BACCHUS

Impact of Biogenic versus Anthropogenic emissions on Clouds and Climate: towards a Holistic UnderStanding

Collaborative Project

SEVENTH FRAMEWORK PROGRAMME
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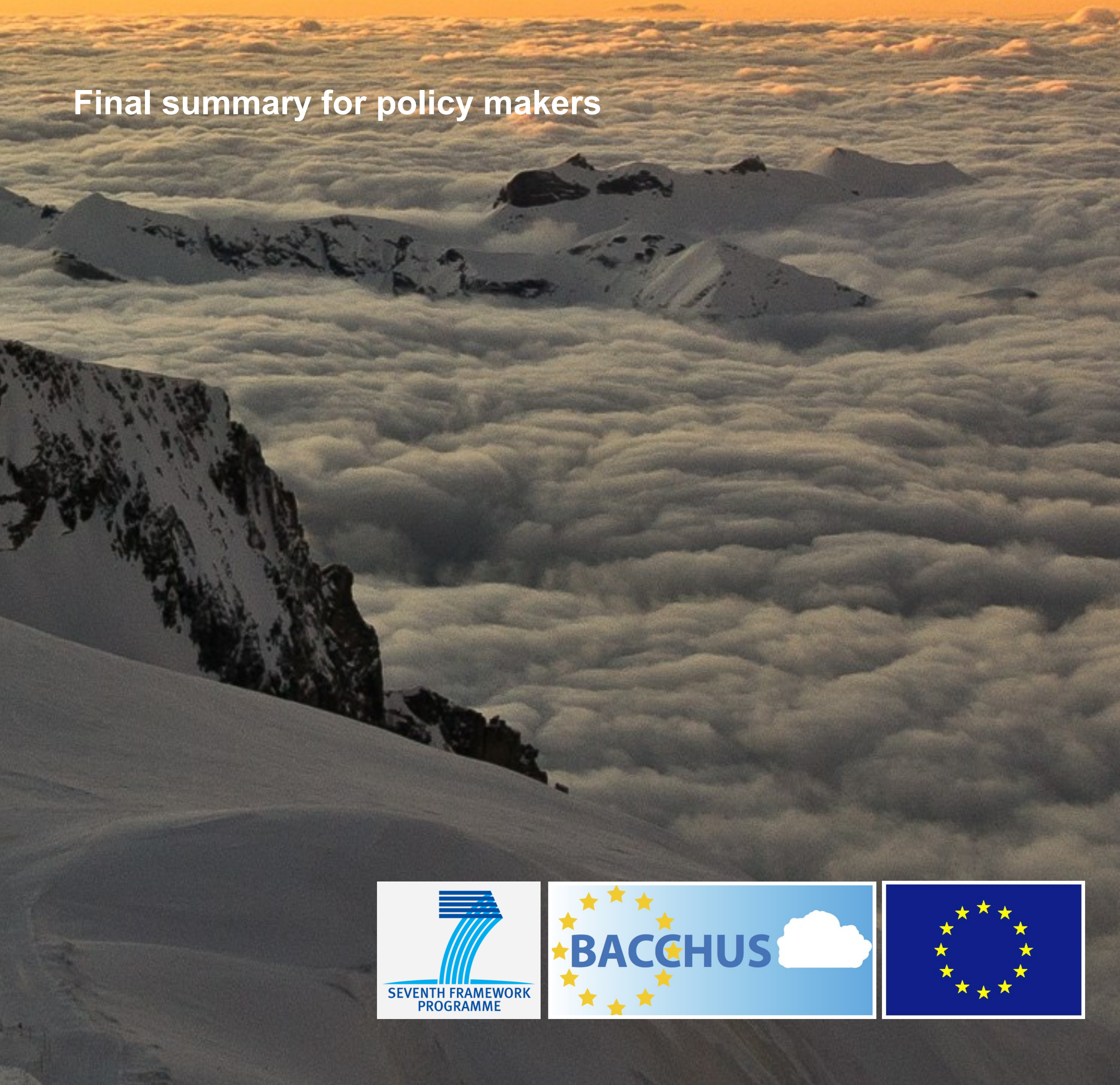
Summary of results
See attached PDF document.

