# WRF-Chem Study of the Aerosol-Cloud-Interactions over the Eastern North Atlantic

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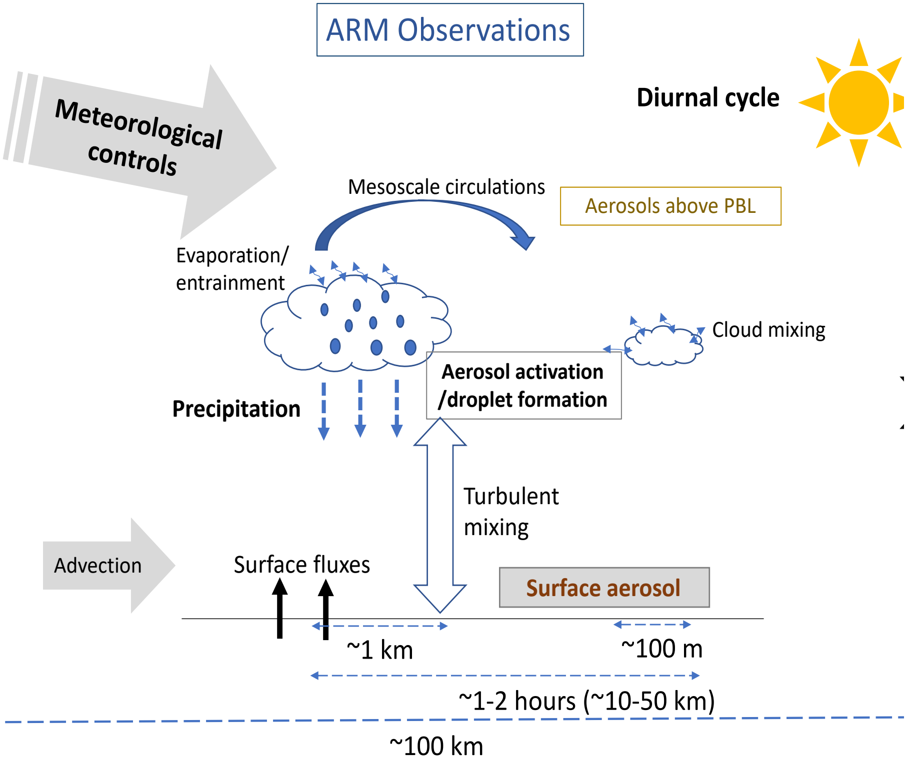
# Aerosol-cloud interactions in MBL warm clouds




- The radiative forcing associated with aerosol-cloud interactions ("aerosol indirect effect (AIE)") in liquid-phase clouds remains a large source of uncertainty in our understanding of anthropogenic climate change (e.g., *Ghan et al., 2016; Smith et al., 2020*).

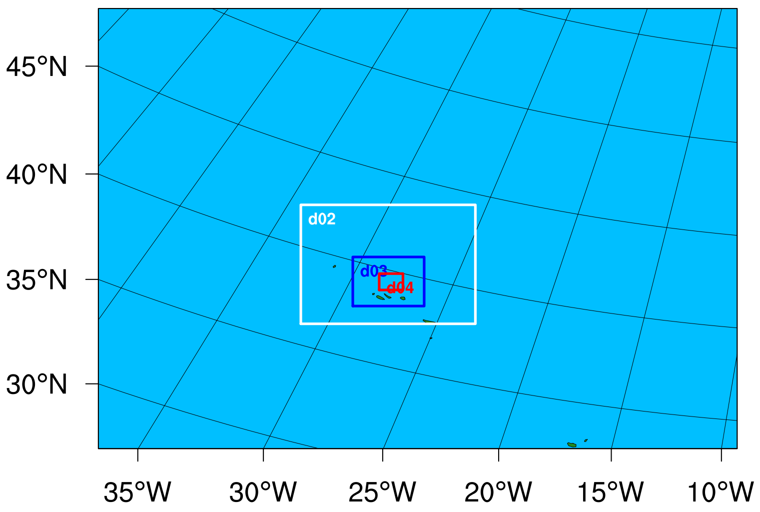
- Given that the resolution of E3SMv4 (Simple Cloud Resolving E3SM Atmosphere Model, SCREAM) will reach a global convection permitting model (CPM) grid spacing of ~3 km, it is urgent to determine whether substantial improvements in GCM spatial resolution can help bring simulated aerosol-cloud interactions closer to observations.

- Answering these questions and reducing the bias of the AIE in E3SM through physically based approaches will require deeper understandings of aerosol-cloud interactions from observations and simulations close to the scale of large-eddy simulation (LES).

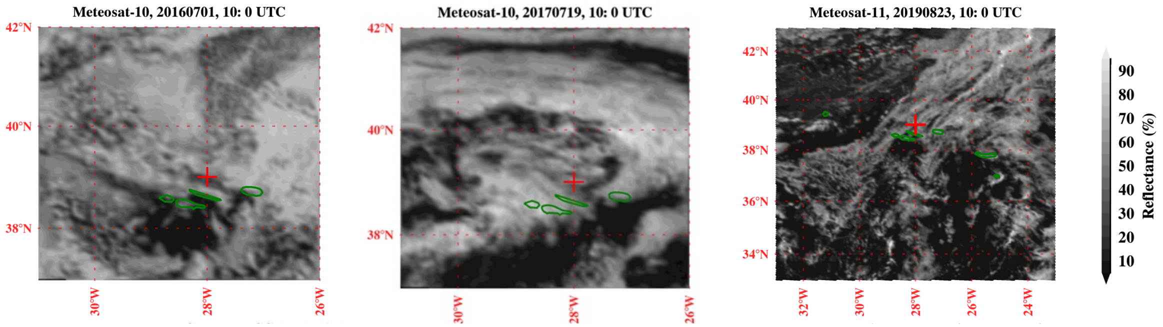
- *Zheng et al., (JGR in review)* estimated the meteorological covariations of aerosol and marine boundary layer (MBL) cloud properties in the Eastern North Atlantic (ENA) region, characterized by diverse synoptic conditions.

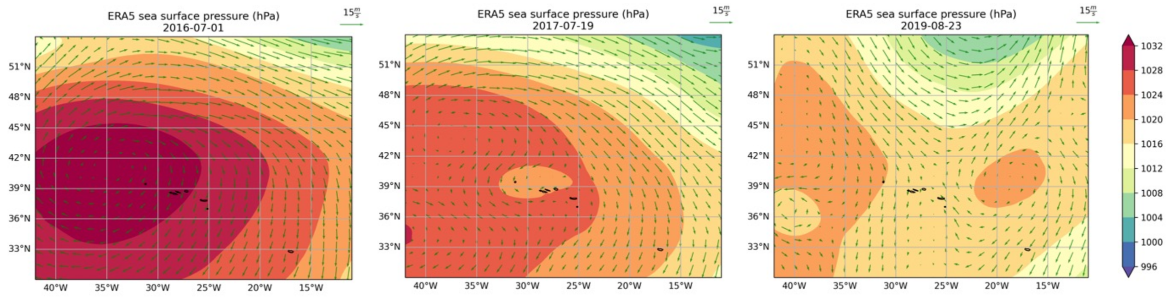
- To further investigate the impacts of realistic aerosol chemical components and aerosol spatiotemporal variation on the AIE, this study adopts the WRF-Chem model to examine aerosol-cloud interactions close to the scale of LES over the ARM ENA site across different synoptic regimes.

# Methodology – Model configuration




- Model: **WRF-Chem v4.4.2**
- Chem option and emissions:
  - RADM2-MADE/SORGAM chemistry (two-moment 3 modes aerosol scheme)
  - Sea salts
- Radiation scheme: NASA Goddard longwave/shortwave schemes
- Microphysics scheme: Two-moment Morrison scheme
- Domain resolution: **5 km/1.67 km/0.56 km/0.19 km** (75 vertical layers)
- Time step: 30/10/3/1 sec
- Simulation periods:
  - Case 1 (20160701) – 2016/06/30 12Z ~ 2016/07/02 00Z
  - Case 2 (20170719) – 2017/07/18 12Z ~ 2017/07/20 00Z
  - Case 3 (20190823) – 2019/08/22 12Z ~ 2019/08/24 00Z
  - First 12 hours are for spin-up.




•Case 1 (Regime 0): Ridge + surface high system. Thin stratocumulus clouds.
•Case 2 (Regime 4): Post trough + surface high system. Solid stratocumulus clouds
•Case 3 (Regime 3): Weak trough. Broken thicker clouds often along with deep clouds.

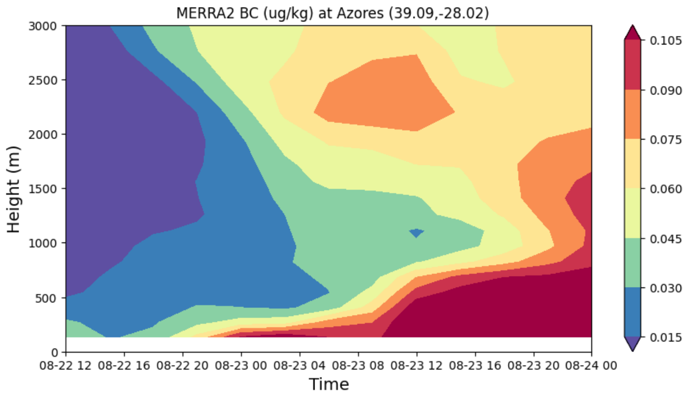
# Methodology – Model configuration (cont.)

