# BACCHUS

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

Collaborative Project

SEVENTH FRAMEWORK PROGRAMME
ENV.2013.6.1-2

Atmospheric processes, eco-systems and climate change

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| **Responsible scientist/administrator:** | Moa Sporre (UiO) |
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| **Contributor(s):** | Moa Sporre (UiO), Terje Berntsen (UiO), Alf Grini (UiO), Risto Makkonen (UHEL), Jens Debernard (UiO) |
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| **Internal reviewer:** | Ulrike Lohmann (ETHZ) , Risto Makkonen (UHEL) |

## Summary of the results

### Objectives

This deliverable is related to research question 2b in the BACCHUS DoW: What are the main feedback mechanisms involving aerosol-cloud interactions between the terrestrial and marine biosphere and the climate, including local changes in precipitation? How will these aerosol-cloud interactions change in a changing climate?

The main focus of this deliverable has been to investigate feedback mechanisms involving the terrestrial biosphere, aerosols, clouds and climate. Such a feedback is shown in Fig 1, (Fig 1.6 from the BACCHUS DoW). The objective has been to investigate each step along this feedback loop but also to estimate the overall importance of this feedback in projecting the future climate. Another objective of this deliverable is to investigate how sensitive the climate in Earth System Models (ESM) is to processes within this feedback loop.

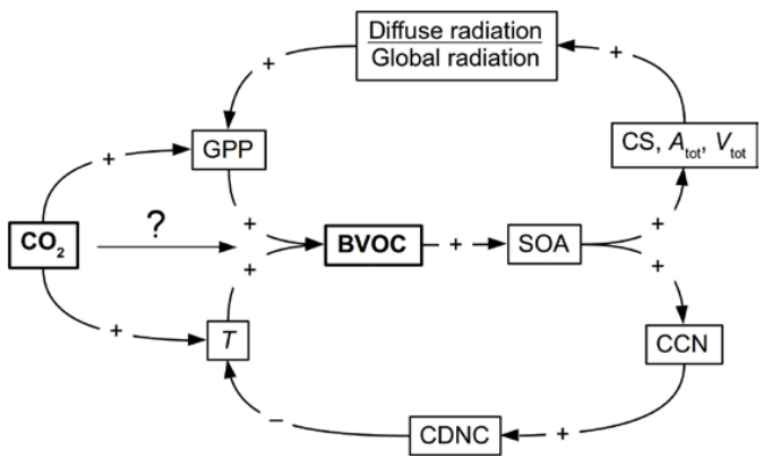


Figure 1. Possible feedback loop between the biosphere and global warming starting with an increase in $CO_2$ that affects gross primary production (GPP), temperature (T), which in turn affects the concentration of SOA via BVOC. If an increase in SOA influences cloud properties via increases in CCN and CDNC, it could reduce temperature. On the other hand, an increase in the total aerosol scattering cross section (CS), total area ($A_{tot}$) and volume ($V_{tot}$), will increase the fraction of diffuse to global radiation, which increases GPP. Figure modified from Kulmala et al. (2013).

### Experimental Setup

The feedback has been investigated using the Norwegian Earth System Model (NorESM) (Bentsen et al. 2013; Iversen et al. 2013; Kirkevåg et al. 2013). The emissions from the BVOCs (isoprene and monoterpenes) are calculated by MEGAN (Model of Emissions of Gases and Aerosols from Nature) version 2.1, which is included in CLM (the Community Land Model), the land model in NorESM. The atmospheric model CAM-Oslo (the Community Atmosphere Model with the OsloAero aerosol module) is run interactively with the land model and both the vegetation and BVOC emissions can respond to the changes in temperature, radiation and $CO_2$. In CAM-Oslo, isoprene and monoterpene can react with $O_3$, OH and $NO_3$. The reaction between $O_3$ and monoterpene yield low-volatile SOA (LVSOA), which can contribute to new particle formation in the model. The other 5 reactions (oxidation of monoterpene with OH, $NO_3$ and isoprene with $O_3$,

OH, $NO_3$) result in semi-volatile SOA (SVSOA) which can condense onto pre-existing aerosol particles.
The model was run with fixed sea surface temperatures (SST). Three experiments were set up to investigate the BVOC feedback. In the first experiment, the response of the feedback to changes in $CO_2$ was tested by doubling $CO_2$ with respect to present-day levels, denoted as 2x$CO_2$. Note that in this experiment the main effect of $CO_2$ is not on temperature (since the SSTs are fixed), but on plant responses to enhanced $CO_2$ in the air. In the second experiment, the feedback response to a change in temperature was tested by increasing the SST to year 2080 levels according to RCP8.5 (denoted +SST), roughly corresponding to the temperature response at 2x$CO_2$ concentrations. In the last experiment, we increased both $CO_2$ and SST to be able to study the full impact of the feedback (2x$CO_2$+SST). To test whether the expected decrease in anthropogenic emissions in the future would affect the importance of the feedback we also ran this experiment with emissions of aerosol and precursor gases at pre-industrial levels (2x$CO_2$+SST-PI).
In order to evaluate the strength of the feedback, two simulations were ran for each experiment. One simulation with interactive BVOC emissions that responded to changes in climate and $CO_2$ (FB-ON) and one simulation where the BVOC emissions were kept constant at present-day levels (FB-OFF). To ensure that differences in meteorological conditions, inevitable when models are free-running, are not masking the effect from the feedbacks, the FB-ON and FB-OFF simulations were nudged to the same meteorology, one for each experiment. Thus, the two simulations in each experiment are almost identical, except for the impact of BVOC emissions on fast responding physical processes such as cloud formation.

