RETRIEVAL OF ICE CLOUD MICROPHYSICAL PROPERTIES USING AIRS AND SYNERGY WITH CALIPSO

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Abstract
We present a cloud property retrieval scheme, which is based on a weighted $\chi^2$ method using channels around the 15 micron CO$_2$ absorption band, to determine effective cloud emissivity and cloud pressure. The influence of channel choice, cloud detection, spatial resolution and of assumed atmospheric profiles on the retrieval are discussed. Results for July 2003 and January 2004 are compared to ISCCP and MODIS cloud properties of the same time period, as well as to the cloud climatology of TOVS Path-B. A comparison is made with the CALIOP lidar for August 2006. We developed a cirrus microphysical retrieval scheme, matching spectral emissivity differences retrieved from AIRS with simulated ones from optical crystal properties using the 4A radiative transfer model coupled with DISORT.

INTRODUCTION

Cirrus clouds have been identified as one of the atmospheric components which significantly influence the radiative processes in the atmosphere. They are globally distributed and are characterized by a large spatial coverage, about 30 % of the earth (Wyile and Menzel 1999; Stubenrauch et al. 2006a). The complex microphysical characteristics of thin ice clouds encounter difficulties to assess correctly their radiative properties. Indeed, many climate models still represent ice crystal as hexagonal columns in the computation of cirrus radiative properties. Introducing more realistic ice crystal shapes and sizes leads to variation of cirrus albedo (Stubenrauch et al. 2007) and significant changes in the annual mean of radiative fluxes at the top of atmosphere, up to 10 and 25 Wm$^{-2}$ for emitted longwave and reflected shortwave, respectively (Kristjánsson et al. 2000).

In situ measurements of cirrus are relatively scarce because these clouds are located at high altitudes. Then, determination of cirrus cloud properties on a global scale requires the use of space-based remote sensing. King et al. (2003) and Platnick et al. (2003) described an approach using visible and near-infrared (IR) spectral signatures to infer cloud properties (optical thickness and effective particle size) from the Moderate Resolution Imaging Spectroradiometer (MODIS) on Terra and Aqua platforms. Other algorithms have been applied to different satellite sensors such as the Advanced Very High Resolution Radiometer (AVHRR) (Ou et al. 1999; Minnis et al. 1993), the Along Track Scanning Radiometer-2 (ATSR-2) (Baran et al. 2003) or Polarization and Directionality of the Earth’s Reflectances (POLDER) (Doutriaux-Boucher et al. 2000). However, such approaches are limited to daytime application because solar illumination is necessary. Moreover, imaging radiometers can not always detect optically thin ice clouds, especially when these are located above a thicker and lower cloud (Stubenrauch et al. 1999a, Wei et al. 2004).

Microphysical properties of semi-transparent ice cloud can be reliably studied with high resolution infrared sounders (Bantges et al. 1999, Stubenrauch et al. 1999b; Huang et al. 2004; Chung et al. 2000). A global climatology of $D_e$ and ice water path (IWP) of semi-transparent cirrus has been established from the TIROS-N Operational Vertical Sounder (TOVS) Path-B for the period 1987-1991, using cirrus emissivities at 8 and 11 microns (Stubenrauch et al. 1999b). An uncertainty study by Rädel et al. (2003) has shown that $D_e$ can be overestimated by up to 25% in the case of underlying
water clouds or partial horizontal cloud cover. Cloud vertical distribution with high spatial resolution is necessary to refine these results.

Collocated data available from different satellites composing the A-Train (Schoeberl et al. 2002) represent a convenient opportunity to undertake finer studies on semi-transparent ice clouds. Operational since May 2003, the Atmospheric Infrared Sounder (AIRS) on AQUA has a high spectral resolution permitting accurate high clouds properties retrieval. This study can be completed by a geometrical description of clouds with a high vertical resolution, in particular the number of layer and geometrical cloud thickness. The Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) on the CALIPSO satellite is able to provide such information since June 2006.

