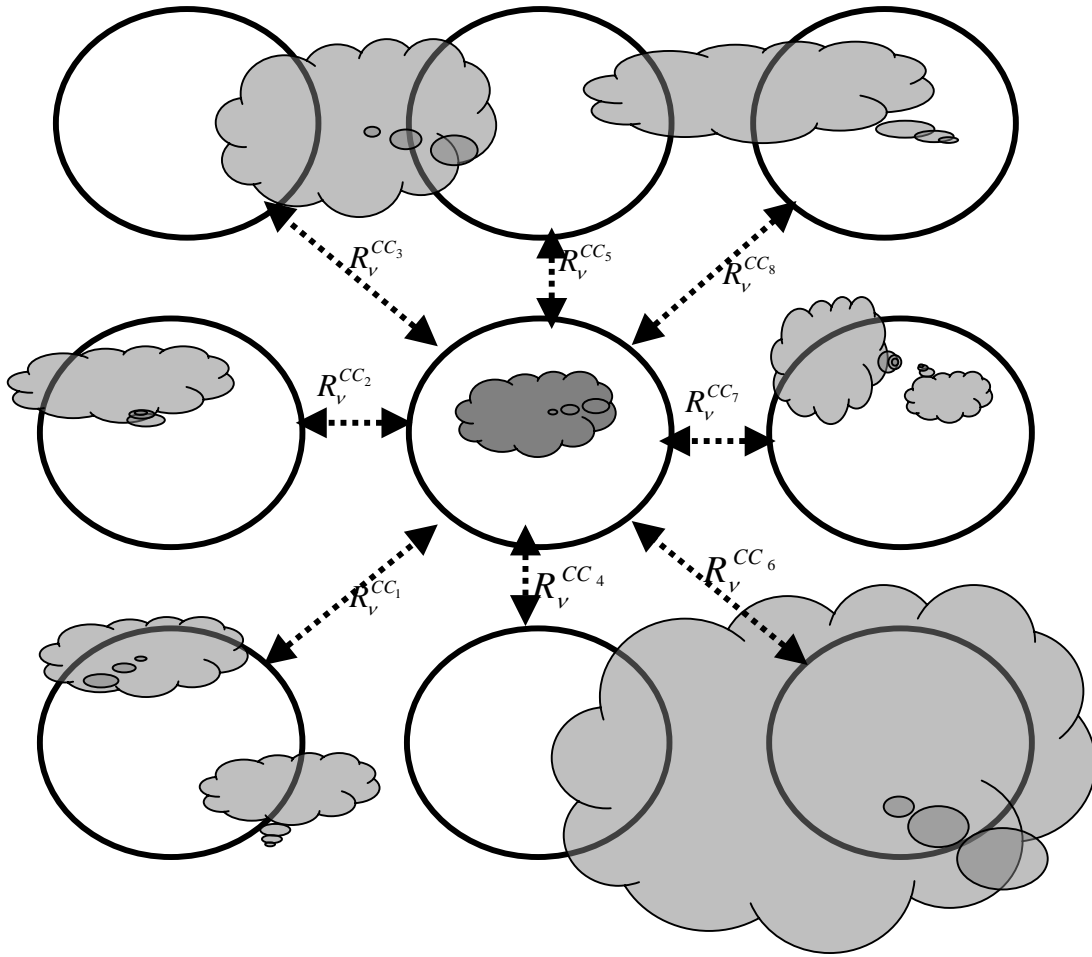
Figure 3. The diagram of the principal footprint and its 8 surrounding supplementary footprints in the optimal cloud-clearing procedure.
