



**Co-funded by
the European Union**



Horizon Europe

(HORIZON-CL5-2021-D1-01)

Non-CO2 Forcers and their Climate, Weather, Air Quality and Health Impacts

FOCI

Deliverable 2.3

Biogenic and anthropogenic strength for the current climate feedback

Grant Agreement No.	101056783	
Project acronym	FOCI	
Project full title	Non-CO2 Forcers and their Climate, Weather, Air Quality and Health Impacts	
Call	HORIZON-CL5-2021-D1-01	
Deliverable name	D2.3 Biogenic and anthropogenic strength for the current climate feedback	
WP contributing to the deliverable	WP2	
Task producing the deliverable	Task 2.3	
Type	<input checked="" type="checkbox"/>	Report
	<input type="checkbox"/>	Prototype
	<input type="checkbox"/>	Demonstrator
	<input type="checkbox"/>	Other: Data
Dissemination level	<input checked="" type="checkbox"/>	Public
	<input type="checkbox"/>	Sensitive
	<input type="checkbox"/>	UE/EU-Restricted
Due date of deliverable	Month 24	
Actual submission date	Month XX	
Lead beneficiary	FMI	
Author(s)	Risto Makkonen (FMI), Joonatan Strang (FMI), Sara Marie Blichner (SU), Simo Hakala (SU), Tuukka Petäjä (UHEL), Tuomo Nieminen (UHEL), Putian Zhou (UHEL), Andrea Pozzer (MPI-C)	
Other Contributor(s)		
Reviewer(s)	Katerina Šindelárová (CU)	
Keywords	FOCI, deliverables	

ACKNOWLEDGEMENTS

This project has been co-funded by the European Union with funding from the European Union's Horizon Europe research and innovation programme under grant agreement No. 101056783 and from UKRI under the UK Government's Horizon Europe Guarantee (UKRI Reference Numbers: 10040465, 10053814 and 10050799).

Version	Date	Modified by	Comments
0.5	7 December 2024	Risto Makkonen, all authors	First order draft written
1.0	27 Jul 2025	Risto Makkonen	Revisions made to incorporate reviewer's comments

	Name	Date
Verification Final Draft by WP leaders	Tuukka Petäjä (UHEL)	29 Jul 2025
Check before upload by project Coordinator	Tomáš Halenka (CU)	7 Aug 2025

TABLE OF CONTENTS

TABLE OF CONTENTS	3
EXECUTIVE SUMMARY	4
CONTRIBUTION TO THE FOCI OBJECTIVES	5
1. INTRODUCTION	6
2. EVALUATION OF FEEDBACK COMPONENTS AGAINST OBSERVATIONS.....	6
3. RESPONSE OF SIMULATED AEROSOL TO DOUBLING OF BVOC EMISSIONS.....	7
4. INVESTIGATING THE SENSITIVITY OF THE BVOC-CLIMATE FEEDBACK IN PRE-INDUSTRIAL AND PRESENT-DAY CONDITIONS USING THE CMIP6 VERSION OF NORESM2	11
5. BIOGENIC FEEDBACK UNCERTAINTIES IN HIGH NORTHERN LATITUDES.....	13
6. INVESTIGATING THE HUMAN IMPACT ON THE BVOC-CLIMATE FEEDBACK.....	14
7. REFERENCES	15

EXECUTIVE SUMMARY

This document is the deliverable “D2.3: Biogenic and anthropogenic strength for the current climate feedback” for the European Union project “FOCI: Non-CO2 Forcers and their Climate, Weather, Air Quality and Health Impacts” (hereinafter also referred to as FOCI, project reference: 101056783). The D2.3 is assessing mainly the effects of BVOC and their interaction with the climate change, as well as the feedbacks of anthropogenic activities. It is shown especially on the analysis of NorESM2 from small AerChemMIP ensemble and in validation for two stations in Finland and Brasil. In this report the current state of biogenic aerosol climate feedback and evaluation of anthropogenic impact on the feedback strength is synthetised.

CONTRIBUTION TO THE FOCI OBJECTIVES

When analysing the effects of non-CO₂ climate forcers in the climate system, we need to consider both natural and anthropogenic processes, whose certain part is produced by the atmospheric chemistry. At the beginning of that, there are natural and anthropogenic emissions. The Deliverable 2.3 is assessing mainly the effects of BVOC and their interaction with the climate change, as well as the feedbacks of anthropogenic activities. Thus, the D2.1 contributes to the following FOCI objectives:

1. To examine and evaluate the climate relevant processes and feedbacks of natural aerosols and BVOCs, as precursors for SOA based on new and available observations datasets (WP2). These are to be contrasted with the feedbacks of anthropogenic primary and secondary aerosols compiled in WP 1.
2. To integrate observational and modelling datasets and data products for improving and evaluating multiscale climate and atmospheric composition models (cross-cutting activity).

1. INTRODUCTION

There has been a strong development of analysis methods for evaluating feedbacks around biogenic SOA and the COBACC feedback loop. These analysis frameworks have been successfully used for evaluating Earth System Models, including the FOCI models. Blichner et al. (2024) quantified the impact of biogenic aerosol growth on climate-relevant feedbacks, and the analysis included models EC-Earth, NorESM, ECHAM-SALSA and UKESM. Tang et al. (2023) evaluated parts of the biogenic aerosol feedback loop in Northern high-latitudes using the EC-Earth model framework, including analysis of impact of BVOCs (Biogenic Volatile Organic Compounds) on aerosol growth to CCN sizes. Similarly, the work of Vella et al. (2024) investigates the human influence on the COBACC feedback loop. Firstly, the effect of present-day deforestation compared to the potential natural vegetation is investigated. In addition, the effect of an extreme reforestation scenario, where present-day crop and grazing land are restored to natural vegetation are investigated, with special focus on aerosols, clouds and radiation. Impact of nanoparticle aerosol growth on CCN has been documented in review by Stolzenburg et al. (2023). The paper includes a review of aerosol growth in 13 modeling studies and specific analysis of growth rate impacts in EC-Earth, NorESM and ECHAM. UHEL has further developed methods for evaluating simulating particle growth rates (Task 2.2), and additional diagnostics have been implemented to the M7 model for aerosol number fluxes from mode to another, which together with the organic and inorganic mass fluxes can be used to evaluate size-dependent growth rates. This data has been preliminarily tested against size-dependent GR from observations. In this report we synthesize the current state of biogenic aerosol climate feedback and evaluate anthropogenic impact on the feedback strength.