We present a cloud property retrieval method determining cloud pressure and spectral emissivity from AIRS radiances at a spatial resolution of 13.5 km (at nadir), which is based on the TOVS retrieval (Stubenrauch et al. 1999c). For the retrieved semi-transparent cirrus we propose a method to estimate effective ice crystal diameter $D_e$, ice water path IWP and ice crystal shape (hexagonal columns or aggregates) from spectral emissivity differences. Advantages of CALIOP data to refine these results are also discussed.

CLOUD PROPERTIES RETRIEVAL FROM AIRS

The AIRS instrument

The AIRS sounds the atmosphere in three spectral bands (3.74-4.61 micron, 6.20-8.22 micron and 8.80-15.40 micron) using 2378 channels (Chahine et al. 2006). 324 channels optimal for sounding have been selected to be provided to the different AIRS Science Team members. The spatial resolution of these measurements is 13.5 km at nadir. Nine AIRS measurements (3x3) correspond to one AMSU footprint. AIRS L2 atmospheric profiles are retrieved from cloud-cleared AIRS radiances (Chahine et al. 2001) within each AMSU footprint (Susskind et al. 2003). They provide temperature and water vapour mixing ratio at 28 pressure levels from 0.1 hPa to the surface. A validation with radiosonde data (Divakarla et al. 2006) has shown that the accuracy is close to 1 K in 1 km layers for temperature and better than 15% in 2 km layers for water vapour.

The cloud retrieval algorithm

For the 324 AIRS channels, at all viewing zenith angles, clear sky radiances and cloudy radiances at 30 pressure levels have been simulated using about 2000 representative atmospheric temperature and humidity profiles and the Automatized Atmospheric Absorption Atlas (4A) radiative transfer model (Scott and Chédin 1981). These 2000 atmospheric situations have been classified into five air masses (from tropical to polar) in the Thermodynamic Initial Guess Retrieval (TIGR) dataset (Chevallier et al. 1998) which also archives the simulated AIRS radiances. The simulations over different land surface types have been performed using IR surface emissivities over land (Péquignot 2006). Systematic biases between observed and simulated brightness temperatures due to the radiative transfer model and to instrument calibration are removed by applying corrections to the measured AIRS brightness temperatures. At present, these corrections have been computed only during night for the latitude band from 30°N to 30°S over ocean. Therefore the cloud property retrieval has so far only been applied to the AIRS measurements at 0130 (LST) and to these regions.

The cloud property retrieval is based on a weighted $\chi^2$ method (Stubenrauch et al. 1999c), computing the effective cloud emissivity $\varepsilon$ as in Eq. 1 at different wavelengths $\lambda_i$ and assuming 30 different cloud heights $p_k$ (from surface to 106 hPa). $I_m$ is the measured radiance, $I_{clr}$ is the clear sky radiance and $I_{cld}$ is the radiance emitted by a homogenous opaque single cloud layer.

$$\varepsilon(p_k, \lambda_i) = \frac{I_m(\lambda_i) - I_{clr}(\lambda_i)}{I_{cld}(p_k, \lambda_i) - I_{clr}(\lambda_i)} \quad \text{for } i = 1, N$$
Minimizing $\chi^{'2}$ in Eq. 2 leads to a coherent answer in effective emissivity $\varepsilon$ and the corresponding pressure $p_{cld}$ of the cloud. Empirical weights $W^{'2}(p, \lambda)$ reflect the effect of the brightness temperature uncertainty on the cloudy and clear radiances at each cloud level within the air mass class closest to the observation (Stubenrauch et al. 1999c). When the $\chi^{'2}$ method does not provide a physical value of $\varepsilon (> 2$ or $=0)$, the scene is reset to clear sky.

