I. Introduction

Cirrus cover about 30% of the globe and have been identified as one of the most influential atmospheric components on the Earth's radiative budget. In order to improve the characterization of cirrus clouds within Global Circulation Models, modelers need global observations of cloud properties. Due to their complex microphysical characteristics (non-spherical ice crystals of various shapes and sizes) their physical and radiative properties are still not completely understood. Because of its high spectral resolution, the Atmospheric InfraRed Souder (AIRS) onboard the NASA Aqua satellite is used for the identification of cirrus, during day and night. Bulk microphysical properties are determined for semi-transparent ice clouds. The retrieval is based on the spectral difference of cirrus emissivity in the domain between 8 and 12 micron.

After a sensitivity study on hypotheses used in the retrieval, we present bulk microphysical properties (IWP, effective diameter De and occurrence of dominant ice crystal shape) derived from AIRS from 2003 to 2009. We also study these properties in relation with other atmospheric properties. Therefore, AIRS has been colocated with the spaceborn lidar CALIOP of the CALIPSO mission and the Cloud Profiling Radar (CPR) of the CloudSat mission. These active instruments deliver accurate information on cloud layers and their geometrical thickness.

II. Methodology

A spectral information is needed to retrieve both De and IWP

A spectral information is needed to retrieve both De and IWP

The use of one emissivity leads to multiple solutions

A spectral information is needed to retrieve both De and IWP

Insensitive for optically thin and thick ice clouds

Maximum of sensitivity for IWP < 120 g/m²

De < 90 µm

IWP < 120 g/m²

- Applied to High clouds : p<sub>irm</sub> < 440 hPa
- Ice particles : T<sub>irm</sub> < 260K
- S-T clouds : 0.2 < ε<sub>p</sub> < 0.85
- 0.2 < T<sub>vis</sub> < 1.9
- 0.4 < T<sub>vis</sub> < 3.8

- Sensitivity up to : De < 90 µm

Simulated De as function of IWP for different values of effective cloud emissivity

Simulated spectral cirrus emissivity difference between 8 and 12 µm as function of cirrus emissivity at 12 µm, for different values of De (7,10, 15, 20, 30, 40, 60, 80 µm from top to bottom)

Simulated normalized spectral emissivity difference as function of wavelength, separately for ice crystals in the form of aggregates (full lines) and hexagonal columns (broken lines). As example, we present results for two IWP's and three De's. 17 initial AIRS channels are indicated; the final channel selection of six channels evenly distributed (two around 9 µm and two around 12 µm) is represented as black squares. Additional channels did not improve the results, as has already been shown by (Kahn et al. 2004 in ACP).
III. Sensitivity study

Assumptions made for the simulation of Cirrus emissivities
- On the ice crystals:
  - Randomly oriented ice crystals, distributed according to a bimodal size distribution (Mitchell et al. 1996)
  - Single scattering properties ($\beta_{\text{scat}}, \omega_0, \mu$) of ice aggregates (Baran et al. 2003)
- On the cloud:
  - Vertically homogenous single-layer cloud
  - Cloud height: $Z_{\text{cld}} = 10\text{km}$
  - Vertical extent $\Delta h_{\text{cld}} = 1\text{km}$
  - Surface temperature: $T_s = 300\text{K}$
  - Lapse rate: $6.5\text{K/km}$
- Correlation between bulk microphysical properties and cloud temperature
  - Two regimes are apparent:
    - $T_{\text{ice}} < 230\text{K}$: De and IWP increase with increasing $T_{\text{ice}}$
    - $T_{\text{ice}} > 230\text{K}$: slight decrease of De and IWP,
      fraction of hexagonal columns among the ice crystals strongly increases
  - $\Rightarrow$ indication that cirrus clouds contain only ice when $T_{\text{ice}} < 230\text{K}$, mixed phase clouds for $T_{\text{ice}} > 230\text{K}$
  - We only consider cirrus with Tcld $< 230\text{K}$ (~50% of semi-transparent cirrus)

