Cloudy sounding and cloud-top height retrieval from AIRS alone single field-of-view radiance measurements

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Abstract

High-spectral resolution measurements from the Atmospheric Infrared Sounder (AIRS) onboard the EOS (Earth Observing System) Aqua satellite provide unique information about atmospheric state, surface and cloud properties. This paper presents an AIRS alone single field-of-view (SFOV) retrieval algorithm to simultaneously retrieve temperature, humidity and ozone profiles under all weather conditions, as well as cloud top pressure (CTP) and cloud optical thickness (COT) under cloudy skies. For optically thick cloud conditions the above-cloud soundings are derived, whereas for clear skies and optically thin cloud conditions the profiles are retrieved from 0.005 hPa down to the earth's surface. Initial validation has been conducted by using the operational MODIS (Moderate

Resolution Imaging Spectroradiometer) product, ECMWF (European Center of Medium-range Weather Forecasts) analysis fields and radiosonde observations (RAOBs). These inter-comparisons clearly demonstrate the potential of this algorithm to process data from high-spectral infrared (IR) sounder instruments.

1. Introduction

The AIRS instrument measures radiances in 2378 spectral channels within the spectral range from 650 cm^{-1} to 2675 cm^{-1} (corresponding to 3.74 μm to 15.4 μm). The spectral coverage includes strong CO_2 absorption necessary for temperature profile retrievals, window regions that are used for retrieving the surface and cloud properties, and a strong water vapor absorption band for humidity soundings. The maximum scanning angle of AIRS is 49.5 degrees, the swath width is 1650 km, and the footprint size is 13.5 km at nadir. More specifications about the AIRS instrument can be found elsewhere [e.g., *Aumann et al.,* 2003; *Chahine et al.,* 2006]. Since one footprint (due to its size) contains clear and/or cloudy scenes with varying properties (e.g., fraction, height, phase), sounding retrievals using AIRS-only measurements under all sky conditions are quite challenging. According to *Smith et al.* [2005] there are essentially three ways to deal with cloudy radiances: (1) assuming opaque cloud conditions, (2) cloud clearing, and (3) making use of a physically based radiative transfer model. In approach (1) the sounding retrievals can be derived down to the cloud top level. Cloud clearing combines the cloudy radiances with clear measurements from another instrument; for example, AMSU (Advanced Microwave Sounding Unit) radiances are used in the AIRS operational retrieval system [*Susskind et al.,* 2003], and MODIS measurements are used for AIRS single FOV cloud clearing [*Smith et al.,* 2004 , *Li et al.,* 2005b]. Approach (3) was first applied on AIRS measurements in *Smith et al.* [2005]. Using measurements from the aircraft sounder NPOESS (National Polar-orbiting Operational Environmental Satellite System) Airborne Sounder Testbed – Interferometer (NAST-I) with high spatial resolution (2 km at nadir) offers the advantage of cloudy FOVs with less varying cloud height and optical properties. Statistical and physical inversion methods using a cloudy radiative transfer model have been developed to process NAST-I radiances for accurate retrieval of temperature and moisture profiles below optically thin clouds [Smith et al., 2005a; *Zhou at al.,* 2005; 2007a; 2007b]. The algorithm for NAST-I cloudy sounding has been adjusted to be suitable for AIRS footprint in this paper. The main differences between the NAST-I method and AIRS cloudy sounding algorithm, as presented in this paper, are that (1) the latter uses a different training set (global instead of regional and seasonal), (2) assigns ice cloud-top and/or water cloud-top to each profile, the cloud-top assignment is a little different from that in NASTI algorithm which assumes two cloud levels and alters the profile to be isothermal blow the lower cloud level, (3) performs different classification procedures in retrieval, (4) uses an IR technique to obtain the cloud phase in the retrieval step, and (5) uses MODIS product for independent comparisons. Initial results of inter-comparisons with the operational MODIS cloud-top pressure (CTP) product, ECMWF analysis and radiosonde observations are promising for the processing of data from future advanced IR sounder instruments like IASI (Infrared Atmospheric Sounding Interferometer) and CrIS (Cross-track Infrared Sounder).