- Numerical model setup:
  - Running WRF for D1 and D2
  - Creating initial and boundary conditions from D2 (ndown) + aerosol conditions (every 5 mins)
  - Running WRF-Chem for D3 and D4

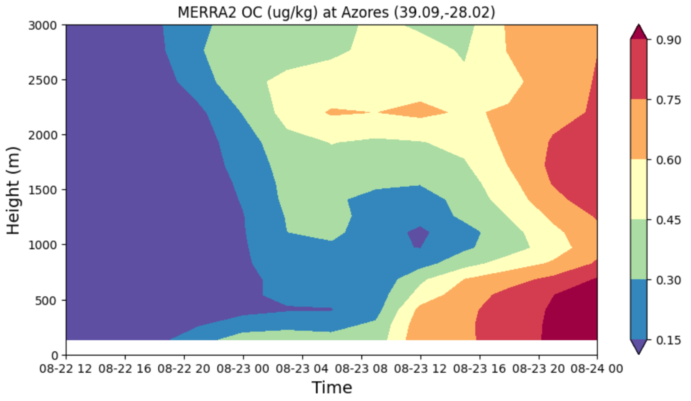
- Experimental design:
  - Control runs: add **MERRA2 BC, OC, $SO_4$, and $SO_2$** into WRF restart file at 13 Z and boundary condition (wrfbdy_d01)
  - Perturbed runs: add **5 times of MERRA2 BC, OC, $SO_4$, and $SO_2$** into WRF restart file at 13 Z and boundary condition (wrfbdy_d01)
  - The Aiken mode and the accumulation mode are counted for 20% and 80% of the aerosol mass ( BC and OC), but conversely for $SO_4$. Aerosol number concentration is estimated based on Liu et al., (2012 ).

2019/08/23

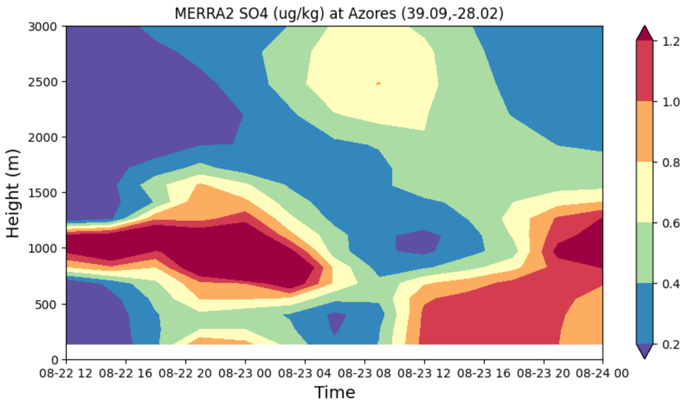
**BC**



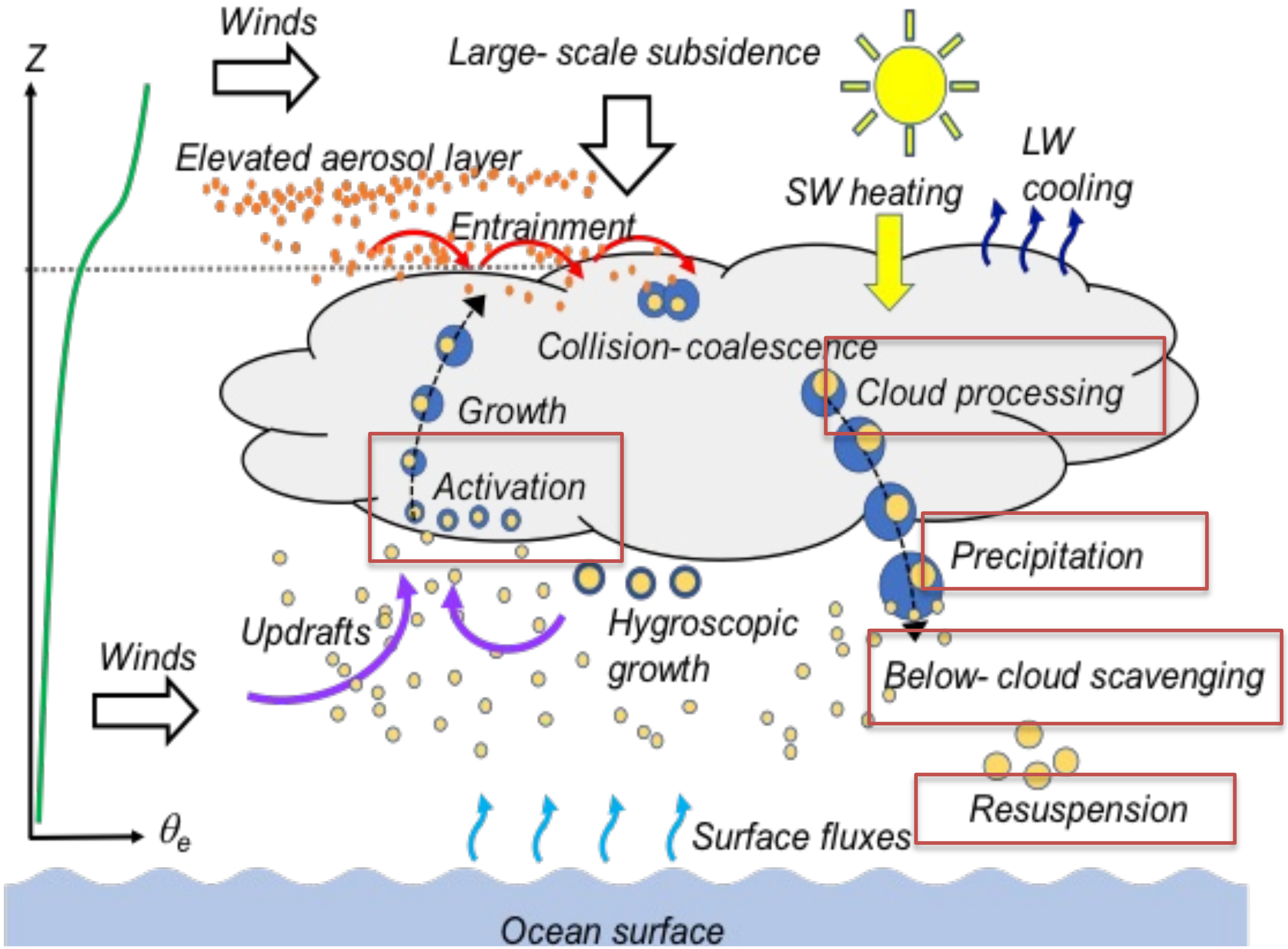

**OC**




**$SO_4$**

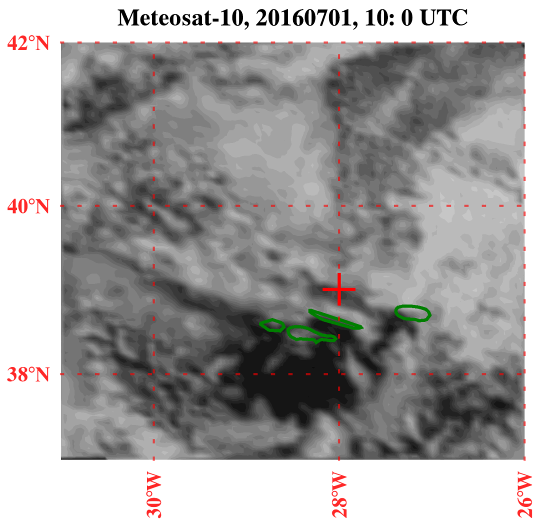


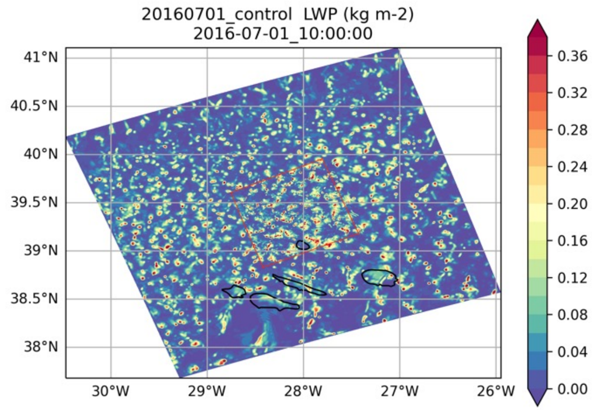
# Aerosol-cloud interaction



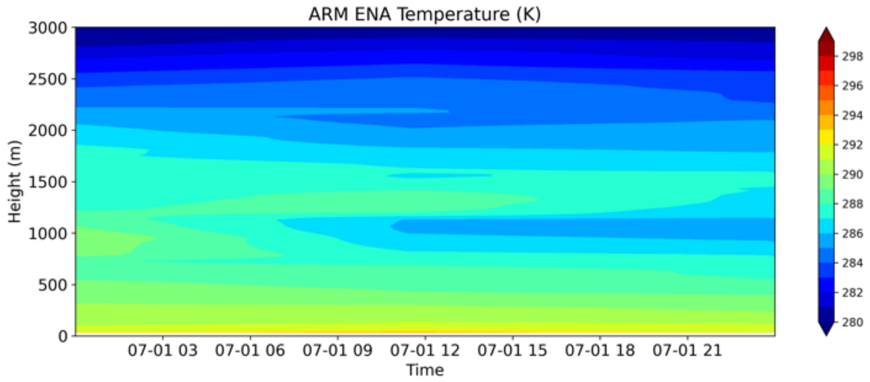
# Model evaluation (20160701_control)

- The model well exhibits the formation of overcast stratocumulus clouds.
- The model successfully represents the diurnal cycle of LWP but underestimates.