There were also sensitivity simulations ran to test how sensitive the cloud forcing in the model is to changes in the parametrizations of BVOC/SOA. All sensitivity simulations were run for 10 years and nudged to ERA-data (from the European Center for Medium Range Forecasts) for the years 2000-2009. The 6 sensitivity simulations are:

- CTRL – a control simulation with the standard model setup.
- Yield_higher – the yield for all equations involving SOA formation from BVOCs is increased by 50%.
- Yield_lower – the yield for all equations involving SOA formation from BVOCs is decreased by 50%.
- no_LVSOA – all SOA formed from BVOC goes to the SVSOA and none goes to the LVSOA. The LVSOA can contribute to nucleation in the ESM while the SVSOA only condenses onto existing particles.
- no_isoprene – the isoprene emissions are turned off.
- no_monoterpene – the monoterpene emissions are turned off.

## Results

### 1.1. Feedback investigation

The difference in the emissions between the FB-ON and FB-OFF is shown in Fig. 2. The feedback results in increasing BVOC emissions, especially in the tropics where also the BVOC emissions are the highest. The largest relative increase in the emissions occurs over the boreal forest in the Northern Hemisphere. The smallest effect of the feedback is seen in the experiment where only

$CO_2$ was changed and the largest effect is seen in the experiments where both $CO_2$ and temperature were changed. The BVOC emissions are lower in the FB-ON simulations for some tropical regions, in the simulations with increased SST (Fig 2b). This is caused by a decrease in the vegetation that seems to be caused by heat stress.

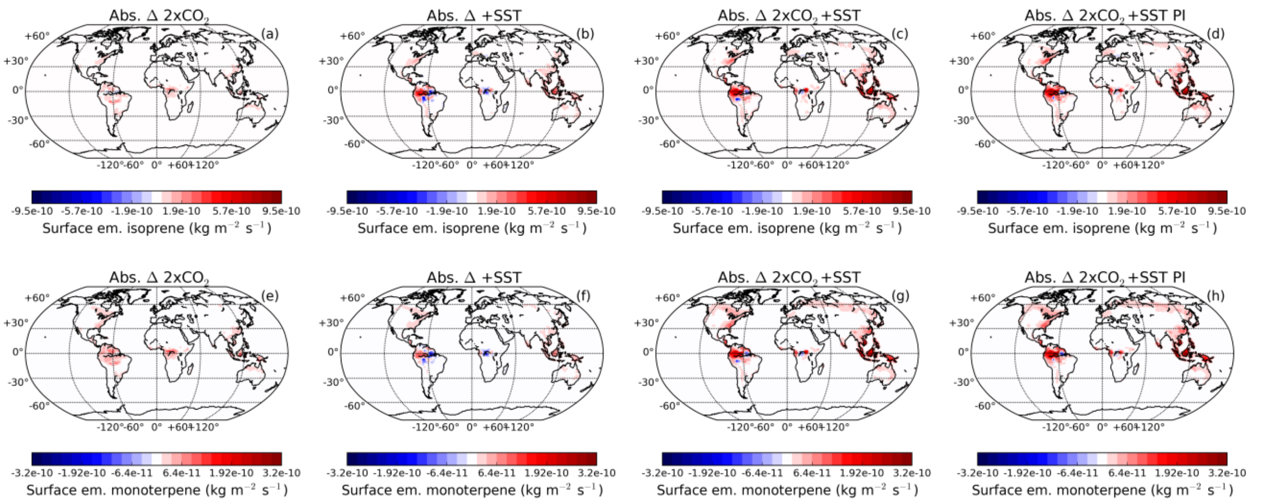

Figure 2. The difference in isoprene (a-d) and monoterpene (e-h) between the FB-ON and FB-OFF simulations for the four feedback experiments.

The higher BVOC emissions due to the feedback loop result in a higher SOA production, as can be seen in Fig. 3. The largest difference in column burden of SOA due to the feedback loop occurs over the tropics and downwind of these regions. Moreover, the difference in column burden of SOA is also large over the boreal forest regions and downwind of these as a result of the feedback loop. The feedback effect on the SOA column burden is lowest in Fig. 3a where only $CO_2$ is changed and the largest effects on SOA are seen in Fig. 3c and d. The lower SOA values over Africa in the FB-ON simulation (Fig. 3b) are a result of the decreasing BVOC emissions. The differences in aerosol number concentration ($N_a$) in Fig 3 e-h show similar patterns as the differences in SOA, but the difference in $N_a$ does not extend downwind of the sources.

