Constraining Aerosol Effect on Deep Convection with EarthCARE and the ECOMIP intercomparison

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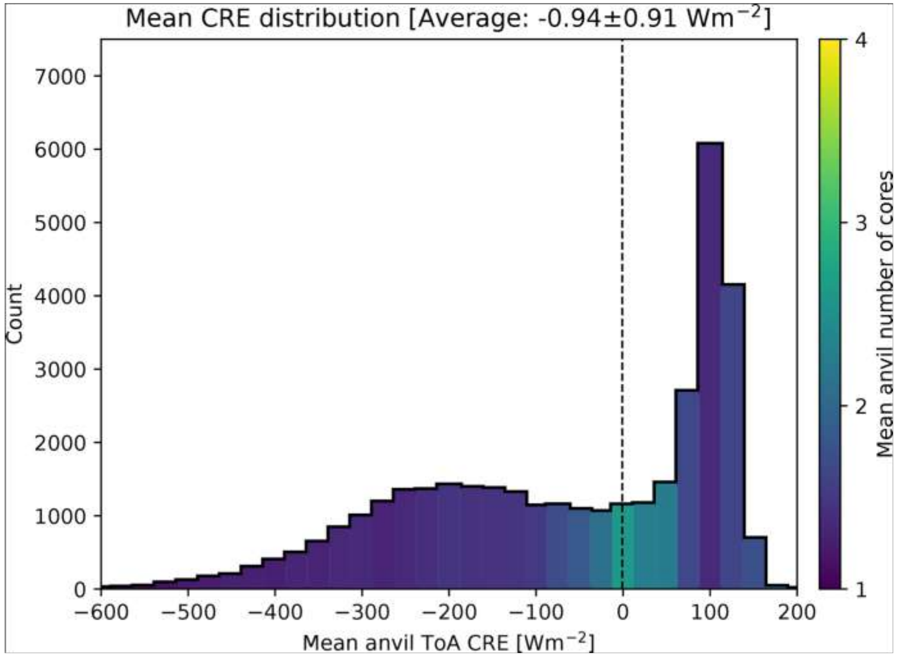
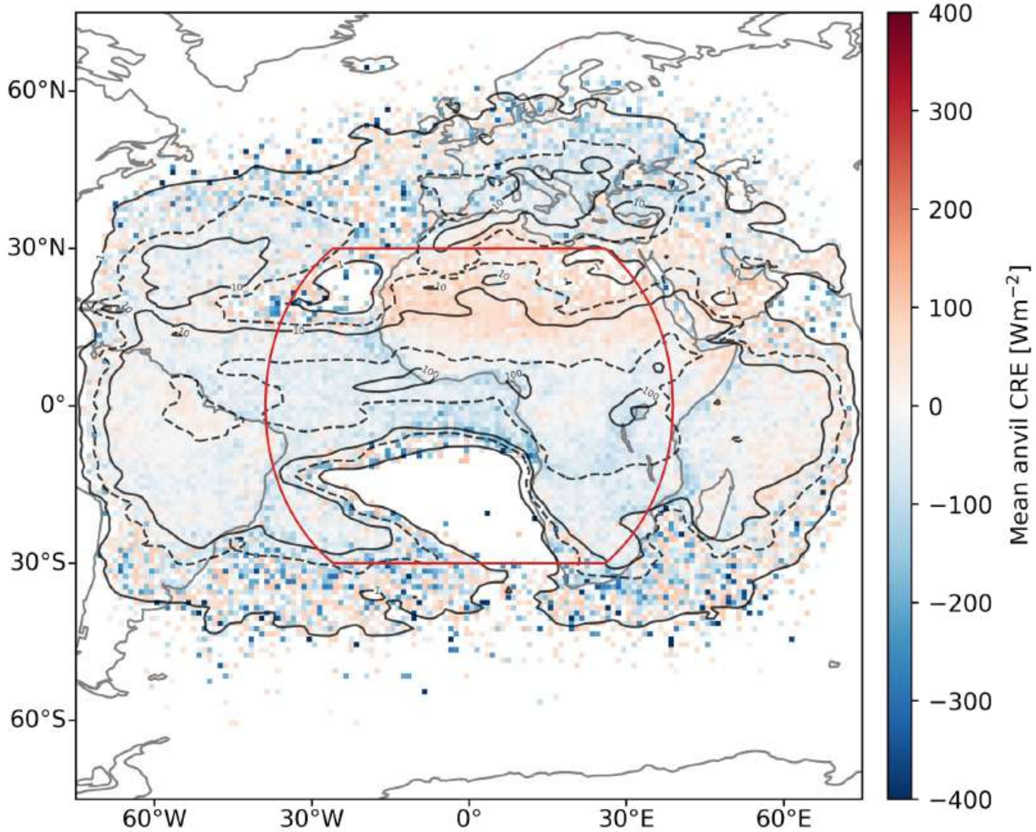
Convective cloud radiative effect



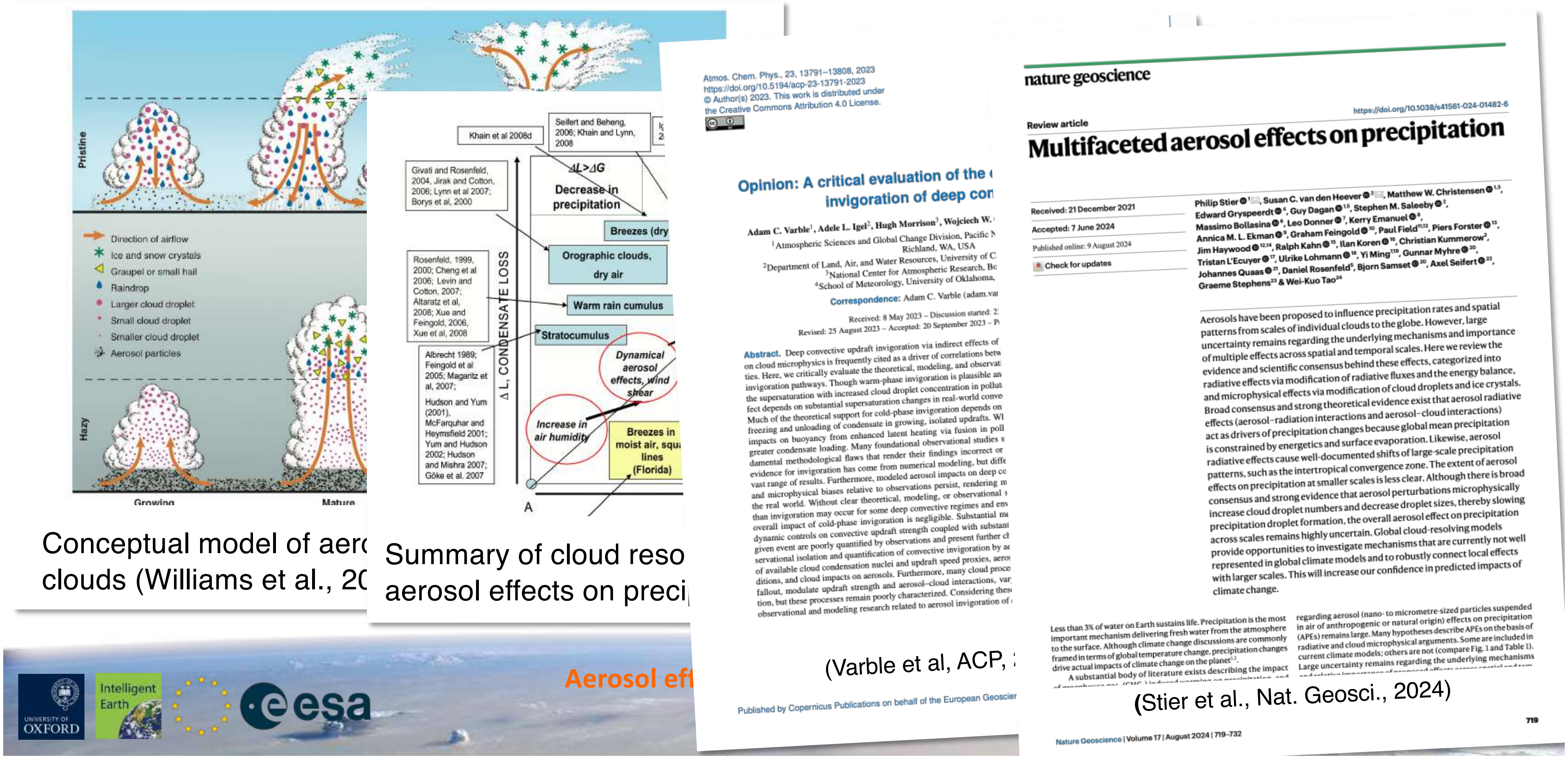


Anvil CRE from tobac-flow (Jones et al., AMT, 2023) tracked systems applied to ESA CCI+ SEVIRI retrievals.

Convective anvil cloud radiative effect

(Jones et al., ACP, 2024)

Aerosol effects on convective clouds



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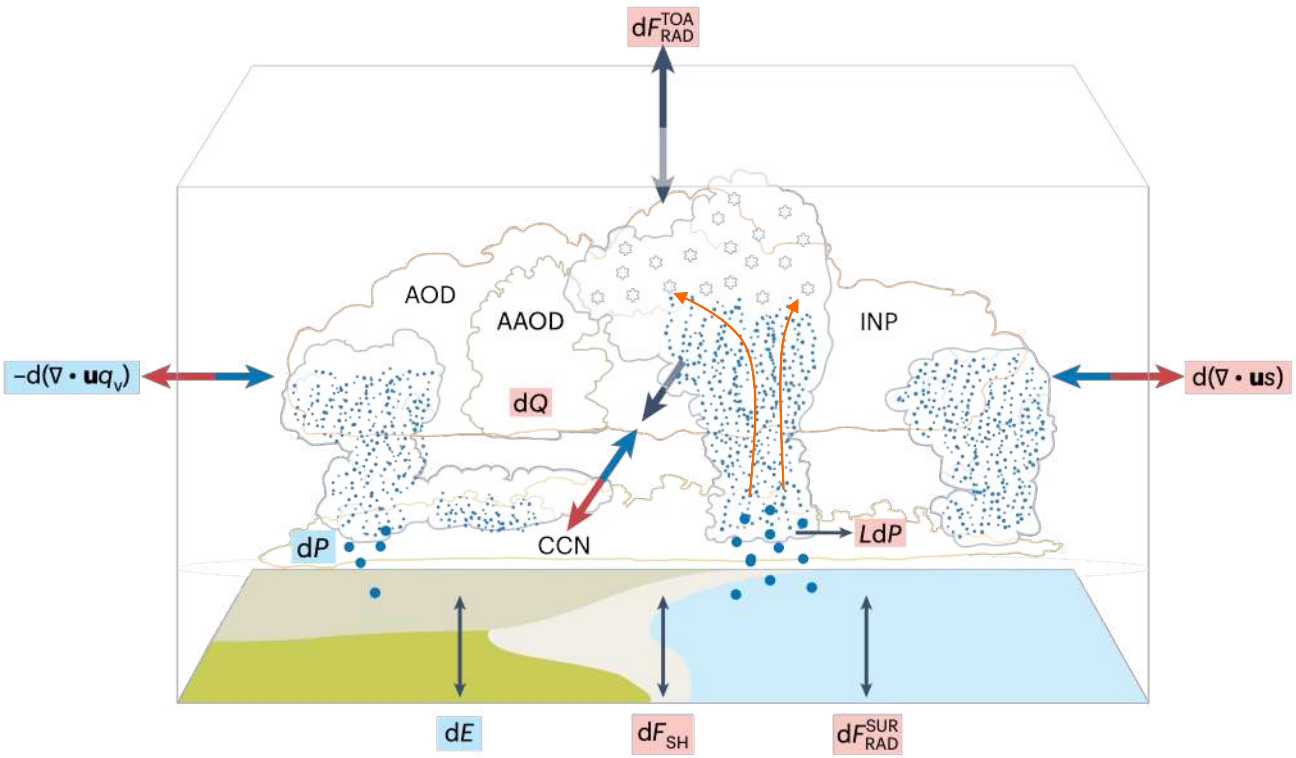

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Review article

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Multifaceted aerosol effects on precipitation

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Check for updates

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Aerosols have been proposed to influence precipitation rates and spatial patterns from scales of individual clouds to the globe. However, large uncertainty remains regarding the underlying mechanisms and importance of multiple effects across spatial and temporal scales. Here we review the evidence and scientific consensus behind these effects, categorized into radiative effects via modification of radiative fluxes and the energy balance, and microphysical effects via modification of cloud droplets and ice crystals. Broad consensus and strong theoretical evidence exist that aerosol radiative effects (aerosol–radiation interactions and aerosol–cloud interactions) act as drivers of precipitation changes because global mean precipitation is constrained by energetics and surface evaporation. Likewise, aerosol radiative effects cause well-documented shifts of large-scale precipitation patterns, such as the intertropical convergence zone. The extent of aerosol effects on precipitation at smaller scales is less clear. Although there is broad consensus and strong evidence that aerosol perturbations microphysically increase cloud droplet numbers and decrease droplet sizes, thereby slowing precipitation droplet formation, the overall aerosol effect on precipitation across scales remains highly uncertain. Global cloud-resolving models provide opportunities to investigate mechanisms that are currently not well represented in global climate models and to robustly connect local effects with larger scales. This will increase our confidence in predicted impacts of climate change.

Less than 3% of water on Earth sustains life. Precipitation is the most important mechanism delivering fresh water from the atmosphere to the surface. Although climate change discussions are commonly framed in terms of global temperature change, precipitation changes drive actual impacts of climate change on the planet[1,2].

