3.6 AN INVESTIGATION OF THE CHARATERISTATION OF CLOUD CONTAMINATION IN HYPERSPECTRAL RADIANCES

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1. INTRODUCTION

NASA has launched a number of new satellites as part of the Earth Observing System (EOS) to study the Earth from space and to improve our understanding and prediction of the Earth system. A number of these sensors (e.g., the Moderate Resolution Imaging Spectrometer (MODIS), the Atmospheric Infrared Sounder (AIRS), the Cloud Profiling Radar (CPR), and the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP)) also provide unique opportunities to measure atmospheric variables important for short-term weather studies.

Many meteorological centers, including the National Centers for Environmental Prediction (NCEP), United Kingdom Meteorological Office (UK Met Office), Météo-France, and European Center for Medium-range Weather Forecast (ECMWF) are currently investigating the direct assimilation of satellite measured radiances into weather forecast models. However, the use of radiances is not with out complications, stemming from the sheer volume of the radiance data (particularly from high spectral resolution instruments such as AIRS) and cloud contamination. Typically, only data from cloud-free scenes are used in data assimilation approaches (Collard 2004; Auligné and Rabier 2004). Recent work on the global scale by the ECMWF is taking a more aggressive approach by incorporating uncontaminated radiances coming from portions of the atmosphere above low clouds (McNally et al. 2004). NCEP, in conjunction with the Joint Center for Satellite Data Assimilation (JCSDA), is also implementing approaches for maximizing the use of radiance data in cloudy footprints (Derber et al. 2004). These approaches have yet to be analyzed on the regional scale in short-term prediction models.

The objective of the research supporting this paper is to demonstrate an approach that maximizes the use of AIRS radiance observations in short-term (0-48h) weather prediction. This paper focuses on identifying uncontaminated radiances, both between cloud systems and above low and middle level clouds. The approach has developed new methods to identify cloud contamination in AIRS radiances by utilizing its hyperspectral nature, allowing for the assimilation of only cloud-free radiances into a state of the art regional weather forecast model. Validation of approach has begun with preliminary data from the CPR on CloudSat. The research will benchmark improvement in regional weather forecasts through collaborations with NASA's Short-term Prediction and Research Transition Center (SPoRT, Goodman et al. 2004) and show the relevance to large scale modeling activities like those at the JCSDA (Le Marshall et al. 2004, Le Marshall et al. 2006). The research fully supports the NASA Earth science weather focus area and is being performed in conjunction with scientists at the NASA SPoRT Center who are currently transferring unique NASA remote sensing and modeling capabilities to several local NWS Forecast Offices in the Southeast U.S.

2. DESCRIPTION OF PROBLEM

It has been estimated that only about 5-10% of the AIRS footprints are truly cloud-free on a global basis (Huang and Smith, 2004). The number of cloud-free fields of view over a regional area, such us the continental United States, can vary considerably from day to day and the cloud-free regions often are those not associated with high impact weather events. While the EOS AIRS science team produces a set of "cloud-cleared" radiances (Susskind et al. 2003) to retrieve profiles of temperature and moisture and for global data assimilation, the utility of these radiances for assimilation has not been fully demonstrated.

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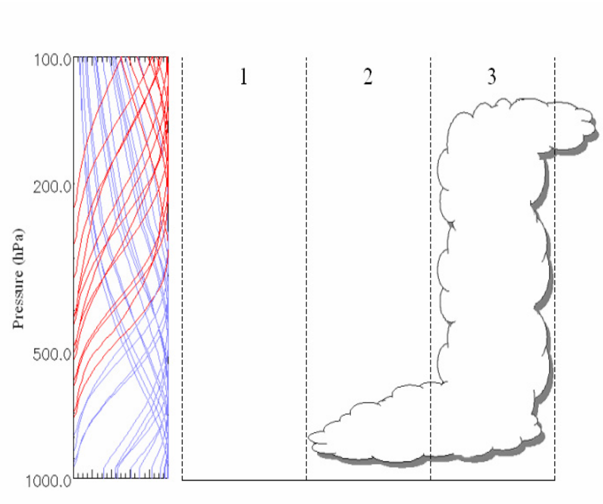

Figure 1 – Visual schematic to explain the CO_2 sorting technique. Red and blue lines show the Weighting Function for a selection of AIRS Bands. Column 1 represents a clear IFOV. Column 2 represents a cloudy IFOV with a low cloud. Column 3 represents a cloudy IFOV with a high cloud.