Changes with respect to the DoW
No changes with respect to the Dow.

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



Final summary for policy makers

SEVENTH FRAMEWORK PROGRAMME

BACCHUS

BACCHUS at a glance

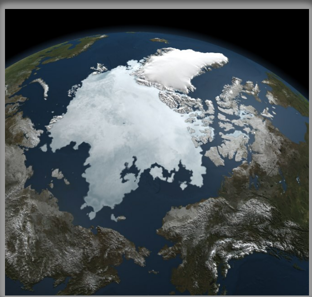
Clouds are important climate regulators. In the BACCHUS project key processes controlling clouds and climate and their feedbacks were quantified. This has been done by combining advanced measurements of cloud and aerosol properties in field projects and long-term observations with state-of-the-art numerical modelling.

Key findings

Ice nucleating aerosol particles

Aerosol particles are seeds on which cloud droplets and ice crystals form. In contrast to well-mixed, long-lived greenhouse gases, which warm the climate, aerosol particles cause a cooling. BACCHUS focused especially on the aerosol particles that act as ice nucleating particles. In fact, it created a database to gather measurements of these particles worldwide. These were primarily obtained from observations near the Earth's surface. Despite a high temporal and spatial variability of ice nucleating particles, one conclusion from BACCHUS was that most ice nucleating particles are of natural origin and are dominated by mineral dust and biological particles, such as pollen, bacteria and marine organic carbon. Land use changes due to human activities could therefore affect clouds through changes in emissions and properties of ice nucleating particles.

The Arctic environment



The Arctic is a unique environment. It has experienced and will experience rapid changes in the future. The large temperature increase is due to a combination of increased poleward heat transport and local feedbacks in the Arctic. An ice-free ocean also leads to more aerosol emissions, both natural (sea salt and sulphate) and through the expected increase in shipping. The BACCHUS project has shown that in a polluted Arctic, clouds will be thicker because of the increase in aerosol particles. Depending on local factors (environmental conditions, time of the year, meteorology) and also on the numerical model used, the timescale and amplitude of the aerosol response differs. A quantification of aerosol effects in Arctic clouds remains challenging. Overall, the Arctic remains a poorly understood natural system, which makes it potentially vulnerable to inadvertent pollution.

Atmosphere-biosphere-interactions

Changes in climate affect natural aerosol emissions and their precursors. More biogenic volatile organic carbon will be emitted that leads to more aerosol particles. This results in more but smaller cloud droplets and more reflection of sunlight back to space. It causes a cooling, which partly offsets the greenhouse gas warming. This feedback loop cannot be regarded as isolated from anthropogenic emissions. The biosphere is changed by human activities. Therefore, a proper assessment of anthropogenic interference requires studying anthropogenic emissions in concert with biogenic emissions.

Outlook and research gaps

- Combine surface observations of aerosol particles with measurements in and around clouds.
- A quantitative understanding of the effect of anthropogenic pollution for Arctic clouds is needed.
- A quantitative understanding of the role of natural aerosol emissions in the Anthropocene is required.

BACCHUS facts

The core idea of BACCHUS has been to quantify key processes controlling clouds and climate and their feedbacks. This has been done by combining advanced measurements of cloud and aerosol properties in field projects and long-term observations with state-of-the-art numerical modelling (Figure 1). Specifically, BACCHUS aimed to characterize the importance of biogenic versus anthropogenic aerosol emissions for cloud formation and climate.

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 (INPs).

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.

