Synergistic use of AIRS and MODIS radiance measurements for atmospheric profiling

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[1] Retrieval of atmospheric profiles from combined radiance measurements of the Atmospheric InfraRed Sounder (AIRS) and the MODerate resolution Imaging Spectroradiometer (MODIS) onboard the NASA Aqua satellite is investigated. The collocated operational MODIS cloud mask product and the clear-sky InfraRed (IR) radiance measurements are used to characterize the AIRS sub-pixel cloud fraction and improve the atmospheric sounding and the surface parameters at the AIRS single field-of-view (SFOV) resolution. The synergistic algorithm employs an eigenvector based regression with additional information from MODIS measurements. The regression coefficients are derived from a global dataset containing atmospheric temperature, moisture, and ozone profiles. Evaluation of the retrieved profiles is performed by comparisons between AIRS soundings, European Centre for Medium-Range Weather Forecasts (ECMWF) analysis fields and radiosonde observations from the Cloud And Radiation Testbed (CART) in Oklahoma. Spectral radiance calculations from the sounding retrievals agree with the observations from AIRS adjacent clear neighbor footprint quite well. These comparisons demonstrate the potential advantage of synergistic use of high-spectral sounder and high-spatial imager over either system alone. Citation: Liu, C.-Y., J. Li, E. Weisz, T. J. Schmit, S. A. Ackerman, and H.-L. Huang (2008), Synergistic use of AIRS and MODIS radiance measurements for atmospheric profiling, Geophys. Res. Lett., 35, L21802, doi:10.1029/2008GL035859.

1. Introduction

[2] The Atmospheric InfraRed Sounder (AIRS) instrument [Chahine et al., 2006] and the MODerate resolution Imaging Spectroradiometer (MODIS) measurements [King et al., 2003] from National Aeronautics and Space Administration’s (NASA) Earth Observing System’s (EOS) Aqua satellite enables global profiles of atmospheric temperature and water vapor with high vertical resolution [Susskind et al., 2003], and monitoring of the distribution of clouds [Ackerman et al., 1998] with high spatial resolution (1 km at nadir), respectively. Due to the relatively poor spatial resolution of AIRS (13.5 km at nadir), the chance for an AIRS footprint being completely clear is less than 10% [Huang and Smith, 2004]; however, accurate soundings with single FOV (SFOV) spatial resolution under both clear and cloudy skies remains important. The operational AIRS sounding product is based on 3 × 3 fields-of-view (FOVs), which is useful for numerical weather prediction and climate studies, but this spatial resolution lacks the capability to address certain meteorological applications such as preserving spatial gradients for monitoring and predicting mesoscale features. Since one AIRS footprint (due to its footprint size) contains both clear and/or cloudy scenes, sounding retrievals using AIRS-alone measurements for all sky conditions is quite challenging. Determining the cloud fraction within the AIRS scene using collocated MODIS observations could improve the AIRS retrieval. MODIS cloud products used in this study include the cloud mask (MYD35) [Frey et al., 2008; Ackerman et al., 2008] that provides each MODIS 1 km pixel with a confidence on the pixel being clear. The MODIS 1 km pixels are spatially collocated within each AIRS SFOV, and hence the given AIRS SFOV cloud fraction can be derived from the MYD35 cloud mask product. A statistical and a physical inverse method has been developed to retrieve temperature and moisture profiles in clear skies or under optically thin clouds [Smith et al., 2005; Zhou et al., 2007; Weisz et al., 2007a, 2007b]. Smith et al. [2004] suggested that there are essentially three ways to deal with cloudy radiances in the sounding process: (1) assume opaque cloud conditions and retrieve the profile above the cloud, (2) cloud-clear the radiances, and (3) make use of a physically based radiative transfer model in the retrieval. This paper is an extension of approach (2), where MODIS determined clear-sky pixels provide additional information to the AIRS measurement.

