# Future warming exacerbated by aged-soot effect on cloud formation

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(Nature Geoscience, 2020)

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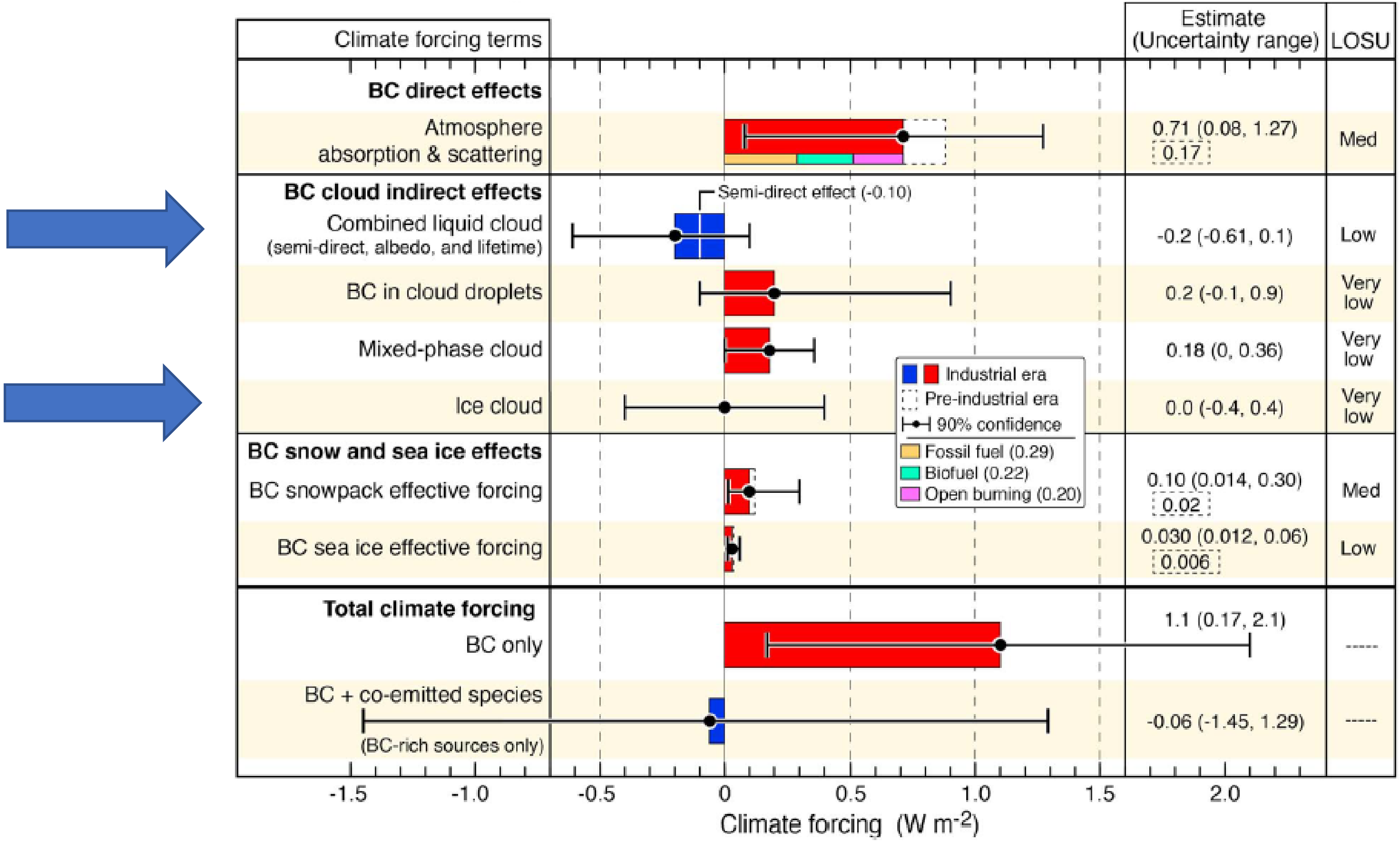
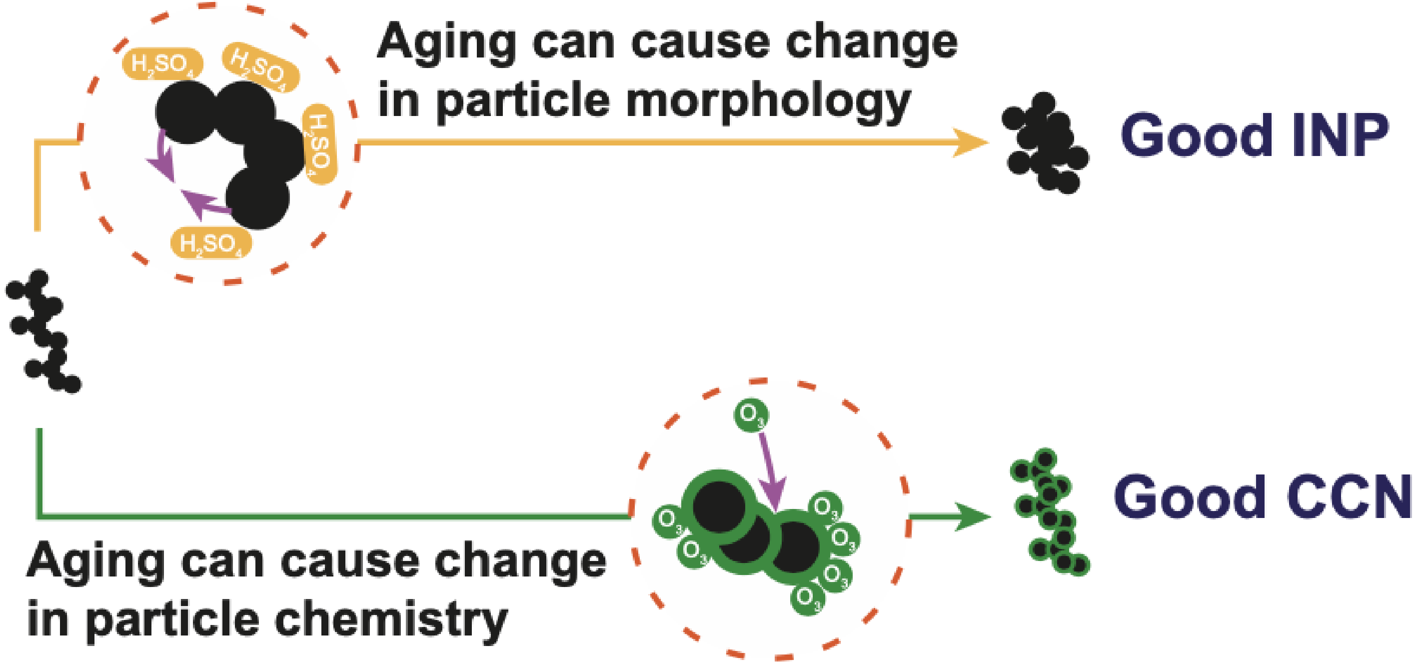
# Climate forcing of soot and co-emitted species (1750-2005)