2. EVALUATION OF FEEDBACK COMPONENTS AGAINST OBSERVATIONS

As anthropogenic aerosol and aerosol precursor emissions are reduced as a result of air quality reform, a warming is expected. The size of this warming is highly dependent on the natural aerosol baseline and what happens with natural aerosols in response to warming.

One feedback that has received increasing attention in recent years involves the rise in emissions of biogenic volatile organic compounds (BVOCs) with higher temperatures, leading to increased secondary organic aerosol (SOA) production, which cools the Earth's surface by affecting cloud properties. Motivated by significant variability in feedback strength across Earth System Models (ESMs), this study evaluates the process representation of the feedback terms in four ESMs. To achieve this, long-term observational data from measurement stations from the boreal (SMEAR-II station) and tropical forest (ATTO station), along with satellite data (MODIS) were used (Blichner et al., 2024). The evaluation focuses on the relationships between the variables in the feedback loop – temperature to organic aerosol, organic aerosol to particle number concentration and particle number concentration to cloud properties – rather than the more traditional approach of evaluating mean, absolute properties (concentration, number etc.).

The analysis identifies specific issues in the models, particularly in the processes that convert changing emissions into radiative forcing. Based on the four ESMs studied, the following key issues are highlighted:

1. Although the models generally capture the temperature dependence of organic aerosol (OA) mass concentration in boreal forests (SMEAR-II), the response in tropical forests (ATTO) is much more

variable. Notably, UKESM shows no temperature response at ATTO and exhibits diverse overall OA mass concentration.

2. The models display significant variability in how OA influences particle number and size, indicating that the dynamics of size distribution are crucial for determining feedback strength.
3. The relationships between OA mass concentration and particle number concentration directly impact the strength of OA's effect on clouds.
4. The hygroscopicity of OA in the models may influence the total feedback. This is evident in UKESM for the boreal region, where the cloud response to OA is relatively weak, despite the model being sensitive to N100 (similar to EC-Earth and ECHAM-SALSA).

The results suggest that the weakest feedback estimates can be ruled out, but compensating errors in the models make it hard to determine the strongest feedbacks. Overall, the study's process-based evaluation approach appears useful in identifying uncertainties and improving the accuracy of aerosol feedback predictions in models.

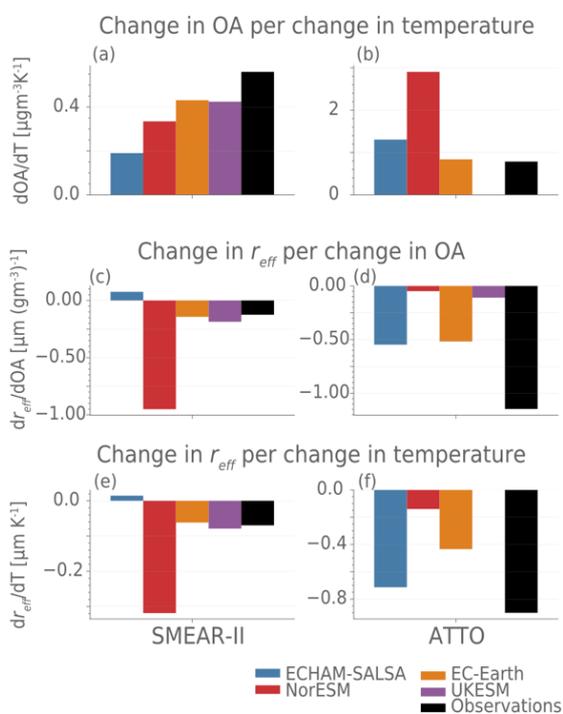


Figure 1. Estimated strength of the terms in the feedback loop (r_{eff} =cloud droplet effective radius, OA=organic aerosol mass, T =temperature) at the two stations. See Fig. 5 in Blichner et al. (2024).

3. RESPONSE OF SIMULATED AEROSOL TO DOUBLING OF BVOC EMISSIONS

Here we present analysis of CMIP6 piClim-2xVOC experiments, where pre-industrial conditions of CMIP6 models were perturbed by doubling biogenic VOC emissions (Collins et al., 2017). Very few models participated in these Tier-3 AerChemMIP simulations, namely CESM2-WACCM, NorESM-LM, EC-Earth3-AerChem, GISS-E2-1-G, UKESM1-0-LL and GFDL-ESM4. We focus on the potential impact of BVOC on

cloud droplet number concentrations (CDNC), especially in two distinct locations, ATTO (Brazil) and Hyytiälä (Finland). Several aerosol-chemistry feedbacks of CMIP6 models were investigated already by Thornhill et al. (2021), including BVOC feedback in 5 models (EC-Earth3-AerChem results became later available). In this section there are results from two NorESM simulations: the r1i1p1f1 corresponds to standard CESM2 parameterisations as CESM2, while r1i1p2f1 simulations use the same parameterisation as the fully-coupled NorESM2-LM.

