Aerosol Monitoring and Modeling

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Presentation to ECMWF seminar on Global Earth-System Monitoring

5-9 September 2005
Aerosols are an integral part of the Earth’s system.

- **DMS** (sea salt) from oceans
- **dust** from deserts
- **SO₂** from industries and cities
- Carbonaceous material from forests

CCN (Cloud Condensation Nuclei) formation is influenced by:
- Wind and convection
- Temperature (T), fractional cover (Fs), soil moisture, and wind speed
- Precipitation

The diagram illustrates the interconnections of these elements and their environmental impacts.
OUTLINE

1. Why do we need to monitor aerosols globally?

2. Design of an aerosol monitoring system

3. GEMS-aerosol
OUTLINE

1. Why do we need to monitor aerosols globally?

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3. GEMS-aerosol
Reasons for getting interested in aerosols

• climate effect (clear-sky, cloudy-sky)
  - anthropogenic aerosols are responsible for a radiative forcing
  - anthropogenic aerosols may modify the hydrological cycle
  - natural aerosols may response to climate change

• visibility ==> tourism, aviation

• air quality issues ==> human health, ecosystems

• improvement in meteorological (re)analysis

• improvements in weather forecasts

• deposition and acid rain issues ==> ecosystems

• satellite atmospheric corrections
  ==> retrieval of the properties of ocean, land, and atmosphere

• role of aerosol deposition on ocean biology

• depletion of the stratospheric ozone layer
Terminology: direct and indirect effects

• **Direct effect:** extinction of sunlight by aerosols in clear-sky (+extinction and emission of longwave radiation)

• **Semi-direct effect:** impact of aerosol absorption in clear- (and cloudy-) sky on the temperature and humidity profiles and hence on cloud formation

• **First indirect effect:** increase in cloud optical depth due to an increase in the number and a decrease in the size of cloud droplets (for a fixed liquid water content)

• **Second indirect effect:** increase in the cloud liquid water content, cloud height, or cloud lifetime due to a reduced precipitation efficiency
Aerosol direct effects

- Aerosols do scatter and absorb sunlight radiation.

- Anthropogenic aerosols suspected to be responsible for a negative radiative forcing of climate.

- Climate has not warmed as much as it would have in the absence of anthropogenic aerosols.

- The magnitude of the aerosol direct effect is now bound but remains uncertain.
Aerosol indirect effects

First indirect effect

- Increased CDNC (constant LWC), "Twomey" effect

Second indirect effect

- Drizzle suppression
- Increased LWC
- Increased cloud height (Pincus and Baker, 1994)
- Increased cloud lifetime (Albrecht, 1989)
- Indirect effect on ice clouds + Contrails
Specific climate effects of black carbon aerosols

The semi-direct effect

Altitude

Temperature profile

Change in convection and cloudiness

Heating

Cooling

specific climate effects of black carbon aerosols
As aerosol concentrations increase and visibility decreases, there is
- a whitening of the landscape,
- loss of texture,
- loss of contrast.
Peat fires, Moscow, September 2002
11 August 2005

“Malaysia has declared a state of emergency as the air pollution index soars to extremely hazardous levels on the west coast, which is worst-hit by smoke from fires in Sumatra.”
Global aerosol tools relevant to AQ!

Maps of aerosol optical depth from MODIS instrument

WINTER

SUMMER
Figure 14. Relationship between 24-hour PM$_{10}$ concentrations and daily averaged AERONET $\tau_a$ measurements from August to October 2000 in northern Italy.

Chu et al., JGR, 2003
Global aerosol tools relevant to AQ!

Wang and Christopher, GRL, 2003

Figure 2. (a) Spatial distribution of MODIS AOT and linearly derived AQI from Terra on Sept 11, 2002. Also shown are the 700mb geopotential heights. Grey regions are areas where MODIS AOT is not available due to possible sun glint or cloud contamination. (b) Relationship between MODIS AOT and PM$_{2.5}$ mass. (c) Monthly variation of PM$_{2.5}$ and MODIS and Sunphotometer (SP) AOT, inset shows the diurnal variations (in Central Standard Time, CST) of PM$_{2.5}$ in different seasons. (d) AQI derived from MODIS data. The box shows the ±1 standard deviation of PM$_{2.5}$ and AOT centered in the mean value (red filled circles) in each bins. The red line in the box shows the median value in each bin.
Hypothesis: some of it may be caused by large events of stratospheric aerosols

If true, there must have been a (transient) effect of tropospheric aerosols on the land carbon sink during the XX century.
Aerosol impact on NWP forecasts

Aerosols can affect NWP forecasts, analysis and reanalysis through three different ways:

1. Aerosols may adversely impact satellite data or satellite retrievals which are assimilated in the NWP suite

2. Aerosols modify the clear-sky radiative fluxes with impact on the surface and atmospheric temperature profile (unaccounted term in the equation for energy conservation => imperfect model).

