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RETRIEVAL OF CLOUD MICROPHYSICS FROM BLENDED MODIS CLOUD PRODUCTS AND AIRS RADIANCE MEASUREMENTS

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1. INTRODUCTION

Clouds play an important role in the Earth's water and energy budgets. Their impact on the radiation budget can result in a heating or a cooling of the planet, depending on the radiative properties of the cloud and its altitude (Stephens and Webster 1981; Stephens et al. 1990). Because clouds have such a large effect on the Earth's radiation budget, even small changes in their abundance or distribution could alter the climate more than the anticipated changes in trace gases, aerosols, or other factors associated with global change. Numerical model studies show that cloud parameters, such as cloud-top pressure (CTP), effective cloud emissivity or effective cloud amount (ECA), cloud particle size (CPS) in diameter, cloud optical thickness (COT) at 0.55 μm wavelength, ice water path (IWP), and liquid water path (LWP) are important parameters in our weather and climate prediction (Diak et al. 1998; Bayler et al. 2000; Kim and Benjamin 2000; Stephens et al. 1990).

Moderate-Resolution Imaging Spectroradiometer (MODIS) onboard the NASA's Earth Observing System (EOS) Terra and Aqua satellites provides multispectral broad band measurements and cloud products (King et al. 2003; Platnick et al. 2003) with high spatial resolution not seen before, while the Atmospheric Infrared Sounder (AIRS) (Aumann et al. 2003) on EOS Aqua satellite is a high spectral resolution ($v/\Delta v = 1200$, where v is the wavenumber and Δv is the width of a channel) IR sounder with 2378 channels. MODIS measurements provide the crucial information to quantify ice water content for optically thin cirrus (King et al., 1992), enabling a global

assessment of ice water path (IWP) in cirrus clouds. IWP measurements are urgently needed for the evaluation of cloud forcing, net radiation balance, and cloud formation and parameterization in General Circulation Models (GCMs). AIRS is well suited for cloud microphysical property sensing such as CPS (in diameter) and COT with its high spectral resolution IR radiances during both day and night. LWP or IWP can then be inferred from CPS, COT and the mean extinction efficiency of the clouds. Taking advantage of high spectral resolution AIRS longwave cloud sensitive radiance measurements, theoretically, CTP and ECA can be retrieved with better accuracy than that from MODIS.

The focus of this manuscript is to derive high quality cloud microphysical properties such as CPS and COT from the synergistic use of MODIS and AIRS during both the daytime and the nighttime. Our approach takes the advantage of the significant amount of spectral and spatially independent information provided by the MODIS and AIRS sensors. For example, the operational MODIS cloud mask and the cloud phase mask (CPM) with 1km spatial resolution collocated to the AIRS footprints provide better AIRS sub-pixel cloud detection and phase determination due to the MODIS visible (VIS), near infrared (NIR) and the 8.5 μm spectral bands (AIRS has coarser spatial resolution and does not have the 8.5 μm channels). The MODIS/AIRS cloud products will improve and validate cloud information derived from other EOS satellites, as well as the operational weather and environmental satellites.

A simulation study shows that the accuracy of cloud microphysical property retrieval is sensitive to the error of CTP (Li et al. 2004c). The CPS and COT retrievals from AIRS longwave radiance measurements with Minimum Residual (MR) algorithm have been compared with the operational MODIS cloud microphysical property products (MYD06). High correlation between operational MODIS and AIRS MR retrievals was

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found for CPS and COT. MODIS provides cloud microphysical properties during the daytime with high spatial resolution, while AIRS provides cloud products with high accuracy but relatively coarse spatial resolution during both the daytime and the nighttime. Synergistic use of high spatial resolution MODIS cloud products and AIRS longwave cloudy radiance measurements, described in this paper, can be applied to process EOS direct broadcast MODIS/AIRS data (Huang et al. 2004).

2. FAST RADIATIVE TRANSFER MODEL AND THE MR, 1DVAR RETRIEVAL SCHEMES

Through the joint efforts of University of Wisconsin-Madison and Texas A&M University, a fast radiative transfer cloud model for hyperspectral IR sounder measurements has been developed (Wei et al. 2004). For ice clouds, the bulk singlescattering properties of ice crystals are derived by assuming aggregates for large particles, hexagonal geometries for moderate particles and droxtals for small particles (Yang et al. 2001; 2003). 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 $0.55 \mu\text{m}$. The detailed parameterization scheme has been reported in the previous work, (Wei et al. 2004), and more fast radiative transfer model details are described by Li et al. (2004c). Figure 1 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, indicative of cloud microphysical properties retrievable from the AIRS longwave window regions ($790 - 950 \text{ cm}^{-1}$ and $1050 - 1130 \text{ cm}^{-1}$) radiance measurements.

