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Cirrus cloud optical and microphysical properties determined from AIRS infrared spectra

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[1] We developed an efficient thermal infrared radiative transfer model on the basis of the delta-four-stream approximation to facilitate high-spectral-resolution remote sensing applications under cirrus cloudy conditions in the Atmospheric Infrared Sounder (AIRS) data. Numerical experiments demonstrated that sensitivity in the 800-1130 cm^{-1} thermal infrared window spectral region is sufficiently distinct for the inference of cirrus optical depth and ice crystal mean effective size and shape factor. We analyzed 312 nighttime cirrus pixels in two AIRS granules over ARM TWP sites and applied the radiative transfer model to these cases to determine cirrus optical depth and ice crystal mean effective size, based on a look-up table approach. The retrieval program has been evaluated through an error budget analysis and validation effort by comparing AIRS-retrieved results with those determined from ground-based millimeter-wave cloud radar data at ARM TWP sites, for five AIRS pixels that were collocated and coincident with ground-based measurements. **Citation:** Yue, Q., and K. N. Liou (2009), Cirrus cloud optical and microphysical properties determined from AIRS infrared spectra, *Geophys. Res. Lett.*, *36*, L05810, doi:10.1029/2008GL036502.

1. Introduction

[2] Ground-based lidar measurements have shown that cirrus clouds can form at an altitude from 9–18 km in the tropics [*Comstock et al.*, 2002]. Composed of nonspherical and irregular ice crystals with sizes ranging from a few microns to thousands, determination of the cirrus microphysical and optical properties directly from satellites is an involved and challenging task.

[3] In the past few years, the Atmospheric Infrared Sounder (AIRS), a high-spectral-resolution sensor in the thermal infrared spectral region, has provided rich information content for the determination of a variety of atmospheric parameters. It measures upwelling radiances in 2378 spectral channels ranging from 650 to 2675 cm^{-1} [*Aumann et al.*, 2003]. In addition to strong CO_2 and H_2O bands for temperature and humidity profile retrievals, AIRS also has window channels that are particularly useful in inferring surface and cloud properties for both daytime and nighttime.

[4] By combining a thin cirrus approximation without scattering contributions and a clear radiance calculation from an efficient transmittance program referred to as OPTRAN [*Kleespies et al.*, 2004], *Yue et al.* [2007] developed a fast radiative transfer model that has been applied to AIRS window spectra for retrieval of the optical and microphysical properties of optically thin cirrus clouds. With multiple scattering for cloud particles neglected in the infrared window wavelengths, systematic discrepancies increase between AIRS-measured radiance spectra and model-computed results as the cirrus optical depth becomes greater than 0.3. We have developed a new efficient radiative transfer model by incorporating the delta-four-stream (D4S) approximation for infrared radiative transfer to account for multiple scattering contributions in the AIRS window channels for the purposes of retrieving cirrus cloud optical and microphysical properties in all atmospheric conditions.

[5] This paper is organized as follows. Section 2 presents the newly developed infrared radiative transfer model along with a brief discussion on D4S approximation for multiple scattering, and describes the methodology used to infer cirrus optical depth and ice crystal size from AIRS data. In Section 3, we present the results based on sensitivity study, apply the retrieval methodology to 312 AIRS tropical cirrus pixels in two granules over the ARM TWP sites, and compare retrieved AIRS cirrus cloud properties of five pixels with ground-based ARM cloud radar retrieval results. A summary is given in Section 4.

2. Infrared Radiative Transfer Model for Cirrus Cloudy Atmospheres

[6] The D4S for infrared radiative transfer has been discussed in detail by *Liou et al.* [1988], *Fu and Liou* [1993], and *Liou et al.* [2005]. The solution of this approximation involving two upward and downward radiative streams is in analytic form and its accuracy has been comprehensively checked. Because of the specific solution form for radiative transfer, the computational effort for upwelling radiances can be optimized. Furthermore, because of the isotropic emission source in the thermal infrared radiative transfer, the double Gauss quadrature formula can be employed to produce higher accuracy in radiance calculations [*Liou et al.*, 2005]. The accuracy of the D4S approximation for thermal infrared radiative transfer in cirrus cloudy atmospheres for AIRS channels (e.g., 926 cm^{-1}) has been assessed by comparing with the "exact" adding-doubling method developed by *Liou et al.* [2005]. We have demonstrated excellent agreement between the two with a mean difference and a root-mean-square of less than 0.25% and 0.4%, respectively.