3. Aerosols modify cloud properties (unaccounted for in the model).
CM3 = 3-month running mean difference in $B_{\text{calculated}} - B_{\text{measured}}$ for different HIRS channels

Aerosol impact on satellite retrievals (II)

Pierangelo et al.,
Aerosols may improve weather forecasts (I)

Aerosols may improve weather forecasts (II)


OLD

NEW
OUTLINE

1. Why do we need to monitor aerosols globally?

2. Design of an aerosol monitoring system

3. GEMS-aerosol
Ground-based networks (examples)

AERONET (PHOTONS)
aeronet.gsfc.nasa.gov
www-loa.univ-lille1.fr/photons

World Data Centre for Aerosols
(GAW / WMO) www.ei.jrc.it/wdca/

+ EMEP / IMPROVE

lidarb.dkrz.de/earlinet/
Aerosol-relevant satellite data (examples)

MODIS aerosol optical depth

MOPITT CO concentrations

ATSR fire counts

ATSR (G. de Leeuw, TNO)
The report summarizes
- ground in-situ
- aircraft in-situ
- spaceborne remote-sensing
- ground remote-sensing

and suggests priorities

Implementation plan ongoing
# IGACO – Tropospheric aerosols

## COMPONENT

| Component                                      | col/pro | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 | 99 | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
|-----------------------------------------------|--------|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Non-Satellite Global                          |        |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Ground-based in situ                          |        |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Ground-based total column                     |        |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| AOD from solar radiation measurements         |        |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Radiometry & sun photometry                   |        |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Ground-based vertical profile Lidar           |        |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Aircraft                                       |        |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| MOZAC                                         | UT     |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| CARIEIC                                        | UT     |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Metereological (Operational) Satellites       |        |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| METEOSAT - GOES                               | C      |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| NOAA / AVIRI                                  | C      |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| MSG - GOES - MTG                              | C      |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| METOP - NPOESS - AVHRR3 - VIIRS              | C      |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Research Satellites                           |        |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| NIMBUS 7/METEOR-ERS2-ADEOS-EP / TOMS          | C      |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| ERS / ATSR                                     | C      |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| TERRA-AQUA / MISR-MOIS                        | C      |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| ENVISAT / MERIS-AATSR-SCIAMACHY               | C      |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| AURA / ONI                                     | C      |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| PARASOL / POLDER                              | C      |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| ICESAT-CALIPSO / GLAS-llidar                  | P      |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| NPP / VIIRS                                   | C      |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| ADM                                           | P      |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| NPOESS VIIRS                                  | C      |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |

**Legend:**

- **DEMONSTRATION**
- **PRE-OPERATIONAL**
- **OPERATIONAL** Data available in near real-time
- **PROPOSED**
- **C** = column
- **P** = profile
- **T** = tropospheric
- **S** = stratospheric

**Legend for Operational Phase:**

- More integration required especially between air quality other monitoring networks
- Enhanced integration required among the different networks
- Efforts required to coordinate activities for operational use

**Legend for Research Phase:**

- Limited, but long-term information, no operational retrieval
- Significant long-term information, no operational retrieval planned
- Delicate long-term information, no operational retrieval planned

**Legend for Atm. Processing:**

- Dedicated to aerosol
## IGACO – Stratospheric aerosols

<table>
<thead>
<tr>
<th>COMPONENT</th>
<th>col/prof</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Satellite Global</td>
<td></td>
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<tr>
<td>AOD from solar radiation measurements</td>
<td></td>
</tr>
<tr>
<td>Sunphotometry (spectral)</td>
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<tr>
<td>Lidar NDSC</td>
<td>P</td>
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<tr>
<td>Lidar EARLINET regional EUROPE</td>
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<tr>
<td>Balloon vertical profile</td>
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<tr>
<td>Aircraft</td>
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<tr>
<td>CARIBIC</td>
<td>LS</td>
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<td>MOZAIC</td>
<td>LS</td>
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<td>Satellite</td>
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<tr>
<td>UARS/HALOE</td>
<td>P</td>
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<tr>
<td>ERBS-METEOR3M / SAGE HI-III</td>
<td>P</td>
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<tr>
<td>SPOT 3/4 P0AV II/III</td>
<td>P</td>
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<tr>
<td>AQUA / AIRS-AMSPE</td>
<td>P</td>
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<tr>
<td>ENVISAT / MIPAS-GOMOS-SCIAMACHY</td>
<td>P</td>
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<tr>
<td>ODIN / Osiris</td>
<td>P</td>
</tr>
<tr>
<td>AURA/HIRDLS - TES</td>
<td>P</td>
</tr>
<tr>
<td>CALIPSO LIDAR</td>
<td>P</td>
</tr>
</tbody>
</table>

