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Atmospheric Profile Retrieval with AIRS Data and Validation at the ARM CART Site

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ABSTRACT

The physical retrieval algorithm of atmospheric temperature and moisture distribution from the Atmospheric InfraRed Sounder (AIRS) radiances is presented. The retrieval algorithm is applied to AIRS clear-sky radiance measurements. The algorithm employs a statistical retrieval followed by a subsequent nonlinear physical retrieval. The regression coefficients for the statistical retrieval are derived from a dataset of global radiosonde observations (RAOBs) comprising atmospheric temperature, moisture, and ozone profiles. Evaluation of the retrieved profiles is performed by a comparison with RAOBs from the Atmospheric Radiation Measurement (ARM) Program Cloud And Radiation Testbed (CART) in Oklahoma, U. S. A.. Comparisons show that the physically-based AIRS retrievals agree with the RAOBs from the ARM CART site with a Root Mean Square Error (RMSE) of 1 K on average for temperature profiles above 850 hPa, and approximately 10% on average for relative humidity profiles. With its improved spectral resolution, AIRS depicts more detailed structure than the current Geostationary Operational Environmental Satellite (GOES) sounder when comparing AIRS sounding retrievals with the operational GOES sounding products.

Key words: AIRS, physical retrieval, atmospheric profile, and ARM CART site

1. Introduction

The AIRS instrument (Atmospheric Infra Red Sounder; Aumann et al., 2003) onboard NASA's (National Aeronautics and Space Administration) Earth Observing System Aqua satellite is a high spectral resolution ($\nu/\Delta\nu$=1200, where ν is the wavenumber and $\Delta\nu$ is the width of a channel) infrared sounder with 2378 channels. AIRS measures radiances in the infrared region 3.74–15.4 μm, from which may be retrieved vertical profiles of atmospheric temperature and water vapor from the Earth's surface to the lower stratosphere (together with microwave measurements) with a horizontal resolution of 13.5 km at the nadir of AIRS (microwave measurement has a resolution of 3×3 AIRS measurement). AIRS is a multi-purpose instrument for measuring global atmospheric temperature, water vapor, trace gas concentration, surface temperature, surface emissivity, and aerosols, as well as cloud parameters and cloud properties. Table 1 shows its spectral characteristics. For comparison, the spectral characteristics of the High Resolution Infrared Radiation Sounder 3 (HIRS/3) instrument onboard the current polar-orbiting operational weather satellites is given in Table 2.

AIRS observations will lead to significant advances in weather prediction and a better understanding of the climate (Goldberg et al., 2003). Improved sounding capability is fully anticipated from the high spectral resolution AIRS (Susskind et al., 2003). In this

Table 1. AIRS Spectral Characteristics.

Band	Number of Channels	Wavenumber (cm^{-1})	Wavelength (μm)
1	1262	650–1136	8.80–15.40
2	602	1217–1613	6.20–8.22
3	514	2181–2665	3.74–4.61

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Table 2. HIRS/3 Spectral Characteristics.

Channel Number	Wavenumber (cm^{-1})	Wavelength (μm)	Main Absorber	Sounding Purpose
1–7	669–749	13–15	CO_2	Atmospheric temperature
8	900	11.1	Window	Surface temperature
9	1030	9.7	O_3	Ozone amount
10	802	12.5	Window	Water vapor
11–12	1365–1533	7.3, 6.5	H_2O	Water vapor
13–17	2188–2420	4.3	CO_2/N_2O	Atmospheric temperature
18–19	2515–2660	4.0, 3.7	Window	Surface temperature
20	14 500	0.69	Window	Cloud detection

study, a sounding retrieval procedure is used to generate atmospheric temperature, water vapor, and ozone profiles as well as the surface skin temperature and the infrared surface emissivity from AIRS measurements. The algorithm is a statistical approach followed by a non-linear physical iterative procedure (Li and Huang, 1999; Li et al., 2000; Zhou et al., 2003; Wu et al., 2004). The algorithm has been used to process data from the Advanced TIROS-N Operational Vertical Sounder (ATOVS) and the National polar-orbiting operational environmental satellite system Airborne Sounder Testbed-Interferometer (NAST-I). It is critical to evaluate and refine the algorithm for operational processing of the data from hyperspectral infrared sounders such as AIRS. Although Susskind et al. (2003) developed a physically-based inversion procedure for operational sounding retrieval which combined radiance measurements from one microwave sounder footprint and nine AIRS footprints, an algorithm for single infrared sounder footprint retrieval is necessary because there will not be a microwave sounding unit on any geostationary satellite in the foreseeable future. Evaluation of the physical retrieval algorithm for hyperspectral infrared sounder data processing is carried out in this paper. Time and space collocated AIRS retrievals, radiosonde observations (RAOBs), and operational Geostationary Operational Environmental Satellite (GOES) sounding products are used to verify and evaluate the sounding capability of AIRS data. It is found that the retrieval algorithm for AIRS clear-sky sounding is robust and that the AIRS retrievals agree with the RAOB with an RMSE of 1 K for temperature and 10% for relative humidity for most vertical layers.