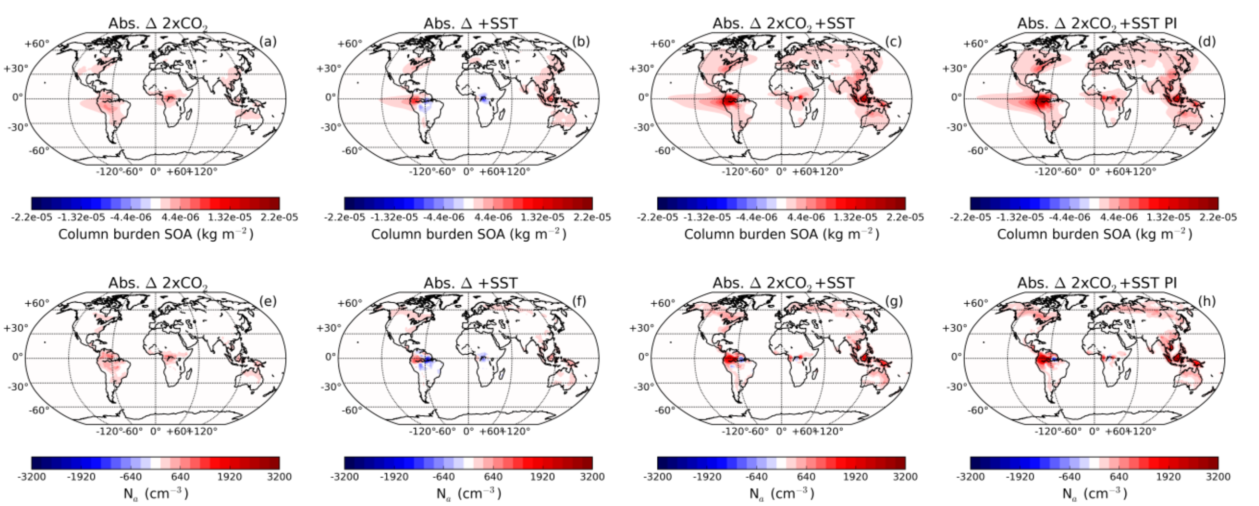

Figure 3. The difference in column burden of SOA (a-d) and the total aerosol number concentration in the lowest model layer (d-h) between the FB-ON and FB-OFF simulations for the four feedback experiments.

1.2. Temperature feedback

Starting with the lower half of the feedback loop in Fig. 1 we next look at CCN (cloud condensation nuclei) to determine whether the amount of CCN is increased due to the feedback loop. The difference in CCN between the FB-ON and FB-OFF simulations is shown in Fig. 4. The CCN concentrations at low supersaturations (0.2%) increase over polluted regions, particularly noticeable in Fig. 4c. There are higher $N_a$ in these regions and it seems that the largest absolute changes also occur here. In some regions over the boreal forests, the amount of CCN at 0.2% supersaturation decreases since there are more particles to compete for the condensing vapors. This results in fewer particles being able to grow large enough to be activated into cloud droplets at 0.2% supersaturation.

At higher supersaturations (1%), the CCN concentrations increase almost everywhere. However, the regions that saw a decrease in the CCN at 0.2% are associated with more smaller particles that inhibit the growth of larger particles. These show an increase in CCN at 1%. At 1% supersaturation, also the smaller particles can be activated into cloud droplets, which increases the CCN concentration.

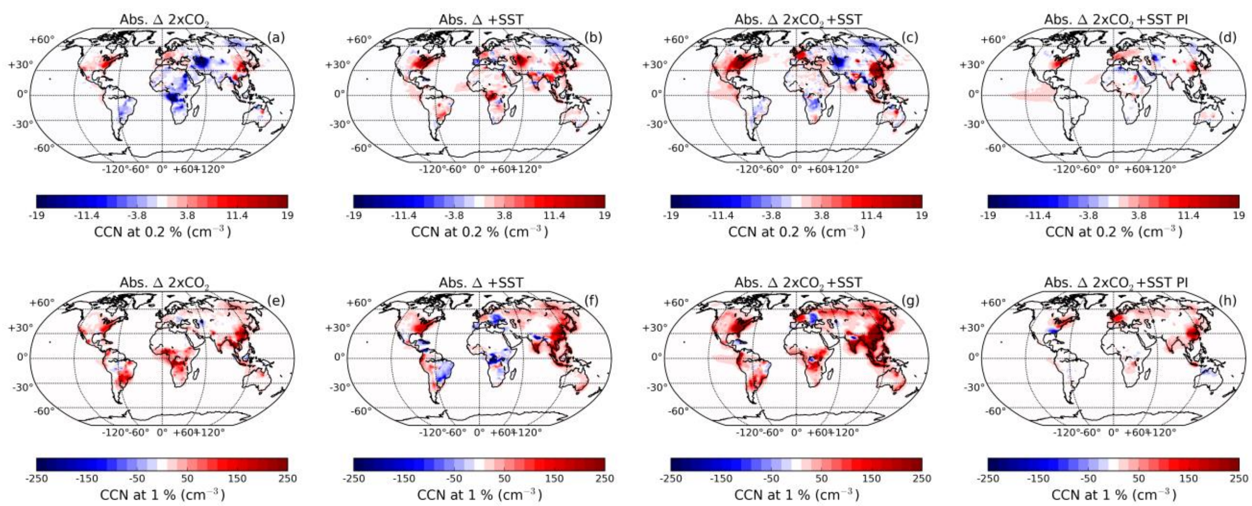


Figure 4. The difference in CCN at 0.2% supersaturation (a-d) and CCN at 1% supersaturation (e-h) between the FB-ON and FB-OFF simulations for the four feedback experiments. Note the different color scales for subfigures (a-d) and (e-h).

Continuing along the lower part of the feedback loop in Fig. 1, we will now look at cloud properties. The vertically averaged cloud droplet number concentration (CDNC) is plotted in Fig 5. The strongest effect on CDNC from the feedback loop is seen in the simulations where both $CO_2$ and SST are changed (Fig 5 c and d). There are higher values of CDNC associated with the feedback loop in the Arctic, the boreal forest regions in the NH as well as over and downwind of the tropics. The CDNC increases in those regions with large absolute differences in CCN in Fig. 4 but also regions downwind of these. Clouds in these regions form in clean environments and are susceptible to smaller changes in CCN that do not show up in the plots with absolute differences.

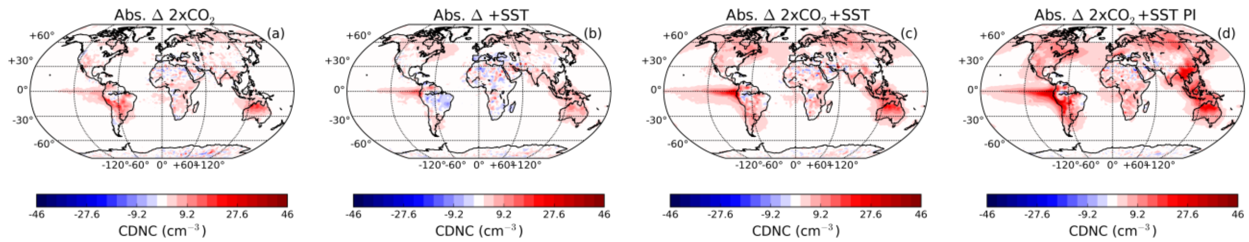


Figure 5. The difference in the vertically averaged CDNC between the FB-ON and FB-OFF simulations for the four feedback experiments.