### Key:
- **DEMONSTRATION**: Data available in near real-time for operational purpose.
- **PRE-OPERATIONAL**: Data available in near real-time for demonstration purpose.
- **OPERATIONAL**: Data available in near real-time and replacement guaranteed by agency.
- **PROPOSED**: No distinction between stratospheric and tropospheric contributions.
- UT/LS: upper trop./lower strat.
- C = column
- P = profile
- T = troposphere
- S = stratosphere

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### Areas of interest

<table>
<thead>
<tr>
<th>Area</th>
<th>Climate</th>
<th>Air Quality</th>
<th>Health Effects</th>
<th>Ecosystem</th>
<th>Emissions</th>
<th>Monitoring</th>
<th>Protocol Monitoring &amp; Legislation</th>
<th>Atmospheric Correction</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
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<td>22</td>
<td>26</td>
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<td>21</td>
<td>28</td>
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</tr>
</tbody>
</table>

**Legend:**
- Climate
- Air Quality
- Health Effects
- Ecosystem
- Emissions
- Monitoring
- Protocol Monitoring & Legislation
- Atmospheric Correction
- Other *
97% of users interested in aerosols (3% in gas species)
91% of users interested in tropospheric aerosols
38% of users interested in stratospheric aerosols
Present use of aerosol data

Satellite Data
Lidar
Sun Photometer
In Situ Ground Based Data
In Situ (Balloon, Aircraft) Data
Requirements for satellite data

Spatial resolution

Time resolution (average)

Timeliness
OUTLINE

1. Why do we need to monitor aerosols globally?

2. Design of an aerosol monitoring system

3. GEMS-aerosol
Figure 6a. Frequency maps of MODIS aerosol retrievals for spring (March–May 2001), summer (June–August 2001), autumn (September–November 2001), and winter (December 2000–January 2001). Frequency (%) is calculated using MODIS L3 daily products as the number of days with successful retrievals in 1° × 1° grids divided by the total number of calendar days in the season. Filled value (e.g., −9999) is filled in grids with unsuccessful retrieval. Note that a single retrieval from a 10 × 10 km² area of L2 is allowed to represent a 1° × 1° area of L3.
Aerosol monitoring in GEMS

modelling

Spaceborne remote sensing

data assimilation

Operational Weather Centre

Analyses

Users community: meteorology/climate/pollution/ecosystems/atmospheric corrections

in-situ (ground, aircraft)

Ground-based remote-sensing

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Aerosol monitoring in GEMS

- Emissions
  - AER_2
    - Aerosol models
      - DAEDALUS
      - PHOENICS
      - GlobAER (ESA)
    - Methodology
  - AER_1
    - Aerosol model
  - AER_3
    - Data assimilation
    - Aerosol satellite data (AOD, radiances)
- Fire counts
- Emissions
- Boundary conditions
- Heterogeneous chemistry
- Oxidants
- GRG
- Various datasets / CREATE
- GHG
- RAQ
- Emission maps
- ESA
- NASA
- ESA
- EUMETSAT
- NASA
## Aerosol monitoring in GEMS

<table>
<thead>
<tr>
<th>Products</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>4D distribution of aerosol concentrations at 50-100 km resolution (troposphere and stratosphere)</td>
<td>climate research; monitoring of the atmospheric chemical composition; monitoring of the stratosphere (air traffic); monitoring of volcanic eruptions for local populations; initial and boundary conditions for regional air quality models</td>
</tr>
<tr>
<td>4D distribution of aerosol optical properties at 50-100 km resolution (troposphere and stratosphere)</td>
<td>atmospheric corrections for remote sensing of land surfaces and ocean; prediction of surface UV radiation</td>
</tr>
<tr>
<td>Surface distribution of particulate matter PM</td>
<td>regional air quality</td>
</tr>
<tr>
<td>Improved visibility range</td>
<td>air traffic, tourism</td>
</tr>
<tr>
<td>Improved photosynthetically active radiation (PAR) at the surface</td>
<td>study of the carbon cycle; monitoring of the Kyoto protocol</td>
</tr>
<tr>
<td>Aerosol deposition flux (dry and wet)</td>
<td>study of the ocean biology; impact on ecosystems (acid rain monitoring)</td>
</tr>
<tr>
<td>Improved photolysis rates</td>
<td>regional air quality; global monitoring of the atmospheric chemical composition</td>
</tr>
<tr>
<td>Improved surface, atmospheric, and top-of-atmosphere radiative budget</td>
<td>climate research</td>
</tr>
</tbody>
</table>
Aerosol modelling

