Impact of Biogenic versus Anthropogenic emissions on Clouds and Climate: towards a Holistic Understanding (BACCHUS)

Mid-term summary for policymakers

Foreword

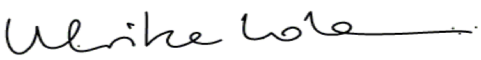
The response of clouds to a changing climate and their effect on the radiative budget of the Earth is the most uncertain climate feedback. Interactions between aerosols and clouds play a key role in the anthropogenic radiative forcing of the climate system, but remain the most uncertain of all forcing agents and are still associated with a low scientific level of understanding.

A major part of the uncertainty in how aerosol and cloud processes respond to changes in anthropogenic and natural aerosol emissions is due to lack of fundamental understanding about ice-containing clouds and to the incomplete knowledge of the coupling between the biosphere and atmosphere.

The goal of the BACCHUS project is to explore these two topics as they may turn out to be key in the climate system. Specifically, measurement capabilities of ice nucleating particles are still insufficient and our understanding of ice formation and ice cloud evolution in different environments is poor. In addition, as the biosphere responds to warming in a changing climate, coupling between the biosphere and the atmosphere due to aerosol-cloud interactions may play an important role in regulating climate change via aerosol and cloud formation.

Understanding the natural aerosol abundance before pollution occurred is essential for identifying the magnitude of the anthropogenic forcing due to aerosol-cloud interactions, but also for understanding changes resulting from altered global biogenic emissions related to anthropogenic activity. In BACCHUS these complex aerosol-cloud interactions and feedbacks involving natural aerosols are investigated to improve their representation in Earth System Models to reduce the uncertainty of the impact of biogenic and anthropogenic emissions on clouds in future climate projections.

The BACCHUS project gathers Europe's and Israel's leading scientists in aerosol and climate research. After two years since the project start, we have achieved considerable progress in our understanding of aerosol-cloud interactions and their effects on climate. This brochure presents a summary of our findings so far, and I hope it will be useful for stakeholders, policymakers, and the interested public.