BACCHUS

IMPACT OF BIOGENIC VS. ANTHROPOGENIC EMISSIONS ON CLOUDS AND CLIMATE: TOWARDS A HOLISTIC UNDERSTANDING

Instrument:	FP7 collaborative project
Total Cost:	EUR 11,463,091
EC Contribution:	EUR 8,746,587
Duration:	54 months
Start Date:	1 Dec 2013
Consortium:	21 partners from 13 countries
Project Coordinator:	ETH Zürich (CH)
Project Web Site:	www.bacchus-env.eu
Key Words:	Aerosol-cloud interactions, climate feedbacks, biosphere, organic carbon, climate change, Arctic, Amazon, ice nucleation, field studies, satellite studies, long-term observations, process & earth system models

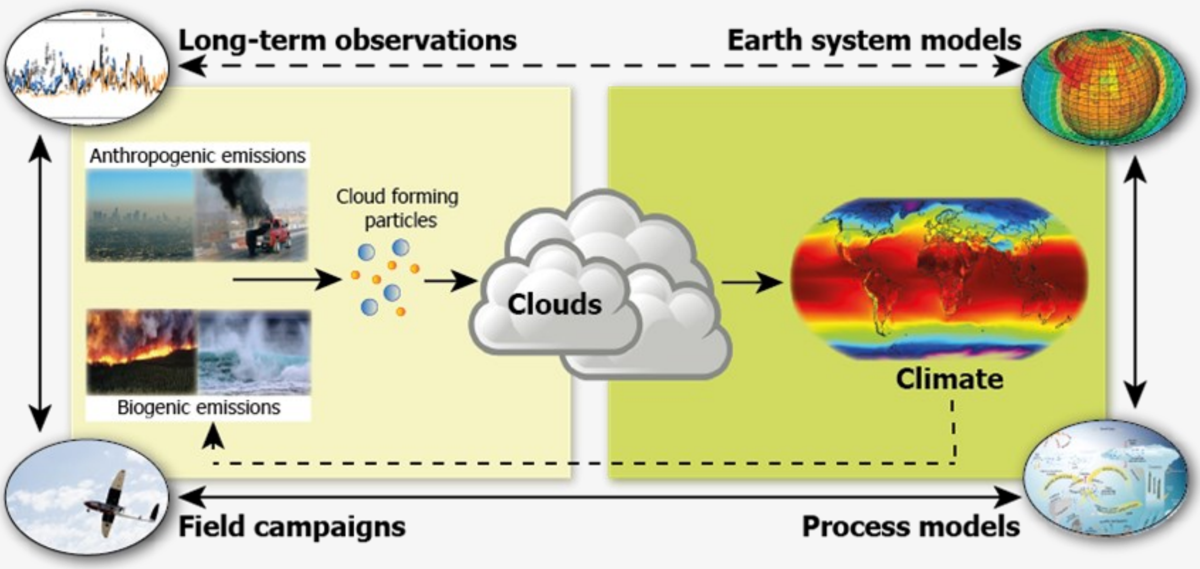


Figure 1: Objectives of the BACCHUS project.

BACCHUS in a broader context

How clouds change in a warmer climate remains uncertain. Interactions between aerosols and clouds play a key role for changes in the Earth's energy budget since pre-industrial times but are still associated with a large spread and low scientific level of understanding (see Figure 2).

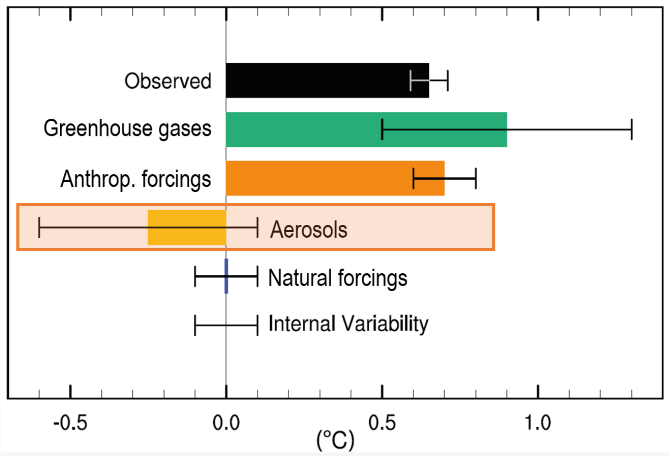


Figure 2: Assessed likely ranges (whiskers) and their midpoints (bars) for warming trends over the 1951–2010 period due to well-mixed greenhouse gases, anthropogenic forcings, aerosol (anthropogenic forcings other than well-mixed greenhouse gases), natural forcings and internal variability. Figure adapted from Stocker et al., 2013.