Since we are running simulations with fixed SST, the temperature in the model cannot freely respond to the changes in the cloud properties associated with the feedback loop and we can therefore not estimate the impact of clouds on temperature using these simulations. However, studying the difference in net cloud forcing (NCF) between the FB-ON and FB-OFF simulations indicates in which direction the temperature change would go and whether the changes in the cloud properties have the potential to affect temperature. The results for NCF are shown in Fig. 6. The difference NCF is negative, indicating that the feedback contributes with a reduction in the warming caused by the greenhouse gases, consistent with the feedback loop in Figure 1. The negative NCF is strongest in the experiments with changes of both the $CO_2$ and SST (Fig. 6c and d) and over and downwind of the tropics as well as over the boreal forest regions and the Arctic. The global average difference in NCF for the 2x$CO_2$+SST simulations is -0.42 W $m^{-2}$. The magnitude of this NCF (approx. 25% of the current CO2 forcing) indicates that the feedback can be potentially important for climate.

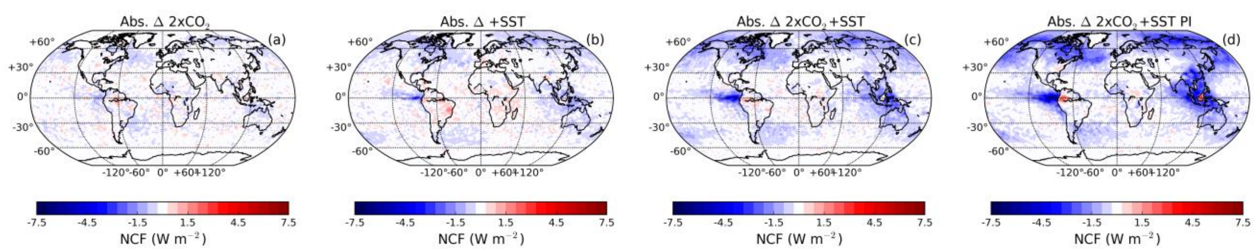


Figure 6. The difference in the NCF (calculated according to Ghan (2013)) between the FB-ON and FB-OFF simulations for the four feedback experiments.

## 1.3. GPP feedback

Next, we investigate the upper part of the feedback loop in Fig 1. The aerosol optical depth (AOD), which can be used as a proxy for the aerosol scattering cross section (CS), total area ($A_{tot}$) and volume ($V_{tot}$) is plotted in Fig. 7 (a-d). AOD is higher over the regions where the emissions increase the most, in particular over the tropics. As in the case for many of the other variables, we see the strongest impact on the AOD in simulations with changes of both SST and $CO_2$. In Fig. 7 (e-h) the ratio between the diffuse radiation and the global radiation (R) is shown. In the tropics, where AOD increases strongly, we find that the differences in R correspond to the differences in AOD but are limited to a difference of 8 %. However, in the other regions the AOD effect on R seems to be missing. In a more thorough investigation of this (not shown), we find that R is dominated by differences in cloud fraction rather than the differences in AOD. Thus, what happens to the clouds in the lower part of the feedback loop is dominating the effect of the AOD. Furthermore, looking at the differences in GPP (Fig. 7 i-l), it does not seem as if the differences in R have any effect on the differences in GPP as confirmed by further statistical analysis. GPP is instead dominated by what temperature changes. Hence, also the response of GPP is dominated by the lower part of the feedback loop in Fig. 1. To conclude, using NorESM, we find no support for the upper part of the feedback loop.