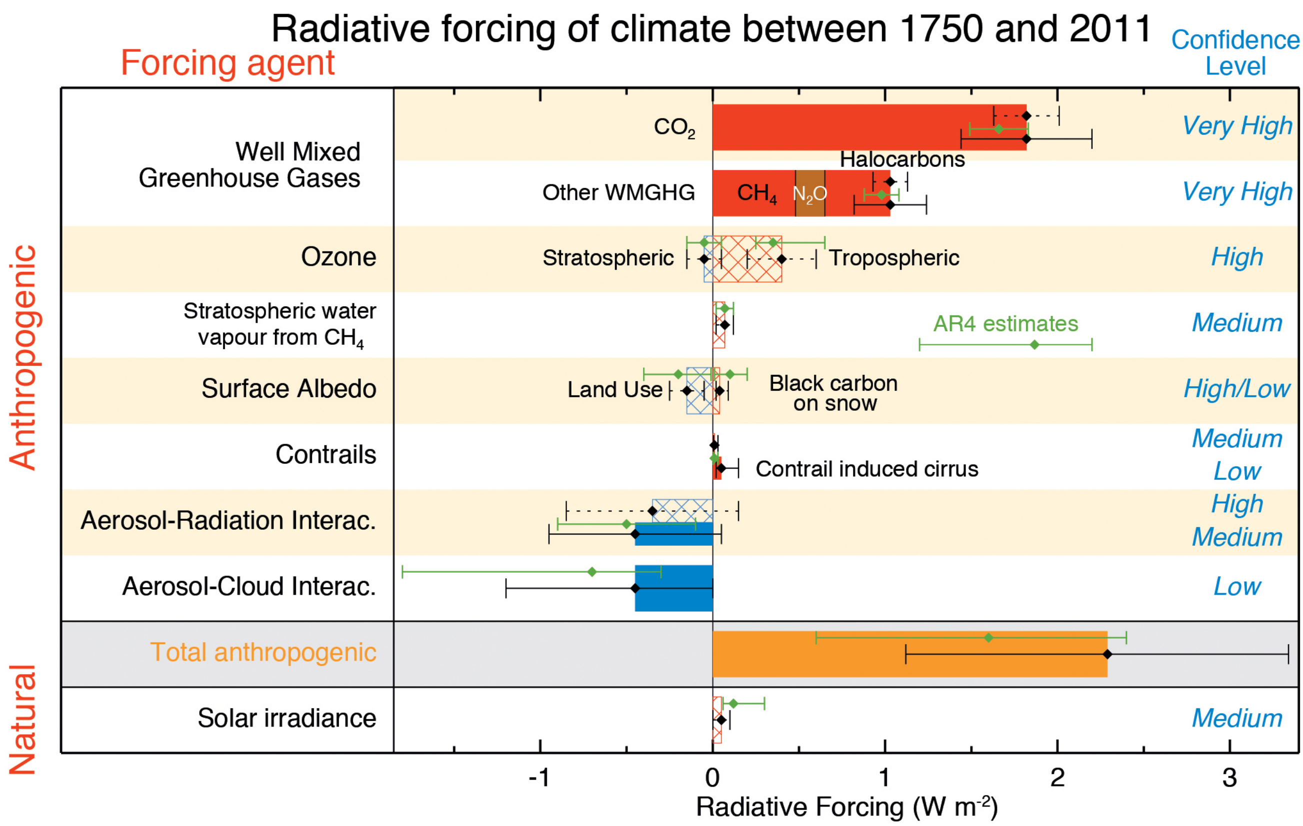


Ulrike Lohmann,
BACCHUS project coordinator

The effect of aerosols in the atmosphere

“The radiative forcing (RF) of the total aerosol effect in the atmosphere, which includes cloud adjustments due to aerosols, is –0.9 [–1.9 to −0.1] W m^{-2} (medium confidence), and results from a negative forcing from most aerosols and a positive contribution from black carbon absorption of solar radiation. There is high confidence that aerosols and their interactions with clouds have offset a substantial portion of global mean forcing from well-mixed greenhouse gases. Aerosols continue to contribute the largest uncertainty to the total RF estimate.”

Summary for Policymakers, IPCC, 2013.



Fact Box: **Radiative Forcing (RF)**
Difference in insolation (sunlight) absorbed by the Earth atmosphere system and energy radiated back to space. RF is quantified at the tropopause in watts per square meter after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures and state held fixed at the unperturbed values. A positive forcing (more incoming energy) warms the system, while negative forcing (more outgoing energy) cools it.

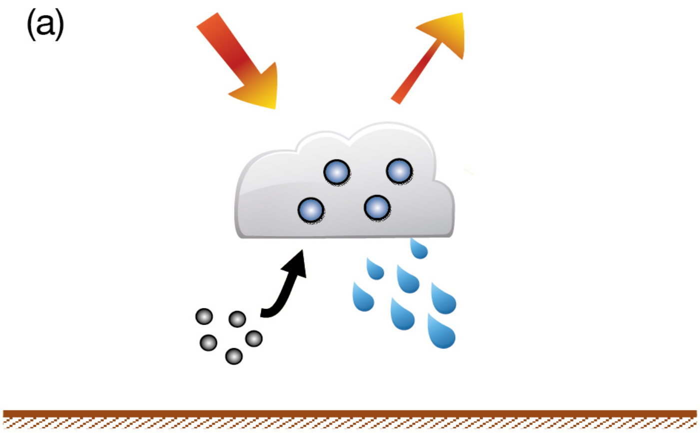
Aerosol-cloud interactions

Aerosols affect climate in many ways.

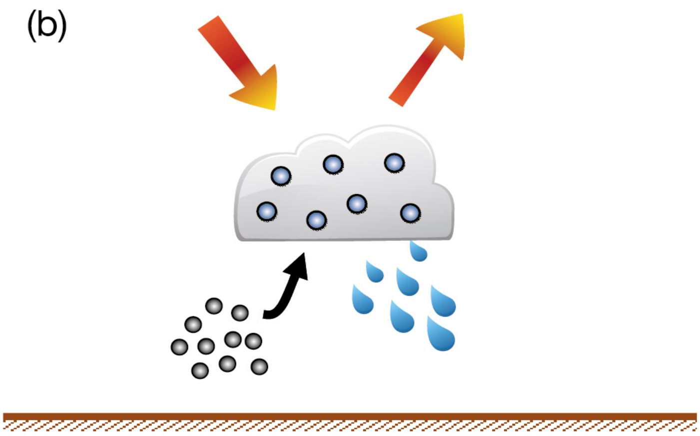
They scatter and absorb sunlight, which modifies the Earth's radiative balance.

Aerosols also serve as cloud condensation and ice nucleation sites, on which cloud droplets and ice particles can form. When influenced by more aerosol particles, clouds of liquid water droplets tend to have more, but smaller droplets, which causes these clouds to reflect more solar radiation back to space. There are however many other pathways for aerosol–cloud interactions, particularly in mixed-phase clouds (containing liquid water and ice) and cirrus clouds (exclusively containing ice crystals), where phase changes between liquid and ice water are sensitive to aerosol concentrations and properties.