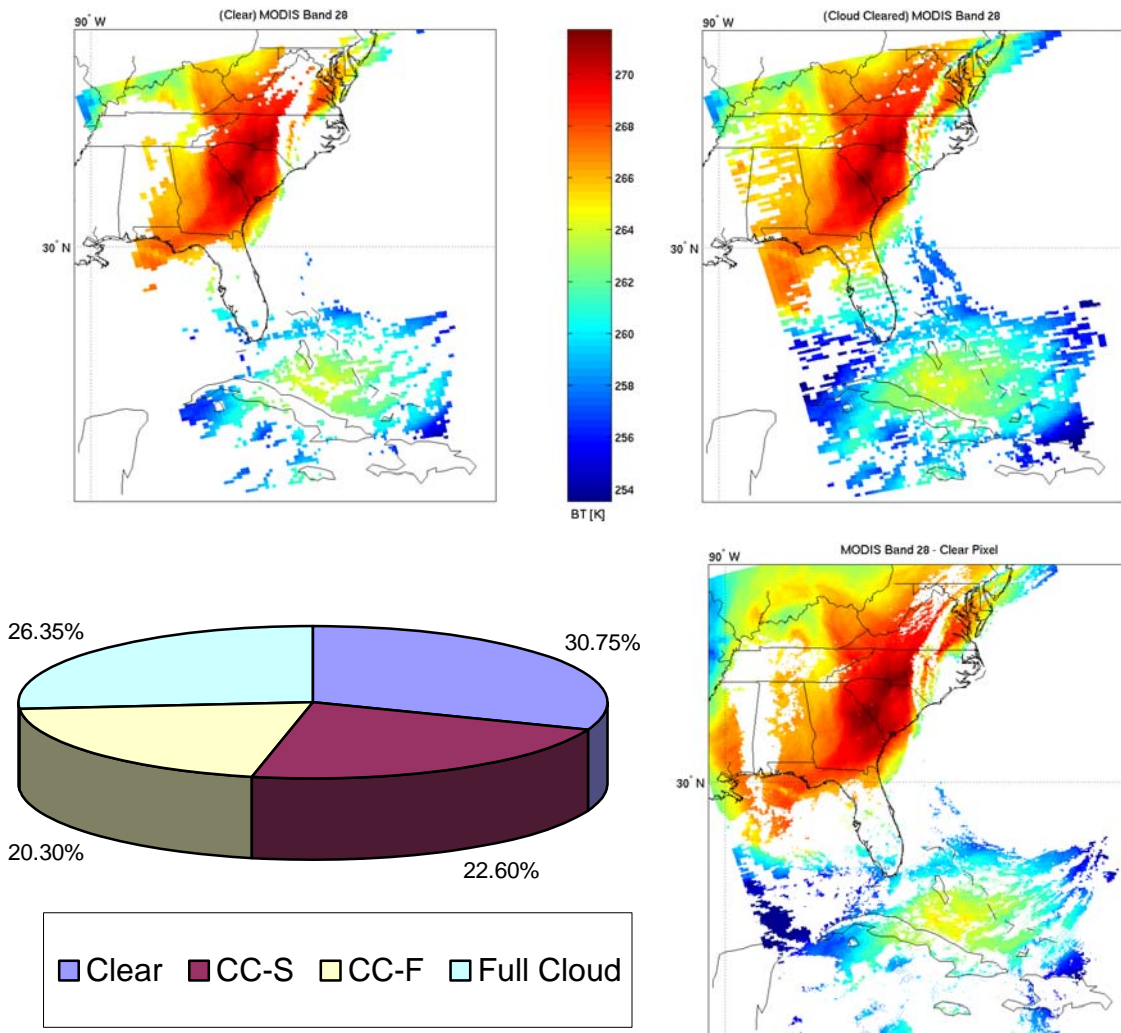
Figure 4. The BT images of MODIS band 28 (7.3 μm) convoluted from the AIRS clear footprints (upper left panel), the one convoluted from AIRS clear plus successful cloud-cleared footprints (upper right panel), the MODIS clear BT observations with 1 km spatial resolution (lower right panel), and the percentages 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.