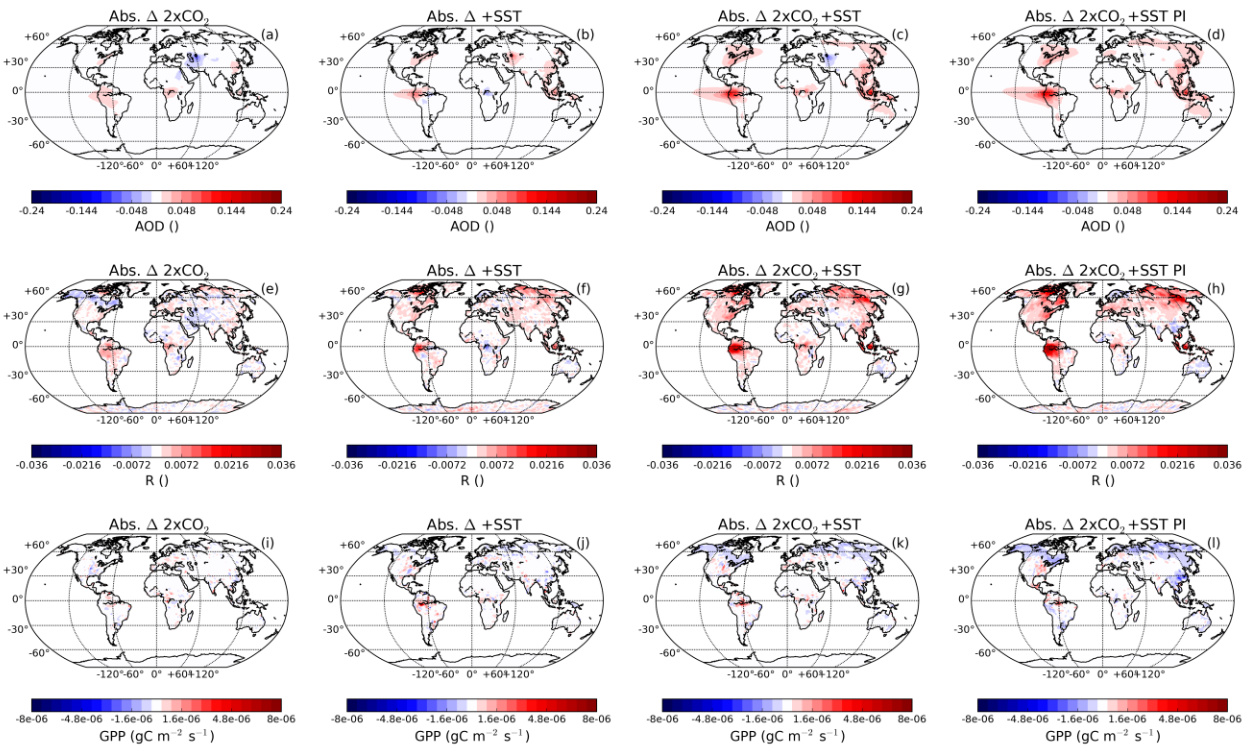

Figure 7. The difference in AOD (a-d), R (e-h) and GPP (i-l) between the FB-ON and FB-OFF simulations for the four feedback experiments.

The differences in AOD between FB-ON and FB-OFF simulations do however seem to influence the climate in a more direct way. In Fig. 8, the net direct aerosol forcing (NDAF) is shown. It increases with increasing AOD and causes a cooling. This effect is most pronounced over the tropics as well as the boreal forest with up to -2.2 $Wm^{-2}$. The global average difference in NDAF between the FB-ON and FB-OFF simulations for the $2xCO_2$+SST experiment is -0.05 $Wm^{-2}$. This indicates that also the cooling from increased scattering of particles associated with the feedback loop should be taken into account.

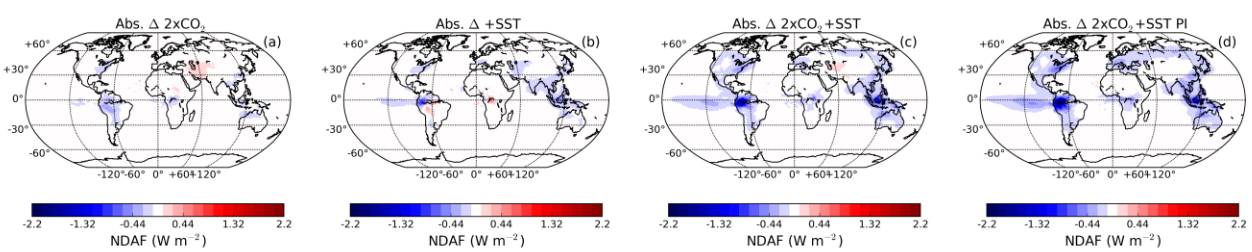

Figure 8. The difference in the NDAF (calculated according to Ghan (2013)) between the FB-ON and FB-OFF simulations for the four feedback experiments.

### 1.4. Sensitivity simulations

The results from the sensitivity studies will be presented next. The annual global SOA production increases by almost 40 Tg year$^{-1}$ when the yields are increased and decreases by the same amount when the yields are lowered (Fig. 9). Turning off the isoprene emissions decreases the SOA production even more, while turning off monoterpenes results in a smaller reduction. The test with no LVSOA hardly changes the SOA production at all. The SOA production due to the BVOC feedback for the 2x$CO_2$+SST simulations was 46.2 Tg year$^{-1}$ which is 16 % higher than from the 50% increase in all yields.

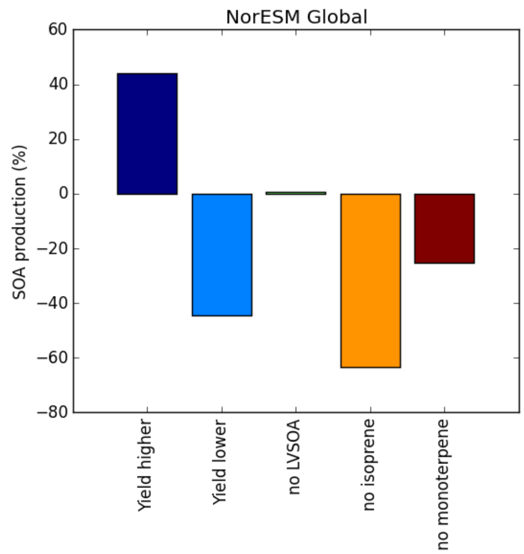


Figure 9. The relative difference in global SOA production between each of the sensitivity experiments and the control case.

The differences in the global averaged $N_a$ in the lowest model layer between the sensitivity simulations and the CTRL case can be seen in Fig. 10. Raising/lowering the SOA yields results in higher/lower amounts of aerosol particles with a stronger decrease for the lower yields and increase for the higher yields. For the simulation without isoprene there is virtually no change in $N_a$. The simulations where there is no LVSOA (no LVSOA and no monoterpenes) both result in strong reductions in $N_a$ since there is no contribution from BOVC to nucleation in these simulations.

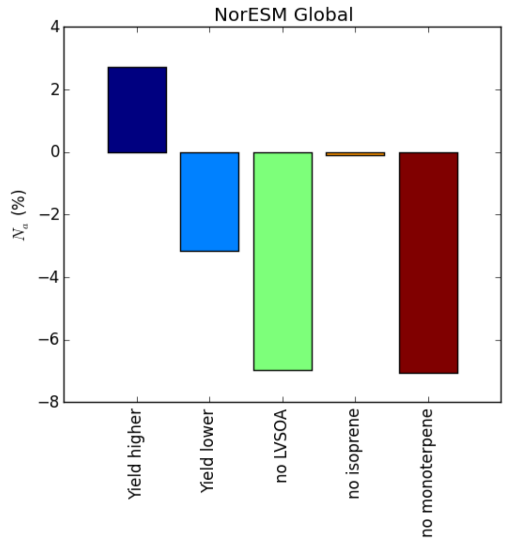


Figure 10. The relative difference in globally averaged $N_a$ between each of the sensitivity experiments and the control case.