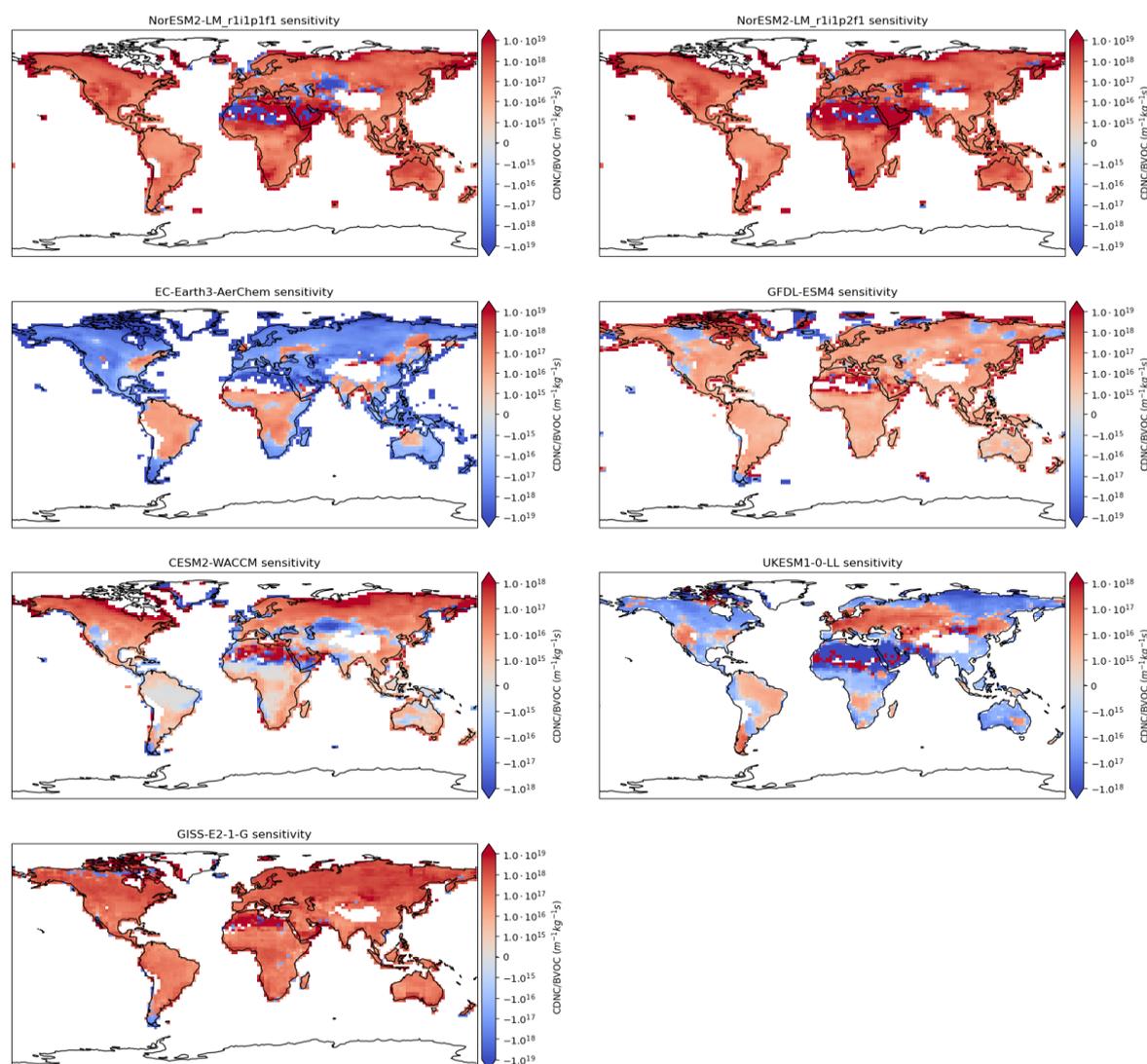


Figure 2. Sensitivity of CDNC to doubled BVOC emission.

For each 6 models, we have calculated the sensitivity of low-level CDNC to the doubling of BVOC emission. The sensitivity is calculated individually for each gridcell as the ratio of CDNC change to the BVOC change in the gridcell. Figure 2 shows the sensitivity maps for terrestrial regions. The sensitivities vary significantly between models in magnitude and even sign of CDNC sensitivity. There are certain similarities throughout the model ensemble, for example high-latitudes are generally more sensitive to BVOC perturbation than tropical regions. Simulated negative sensitivities (i.e. CDNC decreases with increasing BVOCs) has been reported earlier e.g. by Sporre et al. (2020). We will use these sensitivity maps with historical BVOC emissions to quantify potential BVOC-driven CDNC change in current climate.

As a first approximation, biogenic VOC emissions would be assumed to increase with recent climate warming. However, several other drivers have a role in VOC emission processes, for example CO₂ inhibition. Figure 3 shows BVOC emission change in five models during 1960–2014 (excluding EC-Earth3-AerChem which doesn't have an interactive BVOC scheme). It should be noted that the models consider historical land-use change modulating vegetation-driven emissions. Three models indicate significant BVOC emission increase in South America, but two models show even decreased emissions through Amazon (GISS and UKESM). All models generally agree on increased BVOC fluxes in North America and high-latitude Eurasia, even as GISS indicates minor BVOC decrease throughout Siberia. The displayed discrepancies in emission trends clearly indicate a challenge to constrain recent BVOC-driven changes in aerosols and aerosol-climate impacts.