Aerosol-cloud interactions



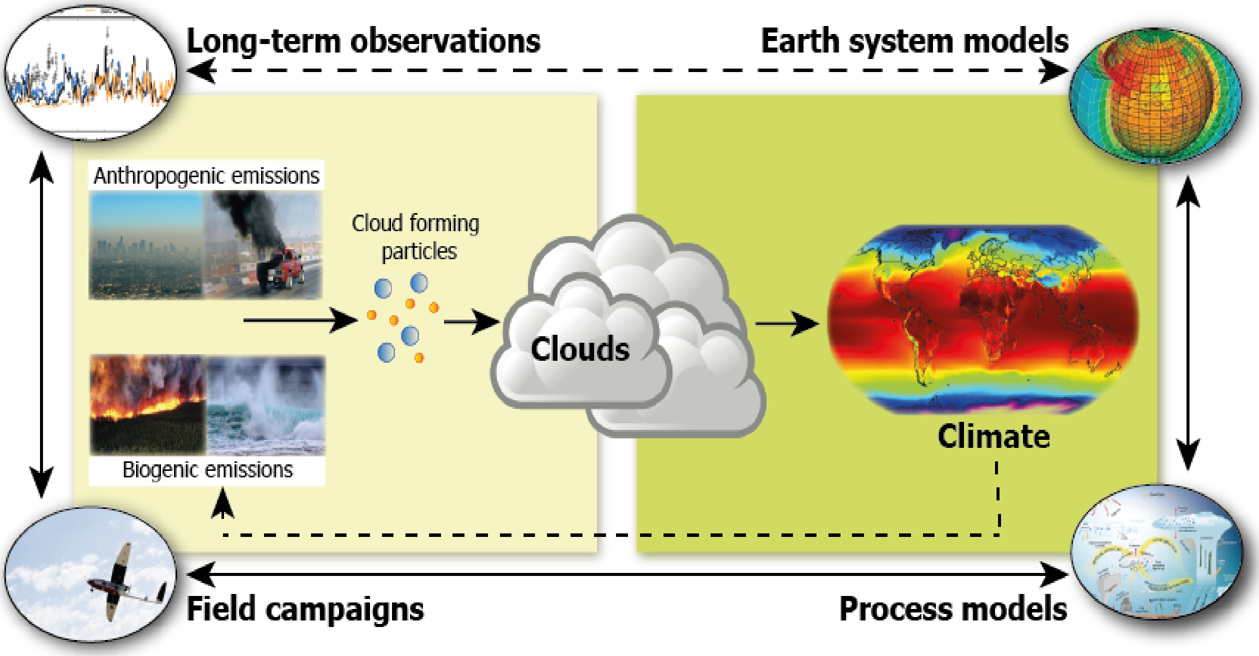
Aerosols serve as cloud condensation nuclei upon which liquid droplets can form.



More aerosols result in a larger concentration of smaller droplets, leading to a brighter cloud. However there are many other possible aerosol–cloud–precipitation processes which may amplify or dampen this effect.

Source text and graphics: Frequently Asked Questions, IPCC 2013

Objectives of BACCHUS



The core idea of BACCHUS is to quantify key processes controlling clouds and climate and their feedbacks. This is done by contrasting processes in climate-relevant environments such as tropical areas as key regulators of climate and the Arctic, which experiences the most profound climatic changes and may be prone to irreversible transitions. We combine advanced measurements of cloud and aerosol properties with state-of-the-art numerical modeling. Specifically, BACCHUS aims to characterize the importance of biogenic versus anthropogenic aerosol emissions for cloud formation and climate. In addition, we evaluate data from well-established sites at the coast of the North Atlantic, in the boreal forest, and in the Alps, which enable us to identify relevant parameters through long-term observations and to develop methods to critically test the resulting parameterizations and feedback processes.

This core idea has been developed around two central objectives:

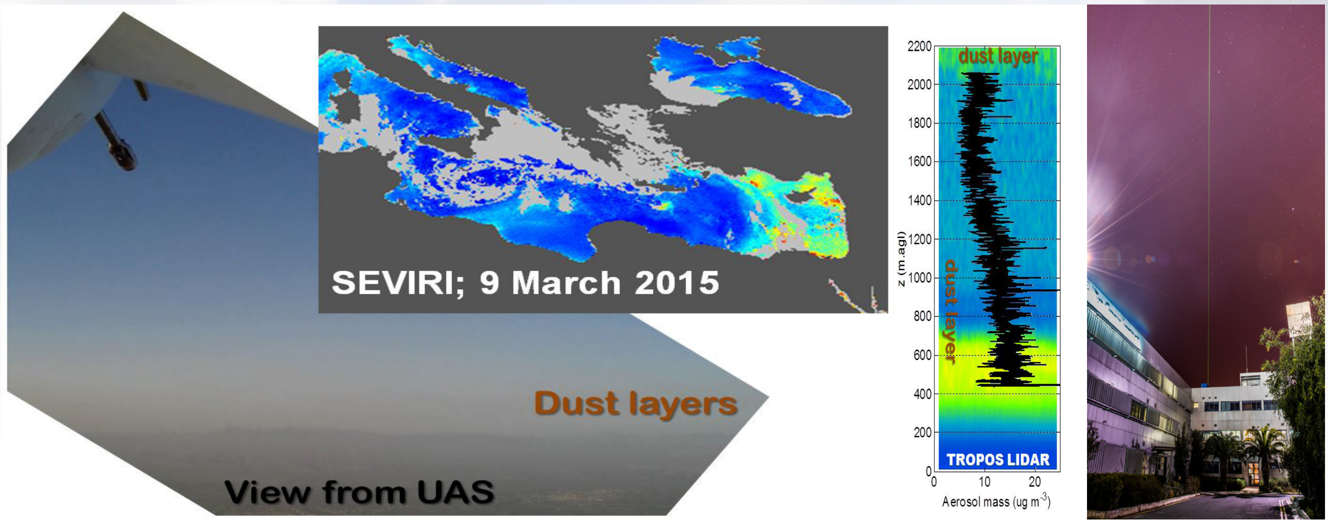
Objective 1:
To develop a robust methodology to quantify the influence of anthropogenic aerosol on cloud properties based on the estimate of the background levels of natural aerosols in various environments, identification of their sources and their role in aerosol-cloud processes. Emphasis is placed on changing cloud properties arising from aerosol-cloud interactions with a particular focus on the ice-phase, as well as the involvement of biogenic and organic aerosols in modifying the properties of cloud condensation nuclei (CCN) and ice nucleating particles (INP).