In regions of developing storms and storm systems, the antecedent weather conditions often consist of low-level clouds, representing moisture inflow or changes in atmospheric stability accompanied by strong thermal gradients associated with developing upper level jets. Clearly there is a need to increase the amount of radiance data from meteorologically significant regions used in forecast models. While the AIRS spectrum of radiance data associated with these weather systems may typically be deemed as cloud-contaminated because of the presence of clouds in the field of view, only a subset of AIRS channels may actually be affected, those whose weighting functions show sensitivity to the clouds in lower layers of the atmosphere as indicated in Fig. 1. This figure shows a set of typical AIRS weighting functions. The weighting functions indicate the layer of the atmosphere for which each channel measures atmospheric emission. As seen in the figure, many of the middle and upper tropospheric temperature channels (presented in red) remain unaffected by low-level clouds but are typically not used in the assimilation process (McNally and Watts 2003; Garand and Beaulne 2004).

3. DESCRIPTION OF TECHNIQUE

The algorithm being developed for the identification of cloud-free channels within a scene of low and middle level clouds is based on the CO_2 sorting technique (Holz et al. 2006). An example of this is presented in Fig. 2. Initially, the CO_2 sorting technique was used to classify cloud top pressure, but in the current application, the tropospheric AIRS channel brightness temperatures in the CO_2 absorption region (13 to 15 μm) are used to identify channels not affected by clouds. In the figure the solid black line represents the sorted AIRS brightness temperatures in the CO_2 region corresponding to a clear field of view and the blue line to an adjacent mid-level cloudy field of view. AIRS channels which sense emission from the lower part of the troposphere will be affected by the presence of a mid-level cloud (blue line) and measure colder temperatures than a cloud free spectrum (black line). The separation point between channels that are "cloud-free" and ones affected by clouds is where the two curves diverge, as indicated by the vertical red line. Thus, channels to the left of this line are not affected by the presence of clouds in the observed field of view. The separation point will occur at lower brightness temperatures for higher clouds, thus providing fewer channels uncontaminated by clouds, while low-level clouds will separate at higher brightness temperatures. The magnitude of the separation of the two lines, however, is a function of the effective cloud fraction (ECF), which is the product of the cloud emissivity and the physical cloud fraction of an instantaneous field of view (IFOV). Thus, the tuning of the algorithm to detect the separation point

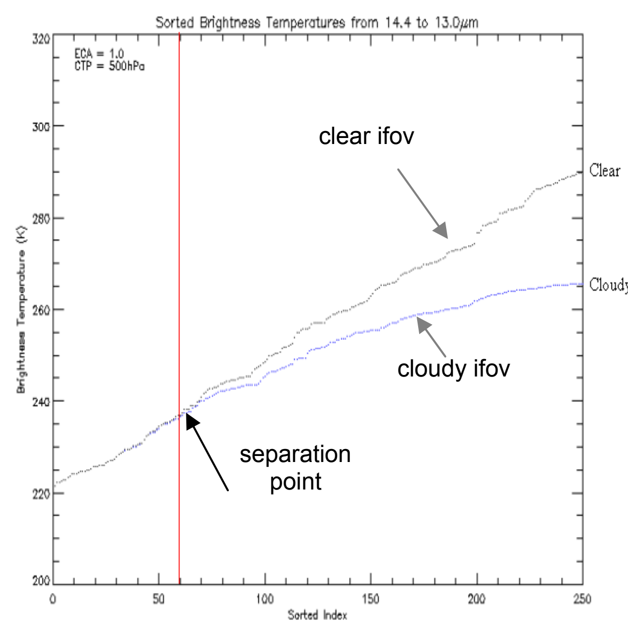

Figure 2 – Clear (black) and Cloudy (blue) simulated sorted AIRS spectra. The red line denotes the separation point.

incorporates more advanced approaches than a simple brightness temperature separation threshold approach.