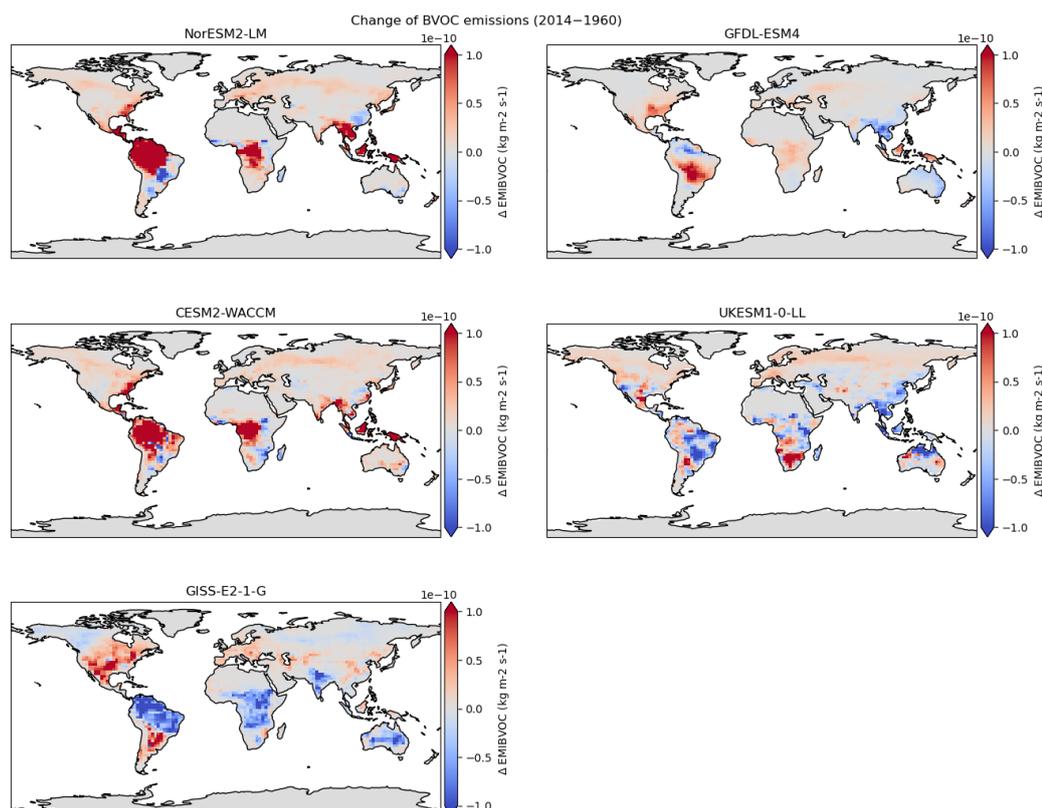


Figure 3. Change in BVOC emission during 1960 and 2014.

Figures 4 and 5 show both simulated CDNC from CMIP6 historical simulations (1960–2014) and BVOC-driven CDNC change quantified from the above sensitivities for ATTO and Hyytiälä stations, respectively. In Hyytiälä, the simulated historical CDNCs either decline throughout the 1960–2014 period (EC-Earth), or at least after 1980–1990 driven by decreasing anthropogenic aerosol emissions in Europe. In contrast, the BVOC emission changes around Hyytiälä would lead to increasing CDNC in all models except EC-Earth. Keeping in mind that the BVOC-driven CDNC change is merely diagnosed from BVOC emission change and pre-calculated sensitivity of CDNC to BVOC emissions, we can compare the magnitude to the trend in simulated CDNC during the historical period 1960–2014. The BVOC-driven signal in CDNC remains rather small compared to the total CDNC variations, around 1% except up to 10% in NorESM. In ATTO, all models simulate an increase of CDNC during the study period. Also, the magnitude of diagnosed BVOC-driven CDNC change is relatively closer to historical trends, compared to Hyytiälä. Based on NorESM (EC-Earth), even 25% (10%) of historical CDNC trend in ATTO could be explained by BVOC-emission changes. Other models indicate more variability

and less clear trends during the 55-year period. Figure 6 summarizes the historical and BVOC-driven CDNC changes, indicating multi-model variability and trend-lines for both historical and BVOC-CDNC change.

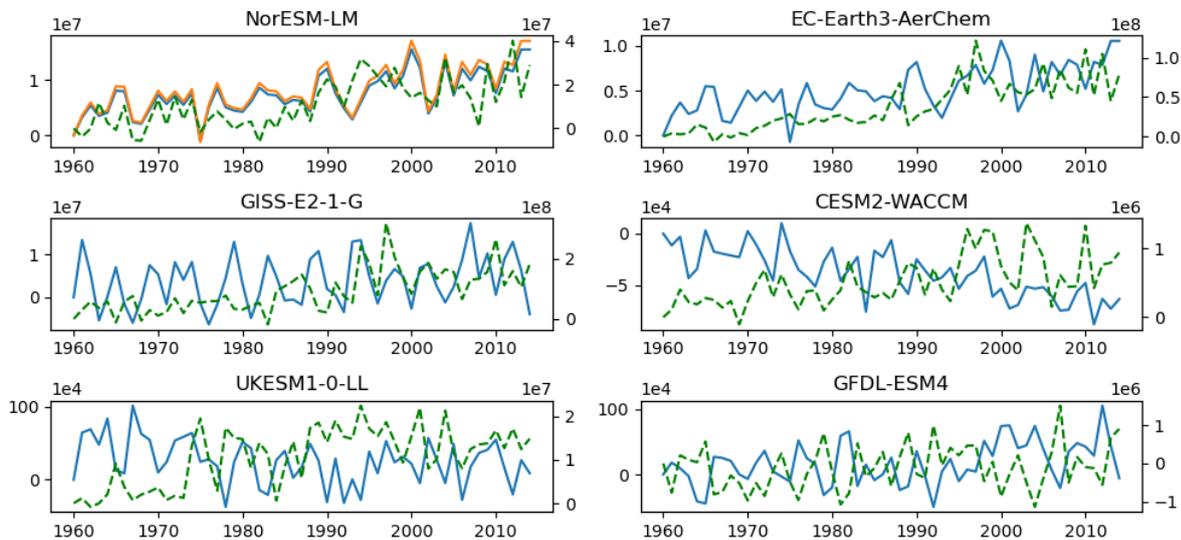


Figure 4. Simulated historical CDNC (dashed lines) and diagnosed BVOC-driven CDNC change (solid lines) in ATTO, Brazil. The first panel shows results with two sensitivities for NorESM, calculated from *r1i1p1f1* and *r1i1p2f1* realisations.