It is also very important to compare the sounding capability of a hyperspectral infrared sounder and the current lower spectral resolution, multi-spectral sounders and imagers such as the GOES sounder and the MODerate-resolution Imaging Spectroradiometer (MODIS). It has been demonstrated that the hyperspectral infrared sounder has much improved vertical resolution over the current lower spectral resolution sounders (Li et al., 2004a, b; Wang et al., 2005). However, general retrieval comparisons have not been carried out adequately due to lack of a time-and-space-collocated sounder and in-situ measurements. In this paper, collocated AIRS, MODIS, GOES, and RAOB observations at the ARM CART site are used for this purpose. Comparisons between the AIRS retrievals and the current GOES sounding products indicate the advancement of a hyperspectral infrared sounder over the current operational broadband infrared sounder on sounding measurements, especially for water vapor soundings that are critical for improving numerical weather predictions.

Section 2 describes the methodology used for sounding retrieval from hyperspectral AIRS data. Section 3 presents the results and their validation as well as comparisons between AIRS and the current GOES sounder. A discussion of issues affecting AIRS retrieval is given in section 4. Conclusions are presented in section 5.

2. Methodology

2.1 *AIRS cloud mask*

The first step is to perform a cloud detection procedure for each AIRS footprint. Only AIRS clear-sky footprints are processed by the retrieval algorithm. The MODIS pixels with 1 km spatial resolution are collocated within an AIRS footprint (Li et al., 2004c). Once the MODIS pixels are collocated with the AIRS footprints, the cloud properties within the AIRS subpixels 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., 2004c). 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., 2004c). For each AIRS footprint, the proportion of clear coverage (0∼1) is determined by accounting for the percentage of MODIS pixels with statuses of "confidently clear" and "probably clear" (Ackerman et al., 1998) within the footprint.

2.2 *Retrieval algorithm*

The atmospheric temperature and moisture retrieval algorithm in this paper is a statistical regression followed by a non-linear physical iterative procedure. To derive the regression coefficients, AIRS radiances are calculated from a global set of RAOBs that quantify a range of atmospheric states. An ensemble of computed AIRS radiances with associated atmospheric profiles is created for the regression relationship. This method is often used to generate a first guess for a non-linear physical retrieval algorithm, as is done in the international ATOVS processing package (Li et al., 2000). The physical retrieval procedure involves linearization of the radiative transfer model and inversion of the radiance measurements. The radiative transfer calculation of the AIRS sounder spectral radiances is performed using a fast transmittance model called the Stand-Alone Radiative Transfer Algorithm (SARTA) (Strow et al., 2003). This model has 101 pressure level vertical coordinates ranging from 0.05 to 1100 hPa and uses line-by-line radiative transfer model calculations based on the high spectral resolution transmission molecular absorption spectroscopic database HITRAN 2000 (Rothman et al., 1998). The calculations take into account the satellite zenith angle and absorption by well-mixed gases (including nitrogen, oxygen, and carbon dioxide), water vapor, and ozone.

2.3 *Training dataset*

Statistical regression retrievals of atmospheric profiles from AIRS require a global dataset of temperature, moisture, and ozone profiles in addition to estimates of surface skin temperature and emissivity. A new dataset consisting of more than 12 000 global profiles of temperature, moisture, and ozone has been created. A radiance calculation for each training profile is made using SARTA V1.05. These calculations require a surface skin temperature and emissivity value for each profile. In the past, surface skin temperature and emissivity were assigned randomly to each profile in the regression retrieval algorithms, including MODIS atmospheric retrieval (Seemann et al., 2003), ATOVS retrieval (Li et al., 2000), and NAST-I retrieval (Zhou et al., 2003). Emissivity is assigned using a mean of 0.84 and a standard deviation of 0.15 at 4 μm, a mean of 0.95 and a standard deviation of 0.03 at 9 μm, and linearly interpolated in between. The surface skin temperature / air temperature difference is given a mean of zero and a standard deviation of 10 K. Recently, work has been done to better characterize the surface skin temperature / air temperature and the global emissivity in order to assign more realistic values to the training profiles upon a sound physical basis.

