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CLOUD CLASSIFICATION AND CLOUD PROPERTY RETRIEVAL FROM MODIS AND AIRS

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1. INTRODUCTION

The Moderate-Resolution Imaging Spectroradiometer (MODIS) and the Atmospheric Infrared Sounder (AIRS) measurements from the Earth Observing System's (EOS) Aqua satellite enable global monitoring of the distribution of clouds. The MODIS is able to provide at high spatial resolution (1 ~ 5km) a cloud mask, surface and cloud types, cloud phase, cloud-top pressure (CTP), effective cloud amount (ECA), cloud particle size (CPS), and cloud optical thickness (COT). The combined MODIS/AIRS system offers the opportunity for cloud classification and property retrievals improved over those possible from either system alone; this is demonstrated in this study with both simulated and real radiances. A fast cloudy radiative transfer model for AIRS accounting for cloud scattering and absorption has been created. A variational (1DVAR) methodology is used to retrieve the CTP, ECA, CPS and COT from AIRS longwave window region (650 – 950 cm^{-1} and 1050 – 1130 cm^{-1}) cloudy radiance measurements. Operational MODIS CTP, ECA, CPS and COT products with high spatial resolution serve as background and first guess information in the AIRS 1DVAR cloud retrieval process.

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The cloud properties can also be derived from AIRS longwave radiance measurements with the Minimum Residual (MR) algorithm. Both 1DVAR and MR need the the MODIS cloud mask, cloud phase mask (CPM) as input. The MODIS cloud classification mask (CCM) is used for retrieval verification. The atmospheric temperature profile, moisture profile and surface skin temperature used in the AIRS radiance calculation in the cloud retrieval processing are from the European Center for Medium-range Weather Forecasting (ECMWF) forecast analysis. Both the 1DVAR and MR approaches are applied to process the AIRS longwave cloudy radiance measurements; results are compared with operational MODIS cloud products, and the GOES cloud products, as well as the ground observations. This study is relevant to optimal use of data from the Advanced Baseline Imager (ABI) (Schmit et al. 2004) and Hyperspectral Environmental Suite (HES) system – ABI / HES which is to fly on the Geostationary Operational Environmental Satellite (GOES-R).

2. AIRS SUB-PIXEL CLOUD CHARACTERIZATION USING MODIS

MODIS is a key EOS instrument for conducting global change research. It provides global observations of Earth's land, oceans, and atmosphere in 36 visible (VIS), near infrared (NIR) and infrared (IR) regions of the spectrum from 0.4 to 14.5 μm. MODIS measurements record biological and geophysical processes on a global scale every 1 to 2 days in unprecedented detail. MODIS masks have been available to scientific communities. Some important masks include:

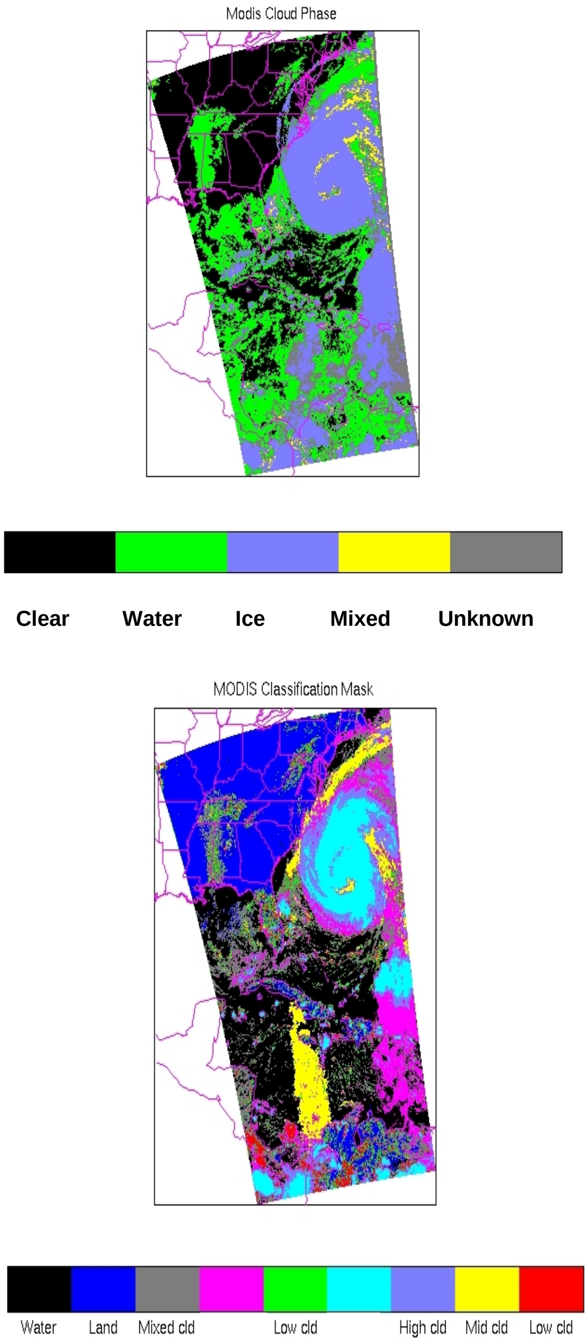

Figure 1. The Aqua MODIS cloud phase mask (upper panel) and classification mask (lower panel) at 1km resolution at 1820UTC on 17 September 2003 (Hurricane Isabel). L: Low clouds; H: high convective clouds.

(1) Cloud mask, which provides each MODIS 1km pixel with a clear index (confident clear, probably clear, confident cloudy, probably cloudy).

(2) Cloud phase mask (CPM) that provides each MODIS 1km pixel a phase index (water clouds, ice clouds, mixed phase, etc.).

(3) In addition, a classification technique has been developed at CIMSS (Li et al 2003) for deriving the classification mask from MODIS multispectral band radiance measurements. The classification mask provides surface types such as water, land, snow, desert, and cloud types such as low clouds, mid-level clouds, high clouds, etc. Note that MODIS cloud classification mask is not an operational product. Figure 1 shows the cloud phase mask (upper panel) and classification mask (lower panel) at 1km resolution at 1820UTC on 17 September 2003. It shows that the pattern of ice clouds from the cloud phase mask is similar to the high clouds from the classification mask, while the pattern of water clouds from the cloud phase mask is similar to the low clouds in the classification mask for the hurricane Isabel. The hurricane center (eye) is well identified by the MODIS classification mask.

These MODIS mask products provide AIRS sounder sub-pixel cloud characterization during day and night (Li et al. 2004a): (a) collocated MODIS 1km cloud mask tells if an AIRS footprint is clear or cloudy, (b) collocated MODIS 1km cloud phase mask indicates whether an AIRS sub-pixel contains water clouds, ice clouds, or mixed phase clouds which is required in the cloud microphysical property retrieval; (c) collocated MODIS 1km classification mask helps to determine whether an AIRS sub-pixel is partly cloudy or overcast, and whether it is characterized by single-layer clouds or multi-layer clouds.

3. FAST CLOUD RADIATVE MODEL FOR AIRS

Through the joint efforts of University of Wisconsin-Madison and Texas A&M

University, a fast radiative transfer cloudy model for hyperspectral IR sounder is developed (Wei et al. 2004). For ice clouds, the bulk single-scattering properties of ice crystals are derived by assuming aggregates for large particles, hexagonal geometries for moderate particles and droxtals for small particles. For water clouds, spherical water droplets are assumed, and the classical Lorenz-Mie theory is used to compute their single-scattering properties. In the model input, the cloud optical thickness is specified in terms of its visible optical thickness at the wavelength of 0.55 μm. The IR COT for each AIRS channel can be derived via the following relationship:

$$\tau = \frac{<Q_e>}{2}\tau_{vis}, \quad (1)$$

where τ is the cloud optical thickness and $<Q_e>$ is the bulk mean extinction efficiency. Given the visible COT and CPS, the IR COT, the single-scattering albedo, and asymmetry factor can be obtained from a pre-described parameterization of the bulk radiative properties of ice clouds and water clouds. The detailed parameterization scheme has been reported in the previous work (Wei et al. 2004). The cloudy radiance for a given AIRS channel can be computed by coupling the clear sky optical thickness and the cloud optical effects. Specifically, the cloud optical effects are accounted for by using a pre-computed look-up table of cloud reflectance and transmittance on the basis of fundamental radiative transfer principles. The clear sky optical thickness is derived from a fast radiative transfer model called Stand alone AIRS Radiative Transfer Algorithm (SARTA) (Strow et al. 2003; http://asl.umbc.edu/pub/rta/sarta/); it has 100 pressure layers (101 pressure levels) with vertical coordinates from 0.005 to 1100 hPa. The computation takes into account the satellite zenith angle, absorption by well-mixed gases (including nitrogen, oxygen etc.), water vapor (including the water vapor continuum), ozone, and carbon dioxide. Studies show that the slope of an IR cloudy brightness temperature (BT) spectrum between 790 (12.6 μm) and 960 cm^{-1} (10.4 μm) is sensitive to the CPS, while the cloudy radiances are sensitive to COT in the region of 1050 (9.5 μm) – 1250 cm^{-1} (8 μm) for ice clouds (Wei et al 2004). The root mean square (RMS) difference between the IR fast cloudy model and the Discrete Ordinates Radiative Transfer (DISORT) calculation is less than 0.5 K for most AIRS spectral channels (Wei et al. 2004). Figure 2 shows the AIRS brightness temperature (BT) calculations for ice clouds with various COTs and CPS. There are very good radiance signals for COT and CPS in the AIRS longwave window region, an indicative of cloud microphysical properties retrievable from the AIRS longwave window regions (790 – 950 cm^{-1} and 1050 – 1130 cm^{-1}) radiance measurements.

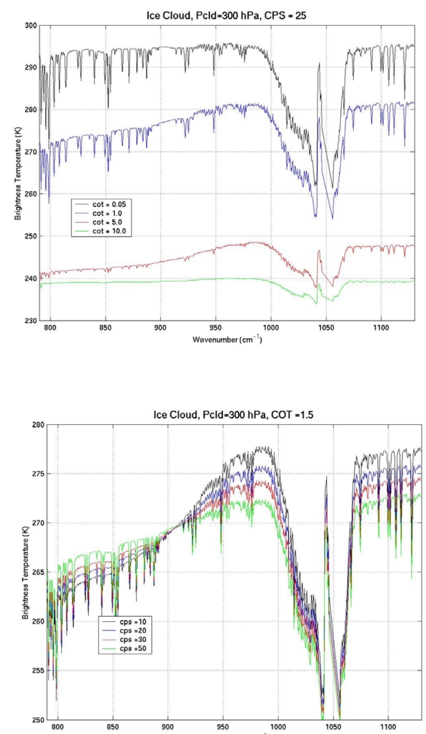

Figure 2. AIRS (BT) calculations for ice clouds with various COTs (upper panel) and CPS (lower panel). The tropical atmosphere is used for the caculations.

4. MR AND 1DVAR ALGORITHMS

CTP, ECA, CPS and COT can be derived from the AIRS radiance measurements. The AIRS MR CPT, ECA, CPS and COT take an estimate of CPT, ECA, CPS and COT from minimum residual (MR) method (Li et al. 2004b; 2004c). The MR method seeks the CTP and ECA by minimizing the differences between observations and calculations using AIRS longwave CO_2 absorption channels between 650 – 790 cm^{-1}, while it seeks the CPS and COT by minimizing the differences between observations and calculations using AIRS longwave window channels between 800 and 1130 cm^{-1} (the 9.6 μm ozone absorption channels are excluded). For details on MR algorithm, see Li et al. (2004b; 2004c).

