Cloud detection and clearing for the MOPITT instrument

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ABSTRACT

The Measurement Of Pollution In The Troposphere (MOPITT) instrument, which will be launched on the Terra spacecraft, is designed to measure the tropospheric CO and CH_4 at a nadir-viewing geometry. The measurements are taken at 4.7μm in the thermal region, and 2.3 and 2.2 μm in the solar region for CO mixing ratio retrieval, CO total column amount and CH_4 column amount retrieval, respectively. To ensure the required measurement accuracy, it is critical to identify and remove any cloud contamination to the channel signals. In this study, we develop an algorithm to detect the cloudy pixels, to reconstruct clear column radiance for pixels with partial cloud covers, and to estimate equivalent cloud top positions under overcast conditions to enable CO profile retrievals above clouds. The MOPITT channel radiances, as well as the first guess calculations, are simulated using a fast forward model with input atmospheric profiles from ancillary data sets. The precision of the retrieved CO profiles and total column amounts in cloudy atmospheres is within the expected ±10% range. Validations of the cloud detecting thresholds with MODIS Airborne Simulator (MAS) data and MATR (MOPITT Airborne Test Radiometer) measurements are also carried out and will be presented separately.

Keywords: MOPITT CLOUD TROPOSPHERIC CO CH_4

1. INTRODUCTION

The Measurements of Pollution in the Troposphere (MOPITT) instrument (Drummond, 1992), scheduled for launch aboard Terra spacecraft, is designed to measure tropospheric CO and CH_4. This instrument will scan the earth at nadir with a spatial resolution of 22x22 km, and will achieve a global coverage within approximately 3 days. MOPITT instrument is a gas correlation radiometer that measures CO at the spectral regions of 4.7 and 2.3 μm, and CH_4 at 2.2-μm solar region. The thermal channel measurements will be used to retrieve CO profiles in the troposphere at 5 vertical levels, while the solar channels will be used to retrieve CO and CH_4 total column amount (Pan et al., 1998). The anticipated accuracy is 10% for CO measurement and 1% for CH_4 column amount.

One of the major challenges related to space-borne sensors that measure the tropospheric properties is the treatment of cloud contamination in the instrument field of views (FOVs). It includes identifying the cloudy pixels and retrieving the atmospheric properties from the cloudy FOVs. The former is generally called cloud detection, which involves defining the observable quantity that discriminates between cloudy and clear scene, and determining the value that represents the contrast. The most common cloud detection technique is the threshold method that makes use of radiance variations in wavelength, space, or time (Rossow, 1989).

Smith (1968) developed N* method to remove the cloud effect in the process of retrieving temperature profiles. Some other algorithms were based on the N* method, such as that by Smith et al. (1993) that uses collocated AVHRR (Advanced Very High Resolution Radiometer) and HIRS/2 (High-resolution Infrared Radiation Sounder) channels to provide clear column radiance estimation and calculate cloud cover contrast between adjacent pixels. Chahine (1974) has developed a method in which the temperature profiles, cloud height and cloud amount is derived simultaneously in an iterative relaxation retrieval scheme. It uses the knowledge of adjacent pixels without *a priori* temperature information or cloud-free observations; however, it requires careful choice of instrument spectral coverage.

This paper describes the MOPITT cloud algorithm that includes the detection of cloudy pixels, clearing cloud for pixels with non-uniform cloud covers, and determining cloud top heights for overcast conditions to enable retrievals above clouds. Section 2 describes the cloud detection algorithm. Section 3 discusses an attempt to use the remotely sensed data through cloudy atmosphere by cloud clearing and by retrieving CO profiles above clouds. Section 4 summarizes the current status of the MOPITT cloud algorithm.

2. CLOUD DETECTION

MOPITT channel radiative properties, signal characteristics and sensitivities have been discussed by Pan *et al.* (1995) and Edwards *et al*. (1999). Cloud detection for MOPITT instrument uses two independent methods, threshold method and estimation of cloud top pressures, which will be discussed in the following subsections. When any pixel is detected as cloudy by one of the methods, the pixel is classified as cloudy.