To characterize global surface skin temperature as a function of surface air temperature, solar zenith, and azimuth angles, the MODIS land surface temperature product is used together with global RAOBs. For two years (2001–2002) of data, MODIS land surface products and RAOBs are collocated within 3 hours and 0.1 degree of latitude and longitude. The resulting surface skin temperature / air temperature pairs are divided into different ecosystems. To assign surface emissivity to each profile, we take advantage of some laboratory measurements of emissivity from the MODIS emissivity library (http://www.icess.ucsb.edu/modis/EMIS/html/em.html). The drawback of the laboratory measurements is that the materials measured are not physically representative of global ecosystems.

3. Preliminary results and their validation

3.1 *Data*

AIRS radiances are used to verify and evaluate the algorithm. One example of an AIRS spectrum from a real measurement is given in Fig. 1. The large numbers of AIRS measurements and the computational cost required to process all AIRS channels are prohibitive in the framework of a physical scheme. The same subset of 394 channels is utilized for both statistical regression and physical retrieval in our study. The red spots in Fig. 1 indicate the positions of the selected channels in the whole AIRS spectrum. Comparisons between collocated temperature and moisture soundings from AIRS and RAOBs at the ARM CART site in Oklahoma are made for this purpose. Aqua passes over the ARM CART occurred daily between 0800 and 0900 UTC and between 1900 and 2000 UTC. Radiosondes are launched at approximately 0800, 0900, 1900, and 2000 UTC. AIRS retrieved profiles are compared with RAOBs for 335 cases from 20 July 2002 to 30 April 2003. Collocated MODIS operational products, such as cloud mask and cloud phase, are used for AIRS cloud detection. Collocated operational GOES sounding products are used for evaluating the improvement of the hyperspectral infrared sounder over the lower spectral infrared sounder.

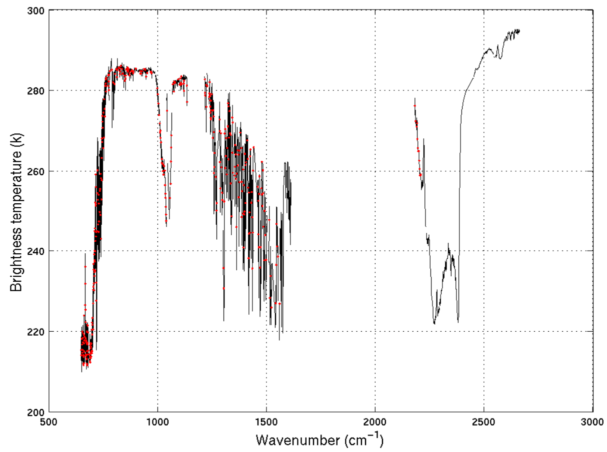

Fig. 1. The spectrum of AIRS observed brightness temperature.

3.2 *Statistics of profile retrieval*

Figure 2 shows the RMSEs of temperature (left panel) and water vapor mixing ratio (right panel) for both the statistical regression and physical retrievals compared with RAOBs. Due to the AIRS large field of view with cloud contamination, only 20 clear cases are chosen to satisfy the AIRS clear-sky radiances for retrieval from 20 July 2002 to 30 April 2003. Retrieval from both AIRS and microwave measurements (Susskind et al., 2003) or the cloud-cleared radiances (Li et al., 2005) from an AIRS footprint with partial clouds will provide reliable soundings under partly cloudy situations. Both the regression and physical retrievals show general agreement with the RAOB temperature profile. For levels above 850 hPa, the RMSE between AIRS and RAOB collocated in time and space is less than 1 K on average for regression retrievals and physical retrievals alike. For the near-surface levels, physical retrievals are 0.5 K better than regression. However, the RMSE of boundary layer temperature is still greater than 1 K, which is due to cloud contamination, infrared surface emissivity uncertainty, and the large boundary layer temperature variability; it is difficult to retrieve the fine structure near the surface. It can be seen from the right panel that the RMSE of the moisture profile for the physical retrieval is approximately 10%. The physical retrieval provides much better moisture profiles than the statistical regression. On average, the physical retrieval is improved by 5% over the regression for water vapor humidity. The comparison between AIRS retrievals and the current operational GOES sounding product (Li et al., 2004a) is also included in Fig. 2; GOES uses radiances measured