A major part of the uncertainty in how aerosol and cloud processes respond to changes in anthropogenic and natural aerosol emissions is due to the lack of a 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 has been to explore these two topics as they seem to be key in the climate system. Specifically, measurement capabilities of ice nucleating particles were still insufficient at the beginning of the project as was the global coverage of measurements of ice nucleating particles. This limited our understanding of ice formation and ice cloud evolution in different environments. In addition, as the biosphere responds to warming in a changing climate, couplings 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.

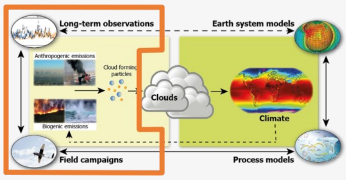
Understanding the natural aerosol abundance before the industrial era is essential for identifying the magnitude of the anthropogenic forcing due to aerosol-cloud interactions as well as changes in natural aerosols due to anthropogenic activity. In BACCHUS these complex aerosol-cloud interactions and feedbacks involving natural aerosols have been further investigated.

The BACCHUS project gathered Europe's and Israel's leading scientists in aerosol and climate research, the highlights of which are presented in this brochure, which is intended for stakeholders, policymakers, and the interested public.

By having provided a more accurate estimate of the background aerosol concentrations representative of pre-industrial times, BACCHUS contributes to an improved quantification of the anthropogenic aerosol radiative forcing since the pre-industrial times. To avoid dangerous anthropogenic interference with the climate system, the United Nations Framework Convention on Climate Change has adopted to limit global warming below 2 ºC (2 degree target). Allowable emissions to stay below the 2 ºC target depend heavily on Earth's climate sensitivity, i.e. by how much the Earth's temperature warms when CO_2 concentrations are doubled. Within BACCHUS this climate sensitivity was studied and how it depends on the present state of mixed-phase clouds, that is clouds that contain both cloud droplets and ice crystals.

A better understanding of biosphere-aerosol-cloud-climate interactions as achieved in BACCHUS allows to better inform the policy makers and thus to ensure a better protection of humans and ecosystems' health. BACCHUS will be particularly closely allied with the current and on-going review of the European Commission's Thematic Strategy on Air Pollution and Air Quality regulation.

Highlight — Global impact through data leveraging



Ground-based INP data were put in a broader context by having collected cloud-relevant data also by remote sensing (lidar, radar, satellites) and vertical profiles of some aerosol/cloud properties with unmanned aerial vehicles in previously undersampled regions (BACCHUS participation in Barbados, Cyprus, Amazon, RV Polarstern cruises, PEGASO, ACE-SPACE as indicated in Figure 3).

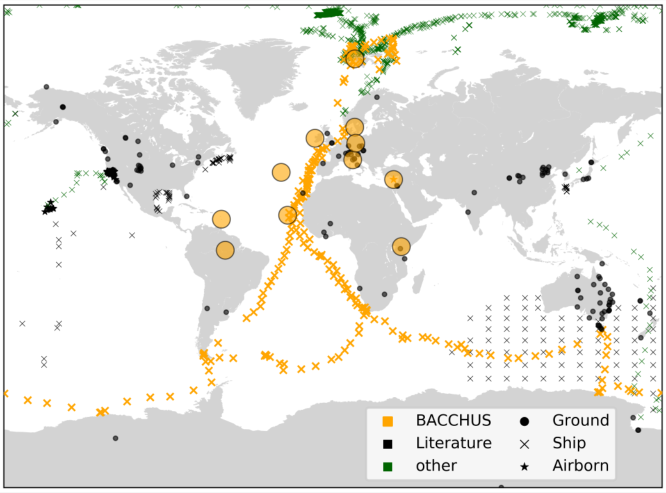


Figure 3: Locations of ice nucleating particle measurements from literature (black), data obtained within the BACCHUS project (yellow) and other recent data (green).