2.1. Threshold Method

In general, clouds are characterized as colder and having higher solar reflectance than the earth surface. The temperature differences between clouds and the surface are shown from 4.7-μm channel radiance, and the differences in the boundary reflectance are revealed from the solar channels. MOPITT cloud detection threshold method uses both solar and thermal channels for daytime passes and thermal only for nighttime passes.

The reference clear column radiance is calculated by a fast radiative transfer model (Edwards *et al*., 1999) with input data from a set of ancillary meteorological and climate data. This forward model takes into account the contributions from H_2O, CO_2, O_3, N_2O, CO and CH_4, and it requires the input of temperature vertical distribution, surface temperature, emissivity and reflectivity. Currently, CO_2, O_3, N_2O profiles from climatological data sets are used. The real time meteorological data, i.e. temperature and water vapor distributions, is provided by NASA Data Assimilation Office (DAO). The surface reflectance near 2.2 and 2.3 μm solar region was retrieved from LANDSAT TM (Yu and Drummond, 1998). The 4.7-μm thermal emissivity distribution over the globe is determined from Fu and Lion model parameters that are assigned to each USGS scene type (Belward and Loveland, 1996), described by Gupta et al. (1999). There is no seasonal variation in the emissivity data set currently, and additional work is necessary.

The MOPITT threshold method uses average signals from the 2.3-μm band LMC at cell pressure 800mb (named as ch6A), and average signals from the 4.7-μm LMC at cell pressure 800mb (as ch5A). Both ch5A and ch6A are used during daytime, and only ch5A is used for nighttime cases. Although the sensitivities of A-signals to the cloud fractions are different for each channel, the A-signals of all four thermal channels, or four solar channels, respond to surface or cloud similarly. The A-signal from only one thermal, or solar, channel is necessary to detect clouds if the FOVs from all detectors are collocated. This is not necessarily true for the MOPITT instrument, and it may be decided at a later time that all channels are necessary in cloud detection.

MOPITT cloud thresholds, based on observed channel radiance and model calculated clear column radiance, are defined as, for daytime

$$\begin{cases} Rch5A_{Calculated} - Rch5A_{Observed} \geq 0.005, \text{ or} \\ \dfrac{Rch5A_{Observed}}{Rch5A_{Calculated}} \leq 0.93 \text{ (or } > 1.1 \text{ near polar regions), or} \\ \\ \dfrac{Rch6A_{Observed}}{Rch6A_{Calculated}} > 1.5, \end{cases} \tag{3}$$

and for nighttime

$$\begin{cases} Rch5A_{Calculated} - Rch5A_{Observed} \geq 0.005, \text{ or} \\ \dfrac{Rch5A_{Observed}}{Rch5A_{Calculated}} \leq 0.97 \text{ (or } > 1.1 \text{ near polar regions).} \end{cases} \tag{4}$$

In equations (3) and (4), R_{ch5A} and R_{ch6A} are average radiance from ch5A and ch6A, respectively. Both difference and ratio of the radiance between the observed and calculated are used to reflect different aspects of the contributions. For example, when the ratio is taken of solar channel average signals, certain solar irradiance related terms cancel and more emphasis is placed on the surface characteristics.

The one day coverage of MOPITT channel radiance is simulated using DAO August 1, 1998 meteorological data set. Cloud information provided by DAO includes cloud fraction, cloud top pressure and cloud temperature. The cloud fraction varies from 0 to 1, and the cloud top pressures span approximately 90 –10kPa. Single layer, opaque clouds are assumed with a thermal emissivity of 0.98, and solar reflectivity of 50%. Polar regions (latitude > 65N or < -60S) are excluded in the simulations due to the frequent temperature inversions at night, and to avoid the affect on the daytime signals of possible snow and ice coverage.

The accuracy of cloud detection is evaluated by comparing the retrieved CO amounts from a clear and a cloudy simulation. Fig. 1 (a) depicts the percentage differences of CO total column amount between the two runs for pixels identified as clear by MOPITT cloud thresholds. The x-axis shows the cloud covers that are included in the simulations. Therefore, the data points shown on the graph are those with cloud contamination but which failed to be detected. The majority of the undetected pixels are those with low percentage cloud cover (less than 10%), and the differences from the clear run is primarily within 10% range. The pixels with more than 10% cloud cover are mainly from low clouds and are nighttime cases. Under these conditions, there is not enough contrast between the simulated cloudy radiance and the calculated clear column radiance. However, failure to detect this type of scene does not impact the retrieved results significantly, and, as shown in Fig. 1 (a), almost all data are within ±10% difference, which meets MOPITT measurement accuracy requirement.