To minimize highly nonlinearity of clouds in AIRS radiances, the MODIS+AIRS 1DVAR algorithm for CTP, ECA, CPS and COT retrievals uses the operational MODIS CTP, ECA, CPS and COT (King et al. 2003; Platnick et al. 2003) as the background information to obtain the cloud parameters from the AIRS longwave spectral band cloudy radiance measurements. AIRS channels with wavenumbers between 650 and 790 cm^{-1} are used for CTP and ECA retrieval (Li et al. 2004b), while the channels between 800 and 1130 cm^{-1} are used in the CPS and COT retrieval (Li et al. 2004c). For details on the 1DVAR cloud property retrieval, see Li et al. (2004b; 2004c).

5. RETRIEVAL OF CLOUD PROPERTIES FROM MODIS AND AIRS

A granule of AIRS data was studied. Each granule contains 135 lines with each line containing 90 pixels. Figure 3 shows the AIRS (granule 184) longwave window channel 763 (901.69 cm^{-1}) brightness temperature (BT) images at 1825UTC on 17 September 2003 for Hurricane Isabel. The red color indicates warm scene or clear skies, while the blue color represents cold scene or cloudy skies. Boxes A1 and A2 in Figure 6 indicate the two small areas on the hurricane center and edge. The 1 km MODIS pixels are collocated within an AIRS footprint better than 1 km provided that the geometry information from both instruments is accurate (Li et al. 2004a). Radiances from 14 MODIS spectral bands are used to estimate whether a given view of the Earth surface is affected by clouds, aerosol, or shadow (Ackerman et al. 1998), and the MODIS operational cloud mask product MYD35 (MOD35 for Terra MODIS) was used in this study. The AIRS footprint is determined to be cloudy for cloud retrieval only when the percentage of the clear MODIS pixels within the AIRS footprint is less than 3%. The atmospheric temperature and moisture profiles as well as the surface skin temperature are taken from the ECMWF forecast model analysis in both the 1DVAR and the MR retrievals.

Figure 4 shows the COT (upper panel), and the CPS (lower panel, in μm) images with the MR algorithm. The CPS from the AIRS MR is similar to that from the operational MODIS (not shown) in pattern. However, the CPS retrievals inside the hurricane are a little noisy due to the CPS information limitation for very thick clouds. AIRS IR radiance measurements are saturated for cloud microphysical properties when viewing opaque convective clouds. Figure 5 shows the COT retrieval image (left panel) with the MODIS+AIRS 1DVAR algorithm for the same hurricane case, it can be seen that both the MODIS+AIRS 1DVAR and the AIRS MR obtain the similar COT results. However, the MODIS+AIRS 1DVAR is more computationally efficient than the AIRS MR. The scatterplot between the operational MODIS COTs and the AIRS MR COTs are also shown in Figure 5 (right panel), the differences are large between the operational MODIS VIS/NR COTs and the AIRS IR COTs. However, the correlation between the operational MODIS COTs and the AIRS IR COTs is high (greater than 0.75 in this case), revealing that AIRS is able to provide useful COT information during both the daytime and the nighttime.