A substantial body of literature exists describing the impact

regarding aerosol (nano- to micrometre-sized particles suspended in air of anthropogenic or natural origin) effects on precipitation (APEs) remains large. Many hypotheses describe APEs on the basis of radiative and cloud microphysical arguments. Some are included in current climate models; others are not (compare Fig. 1 and Table 1). Large uncertainty remains regarding the underlying mechanisms

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719

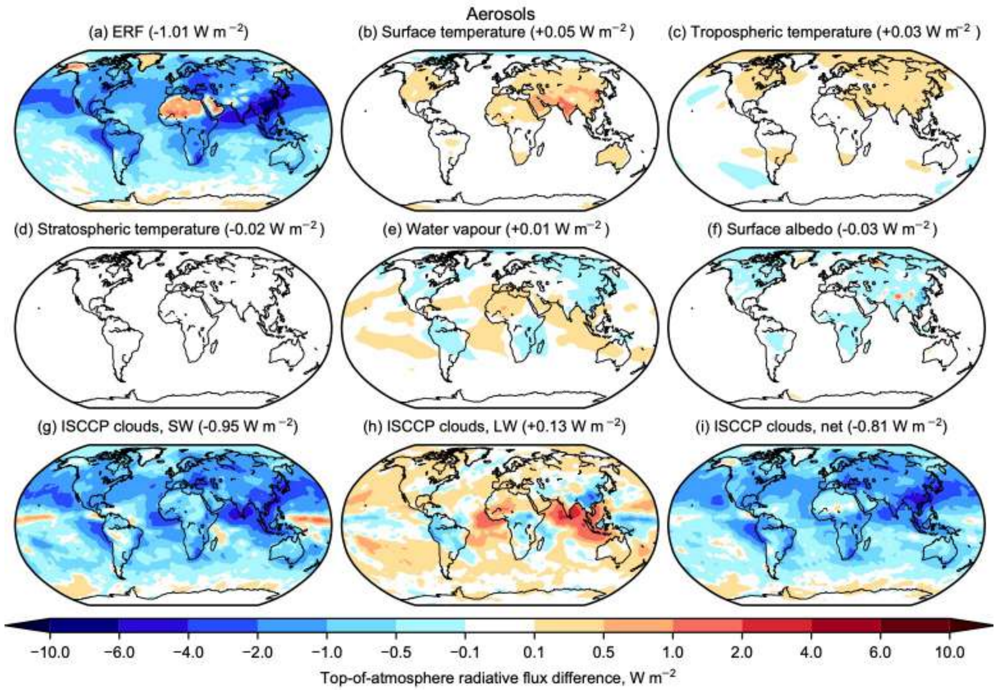
(Stier et al., Nat. Geosci., 2024)

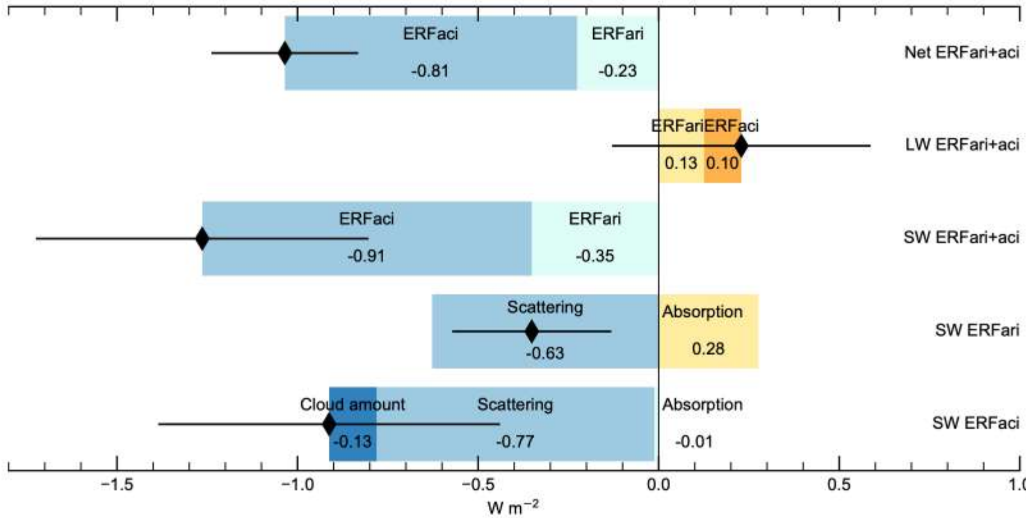
Aerosol effects on convective clouds

Philip Stier

Global aerosol modelling in CMIP6

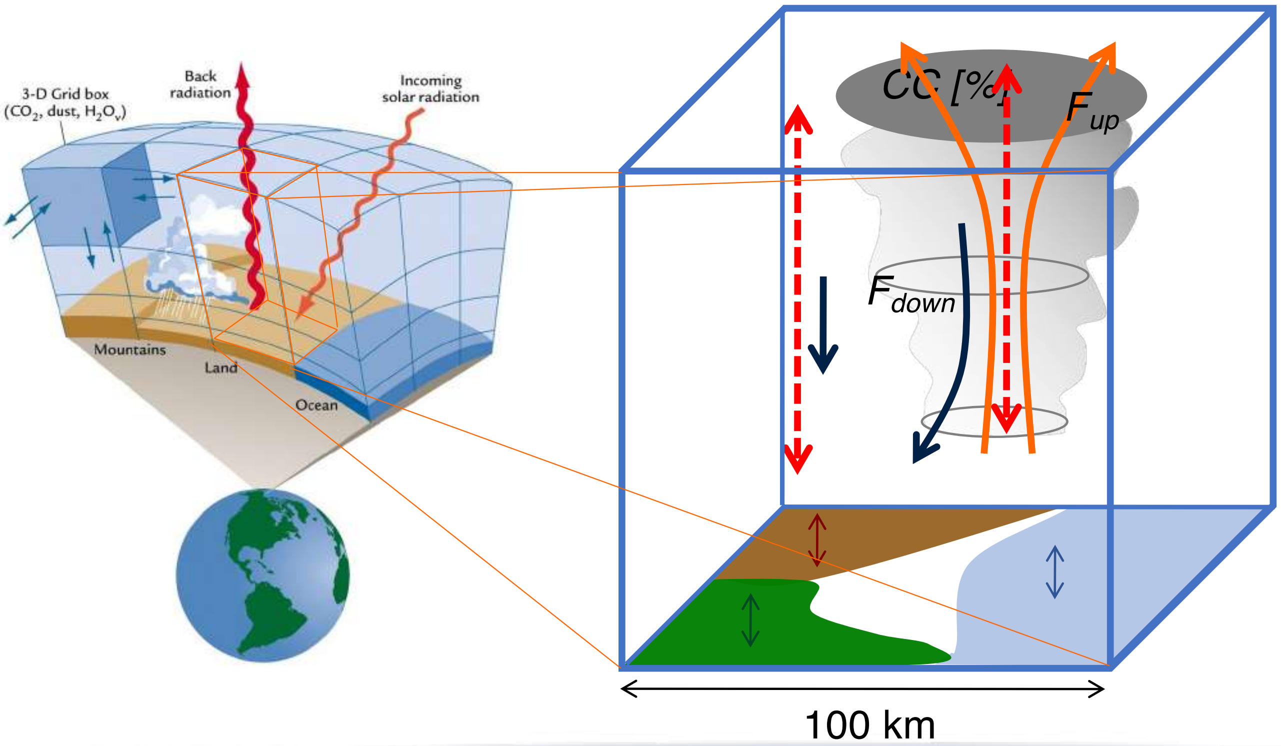
Aerosol ERF and adjustments in CMIP6 models – does not include aerosol effects on convection:





Global aerosol modelling in CMIP6

Traditional CMIP climate models…



Parameterised fractional cloud cover

Large scale mean in-cloud liquid-, ice-water (or sub-grid scale pdf)

Mean up- and down-drafts, compensating subsidence

No explicit convective updraft microphysics, no explicit coupling of convection to aerosols

Aerosol-Convection Interactions

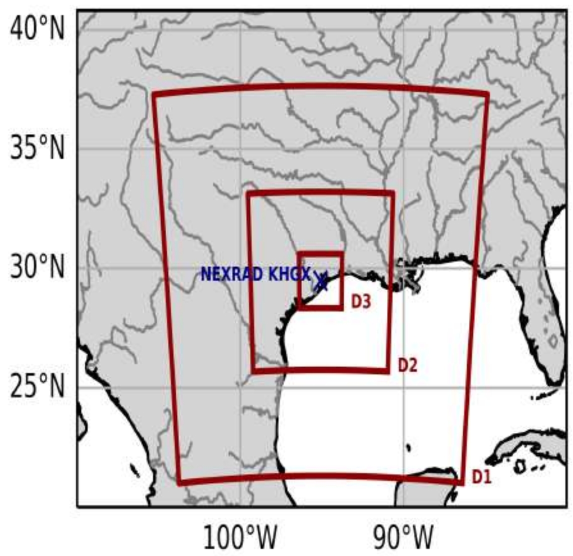
Houston deep convection **cloud resolving modelling** case study:

Model intercomparison:

- 6 state-of-the-art CRMs:
  WRF (3x), RAMS, COSMO, UM
- Identical simulation setup
- High frequency output and detailed microphysical process rates
- **Simulation length 27h to capture impacts of CCN on diurnal cycle.**

Aerosol perturbations

- Idealised **low** (CN_{100nm}=500 cm^{-3}) and **high** (CN_{100nm} =4000 cm^{-3}) aerosol profiles based on observations



Deep convection model intercomparison

(Marinescu et al., 2022; Saleeby et al., 2025; **van den Heever et al., in review**)

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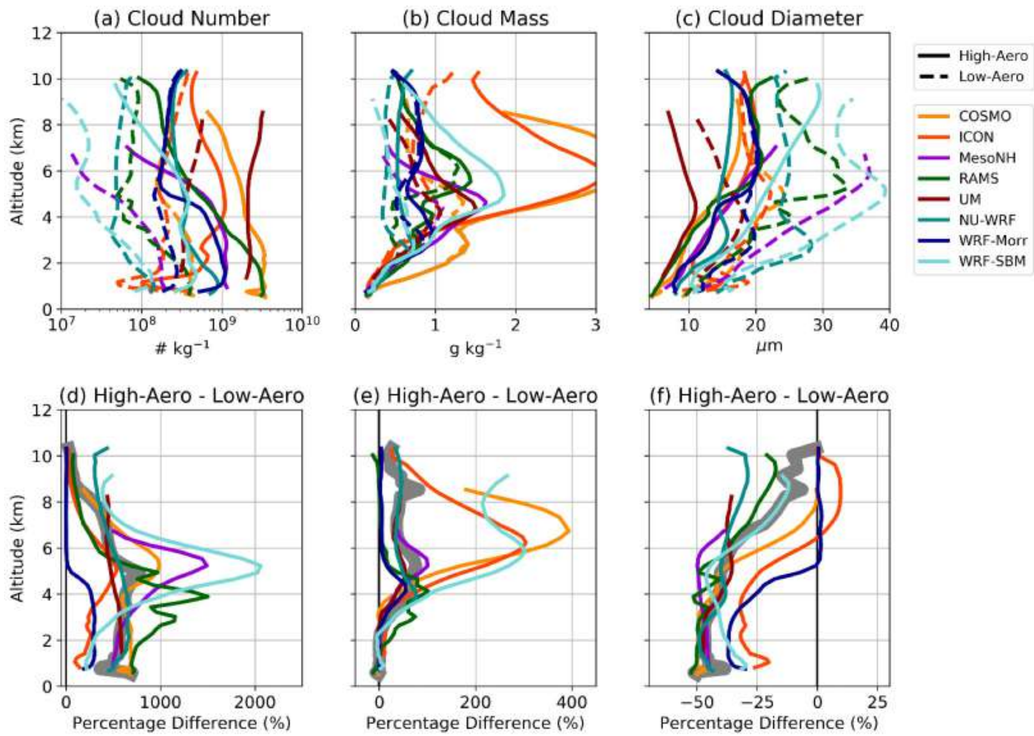

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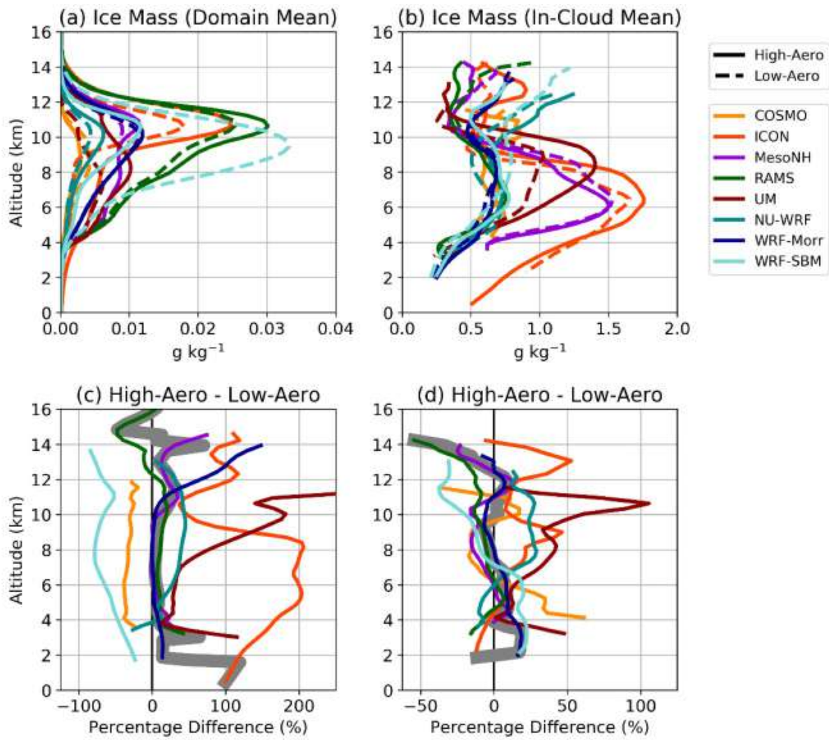