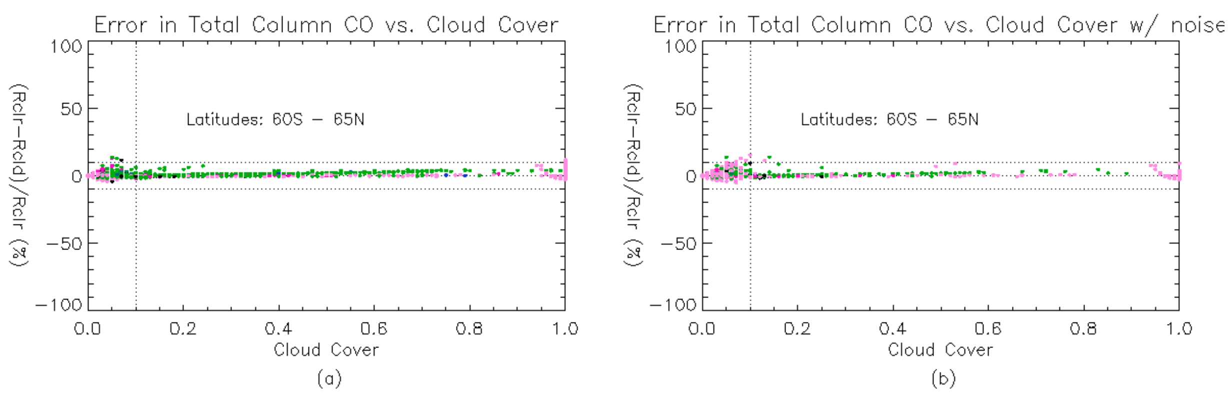

Fig. 1: Effect of the threshold uncertainty on the retrieved total column CO amount. (a): Percentage error of undetected cloudy pixels, and (b): same as (a) except that noise is included in the cloud detection.

There are two major sources of uncertainties in estimating the clear column radiance: model uncertainties and the noise introduced by the input data. While the model systematic bias can be validated and compensated for, the input data noise has to be anticipated in determining the cloud detection thresholds. MOPITT average signals are most sensitive to the surface temperature and emissivity or reflectivity. While emissivity and reflectivity are prescribed in the processor, the surface temperature is provided by DAO reanalysis, which is subject to random error. Noise is added to the clear radiance estimation by perturbing the input profiles and surface quantities randomly. The cloud detection accuracy for simulations with noise is shown in Fig. 1 (b). The uncertainties for pixels with less cloud cover slightly increase, although they still fall in the range of accuracy requirement. When the noise is included in the reference radiance, a number of observed clear pixels will be considered cloudy by mistake, and hence, the global data coverage will decrease. Considerations of both cloud cover and noise are incorporated into MOPITT cloud detection thresholds.

MOPITT cloud detection assigns output products with confidence levels so the data users can estimate the uncertainties involved in data processing that are due to the cloud algorithm. In general, daytime data are assigned with higher confidence since both solar and thermal information is used. Data over the ocean has a higher confidence level since the input data, especially the surface quantities, are generally less uncertain.

2.2. Cloud Top Pressure Estimated from CH_4 channels

The MOPITT instrument measures total column CH_4 at 2.2 μm through reflected solar radiation, and the channel D/A signals are used to retrieve CH_4 total column amount (Pan et al., 1995). CH_4 can be approximated as a uniformly distributed gas in the atmosphere to a good accuracy (about 1%). Therefore, the measured total column CH_4 can be used to determine the altitude of the surface. When an optically thick cloud is presented in the FOV, the measured column of CH_4 represents the portion above the cloud. An equivalent cloud top can be determined when the FOVs are partially covered with clouds or when the clouds are optically thin.

