CLOUD-TRAIN
Marie-Curie Initial Training Network 316662
Publishable Summary
first period: 1 Oct 2012 – 30 Sep 2014

SUMMARY OF PROJECT OBJECTIVES

The aim of "CLOUD-TRAIN" is to establish a multi-site network of Early Stage Researchers (predominantly PhD students) and Experienced Researchers at 10 partner institutions across Europe. The role of aerosol nucleation for atmospheric CCN levels, clouds and climate is investigated. The influence of various vapours and ions for aerosol nucleation, growth and cloud processes is studied to significantly improve our understanding of natural and anthropogenic climate forcing as well as feedback mechanisms.
The network is centred around three sets of common experiments on ternary and multi-species nucleation (ion-induced and neutral) and ion-aerosol-cloud interaction carried out at CERN. All trainees contribute to these experiments. The experiments are conducted at the unique aerosol chamber "CLOUD" that is exposed to a CERN ionizing particle beam where the effects of cosmic rays on aerosol and clouds can be efficiently simulated. Nucleation experiments are performed at an unprecedented level of precision and completeness using highly innovative instrumentation.
A high quality training programme is set up for the fellows. Additional to the experiments at CERN, they are brought together for network training events such as annual summer schools and workshops for integral data analysis. Inter-sectoral exchange is fostered through a secondment programme for all fellows.
The main scientific project objectives include:

a) *New experimental results on nucleation and growth in the presence of multi-component mixtures of vapours of atmospheric relevance:* Perform nucleation experiments of atmospheric relevance for ion-induced and neutral aerosol nucleation over a wide range of environmental conditions. Achievements are expected for:
   - Direct comparison of nucleation and growth rates for ion-induced and neutral processes.
   - Identification and quantification of key oxidized organic substances participating in atmospheric nucleation and initial growth at atmospherically relevant concentrations.
   - Observation of the nucleation process at the level of individual molecular steps.
   - Direct measurement of (size-dependent) particle growth in the 1-5 nm size range.

b) *New experimental results on the impact of charge on cloud droplet formation, ice particle formation and cloud microphysics.* Experiments are conducted on droplet activation, liquid phase chemistry, heterogeneous and homogeneous ice nucleation and for a range of CCN and IN species. The experiments include, for example, studies of the effect of charge on ice formation, ice growth, ice habit and surface properties.

c) *New input for global climate models: Development of parameterisations of ion-induced and neutral aerosol formation, and cloud activation mechanisms for global climate models, including multi-component nucleation; improved aerosol growth schemes and reduced uncertainty of radiative forcing.* Improved assessment of cosmic rays as a potential mechanism for present-day or pre-industrial climate variability.

WORK PERFORMED SINCE THE BEGINNING OF THE PROJECT

Within the first two years of the CLOUD-TRAIN project, the CLOUD chamber facility was equipped with a potent gas expansion system to enable adiabatic expansion experiments in which warm liquid clouds, super-cooled liquid clouds, mixed-phase clouds or ice clouds can be studied.
Since the beginning of the project in Oct. 2012 the CLOUD chamber facility at CERN was operated during three dedicated experimental periods: CLOUD7 (Oct 2012-Dec 2012), CLOUD8 (Sep 2013-Dec 2013), and CLOUD9 (Sep 2014-Nov 2014). Several hundred individual experiments were performed. CLOUD7 focused on aerosol nucleation and growth experiments for the ternary dimethylamine-sulfuric acid-water system and on multi-component nucleation from α-pinene oxidation products, sulphuric acid and water, simulating conditions similar to the situation in a boreal forest. The α-pinene chemistry was initiated by pure ozone oxidation (with additional OH scavenger), by pure OH oxidation, and by combined ozone and OH oxidation.
During CLOUD8 aerosol formation experiments α-pinene oxidation were performed in the first three weeks, then the experimental focus was switched to adiabatic expansion experiments where first warm and super-cooled liquid clouds were produced and the liquid phase chemistry of SO_2 and of organic substances were studied and then experiments on the formation of ice clouds were conducted.
CLOUD9 focused on a) liquid-phase cloud chemistry, b) ice formation and ice properties, and c) ion processes. It was mainly conducted after the end of the reporting period and will not be discussed further in this report.
The global aerosol model GLOMAP has been run to test the sensitivity of global CCN concentrations to new aerosol formation mechanisms that represent the new findings from the experimental measurements during CLOUD7 and CLOUD8.
All ESRs and ERs received a comprehensive training at their host institutes as well as part of the network wide trainings. The fellows participated in two summer schools, several data workshops and many further training activities. Several secondments were conducted. Complementary skill training was part of the training program.