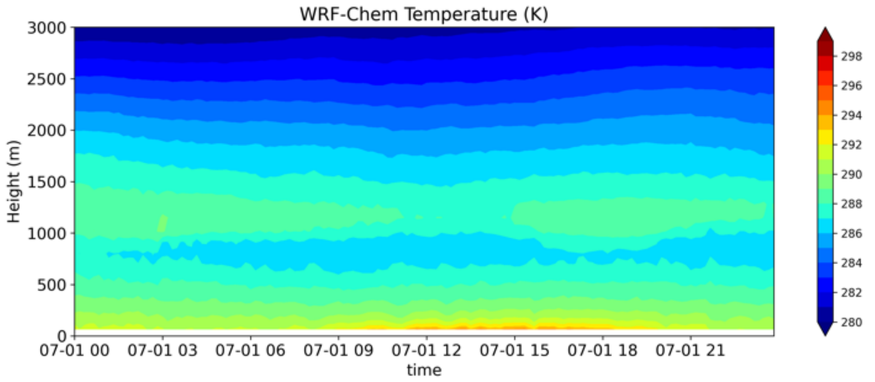


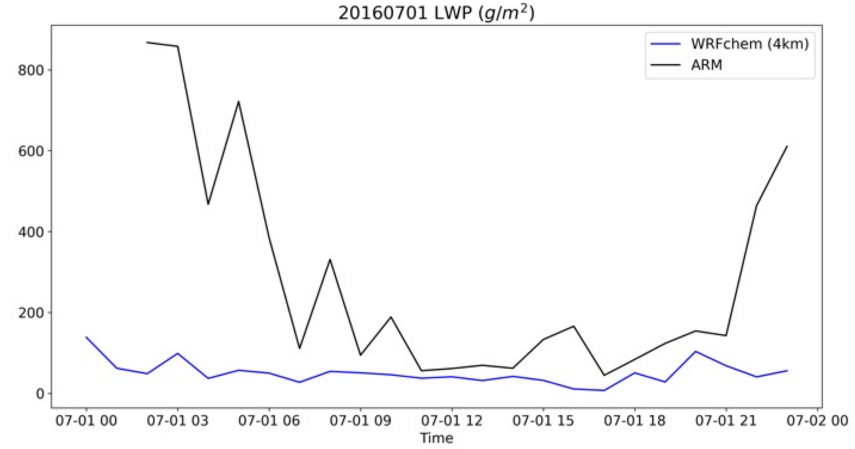



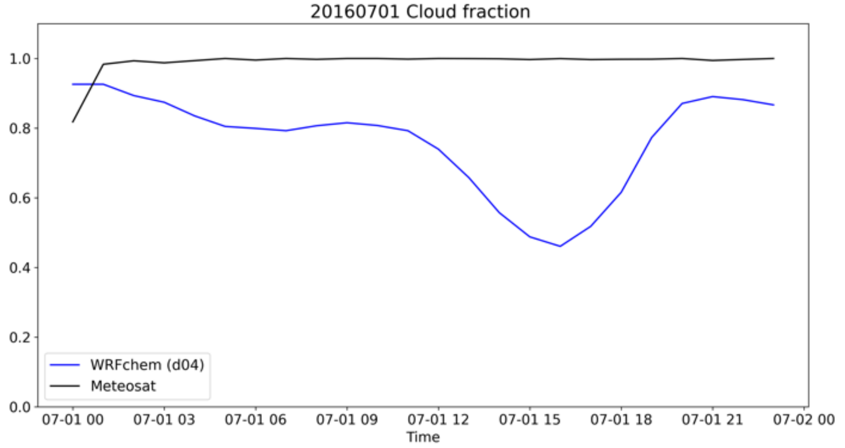

Obs.




WRF-Chem

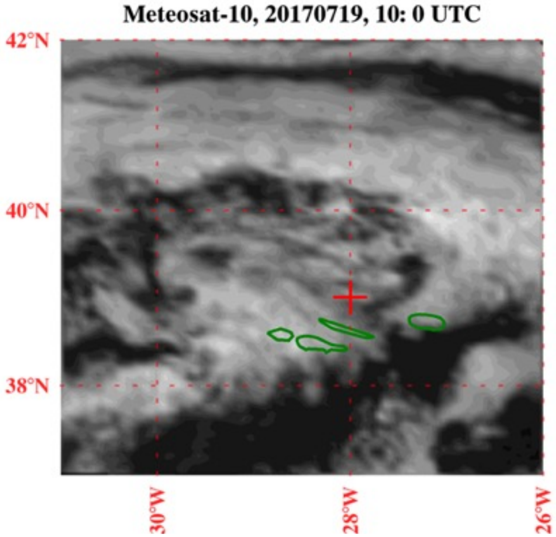


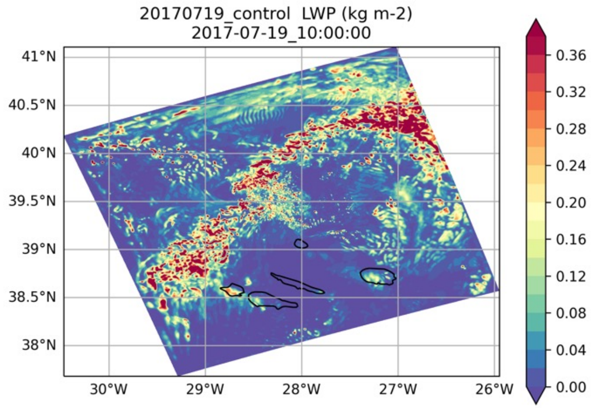



# Model evaluation (20170719_control)

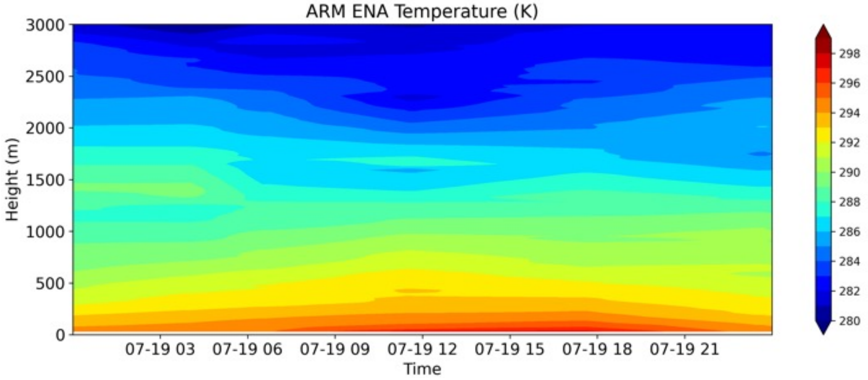
- The underestimation of the cloud layer from the model simulations results in insufficient longwave cooling at the cloud top, which may contribute to a weaker boundary layer inversion and a shallower boundary layer depth identified in the previous section (negative feedback) .