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From HAM to HAM-lite

ECHAM-HAM (Stier et al., 2005; Zhang et al., 2012; Tegen et al., 2019) & **ICON-HAM** (Salzmann et al., 2022)

- **Aerosol compounds:**

  Sulfate | Black Carbon | Organic Carbon | Sea Salt | Mineral Dust

- **Resolve aerosol size-distribution by 7 log-normal modes**
- **Mode size, mixing state, composition predicted by microphysical aerosol module M7** (Vignati et al., 2004)

MODES IN M7	Hydrophilic	Hydrophobic
NUCLEATION ($r < 0.005\ \mu m$)	1 N_1, M_{SO_4}	
AITKEN ($0.005\ \mu m < r < 0.05\ \mu m$)	2 N_2, M_{SO_4}, M_{BC}, M_{OC}	5 N_5, M_{BC}, M_{OC}
ACCUMULATION ($0.05\ \mu m < r < 0.5\ \mu m$)	3 N_3, M_{SO_4}, M_{BC}, M_{OC}, M_{SS}, M_{DU}	6 N_6, M_{DU}
COARSE ($0.5\ \mu m < r$)	4 N_4, M_{SO_4}, M_{BC}, M_{OC}, M_{SS}, M_{DU}	7 N_7, M_{DU}

Global km-scale ICON-HAM-lite

(Weiss, Herbert, Stier, GMD, 2025)

From HAM to HAM-lite

ICON-HAM-lite (Weiss, Herbert, Stier, GMD, 2025)

- **Aerosol compounds:**

  Sulfate — Black Carbon — Organic Carbon — Sea Salt — Mineral Dust

- **Prescribe aerosol size-distribution by n log-normal modes**
- **Mode size, mixing state, and composition prescribed**

MODES	Hydrophilic
AITKEN (0.005 $\mu m < r < 0.05\ \mu m$)	
ACCUMULATION (0.05 $\mu m < r < 0.5\ \mu m$)	N_{BB}, N_{AV}
COARSE (0.5 $\mu m < r$)	N_{SS}, N_{DU}

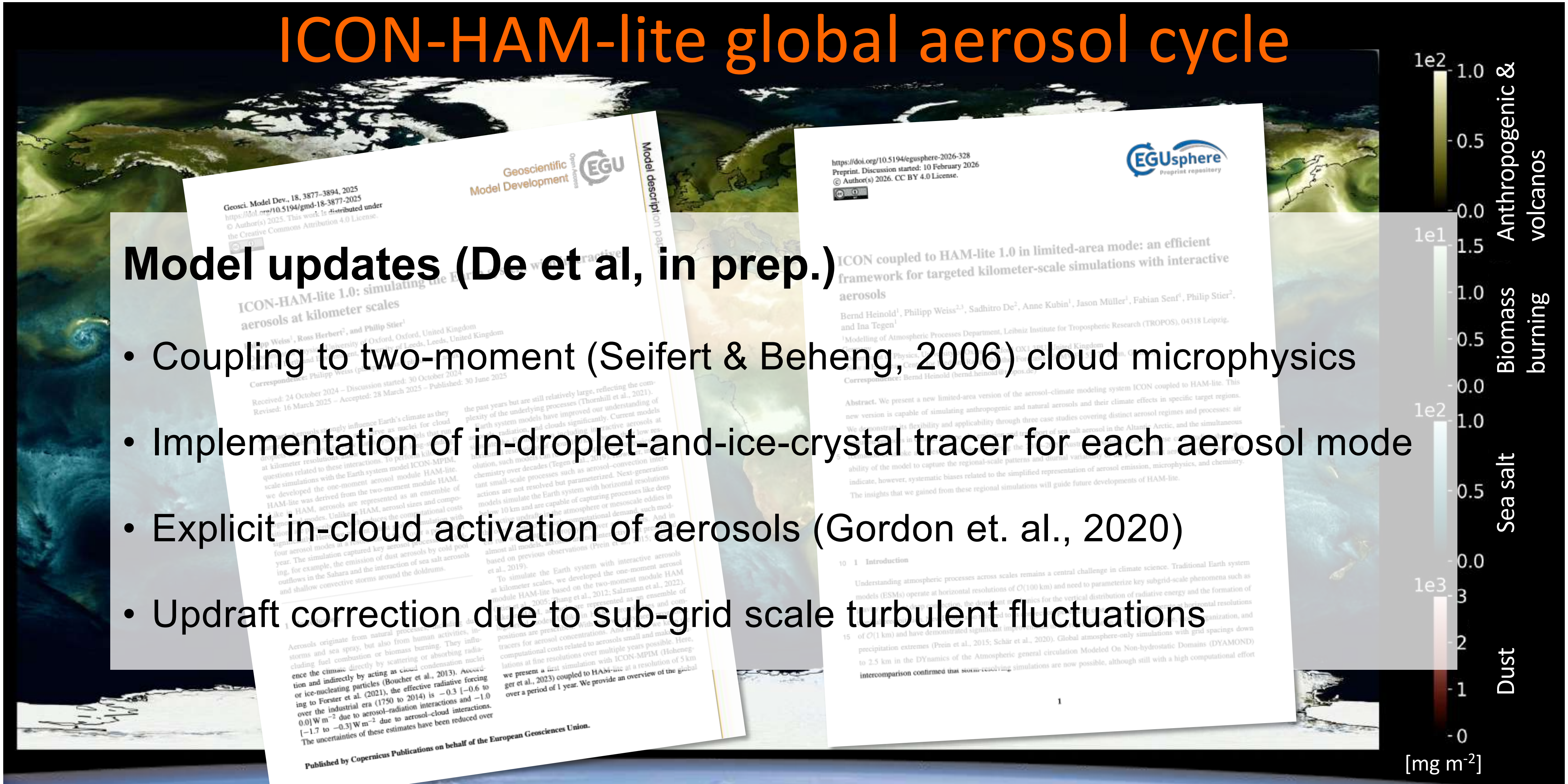
Minimal global configuration with just 4 modes/tracers:

- Biomass burning (BB)
- Anthropogenic & volcanic (AV)
- Sea salt (SS)
- Dust (DU)

Global km-scale ICON-HAM-lite

(Weiss, Herbert, Stier, GMD, 2025)

ICON-HAM-lite global aerosol cycle



Model updates (De et al, in prep.)

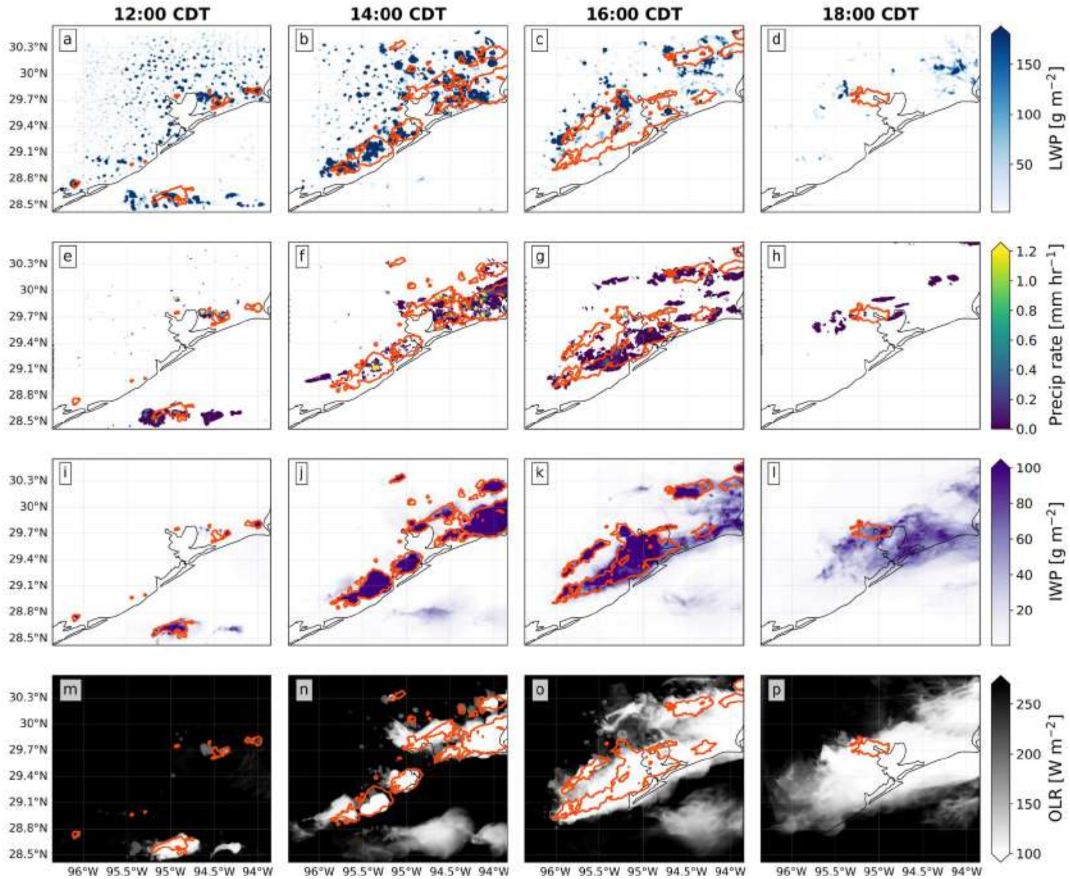
- Coupling to two-moment (Seifert & Beheng, 2006) cloud microphysics
- Implementation of in-droplet-and-ice-crystal tracer for each aerosol mode
- Explicit in-cloud activation of aerosols (Gordon et. al., 2020)
- Updraft correction due to sub-grid scale turbulent fluctuations

Global & regional km-scale ICON-HAM-lite

(Weiss, et al., GMD, 2025; Heinold et al., GMD, in review; De et al., in prep.)

TRACER Campaign Simulations

- Regional ICON-HAM-lite simulation at 600m resolution
- Sea breeze case 17 June 2022
- Baseline simulation plus 0.3- and 3-times aerosol perturbation runs



TRACER ICON-HAM-lite simulations

(Maor Sela, Poster P061)

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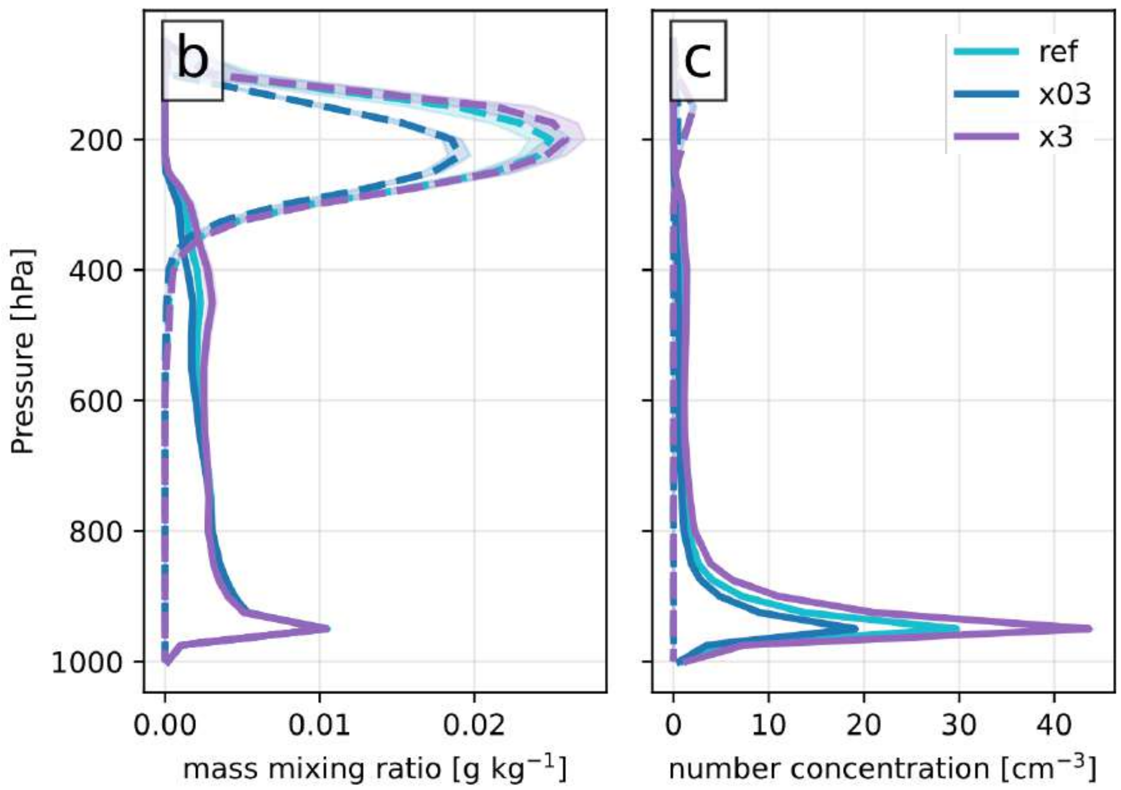
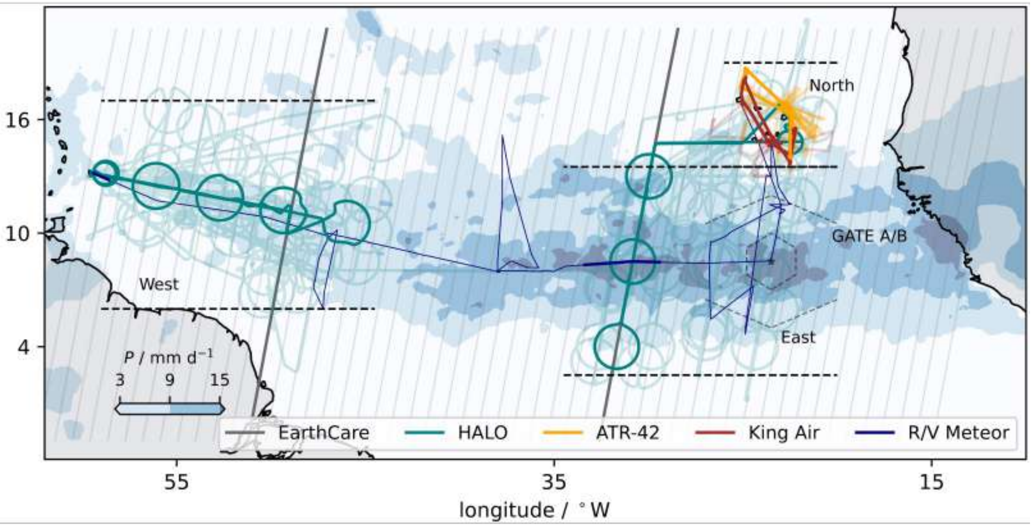
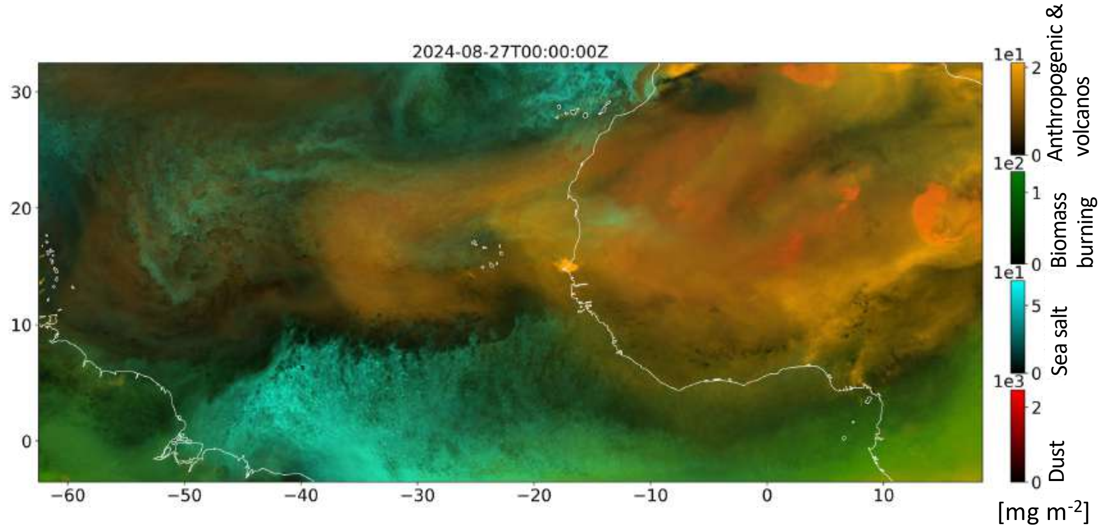