The AIRS MR method seeks the CPS and COT by minimizing the differences between observations and calculations using AIRS longwave channels 790 cm^{-1} ($12.7 \mu\text{m}$) - 1130 cm^{-1} ($8.85 \mu\text{m}$). There are three steps for CPS and COT retrieval using the MR scheme.

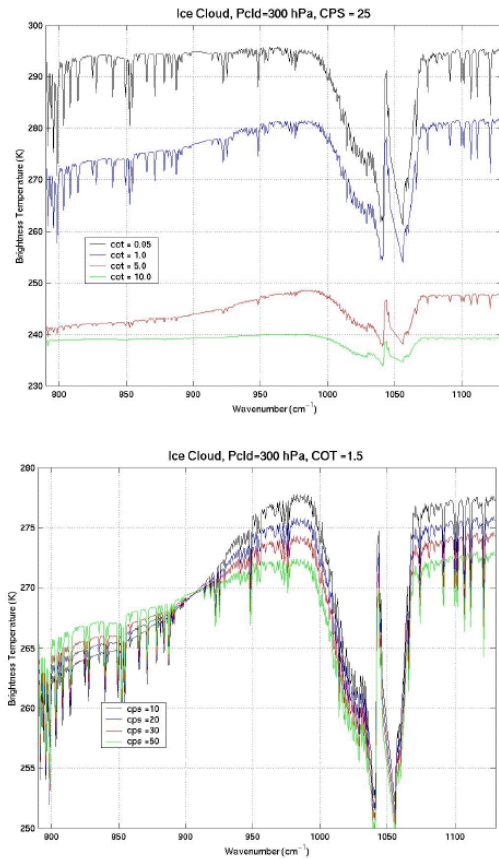


Figure 1. AIRS (BT) calculations for ice clouds with various COTs (upper panel) and CPSs (lower panel). A tropical atmosphere is used for the calculations.

Step 1: with retrieved CTP and ECA from AIRS radiances of CO_2 channels (Li et al. 2004b), and initial COT is estimated as

$$\tau_{vis}^* = -2 \ln(1.0 - N \mathcal{E}_c) \quad (1)$$

where $N \mathcal{E}_c$ is the ECA from AIRS radiances in CO_2 region ($700 - 790 \text{ cm}^{-1}$) (Li et al. 2004b), and τ_{vis}^* is the initial COT.

Step 2: with estimated initial COT, the CPS is retrieved with MR scheme using AIRS channels with wavenumbers between $800 - 960 \text{ cm}^{-1}$.

Step 3: with retrieved CPS from step 2, the estimated COT is retrieved with the MR scheme using AIRS channels with wavenumbers between $1080 - 1130 \text{ cm}^{-1}$.

In practice, these three steps are iterated for the improved retrieval of CPS and COT with the MR scheme.

To minimize the high nonlinearity of AIRS radiances to the cloud microphysical properties, the MODIS+AIRS variational (1DVAR) algorithm for CPS and COT retrievals uses the operational MODIS 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 790 and 1130 cm^{-1} are used in the CPS and COT retrieval. Given the AIRS observed cloudy radiance, R^m , for each channel, then $R = R(T, q, T_s, \varepsilon_s, D_e, \tau_{vis})$, which has the form

$$Y = F(X) + \eta \quad (2)$$

where the vector X contains CPS and COT. The atmospheric temperature profile $T(p)$, moisture profile $q(p)$, surface skin temperature T_s and the infrared surface emissivity ε_s , are assumed to be known from the ECMWF forecast analysis. Y contains N satellite observed cloudy radiances (R^m), $F(X)$ is the fast cloud radiative transfer model, and η is the observation error vector. The linear form of Eq. (2) is

$$\delta Y = F' \cdot \delta X \quad (3)$$

where F' is the linear or tangent model of the forward model F , which is outlined by Eq. (2).