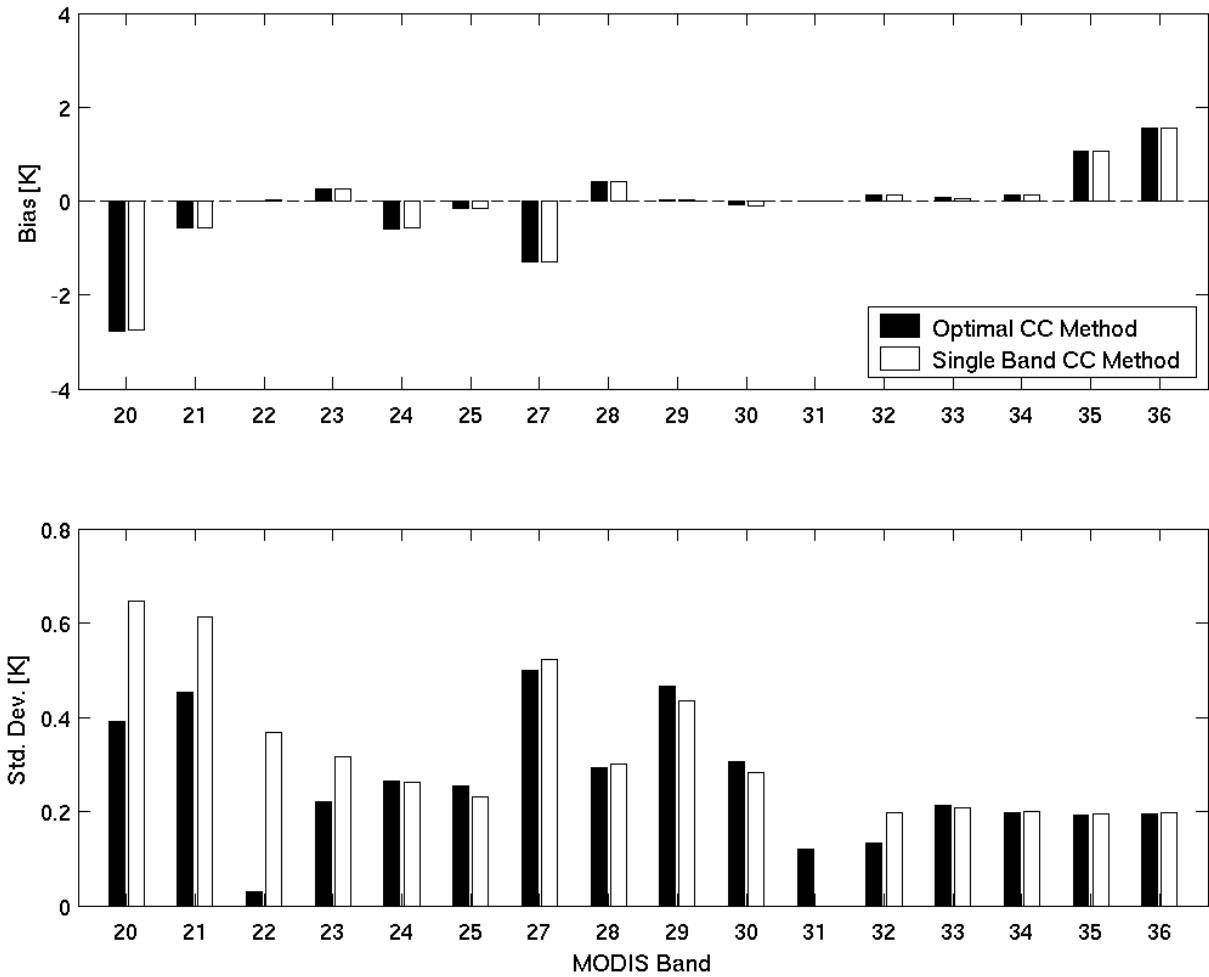
Figure 5. The bias and standard deviation between the MODIS clear BT observations and convoluted AIRS cloud-clearing BTs from all footprints with both the optimal cloud-clearing and the single band N cloud-clearing successful.