The accuracy in $p_{cld}$ is limited to the pressure level step of about 35 hPa in the simulations.

$$\chi^{'2}(p_k) = \sum_{i=1}^{N} \left[ (I_{icld}(p_k, \lambda_i) - I_{iclr}(\lambda_i)) \cdot \varepsilon(p_k) - (I_m(\lambda_i) - I_{iclr}(\lambda_i)) \right] * W^{'2}(p_k, \lambda_i) \quad (2)$$

The clear sky radiance used in Eqs. 1 and 2 corresponds to the clear sky situation of the TIGR profiles closest to the retrieved atmospheric profiles. Therefore the AIRS L2 atmospheric profiles (version 4) have been combined with the AIRS radiance measurements and have then been interpolated to the 4A pressure levels. A proximity recognition between the retrieved atmospheric profiles (21 temperature levels between surface to 106 hPa and 8 water vapour layers between surface and 162 hPa) and the TIGR profiles leads to the TIGR profile closest to the observation. The clear and cloudy radiances in Eqs. 1 and 2 are averages, using TIGR profiles for which the difference to the AIRS L2 data in temperature and water vapour, summed over all levels and layers, lies within 5% of the minimum difference. The difference in water vapour is weighted by a factor 0.5 when added to the temperature difference. The cloud property retrieval is applied to all cloudy AIRS spots.

Differences between spectral emissivities at 8 and 12 $\mu$m ($\Delta \varepsilon_{12-8}$) and emissivity at 12 $\mu$m ($\varepsilon_{12}$) have been analyzed. We reset to clear-sky every case presenting non-physical spectral emissivity differences. Table 1 lists these conditions, they constitute an a posteriori cloud detection.

<table>
<thead>
<tr>
<th>Cloud level</th>
<th>Cases kept as cloudy</th>
</tr>
</thead>
<tbody>
<tr>
<td>All clouds</td>
<td>$\varepsilon_{12} &gt; 0.03$</td>
</tr>
<tr>
<td>High: $p_{cld} &lt; 440$ hPa (thin cirrus only)</td>
<td>$\Delta \varepsilon_{12-8} &gt; 0$</td>
</tr>
<tr>
<td>Midlevel: $440 &lt; p_{cld} &lt; 680$ hPa</td>
<td>$-0.02 &lt; \Delta \varepsilon_{12-8} &lt; 0.20$</td>
</tr>
<tr>
<td>Low: $p_{cld} &gt; 680$ hPa</td>
<td>$-0.20 &lt; \Delta \varepsilon_{12-8} &lt; 0.20$</td>
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Table 1: spectral emissivity differences ranges considered as cloudy cases in function of cloud pressure

We have chosen AIRS channels corresponding closely to the five channels used in the TIROS-N Operational Vertical Sounder (TOVS) Path-B cloud retrieval (Stubenrauch et al. 1999c): 87, 102, 99, 126 and 136 (out of the 324 channels). The contribution of these channels in measuring the atmosphere is shown in figure 1 as the derivative of the transmission function and pressure.

Figure 1: Weighting functions of six AIRS channels (out of the 324 channels) used in the cloud property retrieval.
Comparisons with other datasets

Cloud properties are given by different satellite climatologies: the International Satellite Cloud Climatology Project (Rossow and Schiffer 1999) makes use of imagers on geostationary and polar orbiting NOAA satellites from 1983 up to now. Among the many variables we use monthly mean cloud amount and cloud pressure as well as high, midlevel and low cloud amount (the latter three determined during daytime) from July 2003 and January 2004 for the comparison with AIRS.

The MODIS instrument onboard the NASA Terra and Aqua satellites provide cloud properties (King et al. 2003, Platnick et al. 2003) since 2000. We use MODIS MYD08-M3 (from Aqua observed at 13h30 LST) monthly averages during daytime of cloud amount and cloud pressure. These data were acquired using the GES-DISC Interactive Online Analysis Infrastructure (Giovanni) as part of the NASA Goddard Earth Sciences Information Services Center (DISC).

The TOVS Path-B climatology (Scott et al. 1999, Stubenrauch et al. 2006a) is established from TIROS-N Operational Vertical Sounder measurements onboard the polar orbiting NOAA satellite and covers at present the period from 1987 to 1995. Recently this dataset has been reanalyzed. The results of this reanalysis are presented here.