Prior to BACCHUS, only very few measurements of INPs existed over the oceans, indicated by the black crosses in Figure 3. BACCHUS helped tremendously to chart the global picture by having conducted and participated in various field experiments. Of particular relevance for the oceanic INP concentrations were the research cruises across the Atlantic, in the Arctic and around Antarctica (ACE-SPACE).

In addition to ship based expeditions and several field deployments to remote locations, two major field activities with focus on aerosol chemical composition, microphysical, and cloud-relevant properties were realized within BACCHUS.

At Mace Head at Ireland's west coast, very clean marine air was sampled and in Cyprus the highly polluted and dusty Middle East/Eastern Mediterranean environment was probed. The results confirmed that most INPs are of natural origin. Of these, biological particles are the best INPs, initiating ice nucleation already at temperatures higher than -10 °C. Dust particles are almost everywhere (together with haze and smoke) and control heterogeneous ice formation in the temperature range between -18 to -35°C. Marine particles are less efficient INPs. The concentration of marine INPs is roughly 1000 lower than INPs from dust particles. However, as is visible from Figure 4, the local concentration of INPs can vary between 0.1 and 1000 m^{-3} because sometimes dust and biological particles are transported far distances over the oceans.

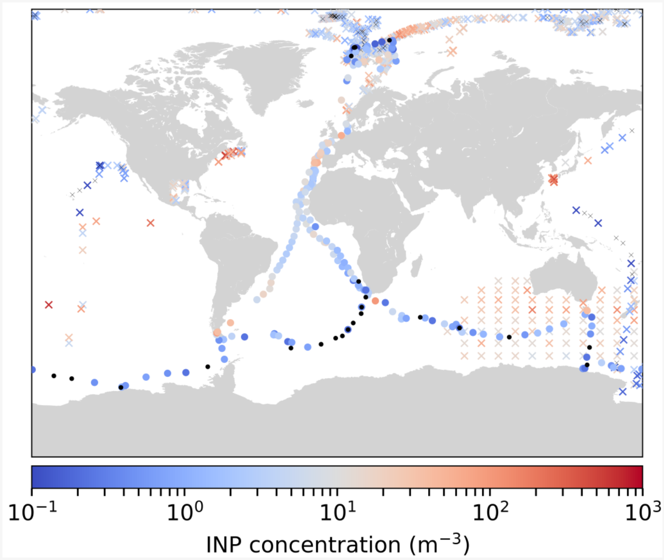
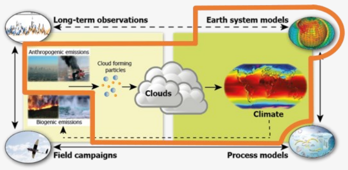


Figure 4: World map of INP concentrations at –15 °C over the oceans at the project end of BACCHUS. Data courtesy of André Welti, Caroline Leck, Paul DeMott.

The INP data are currently being synthesized in the INP database allowing to conduct meta-analysis on INPs. Much of this information is already or will be used in the numerical model simulations in order to validate and improve the global climate models used for future climate projections.

Highlight — Importance of Arctic pollution in the future



Ship emissions in the future Arctic

The Arctic sea ice area in late summer (Jul/Aug) and early autumn (Sep/Oct) will considerably decrease in the future, which will enhance the emissions of natural aerosol particles from the ocean (e.g. sea salt and organics). Furthermore, the ship traffic across the Arctic Ocean might increase with less sea ice, which would also lead to an increase in aerosol particle concentration (e.g. soot). These aerosol particles can impact radiation directly or indirectly by changing cloud microphysical properties.

Using a global aerosol-climate model, the natural aerosol emissions were found to be enhanced over the Arctic Ocean (the year 2050 compared to the year 2004). Both changes in aerosol particles and meteorology lead to an increase in the cloud thickness, i.e. both the number concentration and the size of the cloud droplets will increase in future (Figure 5).