Bond et al., 2013

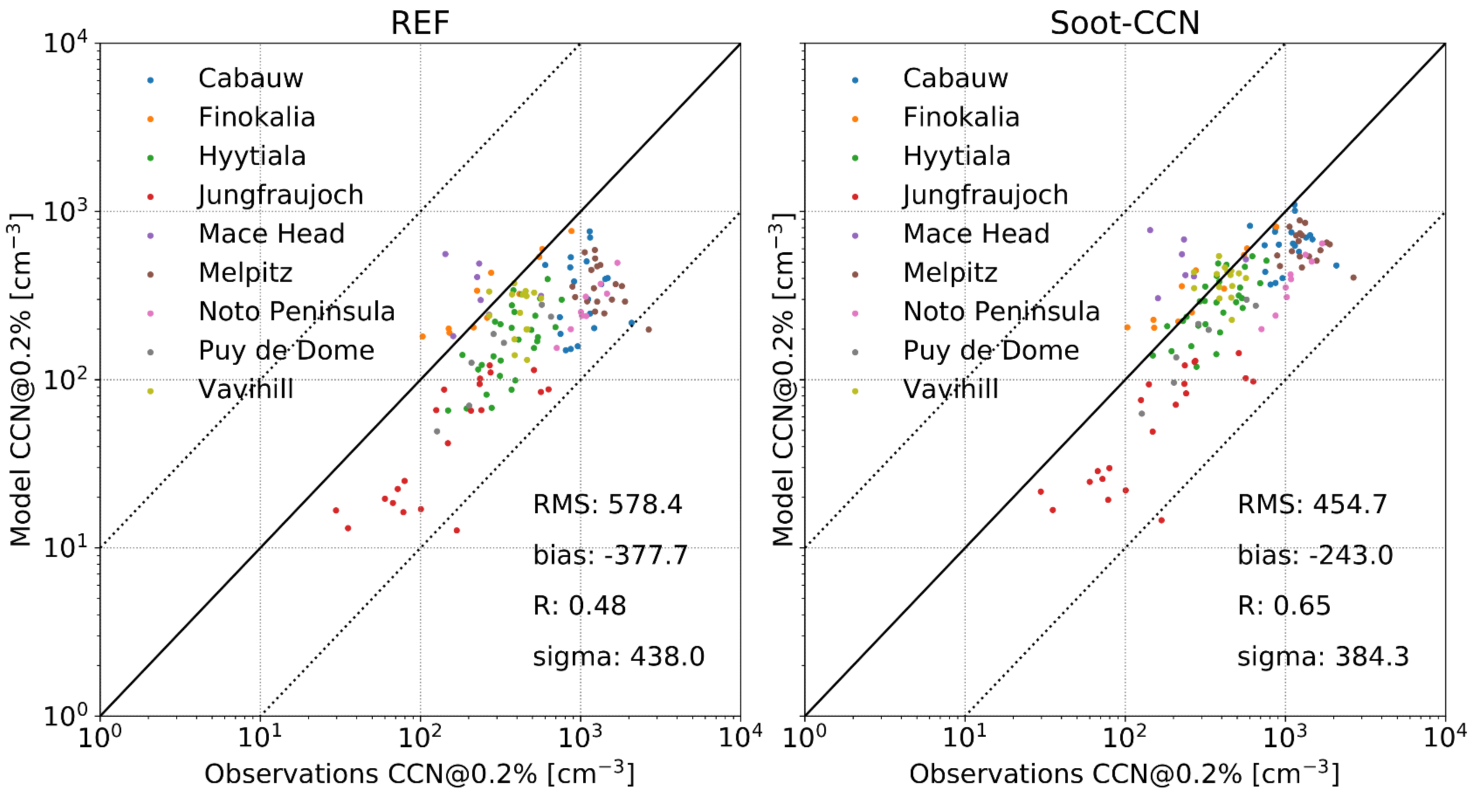
# Mechanisms of soot aging considered in this study



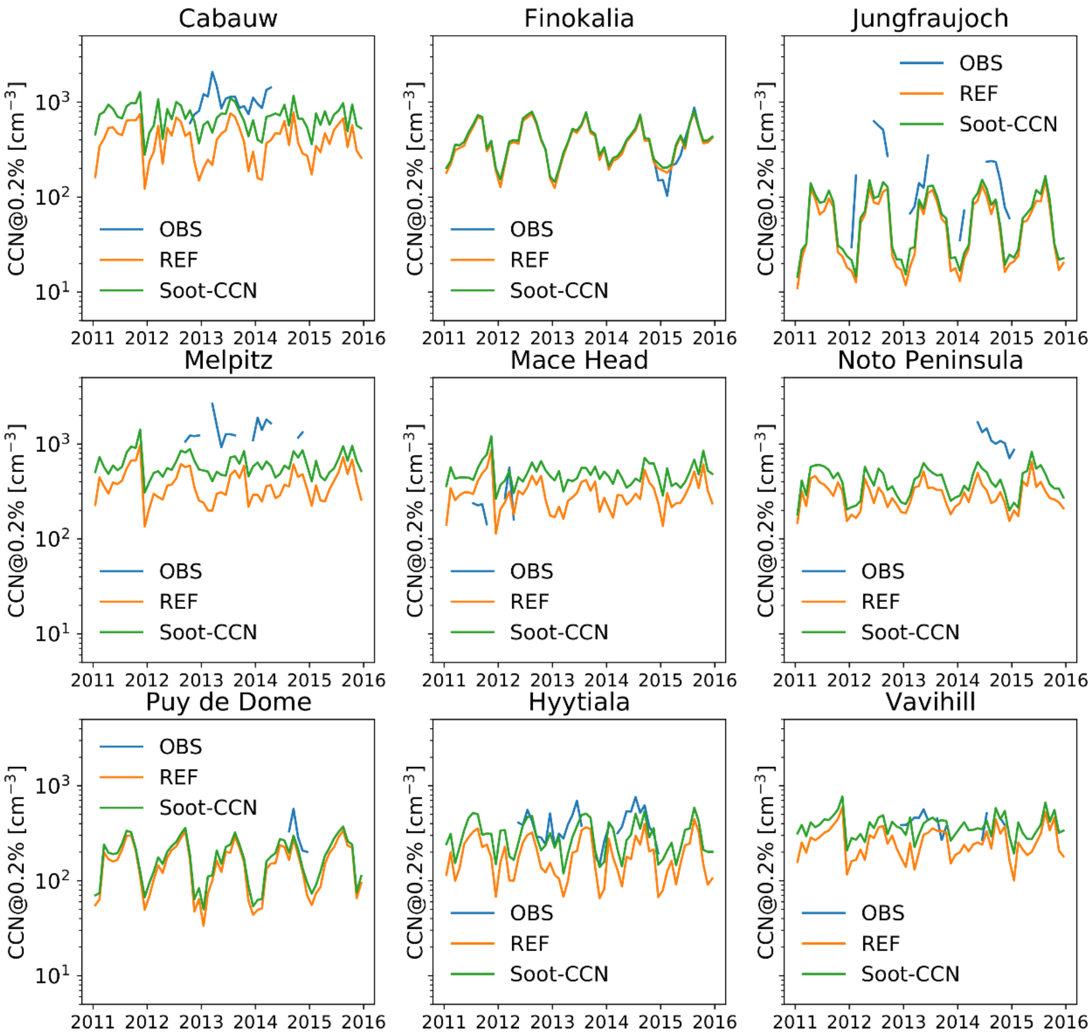

(Mahrt et al. JGR/ESPI, 2020)