2. Methodology used for AIRS alone SFOV cloudy sounding

The IMAPP AIRS retrieval software (latest version v1.3 was released in November 2006), which delivers atmospheric and surface parameters with a validity restricted to clear skies, was used as the starting point for the cloudy retrieval methodology. The clear sky algorithm is based on eigenvector regression. The regression training set [*Borbas et al.*, 2005] consists of approximately 15000 globally distributed profiles (including surface parameters) and their associated computed radiances, which were generated by the Stand-alone Radiative Transfer Algorithm (SARTA v106, *Strow et al.,* 2003). The training set is classified based on the brightness temperature (BT) in the longwave window region and the AIRS viewing angles. In addition to the simulated IR radiances, the surface pressure (extracted from analysis data provided by the National Centers of Environmental Prediction, NCEP) and solar zenith angle are also used as predictors. The sounding retrieval product, obtained at AIRS single FOV resolution, includes temperature, humidity and ozone profiles, as well as surface skin temperature and surface emissivities. The surface IR emissivities are retrieved at 10 IR wavenumber points. Detailed information about the IMAPP AIRS retrieval algorithm under clear skies can be found in *Weisz et al.* [2003; 2006].

From the regression training set ~6200 profiles can be assigned with a CTP between 900 and 200 hPa according to their relative humidity (RH). Out of these ~2160 profiles are assumed to be ice clouds (those with CTP < 450 hPa) whereas ~4010 profiles are assumed to be water clouds (CTP > 400 hPa). Figure 1 displays the locations of the clear profiles, as well as profiles with water clouds and ice clouds.

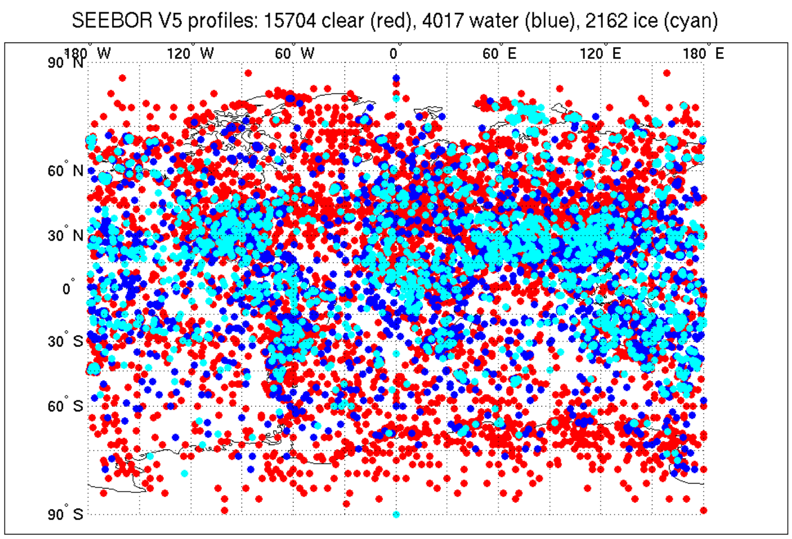

Figure 1. Global distribution of training set profiles. Clear sky pixels, water cloud and ice cloud pixels are indicated as red, blue and cyan dots, respectively.

Cloud optical thickness (COT) values between 0.001 and 2 were assigned randomly to each profile in both classes (water and ice). For ice clouds the effective particle radius (R_e) was computed inserting COT into an equation that is given in *Heymsfield et al.* [2003]. With a random error of 10% added to R_e, a range between 10 and 30 μm was obtained. For water clouds an effective particle radius distributed between 5 to 25 μm was randomly assigned to the profiles. The assignment of COT and R_e to the a profile is similar to *Zhou et al.* [2005], although the CTP assignment is different.

Through joint efforts of the 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 single-scattering properties of ice crystals are derived by assuming aggregates for large particles (>300 μm), hexagonal geometries for moderate particles (50 – 300 μm) and droxtals for small particles (0 – 50 μm). 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 μm. The IR COT for each AIRS channel can be derived from the visible COT. The cloudy radiance for a given AIRS channel can be computed by coupling the clear sky optical thickness and the cloud optical effects. The clear sky optical thickness is derived from the fast radiative transfer model SARTA. Once the cloudy radiances have been calculated, a regression is performed to output two sets of regression coefficients (water and ice). In addition to this classification based on the cloud phase, the viewing angle classification is also applied in the cloudy retrieval process.

A cloud phase detection method based on an IR technique [*Strabala et al., 1994*] is applied to the AIRS BT spectrum for identifying clear, ice clouds, water clouds and mixed phase clouds for a given AIRS footprint. If the pixel is clear, then the clear regression coefficients are applied to the AIRS BT spectrum, and the retrieval is performed as in version 1.3 of the IMAPP AIRS retrieval algorithm. One improvement to the clear sky algorithm involves using emissivity eigenvectors in the regression [*Zhou et al.,* 2001; *Smith et al.,* 2005b], and a hyperspectral emissivity spectrum is simultaneously obtained along with the sounding products; a manuscript on handling hyperspectral emissivities in sounding retrieval is under preparation.