IV. Applicability of the retrieval

- Six AIRS spectral cirrus emissivities are compared to LUT's simulated for ice crystal aggregates and hexagonal columns. The retrieval provides De, IWP and corresponding shape which fit best the observations.
- Correlation between bulk microphysical properties and cloud temperature (continued)
- Conclusions very similar to TOVS sensitivity study (Rädel et al. 2003)
- AIRS uncertainties smaller (+3%) concerning horizontal heterogeneity because of better spatial resolution (13km instead of 100km, not shown)
- Small differences between SSP's of Baran (aggregates and Mitchell (polycristals)
- No difference between single-layer and multi-layer clouds (not shown)

V. Geographical Distributions

- Tropics:
  - Most high clouds in Intertropical Convergence Zone, shifting towards summer hemisphere.
  - Semi-transparent ice clouds surrounding convective systems these regions also contain more multi-layer situations
- Midlatitudes:
  - More high clouds in winter than in summer (larger difference in SH)
  - Difference larger when considering only high semi-transparent ice clouds
  - More single layer ice clouds in summer than in winter
  - More single layer ice clouds over land than over ocean

<table>
<thead>
<tr>
<th>(De$^{\text{obs}}$ − De$^{\text{mod}}$)</th>
<th>(IWP$^{\text{obs}}$ − IWP$^{\text{mod}}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Thin clouds}$</td>
<td>$\text{Thick clouds}$</td>
</tr>
<tr>
<td>15µm</td>
<td>60µm</td>
</tr>
<tr>
<td>$\text{SSP}(\text{Baran} \rightarrow \text{Mitchell})$</td>
<td>$\text{SSP}(\text{Baran} \rightarrow \text{Mitchell})$</td>
</tr>
<tr>
<td>$\Delta_{\text{De}} =$ 1%</td>
<td>$\Delta_{\text{IWP}} =$ 1%</td>
</tr>
<tr>
<td>$\Delta T_{\text{cld}} =$ 10K</td>
<td>$\Delta T_{\text{cld}} =$ 10K</td>
</tr>
<tr>
<td>$\Delta_{\text{De}} =$ 1%</td>
<td>$\Delta_{\text{IWP}} =$ 1%</td>
</tr>
<tr>
<td>$\Delta_{\text{De}} =$ 1%</td>
<td>$\Delta_{\text{IWP}} =$ 1%</td>
</tr>
<tr>
<td>Lapse Rate (6.5 − 13.5°C/km)</td>
<td>Lapse Rate (6.5 − 13.5°C/km)</td>
</tr>
</tbody>
</table>

Compilation of uncertainties sources and their influence on the retrieval of the mean ice crystal size
VII. Comparison with GEWEX data base

Correlations between bulk microphysical properties and cloud effective emissivity over the period 2003-2009 over ocean (right) and over land (left).

Correlations between bulk microphysical properties and cloud apparent thickness over ocean (right) and land (left), collocated AIRS-Calipso data 2007-2008.

IV. Correlations

- Retrieval sensitive for $0.2 < e_c < 0.85$
- De increases with increasing emissivity
- Strong correlation between IWP and effective emissivity as expected
- Optically thick ice clouds contain more aggregates than optically thin ice clouds
- Weaker correlations in South midlatitudes in summer

Correlations between bulk microphysical properties and cloud effective radius over 2003-2009. From top to bottom, cloud emissivity, ice water path, effective radius and dominating shape.

Further investigations necessary

- De increases with increasing apparent geometrical thickness, especially in South midlatitudes
- IWP increases with increasing apparent geometrical thickness, stronger correlations in the midlatitudes than in the tropics (probably linked to different climate regimes, fronts and anvils)
- More columns in geometrically extended cirrus in tropics, nearly no correlation in midlatitudes (as above probably linked to different climate regimes, fronts and anvils)
- IWP strongly correlated to emissivity (see above)

Bulk microphysical properties over 2003-2009. From top to bottom, cloud emissivity, ice water path, effective radius and dominating shape.