(Friebel et al. ACP, 2019)

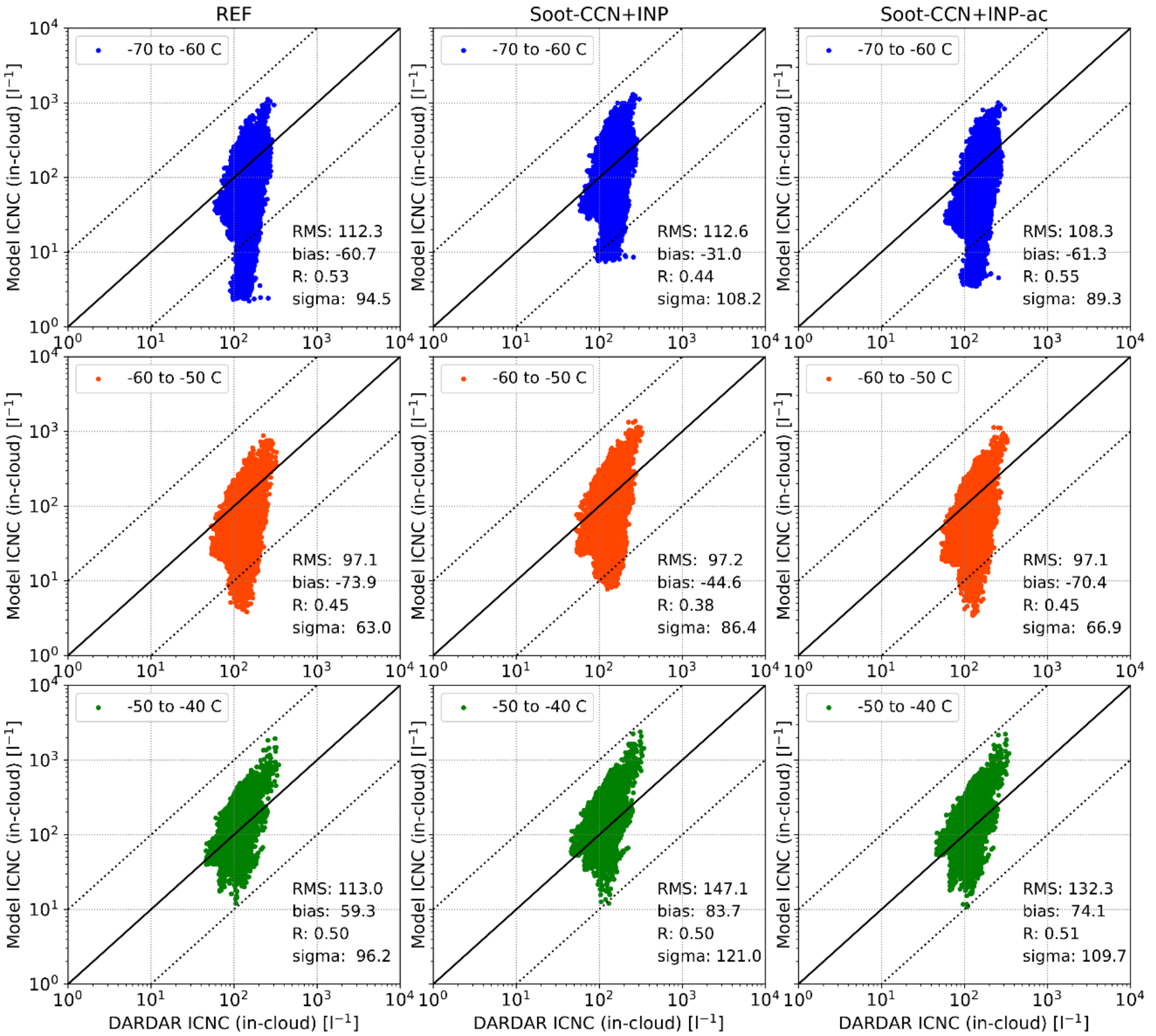
# Model validation (ECHAM-HAM)