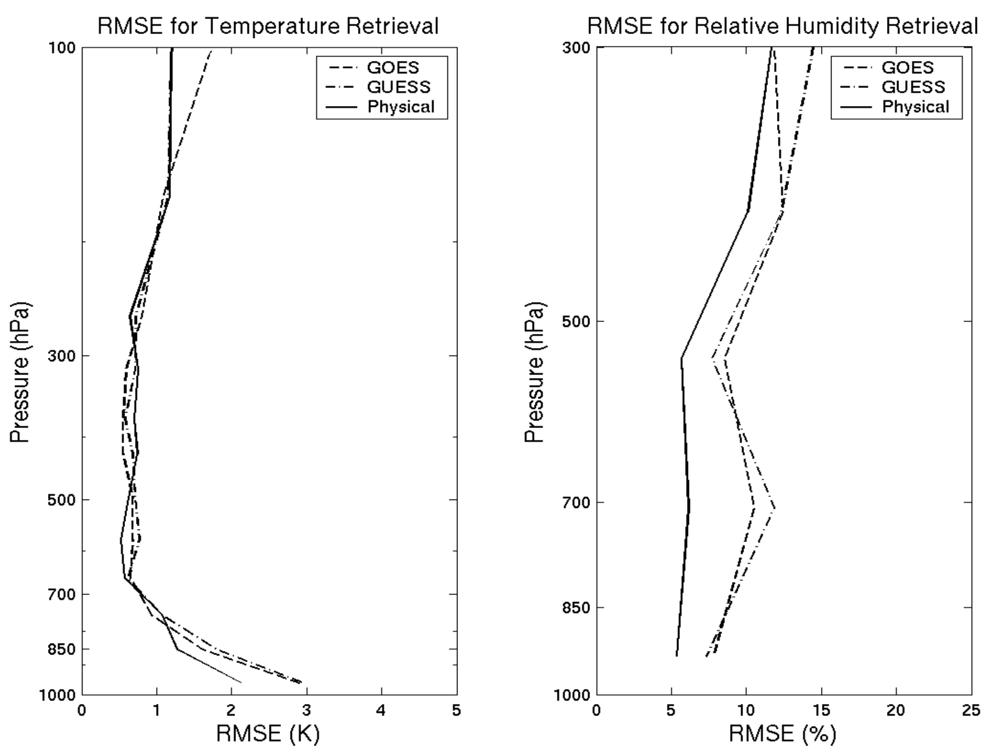

Fig. 2. The RMSE of temperature (left panel) and water vapor mixing ratio (right panel) for statistical regression (GUESS), physical retrieval (Physical), and GOES operational retrieval (GOES).