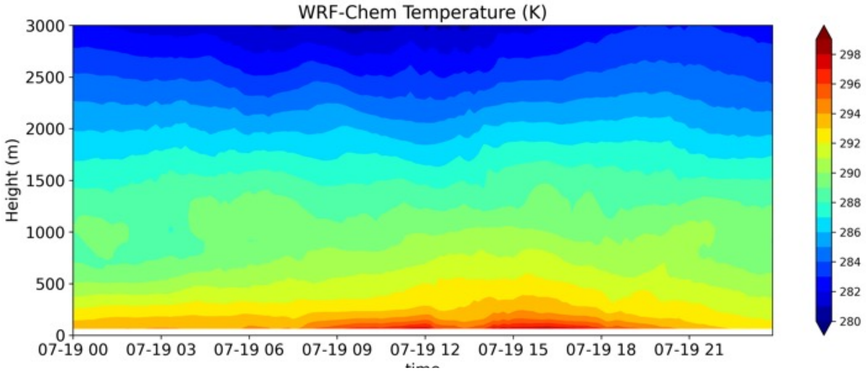


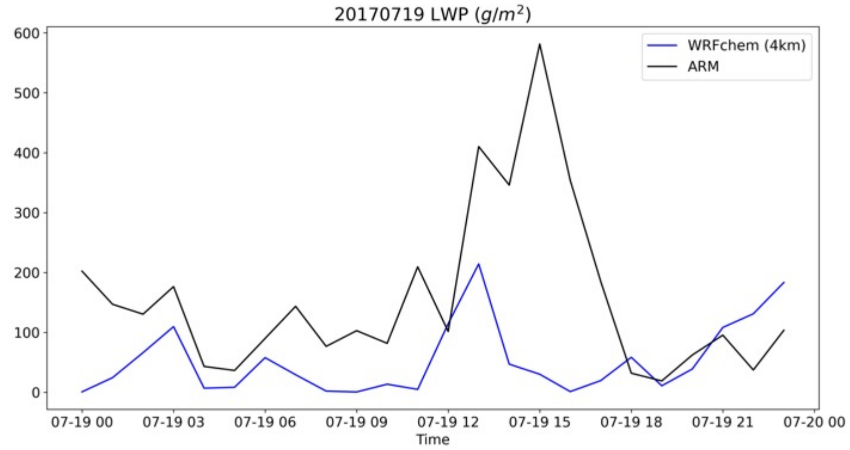



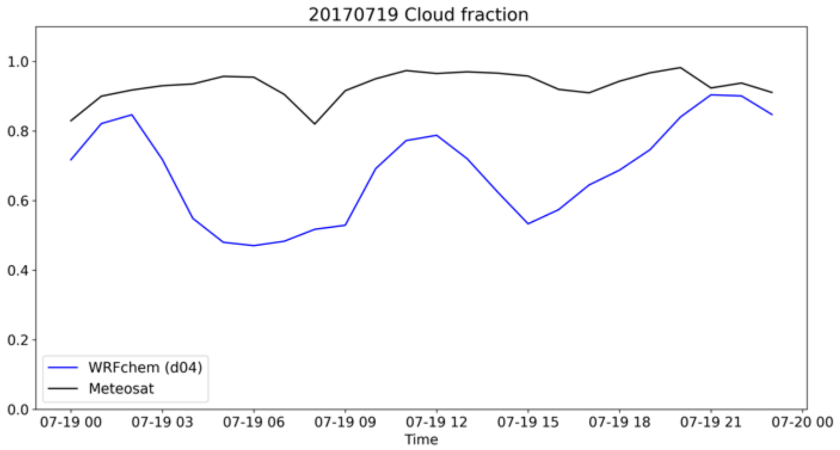

Obs.

WRF-Chem



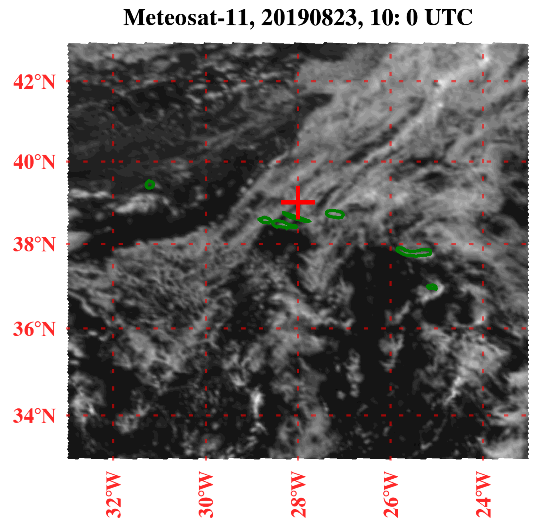



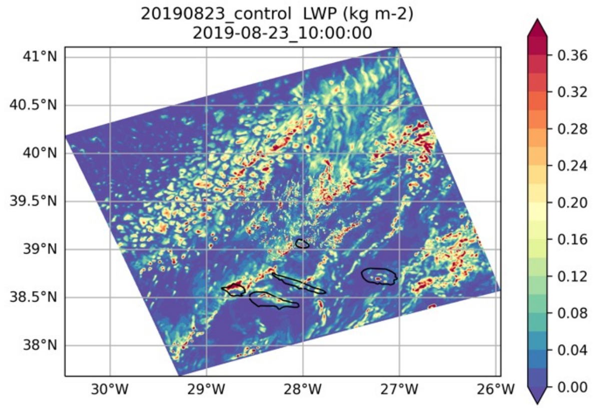



# Model evaluation (20190823_control)

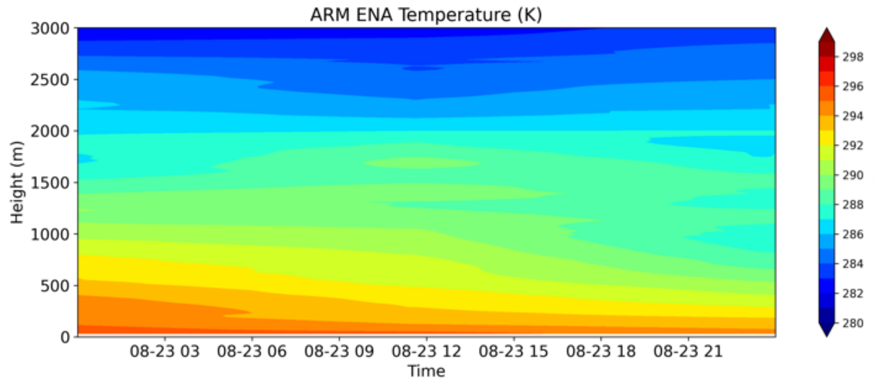
- A 5-minute moisture input from the boundary condition using WRF downscaling might not be sufficient to transport moisture into the inner domain.
- The model misses the second system.

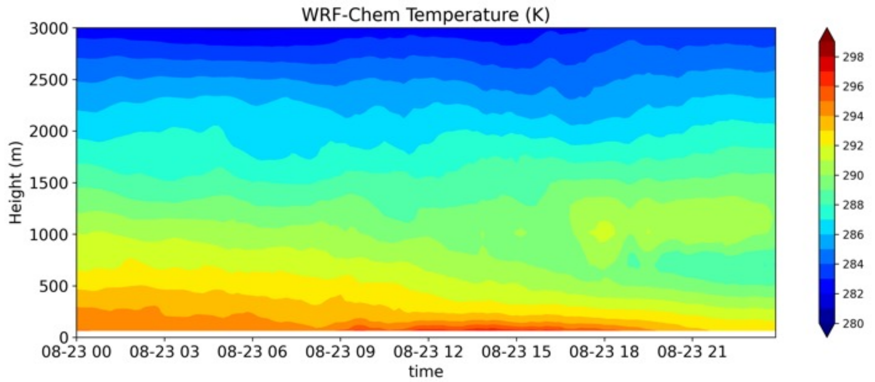


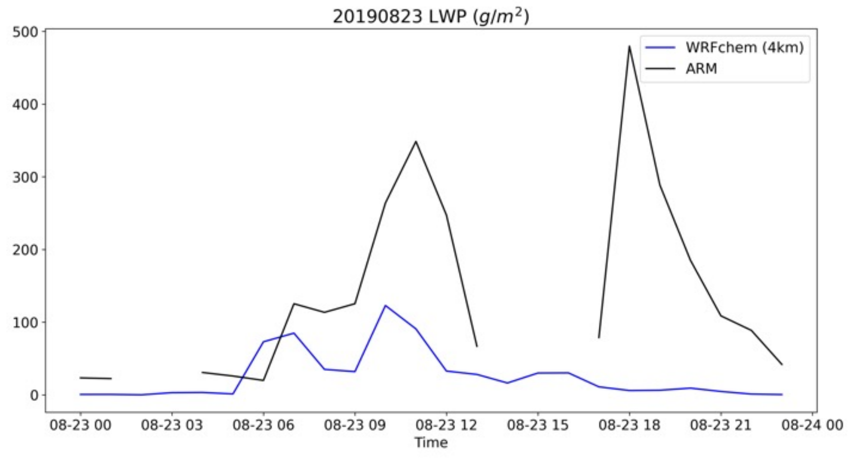



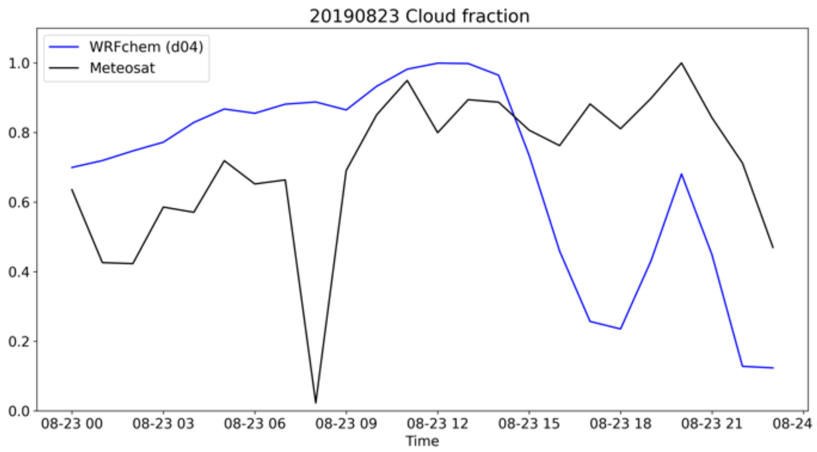

Obs.