To determine the separation point, a cloud-free spectrum is needed to be compared to the cloudy spectrum. The cloud-free spectrum can come from a known "clear" field of view adjacent to the cloudy one or from a modeled atmosphere. A truly "cloud-free" spectrum which represents the near-clear environment is often difficult to obtain so a set of AIRS CO_2 channels representing cloud-free conditions is obtained from a modeled atmosphere and is used in an appropriate radiative transfer algorithm. The development of the CO_2 sorting channel detection algorithm has been developed to utilize the stand-alone AIRS radiative transfer algorithm (SARTA, Strow 2003) in a stand-alone mode as well as the Community Radiative Transfer Model (CRTM, Weng et al. 2005) within the Gridpoint Statistical Interpolation (GSI) data assimilation system (Wu et al. 2002) framework.

In the CO_2 sorting algorithm, two antecedent tests are used to determine if a separation point exists, and three tests determine the location of the separation point. The first antecedent test checks to see if separation occurs by comparing the clear spectrum to the observed spectrum. If the observed spectrum is warmer than the clear spectrum, it is assumed to be cloud-free since a separation point does not exist. The second antecedent test checks the change in brightness temperature (ΔT_b) between the warmest and coldest brightness temperatures in the observed spectrum. If the ΔT_b exceeds a threshold, currently 15K, then the tropospheric channels are assumed to be completely contaminated and the separation point is not determined.

The three separation tests consider the nature of the spectrum, as compared to the clear-sky spectrum, to determine the separation point. The first test, the tangential adjustment method, sets the separation point as an intersection of lines tangential to the cloudy and clear spectra at a given ΔT_b, which has been optimally determined from training data. The second test, the percentage adjustment method, determines the separation point as the percentage of the index where the clear and cloudy spectra exceed a ΔT_b. The percentage and ΔT_b have also been optimally determined from training data. The third separation test is the probabilistic test. This test currently considers four characteristics of the sorted spectra: the ΔT_b of the sorted spectra, the ΔT_b of the curves fitted to the spectra, which are sigmoidal curves, the derivative of the ratio of the sorted spectra, and the derivative of the product of the sorted spectra. From these relationships, a gaussian probability is determined from a training dataset. The probabilities are then linearly combined using weights determined by a least-squares regression from the training dataset to determine the probability that a given point on the sorted spectra is the separation point. The sorted index of max probability is then determined to be the separation point. The separation point is taken as the result of the three tests corresponding to the coldest T_b.

The results of this study focus on the pressure of the separation point (p_{sp}). This pressure is determined by log-interpolating the brightness temperature of the separation point to a pressure-height using a collocated profile from the NAM. It is noted that the p_{sp} is not direct cloud height, but is representative of the first channel which is determined to be uncontaminated by clouds. Therefore, the channel is likely to peak well above the cloud height.

In the analysis which follows, the separation pressure it is compared to the more conventional cloud top pressure (CTP) retrievals. The CTPs are determined using the CO_2 slicing technique (Smith and Platt 1978; Menzel et al. 1983; Liou 2002). This technique was originally investigated using multispectral sounders and uses a solution to the radiative transfer equation to solve for the CTP. The CO_2 slicing technique assumes that there is only a single layer, infinitesimally thin cloud within the IFOV. The methodology of McCarty and Jedlovec 2006, which utilizes a subset of channels in the 15μm CO_2 absorption region, was used to adapt the technique to the AIRS instrument. The use of these retrieved CTPs in this study provides both an ancillary AIRS view of the clouds as well as a means for future comparison for situations where CloudSat data is unavailable or inapplicable.