[7] The cloudy upwelling radiance at the top of the atmosphere (TOA) for a given AIRS channel can be computed by combining the clear sky optical depths, which are determined from the OPTRAN transmittance model, and the cloud single-scattering properties, including single-scattering

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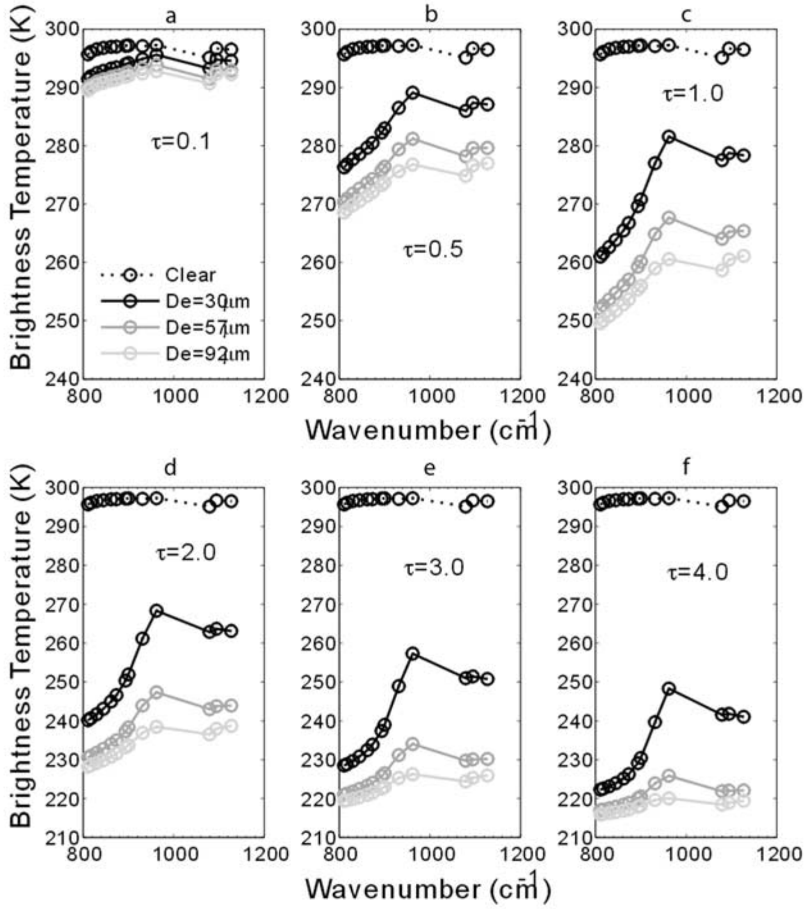

Figure 1. Sensitivity of the sub-band BT spectra to variation in optical depth and mean effective diameter for optical depths of (a) 0.1, (b) 0.5, (c) 1.0, (d) 2.0, (e) 3.0, and (f) 4.0. A standard tropical atmosphere was used in the calculation. Surface and cloud temperature were set to be 300 K and 200 K, respectively. Circles indicate the position of each sub-band. Black, gray, and light gray solid lines indicate a cirrus layer with mean effective diameters of 30, 57, and 92 μm, respectively. Clear sky BT spectrum (cloud optical depth = 0) is also shown by the dashed line for comparison purposes.

albedo, extinction efficiency, and asymmetry factor presented by *Yue et al.* [2007]. Nine size distribution (SD) and 11 habit distribution (HD) models collected from a number of field campaigns were used to represent tropical cirrus clouds. For a certain SD-HD set, the single-scattering properties of individual ice particles [*Yang et al.*, 2005] were integrated over SD and HD to obtain the bulk single-scattering properties for application to remote sensing.