Objective 2:
To characterize and understand the key interactions and feedback mechanisms in the terrestrial and marine biosphere-atmosphere-cloud-climate system by building on advanced in-situ observations, remote sensing, and numerical models operating over a wide spectrum of spatio-temporal scales and complexity. BACCHUS focuses on both the terrestrial and marine biosphere.

Observing aerosols in the atmosphere

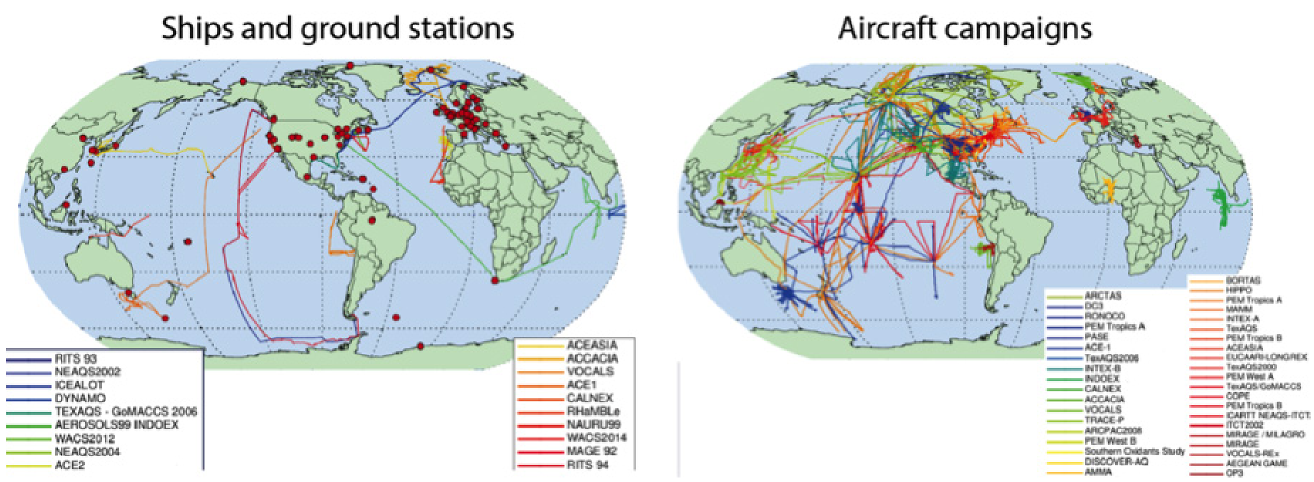
In 2015, BACCHUS partners have participated in several international measurement campaigns to collect scientific information on CCN, INP, and microphysical aerosol properties. These measurements are being collected and made available to the BACCHUS consortium and external users in several databases, among them the newly installed BACCHUS IN database.

- Chemistry-Aerosol Mediterranean experiment (ChArMEx) campaign, Cyprus, March 2015
- Mace Head, Ireland
- Finland