[3] The main differences between the AIRS-alone sounding algorithm [Zhou et al., 2007; Weisz et al., 2007a, 2007b] and AIRS/MODIS synergistic sounding algorithm, as presented in this paper, are (1) adding MODIS clear-sky IR brightness temperature (BT) information when the AIRS SFOV is only partially cloudy as determined by MODIS cloud mask product [Li et al., 2004], (2) separating regression coefficients for sounding retrievals based on surface properties or cloud phases, and (3) assigning the cloud microphysical properties in terms of cloud optical thickness (COT) and effective cloud particle diameter (CDe) to compute a large training dataset of cloudy radiances.

[4] Initial results of inter-comparisons between the sounding retrievals and European Centre for Medium-Range Weather Forecasts (ECMWF) analysis, along with radiosonde observations show that synergistic use of data from high spectral resolution IR sounder data (e.g., AIRS...
and Infrared Atmospheric Sounding Interometer) and high spatial resolution imager data (e.g., MODIS and Advanced Very High Resolution Radiometer) is promising. Hyperspectral IR alone sounding algorithms have been developed for cloudy sky conditions, soundings below the clouds are less accurate due to limited sounding information below clouds and the uncertainty of cloudy radiative transfer model. Inclusion of MODIS clear IR radiances can help in the definition of the cloud parameters and condition the structure of sounding below the clouds and increase the accuracy of solution.

2. Methodology Used for Synergistic AIRS and MODIS Single FOV Sounding

[5] To obtain a fast and accurate first estimate of the atmospheric state, a statistical eigenvector (EV) regression based on AIRS hyperspectral resolution measurements with high spatial resolution MODIS observations as additional predictors was developed. The synergistic algorithm starts with the AIRS stand-alone clear and cloudy retrieval software [Weisz et al., 2007a, 2007b], which retrieves atmospheric conditions, surface parameters and cloud-top height. The synergistic AIRS and MODIS algorithm is based on the eigenvector regression. The regression training set [Seemann et al., 2008] consists of 15704 global profiles of temperature, moisture and ozone at 101 vertical levels from 0.005 to 1100 hPa, as well as the surface skin temperature and surface emissivity. The associated clear-sky radiances at AIRS spectra were simulated using Stand-alone Radiative Transfer Algorithm (SARTA v1.07) [Strouw et al., 2003], while the cloudy radiances were computed with a fast hyperspectral cloudy radiative transfer model developed under the joint efforts of the University of Wisconsin-Madison and Texas A&M University [Wei et al., 2004]. The clear radiative transfer calculation of the MODIS spectral band radiances was performed by using a transmittance model called Pressure-Layer Fast Algorithm for Atmospheric Transmittance (PFAAST) [Hannon et al., 1996].

[6] To train the cloudy-sky regression, the AIRS cloudy radiances were simulated using a large number of atmospheric profiles with the following combinations of cloud properties. Each cloudy profile of the training set is assigned a cloud-top pressure (CTP) between 100 and 900 hPa based on the relative humidity profile; where CTP < 500 hPa are assumed to be ice clouds and CTP > 400 hPa are assumed to be liquid water clouds. For each profile with a an assigned CTP, cloudy profiles were generated with 8 COT values assigned between 0.04 and 2, 9 cloud particle diameter (CDe) values assigned between 10 to 70 μm for ice clouds, and 4 to 50 μm for liquid water clouds.

[7] Once the AIRS BTs have been calculated, a regression is generated relating the BTs to the profiles. In the synergistic algorithm, besides the AIRS EVs, eleven clear synthetic MODIS IR spectral band BTs and associated quadratic terms [Seemann et al., 2003] are added as additional predictors. In clear scenes, the coefficients are

Figure 1. Flowchart of the AIRS/MODIS synergistic atmospheric profile retrieval algorithm.
calculated for over water and land separately. Due to the spectral complexity of clouds, the coefficients are done for water and ice cloud phases separately. In addition these classifications are based on the surface type or cloud phase; the training set is also classified based on the averaged AIRS BT in the longwave window region that has 11 channels centered at 910 cm$^{-1}$, and 20 AIRS sensor scan angles. The surface pressure from the National Centers for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS) is also used as a predictor.