A simple exponential curve of CH_4 D/A signals vs. cloud top pressures is obtained by fitting simulated data in each narrow range of solar zenith angles and satellite zenith angles. The equivalent cloud top pressure is written as:

$$Pcloud = a + \exp(b \cdot Rch4_{D/A} + c), \tag{5}$$

where parameters a, b and c are obtained from a nonlinear least squares fitting, and $R_{ch4D/A}$ is the CH_4 D/A channel radiance. A set of parameters is determined for every 5 degrees solar zenith angle and 10 degrees satellite zenith angle. The estimated equivalent cloud top pressure for each pixel location is then compared with the surface pressure to detect cloud, and a threshold of 50mb is used for solar zenith angle less than 35° and of 100mb for solar zenith angle greater than 35°.

For the limited data set we tested, the technique nearly always works for pixels with more than 10% cloud covers. The expression (5) is predetermined and based on model calculations. The advantage of this technique is that it does not rely on input meteorological data to predict clear column radiance, and therefore, it eliminates some uncertainties associated it.

3. CLOUD CLEARING

The retrieval of the tropospheric CO and CH_4 in the presence of clouds is made possible by using two techniques; one to estimate a clear column radiance using neighboring pixels and the other to identify overcast cloud tops and retrieve above clouds. The former makes use of the N* method introduced by Smith (1968), and is discussed in section 3.1.

3.1. N* Technique

The N* method assumes that two adjacent cloudy pixels possess the same radiative and cloud physical properties, and they differ only by the amount of cloud cover. Based on the definition, N* represents the ratio of cloud cover in two adjacent pixels, hence, it is independent of spectral frequencies. N* can be calculated from a reference channel as:

$$N^* = \frac{Robs1 - Rclear}{Robs2 - Rclear}, \tag{6}$$

where R_{clear} is the estimated clear column radiance, and is provided by model calculation in the MOPITT cloud algorithm. R_{obs1} and R_{obs2} are the observed radiances of pixel 1 and 2, respectively, for the reference channel. N* is then applied to all other channels to estimate clear column radiance using the equation:

$$Rclear(i) = \frac{Robs1(i) - N^* Robs2(i)}{1 - N^*}, \tag{7}$$

where *i* indicates the *i*th channel.

The clear column radiance for the reference channel used to calculate N* is obtained from forward model calculations. The solar CO average channels show stronger signal on cloud covers than the thermal channels, and therefore, one solar CO channel (ch6A) is used to calculate N* for daytime cases. For nighttime cases only thermal channels are available, and the average signals for 800mb cell pressure (ch5A) are used to calculate N*s. Since the

MOPITT FOVs are 22x22 km, only two adjacent pixels are necessary to accommodate heterogeneous clouds. Note that in the calculation of clear column radiance, the uncertainties in the observed radiance are magnified by a factor 1/(1-N*), and therefore, it requires that the two pixels posses enough contrast on cloud covers. N* limits of less than 0.6 for daytime and 0.5 for nighttime are used to ensure a CO measurement accuracy of 10%. Fig. 2 shows a similar pair of graphs to Fig. 1 except for pixels cleared by N* method. Almost all data points fall within the 10% accuracy range for CO total column amounts. Since N* method requires adequate cloud cover contrast between adjacent pixels, it works best for heterogeneous clouds and around edges of more uniform clouds.

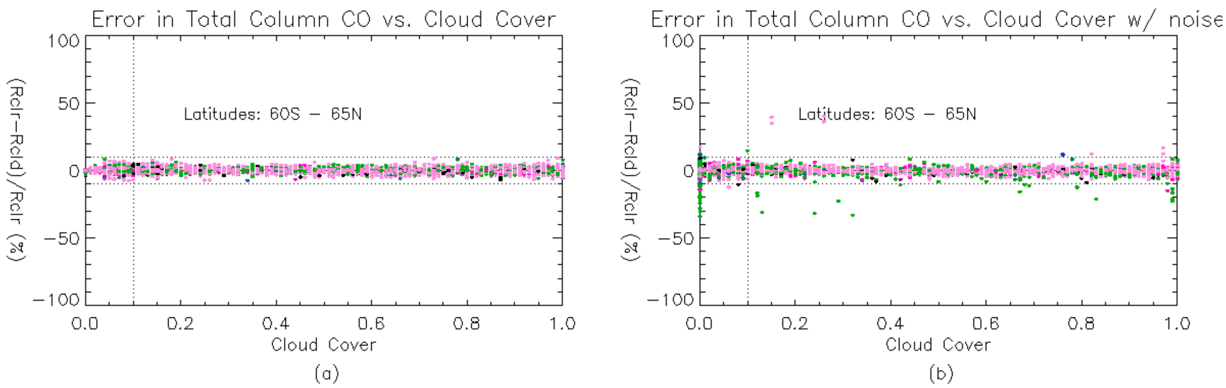

Fig. 2: Same as in Fig. 1, except for N* calculated pixels.