The AIRS L2 retrieved products (version 4) provide in addition to the atmospheric profiles also effective cloud amount and cloud pressure (Susskind et al. 2003).

Figure 2: Geographical maps of pcld for July (left) and January (right) using the datasets AIRS chi2, TOVS Path-B, ISCCP, MODIS, and AIRS L2 described above.

Figure 2 presents geographical maps of monthly averaged pcld for July 2003 (left) and January 2004 (right). The results of our AIRS retrieval (further called “AIRS chi2”) are presented at the top of this figure. Below are those as provided by TOVS Path-B, ISCCP, MODIS, and AIRS L2. The geographical cloud structures of AIRS chi2 and TOVS Path-B are quite similar, with the Intertropical Convergence Zone (ITCZ) appearing as a band of high clouds around the equator, shifting about 10° from July to January towards the summer hemisphere. The Infrared Sounders (AIRS and TOVS) are more sensitive to cirrus clouds than ISCCP. Considering MODIS and AIRS L2 average pcld, one observes that in general MODIS provides larger monthly mean cloud pressures and AIRS L2 much smaller cloud pressures. With MODIS the ITCZ is less apparent than with AIRS chi2, TOVS Path-B and even
ISCCP. Monthly \( p_{\text{cloud}} \) averages of AIRS L2 do not exceed 700 hPa. Since the AIRS L2 cloud properties are very different from the ones of the other datasets we will not consider them further for comparison. We note that version 5 of AIRS L2 products, available since July 2007, do not include \( p_{\text{cloud}} \) anymore.

Figure 3 shows cloud amount for high and low clouds (see table 1) as function of latitude for different datasets over ocean. ISCCP c corresponds to a climatology averaged from 1987 to 1995 to compare with the TOVS Path-B climatology. The curves have similar shapes. Retrievals from infrared sounders (AIRS and TOVS) show more high clouds than those of visible imagers (ISCCP). However, cloud amount from TOVS Path-B and TOVS Reanalysis are always slightly higher than from the AIRS retrieval, especially for high clouds. This seems to be linked to a different method of proximity recognition between retrieved atmospheric profiles and those of the TIGR bank: In the TOVS retrieval this was done using the clarified brightness temperatures, whereas in the AIRS retrieval the atmospheric profiles are directly compared. The effect is still under investigation.

**Sensitivity study**

We have investigated the effect of channel choice, temperature profile, spatial resolution cloud detection, spatial resolution, and choice of atmospheric profiles on the retrieved effective cloud amount and on \( p_{\text{cloud}} \). Therefore we made the corresponding changes in the retrieval procedure. The results are synthesized in figure 4.

**Effect of channel choice**

We have examined if adding channels to the \( \chi^2 \) method would affect the retrieved cloud properties. Figure 1 shows that channel 88 would slightly improve the vertical resolution in the middle to upper
troposphere. However, cloud properties retrieved by using six (or even seven) channels are very similar to those using the initial five channels (see Stubenrauch et al. 2006b).

**Effect of temperature profile**

In the retrieval we use AIRS L2 temperature profiles to compute clear sky and opaque cloud radiances giving the effective emissivity $\varepsilon$. By using the TIGR temperature profiles the amount of low clouds decreases by maximal 10%. There is no significant effect for high cloud amount.

**Effect of spatial resolution**

We have investigated the effect of spatial resolution on the cloud property retrieval. For this study we have averaged the AIRS radiances over the spots within each AMSU footprint (or ‘golf ball’ consisting of 9 AIRS spots). Then the cloud property retrieval had been applied to the radiance averages. Thus we compare a spatial resolution at nadir of 13 km to one of about 40 km. In general, spatial resolution has only a small effect on these cloud amounts. However, it is interesting to note that in the region of the ITCZ the better spatial resolution leads to 5% less HCA. Golf-ball resolution shows a higher LCA outside the ITCZ. Differences in cloud amount between two resolutions indicate the level of spatial heterogeneity of cloud coverage.