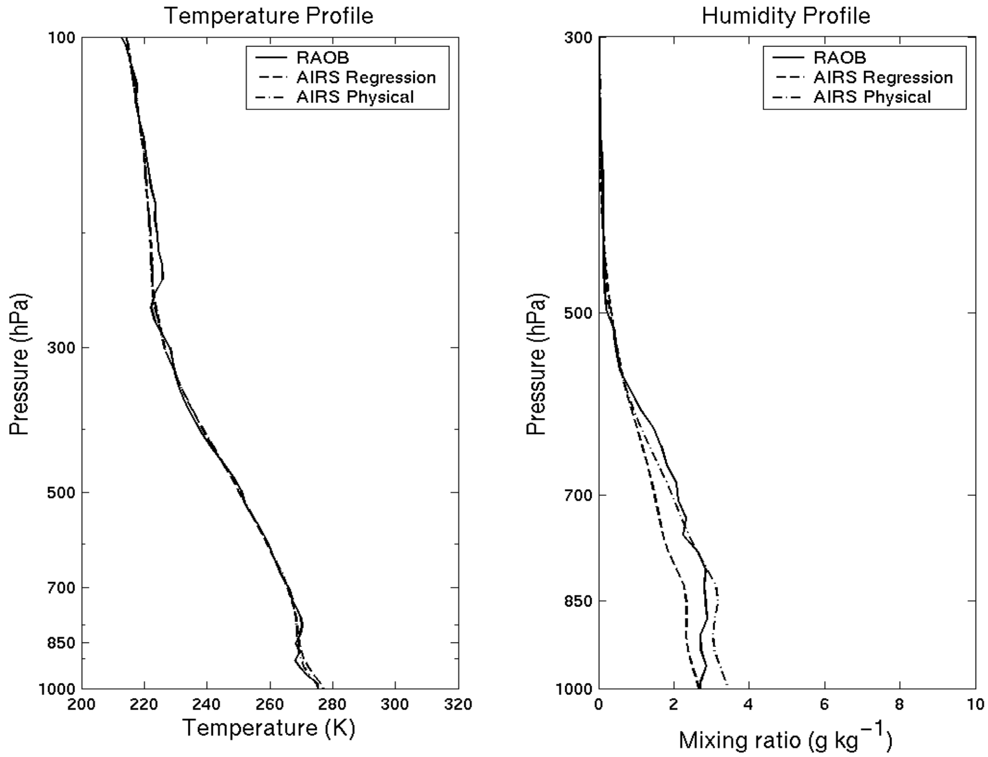

Fig. 3. Comparison of temperature (K) and mixing ratio on 16 February 2003 from the single AIRS FOV retrieved profiles at the ARM CART site at 0949 UTC (AIRS Regression and Physical), and a RAOB.

from a 3 by 3 field-of-view area (approximately 30 km resolution) to retrieve one atmospheric profile. It should be noted that the GOES operational product uses forecasts from a numerical weather prediction model to provide the first guess field. Since the forecast uses the temperature from radiosonde measurements that are spatially and temporally stable, it is expected that not much improvement of AIRS temperature retrievals will be seen over the GOES temperature sounding. However, improvement in the moisture retrieval is seen with AIRS over the current GOES sounder, indicating that AIRS provides forecast-independent moisture information with much better accuracy than the current sounding system.

3.3 *Case studies*

Two examples compare the temperature and moisture profiles from RAOBs at the ARM CART with the AIRS physical and regression retrievals of temperature and moisture. For an atmosphere with a fairly smooth temperature and humidity distribution, such as that shown in Fig. 3, both the AIRS statistical regression and the physical retrieval are in good agreement with RAOB observations. Another comparison of temperature and moisture profiles from a RAOB at the ARM CART with AIRS physical retrievals and statistical regression of temperature and moisture is shown in Fig. 4. For an atmosphere with a smooth temperature distribution, such as that shown in the left panel, both the AIRS statistical regression and the physical retrieval compare well to RAOB observations and the capture the inversion in the lower atmosphere. However, in situations with isolated layers of sharply changing moisture as shown in the right panel, the AIRS physical retrieval is able to better capture the finer-scale structure than the regression retrieval. This is the improved sounding capability achieved by the high spectral resolution AIRS measurement. The operational atmospheric profile product from the low spectral resolution MODIS radiance could not capture the fine-scale structure (Seemann et al., 2003). Figure 5 shows the comparison between the observed and calculated brightness temperatures from retrievals (regression and physical). It can be seen from this figure that the brightness temperatures converge well from the initial regression to the final physical retrieval.