[8] The atmospheric temperature, water vapor and ozone profiles, and surface properties, including surface infrared emissivity and reflectivity, were taken for input to the infrared radiative transfer model from the AIRS Level 2 Support Retrieval product and Standard Retrieval product datasets. Satellite viewing angle was taken from the AIRS viewing geometry given in the AIRS full swath data fields. We used the latest AIRS Version 5 data products in the current analysis. Employing all of the aforementioned AIRS variables, the layer optical depths of absorbing gases in the atmosphere can be computed from the OPTRAN transmittance model.

[9] Cloud top temperature was extracted from the AIRS Level 2 standard product to denote the cirrus altitude in the atmosphere. A cirrus layer is defined by specifying the cirrus optical depth $\Delta\tau_{vis}^{C}$ at a visible wavelength (0.55 μm), and an ice crystal mean effective diameter, D_e, which is defined as 1.5 times the ratio of total volume to total projected area for a specific set of ice crystal SD and HD. This mean effective size is the key parameter representing the scattering and absorption properties of a spectrum of ice particle sizes and habits. The infrared cirrus optical depth $\Delta\tau_{\nu}^{C}$ at a wavelength υ can be derived via the following relationship [*Minnis et al.*, 1998]: $\Delta\tau_{\nu}^{C} = \Delta\tau_{vis}^{C} \langle Q_{ext,\nu}\rangle/2$, where $\langle Q_{ext,\nu}\rangle$ stands for the mean extinction efficiency at an AIRS channel.

[10] Assuming that each pre-divided layer was homogeneous (100 pressure layers from 1100 to 0.016 hPa were used in this study), the absorption and scattering of cloud particles are mixed with gaseous absorption as follows: $\Delta\tau_{i,\nu} = \Delta\tau_{i,\nu}^{C} + \Delta\tau_{i,\nu}^{G}$, where $\Delta\tau_{i,\nu}$ is the total optical depth for the *i*th layer at wavenumber ν and the superscripts *C* and *G* represent contributions from cirrus cloud particles and gaseous absorption, respectively. The combined single-scattering albedo ($\omega_{i,\upsilon}$) and the asymmetry factor ($g_{i,\upsilon}$) can be obtained by $\omega_{i,\nu} = \Delta\tau_{i,\nu}^{C}\omega_{i,\nu}^{C}/\Delta\tau_{i,\nu}$, and $g_{i,\nu} = \Delta\tau_{i,\nu}^{C}g_{i,\nu}^{C}/\Delta\tau_{i,\nu}$, where $\omega_{i,\nu}^{C}$ is bulk single-scattering albedo, $g_{i,\nu}^{C}$ is the bulk asymmetry factor for cirrus cloud layer [*Rathke and Fischer*, 2000]. Following *Liou et al.* [1988], the delta-function adjustment has been applied to account for the forward diffraction peak in the four-stream radiative