![Graphs showing high and low cloud amount over ocean for different latitudes and months.](image)

*Figure 4:* High cloud amount (HCA) and low cloud amount (LCA) over ocean for July 2003 (left) and January 2004 (right) as function of latitude.

**Effect of proximity recognition**

The curve labeled 2-lay prof. shows cloud amount with a different treatment to obtain the TIGR atmospheres which are used to compute the clear sky and opaque cloud radiances in equations 1 and
2. It corresponds to the case when the atmospheric profile is constructed out of TIGR atmospheric profiles which have been found to be closest to the AIRS L2 profiles independently in two different vertical layers (upper layer from 420 hPa to TOA, lower layer from 420 hPa to surface), increasing the probability to reduce the vertically averaged difference between TIGR and AIRS L2 profiles. This feature does not have a significant effect on high clouds. A strong difference is visible for low clouds in July out of the ITCZ.

**Effect of cloud detection**

We used an a posteriori cloud detection resetting to clear sky each event presenting non-physical values for the spectral emissivity difference between 8 and 12 µm (see above). We compare this detection with the multispectral cloud detection V8.1. It has been developed, making simultaneous use of the AMSU microwave sounder, to discard cloudy scenes for CO₂ retrieval in the upper troposphere (C. Crevoisier 2004) and for aerosol retrieval in the lower troposphere (Pierangelo 2005). Low cloud amount is much higher for V8.1 cloud detection, because for partly cloudy scenes, cloud presence is overestimated.

**Preliminary comparison with CALIPSO**

**The CALIOP lidar**

CALIOP is a two-wavelength polarization-sensitive lidar that provides high-resolution vertical profiles of aerosols and clouds. CALIOP utilizes three receiver channels: one measuring the 1064 nm backscatter intensity and two channels measuring orthogonally polarized components of the 532 nm backscattered signal. (about 330 m, every 1000 km). CALIPSO satellite follows AIRS with a time lag of 1 min. 15 s.

**Pclld comparisons**

Figure 5 shows average top and base pressure of the highest clouds in August 2006 viewed by CALIOP. pcld from AIRS chi2 present similar concerning geographical structures. Spatial resolution of lidar observations map appear low because the thin CALIOP field of view (333 m every 200 km) performs less observations than the infrared sounder.
MICROPHYSICAL PROPERTIES OF SEMI-TRANSPARENT CIRRUS RETRIEVAL METHODE

Cirrus emissivity simulation

The sensitivity study in the previous section showed that the AIRS cloud retrieval algorithm presents a relative robustness, especially high clouds. Spectral emissivities between 8 and 12 µm allow us to retrieve microphysical properties. Indeed, the spectral slope of this region depends on the ice crystal effective size and shape, as well as the ice water path (Stubenrauch et al. 1999b; Rädel et al. 2003). However, relationships between $D_e$, IWP and emissivity differences are complex and non-linear. Consequently, we need to simulate these emissivity differences for a large panel of values for $D_e$ (7 to 90 µm) and IWP (1 to 130 g cm$^{-2}$). Such simulations of radiances emitted by semi-transparent cirrus can be made only after introducing single scattering properties of ice crystals (extinction coefficient, single-scattering albedo and asymmetry factor) into a radiative transfer model.

We based our present work on effective ice crystal size retrieval undertaken from TOVS Path-B by Rädel et al. (2003). Therefore, we simulate cirrus spectral emissivities following similar hypotheses as those authors in order to assess AIRS abilities for micro-physical properties retrieval. Our simulations used single scattering properties of ice crystals computed by Baran (2003). Crystals are assumed to be hexagonal columns or aggregates of hexagonal columns with a bimodal size distribution, with an exponential behaviour for small crystals and a $\Gamma$ distribution for larger ice crystals. The line-by-line radiative transfer model 4A has been chosen because of the high spectral resolution of AIRS. 4A has been coupled with the scattering model DISORT (Pierangelo 2005). Atmosphere has been considered without water vapor or aerosol with a constant temperature gradient of -6.5 K.km$^{-1}$. Cloud simulated is a 1-km thick semi-transparent cirrus ($0.3 < \varepsilon < 0.85$) located at 10-km height, ensuring a total ice phase (cloud temperature: $T_{cld} < 253$ K). Emissivities have been simulated so far at nadir only. Results of these simulations have been stored in two different look-up tables, one for each crystal shape (column or aggregate). Figure 6 shows simulated spectral emissivity differences for a constant IWP value (30 g.cm$^{-2}$) and three different representative $D_e$ (20, 40 and 60 µm) for the two crystal shapes presently studied.