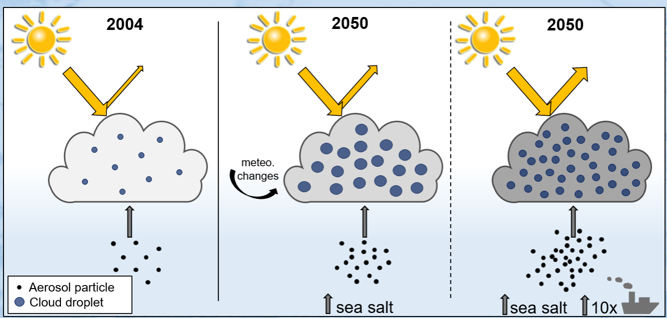


Figure 5: Change of cloud properties in the future without and with high Arctic shipping emissions. Arrows represent change in cloud reflectivity between the different cases, where darker clouds indicate higher optical thickness and thus higher reflectivity.

The cooling effect of both aerosol particles and clouds is larger in the future. This is mainly caused by changes in the surface reflectivity. The radiative effects of aerosols and clouds strongly depend on the surface reflectivity; as an example, a cloud can have a cooling effect if the surface is dark, but a warming effect if the surface is bright (Figure 6).

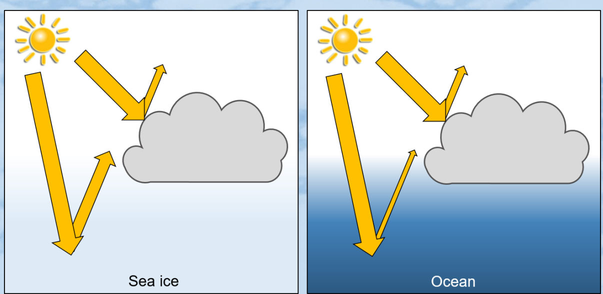


Figure 6: Radiative properties of clouds over sea ice and open ocean.

The reduction in highly reflective sea ice, which is replaced by a dark ocean surface, thus increases the cooling component of aerosols and clouds. Averaged between 75° and 90° N, the radiative forcing of aerosols decreases from 0.53 Wm^{-2} to 0.36 Wm^{-2} and the cloud radiative effect from -36 Wm^{-2} to -46 Wm^{-2} in late summer.

The Arctic ship emissions have a significant impact in our simulations only when increased by a factor of 10, which is an upper estimate considering other Arctic ship emission inventories and uncertainties in emission factors. With the tenfold increase in ship emissions, the cooling effect of clouds in late summer is clearly enhanced (Figure 5). The increase in aerosol particles leads to more cloud droplets and a higher cloud water content (Figure 5), which increases the total surface area of the clouds and enhances their cloud radiative effect from -48 Wm^{-2} to -52 Wm^{-2} (averaged between 75° and 90°N).

Aerosol perturbations in process models

Aerosol perturbations in the Arctic were also investigated in a study including regional climate and large eddy simulation models. All participating models simulated a summertime (Aug 31st - Sept. 1st) period in the Arctic during which the cloud droplet concentration was limited by the available aerosol particles. All models reproduce the observed cloud thinning or break-up when fewer aerosol particles are available. This cloud response is, however, only simulated if aerosol-cloud interactions are calculated interactively. On the other hand, an increase in the cloud droplet concentration increases cloud water content and decreases the net outgoing longwave radiation at the surface, thus having a warming effect on the surface, potentially resulting in an accelerated Arctic temperature increase.

High resolution simulations of springtime stratocumulus mixed-phase clouds show that, if exposed to short-term pollution, clouds equilibrate back to their initial state after 10-14 hours, thus effectively buffering the initial aerosol perturbation (Figure 7). This response is seen in clouds over open ocean and sea ice with the aerosol response over sea ice being longer lasting and slightly delayed. This is due to less moisture available in the boundary layer. A quantification of this effect is pending.