4. RESULTS

In this study, initial verification is performed. Cloud profile cross-sections were obtained from the Level 2 GEOPROF (2B-GEOPROF) product that is produced by the CloudSat Data Processing Center. The 2B-GEOPROF record contains quality controlled cloud profiling (94 GHz) radar observations and a cloud mask that discriminates between cloud returns and noise or clutter effects. Cloud profiling radar data are compared to other remotely sensed

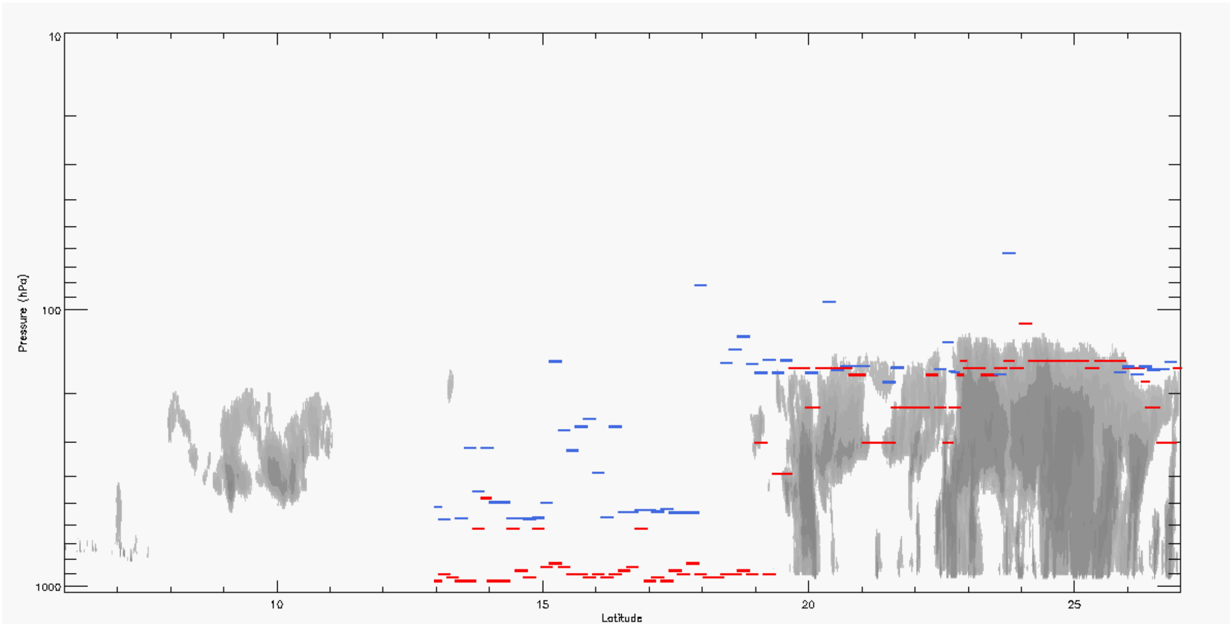

Figure 3 – Contoured CloudSat data (gray), AIRS CO_2 slicing CTP (red), and separation point pressure (blue) for 1845 UTC on 29 Aug 2006, ranging from 6°N to 27°N

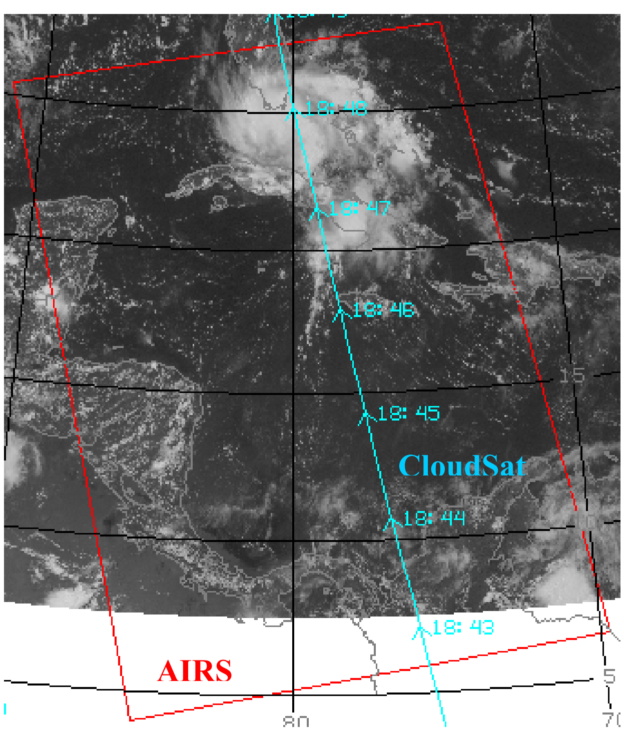

Figure 4 – Outline of AIRS granule at 1841 UTC (red) and the CloudSat orbital track (blue) for the ascending orbit on 29 Aug 2006. The background is the 0.65 μm channel from the GOES Imager at 1845 UTC.