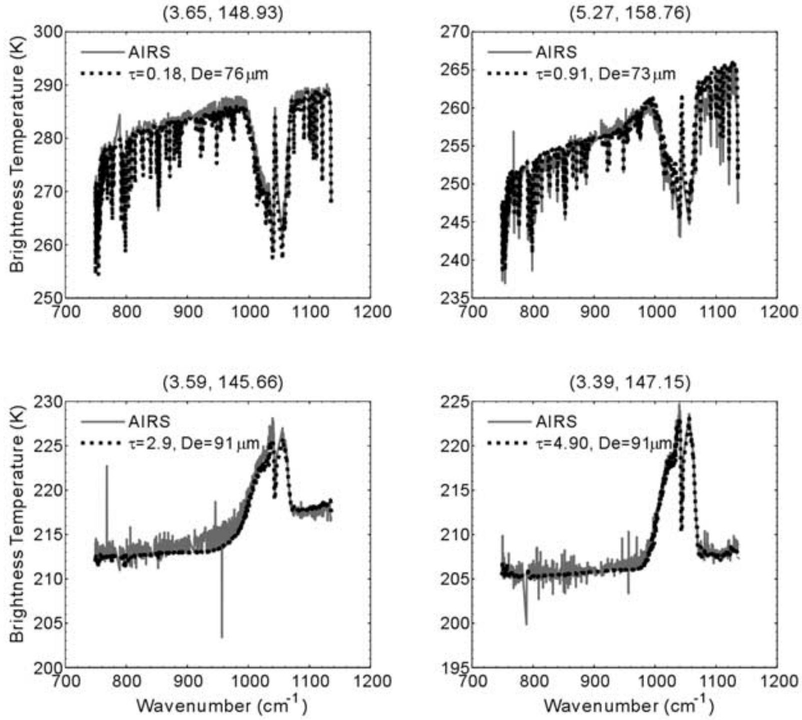

Figure 2. Four AIRS thin cirrus cloudy BT spectra calculated from simulation and observation in the 750–1130 cm^{-1} region. The cloud properties were determined by a minimization method.

transfer approach to increase computational accuracy in the approximation. With the boundary conditions at the surface and TOA defined, the cirrus cloudy upwelling radiance at any satellite viewing angle can be calculated through an integration technique [*Liou et al.*, 2005].

[11] Within the 800–1130 cm^{-1} thermal window, we define the "clean" AIRS sub-bands [*Yue et al.*, 2007] that are used to retrieve cirrus optical depth and mean effective size by (1) removing the band from 959.98 to 964.32 cm^{-1} to minimize the effect due to ozone absorption, and (2) reducing the total number of channels for efficient radiative transfer calculation by choosing 10 AIRS channels within each band. Therefore, there are 13 "clean" sub-bands corresponding to 130 AIRS channels in the current retrieval program.

[12] In the radiative transfer simulation study, we included visible optical depths ranging from 0.01 to 5.0, together with the bulk single-scattering properties corresponding to nine SDs and 11 HDs, to construct the look-up-tables to represent the tropical cirrus radiative properties for retrieval application. Mean brightness temperatures (BTs) are calculated for all 13 sub-bands, followed by the optimal determination of cirrus optical depth and mean effective diameter employing the minimization approach; i.e., minimizing the mean square differences between AIRS observed and model calculated radiances.

3. Results and Discussions

3.1. Sensitivity of AIRS Window Radiances to Cirrus Microphysical Properties

[13] Using the fast radiative transfer program, we investigated the sensitivity of the AIRS longwave window channel radiances to cirrus microphysical properties. A Standard Tropical Atmospheric Profile [*McClatchey et al.*, 1972] was used in the numerical experiments with a prescribed surface temperature of 300 K, a cloud-top temperature of 200 K, and a black surface over tropical oceans. Results are shown in Figure 1 for cirrus clouds with optical depths of (a) 0.1, (b) 0.5, (c) 1.0, (d) 2.0, (e) 3.0, and (f) 4.0 in terms of mean BT spectra for the 13 sub-bands. The circles in Figure 1 indicate the spectral sub-band positions, while the clear BT spectra are also depicted by the dashed curves for comparison purposes.

[14] Lines with different colors in Figure 1 correspond to a cirrus layer with different values of D_e. It is clear that between 800 and 1130 cm^{-1}, colder BTs are associated with larger mean effective diameters and greater optical depths in agreement the previous findings [*Wei et al.*, 2004; *Baran*, 2005]. Moreover, the dependence of spectra on optical depth appears to be related to the magnitude of D_es; that is, as optical depth increases, BTs decrease more rapidly for larger D_es. Figure 1a shows that even for a cirrus optical depth as small as 0.1, the BT difference between cirrus and the clear condition can be as large as 3 K. This magnitude increases to more than 15 K at an optical depth of 2.0, which is much larger than that reported by *Wei et al.* [2004] by about 5 K using the same cirrus optical depth value. Thus, the present model can be applied to the atmosphere containing optically thin cirrus for forward simulation and retrieval.

[15] We have also undertaken an effort to investigate the sensitivity of BT spectra to ice crystal habit. BT spectra are calculated from the same D_e having the same SD but different HDs so that differences in BTs are solely produced by ice crystal habit factor. The results show that the BT difference between the two spectra can be around 5 K when cirrus optical depth is 1.0, and it increases as optical depth increases.