The sensitivity of the CCN concentration does not only depend on the number concentration of aerosol particles but also on the size of the particles. The changes in CCN concentration at 0.2 and 1% supersaturation can be seen in Fig. 11. For the higher and lower yield simulations, the response in the CCN concertation looks similar to the change in $N_a$. The no_LVSOA simulation on the other hand show a decrease in global $N_a$ but an increase in CCN at 0.2 %. The explanation for this is that when no_LVSOA is allowed, there are fewer particles and more SVSOA available for condensation. Since there are fewer particles, there is less competition for the condensing vapors and the existing particles can grow larger. At low supersaturation mainly the larger particles will activate and thus, the extra growth provides more CCN at 0.2%. At 1% supersaturation, the CCN concentration instead decreases a little since at this supersaturation also the smaller particles can activate and there are fewer smaller particles. A similar response can be seen for the no_monoterpene simulation. For the simulation without isoprene emissions, the CCN concentration decreases at both supersaturations since the amounts of condensing vapors are lower and the particles remain smaller. The global changes in these parameters are small with larger regional differences.

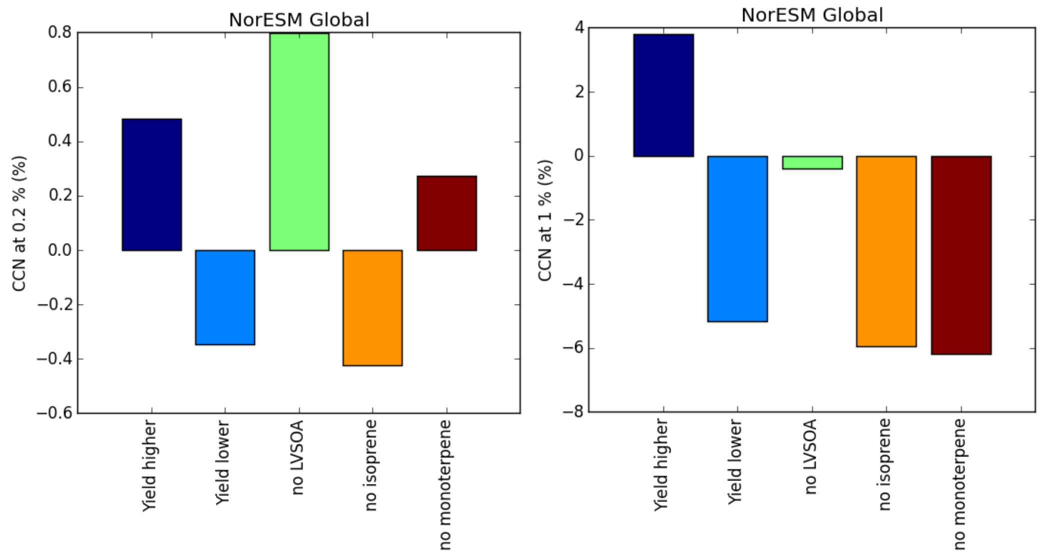


Figure 11. The relative difference in globally averaged CCN at 0.2% (left) and 1% (right) supersaturation in the lowermost model layer between each of the sensitivity experiments and the control case. Note the different scales for the two figures.

The clouds in the model form at various supersaturations and thus the CDNC response (Fig. 12) differs from the CCN response. It is a mixture of the CCN responses shown in the subfigures of Fig. 11. The CDNC increases when the yield is increased and decreases when the yield is decreased, with the decrease being somewhat stronger than the increase. The largest decrease in CDNC is seen in the simulation without isoprene, but for the simulations without LVSOA there is no large impact on the CDNC.

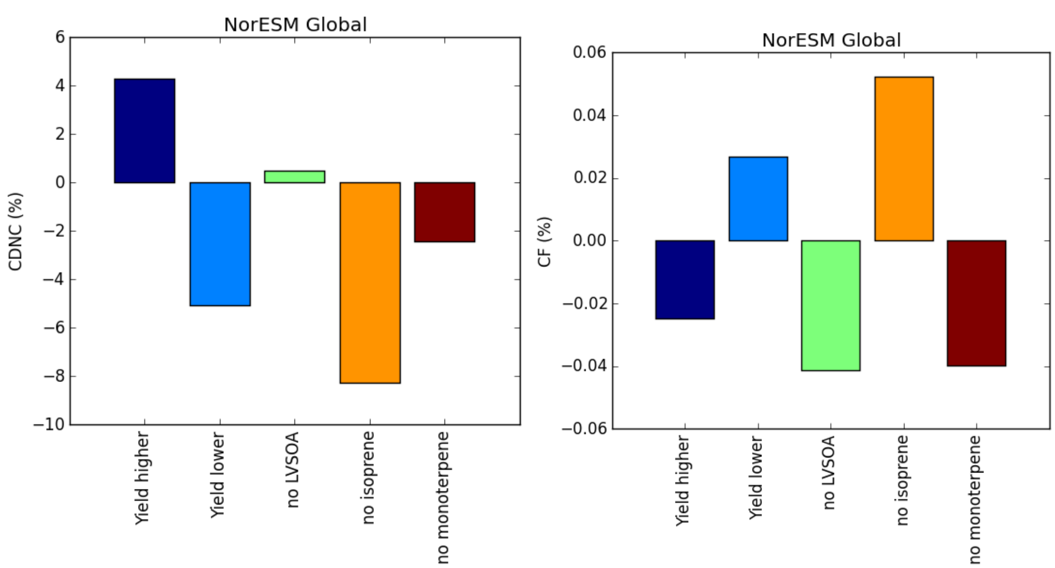


Figure 12. The relative difference in globally averaged CDNC (left) and total cloud fraction CF (right) between each of the sensitivity experiments and the control case.