The 1DVAR approach is to minimize a penalty function $J(X)$, the general form of the 1DVAR solution (Eyre 1989) is given by

$$J(X) = [Y^m - F(X)]^T E^{-1} [Y^m - F(X)] + [X - X_B]^T B^{-1} [X - X_B] \quad (4)$$

where the vector X contains the CPS and COT that need to be solved, X_B is the background information inferred from the MODIS operational CPS and COT products, Y^m is the vector of the AIRS measured cloudy radiances used in the retrieval process, $F(X)$ is a vector of cloudy radiances calculated from any cloud state X through radiative transfer model, E is the observation error covariance matrix which includes instrument noise plus the assumed forward model error, and B is the assumed background error covariance matrix

which constrains the solution. To solve Eq. (4), a Newtonian iteration is used

$$X_{n+1} = X_n + J''(X_n)^{-1} \cdot J'(X_n) \quad (5)$$

and the following quasi-nonlinear iterative form (Eyre, 1989) is obtained

$$\delta X_{n+1} = \left(F_n'^T \cdot E^{-1} \cdot F_n' + B^{-1} \right) \cdot F_n'^T \cdot E^{-1} \cdot \left(\delta Y_n + F_n' \cdot \delta X_n \right) \quad (6)$$

where $\delta X_n = X_n - X_B$, $\delta Y_n = Y^m - Y(X_n)$, and F_n' from Eq. (3) represents the linear terms with δR expansion of Eq. (2).

The background error covariance matrix B is assumed diagonal with a standard deviation of 20% for the MODIS CPS and COT. The logarithm of CPS and COT are used to stabilize the solution of Eq. (6), and the background error is 0.2 for both $\ln D_e$ and $\ln \tau_{vis}$. The measurement error covariance matrix, E , is a fixed diagonal matrix, where each diagonal element is η^2 (see Eq.(2)) that is the square of the AIRS instrument noise plus the square of an assumed forward model error of 0.2 K for each longwave channel. The first guess X_0 , or the starting point of the iteration in Eq.(6), are also the MODIS CPS and COT products.

Operational cloud microphysical property estimates from MODIS measurements with 1km spatial resolution during day (King et al. 2003; Platnick et al. 2003) can serve as the background information in the MODIS+AIRS 1DVAR retrieval of cloud microphysical properties from AIRS high spectral radiance measurements. Figure 3 shows the MODIS CPS (in diameter) averaged to the AIRS footprints for the Hurricane Isabel at 1825UTC on 17 September 2003.

Both MODIS and AIRS data are synergistically used in the MODIS+AIRS 1DVAR and the AIRS MR scheme; both algorithms use the MODIS cloud mask and cloud phase mask (CPM) for AIRS cloud detection and phase determination. The MODIS cloud mask, cloud classification mask (CCM), CPM products provide AIRS sounder sub-pixel cloud characterization during the day and night (Li et al. 2004a):

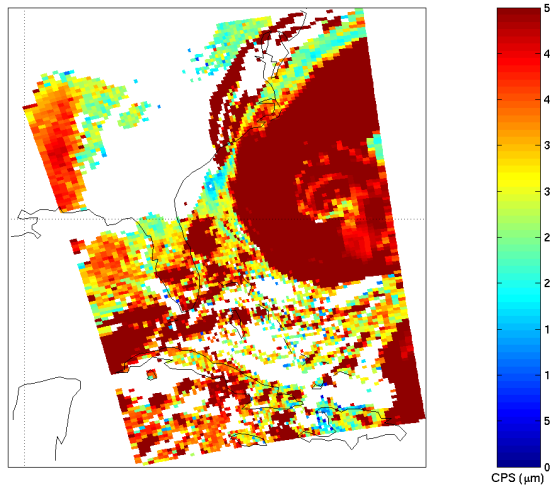


Figure 2. MODIS CPS (in μm) averaged to the AIRS footprints for Hurricane Isabel.

while the blue color represents cold scene or cloudy skies. Boxes A1 and A2 in Figure 3 indicate the two small areas on the hurricane center and edge. The 1 km MODIS pixels are collocated to each AIRS footprint (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 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.

(a) collocated MODIS 1km cloud mask indicates if an AIRS footprint is clear or cloudy, (b) collocated MODIS 1km CPM indicates whether an AIRS sub-pixel contains water clouds, ice clouds, or mixed phase clouds, information required in the cloud microphysical property retrieval; (c) collocated MODIS 1km CCM 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. CCM can also be used to validation the ECA and COT retrievals.