ORCESTRA Campaign Simulations

- 20-day regional ICON-HAM-lite simulation at 5km, analysed last 10 days
- Present day (PD): ERA/CAMS boundary conditions
- Pre-industrial (PI): anthropogenic and biomass burning reduced by factor of 3





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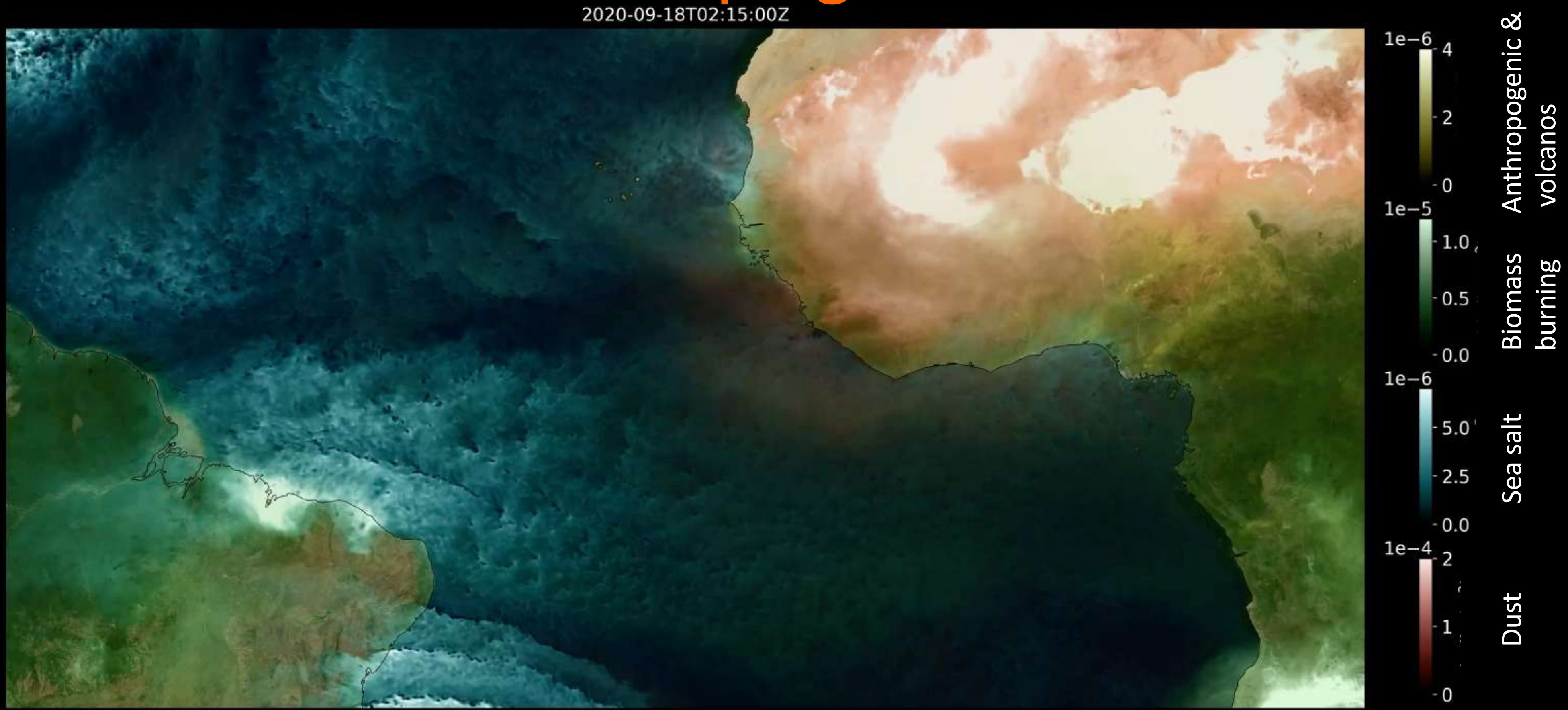
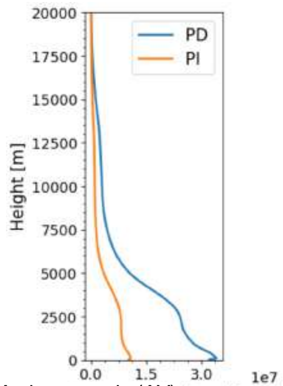


ORCESTRA ICON-HAM-lite simulations

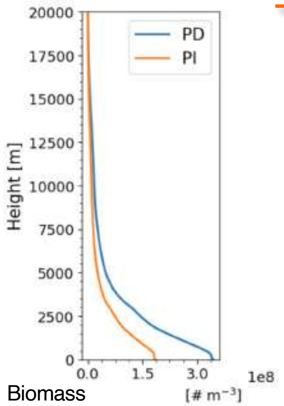
(Sadhitro De)

ORCESTRA Campaign Simulations

Aerosol perturbation:

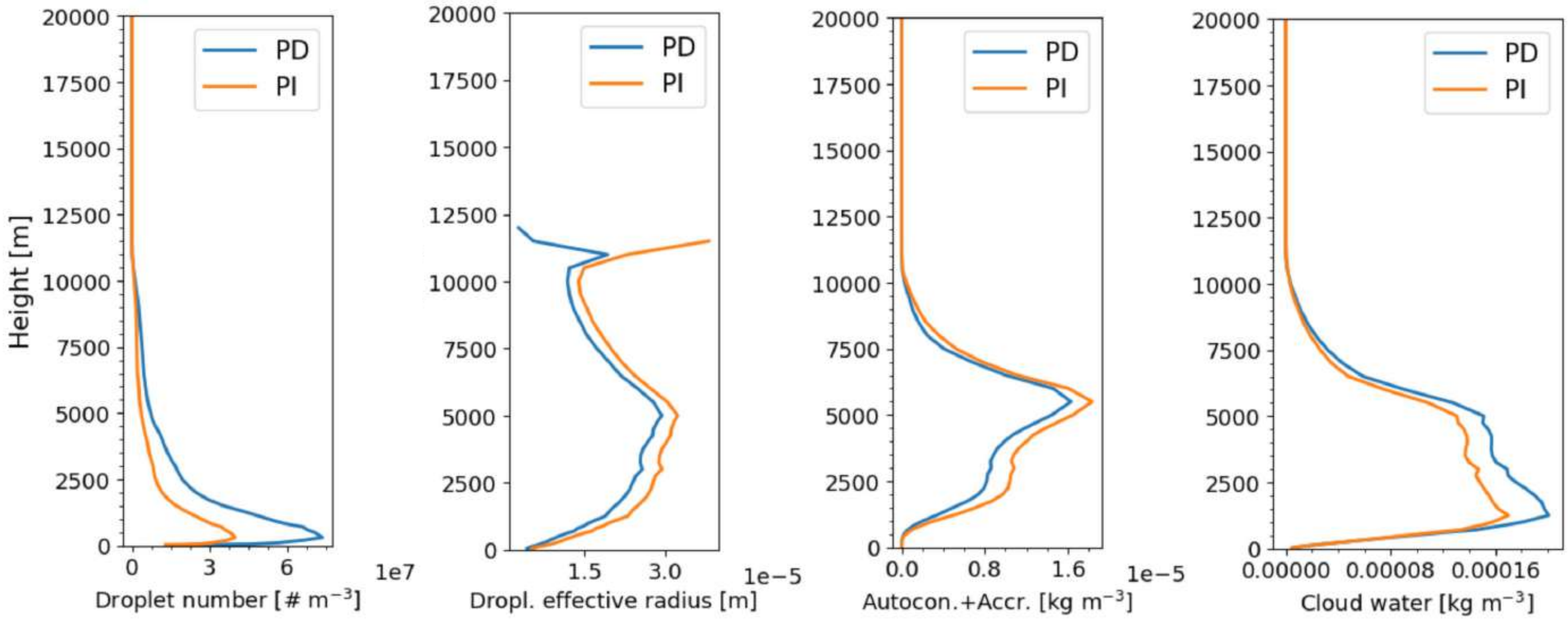


Anthropogenic (AV)



Biomass burning (BB)

Impact on convective updraft (q_c+q_i > 1 mg kg^{-1} and w_{max} > 1 m s^{-1}) microphysics:

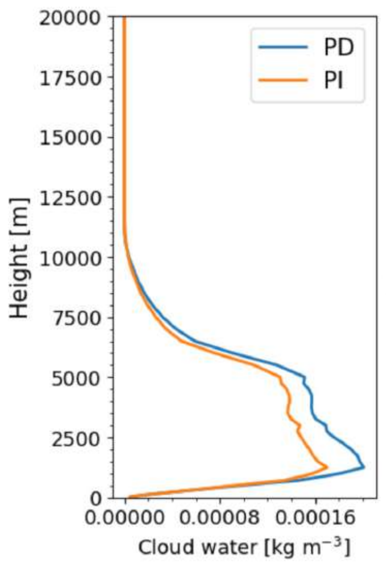


ORCESTRA ICON-HAM-lite simulations

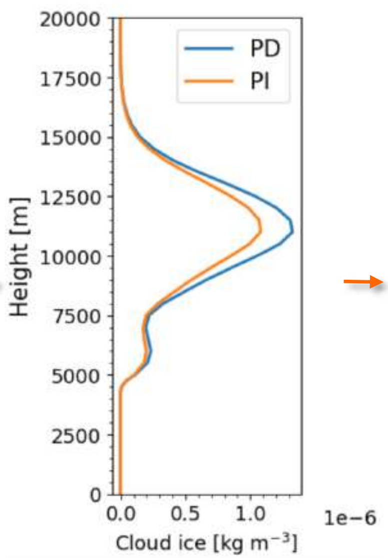
(Sadhitro De)