The change in the NCF with respect to the CTRL simulation can be seen in Fig. 13. Increasing the yield by 50% results in an enhanced NCF of -0.26 Wm$^{-2}$ in the global mean. The NCF responds stronger to a decrease in the yield, which leads to a reduction in the NCF by 0.35 Wm$^{-2}$. Even though there was a small global increase in the CDNC for the no_LVSOA simulation, the NCF is somewhat reduced. This is most likely associated with a reduction in the CF shown in Fig. 12. Moreover, also the simulations without isoprene and monoterpene result in a smaller NCF and removing isoprene has the largest effect of all simulations with 0.52 $Wm^{-2}$. The changes in the yields produce a response that corresponds to half of the difference between the FB-ON and FB-OFF simulations in the feedback loop investigation. This indicates that the model is quite sensitive to the parametrizations regarding BVOC and SOA. Thus, effort is needed to continue developing these parametrizations to make model investigations into BVOC effects on climate more certain.

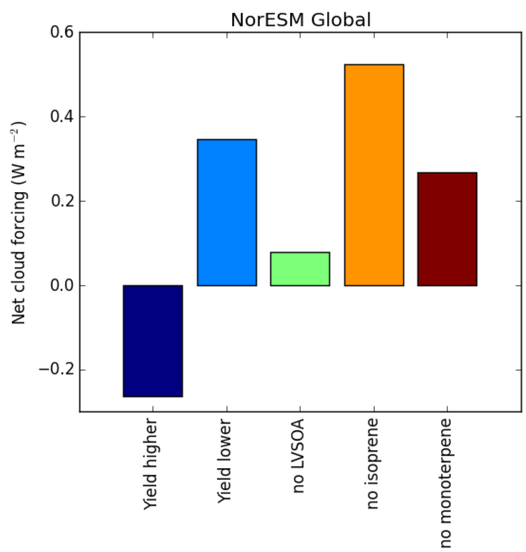


Figure 13. The global average NCF (calculated according to Ghan (2013)) for each case minus the control case.

## 1.5. Coupled NorESM simulations (land, ocean, atmosphere)

As a feasibility study, UHEL performed coupled simulations of the feedback loop with NorESM. The simulations included coupling the atmosphere and aerosol model CAM-Oslo, land model CLM as well as full ocean or mixed-layer ocean model. Four simulations were performed: with and without the feedback loop, and with present-day and doubled $CO_2$ concentrations. With mixed-layer ocean simulations, we analyzed e.g. BVOC fluxes, SOA formation, CDNC and climate parameters after reaching equilibrium. In the coupled simulations, we observe changes in BVOC-SOA-CDNC-coupling during the first 100 years of simulation. As an example of fully coupled (full ocean) simulations, Fig. 14 shows the doubled-$CO_2$ experiment aerosol growth rates. When the feedback mechanisms (Fig. 1) are enabled, the aerosol growth rates increase throughout the first 40 years of the simulation, while the growth rates in the “Feedback off” simulation remain at reference-levels (similar to 1x$CO_2$ control). However, using fully coupled simulations for feedback simulations remains computationally expensive, and most of the quantitative analysis has therefore been done in prescribed-SST (sections 1.1-1.4) and mixed-layer ocean configurations.