In order to retrieval the cloud microphysical properties, the CTP must be determined. The AIRS CO_2 channels with wavenumbers between 700 cm^{-1} and 790 cm^{-1} are used to infer the CTP with either MR algorithm or 1DVAR method (Li et al. 2004b).

3. RETRIEVAL OF CLOUD MICROPHYSICAL PROPERTIES FROM MODIS AND AIRS

We select a granule of AIRS data in this study. Each AIRS granule contains 135 lines with each line containing 90 pixels. Figure 6 shows the AIRS (granule 184) longwave window channel 763 (901.69 cm^{-1}) brightness temperature (BT) image at 1825UTC on 17 September 2003 for Hurricane Isabel. The red color indicates warm scene or clear skies,

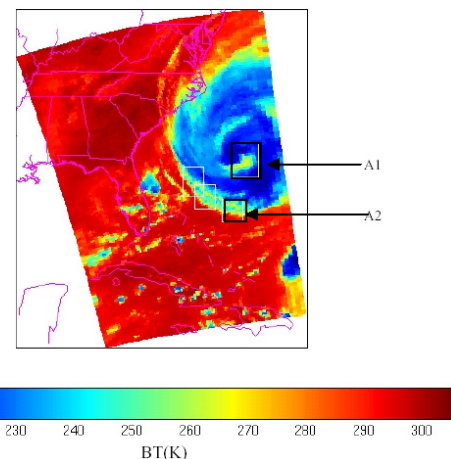


Figure 3. AIRS BT image of granule 184 on 17 September 2003 for channel 763 (901.69 cm^{-1}), boxes A1 and A2 indicate two small areas near hurricane center and edge.

Figure 4 shows the COT (upper panel), and the CPS (lower panel, in (m) images with the MR algorithm. The CPS from the AIRS MR is similar to that from the operational MODIS (see Figure 2) in pattern. However, the CPS retrievals toward the center of the hurricane are a little noisy since AIRS radiance measurements are saturated for cloud microphysical properties when viewing opaque convective clouds and CPS information is limited. Figure 5 shows the COT retrieval image (upper 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 similar COT results. However, the MODIS + AIRS 1DVAR is more computationally efficient than the AIRS MR. The scatterplot between the operational MODIS VIS/NIR COTs (King et al. 2003) and the AIRS MR COTs are also shown in Figure 5 (lower panel); the differences are large. 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 a more detailed analysis. Figure 6 shows the MODIS 1km cloud classification mask (CCM) (Li et al. 2003) superimposed on 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 the 1DVAR (185.779, 238.233, and 345.947 hPa) and 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. The calculations fit the slope of the observations very well, indicating good sensitivity of AIRS radiance measurements to the microphysical properties for ice clouds.

Clouds are very optically thick over most of the cloud shield of the hurricane while are less optically thick in the hurricane center (eye) according to the study. Larger particles are found near center of the tropical cyclone.

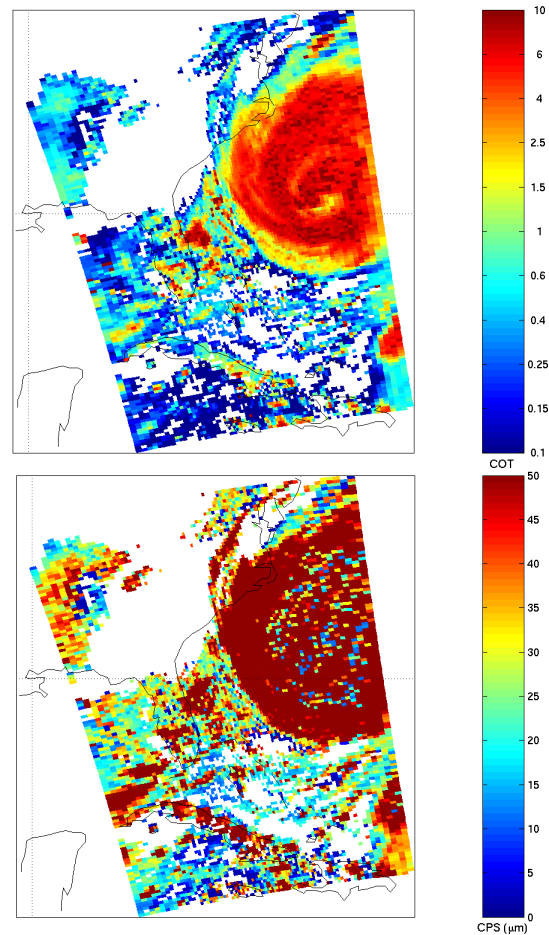


Figure 4. COT (upper panel) and CPS (lower panel, in μm) images with MR algorithm.