Several AIRS footprints are selected for detail analysis. Figure 6 shows the MODIS 1km CCM superimposed to the AIRS footprints for boxes A1 (left panel) and A2 (right panel), three adjacent AIRS footprints in box A1 (F1: line 69, pixel 78; F2: line 70, pixel 78; F3: line 71, pixel 78) representing three layers of thick clouds at the center of hurricane indicated by the 1km classification mask are selected for a retrieval test. Figure 7 shows the AIRS spectra of BT observation (black line), BT calculations with the MODIS+AIRS 1DVAR (red line) and BT calculations with the AIRS MR (blue line) for the three footprints (F1: left panel; F2: middle panel; F3: right panel). The CTP retrievals (Li et al. 2004b) are different for the three footprints and they are well retrieved by either the 1DVAR (185.779, 238.233, and 345.947 hPa) or the MR (200.989, 262.140, and 353.013 hPa). Also the COT retrievals for the three adjacent footprints are consistent with ECA retrievals (Li et al. 2004b) in both the MODIS+AIRS 1DVAR and the AIRS MR. Clouds are thicker outside the center than those inside the center. Calculations with both the MODIS+AIRS 1DVAR and the AIRS MR retrievals fit the observations well for all three footprints. Figure 8 is the same as Figure 6 but for the box A2. The three AIRS footprints in box A2 (F4: line 55, pixel 75; F5: line 56, pixel 76; F6: line 56, pixel 75) represent ice clouds (F5), more ice clouds over the water clouds (F4), and less ice clouds over the water clouds (F6) according to the MODIS 1km classification mask. The calculations fit the slope of the observations very well, indicating good sensitivity of AIRS radiance measurements to the microphysical properties for ice clouds.

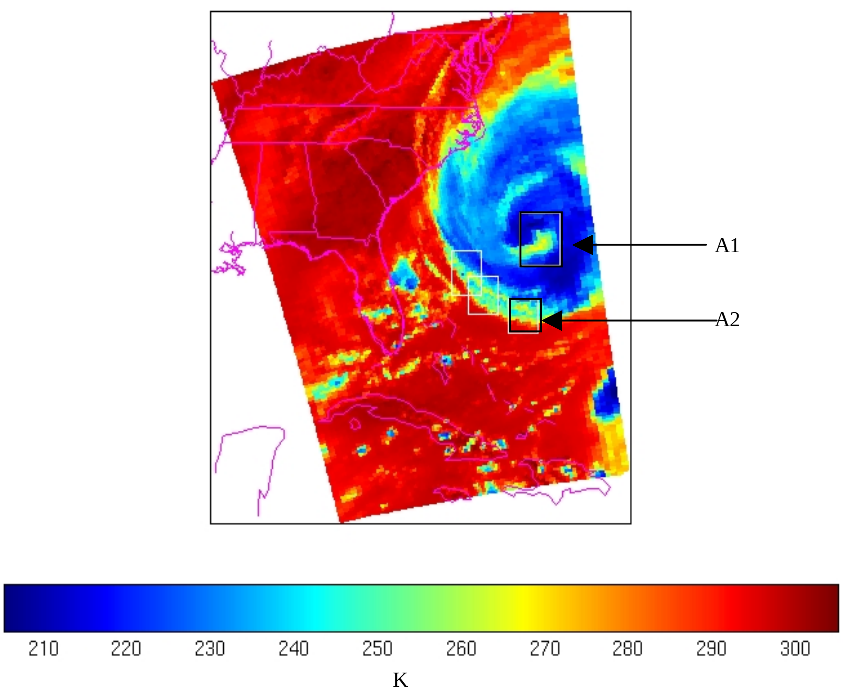

Figure 3. The AIRS BT image of granule 184 on 17 September 2003 at a window channel 763 (901.69cm^{-1}), boxes A1 and A2 indicate the two small areas for hurricane center and edge.