Important criteria for model implementation:

- aerosol parametrisations need to be consistent with the ECMWF physics
- aerosol parametrisations need to be computationally affordable
- choice of aerosol parametrisations guided by skill scores
- to become interactive aerosols should at least not deteriorate the weather scores

Open questions:

- how sophisticated the aerosol scheme should be?
  If plenty of good-quality data to assimilate
    monitoring purposes: simple aerosol scheme is enough
    forecasting purposes: more complex scheme
  If limited availability of good-quality data to assimilate
    a more sophisticated aerosol scheme is desirable

  ==> Balance between data availability, model quality and CPU
      number of model variables > or >> number of satellite variables

- what is the best approach: sectional or modal representation?
Aerosol modelling: sectional approach

Variables: number or mass in each bin.

Processes can be parametrised in each bin as a function of aerosol size.

Assumption may be needed on aerosol mixtures.
Aerosol modelling: modal approach

Assumed shape for the mode size distribution (usually a log-normal)

Variables: number and mass for each mode (average radius can be computed)

Processes can be parametrised as an integral over each mode.

Assumption may be needed on aerosol mixtures
Aerosol modelling: modal approach
HAM-M7

Considered Compounds:

- Sulfate
- Black Carbon
- Organic Carbon
- Sea Salt
- Mineral Dust

Resolve aerosol size-distribution by 7 log-normal modes

- Three modes are composed of solely one aerosol component
- Four modes are internal mixtures of several components
Considered Compounds:

<p>| | | | |</p>
<table>
<thead>
<tr>
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<tr>
<td>Sulfate</td>
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<td>Mineral Dust</td>
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</tbody>
</table>

Resolve aerosol size-distribution by 7 log-normal modes

Three modes are composed of solely one aerosol component

Four modes are internal mixtures of several components

Mode size, mixing state, and composition predicted by microphysical and thermodynamical processes

Detailed description and evaluation in Stier et al., ACP, (2005)
Variational assimilation

Corrected forecast (analysis)

Previous forecast (background)

Assimilation window

time

\[ J = (x - x_b)^T B^{-1} (x - x_b) + (y - H[x])^T R^{-1} (y - H[x]) \]

+ minimisation algorithm

B,R: Covariance error matrices

y: observation

x_b: background

H: obs operator
Development of a prognostic aerosol package in the ECMWF model

Physics
- Radiation
- Vertical diffusion
- Mass-flux convection
- Large-scale condensation
- Cloud scheme

Physics with prognostic aerosols
- Radiation
- Aerosol sources
- Dry deposition
- Sedimentation
- Vertical diffusion
- Mass-flux convection
- Large-scale condensation
- Cloud scheme
- Scavenging in- and below clouds
- Aerosol budget
- Aerosol radiance diagnostics

New routine
Modified routine
Unchanged (at present)
Skill scores

- Correlation coefficients (observed vs simulated aerosol properties)
  - current models perform well on monthly means
  - challenge will be to get good correlation on daily means

- Linear fits: slope, offset

- Root-mean square errors
  - largely used in RAQ

- Taylor diagrams
  - summarizes model performance in terms of correlation coefficient, standard deviation, and RMS.

- Figures of merit
  - useful to test the transport for particular events
  - has been used for ETEX
- Taylor diagrams
Skill scores

- Correlation plots
- Figures of merit
  - useful to test the transport for particular events
  - has been used for ETEX
Conclusions

- GEMS will be a major step forward in global aerosol monitoring.

- Continuous work needed to make the best use possible of satellite data (METOP + NPOESS + spaceborne lidar)

- Monitoring of aerosol absorption is also needed.

- Are aerosol indirect effects important for numerical weather prediction?
1. Aerosol near clouds?

- Cloud
- ??
- Clear
- ??
- Precipitating cloud

2. Aerosol absorption? Land + ocean

=> Aerosol and cloud vertical profiles