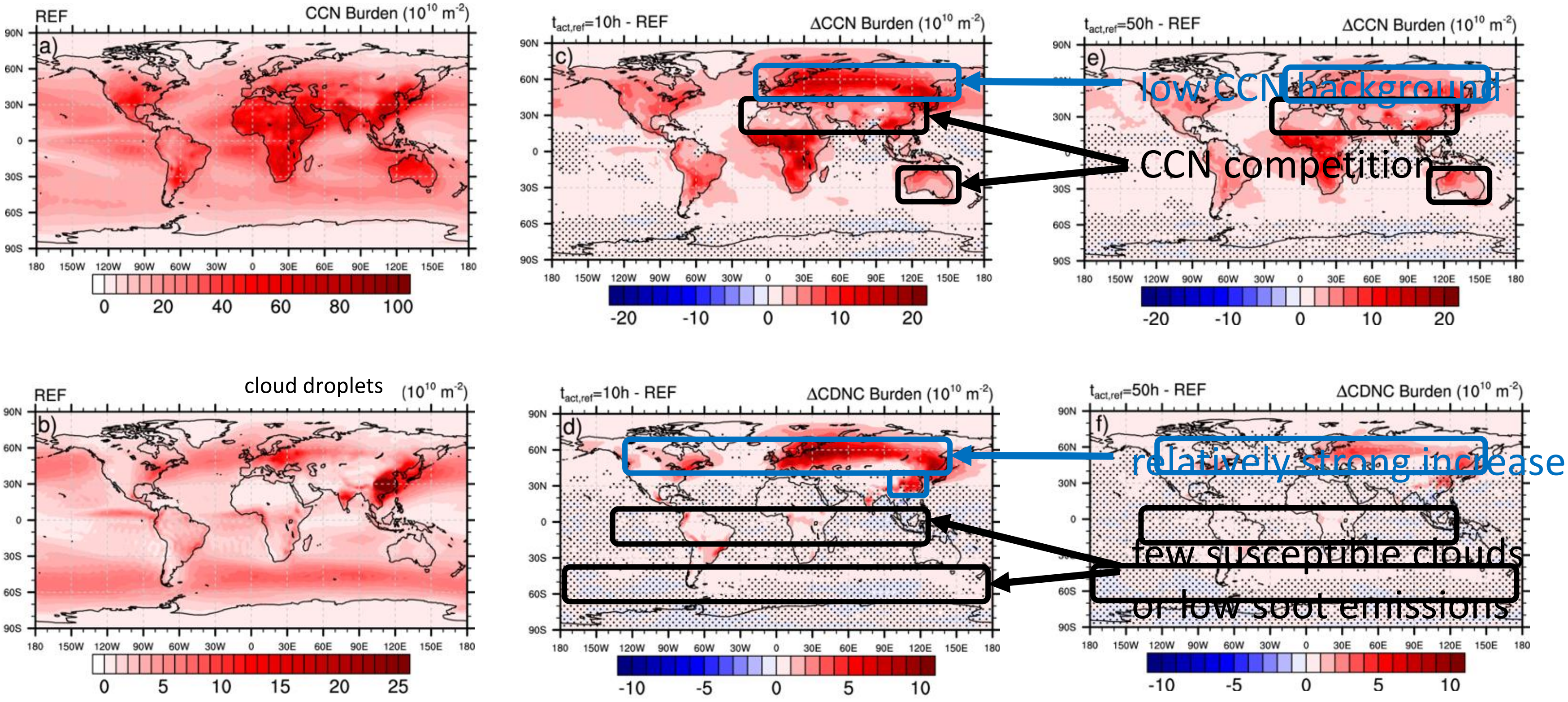
# Model validation



# Model validation



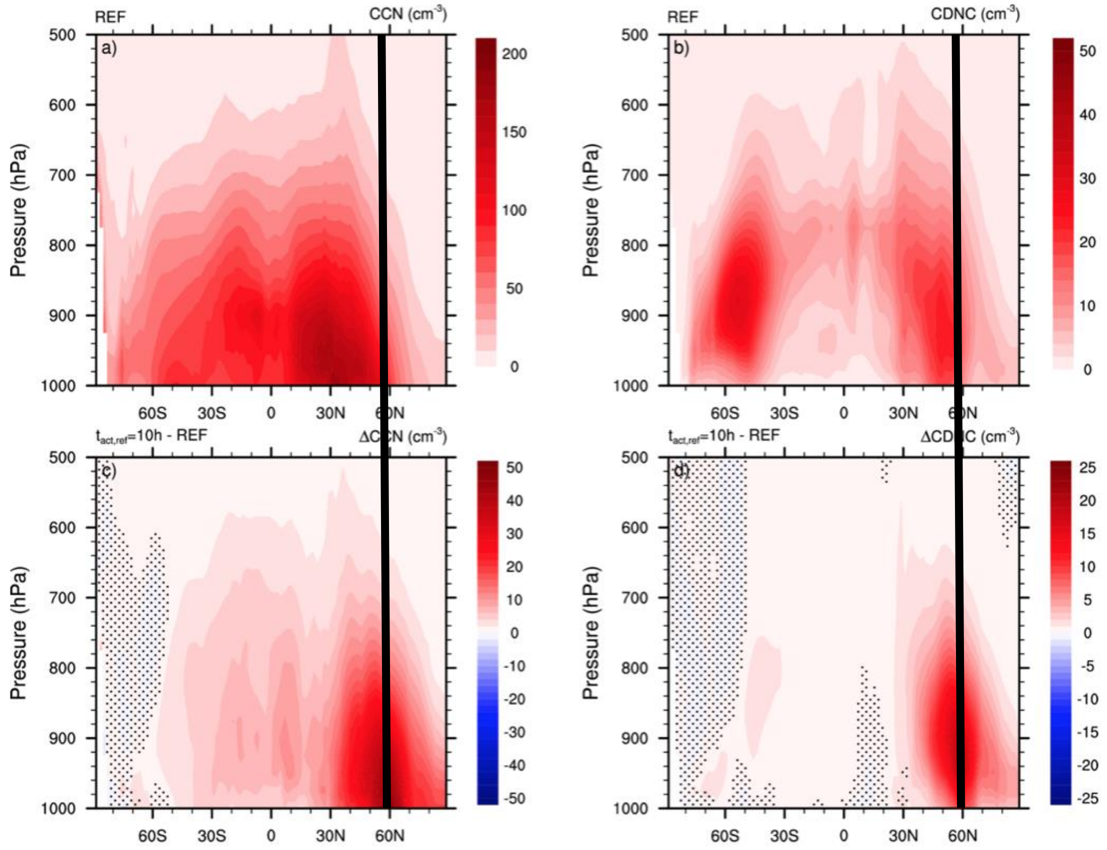
# Climate impact of ozone-aged soot




→ 93% increase in cloud droplet burden north of 60 ºN ($t_{act}$ = 10h)