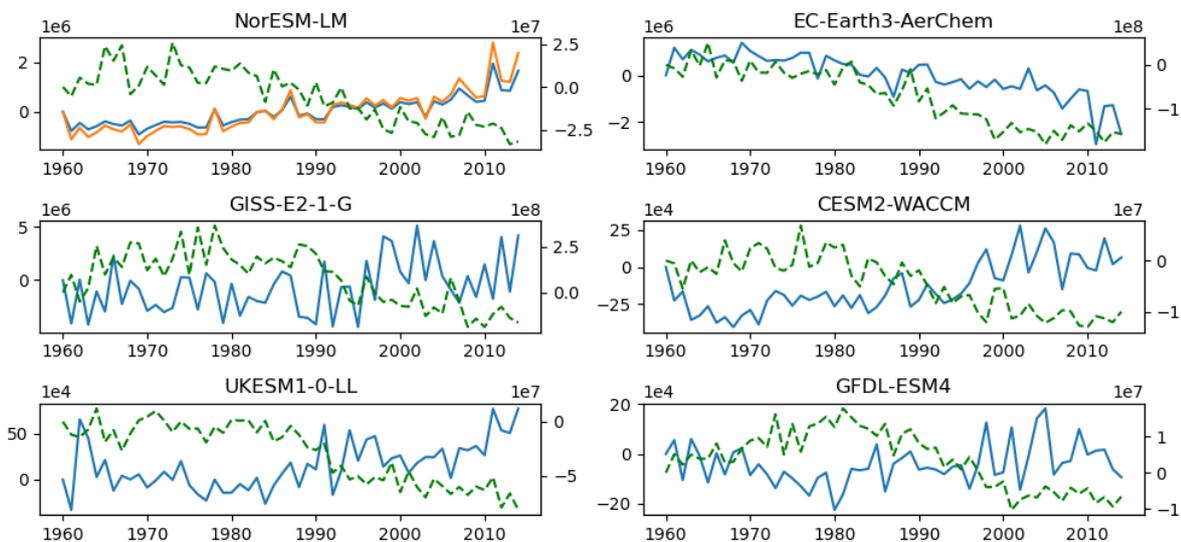


Figure 5. Simulated historical CDNC (dashed lines) and diagnosed BVOC-driven CDNC change (solid lines) in Hyytiälä, Finland. The first panel shows results with two sensitivities for NorESM, calculated from *r1i1p1f1* and *r1i1p2f1* realisations.

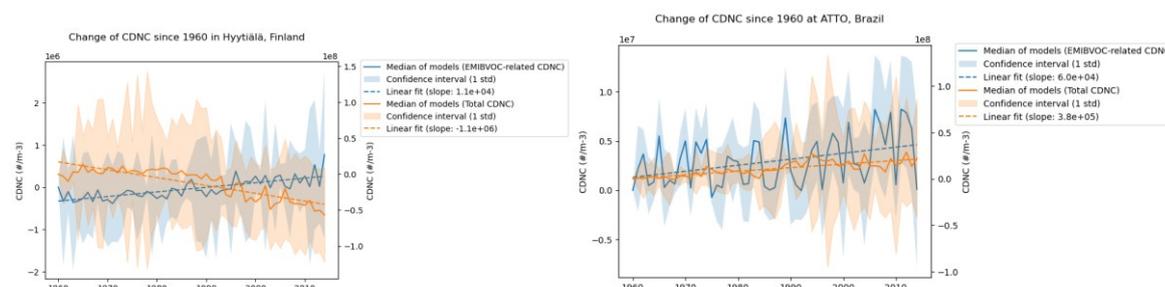


Figure 6. Multimodel CDNC and diagnosed BVOC-driven change.

4. INVESTIGATING THE SENSITIVITY OF THE BVOC-CLIMATE FEEDBACK IN PRE-INDUSTRIAL AND PRESENT-DAY CONDITIONS USING THE CMIP6 VERSION OF NORESM2

The framework for quantifying the BVOC-climate feedback (in $\text{W m}^{-2} \text{K}^{-1}$) implemented by Thornhill et al. (2021) includes multiplying the effective radiative forcing (ERF) from doubling of BVOC emissions (in $\text{W m}^{-2} \text{Tg}^{-1} \text{y}$) in the preindustrial climate by the change in BVOC emissions with climate (in $\text{Tg y}^{-1} \text{K}^{-1}$), obtained after abrupt quadrupling of CO_2 in the preindustrial climate. However, this linear framework combined with large perturbations poses potential issues due to the underlying non-linearities in the aerosol-climate interactions as well as in the BVOC emission responses to climate change. The feedback strength is also expected to be different in the preindustrial climate than today due to anthropogenic activities modulating the aerosol loads and the chemical composition of the atmosphere as well as the extent and type of vegetated areas.

In order to probe the impacts of this framework to the quantification of the BVOC-climate feedback, we performed a series of BVOC perturbation runs, including multiplying the emissions by 0, 0.5, 0.75, 1.25 and 1.5 (in addition to 1 and 2 as in the CMIP6 runs), both in the pre-industrial and present-day conditions. We also utilize NorESM2 runs for CMIP6 where the CO_2 concentration is increased by 1 % per year to study the response in BVOC emissions in a changing climate that is more representative of the historical development.

We find that the radiative forcing from BVOC emission perturbation is dominated by cloud radiative effects and depends logarithmically on the BVOC perturbation in NorESM2 (Fig. 7b, c). As a consequence, using the CMIP6 convention with doubled BVOC emissions underestimates the sensitivity of effective radiative forcing to BVOC emissions by 30 and 16 % in the pre-industrial and present-day conditions, respectively (comparing the right-most markers in Fig. 7a to the values obtained from the lines at $\Delta\text{BVOC} = 0$). Furthermore, the sensitivity of effective radiative forcing to BVOC emissions is found to be 36 % higher in pre-industrial conditions compared to present-day. These results reflect the sublinear dependency of cloud albedo on cloud droplet number concentrations and highlight a substantial decrease in the BVOC-feedback strength with increasing anthropogenic aerosol.