ORCESTRA Campaign Simulations

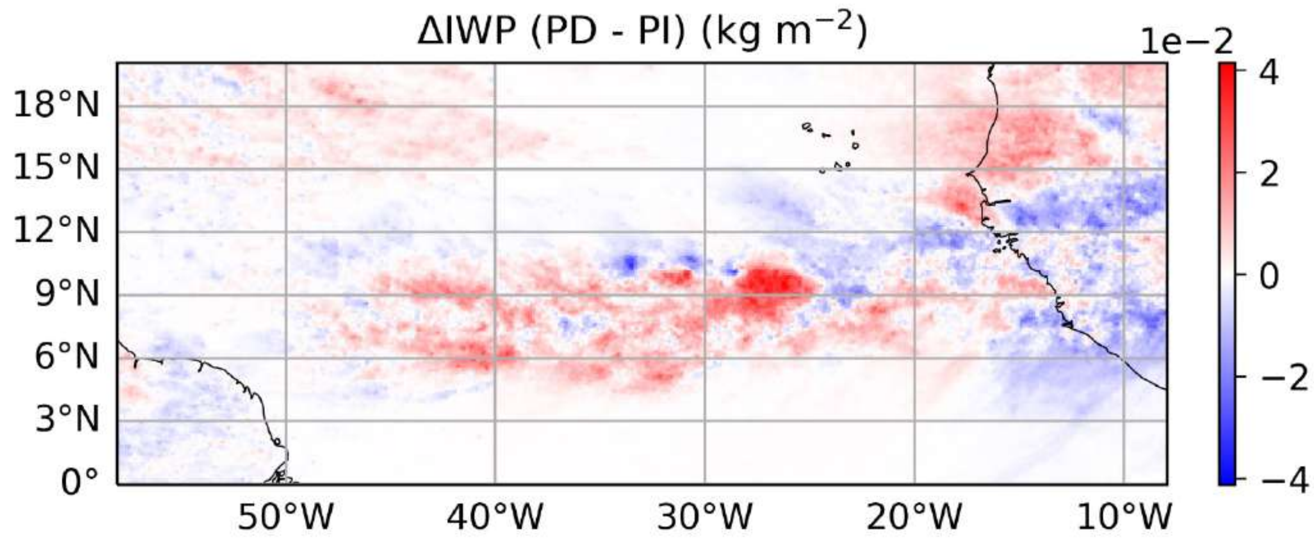
Updraft cloud water



Cloud ice



Cloud ice water path

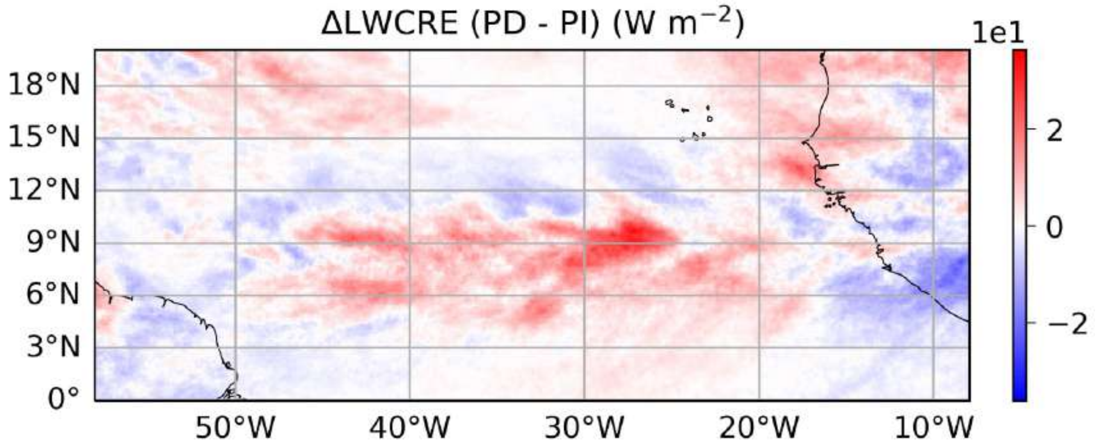


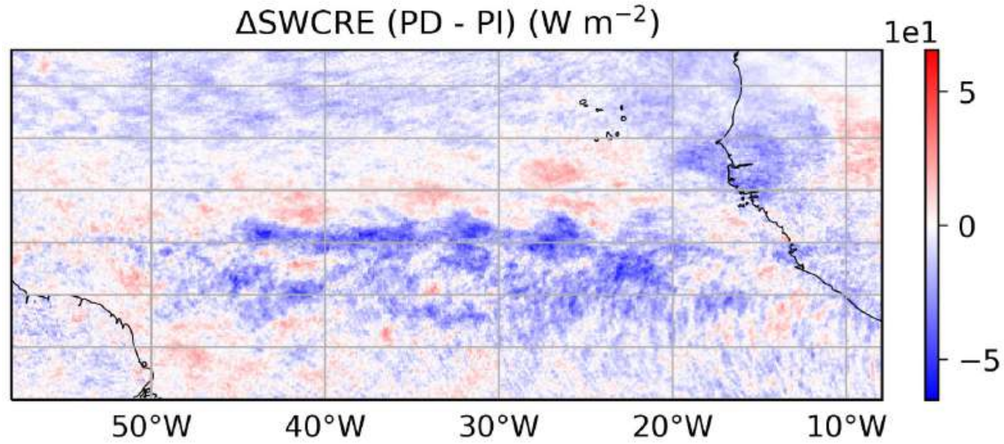
ORCESTRA ICON-HAM-lite simulations

(Sadhitro De)

ORCESTRA Campaign Simulations

Anthropogenic perturbations to anvil cloud radiative effects





ΔCRE_{LW} = 1.4 W m^{-2}

ΔCRE_{SW} = - 6.2 W m^{-2}

ΔCRE_{net} = - 4.8 W m^{-2}

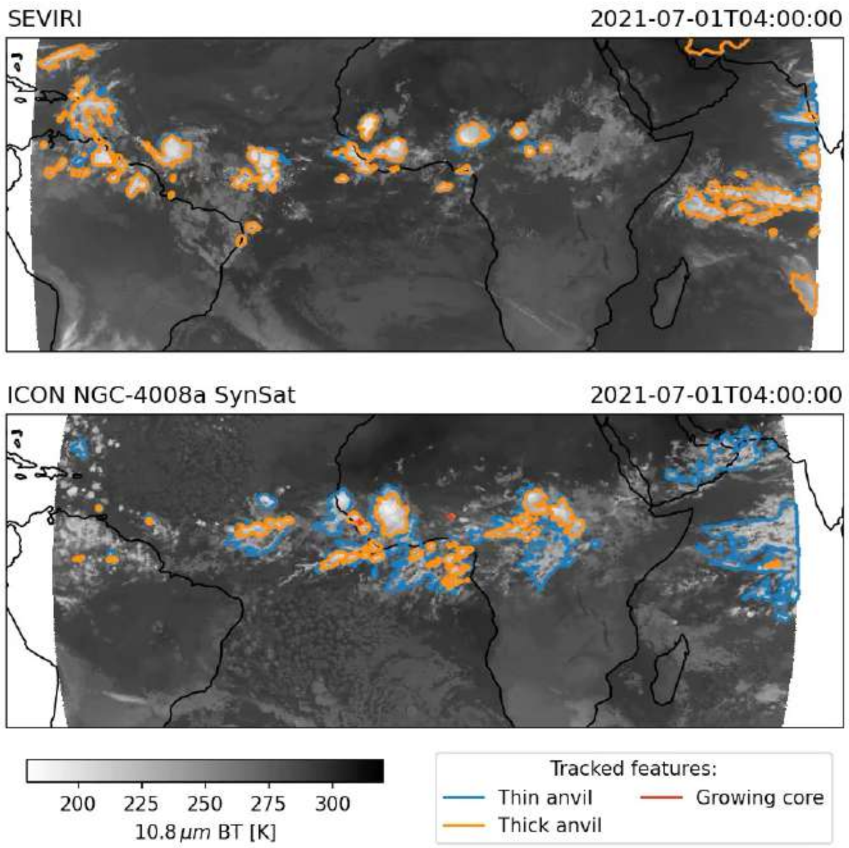
ORCESTRA ICON-HAM-lite simulations

(Sadhitro De)

ORCESTRA Campaign Simulations

Significant anthropogenic radiative effect from aerosol effects on convection simulated by ICON-HAM-lite – but is it real?

Constraining the anvil response – cloud tracking



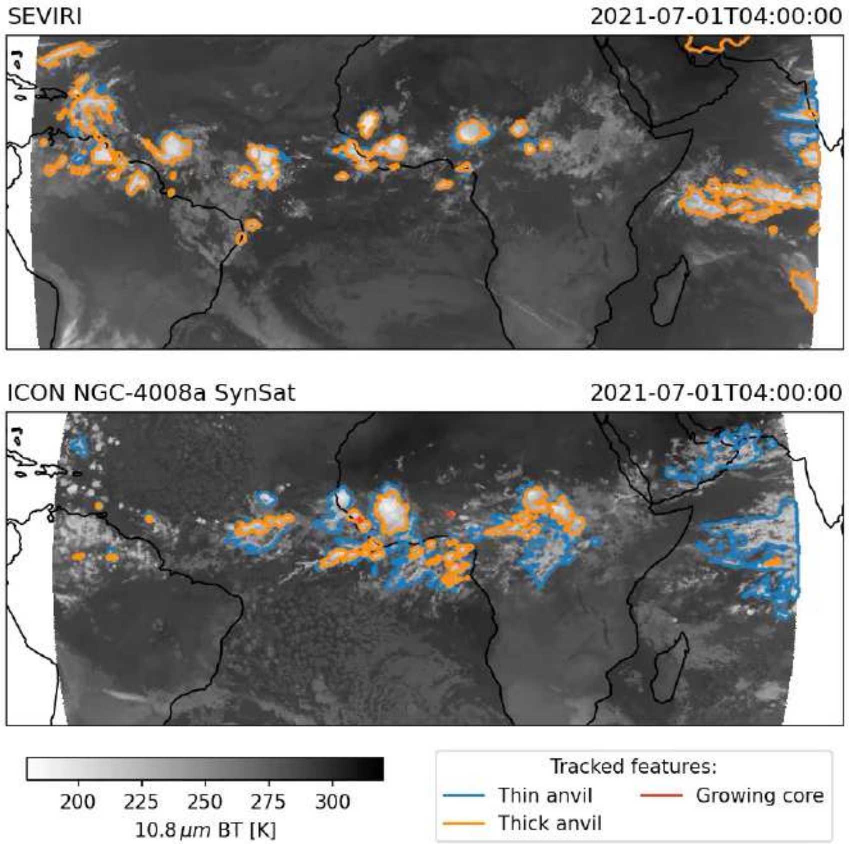
tobac flow (Jones et al., AMT, 2023):

- Detection and tracking of convective cores from cloud top cooling rates in a Lagrangian framework.
- Tracking of associated thin and thick anvils.

Consistent tracking in km-scale ICON model and SEVIRI geostationary satellite data through SynSat forward modelling of satellite radiances from ICON output using RTTOV.

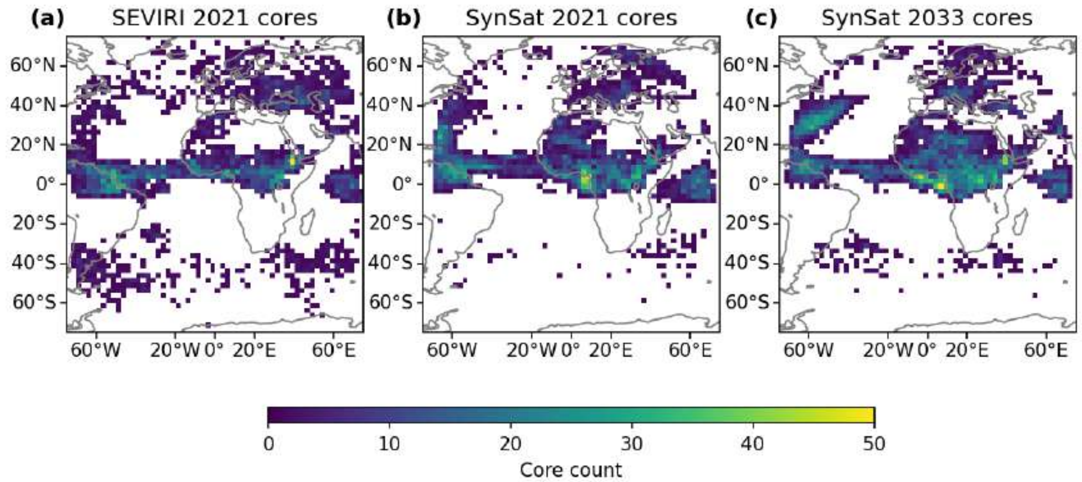
Novel process-based constraints of convective cloud processes in km-scale climate models.

Constraining the anvil response – cloud tracking

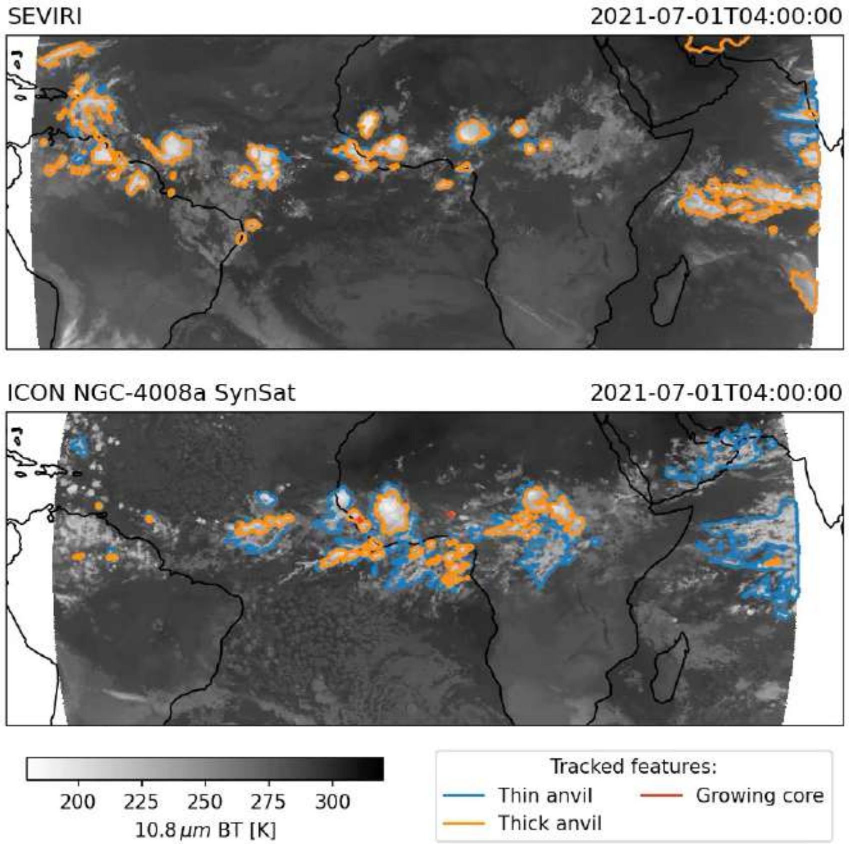


tobac flow (Jones et al., AMT, 2023):

- Comparison of tracked convective cores



Constraining the anvil response – cloud tracking



tobac flow (Jones et al., AMT, 2023):