data sets by performing nearest neighbor matching between the geolocation data from the 2B-GEOPROF record and two-dimensional fields of interest. An auxiliary dataset provided by the CloudSat science team, ECMWF-AUX, is used to convert the heights inherent in the 2B-GEOPROF dataset to pressure levels by interpolating the heights using a collocated ECMWF profile.

The preliminary results shown are from a case occurring at 1841 UTC on 29 Aug 2006. Figure 3 presents a cross section display of CloudSat radar reflectivities, AIRS separation point pressures (from the aforementioned CO_2 sorting approach), and the CTPs from the CO_2 slicing approach. They correspond to the CloudSat track presented in Fig. 4, which shows the orbital track of CloudSat and the concurrent AIRS granule overlying GOES Imagery. AIRS data from the Aqua satellite which precedes CloudSat measurements by 1-2 minute were spatially collocated and used in the calculations and intercomparison. The p_{sp} and CTP values appear to be drastically different from each other. This is to be expected however, because of the inherent differences between the two as the p_{sp} is a proxy of cloud height, and the CTP is a more direct measure of cloud height.

First, the high cloud scenario from the tropical system at the northern end of the granule (Fig. 3) is focused upon. When considering the separation point pressure (p_{sp}) corresponding to these CTPs, there are inherent differences