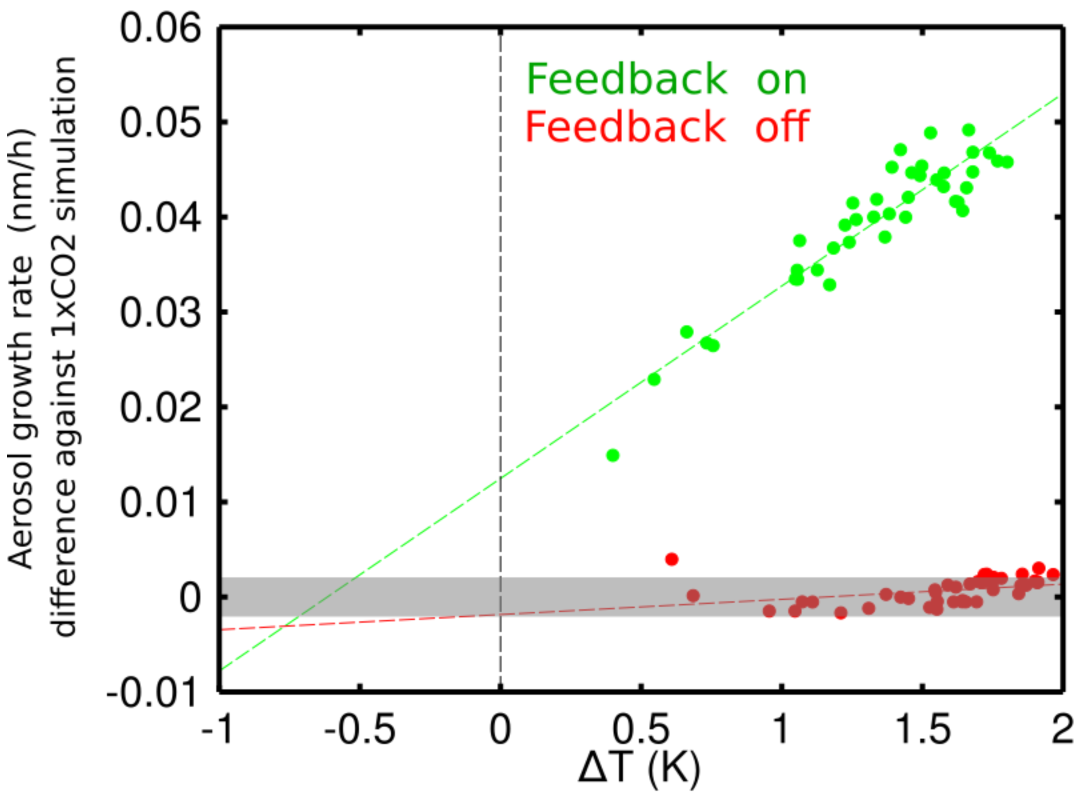


Figure 12. Aerosol growth rate (diagnosed from sulfuric acid and organic vapours) in doubled $CO_2$ simulations, where the BVOC feedback loop is enabled (green, BVOC concentrations are simulated interactively) and where the BVOC feedback loop is turned off (red, BVOC emissions constant). Grey shading indicates the standard deviation in the control (1x$CO_2$) simulation.

Using the above coupling with the mixed-layer ocean, monoterpene emissions increased from 18 Tg $yr^{-1}$ to 28 Tg $yr^{-1}$ in the boreal forest region due to $CO_2$ fertilization. The increase in monoterpenes leads to nearly a doubling of the simulated SOA formation and 10% increase in total particulate organic matter (POM). The effect of the 10% increase in particulate organic matter (POM) can be attributed to the changes in aerosol size distribution via several competing pathways. Increased POM contributed to increased coagulation and a higher condensation sink, possibly decreasing nucleation and subsequent growth. Furthermore, the aerosol size distribution was modified by simultaneous changes in e.g. cloudiness and precipitation. Indeed, the simulated cloud cover over boreal forest increased from 54.1 % to 56.9 % and precipitation increased slightly from 0.09 to 0.10 mm $h^{-1}$.

NorESM was used to simulate an alternative climate-warming scenario, in which BVOC-emissions were not allowed to change (2x$CO_2$-NOFB). The two simulations, one with and one without the climate-BVOC-aerosol feedback loop, allowed us to quantify certain parameters for the feedback. In the 1x$CO_2$ simulation, boreal forest aerosol concentration averaged to 820 $cm^{-3}$ in the surface layer. While the climate change simulation without the BVOC-aerosol feedback showed a decrease in the aerosol concentration to 790 $cm^{-3}$ (possibly due to precipitation changes), the increased SOA formation in 2x$CO_2$-FB resulted in a global aerosol concentration of 880 $cm^{-3}$, i.e. increase of 60 $cm^{-3}$ compared to 1x$CO_2$. Similarly, the column-integrated CDNC increased from 1.9 x $10^6$ $cm^{-2}$

to 2.6 x $10^6$ $cm^{-2}$ with the BVOC-aerosol feedback and only to 2.3 x $10^6$ $cm^{-2}$ without the feedback, highlighting the potential of a negative feedback through indirect aerosol effects.

The strength of the simulated BVOC-aerosol-climate feedback is weaker over tropical regions than in the boreal forest. In the tropics, monoterpene emissions increased by 20%, resulting in a POM increase of only 2%, due to simulated climate change. However, even on the global scale, the BVOC-aerosol-feedback can increase SOA formation by 45% in a doubled $CO_2$ experiment, showing the potential for a strong feedback mechanism during the 21st century.

## Summary

The results from the BVOC-aerosol-climate feedback investigations showed that the lower loop of the feedback mechanism in Fig. 1 dominates over the upper feedback mechanism. Using NorESM, we find no support that the upper part of the feedback loop would globally or even regionally have any big impact on the production of BVOCs. The lower part of the feedback involving clouds has been found to have a potentially important impact on the future temperature and also the direct aerosol forcing contributes with a cooling. Using the results from this deliverable, we propose redrawing the feedback loop as shown in Fig. 13. The sensitivity tests show that the parameters investigated in the feedback study are quite sensitive to BVOC emissions and the parametrizations of SOA formation. E.g., increasing the yield of the SOA formation by 50 % changes the NCF by 65 % of the effect associated with this feedback loop.

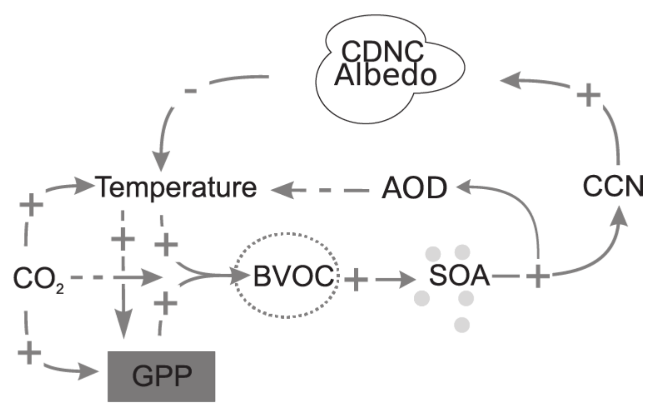


Figure 13. The feedback loop redrawn according to the results from this deliverable.

## Changes with respect to the DoW

The deliverable D4.4 was designed to also include participation from ETH Zurich with the MPI-ESM-HAM model. However, due to unforeseen delays in the MPI-ESM-HAM development, WP4 decided to focus D4.4 efforts towards one model (NorESM) to answer the scientific topic of this deliverable.

## Dissemination and uptake

The results from the feedback study will be published in a paper that is in preparation. There are also plans to write a paper on the results from the sensitivity studies to ensure a wider dissemination of the results.

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