Figure 2. Global statistics of room-mean-square difference (RMSD) (solid curves) and bias (dash curves) between AIRS alone (blue curves), synergistic (red curves) retrievals (2571 profiles) and 6-hour ECMWF analysis fields of (a) temperature and (b) column precipitable water on 15 Aug 2007 over the water and thin ice cloud condition with respect to AIRS SFOV cloud fraction at 0.1 binning of three atmospheric layers. The legends of T1, T2, and T3 (WV1, WV2, and WV3) are the statistics at atmospheric layers for temperature (column precipitable water) at 75–200 hPa (300–700 hPa), 200–800 hPa (700–900 hPa), and 800 hPa (900 hPa) to surface level respectively.

[8] The AIRS SFOV retrieval algorithm is outlined in Figure 1. The main input data include AIRS, MODIS Level-1B (L1B) measurements and MODIS cloud mask product. Quantitative comparison of instruments requires accurate collocation of the instruments’ FOVs [Aoki, 1985]. The collocation designates the instrument with the larger FOV as the principle instrument, in this case the AIRS, and the collocation method locates all FOV of the secondary instrument (MODIS) that fall within each principle FOV. Once the collocation is done, the AIRS footprint cloud fraction is derived from the MODIS cloud mask product to classify the AIRS FOV as clear, partly cloudy or overcast [Li et al., 2004]. If the cloud fraction of a given AIRS FOV is greater than 0.99, which means only very limited or no MODIS clear measurements are present, the AIRS cloudy alone algorithm [Weisz et al., 2007b] is applied, otherwise the synergistic algorithm is used.

[9] If the AIRS footprint is clear, then the clear regression coefficients are applied to the BT spectrum, and the clear retrieval is obtained. If the footprint is cloudy, a cloud phase detection method based on an IR technique [Strabala et al., 1994] is applied to the AIRS BT spectrum for identifying ice clouds, water clouds or mixed phase clouds. After the cloud phase is determined, the appropriate set of coefficients is applied for cloudy sounding retrieval. The clouds are treated as ice clouds if the footprint is identified as mixed phase. For clear skies, or if the retrieved COT is less than 1 (i.e., optically thin cloud), the sounding parameters, including temperature, humidity and ozone profiles as well as surface skin temperature and surface emissivities at 10 IR wavenumbers, are output from the top of the atmosphere down to the surface. In all other cloud cases (i.e., optically...
Figure 3
thick clouds), the sounding parameters are retrieved down to the CTP level.

3. Results and Preliminary Validation

[10] The root-mean-square difference (RMSD) and bias between SFOV sounding retrievals (from AIRS-alone and synergistic AIRS/MODIS algorithms), and 6-hour ECMWF analysis are calculated to evaluate the performance of algorithms. Only pixels within one hour of ECMWF analysis are used for these statistics. Figures 2a and 2b show RMSD and bias of temperature and column precipitable water, respectively, of three atmospheric layers for thin ice cloud over water surface where the atmosphere, surface, and cloud properties are assumed homogeneous within the AIRS SFOV. The synergistic algorithm has both lower RMSD and smaller bias than the AIRS-alone method. There is an increasing trend of RMSD and larger bias when the cloud fraction increases, as the clear-sky MODIS pixels provide less information about the cloudy AIRS SFOV. Increasing of cloud fraction within AIRS SFOV causes alternations of the weighting functions from the clear scene values. Synergistic use of MODIS information not only reduces the RMSD but also minimizes the bias in cloudy sounding, especially in the boundary layer.