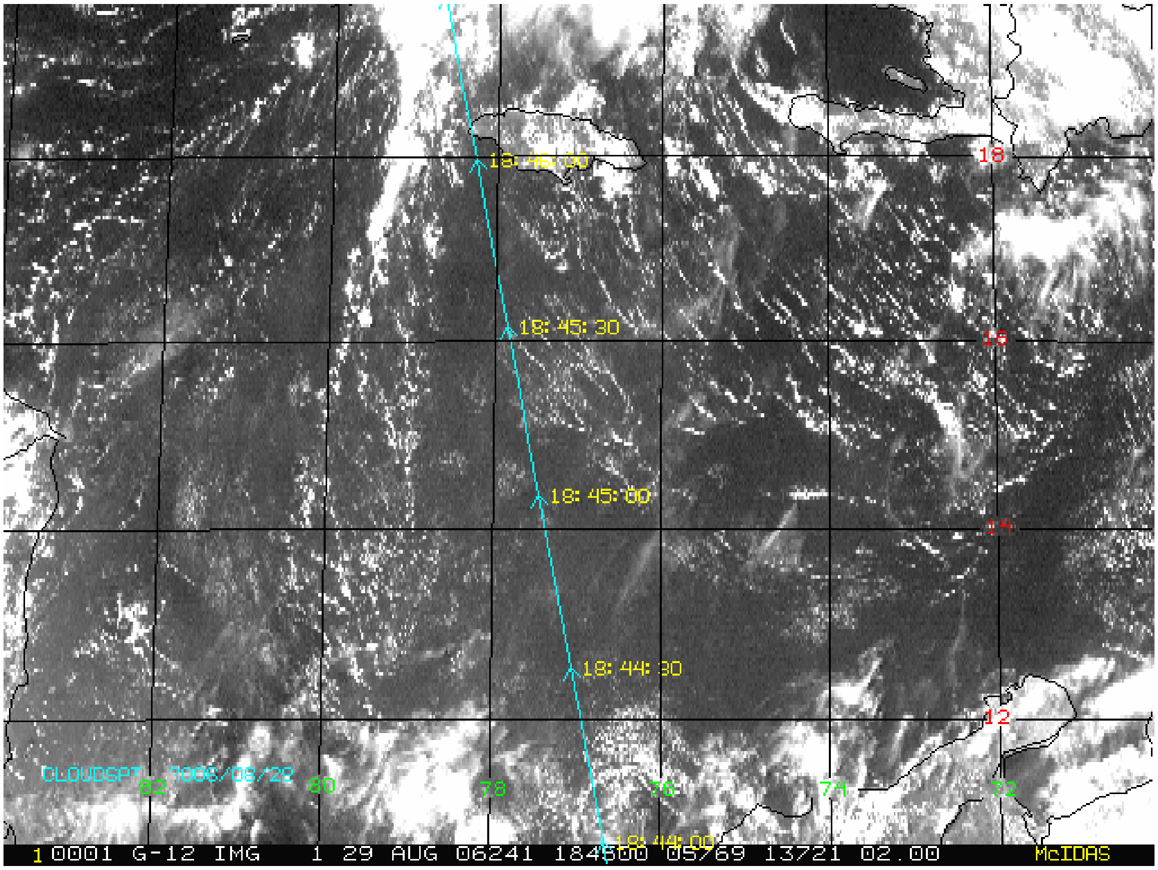

Figure 5 – CloudSat track (cyan) overlying contrast-enhanced GOES Visible imagery.

between the measurements. As noted, the p_{sp} is a log-interpolated pressure determined from the brightness temperature of the AIRS channel at the determined separation point. Therefore, this pressure theoretically corresponds to the first channel which is uncontaminated by a cloud in the AIRS IFOV. It is not an explicit indicator of CTP, but a relative one. Also, there are some p_{sp} values that appear to be near or below the cloud top. This may be a result of the log-interpolation about the tropopause, or may be poor performance of the algorithm. Further investigation of this will be performed.

AIRS CTP values tend to generally agree with CloudSat measurements. In certain situations, such as around 21.5°N and 19.5°N, it tends to predict CTP significantly larger than the highest cloud shown by CloudSat. This is likely due to the breakdown of the single-layer cloud assumption of the implemented CO_2 slicing algorithm.

It is noted that there are far fewer p_{sp} values than retrieved CTPs in this subsection of the scene. This is a result of the aforementioned antecedent ΔT_b test between the warmest and coldest brightness temperatures of the sorted spectra. In this region, no separation point is determined for many IFOVs because all tropospheric channels are determined to be cloud contaminated. Thus, these high, dense clouds are triggering that initial test, which is to be expected in this region.

Second, the area directly south of the tropical system along the CloudSat track (Fig. 3) is considered. The AIRS p_{sp} and CTP values indicate the presence of low-level clouds and are generally consistent with each other. The CloudSat data, however, shows no presence of clouds. When considering the GOES visible imagery (Fig. 5), there is evidence of texture that may be representative of subresolution, boundary layer clouds. These clouds may not be properly resolved by CloudSat, while both the sorting algorithm and the CO_2 slicing CTP retrievals are detecting them.

5. CONCLUSIONS AND FURTHER WORK

This work is being done to develop improved set of AIRS uncontaminated spectral radiances will be analyzed using the GSI system. It is a three-dimensional variational (3DVAR) assimilation (Lorenc 1981) scheme in development by NCEP and is supported by the NASA Global Modeling and Assimilation Office (GMAO), the Global Systems Division (GSD) of the Earth System Research Laboratory (ESRL), and the JCSDA. It is capable of assimilating data from many different observational platforms including radiance data obtained from satellites. The GSI is designed for both global and regional scale applications and will provide initial conditions for the Weather Research and Forecast (WRF) modeling systems (Skamarock et al. 2001). The WRF is intended for a wide range of applications, from idealized research to operational forecasting, with priority emphasis on horizontal grids of 1-10 kilometers. Based on its merits, it will replace existing forecast models such as the MM5 and the RUC system at NOAA/ESRL/GSD.

The sorting technique is showing promising results. Further investigation of the weighting functions relative to the CloudSat data will further emphasize the success of the retrieval and allow for further tuning. Since the technique is already implemented within the GSI system, the following step will be to perform regional model runs based on the GSI analyses incorporating both the AIRS data and the sorting technique. Further results and cases will be presented at the accompanying talk.

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