Table 1. Comparison of the Cirrus Cloud Properties Retrieved From AIRS Data and Derived From MMCR Retrievals for Five Collocated and Coincident AIRS Pixels in Two Granules: 2003.05.16.154 and 2005.03.01.147

	Granule-Pixel				
	G154-1	G154-2	G147-1	G147-2	G147-3
			τ		
MMCR	0.25	1.15	0.04	0.09	0.03
AIRS	0.61	1.11	0.06	0.12	0.02
			D_e (μm)		
MMCR	120	146	63	72	57
AIRS	91	78	59	59	37

Although the magnitude of BT differences due to variation in ice crystal habits is smaller than that in mean effective sizes, the impact of ice crystal habit on thermal infrared regions can be important [*Baran*, 2005]. It appears that sufficient sensitivity exists for ice crystal habit factor in AIRS "clean" channels, a subject requiring future investigation.

3.2. Retrieval of Tropical Thin Cirrus From AIRS Data Over ARM TWP Sites

[16] We selected granule 154 on May 16, 2003 over the ARM TWP sites of Manus Island, collocated and coincident with the AIRS/Aqua overpass, for this study. Only the pixels that had a single-layer cloud having a top temperature colder than $-20°$C were used in the analysis, yielding 299 pixels in this granule for the present investigation. Cirrus optical depth and mean effective diameter are retrieved from the AIRS spectra over the 13 "clean" sub-bands discussed in Section 2. Subsequently, we carried out forward radiative transfer calculations using the retrieved cloud parameters for all AIRS channels from 750 to 1130 cm^{-1}. Comparisons between model-calculated BTs and the AIRS-observed spectra are displayed in Figure 2. Figures 2a–2d correspond to four different pixels in which the retrieved cirrus properties are indicated by the Figure 2 legends for optical depth ranging from 0.18 to 4.9, a much wider coverage than the previous method developed by *Yue et al.* [2007]. Moreover, after accounting for the multiple scattering contribution from ice particles, the average residuals between the model-BT and AIRS-observed spectra are reduced to within ±0.6 K when cirrus optical depths greater than 0.3 are included in the analysis. A larger residual of 2.5 K occurred over the ozone absorption bands probably because of ozone profile uncertainty in the AIRS product.

[17] The retrieved cirrus optical depth and ice crystal mean effective size of the 299 cirrus cases have been collocated following the criteria established by *Yue et al.* [2007] and subsequently compared to those derived from ARM mm-wave cloud radar (MMCR) data [*Mace et al.*, 2002]. Due to AIRS larger pixel sizes, smaller wind speeds within cloud layers, and the short temporal coverage of MMCR cirrus measurements at Manus Island on May 16, 2003, only two pixels that were closest to the ARM site can be collocated and appropriate for comparison. For this reason, we have selected the second case study using the AIRS granule 147 on March 1, 2005, an area covering 0 $\sim$ 1.5°S and 165 $\sim$ 167.5°E over the ARM Nauru Island site, which contains 13 AIRS pixels. In this case, only three pixels were collocated with the MMCR measurements.

[18] Comparisons of the AIRS-retrieved cirrus parameters and the MMCR-retrieved results for the five collocated pixels are listed in Table 1. The cirrus optical depths determined from AIRS data generally agree with the MMCR counterparts. However, the AIRS-inferred ice particle mean effective sizes are smaller than those derived from MMCR retrievals. This discrepancy could be explained by the fact that mm-wave backscattering from ice clouds generally missed small ice particles [*Comstock et al.*, 2002]. Also note that the selection of appropriate cirrus cases between satellite overpass and ground-based observations is rather intricate in terms of time and space. In the two case studies, cirrus clouds observed by the ARM ground-based instrument were changing on the order of minutes. However, for comparison purposes, the cirrus properties were assumed unchanged during the collocation time period, which could be on the order of hours due to AIRS' large pixel size ($\sim$13.5 km at nadir).