[11] Daytime AIRS and MODIS observations on 09 May 2003, which contains a frontal meso-scale cloud system, was chosen to further illustrate the retrieval results. A cross-section from south to north is examined and evaluated by comparing the MODIS true color composited image of the scene (Figure 3a), with the green line showing the location of the cross-section of retrieved relative humidity profiles. The soundings are only displayed to the CTP levels when optically thick clouds are present. Although AIRS-alone method (Figure 3c) can retrieve a moist layer approximately at 550 hPa between latitudes 34.5° and 35.5°, the synergistic AIRS and MODIS (Figure 3d) method retrieves profiles through an area identified as broken clouds in the MODIS true color image (Figure 3a) and MODIS cloud mask (not shown).

[12] The retrieved profiles are compared with a radiosonde measurement at 2230 UTC launched at the Southern Great Plains (SGP) Cloud And Radiation Testbed (CART) site at Lamont, Oklahoma. For this particular cloudy scene, the retrieved temperature profile is not significantly affected by adding MODIS clear radiances information when compared with that from both AIRS cloudy alone and synergistic methods in Figure 3e. However, for water vapor the synergistic method captures more details in the vertical profile than the AIRS-alone method (Figure 3f). The cloud layer and an upper level moist layer (RH approximately 40%) around 200 hPa levels (Figure 3d) are in agreement with the in-situ radiosonde observations. The combined AIRS/MODIS retrieval also better represents the RH in the lowest layer. Differences between the retrievals and radiosonde observations are partly caused by the spatial and temporal differences in the comparisons.

[13] To further investigate the performance of the sounding retrieval algorithms, the calculated AIRS clear BT using the retrieved surface parameters and profiles are compared with nearby clear-sky observations (Figure 3g). The calculated top-of-atmosphere (TOA) BTs, among the three methods are all close to the clear-sky observations, but the synergistic method has the smallest BT differences (BTDs) in the carbon dioxide (CO2) absorption, window and ozone spectral regions. The BTDs of the synergistic method are also close to the atmospheric spectral natural variability (not shown) for any two clear adjacent FOVs within the granule. Larger BTDs for MODIS alone retrievals in 650–750 cm⁻¹ CO2 and 1000–1100 cm⁻¹ ozone channels demonstrate errors in the atmospheric temperature clear-sky case retrieval (Figure 3h). The ~2 K BTD in the channels between 1300 to 1600 cm⁻¹, which have high- to mid-levels moisture weighting function peaks, correspond to the upper-level moist layer (~200 hPa) or the cloud (~550 hPa) altitudes mentioned previously.

4. Summary

[14] Synergistic use of AIRS and MODIS measurements, including the MODIS cloud products improve atmospheric profile estimation. Using MODIS cloud mask to derive the AIRS SFOV cloud fraction and the collocated MODIS clear pixel radiances measurements as additional predictors based on an eigenvector regression to retrieve the atmospheric state and surface parameters, the synergistic AIRS and MODIS method improves in the comparison with either AIRS or MODIS stand-alone method, especially in atmospheric boundary layer.

[15] The synergistic retrieval method is developed using sets of regression coefficients from a dataset containing more than 15000 atmospheric profiles. The retrieval products include temperature, humidity, and ozone from 0.005 hPa to either the surface in clear skies and cloudy skies with broken clouds, or to the cloud-top level when optically thick clouds are present. Comparison with a co-located radiosonde measurement at the SGP CART site is used for validation of the sounding products. The accuracy and capability of the synergistic algorithm by comparisons of the retrievals and in-situ observations is promising. In addition, clear spectra BT calculations using synergistic method retrievals agree quite well with the adjacent clear neighbor AIRS BT measurements.

[16] Future work includes more validation of the retrievals, improvement for cases that include mixed phase clouds, and a hyperspectral emissivity spectrum enhancement [Li et al., 2007] using an iterative physical retrieval at AIRS SFOV resolution. Several studies have applied the combination use of sounder and imager for cloud property retrieval [Li et al., 2004, 2005a], and cloud clearing [Li et al., 2005b]. The long-term approach is to apply the methodology to other instrument like IASI, AVHRR onboard LEO satellite and also to support the development of synergistic algorithm for GEO ABI (Advanced Baseline Imager) [Schmit et al., 2005] and LEO high-spectral IR sounders.

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