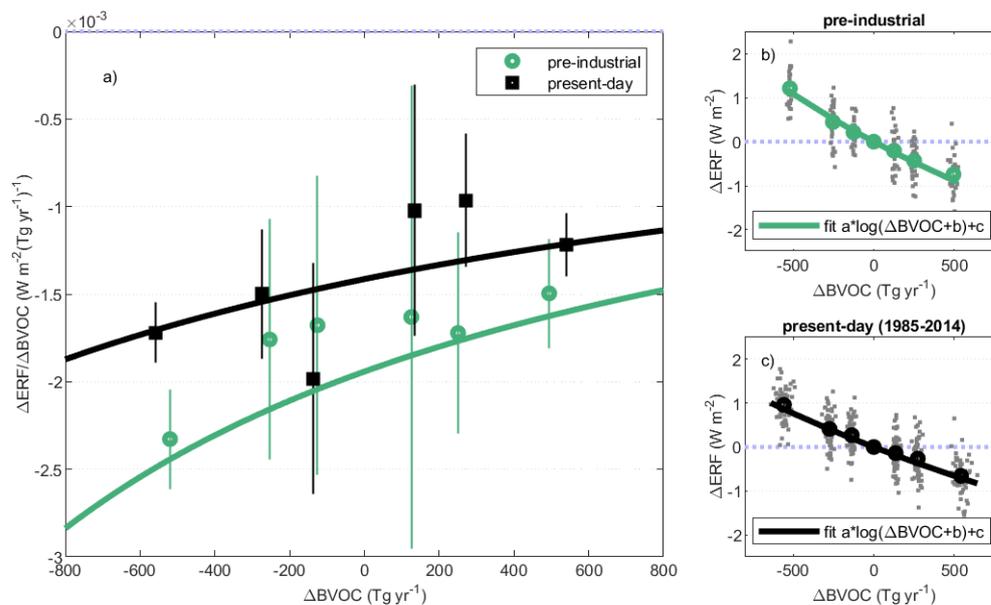


Figure 7: Sensitivity of effective radiative forcing to BVOC perturbation in pre-industrial and present-day climate using NorESM2. In panels b and c, the grey dots represent global annual means, the circles give the 30- and 60-year means (panels b and c, respectively) of each of the perturbations runs and the lines represent logarithmic fits to the annual data that minimize the absolute residuals. In panel a, the markers and bars give the mean sensitivities and their 95% confidence intervals, determined from the annual variation. The lines are obtained as the derivatives of the functions fitted in panels b and c, and their values at $\Delta\text{BVOC} = 0$ are deemed most representative of the actual sensitivity.

In terms of the BVOC emission changes with changing climate, we find a generally decreasing trend in the sensitivity, when the change is driven by 1 % annual increase in CO_2 in NorESM2 (Fig. 8a). This results from the CO_2 inhibition effect gradually becoming more prominent compared to the emission increases due to CO_2 fertilization (Fig. 8b), as the emission changes driven by the radiative impacts of CO_2 alone remains approximately linear (Fig. 8c). This also raises an issue in using the linear approximation and the quadrupled CO_2 experiment in the determination of the sensitivity; in NorESM2, the extremely high CO_2 inhibition at quadrupled concentrations causes the sensitivity to be underestimated compared to the lower CO_2 environment in the historical period (roughly below 400 ppm CO_2 and < 1 K warming).

Combining the results, we find that the BVOC-climate feedback has become weaker in present-day than in the pre-industrial conditions due to both the increasing anthropogenic aerosols and the CO_2 inhibition in NorESM2. We also find that the method used in Thornhill et al. (2021) is likely to underestimate the (short-term) feedback value that is arguably more representative of the ongoing changes. Our initial results on the full feedback strength in pre-industrial and present-day conditions are $0.59 \text{ W m}^{-2} \text{ K}^{-1}$ and $0.40 \text{ W m}^{-2} \text{ K}^{-1}$, respectively, which is significantly higher than the $0.29 \text{ W m}^{-2} \text{ K}^{-1}$ reported for NorESM2 in the pre-industrial climate in Thornhill et al. (2021).