WRF-Chem



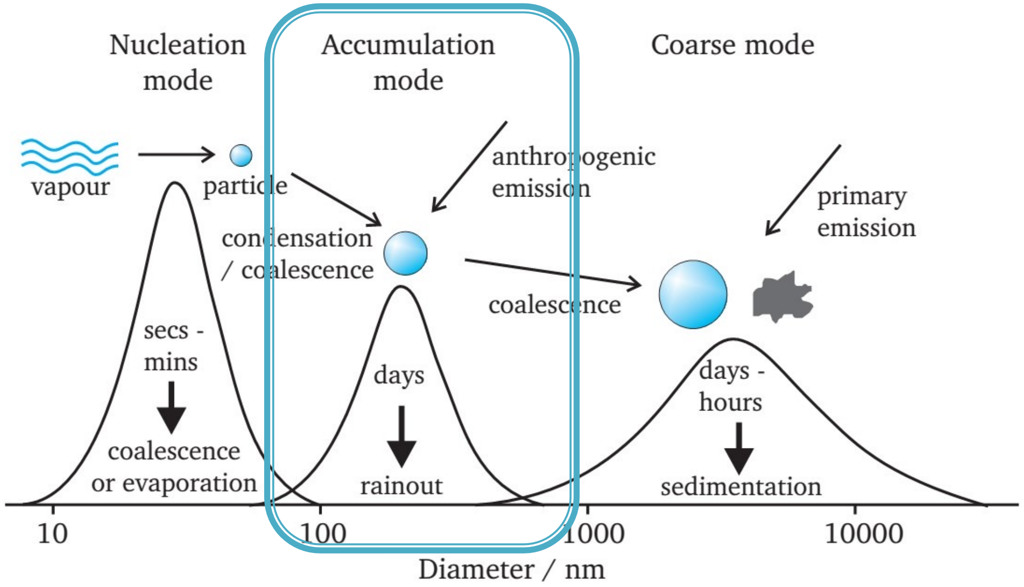



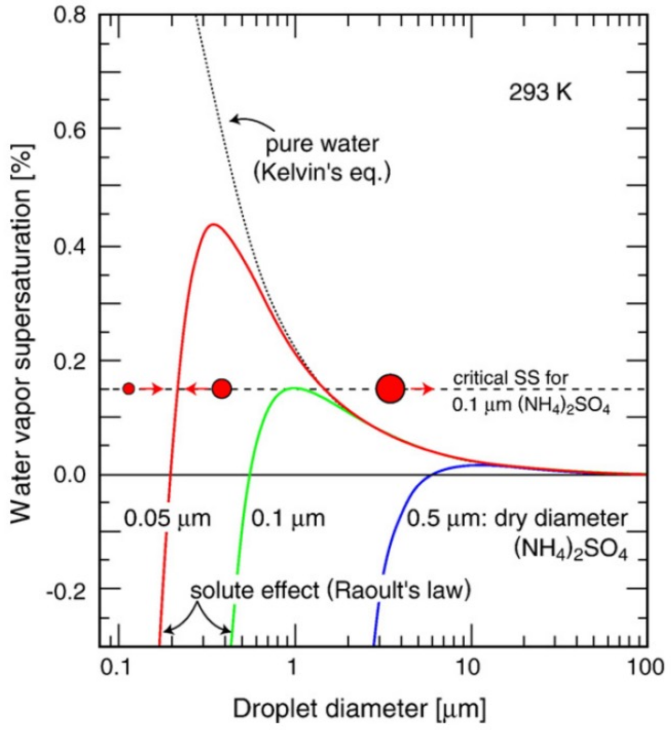



# Aerosol activation

## Two-moment 3 modes aerosol scheme

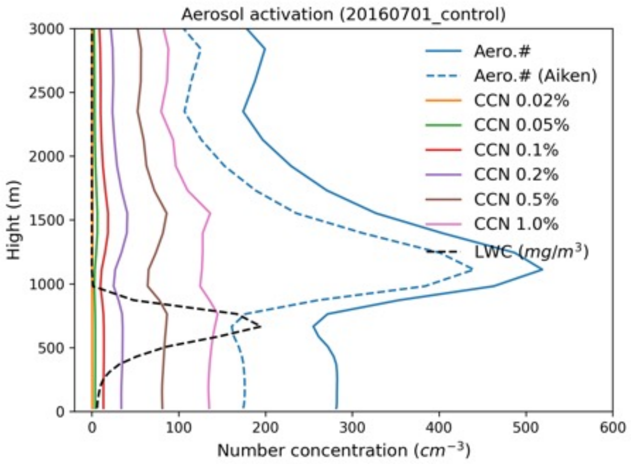


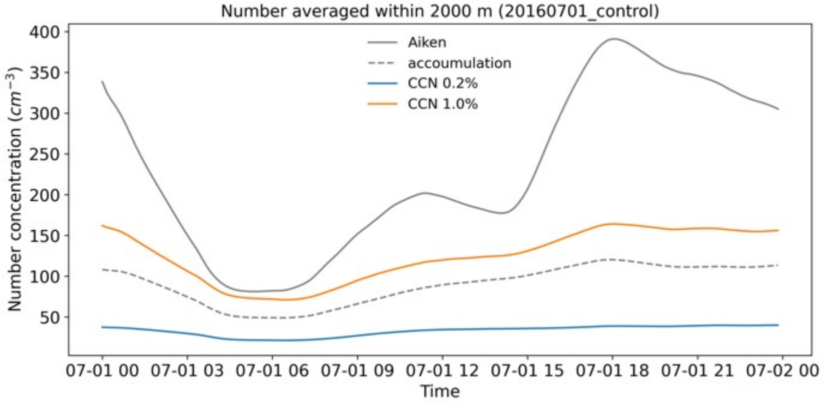

Most likely becomes CCN



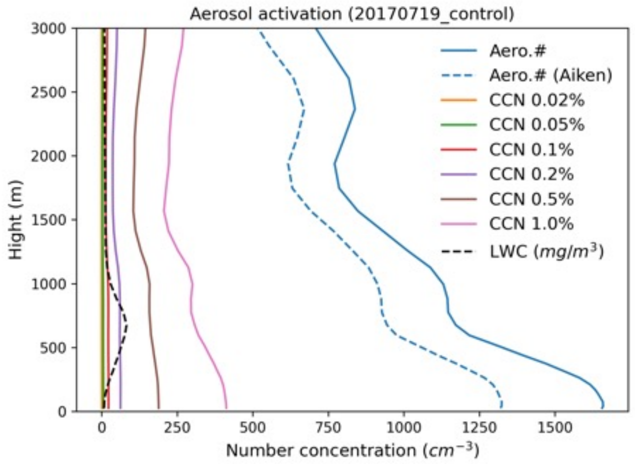
# Aerosol activation

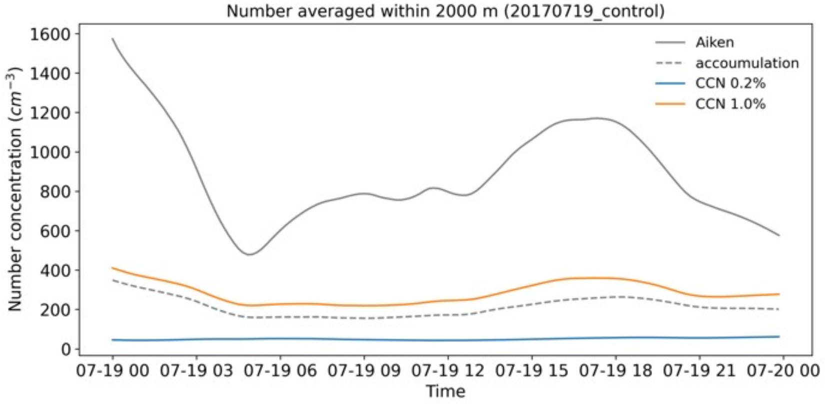