If the pixel is cloudy, then the appropriate set of coefficients is used depending on the cloud phase. If the cloud phase is mixed, then the clouds are treated as ice clouds. If the retrieved cloud optical thickness is less than 1.5 (i.e., optically thin clouds), the sounding parameters are output from the top of the atmosphere down to the surface. In all other cloud cases (i.e., optically thick clouds), the sounding parameters are retrieved down to the cloud top pressure (CTP) level. In addition to temperature, humidity and ozone, COT and CTP are retrieved for every cloudy pixel in a granule.

3. Results and preliminary validation

Nighttime granule 11 on 08 September 2004 was chosen to illustrate the retrieval results. Figure 2 shows the AIRS BT at wavenumber 911 cm^{-1} (top left) and the retrieved cloud phase (top right) for this granule.

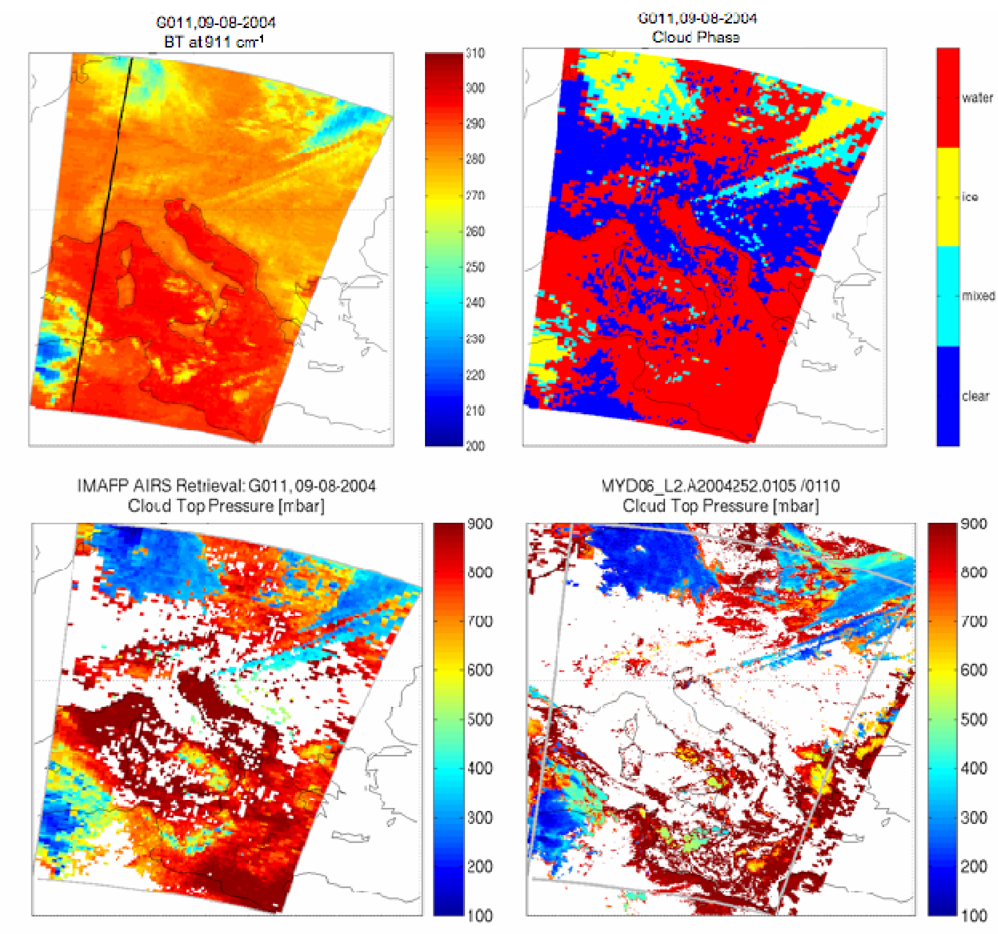

Figure 2. AIRS BT at wavenumber 911 cm^{-1} (top left), retrieved cloud phase (top right), AIRS retrieved CTP (bottom left) and operational MODIS CTP (MYD06) product (bottom right) for granule 11 on 08 September 2004.

The bottom panels of Figure 2 display the CTP retrieved by AIRS (left) and by MODIS (right). It should be mentioned that the operational MODIS (MYD06) CTP product uses sounding profiles from global forecasts, whereas the CTP from AIRS is simultaneously retrieved with the sounding (temperature, moisture and ozone) profiles. The CTP retrievals from AIRS agree very well with the operational MODIS CTP product. Specifically, over the ocean (Mediterranean Sea) the AIRS single FOV algorithm is capable of retrieving very reasonable values for lower clouds, whereas MODIS provides no retrievals due to limited spectral information. The circular feature of the thick cloud in the upper left corner of the granule depicts different cloud heights of mixed and ice clouds as seen in the cloud phase panel of Figure 2.