4. Discussions

A high spectral resolution infrared instrument with

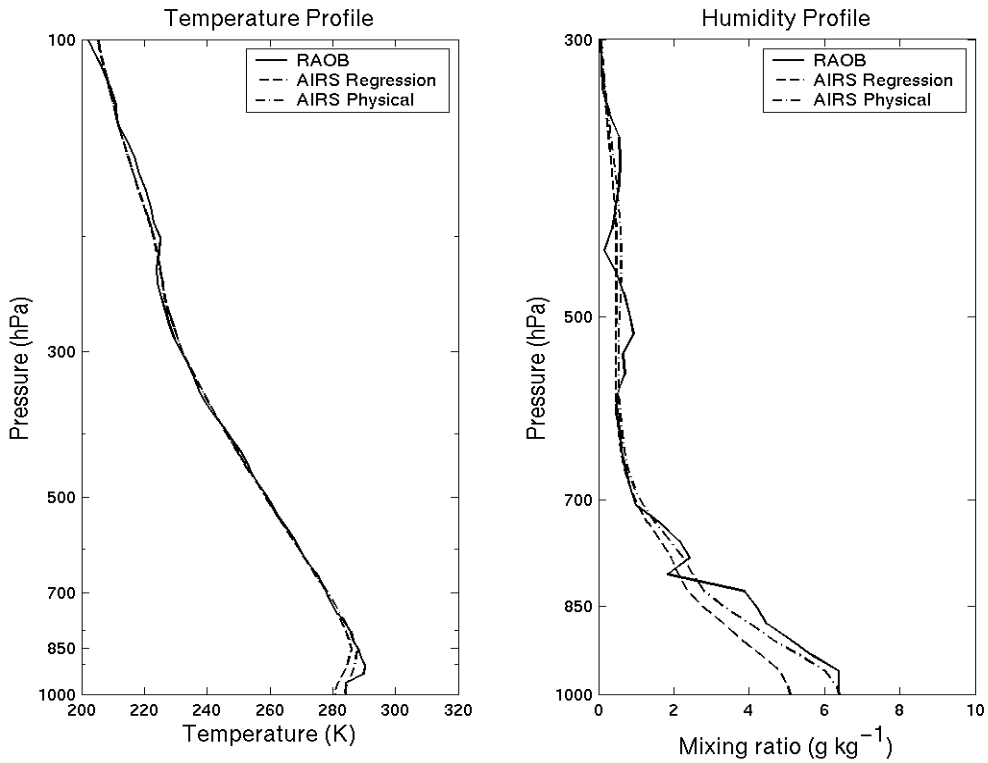

Fig. 4. Comparison of temperature (K) and mixing ratio on 9 January 2003 from the single AIRS FOV retrieved profiles at the ARM CART site at 0744 UTC (AIRS Regression and Physical), and a RAOB. In this situation where the moisture is not smooth, the AIRS physical retrieval captures the vertical structure fairly well.

a large number of channels is crucial to accurately retrieve atmospheric variables. AIRS measurements provide information on the changes in the atmospheric state using a physically-based retrieval of temperature and moisture profiles as well as the surface skin temperature and the infrared surface emissivity. As a first step in the retrieval process, guess profiles of temperature and moisture as well as surface parameters are generated. An iterative physical process results in the final retrievals. The moisture retrievals have provided a noticeable improvement over the first guess, while temperature retrievals have remained very similar to the first guess. The lack of temperature profile improvement in the physical retrieval process might be caused by insufficient use of the AIRS radiance information or the implementation of the radiative transfer calculation in the physical retrieval. This study demonstrates that both temperature and moisture profiles can be improved (by up to ∼0.5 K for temperature in the boundary layer and ∼5% for moisture profiles) when the AIRS radiance measurements are used in our physical retrieval approach. This improvement is significant to the better use of the AIRS measurements.

The results indicate that the physical method is capable of successfully deriving atmospheric parameters. The retrieved profiles are in good agreement with RAOB observations. However, the following issues need to be addressed.

(1) Quantification of the error of the radiative transfer model. There are error sources in both the line-by-line model and the fast model. Quantifying the error of the radiative transfer model and developing a fast and efficient radative transfer model with very high accuracy are crucial for physical retrieval from hyperspectral infrared sounders.

(2) Improvement of cloud detection for the AIRS footprint. Since AIRS has a coarse spatial resolution, the probability of an AIRS footprint being completely clear of cloud is very small. Although the MODIS cloud mask can be used to identify the AIRS sub-pixel cloud properties, an AIRS stand-alone cloud detection algorithm is necessary, especially during the nighttime when the MODIS cloud mask is not reliable due to the lack of visible and near infrared spectral bands. Furthermore, clear channel detection for a cloudy AIRS footprint is also needed; the clear channels alone with the cloud-cleared (Li et al., 2005) channels from an