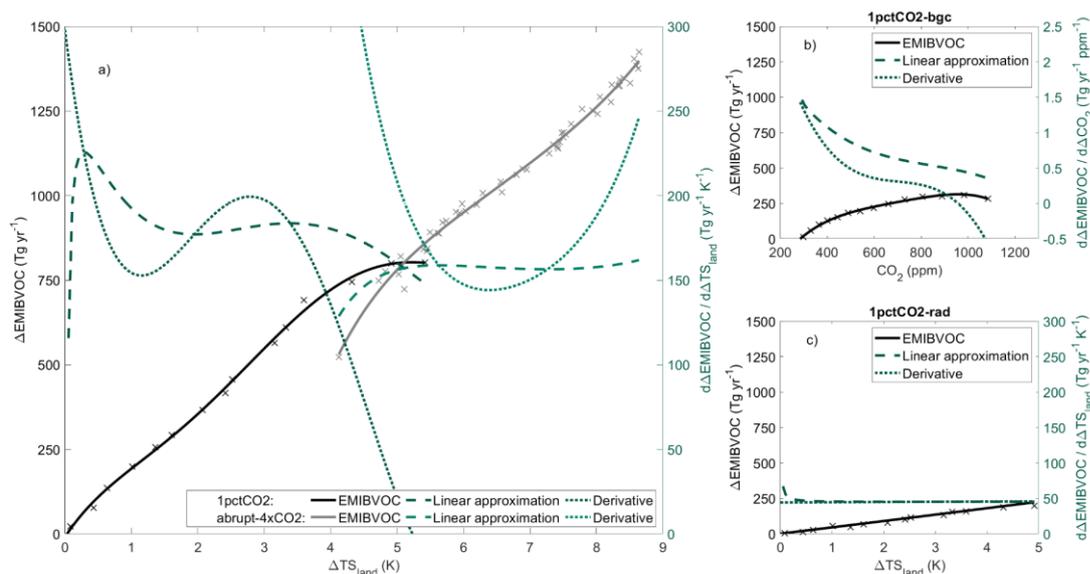


Figure 8: Sensitivity of BVOC emissions to changing climate in experiments where a) the CO₂ concentration is increased by 1 % per year (1pctCO₂) or abruptly quadrupled (abrupt-4xCO₂) from the preindustrial conditions, b) the same as 1pctCO₂, but CO₂ does not affect radiative transfer and c) the same as 1pctCO₂ but CO₂ only affects radiative transfer. In all panels, the crosses represent 10-year averages and the solid lines are polynomial fits to these points (left y-axes) and the dashed and dotted lines give the sensitivity of the BVOC emission to climate determined as the difference or the derivative, respectively (right y-axes).

5. BIOGENIC FEEDBACK UNCERTAINTIES IN HIGH NORTHERN LATITUDES

In Tang et al. (2023), we assessed how the changes of high-latitude BVOC emissions affect the CCN formation under different future scenarios. The climate warming in high latitudes is considered to enhance the BVOC emissions, mainly monoterpene emissions over boreal regions, which results in enhanced SOA formation. However, the changes of vegetation cover complicates the processes. For example, over the Nordic countries and western Russia, the climate warming induced an increase of broad-leaved deciduous trees while a decrease of boreal evergreen needle-leaved trees in the boreal forest region in future scenarios. This results in a corresponding increase of biogenic isoprene emissions usually from broad-leaved trees and a decrease of biogenic monoterpene emissions from needle-leaved trees (see Fig. 2 in Tang et al., 2023). Considering the higher SOA yields from monoterpenes than isoprene, the climate warming over these boreal forest regions will suppress the SOA formation, causing a regional decrease of CCN1.0 concentration, and thus induces a positive feedback which is up to 0.79 W m⁻² regionally for summer months in the standard run driven by CanESM5 SSP585 future scenario. Therefore, the uncertainties of biological processes also need to be considered in the biogenic feedback uncertainties.

Another uncertainty could come from CO₂ inhibition effect on BVOC emissions, which was found in short-term studies (Potosnak et al., 2014; Sharkey and Monson, 2014) but not well understood on a long-term scale. Our results show a weak CO₂ inhibition effect in a SSP119 scenario. However, it apparently decreases both isoprene and monoterpene emissions, causing a significant decrease of CCN1.0 concentration in high latitudes (see Fig. 5 in Tang et al., 2023).

The study by Kulmala et al. (2023) shows that new particle formation (NPF) in the boreal forest environment can significantly enhance aerosol concentrations (also cloud condensation nuclei) and condensation sink, thereby affecting locally the cloud properties and radiation balance. Using data from the Hyytiälä SMEAR II station in Finland, their study shows that even weak NPF can lead to significant increases in condensation sink. Model simulations confirm that NPF contributes dominantly to aerosol and CCN populations in boreal forest environments.

6. INVESTIGATING THE HUMAN IMPACT ON THE BVOC-CLIMATE FEEDBACK

In the work of Vella et al. (2023), the global atmospheric chemistry-climate model EMAC (ECHAM5/MESSy2 for Atmospheric Chemistry, Joeckel et al. 2009) with the interactive vegetation model is used to examine the effects of human-driven land use changes on the biosphere, focusing on variations in BVOC emissions and atmospheric aerosol levels. The model simulates potential natural vegetation, and a land use framework was applied to limit Tree Plant Functional Type cover according to 2015 land transformation data. Two scenarios were analyzed: (1) a comparison between current land cover, including deforested areas for agriculture (DCGL), and the natural vegetation cover (PNV), and (2) an extreme reforestation scenario where agricultural land is restored to its natural state. The results indicate that current deforestation, compared to the PNV scenario, leads to a 26% reduction in BVOC emissions, causing a 0.16 Tg (29%) decrease in global biogenic SOA (bSOA) and a 0.17 Tg (9%) reduction in total organic aerosol (OA). Conversely, the extreme reforestation scenario, compared to current land cover, shows a 22% increase in BVOC emissions, resulting in a 0.11 Tg rise in bSOA and a 0.12 Tg increase in total OA, representing a 26% and 6% rise, respectively. The study also evaluates the changes in cloud condensation nuclei (CCN) and cloud droplet number concentration (CDNC) under each scenario (Fig. 9). For the current deforestation scenario, a positive total radiative effect (aerosol + cloud) of 60.4 mW m⁻² (warming) is observed compared to the natural vegetation scenario, while the extreme reforestation scenario indicates a negative effect (cooling) of 38.2 mW m⁻² compared to the PNV scenario.

