Co-workers:

Reinhold Spang, Lars Hoffmann, Karina Arndt, Sabine Griessbach, Karlheinz Nogei (1)
Michael Höpfner, Gabi Stiller (2)
Richard Siddans, Alison Waterfall (3)
Anu Dudhia, Jane Hurley, Don Grainger (4)
John Remedios, Harjinder Sembhi (5)
ESA: Claus Zehner and Olivier Leonard
Outline

• Motivation

• Overview and project status

• Cloud Scenario Database

• Detection, Macro-Retrieval, Classification, Micro-Retrieval

• Validation Activities

• Summary & Outlook
Limb IR emission observation of clouds

• retrieval of cloud parameter is still a challenging task
• extremely sensitive measurements of optically thin and ultra-thin cirrus clouds
• physics behind these clouds, their impact on the radiation budget or the water entrance into the stratosphere are not well understood

• Sensors: ISAMS, CLAES on UARS, CRISTA-SPAS, and more recent: MIPAS/Envisat (first long record, pole covering, but no cloud products)

The need for:
• Reference radiative transport model spectra
• Effective cloud detection and classification methods
• Fast algorithms for operational products / processing of long record

Major topic of the study:
- Explore the capabilities to retrieve cloud parameters
- Develop a time efficient cloud prototype processor (less than 1 hour processing time per orbit => option: processing of full MIPAS record)
- Geophysical Validation of the processor retrieval products
Overview Implementation of the Study

1. **Scientific analysis** and assessment with algorithm development and compilation of a large reference spectra database is **finalised**

2. **Processor chain** of cloud detection, type determination/classification and retrieval of microphysical parameters is **under construction**

---

**Flowchart MIPclouds Processing**

- **Phase 1**
  - Definition of Cloud Scenarios
  - Optimise Colour Ratios
  - MODELS
    - Database of cloud spectra (+ Jacobians)
  - Determine Classes
  - Determine Retrieval Parameter
  - Product Validation

- **Phase 2**
  - L1B, CR
    - Macroscopic Retrieval Parameter
    - Classification
    - PSC/troposphere
    - Type 1, Type 2, Type 3, Type N
    - Reff / Vol. Dens.
    - Microphysical Retrieval Parameter
Cloud Scenario Database

Volume densities \((0.1 - 10^6 \mu m^3/cm^3)\)
Radius \((PSC: 0.1-10\mu m, \text{Cirrus: 4-90\mu m})\)
Limb Ice Water Path \((\text{e.g. cirrus } 10^{-2} \text{ up to } 10^5 \text{ g/m}^2)\)
Ice water content \((10^{-6} \text{ up to } 1 \text{ g/m}^3)\)
Various geometries \(>320,000 \text{ spectra}\)
Various Compositions \((\text{NAT, STS, ice, Cirrus, Liquid, Aerosol})\)

Cloud thickness: 0.5 – 4 km

Total of 137 cm\(^{-1}\)

Models:
- KOPRA (FZK): single scattering, CSDB
- FM2D/SHDOM (RAL): for validation, reference
- RFM (OXF): non-scattering
# Parameter of Interest

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Comment on validation method, errors, etc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cloudiness flag</td>
<td>cf</td>
<td>status flag for each spectrum 1/0</td>
</tr>
<tr>
<td>Cloud occurrence frequencies</td>
<td>COF</td>
<td>statistical means: SM (e.g. zonally, seasonally)</td>
</tr>
<tr>
<td>Cloud Top Height</td>
<td>CTH</td>
<td>SM, BTR</td>
</tr>
<tr>
<td>Cloud Top Temperature</td>
<td>CTT</td>
<td>SM, BTR</td>
</tr>
<tr>
<td>Cloud Extinction</td>
<td>CEX</td>
<td>SM, CM</td>
</tr>
<tr>
<td>Cloud Base Height</td>
<td>CBH</td>
<td>SM, BTR</td>
</tr>
<tr>
<td>Cloud Top Pressure</td>
<td>CTP</td>
<td>SM, BTR</td>
</tr>
<tr>
<td>Cloud Classification</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stratospheric Cloud Types:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Nitric Acid Trihydrate</td>
<td>NAT</td>
<td>CM, BTR for all types</td>
</tr>
<tr>
<td>- Sulfuric Ternary Solutions</td>
<td>STS</td>
<td>CM, BTR for all types</td>
</tr>
<tr>
<td>- Ice</td>
<td>ICE</td>
<td>CM, BTR for all types</td>
</tr>
<tr>
<td>- Aerosol</td>
<td>AER</td>
<td>CM, BTR for all types</td>
</tr>
<tr>
<td>Cloud types in the free troposphere and UTLS:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Cirrus / Ice clouds</td>
<td>CirC</td>
<td></td>
</tr>
<tr>
<td>- Liquid</td>
<td>LiqC</td>
<td></td>
</tr>
<tr>
<td>- Aerosol</td>
<td>AerC</td>
<td></td>
</tr>
<tr>
<td>Area Density Path</td>
<td>ADP</td>
<td>BTR; along the limb path;</td>
</tr>
<tr>
<td>(*) limb Ice/Liquid Water Path respectively Vol. Density Path</td>
<td>IWP / LWP VDP</td>
<td>BTR, (CM); quantities along the limb path</td>
</tr>
<tr>
<td>(*) limb Ice/Liquid Water Content or Volume Density respectively</td>
<td>IWC / LWC VD</td>
<td>BTR, SM, (CM); only estimates available</td>
</tr>
<tr>
<td>Effective and/or mean radius</td>
<td>$R_{\text{eff}} / R_{\text{mean}}$</td>
<td>BTR, SM, (CM); only course size bin retrieval</td>
</tr>
</tbody>
</table>