To assess performance of the sounding retrieval algorithm under cloudy conditions a cross section from north to south (as indicated in the BT panel of Figure 2 as a solid black line) is examined and evaluated by comparing with the ECMWF model analysis (see Figure 3). The ECMWF analysis data has been interpolated horizontally to the AIRS pixels and vertically to 101 pressure levels that are used in the AIRS radiative transfer calculation. The difference in time between the ECMWF analysis and the AIRS measurements is about 70 minutes. The spatial resolution of the ECMWF analysis is 0.5 degrees. As mentioned above, the parameters are only retrieved to the CTP level when optically thick clouds are present. For temperature (top panels of Figure 3) some minor differences can be seen; for example, ECMWF analysis finds colder temperatures between ~170 and 200 hPa for scanline 1 to 45. Nevertheless, the general pattern of the AIRS retrieved temperature field compares favorably with the ECMWF model. Furthermore, relatively accurate temperature soundings are obtained under thin clouds as can be seen in the area beyond scanline 105.

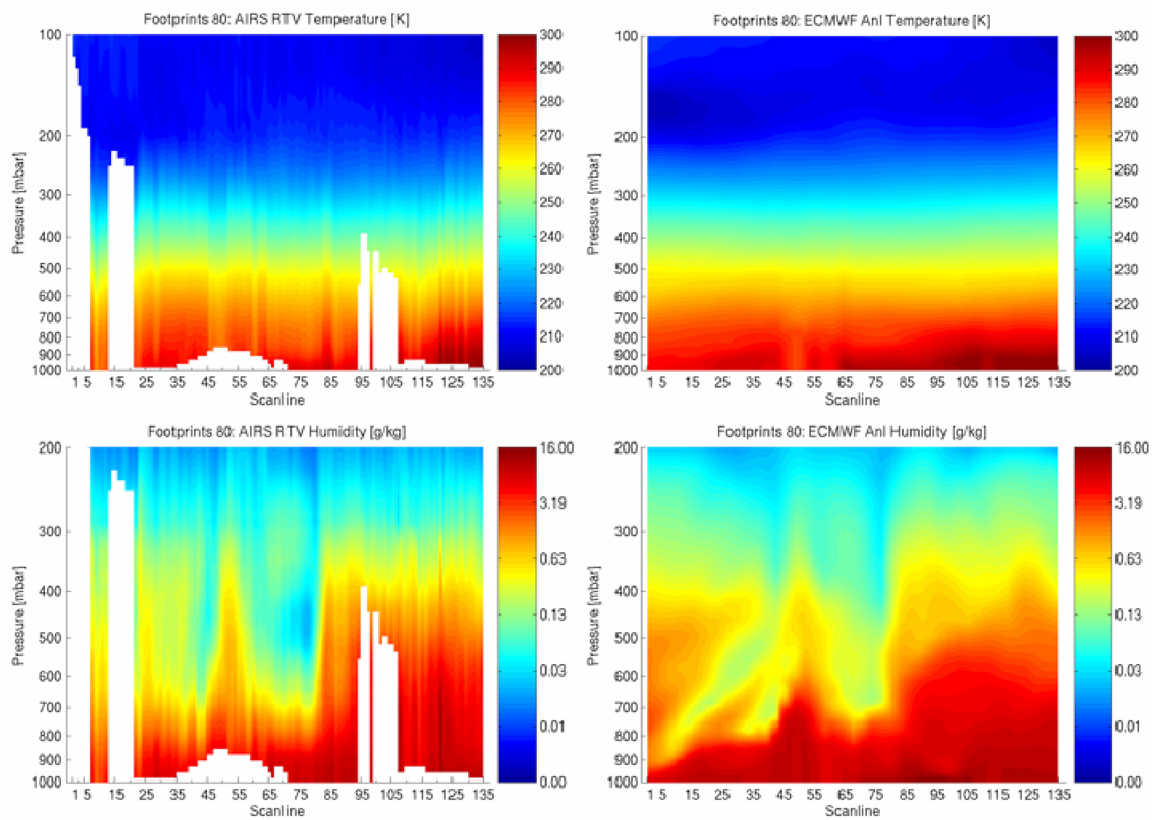

Figure 3. Temperature (top) and humidity (bottom) from the AIRS cloudy sounding retrieval (left) and the ECMWF model analysis (right) for granule 11 on 08 September 2004.