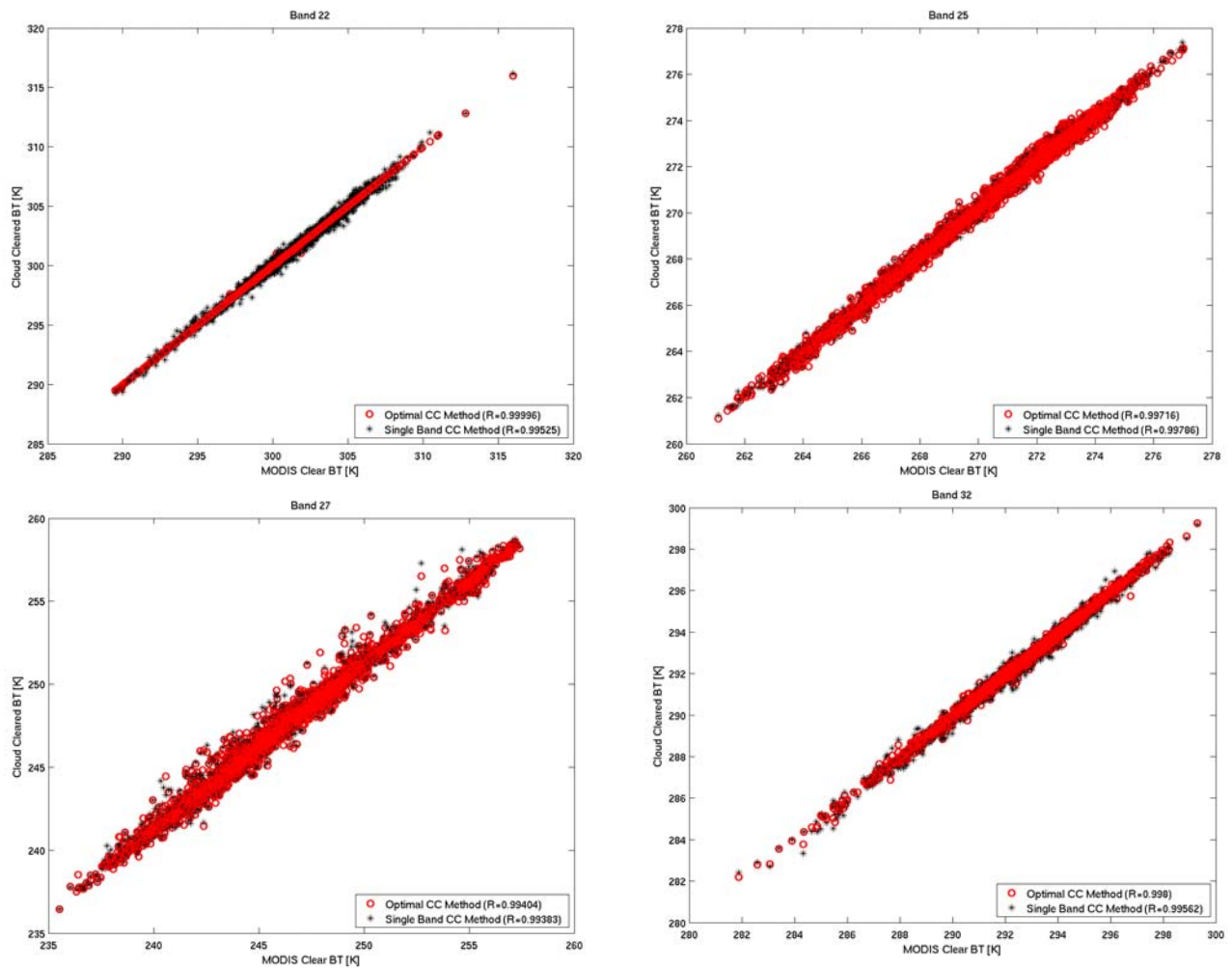
Figure 6. The scatterplot between the MODIS IR clear BT observations and the convoluted AIRS cloud-cleared BT with the traditional single band $\hat{N}$ cloud-clearing approach and the optimal cloud-clearing method for MODIS spectral bands 22 (upper left), 25 (upper right), 27 (lower left) and 32 (lower right).