**SM**: statistical means (zonally or seasonally means for various altitude bins), **CM**: coincidence method for the validation dataset, **BTR**: blind test retrievals.
Detection

  - MW Optimisation for CI-color ratios
  - CI-Threshold profile optimisation


- Radiance Threshold: 960-961 cm\(^{-1}\) (e.g. Hurley, *Diss.*, *Oxford*, 2009)

- Cloud Effective Fraction Retrieval (new by A. Dudhia)

- ‘Summary Flag’ approach: Confidence of detection
Improvements on Cloud Index Methods

1. MIPAS based CI-A Cloud Index
   Threshold Climatology
   (implemented in the Processor)
2. Improved new Color Ratios
3. Improved threshold determination
   (lat, alt, season)

<table>
<thead>
<tr>
<th>Cloud Index</th>
<th>MW1 (cm$^{-1}$)</th>
<th>MW2 (cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI-A</td>
<td>788.20 - 796.25</td>
<td>832.3 - 834.4</td>
</tr>
<tr>
<td>CI-A2</td>
<td>788.20 - 796.25</td>
<td>926.0 - 932.0*</td>
</tr>
<tr>
<td>CI-A3</td>
<td>788.20 - 796.25</td>
<td>947.0 - 952.0*</td>
</tr>
<tr>
<td>CI-B</td>
<td>1246.3 - 1249.1</td>
<td>1232.3 - 1234.4</td>
</tr>
<tr>
<td>CI-D</td>
<td>1929.0 - 1935.0</td>
<td>1973.0 - 1983.0</td>
</tr>
</tbody>
</table>

*Further optimisation possible
Singular Value Decomposition for Cloud Detection

Database of modeled spectra for cloudy and clear atmospheric state (827.5 – 970 cm\(^{-1}\)):

\[ \mathbf{SV}_{\text{clear}} \text{ and } \mathbf{SV}_{\text{cloudy}} \] (altitude dependence)

Least square fit of MIPAS spectra:

\[
L_{\text{fit}} = \sum_{i=0}^{m_{\text{clear}}} \lambda_{\text{clear}_i} \mathbf{SV}_{\text{clear}_i} + \sum_{i=0}^{m_{\text{cloudy}}} \lambda_{\text{cloudy}_i} \mathbf{SV}_{\text{cloudy}_i},
\]

\[
\mathbf{L}_{\text{total}} = \mathbf{L}_{\text{cloudy}} + \mathbf{L}_{\text{clear}}
\]

\[
\frac{\mathbf{L}_{\text{cloudy}}}{\mathbf{L}_{\text{total}}} > 0 \quad \Rightarrow \text{define threshold}
\]

\[
\frac{\mathbf{L}_{\text{cloudy}}}{\mathbf{L}_{\text{total}}} \approx 0
\]


(J. Hurley, Diss., 2009)

MIPclouds: ESA Atmospheric Science Conference, Barcelona, Sep. 7 – 11, 2009
Confidence of Cloud detection

- Qualitative measure of confidence for the detection of a single cloud event by a flagging system (FLAG\textsubscript{method} = 1 for cloudy or 0 for clear-sky or -1 for cloud-constraint)

\[
CONF = \sum_{i=0}^{N_{\text{flag}}} \text{FLAG}_i \times \text{weight}_i
\]

with \(\sum \text{weight}_i = 1\): normalized to the number of methods

- Intention: A simple measure of confidence for potential users
- Optically thin clouds result in smaller confidence (less methods are sensitive)

- Tests with large datasets (‘Validation’) will be necessary
Cloud Classification