4. SUMMARY

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 CPS and COT are described in this paper.

The MODIS cloud mask, CCM, CPM with 1km spatial resolution are used to characterize the AIRS sub-pixel cloud conditions (clear/cloudy, ice/water, single/multilayer) during both the daytime and the nighttime. 1DVAR is used for cloud microphysical property retrieval with the operational MODIS COT and CPS as the background information during the daytime, while MR can be used for cloud microphysical property retrieval during both the daytime and the nighttime.

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, but 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 efficient 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.

Multi-layer clouds occur quite often for the AIRS footprints. The effective CTP is derived for the multi-layer cloudy footprints. More accurate retrieval of multi-layer cloudy microphysical properties requires an efficient fast multi-layer cloudy radiative transfer model that is currently under development.

Specifically the following can be concluded:

- 1) AIRS window channels ($790 - 1130 \text{ cm}^{-1}$) provide abundant information of cloud microphysical properties.
- 2) Error of the CTP estimate is the major source of error in the cloud microphysical property retrieval with IR sounder data.
- 3) There are limitations on the cloud microphysical property retrieval from AIRS observations when the clouds are very thick ($\text{COT} > 10$) or very thin ($\text{COT} < 0.1$).
- 4) The MODIS mask products (cloud mask, CCM, and CPM) are very important in retrieving the cloud properties.
- 5) MODIS and AIRS data provide unprecedented information on cloud properties (CTP, ECA, COT and CPS) to support tropical

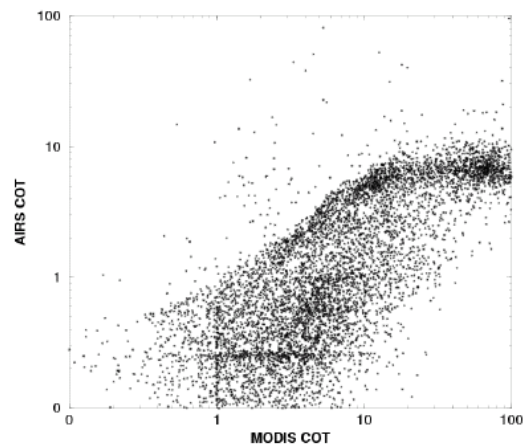
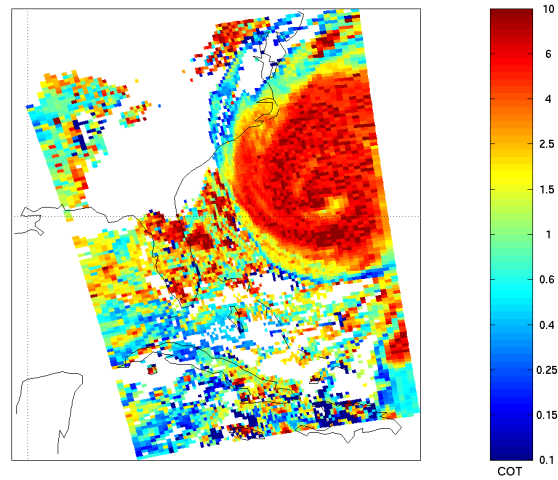


Figure 5. COT image with 1DVAR algorithm for hurricane Isabel (upper panel), and scatterplot between MODIS COTs and AIRS alone COTs (lower panel).

cyclone studies. Both the AIRS MR products during the daytime and the nighttime, as well as the MODIS+AIRS 1DVAR cloud properties during the daytime can be derived for the study of significant weather events such as the tropical cyclone genesis and intensification.

The validation of cloud property products with synergistic use of MODIS and AIRS is ongoing by comparison with other measurements, such as lidar observations, pilot reports, radiosonde observations and in-situ cloud measurements, as well as cloud measurements from other EOS satellites and the operational weather and environmental satellites.