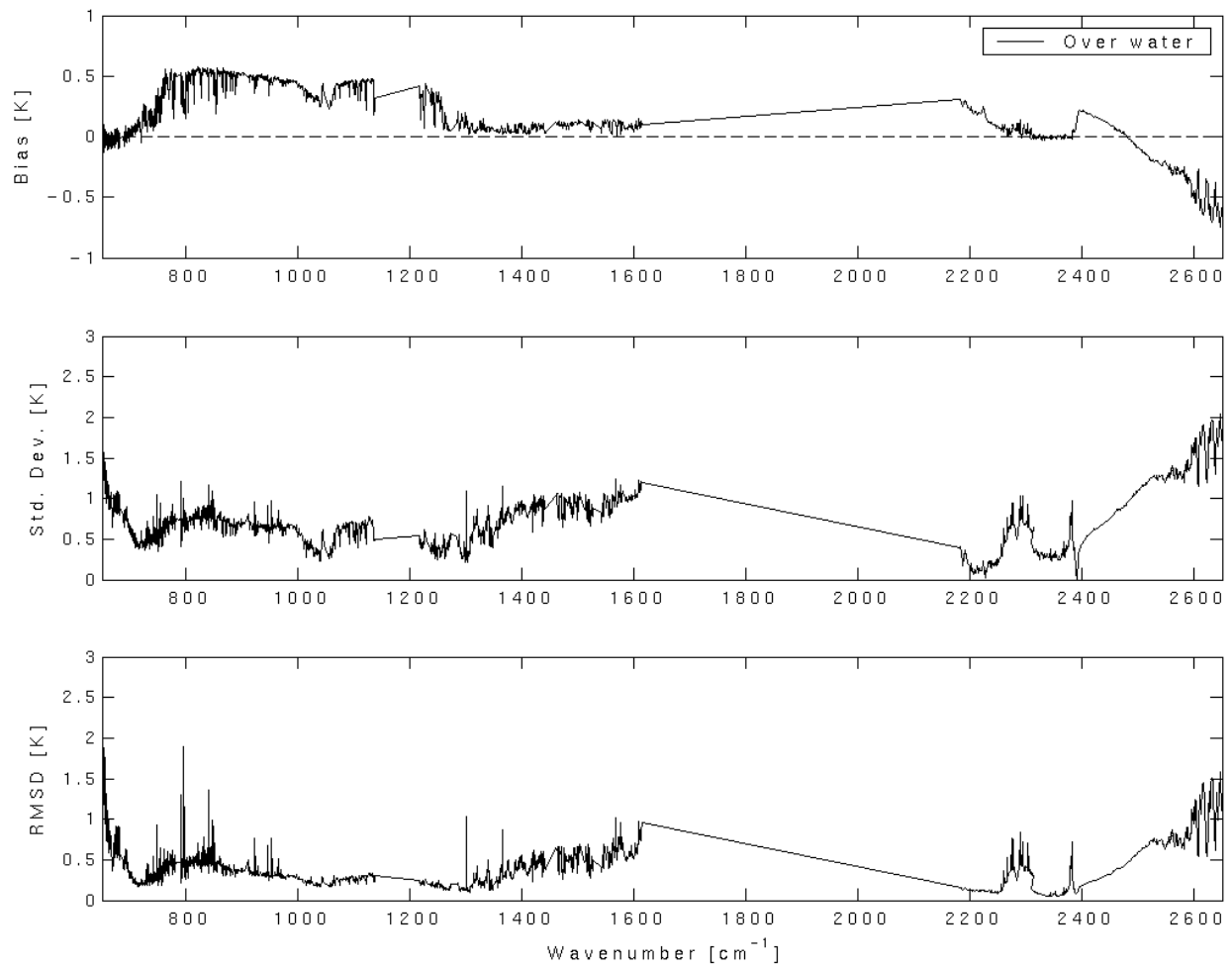
Figure 7. The bias (upper panel) and standard deviation (middle panel) between the AIRS cloud-cleared BT spectra and their nearby clear footprint BT spectra along with the RMSD between the two-adjacent clear AIRS footprint pairs over the water of the granule.