This figure shows clearly the effect of $D_e$ in the spectra. Crystal shape can be distinguished in the spectral region between 10 and 11 µm. Indeed, for a constant $D_e$, the emissivity difference spectrum shows clearly two distinct slopes, as noted in the figure for $D_e = 20$ µm (red and blue dotted lines).

Matching between observed and simulated spectral emissivities

The crystal shape, $D_e$ and IWP retrieval is made by minimizing the difference between simulated spectral emissivity and AIRS retrieved emissivity. In a first step, we retrieved $D_e$ and IWP with a $\chi^2$ minimization (equation 3) for each shape separately (column and aggregate).
\[ \chi_{\text{shape}}^2(D_e, \text{IWP}) = \sum_{i=1}^{N} \left[ \epsilon(\lambda)_{\text{obs}} - \epsilon_{\text{shape}}(D_e, \text{IWP}, \lambda)_{\text{sim}} \right]^2 \ast W_{\text{shape}}^2(D_e, \text{IWP}, \lambda) \]  

(3)

\[ \epsilon(\lambda)_{\text{obs}} \text{ is the AIRS retrieved emissivity and } \epsilon(\lambda)_{\text{sim}} \text{ is the simulated one. } W_{\text{shape}}(D_e, \text{IWP}, \lambda) \text{ represents the standard deviation of } \epsilon(D_e, \text{IWP}, \lambda)_{\text{sim}}. \]  

5 channels are used among the 15 appearing in figure 4.

In a second step, we compute a slope for both shapes:

\[ S_{\text{shape}} = \frac{\epsilon_{\text{shape}}(\lambda_1)_{\text{sim}} - \epsilon_{\text{shape}}(\lambda_2)_{\text{sim}}}{\lambda_2 - \lambda_1} \]  

(4)

with \( \lambda_1=10.2 \) and \( \lambda_1=10.9 \, \mu\text{m} \). We compute also the slope for retrieved emissivities \((S_{\text{obs}})\) at the same wavelengths. Then, the most probable shape is the one giving the minimum value to \(|S_{\text{shape}} - S_{\text{obs}}|\).

First results are currently under interpretation.

CONCLUSION

First results of the AIRS cloud retrieval using a weighted \( \chi^2 \) method on the radiances around the 15 \( \mu\text{m} \) CO\(_2\) absorption band have been presented during night in a latitude band between 30°N and 30°S. The cloud properties retrieved from AIRS are similar to those from the TOVS Path-B climatology. A coarser spatial resolution leads to about 5% higher HCA in the ITCZ. The ITCZ is much better apparent with AIRS, TOVS and ISCCP than with MODIS data. The AIRS L2 data show in general average cloud pressures which are much lower than the other datasets. Sensitivity studies on AIRS retrieval have shown that this algorithm remains robust for high clouds. In particular, our \textit{a posteriori} cloud detection appears as a valuable tool confirming that no external cloud detection is needed for the AIRS cloud retrieval. Adding more channels in the cloud property retrieval did not affect the results, probably because most of the information is already contained in the five channels which sound the atmosphere. The effect of surface emissivities over land and the effect of proximity recognition of the atmospheric profiles are still under investigation. We developed a microphysical properties retrieval method using spectral emissivities between 8 and 12 \( \mu\text{m} \). A comparison with TOVS data shows similarities, but the retrieved values from AIRS seem to be higher. The retrieval is still under development. Collocated CALIPSO measurements will help to obtain a precise knowledge on the cloud vertical structure.

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