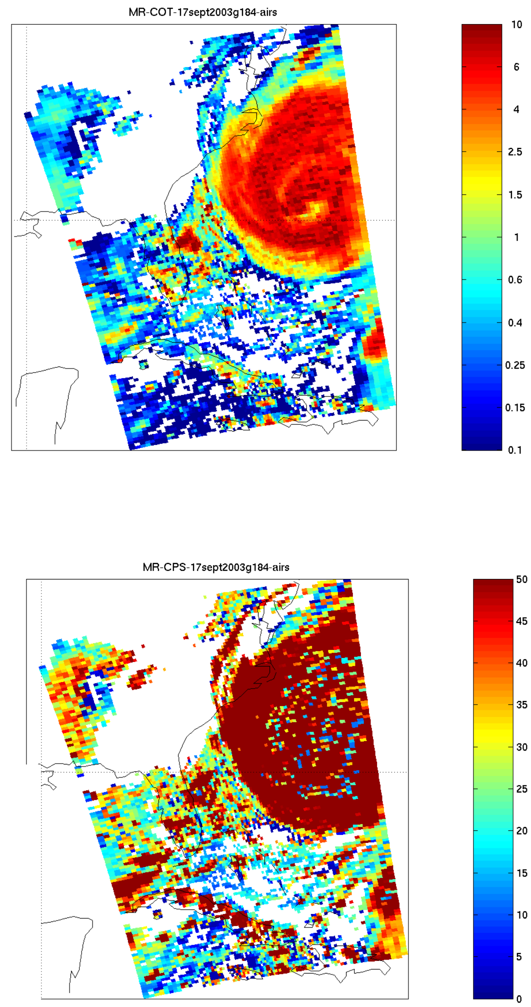

Figure 4. COT (upper panel), and CPS (lower panel, in μm) images with the MR algorithm.

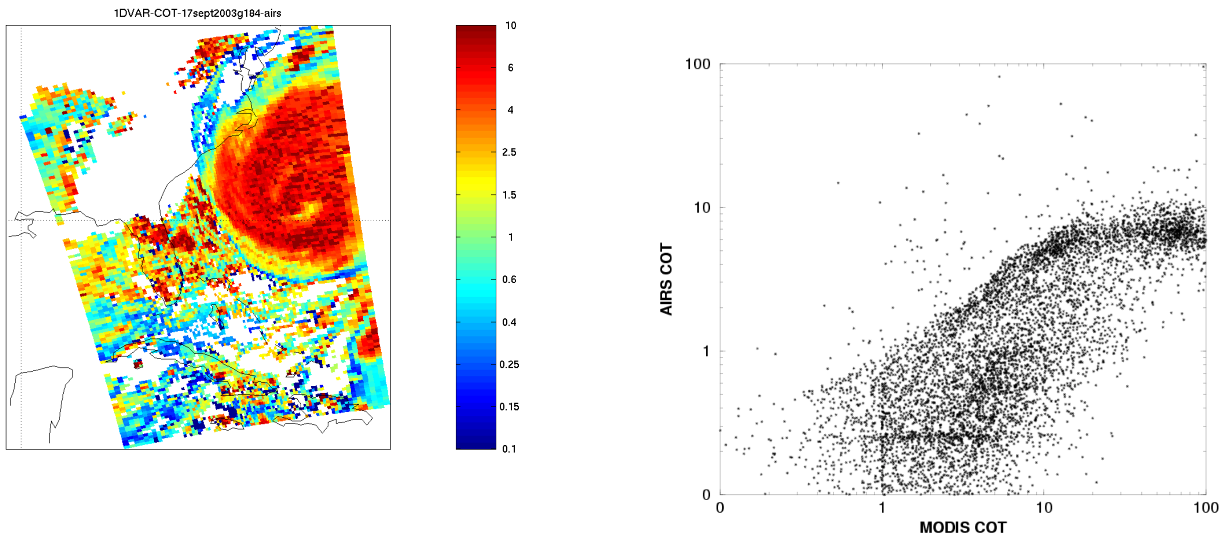

Figure 5. COT image with 1DVAR algorithm for the hurricane Isabel case (left panel), and the scatterplot between MODIS COTs and AIRS alone COTs (right panel).