20160701



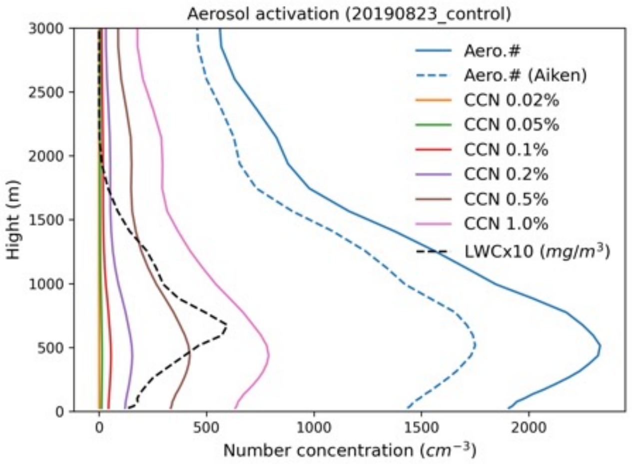



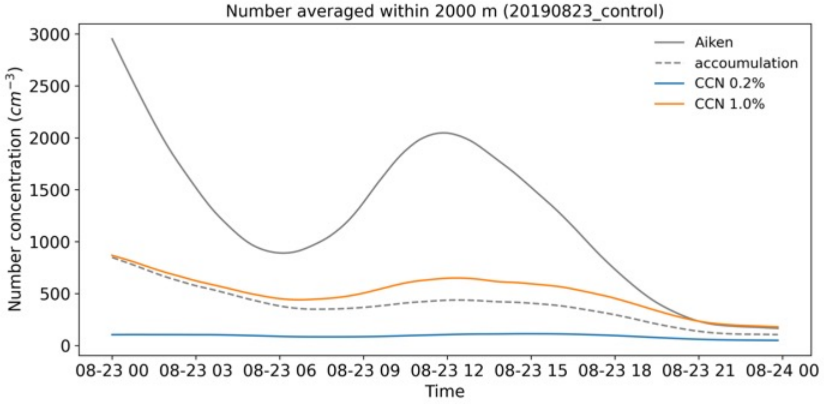

20170719




20190823

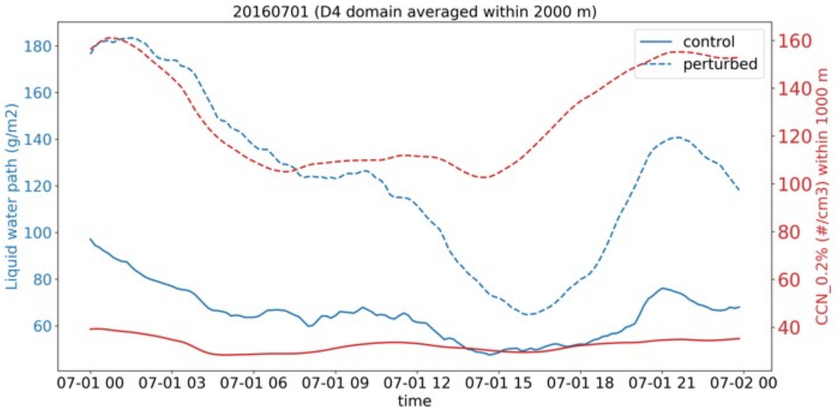


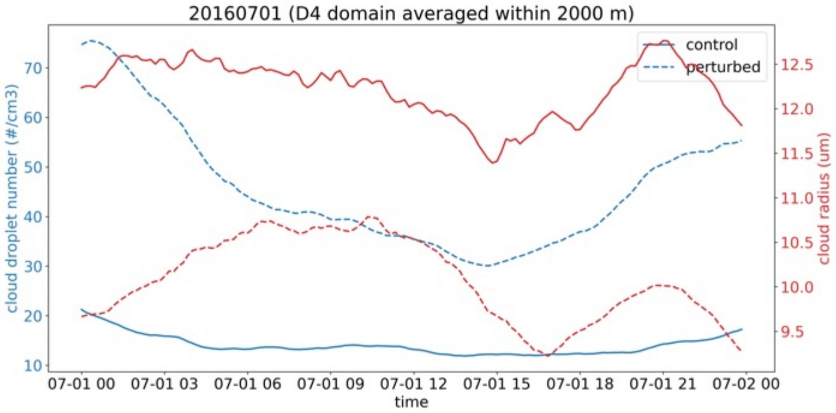



# Aerosol-cloud interaction

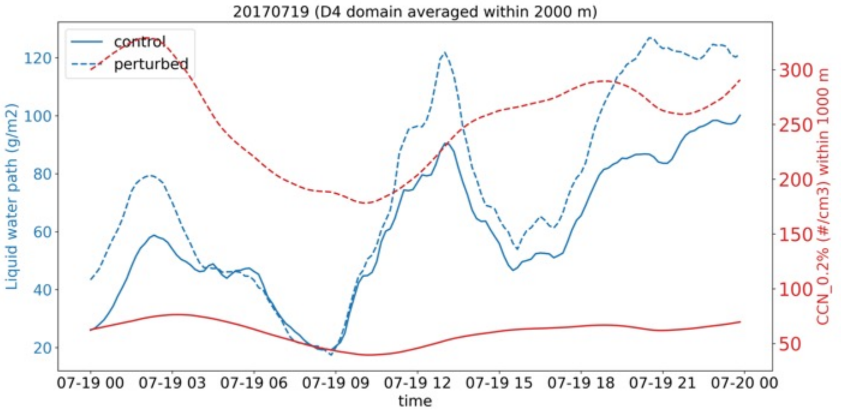
In the perturbed cases, we find higher aerosol-induced LWP, especially during the periods of rainfall