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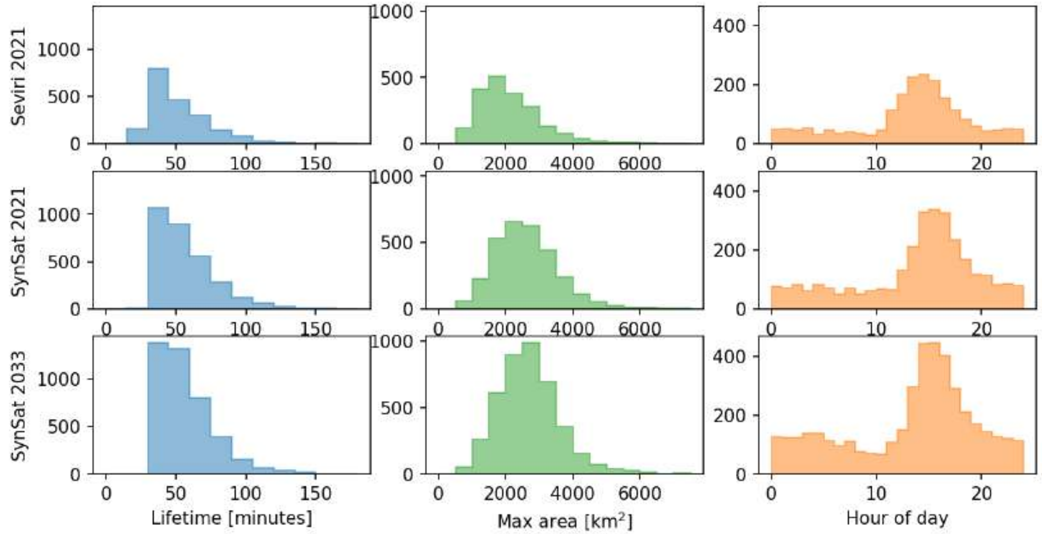
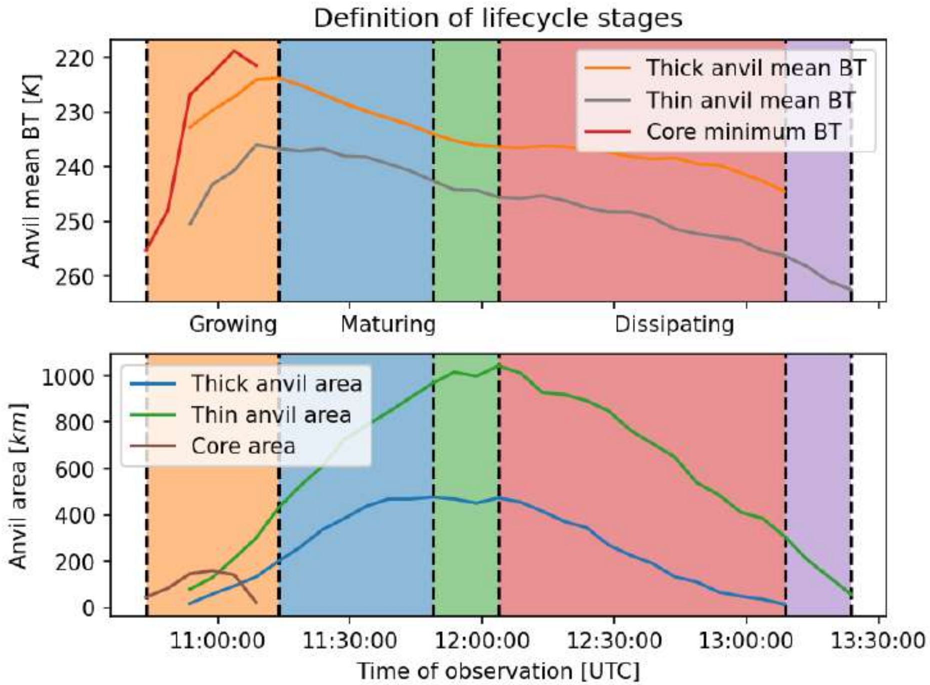


Constraining the anvil response – cloud tracking

Defining the convective lifecycle:



(Futyan & del Genio, 2007)

Constraining the anvil response – cloud tracking

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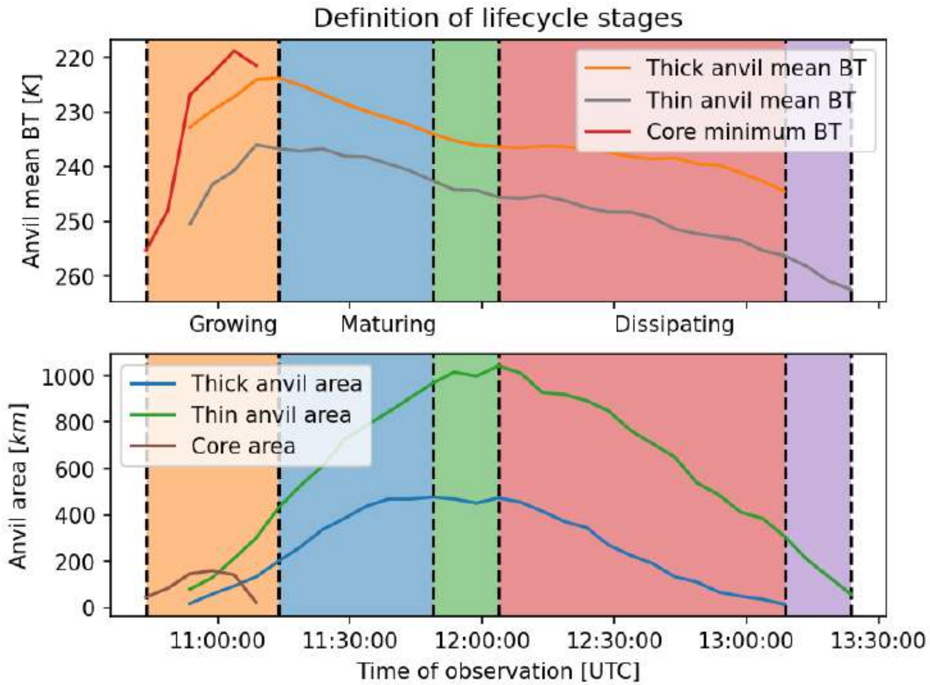
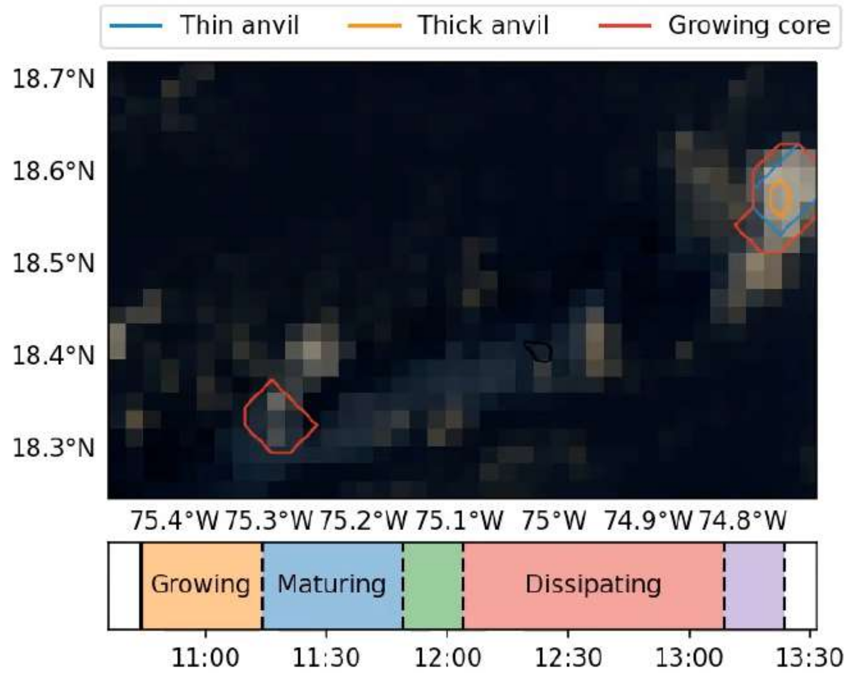
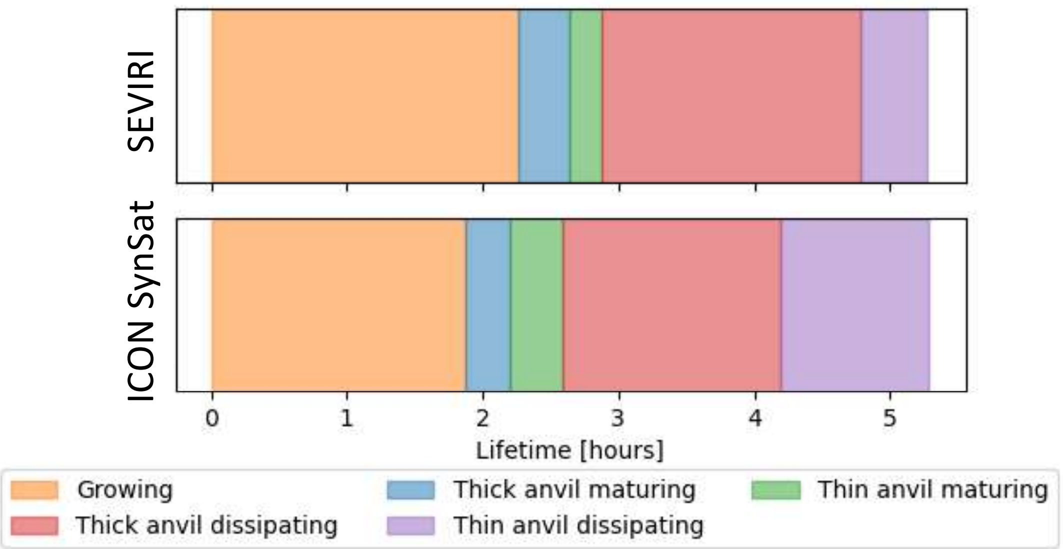


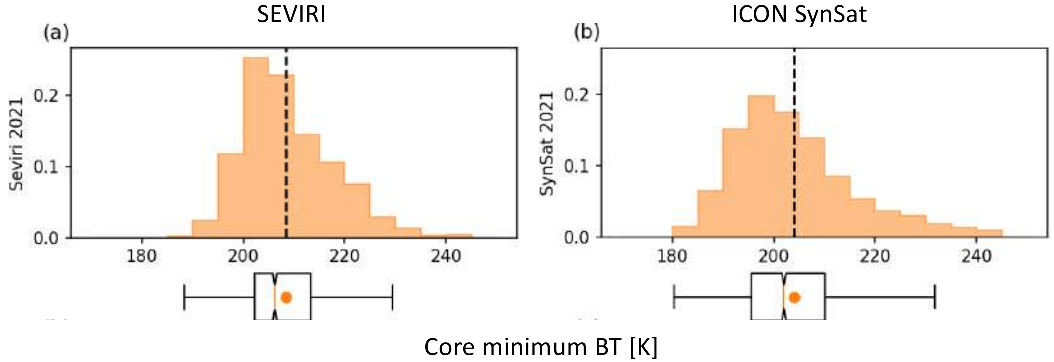
(Based on Futyan & del Genio, 2007)



Constraining the anvil response – cloud tracking

Comparison of tracked deep convection in SEVIRI observations vs synthetic satellite observations from ICON NextGEMS cycle 4 simulations:

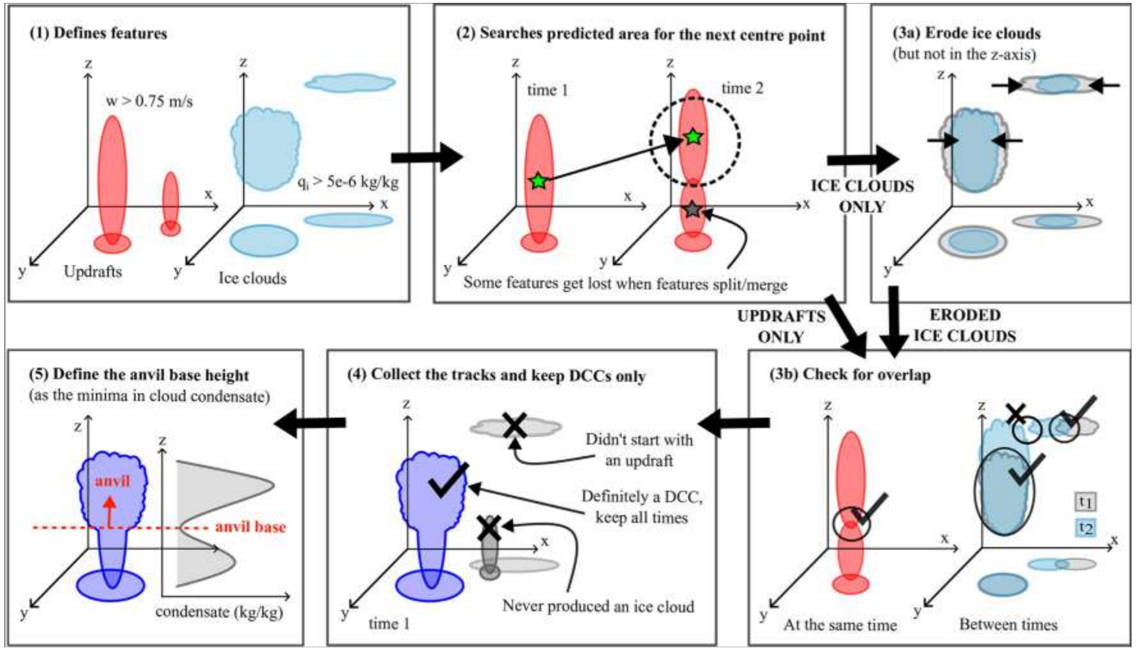




Cores in ICON tend to be colder, and develop faster than those in observations

Constraining the anvil response

Tracking of deep convective clouds using extended *tobac* cloud tracking framework (Heikenfeld et al., GMD, 2019; Sokolowsky et al., GMD, 2024):