Friebel et al., ACP, 2019

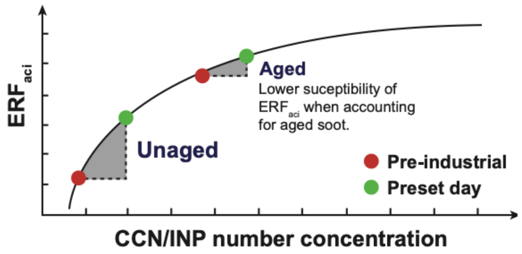
# Climate impact of ozone-aged soot

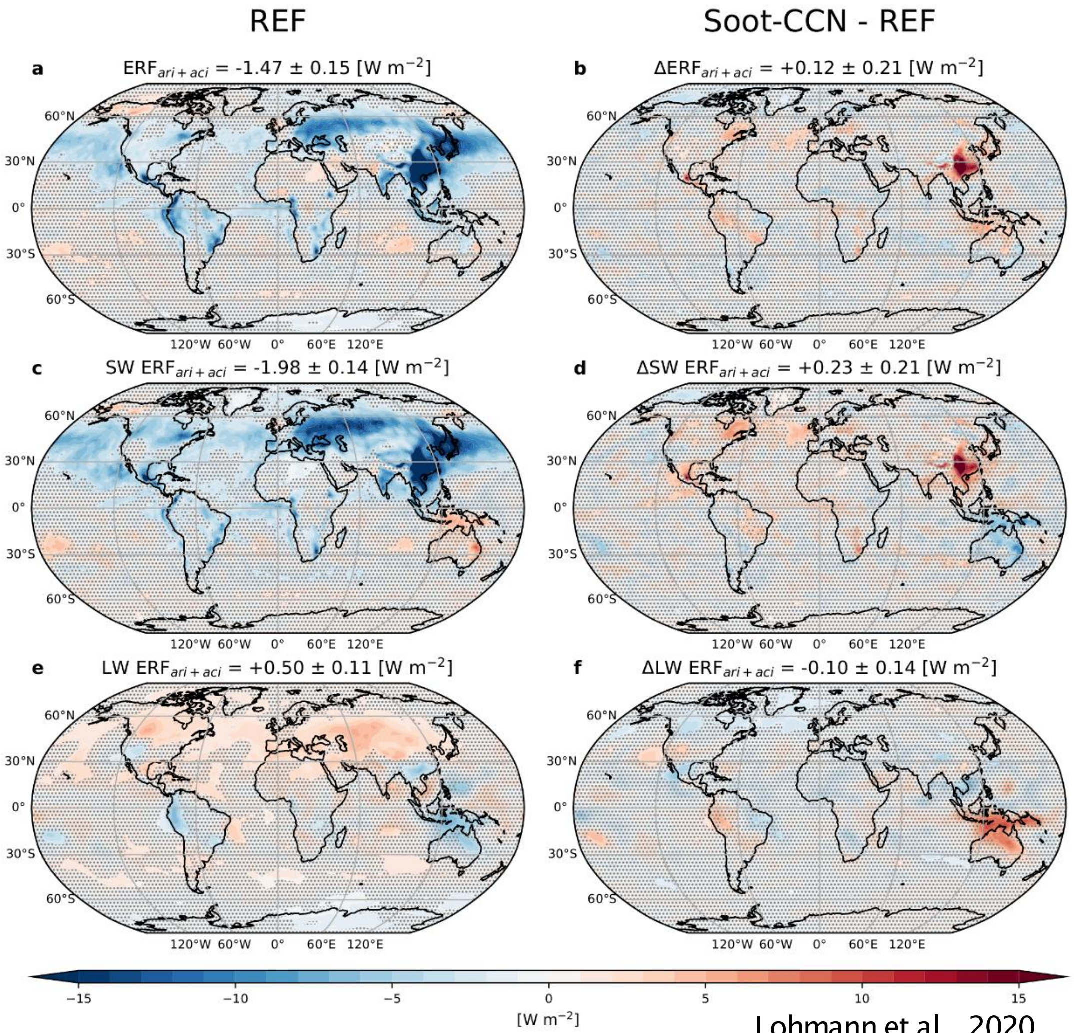



--> Largest impact of ozone as CCN at around 60 ºN

# Radiative impact of ozone-aged soot since pre-industrial times

- Shortwave anthropogenic aerosol effect reduced
- Due to increased pre-industrial CCN
- Regionally largest impact over China