3.3. Retrieval Errors Associated With Model Input Uncertainties

[19] In order to determine the errors in the retrieval subject to input uncertainties and instrument noise from AIRS measurements, we have performed a number of numerical experiments for the case on May 16, 2003. The AIRS BT spectra, temperature profile, water vapor profile, cloud top temperature, ozone profiles, and surface temperature have been randomly added with a bias of ±0.2 K, ±1.0 K, ±15%, ±6.5 K, ±20%, and ±1.0 K, respectively. The magnitude of these uncertainties has been obtained from various AIRS validation projects and the mean absolute errors associated with these biases are listed in Table 2, which shows that uncertainties in the temperature and water vapor profiles are the major error sources, causing an error within 0.05

Table 2. Mean Absolute Errors of the Retrieved Cirrus Optical Depth and Ice Crystal Mean Effective Diameter Subject to Perturbations in Input Parameters and AIRS Instrument Noise[a]

Input Variable	Perturbation Magnitude	$\lvert\Delta\tau\rvert$	$\lvert\Delta D_e\rvert$ (μm)	$\lvert\Delta\tau\rvert/\tau \cdot 100$	$\lvert\Delta D_e\rvert/D_e \cdot 100$
$T(P)$	±1.0 K	0.005819	3.968	3.299	6.3665
$H_2O(P)$	±15%	0.004214	5.144	1.926	6.9625
$O_3(P)$	±20%	6.689e-5	0.3255	0.05857	0.4241
T_{cld}	±6.5 K	0.01368	1.492	0.8942	2.0959
T_{sfc}	±1.0 K	0.001371	2.203	0.8370	4.0494

[a]The definition of notations are $T(P)$, temperature profile; $H_2O(P)$, water vapor profile; $O_3(P)$, ozone profile; T_{cld}, cloud top temperature; and T_{sfc}, surface temperature.

in optical depth and an error within 5 μm in ice crystal effective particle size. Moreover, the retrieved cirrus optical depth is found to be sensitive to the accuracy of cloud top temperature, particularly for a high-level cloud with an effective fraction close to 1.

4. Summary

[20] We developed an efficient infrared radiative transfer model for interpretation of the AIRS spectra in cirrus cloudy atmospheres, as well as for application to the retrieval of cirrus optical depth and mean effective ice crystal size, which is critical to the evaluation of cirrus climate radiative forcing in the tropical regions. The multiple scattering contributions in thermal infrared radiative transfer become significant when cirrus optical depths are larger than about 0.3, and we have incorporated the delta-four-stream approximation coupled with an angular integration approach for remote sensing application. This infrared radiative transfer model has been successfully applied to retrieve cirrus optical depth and mean effective size from the AIRS spectra covering 13 "clean" sub-bands in the 10 μm region of the spectra. We have conducted a number of case studies and selected 312 tropical cirrus cloudy pixels from two AIRS granules collocated and coincident with the mm-wave cloud radar measurements over the ARM TWP sites for analysis and inter-comparison. Using the retrieved cirrus parameters, we have shown that the cloudy BT spectra in AIRS sub-bands simulated from the infrared radiative transfer model deviate from the observed spectra by less than 0.6 K. Moreover, we illustrated that the cirrus optical depth and mean effective ice crystal size retrieved from AIRS spectra are generally consistent with those derived from the ARM MMCR reflectivity results.

[21] Our analysis shows that the sensitivity of infrared BTs to ice crystal habit appears to be smaller than that due to the effects of optical depth and ice crystal size in the 800–1130 cm^{-1} window spectral region. We also investigated retrieval errors associated with the uncertainty and instrument noise in AIRS measurements. Uncertainties in temperature, humidity, and cloud top temperature are the major error sources in the retrieval; however, these uncertainties are much smaller compared to the BT sensitivity to optical depth and ice crystal mean effective size.

[22] The radiative transfer and remote sensing algorithm presented in this paper can be applied to AIRS radiances for the inference of cirrus cloud optical depth and mean effective ice crystal size over the tropical region and - with modification - can be applied to other regions of the globe as well.

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