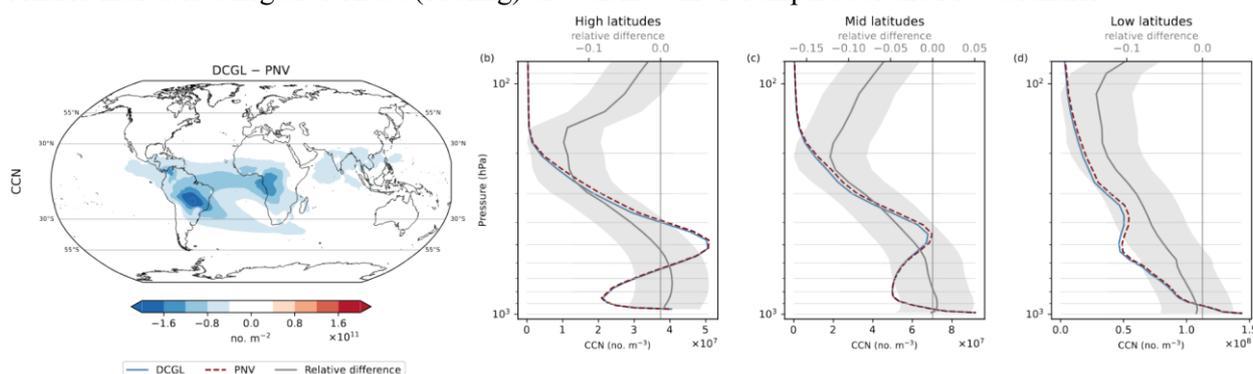


Figure 9: Changes in cloud condensation nuclei (CCN) at 0.2% supersaturation. The map on the left-hand side, show the spatial difference in the total column burden (number of particles per square meter), for CCN, emerging from deforested scenario (DCGL) compared to natural vegetation, i.e. (DCGL – PNV). The panels on the right-hand side show the total-column vertical profiles from DCGL and PNV simulations and their relative difference are shown. The latitude ranges are defined as follows: High latitudes (90–55°S and 55–90°N), mid-latitudes (55–30°S and 30–55°N), and low latitudes (30°S–30°N). The grey area represents 1 standard deviation of the spatio-temporal mean (grey line). Please note the different scales for the relative differences.

7. REFERENCES

- Blichner, S.M., Yli-Juuti, T., Mielonen, T. et al. Process-evaluation of forest aerosol-cloud-climate feedback shows clear evidence from observations and large uncertainty in models. *Nat Commun* 15, 969 (2024). <https://doi.org/10.1038/s41467-024-45001-y>
- Jöckel, P., Kerkweg, A., Pozzer, A., Sander, R., Tost, H., Riede, H., Baumgaertner, A., Gromov, S., Kern, B., *Development cycle 2 of the Modular Earth Submodel System (MESSy2)*, *Geoscientific Model Development*, 3, 717-752, <https://doi.org/10.5194/gmd-3-717-2010>, 2010.
- Kulmala, M., Cai, R., Ezhova, E., Deng, C., Stolzenburg, D., Dada, L., Guo, Y., Yan, C., Peräkylä, O., Lintunen, A., Nieminen, T., Kokkonen, T. V., Sarnela, N., Petäjä, T., and Kerminen, V.-M.: Direct link between the characteristics of atmospheric new particle formation and Continental Biosphere-Atmosphere-Cloud-Climate (COBACC) feedback loop. *Boreal Environment Research*, 28, 1–13, 2023.
- Kulmala, M., Lintunen, A., Lappalainen, H., Virtanen, A., Yan, C., Ezhova, E., Nieminen, T., Riipinen, I., Makkonen, R., Tamminen, J., Sundström, A.-M., Arola, A., Hansel, A., Lehtinen, K., Vesala, T., Petäjä, T., Bäck, J., Kokkonen, T., and Kerminen, V.-M.: Opinion: The strength of long-term comprehensive observations to meet multiple grand challenges in different environments and in the atmosphere, *Atmos. Chem. Phys.*, 23, 14949–14971, <https://doi.org/10.5194/acp-23-14949-2023>, 2023.
- Kulmala, M., Cai, R., Ezhova, E., Deng, C., Stolzenburg, D., Dada, L., Guo, Y., Yan, C., Peräkylä, O., Lintunen, A., Nieminen, T., Kokkonen, T. V., Sarnela, N., Petäjä, T. & Kerminen, V.-M. 2023, ' Direct link between the characteristics of atmospheric new particle formation and Continental Biosphere-Atmosphere-Cloud-Climate (COBACC) feedback loop, *Boreal Environment Research*, vol. 28, pp. 1-13.
- Potosnak, M. J., Lestourgeon, L. & Nunez, O. Increasing leaf temperature reduces the suppression of isoprene emission by elevated CO₂ concentration. *Sci. Total Environ.* 481, 352–359 (2014).
- Sharkey, T. D. & Monson, R. K. The future of isoprene emission from leaves, canopies and landscapes. *Plant Cell Environ.* 37, 1727–1740 (2014).
- Stolzenburg, D., Cai, R., Blichner, S.M., Kontkanen, J., Zhou, P., Makkonen, R., Kerminen, V.-M., Kulmala, M., Riipinen, I., Kangasluoma, J: Atmospheric nanoparticle growth, *Rev. Mod. Phys.* 95, 045002, 2023.
- Tang, J., Zhou, P., Miller, P.A., Schurgers, G., Gustafson, A., Makkonen, R., Yongshuo, H. F., Rinnan, R.: High-latitude vegetation changes will determine future plant volatile impacts on atmospheric organic aerosols. *npj Clim Atmos Sci* 6, 147, <https://doi.org/10.1038/s41612-023-00463-7>, 2023.
- Thornhill, G., Collins, W., Olivie, D., Skeie, R. B., Archibald, A., Bauer, S., Checa-Garcia, R., Fiedler, S., Folberth, G., Gjernundsen, A., Horowitz, L., Lamarque, J.-F., Michou, M., Mulcahy, J., Nabat, P., Naik, V., O'Connor, F. M., Paulot, F., Schulz, M., Scott, C. E., Séférian, R., Smith, C., Takemura, T., Tilmes, S., Tsigaridis, K., and Weber, J.: Climate-driven chemistry and aerosol feedbacks in CMIP6 Earth system models, *Atmos. Chem. Phys.*, 21, 1105–1126, <https://doi.org/10.5194/acp-21-1105-2021>, 2021.

Vella, R., Forrest, M., Pozzer, A., Tsimpidi, A. P., Hickler, T., Lelieveld, J., and Tost, H.: Land use change influence on atmospheric organic gases, aerosols, and radiative effects, EGU sphere [preprint], <https://doi.org/10.5194/egusphere-2024-2014>, 2024.