- Multi colour-ratio / BTD approach for PSC classification (not successful for tropospheric clouds)
- Naïve Bayes Classifier for PSC and Liq/Cir classification
CI-A / BTD Approach for PSC classification

Ice classification: BTD(832 – 948 cm⁻¹)

\[ \text{BTD}_{\text{ICE}} > \text{IceNAT (CI)} \rightarrow \text{FLAG}_{\text{psclICE}} = 1 \]
or
\[ \text{IceNAT} > \text{BTD}_{\text{ICE}} > \text{IceSTS} \]
and
\[ \text{FLAG}_{\text{Ni}} = 1 \]
Naive Bayes Classifier I

“Maximising the Product Probability of single BTD or color Ratios”

Training data set: CSDB
- 1 and 0.5 cm⁻¹ MW pairs
- Optimising the classification result
- BTD better than color ratios

MIPclouds: ESA Atmospheric Science Conference, Barcelona, Sep. 7 – 11, 2009
Naive Bayes Classifier II

PSC results:
- generally excellent results for all types
- quite robust classification
- s4802 with problems (48% HNO3 => NAT-like)

Cir/Liq results:
- more difficult than PSC
- variation with background atmosphere
- results for constraint TH >= CBH
- classification in latitude bands
- optically thin (thick) condition: 1.8 < CI-A < 5.0 (CI-A < 1.8)

More tests:
- boot-strap like method for better confidence

Example:

<table>
<thead>
<tr>
<th>cirrus/liquid</th>
<th>cir-mid</th>
<th>cir-psum</th>
<th>cir-tro</th>
<th>liq-mid</th>
<th>liq-psum</th>
<th>liq-tro</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>liq: 27.27</td>
<td>liq: 40.12</td>
<td>liq: 42.88</td>
<td>liq: 71.14</td>
<td>liq: 46.45</td>
<td>liq: 67.58</td>
</tr>
<tr>
<td>thin</td>
<td>cir: 67.92</td>
<td>cir: 77.95</td>
<td>cir: 20.33</td>
<td>cir: 13.96</td>
<td>cir: 57.49</td>
<td>cir: 3.84</td>
</tr>
<tr>
<td></td>
<td>liq: 32.08</td>
<td>liq: 22.05</td>
<td>liq: 36.50</td>
<td>liq: 85.85</td>
<td>liq: 42.06</td>
<td>liq: 61.86</td>
</tr>
<tr>
<td>thin/mid/</td>
<td>cir: 97.87</td>
<td>cir: 55.22</td>
<td>cir: 70.65</td>
<td>cir: 0.39</td>
<td>cir: 20.93</td>
<td>cir: 9.37</td>
</tr>
<tr>
<td>CBH</td>
<td>liq: 2.13</td>
<td>liq: 35.14</td>
<td>liq: 6.91</td>
<td>liq: 88.82</td>
<td>liq: 65.61</td>
<td>liq: 49.09</td>
</tr>
<tr>
<td>CBH</td>
<td>liq: 32.17</td>
<td>liq: 5.49</td>
<td>liq: 28.60</td>
<td>liq: 18.32</td>
<td>liq: 93.33</td>
<td>liq: 7.19</td>
</tr>
</tbody>
</table>

Table 4.2: Example of Bayes analyses for liquid and cirrus spectra of the CSDB. For training histograms (rows) and test spectra (columns) for all scenarios, optically thin events (CI-A < 1.8), thin (1.8 < CI-A < 5) scenarios for mid-latitude and tangent heights greater than the cloud base height (CBH), and the same extraction for polar summer scenarios. All analyses for classification histograms with 4K bins.
Macrophysical Retrieval

- Optimal estimation retrieval of CTH, CTT, Cloud Extinction (CEX)

- Taking into account large MIPAS field of view retrieving first the cloud effective fraction

- Simple Forward Model:

\[ f_i = (1 - \alpha)B(1 - \tau_i) + \alpha B \]

With:
- \( f_i \) = forward model spectrum
- \( \alpha \) = cloud effective fraction (CEF)
- \( B \) = Planck function
- \( \tau_i \) = transmittance (pre-calculated)
- \( i \) = up to 10 continuum-like micro-windows
  - in the 937 – 960 cm\(^{-1}\) range
Oxford Preliminary Macro Results for 2009

MIPAS Cloud Top Height 20090617

MIPAS Cloud Top Height 20090711

http://www.atm.ox.ac.uk/group/mipas/L1B/
SARYCHEV VOLCANO
(48°06′N, 153°12′E)
Eruption: Jun 12, 2009

Aura/OMI - Average column for 20090611-20090617

MIPclouds: ESA Atmospheric Science Conference, Barcelona, Sep. 7 – 11, 2009
Microphysical Retrieval