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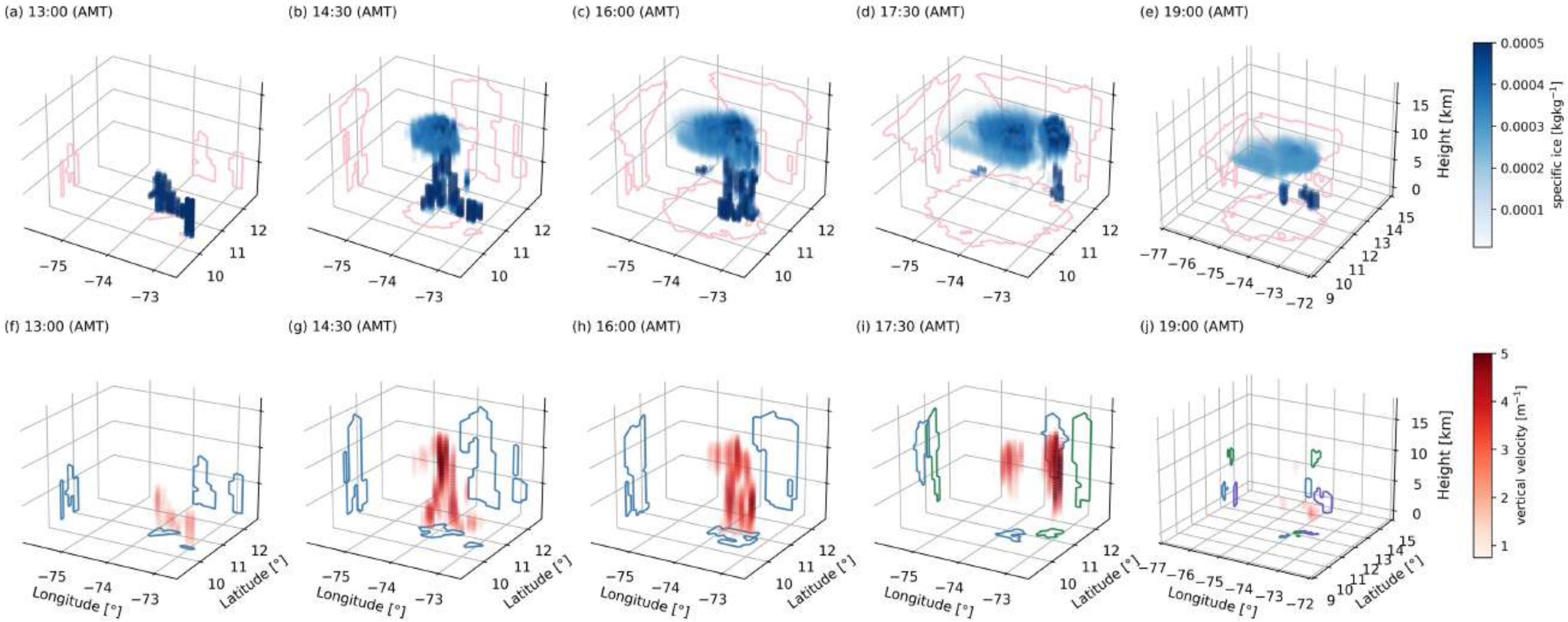

Mathilde Ritman

(Ritman, Jones, Stier, ACP, 2026)

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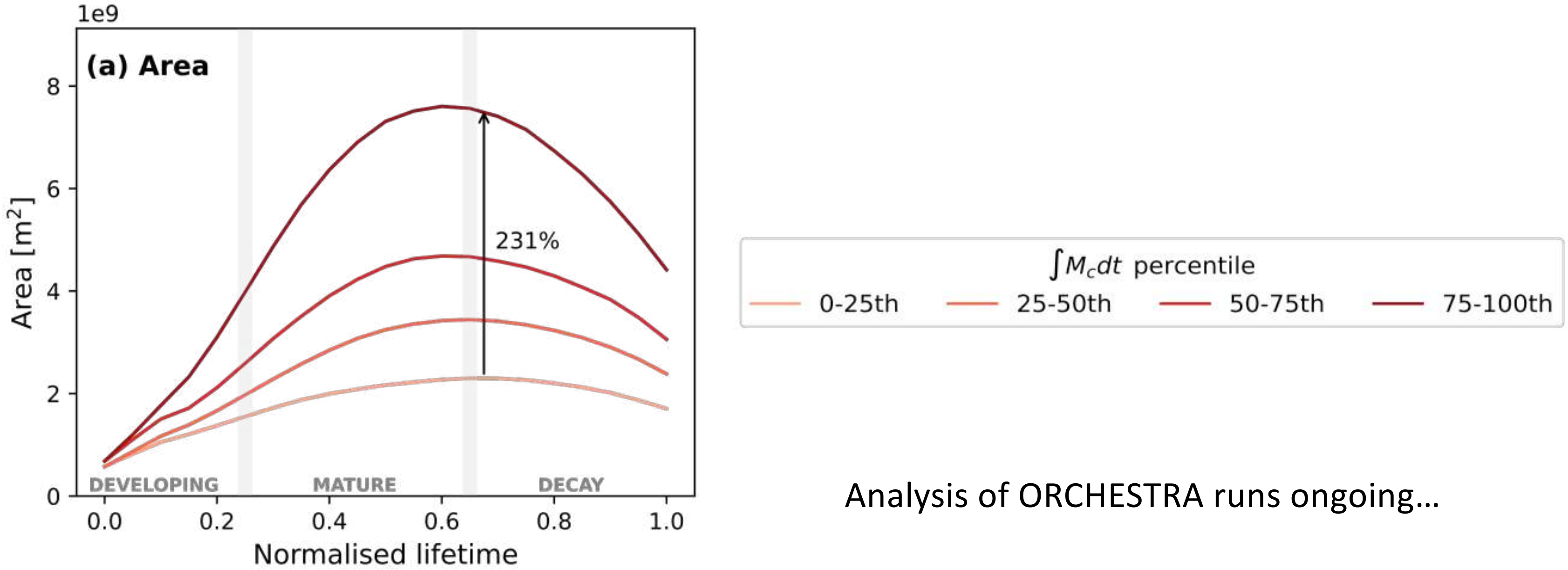

Analysis of ORCHESTRA runs ongoing…

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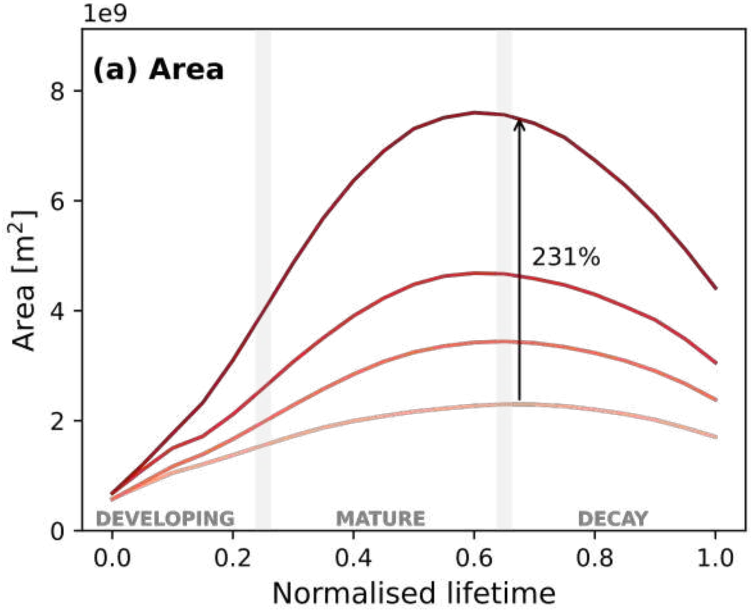
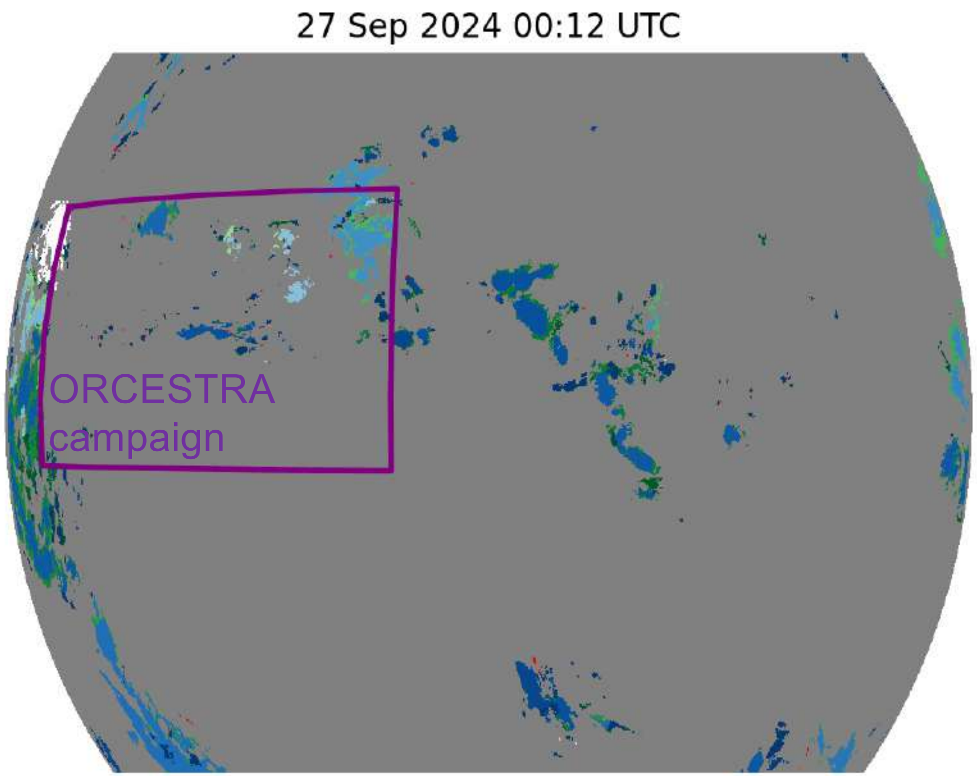
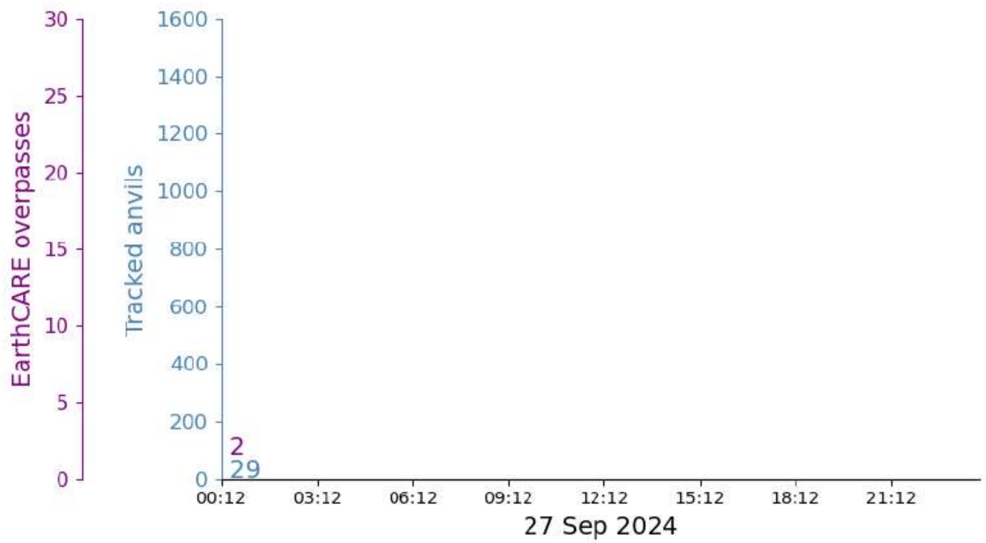


Constraining the anvil response



Tracked clouds in MSG-SEVERI, collocated with EarthCARE for ORCESTRA (William Jones 2026)



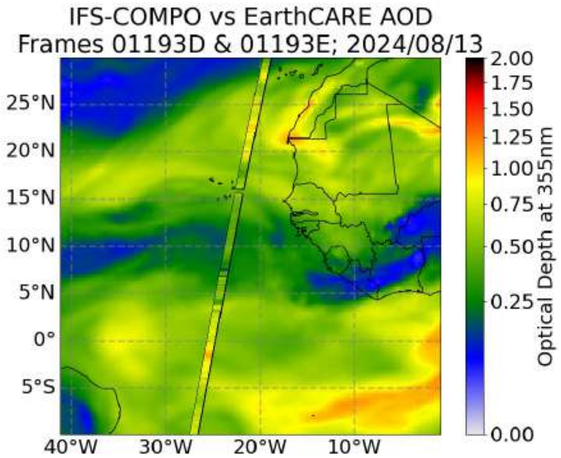
1059 collocated anvil clouds from mid-August to October

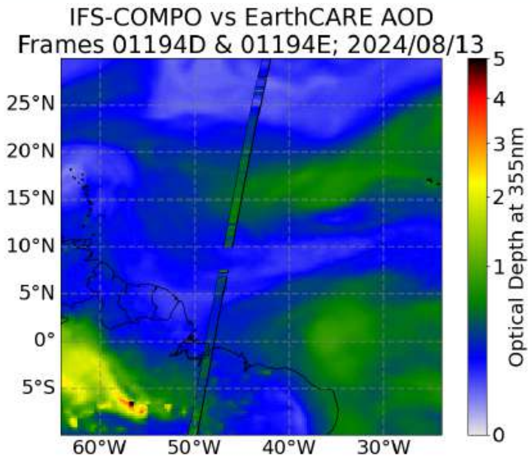
EarthCARE / ORCESTRA Model Intercomparison Project Aerosol Experiment (ECOMIP-Aerosol)