The same inter-comparison between AIRS and ECMWF was conducted for humidity (bottom panels of Figure 3). The AIRS sounding retrieval successfully reproduces the humidity variation shown in the ECMWF model analysis. Again in areas of thin or broken clouds (e.g., between scanlines 7 and 13, and between 105 and 125) the cloudy retrieval achieves very reasonable values, which a clear sky sounding retrieval algorithm would not be able to accomplish.

Root-mean-square errors of the retrieval deviations from the ECMWF fields (not shown) offer further reassurance that the cloudy sounding algorithm is reasonably accurate beneath broken and optically thin clouds. Differences between ECWMF and AIRS are partly caused by the different spatial (horizontally and vertically) resolution and by the difference in time.

It is also worth noting that atmospheric profile retrievals (including ozone) of the layers above the cloud are not affected by the clouds below. That is particularly evident for ozone profiles (not shown), where a clear sky only method yields unrealistic stratospheric ozone values caused by clouds from lower levels. These disturbances are not seen when using the cloudy sounding algorithm.

To further investigate the performance of the sounding retrieval, a co-located radiosonde measurement within granule 11 (southern Italy) was used. The retrieved CTP is 849.8 hPa. For this particular thin cloudy case the temperature profile (not shown) is not significantly affected by clouds when compared with that from the clear sky method. However, for water vapor the improvement is significant when applying the cloudy sounding algorithm. This is illustrated in Figure 4 for relative humidity. The cloudy retrieval captures the atmospheric moisture variation as shown by the radiosonde very well, in particular below the cloud top level where improvements in relative humidity values larger than 10 % can be achieved.

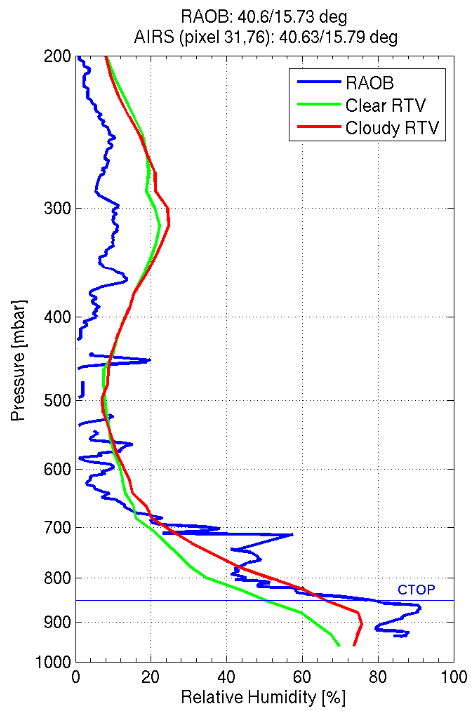

Figure 4. AIRS retrieved sounding profiles (green and red lines refer to the results from the clear sky retrieval and the cloudy retrieval method, respectively) for relative humidity (in percentage from 0 – 100%) compared with one co-located radiosonde measurement (blue). The retrieved cloud top pressure is indicated as a thin blue line.

4. Summary

The probability of having clouds in an AIRS footprint, which is 13.5 km at nadir, is relatively high. An approach to retrieve sounding parameters along with cloud top pressure (CTP) and cloud optical thickness (COT) under cloudy skies is described in this paper. A fast cloudy radiative transfer model accounting for clouds of various phases, cloud particle sizes, and optical thicknesses was used to simulate cloudy radiances representing the regression training set. The simulations are performed for a subset of profiles from the global database with COT and effective particle size randomly assigned to each profile. An eigenvector regression retrieval method is applied to obtain two sets of regression coefficients (one for water clouds and one for ice clouds). The retrieval product includes temperature, humidity and ozone from 0.005 to either the surface for clear skies, and cloudy skies with broken and/or optically thin clouds or to the cloud top level when optically thick clouds are present. AIRS retrieved CTP agrees very well with the operational MODIS (MYD06) product. As for preliminary validation of the sounding products, ECMWF analysis fields were used. The spatial features are well reproduced by the AIRS cloudy sounding profiles. The case study involving a co-located radiosonde measurement further endorses the capability and accuracy of this algorithm.

Future work includes more validation of the current product, sounding improvement for mixed phase clouds, and sounding enhancement by using an iterative physical retrieval scheme at AIRS SFOV resolution. Studies have been conducted on the combination of MODIS and AIRS for cloud property retrieval [Li et al. 2004, 2005a], and cloud clearing [Li et al., 2005b]; a direct sounding approach using MODIS and AIRS will also be investigated. The long-term goal is to apply this methodology to new instruments like IASI and CrIS, and to support the development of other high-spectral IR sounders.

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