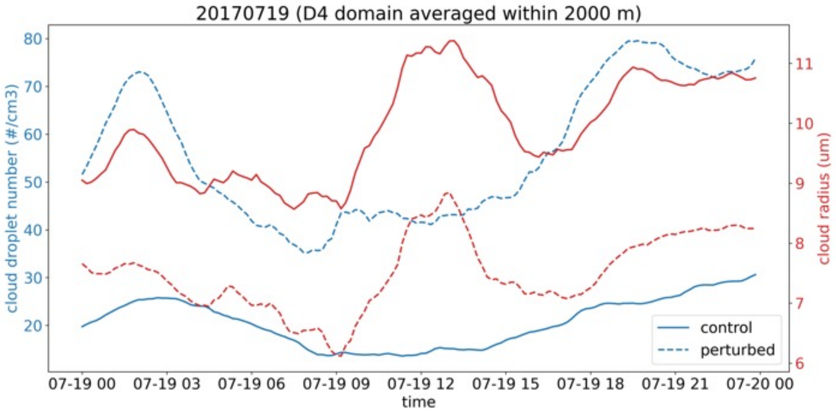
## 20160701



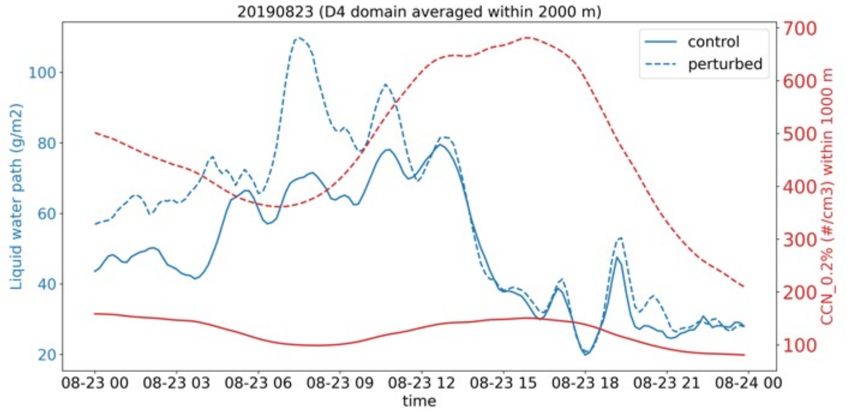



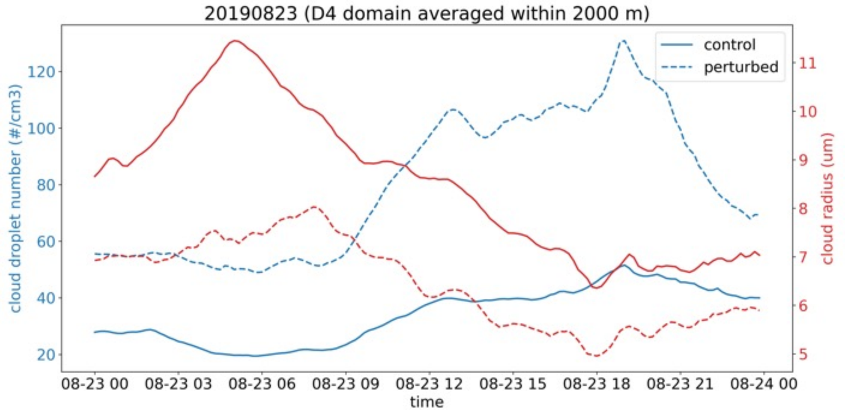

## 20170719



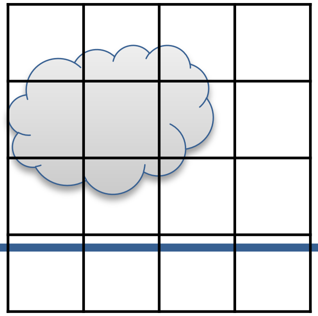




## 20190823



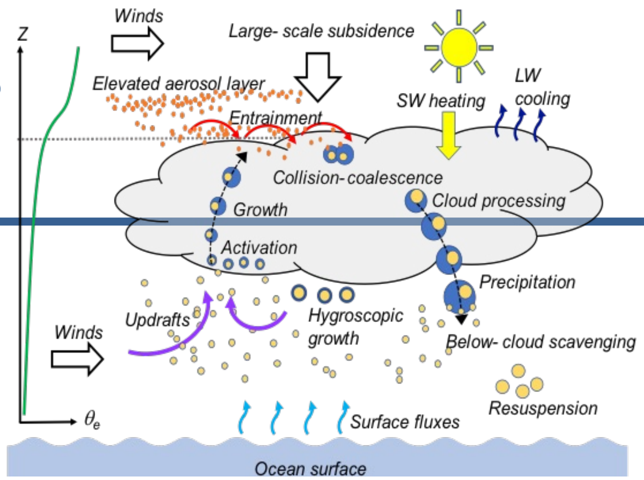



# Aerosol-cloud interaction



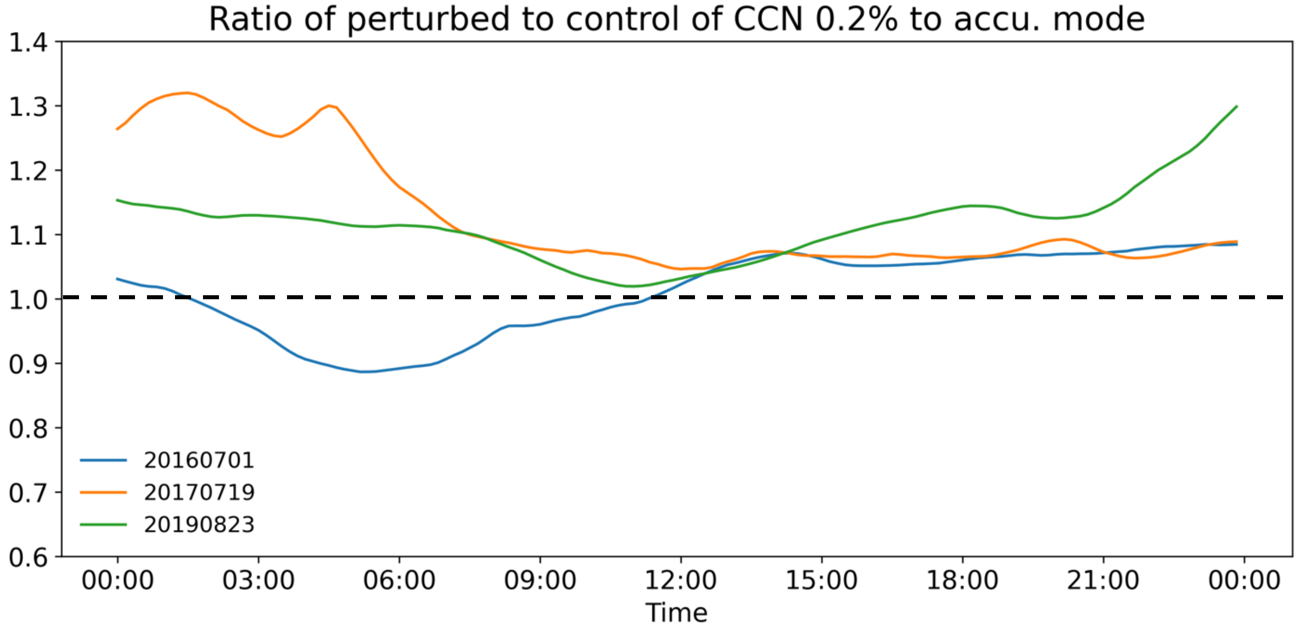
| Area | Case | CCN (cm$^{-3}$) | LWP (g m$^{-2}$) | Nc (cm$^{-3}$) | Re (μm) | RI (mm hr$^{-1}$) |
|---|---|---|---|---|---|---|
| Domain | Control | 73.07 ± 48.77 | 53.17 ± 32.65 | 22.68 ± 11.59 | 9.97 ± 2.31 | 0.009 ± 0.033 |
| | Perturbed | 286.88 ± 183.69 (+293%) | 79.25 ± 56.62 (+49%) | 59.74 ± 27.29 (+163%) | 7.83 ± 2.02 (-21%) | 0.008 ± 0.033 (-11%) |
| Rain | Control | 68.15 ± 48.05 | 58.57 ± 31.69 | 20.17 ± 9.33 | 10.47 ± 2.07 | 0.011 ± 0.035 |
| | Perturbed | 250.14 ± 153.23 (+267%) | 91.81 ± 55.06 (+57%) | 53.01 ± 20.39 (+163%) | 8.35 ± 1.83 (-20%) | 0.009 ± 0.036 (-18%) |
| Non-Rain | Control | 103.73 ± 41.52 | 18.91 ± 9.81 | 38.57 ± 11.93 | 6.81 ± 0.76 | 0 ± 0 |
| | Perturbed | 444.47 ± 217.08 (+328%) | 24.22 ± 15.80 (+28%) | 89.24 ± 33.42 (+131%) | 5.54 ± 0.90 (-19%) | 0 ± 0 |

# CCN evolution in the control and perturbed cases

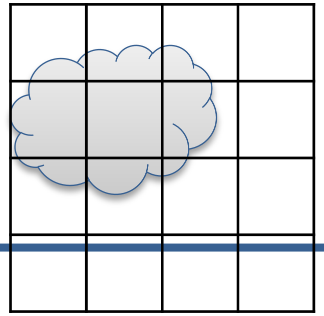


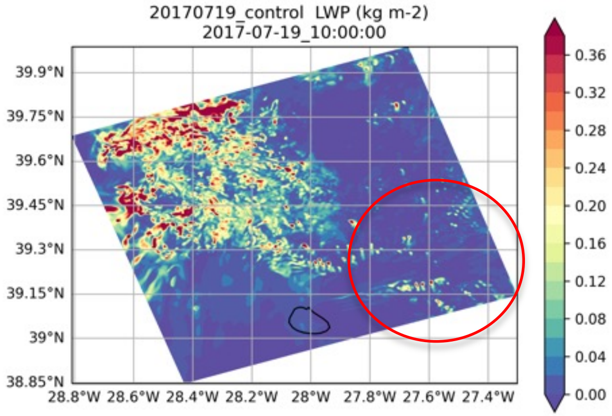

$$\left(CCN_{0.2\%}/Accu.aerosols\right)_{perturbed} \Big/ \left(CCN_{0.2\%}/Accu.aerosols\right)_{control}$$

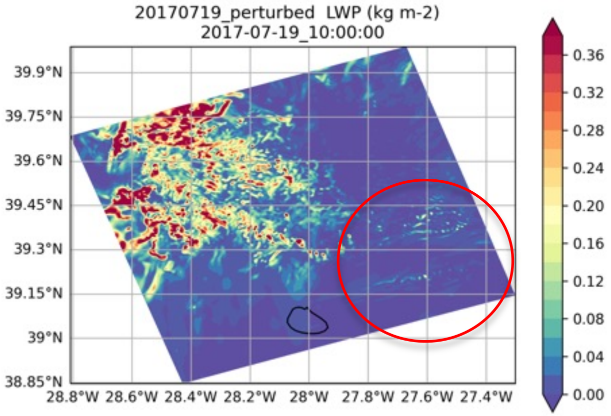
- Accumulation mode aerosols in the perturbed cases are more readily activated as CCN, even at 0.2% supersaturation.
- The non-rain grids over the cloud edge in the perturbed cases can have lower LWP, and then smaller cloud droplets are easy to evaporate. Aerosols in the evaporated cloud are back to accumulation mode and increase the mean radius.