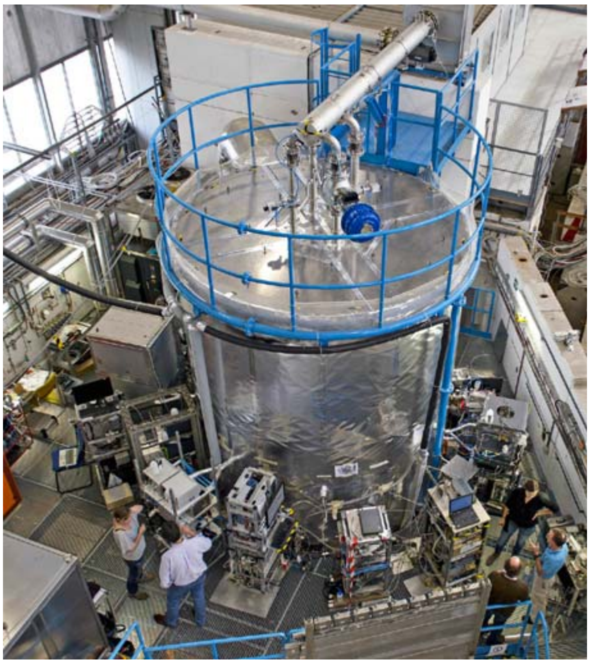

Figure 1: The CLOUD facility with instrumentation during the CLOUD8 experiment. © CERN

MAIN RESULTS ACHIEVED SO FAR

The CLOUD-7 measurements allowed for the first time to study large neutral (i.e. uncharged) molecular clusters during aerosol formation. For the dimethylamine-sulfuric acid system nucleation rates for a broad set of conditions were determined and clusters containing up to ~14 H_2SO_4 and 16 DMA molecules were detected and the temporal evolution of the clusters during nucleation was observed (1,2).
Furthermore, main results included:

- High precision calibration of chamber temperature sensors for adiabatic expansion measurements.
- Measurements of α-pinene oxidation, subsequent nucleation and growth of Extremely Low Volatility Organic Compounds (ELVOCs).
- Measurements of sulphur dioxide and isoprene reactive uptake in supercooled liquid clouds.
- Measurements of IN activation for glassy aerosols.
- Measurements of homogeneous ice formation.
- Parameterisations of the nucleation processes are derived and included in global climate models.

In-depth data analysis and modelling for these measurements is currently ongoing.
Key results from the CLOUD experiment have been published recently in *Nature*, *Science* and *PNAS* (1-4), in part already including results from the CLOUD-TRAIN experiments (1,2). An open access special issue for CLOUD results has been established jointly by *Atmos. Chemistry and Physics* and *Atmos. Meas. Tech* (*"The CERN CLOUD experiment" SI #264 & #344).*

EXPECTED FINAL RESULTS, THEIR POTENTIAL IMPACT AND USE

Further experiments are planned to take place at the CLOUD aerosol chamber in Sep-Nov 2015 and in 2016. Experiments will continue to focus on aerosol nucleation and growth studies with and without ions, on liquid phase chemistry of relevance for processing of trace gases in warm or mixed-phase clouds, and on the study of ice formation and ice particle properties.
The aerosol nucleation studies will be extended in temperature range and will include investigations of day-time vs. night-time as well as pre-industrial vs. present-day chemistry experiments. Results will be published in international peer-reviewed scientific journals, will be presented at major international conferences and an open final conference is planned for summer 2016 at the end of the CLOUD-TRAIN project.
Significant new scientific insight has already been obtained due to the combination of the chamber facility with its unique features and the novel instrumentation. An exact quantification of aerosol nucleation under a large range of atmospheric conditions, a significantly enhanced understanding of the nucleation process at the molecular cluster level and an exact identification of the involved chemical substances can be expected from the investigations. Similarly, significant process understanding is expecte from the liquid and ice cloud experiments is We are confident that all scientific objectives as documented in the DoW (Annex I of the Grant Agreement) will be met by the end of the project.
Within the next period of CLOUD-TRAIN we will derive parameterizations of the aerosol formation processes that will be included in the global model GLOMAP. The influence of this new nucleation scheme on predicted aerosol and CCN number concentration on the global scale will be studied. We expect that our results will be used by other modelling groups to improve aerosol nucleation modelling on all scales. This will improve the representation of aerosols in global climate models and will reduce uncertainty of climate modelling. A better understanding of natural variability as well as anthropogenic influences on climate will have important impacts on political decisions and society concerning our actions with respect to avoiding and mitigating climate change.

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CLOUD-TRAIN web site: http://www.cloud-train.eu

Highlight publications of CLOUD in 2013 and 2014:

(1) Almeida et al., *Nature*, 502, 359-363, doi:10.1038/nature12663, 2013
(2) Kürten et al., *Proc. Nat. Acad. Sci.*, 111, 15019–15024, doi: 10.1073/pnas.1404853111, 2014.
(3) Riccobono et al., *Science*, 344, 717-721, *doi:* 10.1126/science.1243527, 2014.
(4) Schobesberger et al., *Proc. Nat. Acad. Sci.*, 110, 17223–17228, doi: 10.1073/pnas.1306973110, 2013.