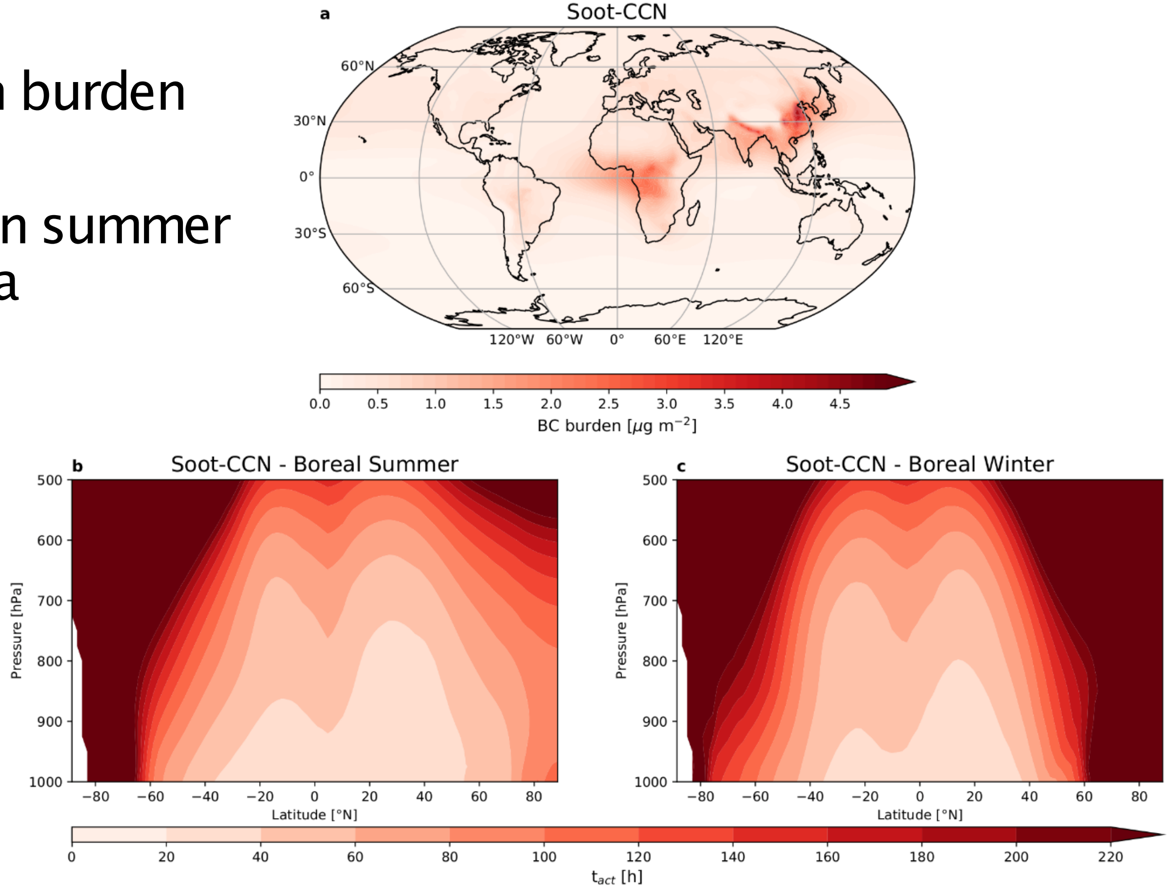


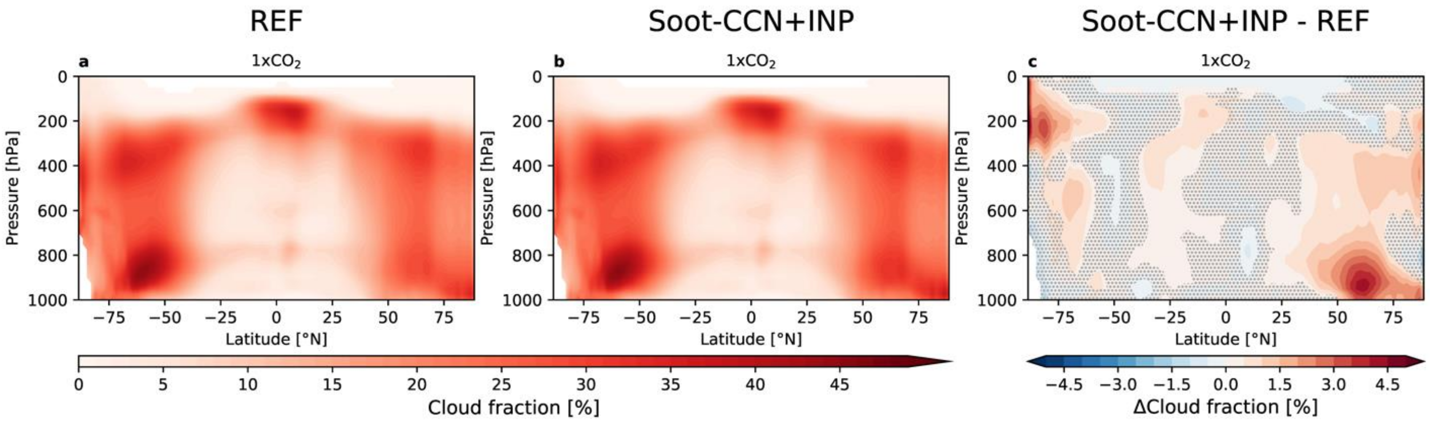

Lohmann et al., 2020

# Annual mean black carbon burden and aging times

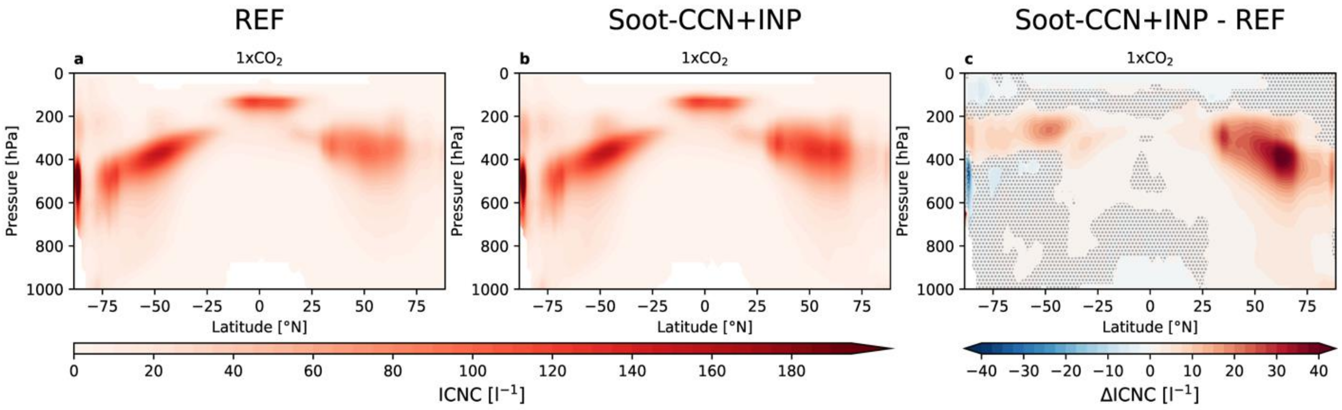
- High black carbon burden in China
- Short aging times in summer and winter in China



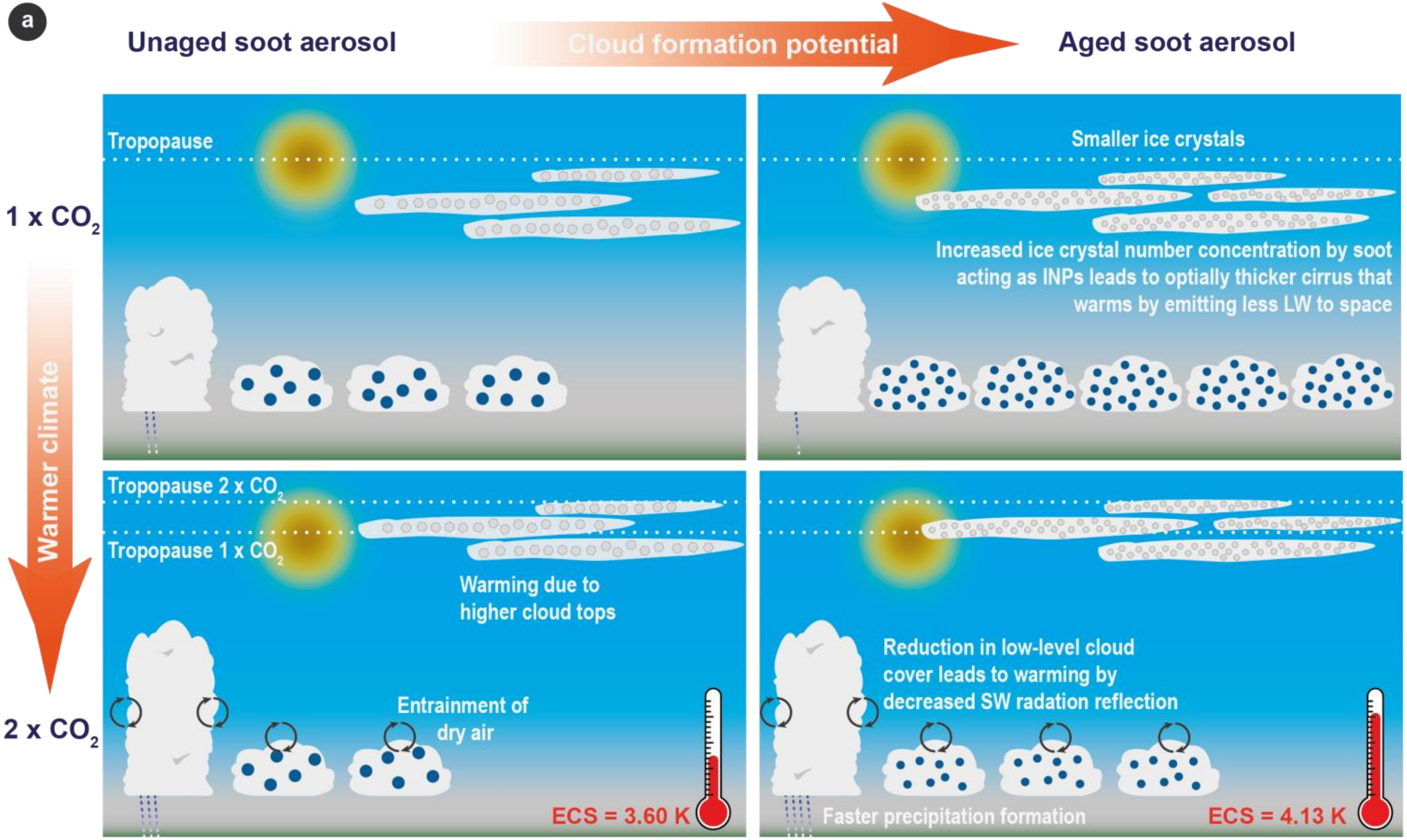
# Changes in cloud cover from aged soot acting as CCN and INP: pre-industrial (1x$CO_2$) and future (2x$CO_2$)



# Changes in ice crystal number concentration: pre-industrial (1x$CO_2$) and future (2x$CO_2$)

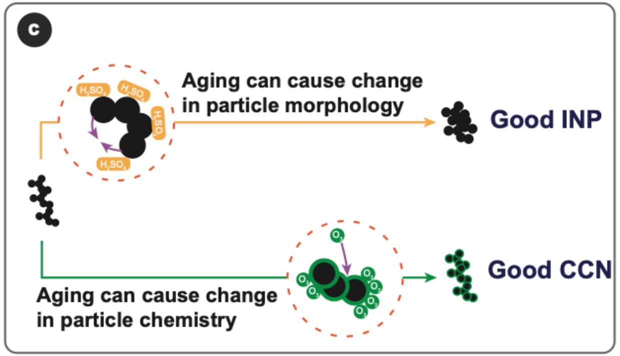


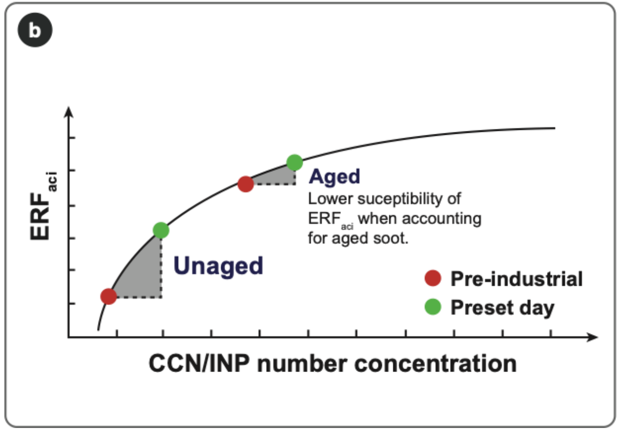
# Summary of the impact of aged soot particles as CCN and INPs



# Summary of the impact of aged soot particles as CCN and INPs

- Soot particles can be aged chemically and physically
- Smaller shortwave indirect aerosol effect (from pre-industrial to present)
- Amplification of warming due to optically thicker cirrus in higher altitudes and a reduction in low-level clouds causes an amplification in global mean precipitation and the hydrological cycle




Thank you for your attention!