1) Radius Retrieval
   Least-square fit of measured $BT_i^{\text{meas}}$ in distinct MWs (827, 941, 1227 cm$^{-1}$) to $BT_i^{\text{CSDB}}$ at $\delta$(CI-A) bins for various $R_{\text{eff}}$ bins:

   - cirrus: 4 to 90 µm,
   - PSC: ice=1-10 µm, NAT=0.5-5 µm

2) Surface Area Density Path: $ADP = \int_{0}^{\infty} A \, dx$, with $A = \frac{3 \cdot V}{R_{\text{eff}}}$

3) Area/Volume Density or IWP/IWC (estimate)
   - with horizontal homogeneity of cloud structure and results of $R_{\text{eff}}$-bin
Area Density Path

- Upper limit for ADP
- Simple fitting procedure for ADP estimate $ADP = f(CI-A)$
  - 4th order polynomial, with ‘lower’ limit for optical thick clouds
  - Latitude and altitude dependent parameter set (lookup tables)

- Advantages:
  - independent from cloud geometry
  - best suited for model comparisons (3D-fields)
## Validation

- Priority of the study: full resolution data set (Jun 02 – Mar 04)

<table>
<thead>
<tr>
<th>Instrument</th>
<th>GS</th>
<th>Miss-time / distance</th>
<th>Number of coincidences</th>
<th>Parameter of interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>FISH FSSP</td>
<td>x</td>
<td>3h/300km 6h/600km</td>
<td>35 140</td>
<td>cf, IWC, cf, size dist.: volume / radius</td>
</tr>
<tr>
<td>NH Lidars (PSC)</td>
<td></td>
<td>4h/400km 8h/800km</td>
<td>65 122</td>
<td>CTH, PSC type, CTH, PSC type</td>
</tr>
<tr>
<td>SH Lidar (PSC)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAGE II (III)</td>
<td>x</td>
<td>4h/400km 4h/400km</td>
<td>1450 950 73 (PW 2002/3)</td>
<td>CTH, CEX, VD, COF, PSCtype, CTH, CEX, VD, CTH, PSCtype</td>
</tr>
<tr>
<td>HALOE POAM</td>
<td>x</td>
<td>4h/400km 4h/400km 4h/400km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GLAS</td>
<td>x</td>
<td>3h/300km 1h/100km</td>
<td>40000G/10700M 3237G/543M</td>
<td>CTH, COF</td>
</tr>
<tr>
<td>SEVIRI (nadir)</td>
<td>x</td>
<td>0/0 seasonal mean</td>
<td>*each profile (&lt;60° lat) -</td>
<td>CTH, COF, CTP, CTT, LWP, Reff., cloud phase (liq/ice) for both instruments</td>
</tr>
<tr>
<td>ATSR (nadir)</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ISCCP D2 D1</td>
<td>x</td>
<td>monthly mean 3h/280km (grid)</td>
<td>-</td>
<td>COF, CTH, CTT, CTP, Liq/Ice Reff (liquid/crystal), Liq/Ice</td>
</tr>
<tr>
<td>GEWEX</td>
<td>x</td>
<td>monthly mean</td>
<td>-</td>
<td>Climatological comparison (e.g HIRS) of various parameters</td>
</tr>
</tbody>
</table>

Table 2: Summary for validation datasets for MIPAS cloud products. GS for 'global' dataset or statistical comparisons.

(*) selected cases of interest only, overlap in operation time only for Feb/Mar 2004.
Summary & Outlook: MIPclouds

- Selection of a set of retrievable cloud parameter
- Development and refinements of various algorithms
- Error Assessment for each parameter
- Product Validation Plan
- Development of a fast cloud parameter processor prototype
  - CPU-costs: ~ 20 min per orbit (1. apodisation, 2. SVD)
  - Code nearly finished, checking internal consistency
  - focusing on FR-mode but applicable to RR-mode as well

Coming soon:
- Processing of large datasets for validation purposes
- Blind Test dataset with ‘realistic’ 3D cloud scenarios
- NRT system for next NH polar winter RECONCILE campaign
Multi Colour-Ratio Approach

MIPAS measurement in SH polar vortex 2003 (Höpfner et al., ACP, 2006)
R1: NAT classification for \( r < 3 \mu m \)
R3: Ice for optical thick conditions
R2: most likely STS
R4: mixed / difficult to classify

\[
N_{\text{thres}}(\text{Cl}_A) = \left(0.1536 + 0.71531 \cdot \text{Cl}_A - 0.03003 \cdot \text{Cl}_A^2\right)^{-1}
\]