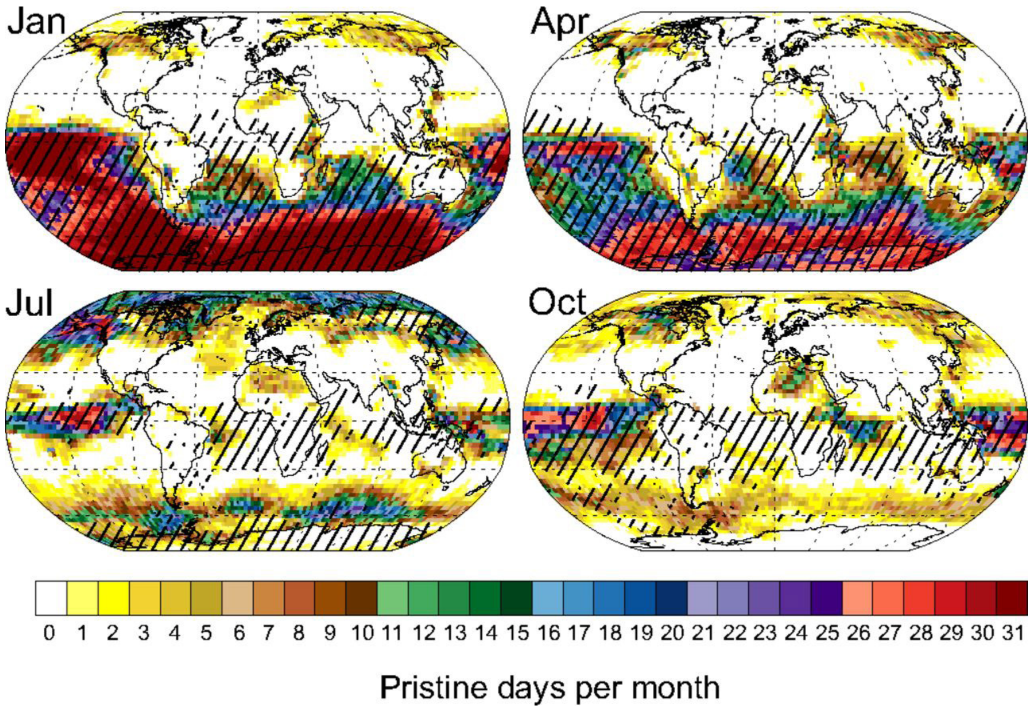


Impressions from the ChArMEx campaign on Cyprus, March 2015: dust event on 9 March 2015 investigated by lidar and unmanned aerial vehicle

Within BACCHUS, the Universities of Leeds, Oxford, and Manchester have created the largest ever consistent model-ready database of aerosol microphysics measurements from aircraft, ships and ground stations as part of the Global Aerosol Synthesis and Science Project (GASSP). The University of Oxford has developed the Community Intercomparison Suite, an e-science tool to efficiently exploit this and many other complex datasets for model evaluation (www.cistools.net).



Where is the atmosphere pristine in aerosols?



Number of days with similar aerosol concentrations in the simulated years 1750 and 2000

The uncertainty in the magnitude of the anthropogenic aerosol effect on climate is a major component in the large uncertainty in anthropogenic aerosol-cloud radiative forcing.

To determine the magnitude of anthropogenic aerosol abundance in the atmosphere, it is essential to know the natural aerosol background. In fact, it would be ideal if pristine* aerosol environments could be studied in the present-day atmosphere. However, the pervasiveness of air pollution makes identification of unperturbed regions difficult.

In a first step, global model simulations were carried out to define pristine aerosol regions in terms of a measure that compares conditions in the years 1750 and 2000 — the number of days with similar aerosol concentrations:

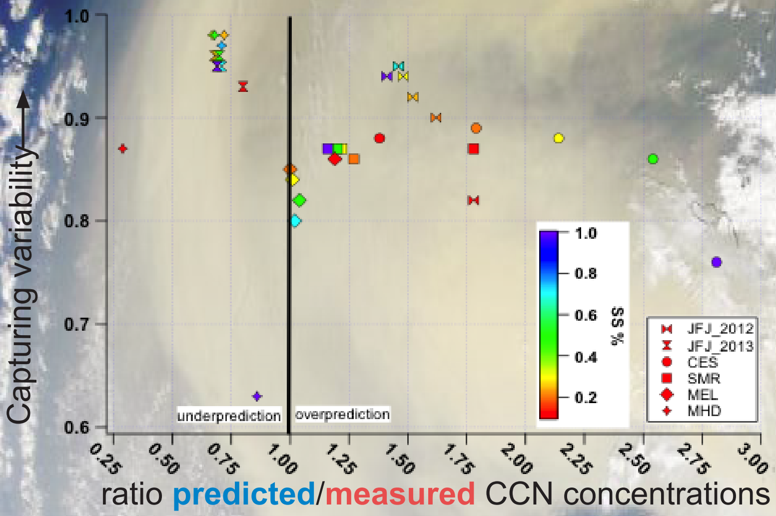
On the global annual mean, pristine aerosol regions cover 12% of the Earth, 16% of the ocean surface, and 2% of the land surface. There is a strong seasonal variation in pristine regions, with the most persistent conditions occurring over the equatorial Pacific. About 90% of pristine regions are found in the Southern Hemisphere. In the Northern Hemisphere, unperturbed conditions are transient and spatially patchy, potentially limiting the usefulness in reducing Northern Hemisphere forcing uncertainty.