# Pore condensation and freezing

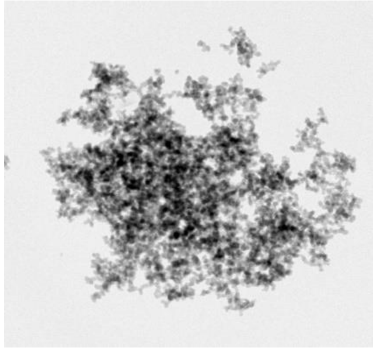
## Non-porous particle

Particle surface

Condensed water

Ice

***RH*$_w$ ≥ 100 %**



## Porous particle

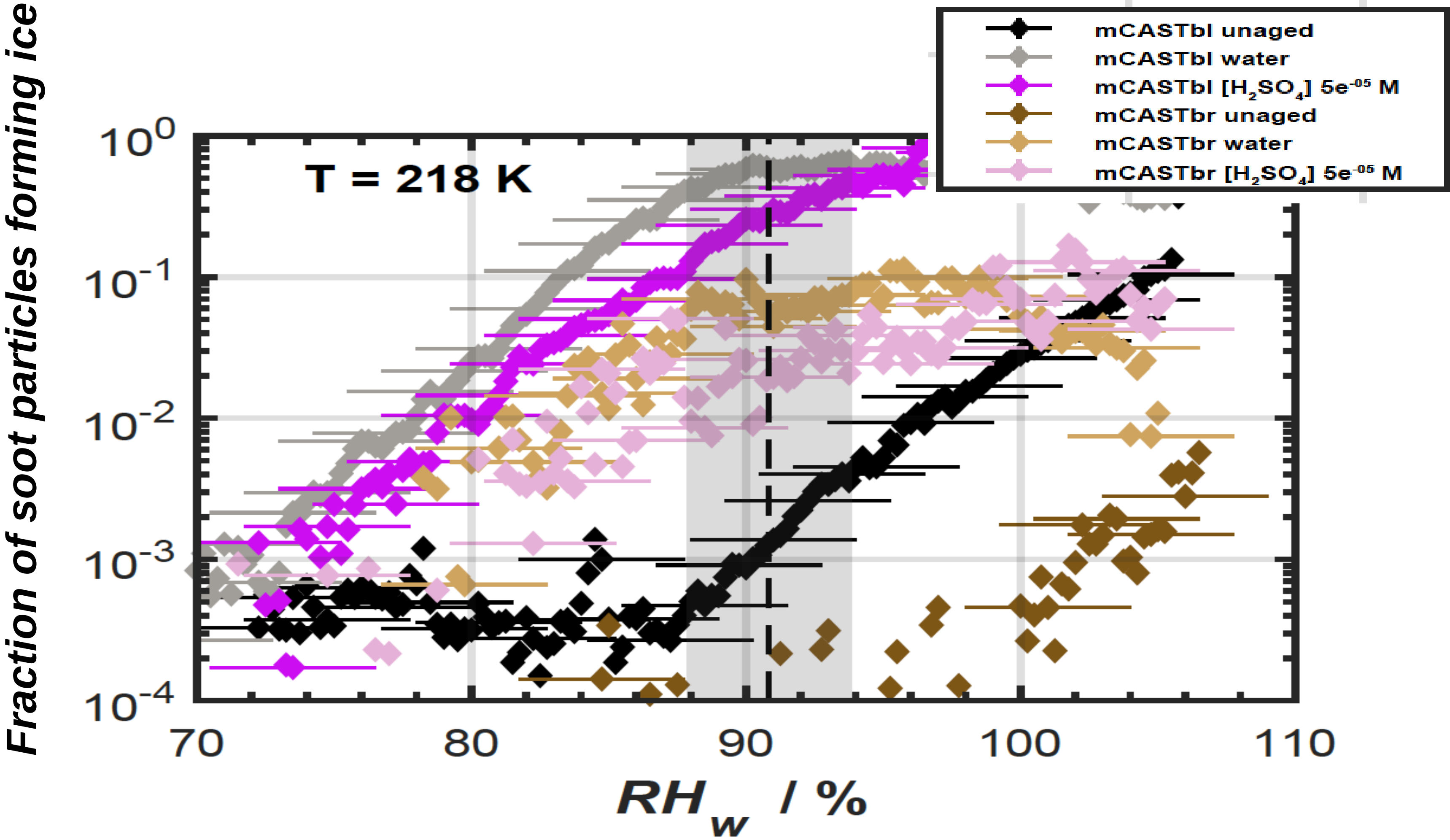
***RH*$_w$ < 100 %**

***T* < 235 K**

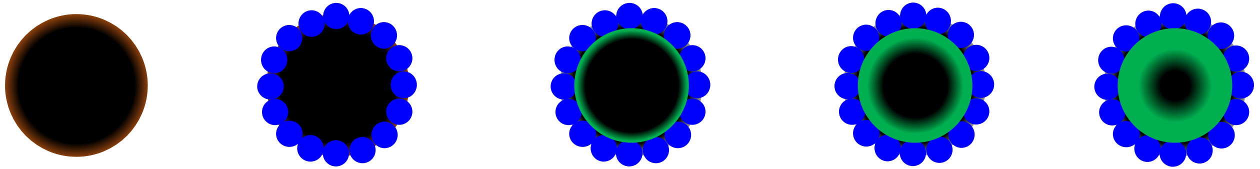
- Water is taken up by capillary condensation at $RH_w$ < 100%.
- Pore water freezes homogeneously at T < 235 K