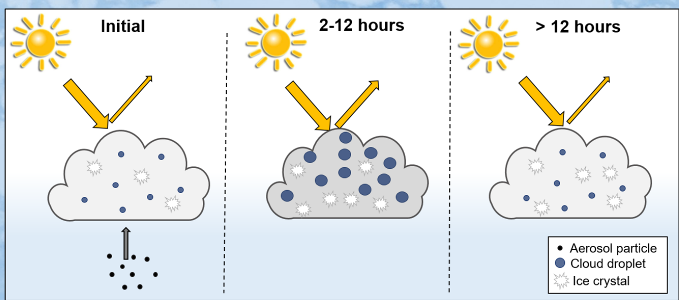
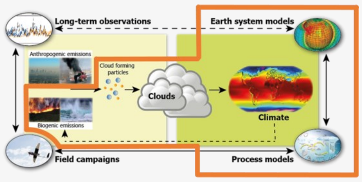


Figure 7: Aerosol buffering effect in Arctic mixed-phase clouds.

Highlight — Importance of biosphere-atmosphere interactions



The aim of BACCHUS has been to determine if climate change affects the emissions of gases, so called BVOCs (biogenic volatile organic compounds) from vegetation. An increase in BVOCs due to climate change leads to the formation of more aerosol particles (SOA, secondary organic aerosols). Higher concentrations of aerosol particles can affect clouds by increasing the number of cloud droplets, causing the clouds to reflect more sunlight (see also Figure 5). This will cause a decrease in temperature, resulting in a negative climate feedback. The initial hypothesis, shown in Figure 8a, also suggested that the increase in SOA would lead to an increase in diffuse radiation, which could be beneficial for plants and increase the biomass production (gross primary production, GPP) and BVOC emissions. The effect on the plants was found to be less important compared to their effects on clouds and temperature in the upper branch of the feedback loop. Instead, the increased scattering of sunlight of aerosol particles causes a noticeable reduction in temperature, as indicated in Figure 8b. The results of BACCHUS show that the feedback loop, including the modified lower branch is relevant for future climate. The feedback could provide a negative radiative forcing of roughly -0.5 W m^{-2} in a 2xCO_2 climate, which is significant compared to the positive radiative forcing associated with a doubling of CO_2 of 3.7 W m^{-2}.