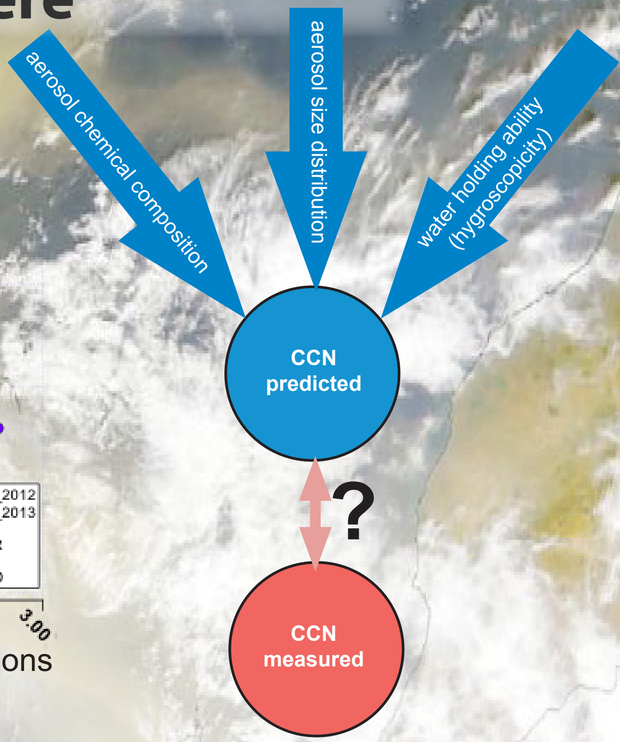
From Hamilton et al. (2014)

BACCHUS global models will be evaluated against the measurements collected in the project in the pristine regions identified in Hamilton et al. (2014).

*The term “pristine” is understood as most likely representing pre-industrial aerosol concentrations and conditions.

Improving our understanding of aerosol emissions to the atmosphere





CCN closure studies (see fact box) for 5 ACTRIS* long-term observation sites were performed. For this purpose, time series of CCN at several supersaturations, as well as of size distributions and chemical composition were collected for Jungfraujoch (JFJ), Cabauw (CES), Hyytiälä (SMR), Melpitz (MEL) and Mace Head (MHD). Aerosol observed at the sites differ in composition and water uptake ability. CCN concentrations were modelled based on measured aerosol size and chemistry and the water absorbing properties of the chemical components.

The predicted CCN variability captures well the variability of observed CCN. However, at most stations the CCN number concentration is over- or underpredicted. Deviations can partially be attributed to difficulties in the determining absolute particle concentrations by the instruments. Small-scale fluctuations in vertical velocity and hence the cooling rate were also found to be able to significantly alter the activated particle fraction.

*ACTRIS: Aerosols, Clouds, and Trace gases Research InfraStructure Network, www.actris.net

Fact box: Parameterizations and aerosol-CCN closure studies

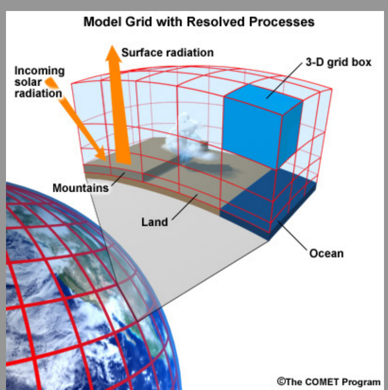


Illustration of grid cells (at the surface) and volumes (in the atmosphere) within a numerical climate model. Image courtesy of MetEd, The COMET Program, UCAR.

Parameterizations:

Physical processes such as radiative transfer, turbulence, convection, or cloud formation act on scales smaller than the grid of a general circulation model. If the complete physics of theses processes were to be computed explicitly for each model time step and at every grid-point, huge data amounts would swamp the computer. Since these processes cannot be neglected, simplifications called parameterizations are developed to describe the gross effects of the small-scale processes within a grid cell as accurately as possible.

Aerosol-CCN closure studies:

Comparison of theoretical predictions based on Köhler theory with observations of CCN concentrations. A successful closure study will accurately predict the concentration of CCN, and the derived relationship may be used as parameterization in a global model.

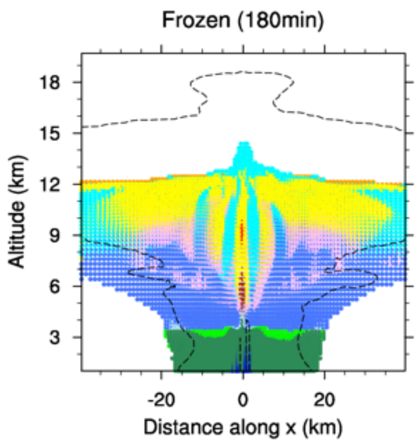
The role of aerosols versus dynamics in cloud processes in contrasting regions of the Earth

To understand aerosol effects on clouds, these have to be distinguished from the impact of updraft velocity that drives cloud formation. To identify key dynamical and microphysical processes controlling cloud systems and the relative roles of natural vs. anthropogenic aerosol emissions in each of them, detailed process modelling studies supported by the BACCHUS in-situ data sets and remote sensing data are being applied.

