The CLOUD experiment

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Aims of the CLOUD experiment:

Scientific main questions:
- How cloudy was the preindustrial atmosphere?
- Do cosmic rays have a role in the climate system?
- To what extend do ions enhance the new particle formation (nucleation and particle growth)?

Climate model simulations require a deep understanding of aerosol nucleation processes. For that measurement data is needed!
The collaboration is atmospheric scientists… and CERN:

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University of Stockholm, Department of Applied Environmental Science, 10691 Stockholm, Sweden
University of Vienna, Faculty of Physics, 1090 Vienna, Austria
Why do atmospheric scientists come to CERN?
To study the role of aerosols and ions on climate change

• Since 1850 the global, average surface temperature has increased by 0.8 °C.
• But what exactly were the driving factors (heating vs cooling)?
• How much will the temperature increase in future? Predictions: 1.5 – 4.5 °C
Why study aerosols?

Scattering and absorption of solar radiation

Aerosol-Radiation Interaction

All cloud droplets form on aerosols!

Increased aerosol particles produce:
1) brighter clouds and
2) more clouds/longer lifetime

Changes in the properties of clouds

1. increased cloud albedo
2. increased cloud lifetime (drizzle suppression)

“indirect effect” (more cloud droplets)

Aerosol-Cloud Interaction
About half of climate-relevant particles are of secondary origin, indirectly produced through gas-to-particle conversion, i.e., nucleation. Examples include phytoplankton blooms, dimethyl sulphide, amines, ammonia, and biogenic vapours.
Secondary aerosol sources and sinks

<table>
<thead>
<tr>
<th>Gas phase precursors</th>
<th>Particle formation by nucleation</th>
<th>Enhanced growth by condensation and coagulation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ionisation</strong> (e.g. cosmic rays)</td>
<td>eg. $\text{N}_2$, $\text{O}_2$, $\text{H}_2\text{O}$</td>
<td>eg. $\text{HSO}_4^-$, ($\text{H}_2\text{SO}_4$)$_n$, $\text{H}_2\text{O}$-$\text{H}_2\text{SO}_4$, VOCs</td>
</tr>
<tr>
<td>eg. $\text{H}_2\text{SO}_4$, $\text{NH}_3$, $\text{SO}_2$, $\text{NO}_x$, Organics</td>
<td>Sulfates, Nitrate, Organics</td>
<td></td>
</tr>
</tbody>
</table>

**Aerosol-cloud interaction:**

- Gas molecules:
  - $<1\text{ nm}$
  - $\sim1-3\text{ nm}$
- Cluster ions and neutral clusters:
  - $>3\text{ nm}$
- Cloud condensation nuclei (CCN):
  - $>100\text{ nm}$
How do ions enhance aerosol nucleation and growth?

a) By stabilization of the critical cluster
b) By faster collisions
How does the CLOUD experiment work?

A summary of the CLOUD experiment at CERN.
The key component:
Ultra-clean chamber for aerosol process measurements

- Pressure: Atmospheric ± 0.3 bar
- Volume: 26.1 m³
- Only metallic seals
- Electropolished inner surfaces
And many other components, and a lot of work!

DT’s contributions

- CLOUD design & construction
- Thermal system
- Gas system
- DAQ & Slow control
- Technical coordination
- Resource coordination
- Safety coordination
- Run coordination

Manpower at CERN (spring 2018 situation): ~5 FTE

- 3 Fellows in EP-DT: 1 CERN + 2 EU (Marie Curie) funded
  Hanna Manninen, Joschka Pfeifer, Stefan Weber
- ~1.5 FTE Staff & FSU in EP-DT, all part-time:
- 0.5 FTE Staff in EN-MME
  Serge Mathot

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World’s cleanest laboratory for studies of atmospheric particle formation

CLOUD is run under precisely controlled laboratory conditions:

• temperature stability: <0.1°C
• temperature range: -90°C to +30°C; cleaning at +100°C
• surface cleanliness: <10 pptv*) organics contamination, stainless steel (and gold), no teflon, no O-rings
• ultrapure gas supplies
• UV system: negligible heat load by use of fibre optics
• field cage 30 kV/m

Unique and highly advanced aerosol chamber already as such!

*) pptv = part per trillion, 1 / 10^{12}
Precise control of the ‘cosmic ray’ beam intensity from the CERN Proton Synchrotron (PS)
2008: PS-T11 beam area, CLOUD's starting point...

2009: 1st beam run

2017: 12th beam run
Ultra-pure air: synthetic air made from liquid nitrogen and liquid oxygen
Gas system built to the highest technical standard of performance
UV light from a fibre-optic system

Precise and uniform adjustment of the H2SO4 concentration by means of UV laser system for the homogeneous, in-situ generation of the precursor gases
To study neutral nucleation, the beam is turned off and an internal electric field of up to 20 kV/m is applied by means of two transparent field cage electrodes. This rapidly (in about 1 s) sweeps out the background ions produced by galactic cosmic rays.
Metallic fan mixing rapidly the fresh gas and ions generated by the pion beam

The fans produce a counter-flow inside the chamber, and ensure good uniformity.
Thermal system enables highly stable operation at any temperature (300-183 K)
Typical CLOUD run
CLOUD simulates real atmosphere

12 consecutive particle formation event days 8–19 April 2007 in Hyytiälä, Finland
CLOUD run: instruments sample from chamber and record continuously.