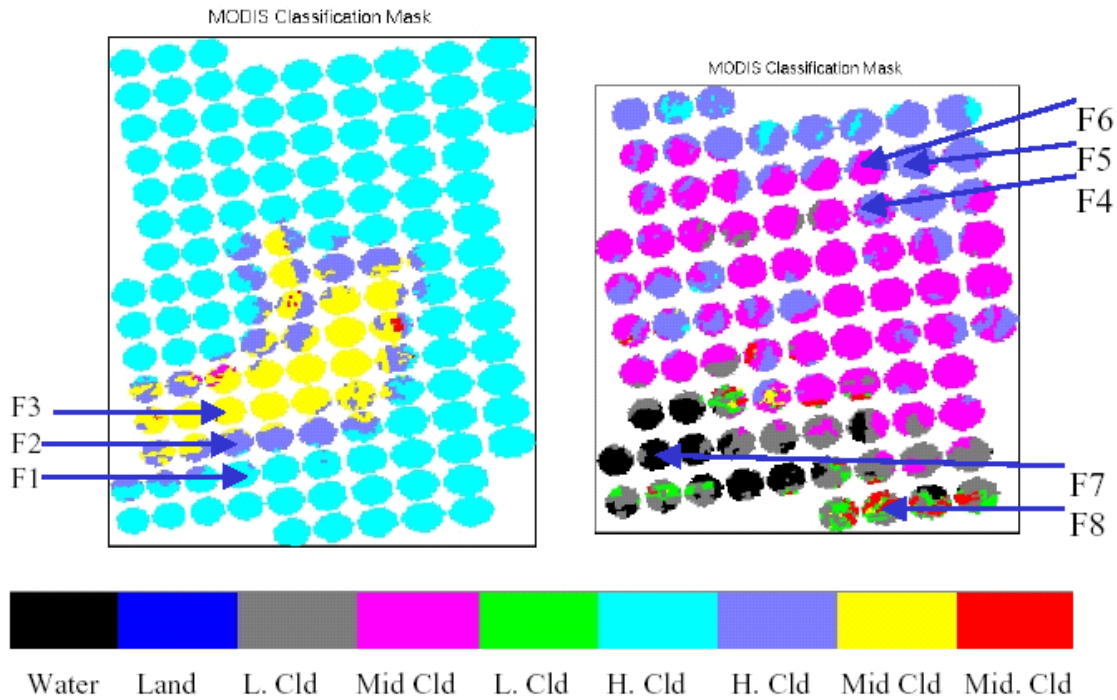


Figure 6. MODIS 1km CCM superimposed on AIRS footprints for boxes A1 and A2. L. Cld: low clouds; H. Cld: high clouds; Mid Cld: medium-level clouds.

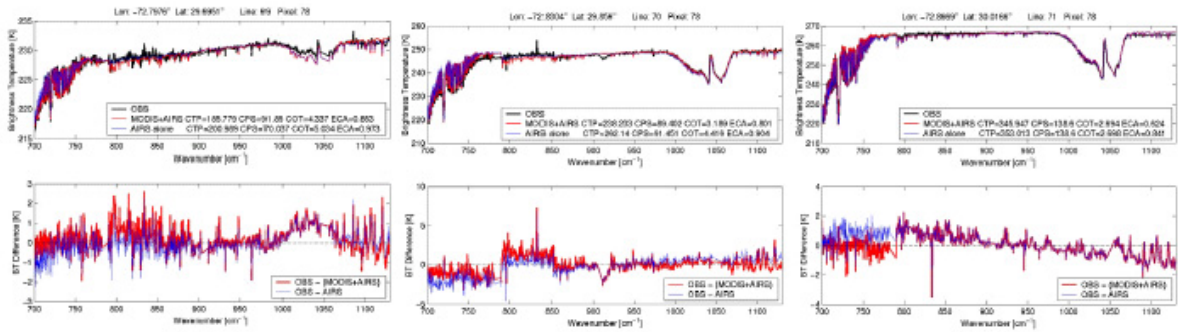


Figure 7. AIRS spectra of BT observations (black line), BT calculations with 1DVAR (red line) and BT calculations with MR (blue line) for AIRS footprints of high clouds (F1), middle-high clouds (F2) and middle clouds (F3), respectively.

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