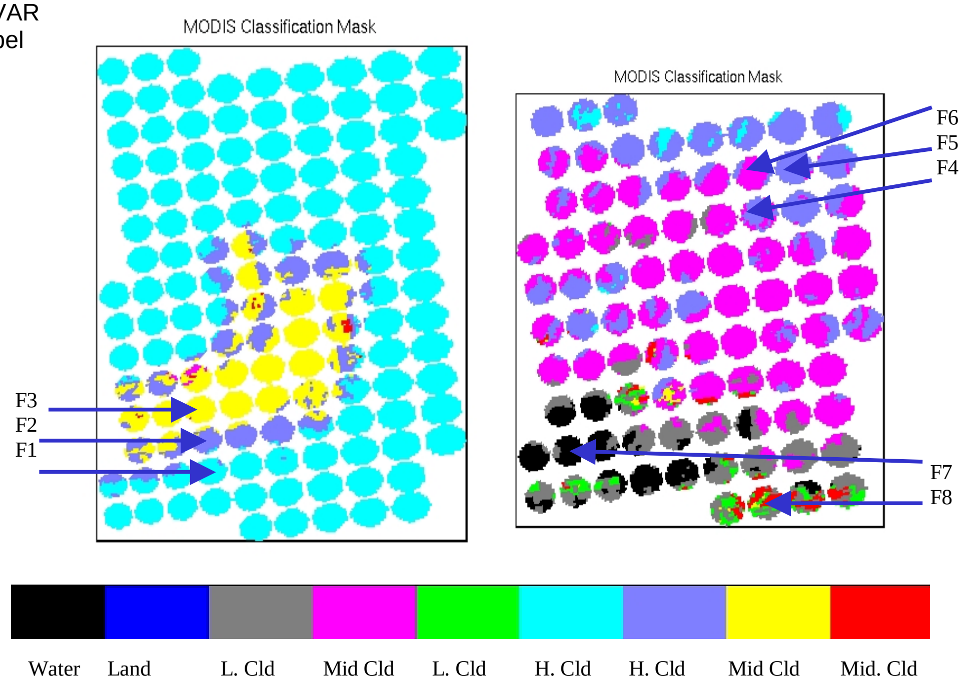

Figure 6. The MODIS 1km CCM superimposed to the AIRS footprints for boxes A1 and A2. Several AIRS footprints for study are shown. L. Cld: low clouds; H. Cld: high clouds; Mid Cld: medium-level clouds.

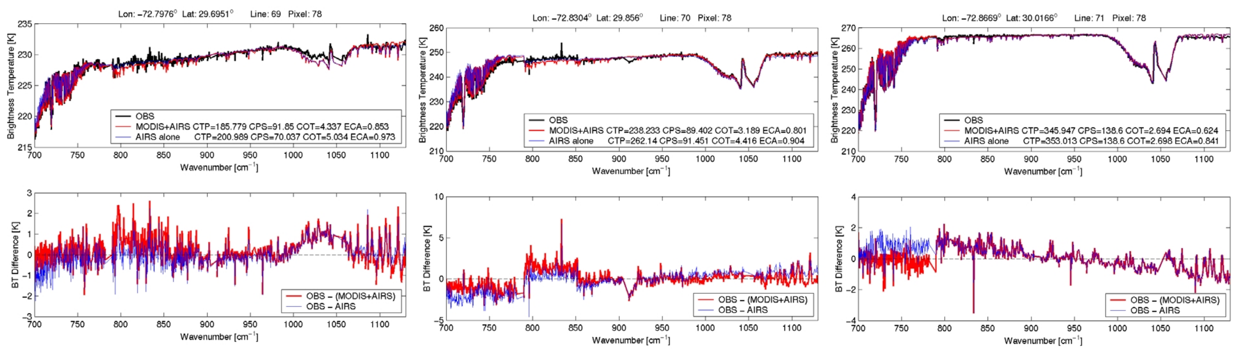

Figure 7. The AIRS spectra of BT observations (black line), BT calculations with 1DVAR (red line) and BT calculations with MR (blue line) for three AIRS footprints F1, F2, and F3, respectively.