Key calculated parameters are nucleation rate of aerosol particles (cm⁻³ s⁻¹) and growth rate (nm h⁻¹).
What has CLOUD shown us about the nature?

CERN’s CLOUD experiment sharpens the climate predictions and has transformed how aerosols are represented in global climate models.
Importance of biogenic aerosol particles

- Huge discovery that **biogenic vapours emitted by trees** and oxidised in the atmosphere have a significant impact on the formation of clouds, **thus helping to cool the planet**

- Addition DMA into system brings the nucleation rate into the range of atmospheric observations

Nearly all nucleation throughout the present-day atmosphere involves ammonia or biogenic organic compounds, in addition to sulfuric acid.
350 nucleation rates from several CLOUD campaigns to build parametrization

The most extensive measurements of nucleation rates covering atmospheric conditions (T, ions, trace gases)

Parametrisation on H2SO4/biogenic nucleation

Global importance of nucleation using global aerosol models

Parametrizations of nucleation from H2SO4/NH3 + H2SO4/Biogenic + Pure biogenic + ions experiments

65% of climate-relevant aerosol particles in the preindustrial atmosphere come from nucleation, and 55% today

Gordon et al. Causes and importance of new particle formation in the present-day and preindustrial atmospheres, JGR 2017
What are our next goals?

Learn more about the clouds and influence of ions.
Nucleation studies

• Ambitious research programme ahead: more complex multi-component systems, marine/arctic environments, polluted urban environments
  - *Which species other than* $H_2SO_4$?
  - *How important are* ions?
  - *What is the role of the biosphere?*
  - *What happens at low temperature?*

• Key challenges are precise temperature regulation, replicating atmospheric photolytic chemistry (developing trace gas generators and light sources) and not contaminating the chamber
CLOUDy studies

- CLOUD microphysics: Effect of scape charge and highly charged CCN for CLOUD formations and lifetime
- Aqueous-phase vs ice-phase cloudy experiments
- Suggested solar-GCR-climate link via global electric circuit and clouds?
- Key challenges are precise temperature regulation, producing highly charged cloud condensation nuclei and producing reproducible clouds via adiabatic expansions
CLOUD runs in 2018

CLOUD13T (4 weeks)
11 Jun - 6 Jul 2018:
- Ion production and loss mechanisms at several temperatures
- Ion non-uniformities with varying beam
- Fan optimisation

CLOUD13 (10 weeks)
24 Sep - 26 Nov 2018:
- Marine new particle formation
- Biogenic nucleation
- Anthropogenic nucleation
- Calibration
Summary

• CLOUD is the only chamber in the world for accurate quantifying of ion-induced nucleation rates. It has become possible by the combination of
  - a highly sophisticated chamber made in CERN standards (‘no compromises’)
  - the availability of the beam allowing us to simulate the atmosphere up to the top of the troposphere
  - the collaboration of the leading groups in aerosol nucleation
  - and the availability of new instrumentation

• With this combination we have the tools to elucidate the nucleation mechanisms and much more!
Thank you for your attention!

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First measurement of the molecular composition of neutral nucleating clusters

Clusters containing up to 14 SA molecules and 16 DMA molecules detected, corresponding to a mobility diameter near 2.0 nm

Kürten et al., Neutral molecular cluster formation of sulfuric acid–dimethylamine observed in real time under atmospheric conditions, PNAS 2014
NAIS results: importance of ions

- Examples above show particle formation under coastal marine conditions (iodine oxides) recorded in present CLOUD12 run.
- Almost all species of new particles studied by CLOUD show significant enhancement from ions (up to a factor 100 faster rate in some cases).
Typically in CLOUD, the negative ions are sulphuric acid dimer (HSO4−.H2SO4.nH2O) and the positive ions are ammonium (NH4+) or ammonium with organics (NH4+.HOM).
CLOUD runs in 2018

28Sep17
- Most extensive array of instruments ever assembled at CLOUD
- 45 instruments
- 11 mass spectrometers
- 18 particle counters/sizers
- 15 gas analysers, etc.
- 5 light sources

CLOUD13T (4 weeks)
11 Jun - 6 Jul 2018: Measure ion production and loss mechanisms at several temperatures, ion non-uniformities with varying beam, and fan optimisation

CLOUD13 (10 weeks)
24 Sep - 26 Nov 2018:
- Marine new particle formation (3 weeks)
- Biogenic nucleation (3 weeks)
- Anthropogenic (3 weeks)
- Calibration and intercomparison
Detector: Neutral cluster and air ion spectrometer (NAIS)

**ION MOBILITY DISTRIBUTION:**
3.2 to 0.0013 cm²/V/s
(0.8 - 42 nm)

**PARTICLE SIZE DISTRIBUTION:**
~2 - 42 nm

**OFFSET MODE:**
background
Detector: Time-of-flight mass spectrometer (API-TOF)