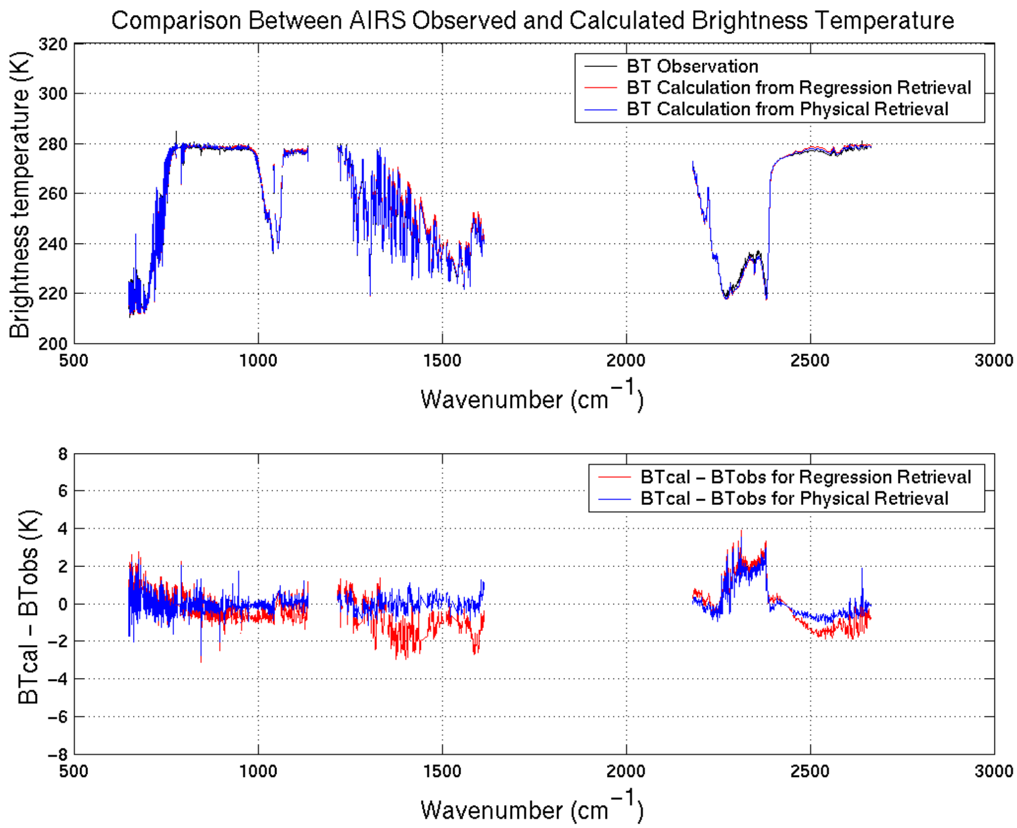

Fig. 5. Comparison between AIRS observed and calculated brightness temperature for the case in Fig. 4.

AIRS footprint with partial clouds will provide reliable soundings under partly cloudy skies.

(3) The training dataset is also very important for retrieval; each profile in the training dataset should have a physically realistic surface emissivity spectrum and surface skin temperature assignment. Although work has progressed in this area, improvement in surface emissivity and skin temperature assignment is still needed.

(4) The inversion technique also needs to be improved; optimal information retrieval from the boundary layer is not yet satisfactory. Although the selection of a smoothing factor in the inverse procedure has been studied (Li and Huang, 1999; Li et al., 2000), we found that the results are very sensitive to the initial assignment of the smoothing factor. An efficient determination of the smoothing factor with less retrieval dependence is necessary for a stable solution.

(5) Synergistic use of other measurements such as surface observations and GPS radio occultation data (Borbas et al., 2002) will improve the AIRS-only sounding. For example, adding surface parameters will improve the performance of physical retrievals in the boundary layer.

5. Conclusions and future work

The physical retrieval algorithm of atmospheric temperature and moisture distribution from the AIRS clear-sky radiances has been refined and evaluated in our study. The algorithm employs a statistical retrieval followed by a subsequent nonlinear physical retrieval. The regression coefficients for the statistical retrieval are derived from a dataset containing more than 12 000 global profiles of atmospheric temperature, moisture, and ozone. Each profile in the training dataset has a more realistic surface emissivity spectrum and surface temperature. Evaluation of retrieved profiles is performed by a comparison with radiosonde observations at the ARM CART site in Oklahoma. Comparisons show that the physically-based AIRS retrievals agree with the RAOBs at the ARM CART site with an RMSE of 1 K on average for temperature profiles above 850 hPa, and approximately 10% on average for relative humidity profiles, and this meets the AIRS design requirements. The comparison between AIRS retrievals and the current operational GOES sounding product shows a slight improvement of AIRS temperature retrievals over the GOES temperature soundings. However, significant improvement has been seen from AIRS moisture retrieval over the current GOES sounder, indicating that AIRS provides forecasts independent moisture information with a much better accuracy than the current sounding system. With its improved spectral resolution, AIRS depicts more detailed structure than the current GOES sounder when comparing AIRS sounding retrievals with the operational GOES sounding products.

Future work will be directed toward retrieving the atmospheric profiles under partly cloudy conditions (using cloud-cleared radiances) and the estimation of cloud parameters and cloud microphysical properties

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