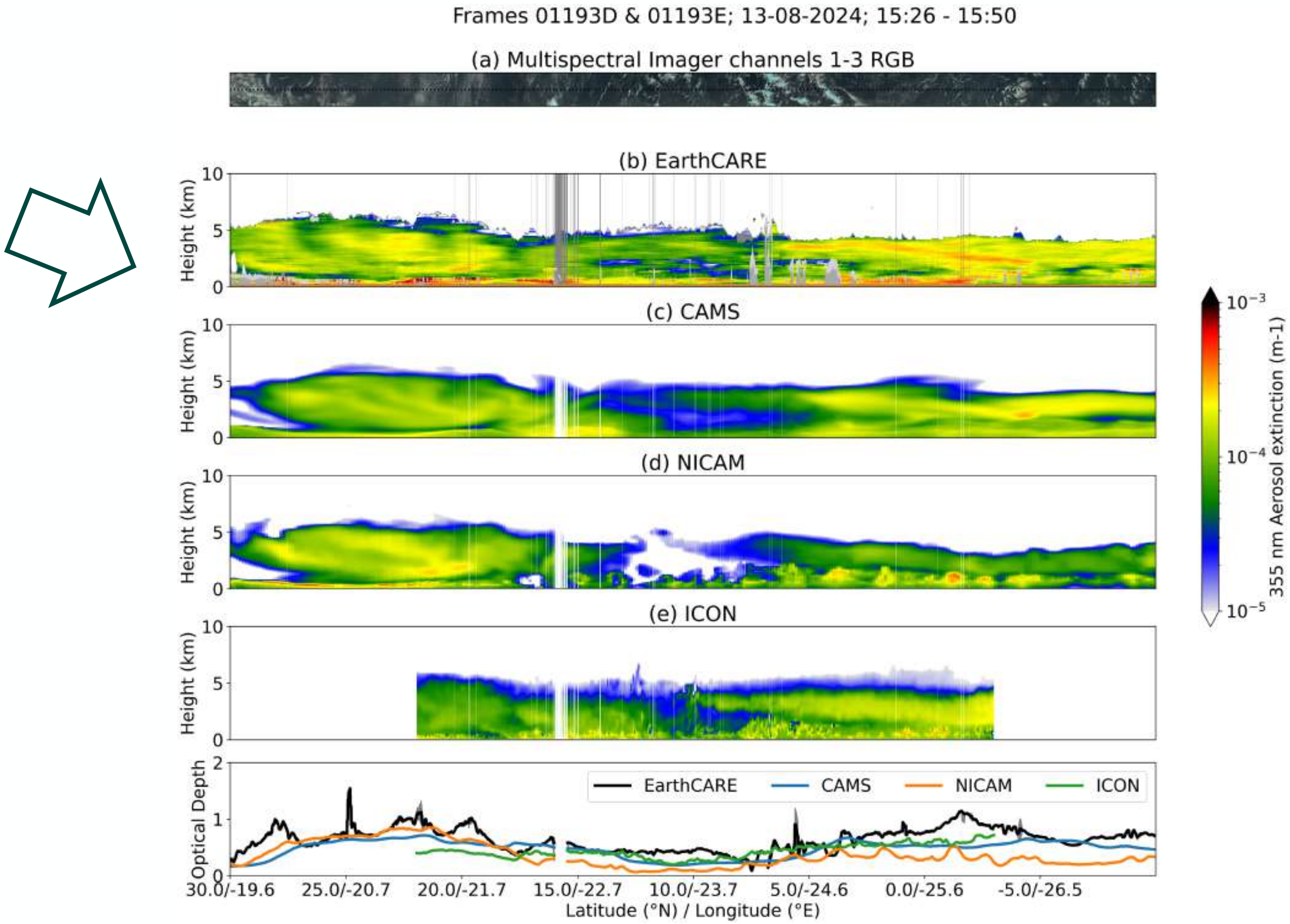
Significant anthropogenic radiative effect from aerosol effects on convection simulated by ICON-HAM-lite – but is it real?

(Peter Hill, Yuhi Nakamura, Sadhitro De)

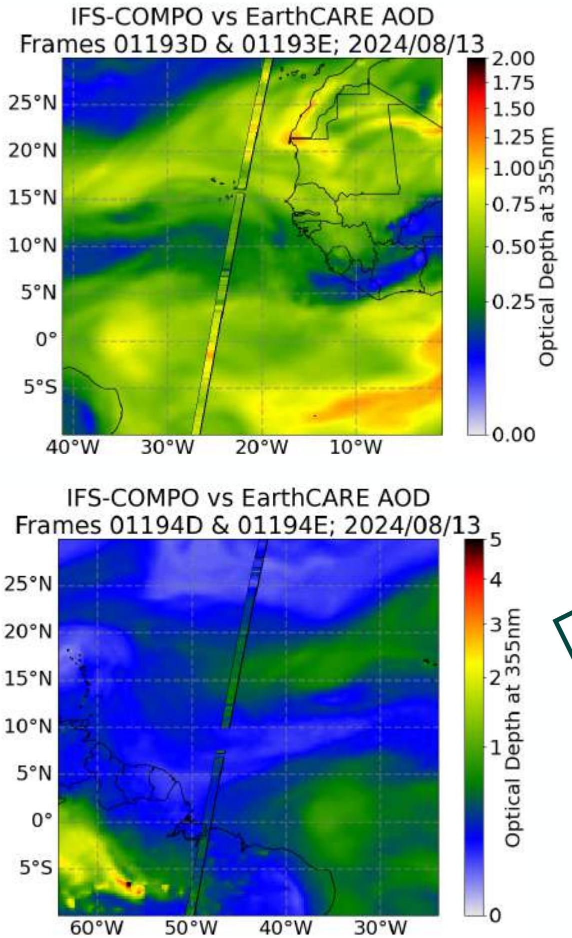
EarthCARE / ORCESTRA Aerosol Model Intercomparison Project (ECOMIP-Aerosol) (Peter Hill, Yuhi Nakamura, Sadhitro De)

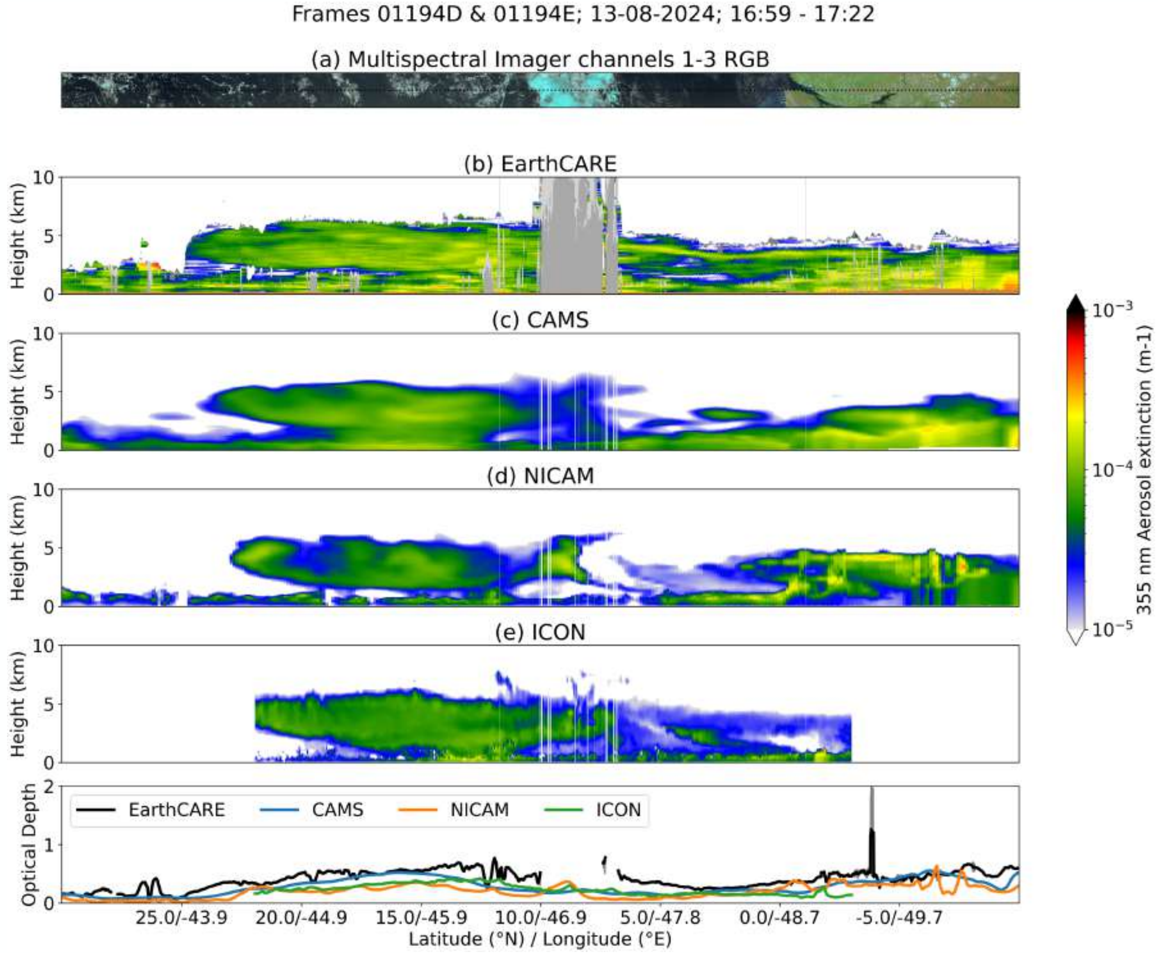




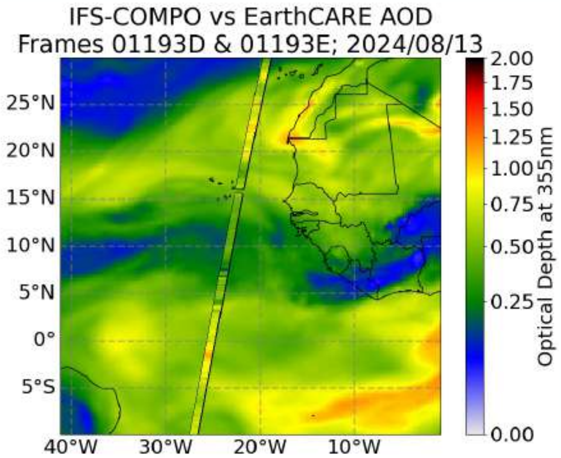


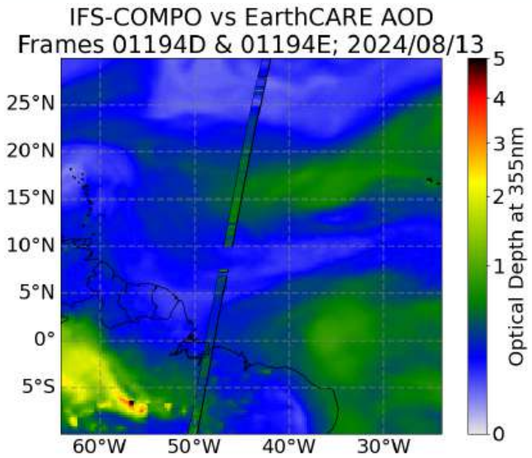
EarthCARE / ORCESTRA Aerosol Model Intercomparison Project (ECOMIP-Aerosol) (Peter Hill, Yuhi Nakamura, Sadhitro De)





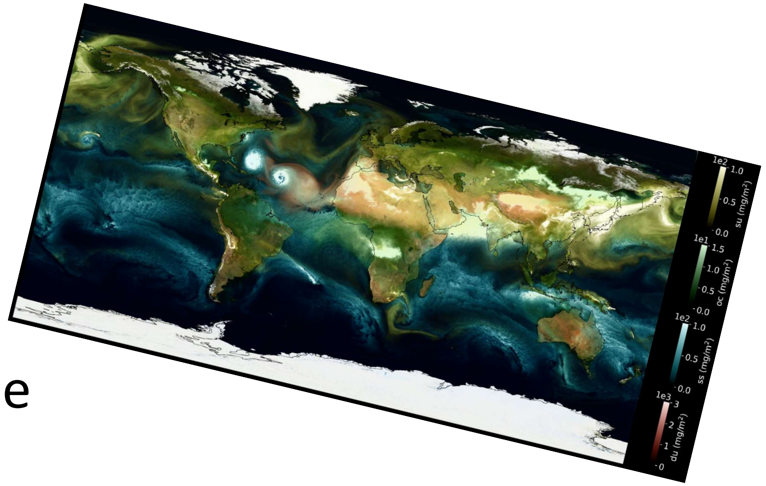
EarthCARE / ORCESTRA Aerosol Model Intercomparison Project (ECOMIP-Aerosol) (Peter Hill, Yuhi Nakamura, Sadhitro De)





- ECOMIP-Aerosol models capture overall structure very well across contrasting aerosol regimes
- Models do not reproduce the high boundary layer extinction values retrieved by EarthCARE
- Propose aerosol perturbation runs as part of ECOMIP-Aerosol

Conclusions



- km-scale aerosol modelling allows us to study aerosol-convection interactions
- The uncertainties are large but as we go to km-scale climate modelling, effects cannot be ignored….
- We perform anthropogenic aerosol perturbation experiments with ICON-HAM-lite for TRACER & ECOMIP-Aerosol in the tropical Atlantic
- For ECOMIP-Aerosol, anthropogenic aerosol increases updraft cloud water and anvil ice with a net radiative effect of - 4.8 W m^{-2}
- First, intercomparison of km-scale aerosol models for ECOMIP-Aerosol shows encouraging results – lots of work to do!
- Need to exploit EarthCARE constraints along the full process chain