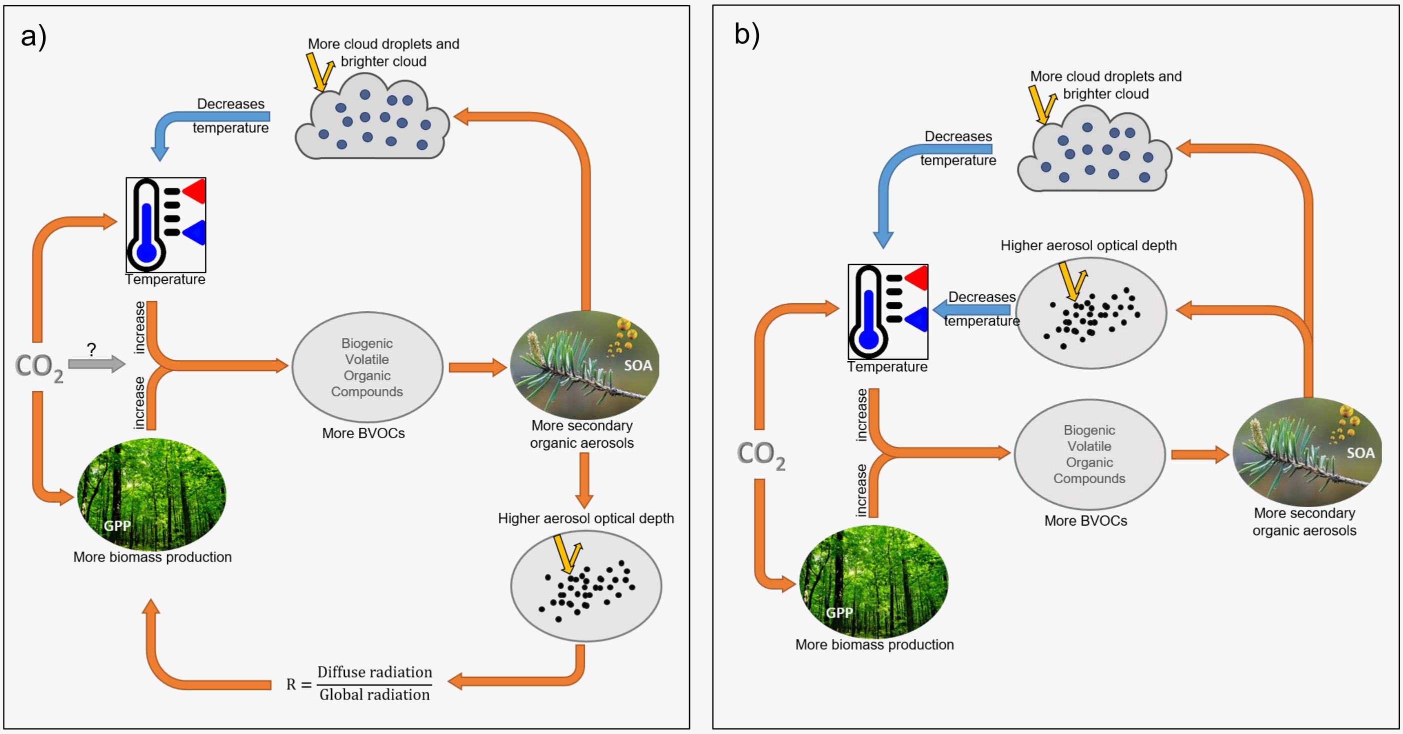


Figure 8: a) Original feedback loop and b) modified feedback loop after the BACCHUS project.

Relevance for EU policy

The BACCHUS project can be linked to other ongoing efforts such as:

- Work initiated during BACCHUS on the anthropogenic aerosol forcing will be relevant for the upcoming sixth assessment report of Intergovernmental Panel for Climate Change (IPCC).
- Work conducted in BACCHUS on Arctic clouds will be incorporated and be beneficial for the Arctic Monitoring and Assessment Programme work on the warming Arctic.
- The UNECE convention on Long-Range Transboundary Air Pollution (LRTAP) programme and Directorate General Environment could benefit from the results obtained in BACCHUS on natural and anthropogenic aerosols.
- Improvements of the Earth System Models during BACCHUS furthers our understanding of climate change and benefits the World Climate Research Programme (WCRP) and Directorate General Clima.

Research needs

BACCHUS results highlight the importance of the following open questions that are relevant for Directorate General Research and Innovation :

- Development of low-weight (and low-cost) instrumentation for unmanned measurement platforms for in-cloud observations and other in-accessible regions.
- Human activities in the Anthropocene affect natural aerosol emissions. Those changed emissions will have an influence on climate next to anthropogenic emissions. However, their detailed climate impact is not yet known and requires further investigations through improved Earth system models.
- The Arctic and other extreme environments are susceptible to rapid climate change. This makes them potentially vulnerable to socio-economic development warranting further research.

What's needed?

- Fundamental research on aerosols and cloud microphysics
- Design of advanced interdisciplinary studies for real-time field experiments in and around clouds
- Large EU projects bringing together the experts in the relevant disciplines

BACCHUS dissemination and outreach

- Inter-journal special issue ACP-AMT-GMD: https://www.atmos-chem-phys.net/special_issue911.html
- List of BACCHUS publications: https://www.bacchus-env.eu/data/pubanddel.html
- Outreach activities and events: see https://www.bacchus-env.eu/

Reference

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Arctic sea ice (1): https://phys.org/news/2010-09-arctic-sea-ice-captured-satellite.html; Credit: NASA Goddard's Scientific Visualization Studio
Forrest site, Hyytiälä, Finland (1): https://www.helsinki.fi/en/programmes/master/forest-sciences/research/hyytiala-forestry-field-station
Mace Head field site, Ireland (4): Photograph by Paul J. DeMott
Cyprus field site, Cyprus (4): https://www.mpic.de/forschung/partikelchemie/gruppe-schneider/projekte/inuit/inuit-cyprus-2017.html
Sea ice during ACE-SPACE (5): Photograph by Julia Schmale
Forrest site with clouds (6): Photograph by Larissa Lacher
Onboard the Russian research vessel *Akademik Tryoshnikov* (7): Photograph by Julia Schmale

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