BACCHUS targets three key cloud regimes: a region of tropical deep clouds (Amazon), a subtropical region characterised by shallow clouds, as well as Arctic clouds which are of crucial importance for a region most strongly affected by climate change.

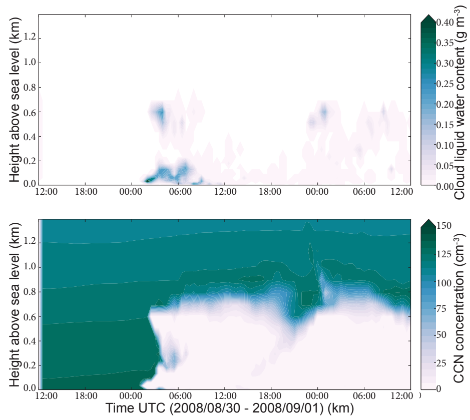
Tropics: ACCRIDION-CHUVA[1]

The campaign region is characterized by deep convective clouds with high aerosol variability from wildfires and urban influence. BACCHUS uses campaign aerosol and cloud property measurements to validate model simulations and to ensure the representativeness of the selected case. It is of crucial importance to constrain ice processes in current and future climate models. BACCHUS process models were employed to study the evolution of ice cloud microphysics in deep convection. Freezing and growth processes dominate in the central updraft of the cloud (yellow and red coloured parts), melting and evaporation dominate in the lower part of the cloud and downdraft areas (green and dark blue areas).



Arctic: ASCOS[2]

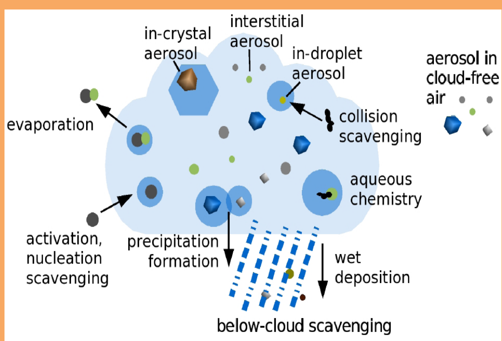
Drizzle collects aerosol as it falls, and removes that aerosol from the atmosphere. Because of the low aerosol concentrations in the Arctic, this process can reduce CCN concentrations below the levels needed to maintain a cloud, as observed during the ASCOS campaign. A newly-developed cloud-aerosol interactions microphysics scheme is able to reproduce this process within model simulations. (see figure to the right).



1 http://www.uni-leipzig.de/~meteo/acridicon-chuva/index.htm
2 http://www.ascos.se

Fact box: Process models

Process models are very comprehensive models of specific climate system components and interactions. They are used in BACCHUS to gain a detailed understanding of the key process driving aerosol cloud interactions that then can be used to develop and constrain their representation in the BACCHUS Earth System Models. Due to their high spatio-temporal resolution, process models are ideally suited for the direct comparison with the in-situ measurements conducted and compiled in BACCHUS.



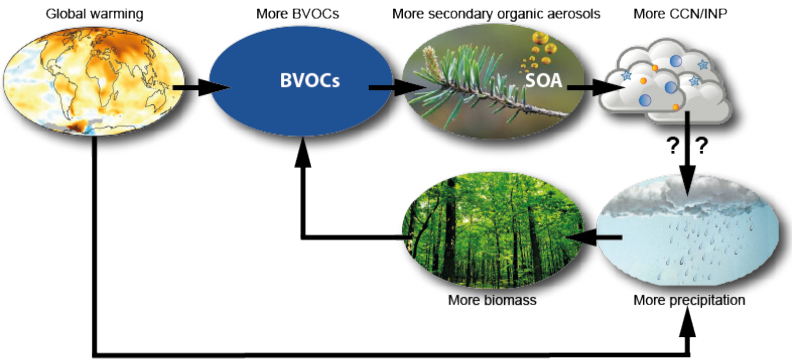
Investigating feedback processes that may enhance or dampen global warming

The climate is changing because of increasing anthropogenic greenhouse gas and aerosol emissions. The climate response to these emissions is determined by feedback processes, which are not well understood. In BACCHUS, we seek to reduce this uncertainty by addressing two of these feedback loops introduced below.

Earth System Models (ESMs) are an important tool in this investigation: they enable us to simulate the interactions between the various sub-systems that influence climate, i.e., the atmosphere, ocean, biosphere, land surface, and soil. For these simulations to be credible, we first need to implement into the models our best current understanding of the physical and chemical processes involved. This is being done in BACCHUS, using three ESMs.