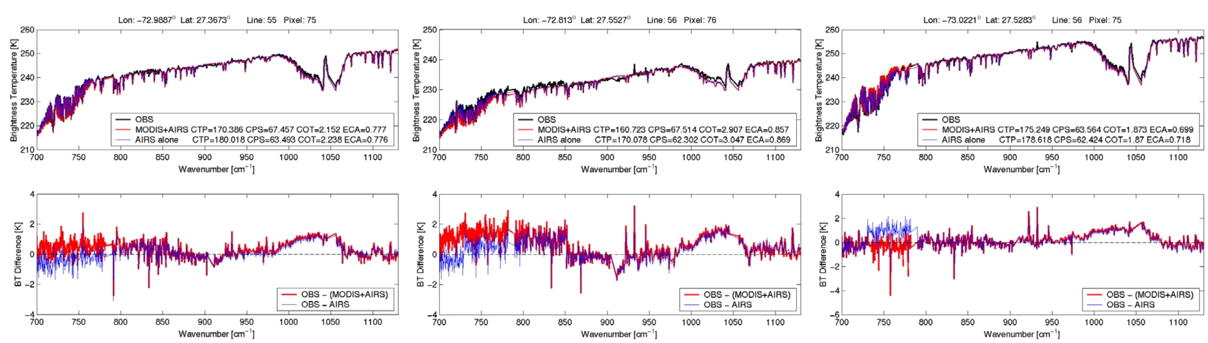

Figure 8. The AIRS spectra of BT observations (black line), BT calculations with 1DVAR (red line) and BT calculations with MR (blue line) for three AIRS footprints of ice clouds (F5), more ice clouds over the water clouds (F4), and less ice clouds over the water clouds (F6).

6. CONCLUSIONS

Two approaches for synergistic use of the MODIS mask products, the operational MODIS cloud microphysical cloud products and the AIRS radiance measurements for retrieving the CTP, ECA, CPS and COT are described in this paper.

The procedures for deriving CTP and ECA are 1DVAR and MR during both the daytime and the nighttime.

The procedures for deriving the cloud microphysical properties from the combination of MODIS and AIRS during the daytime are: (a) the MODIS cloud mask, CCM, CPM with 1km spatial resolution are used to characterize the AIRS sub-pixel cloud condition (clear/cloudy, ice/water, single/multi-layer), and (b) the COT and CPS from MODIS are used as the background in the AIRS 1DVAR cloud retrieval process with help of AIRS sub-pixel cloud information provided by (a).

The procedures for deriving the cloud microphysical properties from AIRS MR during both the daytime and the nighttime are: (a) The MODIS cloud mask, CCM, CPM with 1km spatial resolution are used to characterize the AIRS sub-pixel cloud condition (clear/cloudy, ice/water, single/multi-layer), and (b) the COT and CPS are derived from AIRS longwave cloudy radiance measurements with the MR method with help of AIRS sub-pixel cloud information provided by (a).

Unlike the CTP and ECA retrieval (Li et al. 2004b), the cloud microphysical property retrieval from the MODIS+AIRS 1DVAR is not shown to be better than either the operational MODIS product or the AIRS MR retrieval, this is due to the fact that the operational MODIS product is derived from the VIS/NIR observations, while the MODIS+AIRS 1DVAR and AIRS MR algorithms seek the COT and CPS solutions by fitting the calculations with IR observations. The MODIS+AIRS 1DVAR is similar to the AIRS MR for COT and CPS retrieval in most situations, while it is more computationally efficient. The COTs from the AIRS MR are different from the operational MODIS product, but there is good correlation between them.

In summary, (a) MODIS mask products (cloud mask, CPM and CCM) help the cloud microphysical property retrievals in both the MODIS+AIRS 1DVAR and the AIRS MR, (b) the MODIS+AIRS 1DVAR provides an efficient way for retrieving the cloud property retrievals from AIRS radiance measurements during day, while the AIRS MR provides the cloud microphysical property retrievals from the AIRS radiance measurements during both the daytime and the nighttime.

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