Marcolli, ACP, 2014; David et al., PNAS, 2019

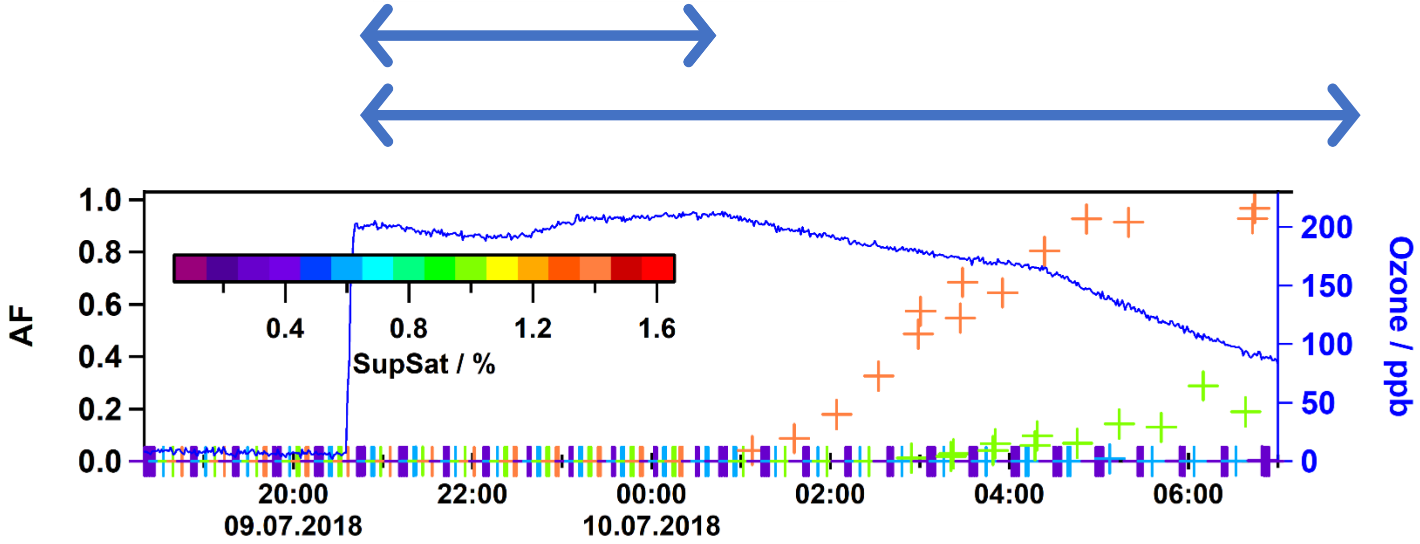
# Acid/Aqueous Soot Ageing Increases INP activity



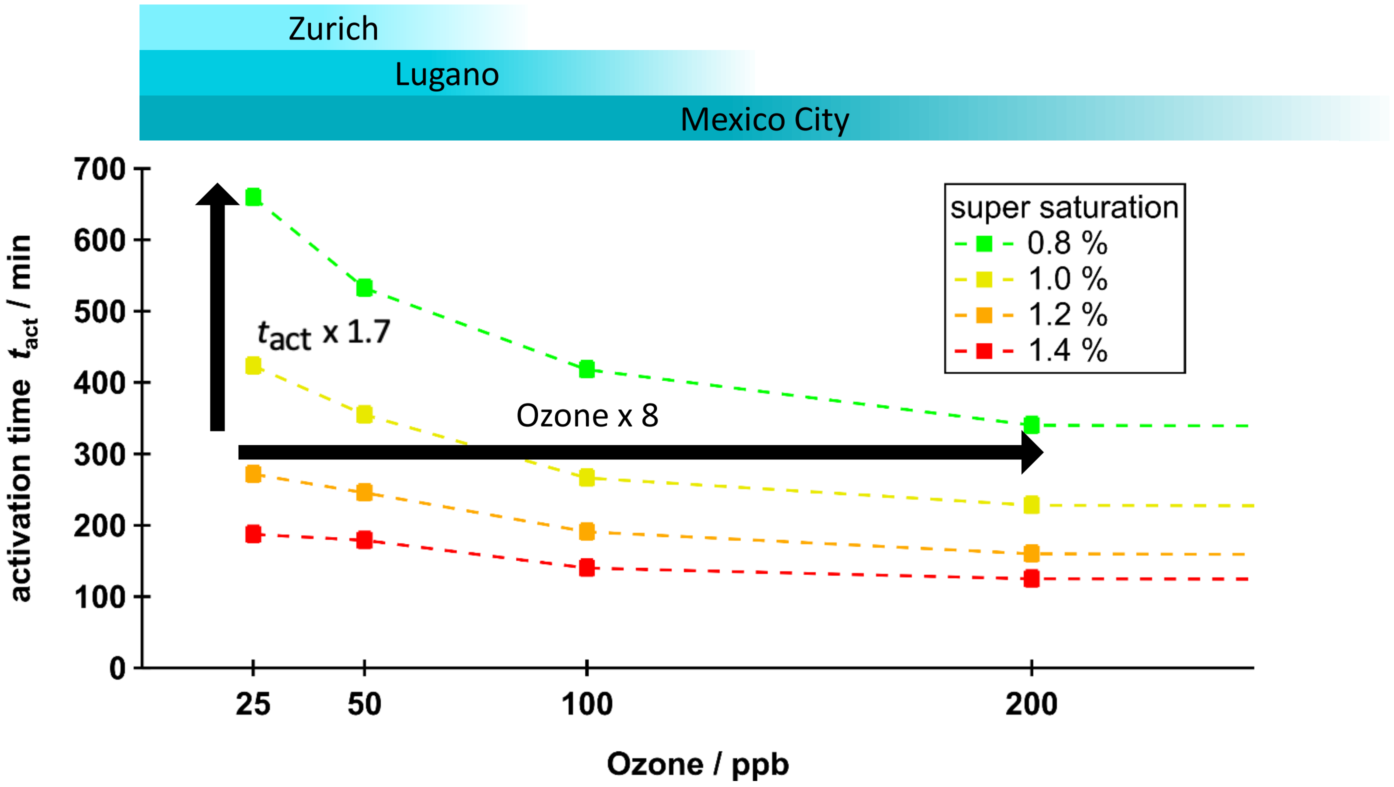
# Activation time $t_{act}$



$t_{act}$ = 3 - 12 h



# Activation time vs. ozone concentration



# Key climate impacts

| Simulation | REF | Soot-CCN | Soot-CCN+INP | Soot-CCN+INP-ac |
|---|---|---|---|---|
| $ERF_{ari+aci}$ – SW [W $m^{-2}$] | -1.98 ± 0.14 | -1.75 ± 0.15 | -1.66 ± 0.17 | -1.78 ± 0.18 |
| $ERF_{ari+aci}$ – LW [W $m^{-2}$] | 0.50 ± 0.11 | 0.40 ± 0.09 | 0.39 ± 0.10 | 0.42 ± 0.11 |
| $ERF_{ari+aci}$ (net) [W $m^{-2}$] | -1.47 ± 0.15 | -1.35 ± 0.15 | -1.27 ± 0.16 | -1.37 ± 0.17 |
| $IRF_{ari}$ (net) [W $m^{-2}$] | 0.03 ± 0.07 | 0.00 ± 0.06 | -0.01 ± 0.06 | 0.09 ± 0.06 |
| Cloud effects (net) [W $m^{-2}$] | -1.64 ± 0.13 | -1.46 ± 0.13 | -1.32 ± 0.14 | -1.64 ± 0.12 |
| ECS [K] | 3.60 ± 0.06 | 4.00 ± 0.05 | 4.13 ± 0.04 | 4.02 ± 0.06 |
| $\Delta$ precipitation [mm $d^{-1}$] | 0.194 ± 0.005 | 0.224 ± 0.006 | 0.238 ± 0.005 | 0.232 ± 0.006 |
| hydrological sensitivity [% $K^{-1}$] | 1.80 ± 0.06 | 1.89 ± 0.06 | 1.94 ± 0.05 | 1.94 ± 0.06 |