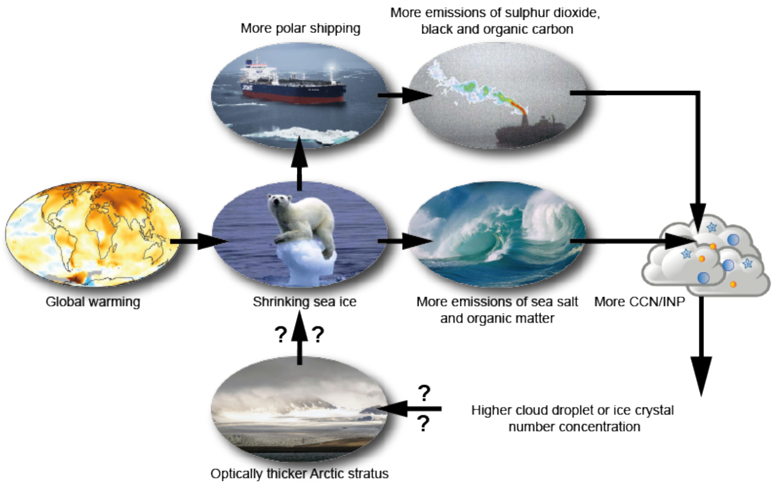
Biosphere-atmosphere-climate feedback:

In connection with photosynthesis, plants emit organic gases, so-called biogenic volatile organic compounds (BVOCs), which subsequently form particles in the atmosphere. Some of these particles influence cloud formation, while others scatter sunlight. In a warmer climate, if vegetation zones do not change, emissions of BVOCs will increase, leading to a climate feedback. If vegetation zones shift, yet more feedbacks are introduced.



Arctic sea ice – aerosol-cloud-climate feedback:

Due to global warming, summertime Arctic sea ice has shrunk by 40% over the last decades, the decline is expected to continue. More open water enables more human activity including polar ship traffic. These activities cause significant emissions of gases like sulphur dioxide (SO_2), which forms sulfate aerosols. The sulfate aerosols may potentially enhance the sea ice melting by making Arctic low clouds more dense, thereby emitting more infrared radiation to the surface, representing a positive feedback. However, if more INP were formed, ice clouds would form that would probably precipitate more resulting in optically thinner Arctic low clouds, representing a negative feedback. Shrinking sea ice may also increase natural aerosol emissions from the Arctic Ocean to the atmosphere, i.e. sea salt, organic matter, and sulfuric gases. In which way anthropogenic and natural aerosol emissions influence Arctic climate will require further investigation.



Mid-term summary

In BACCHUS, observational data of cloud condensation nuclei (CCN) and ice nucleating particles (INP) have been collected and are being stored and provided in the newly launched BACCHUS INP database. This database will be used to compile geographic differences in INP, a major scientific task in BACCHUS needed for future model approaches. To collect INP data, several campaigns have been performed with or without the financial support of BACCHUS. This way, an extensive set of new INP data could be collected. Also, vertically resolved field aerosol and cloud observations in key climate regions from aerosol/cloud lidars and cloud radars are analyzed. Closure studies, validation efforts, quality assurance work and re-analysis of past observations have started to be performed.

One key result from vertical in-situ measurements in air masses influenced by anthropogenic emissions is that more aged particles have a smaller water uptake ability than recently emitted ones. Further observations at a remote high altitude site revealed that aerosol particles from new particle formation events in the free troposphere do not necessarily grow large enough to be activated as CCN. The organic fraction of sea salt is being studied. It peaks when the phytoplankton bloom demises rather than during its growth phase.

Process modeling case studies have been identified and a case study protocol has been developed: The Arctic Summer Cloud-Ocean Study (ASCOS) has been chosen as main Arctic case study. Early results demonstrate sensitivity to changes in sea ice cover and aerosol that will be addressed in the multi-model intercomparison. The ACRIDICON-CHUVA campaign has been selected as the Amazon case study. Early results highlight the potential of the analysis of microphysical pathways to understand the complex ice cloud microphysics involved.

Significant progress has been made in developing parameterizations for marine organic emissions, terrestrial biogenic volatile organic compounds (BVOCs) and their contribution to secondary organic aerosol (SOA) formation and growth for use in ESMs. Two of the ESMs are now able to compute BVOC emissions interactively in a changing climate via their land surface modules, while such capability is being developed in the third model. A new parameterization for fire emissions has been developed and implemented into one of the ESMs. All three ESMs now explicitly simulate monoterpenes and isoprenes linked to the vegetation modules of the models. The condensation of these gases to pre-existing particles enables particle growth to sizes that in some cases are large enough for CCN activation. In this manner, the BVOC schemes link global warming induced changes in the biosphere to clouds and climate. Moreover modeling results based on measurements show that the contribution of marine organics to INPs is important in remote areas such as the southern ocean, whereas mineral dust is found to be dominant in most parts of the northern hemisphere.

References

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