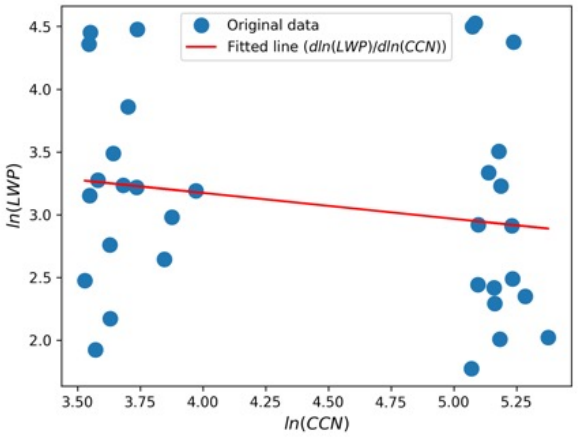


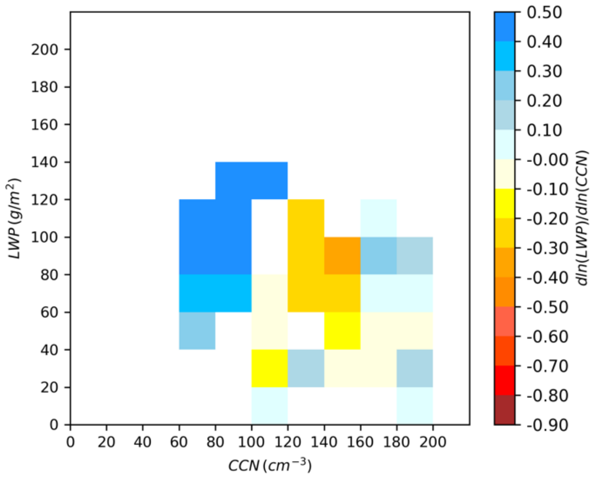
# LWP susceptibility to CCN

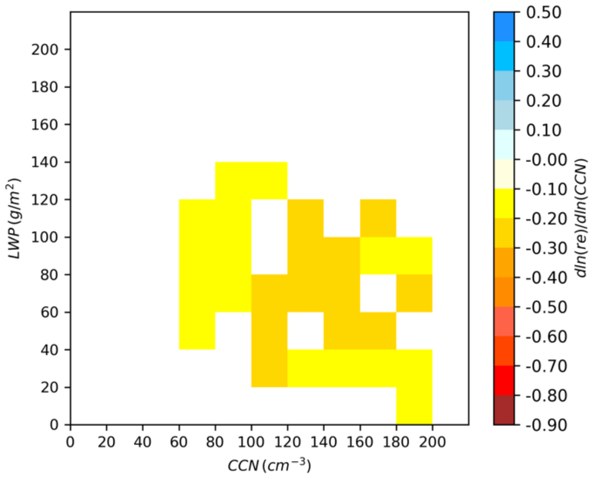




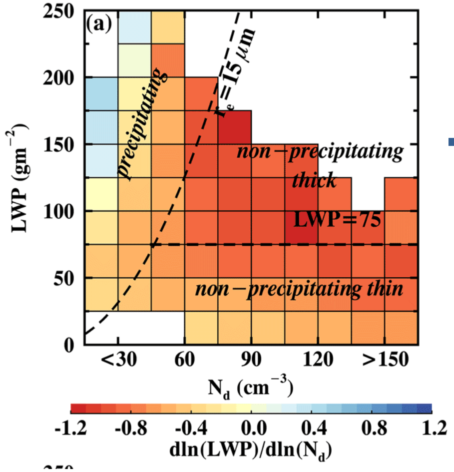

When the mean CCN concentration is less than 100 $cm^{-3}$, the LWP susceptibility becomes strong positive. This suggests that the change in LWP is sensitive to changes in CCN number.

# ENA MBL Cloud LWP susceptibilities

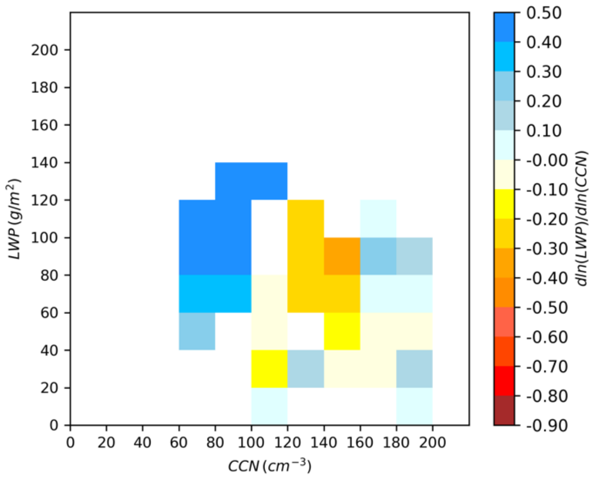
- Precipitating cloud field: positive LWP susceptibility to Nd perturbation in Obs. and WRF-Chem cases
- Non-precipitating thin clouds: negative LWP susceptibility in Obs. and WRF-Chem cases→ drying effect
- Non-precipitating thick clouds: inconsistent signals from MeteoSat and ARM site obs., positive LWP susceptibility in WRF cases

*The cloud drying response to Nd perturbation is weak, while precipitation suppression effect dominates the cloud LWP response in WRF-Chem cases.*

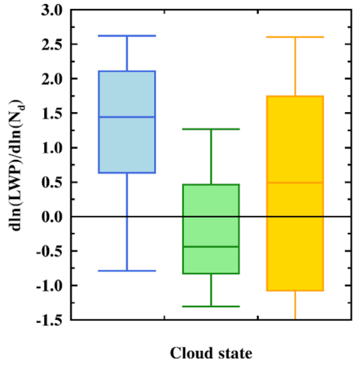
**Obs.**




**WRF-Chem cases**




ARM site obs.

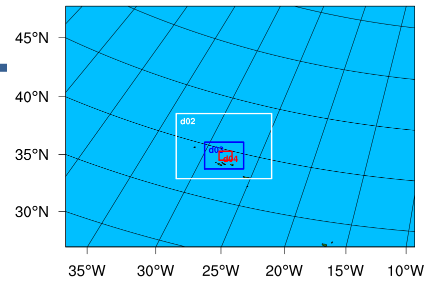


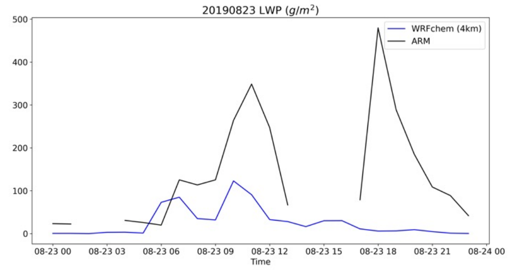

**Precipitating clouds**
**Non-precipitating thin clouds**
**Non-precipitating thick clouds**

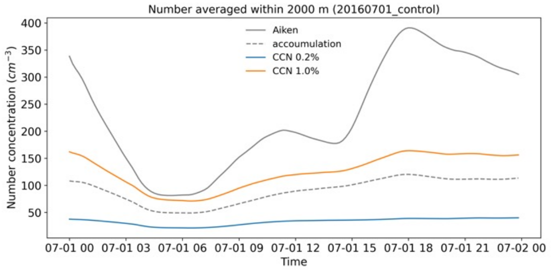
*Qiu, S., et al. (2024)*

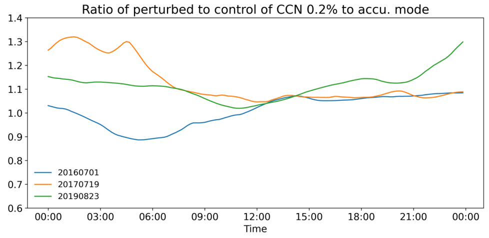
# Summary

- WRF-Chem is configured with an efficient downscaling method (ndown) to reduce half computational time, enabling the examination of aerosol-cloud interactions at scales close to Large Eddy Simulation (LES) over the ARM ENA site across various synoptic regimes.
- The model's performance varies depending on the different cloud structures present in various weather regimes, and the interactions between aerosols and clouds yield different outcomes as well.
  - The WRF-Chem model catches better solid thin cloud in the case of 20160701.
  - With fast cloud system and strong surface wind in the cases of 20170719 and 20190823, the WRF-Chem model is hard to capture the cloud system development and movement.
- Our simulations generate an overabundance of small-sized aerosols, which result in a low concentration of CCN. This discrepancy arises from the assumptions made when constructing the aerosol initial and boundary conditions (80% of $SO_4$ for Aiken mode and 20% for accumulation mode).
- A non-rain cloud at the edge of a cloud is prone to evaporation, and the aerosols released during this process revert to accumulation mode aerosols, which help facilitate the next activation.



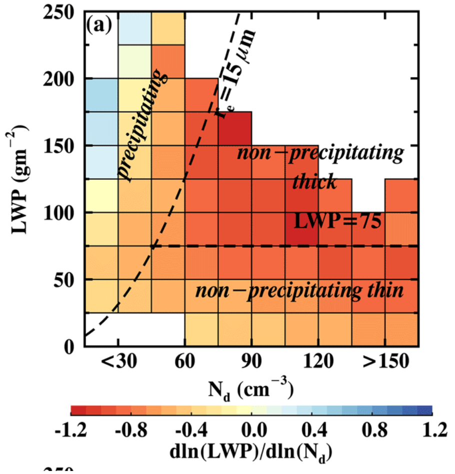



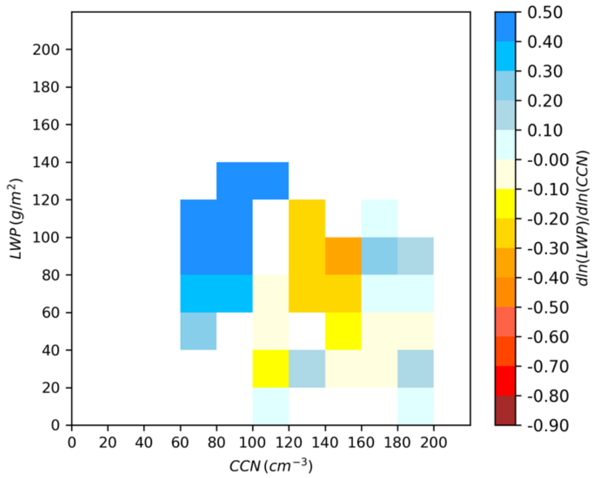
# Summary (cont.)

- The LWP susceptibilities for different cloud droplet numbers derived from observations in Qiu et al. (2024) show the opposite result.  Further investigation is needed to understand the discrepancy between the conclusions drawn from observations and model simulations.

**Obs.**




**WRF-Chem cases**



# Questions?

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