3.2. Determination of Overcast Cloud Tops

A large majority of the clouds over the globe are relatively uniform and optically thick. It is possible to make use of the observations to retrieve CO concentration when an optically thick and uniformly distributed cloud top can be determined. After individual pixels are identified as cloudy, three steps are taken to determine an optically thick overcast cloud top.

First, an equivalent cloud top pressure is obtained for the pixel under consideration from the CH_4 channel D/A signals by using equation (5). Secondly, a spatial area of 1x1° in latitude and longitude surrounding the pixel is selected, and a mean CH_4 D/A signal and a standard deviation (SDV) of all pixels within the area are calculated. When the SDV over mean is less than 1%, and when there are more than 30% of the pixels in the same area having the same properties, these pixels are assigned as having uniform cloud covers. The third step is to determine the opacity of the cloud to exclude cases with optically thin uniform cloud covers. The radiance from a thermal channel can be simulated from the cloud to the top of the atmosphere, then compared with the observed radiance of the same channel. The cloud top temperature is interpolated from the DAO temperature profile based on the estimated cloud top pressure, and the cloud top emissivity is set to 1. If the difference of the thermal ch5A signals for the pixel is less than a small amount (0.005), the pixel is considered optically thick.

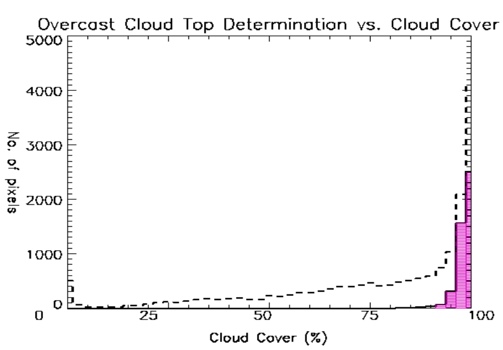

Fig. 3: The cloud cover of pixels determined as having overcast tops (shaded area), compared with total pixels in the simulation.

Fig. 3 shows the histogram of the pixels detected as overcast cloud tops for a small area under testing of 30S to 60N latitude and 45W to 90W longitude during daytime. The pixels in the shaded area are those considered as overcast cloud tops, and the area under the dashed line indicates the cloud covers of all pixels included in the simulation. Those detected as overcast cloud tops generally have more than 95% cloud cover in each pixel. About 2/3 of the simulated overcast cloudy pixels are detected. The MOPITT retrieval algorithm retrieves CO profiles in 5 levels in the troposphere. Only the pixels with cloud top pressures below 400mb level are considered, so that the retrievals for at least 2 layers can be obtained. Under this condition, the complication due to thin cirrus clouds is eliminated since most transparent cirrus clouds are high in the troposphere.

4. SUMMARY

This paper summarizes the current status of MOPITT cloud algorithm. Based on the simulations, both cloud detection and cloud clearing algorithms along with the retrieval algorithm provide CO measurements within the accuracy requirement. The sensitivity of CH_4 accuracy to the uncertainties in the cloud algorithm will be tested in a later time. The validation of our cloud algorithm with MAS data and MATR data is discussed in separate papers. MOPITT cloud algorithm will also incorporate other data resources such as those from MODIS (Moderate-Resolution Imaging Spectroradiometer) products when they become available.

ACKNOWLEDGMENTS

The National Aeronautics and Space Administration (NASA) Earth Observing System (EOS) Program funded this work under contract NAS5-30888. Meteorological data was provided by NASA DAO. Thanks also go to Cheryl Craig and Leslie Mayer for MOPITT data simulation and other software support.

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