New Evidence of Soot Particles Affecting Past and Future Clouds and Climate: Aerosol Impacts on Cloud Formation

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TECHNOLOGIES AND POLICIES TOWARDS ZERO-IMPACTS COMBUSTION
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Research Grants

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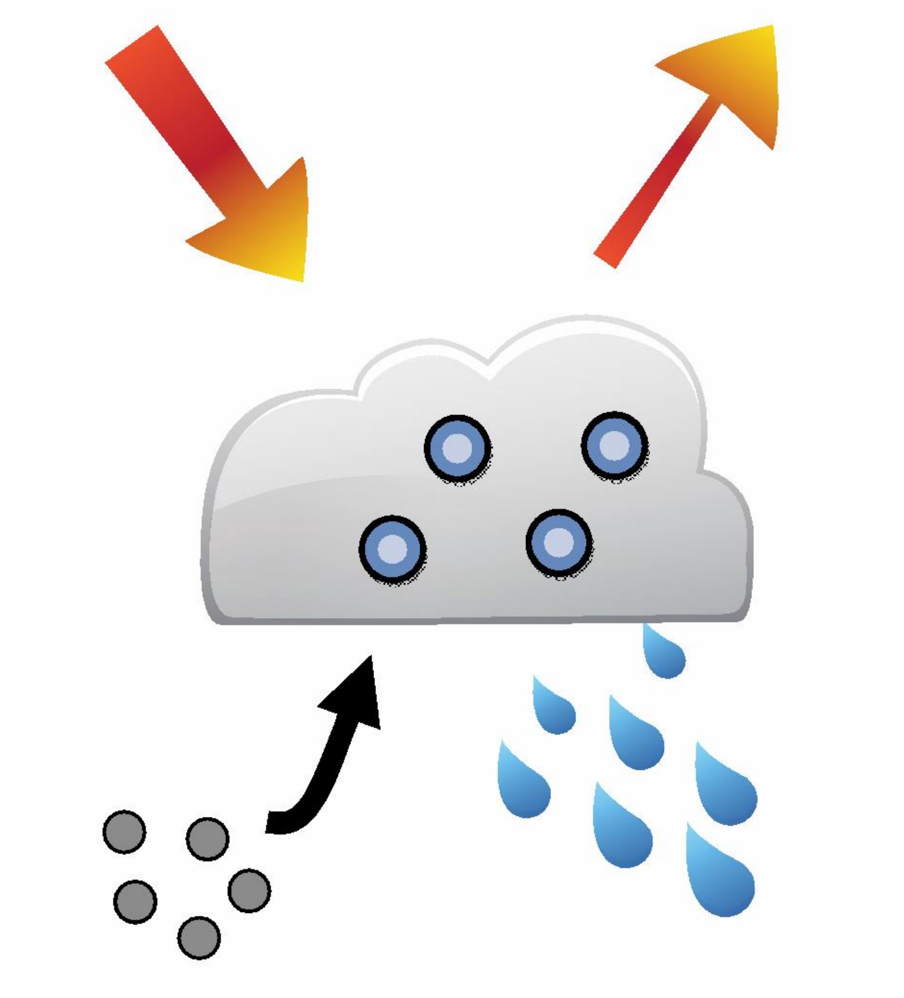
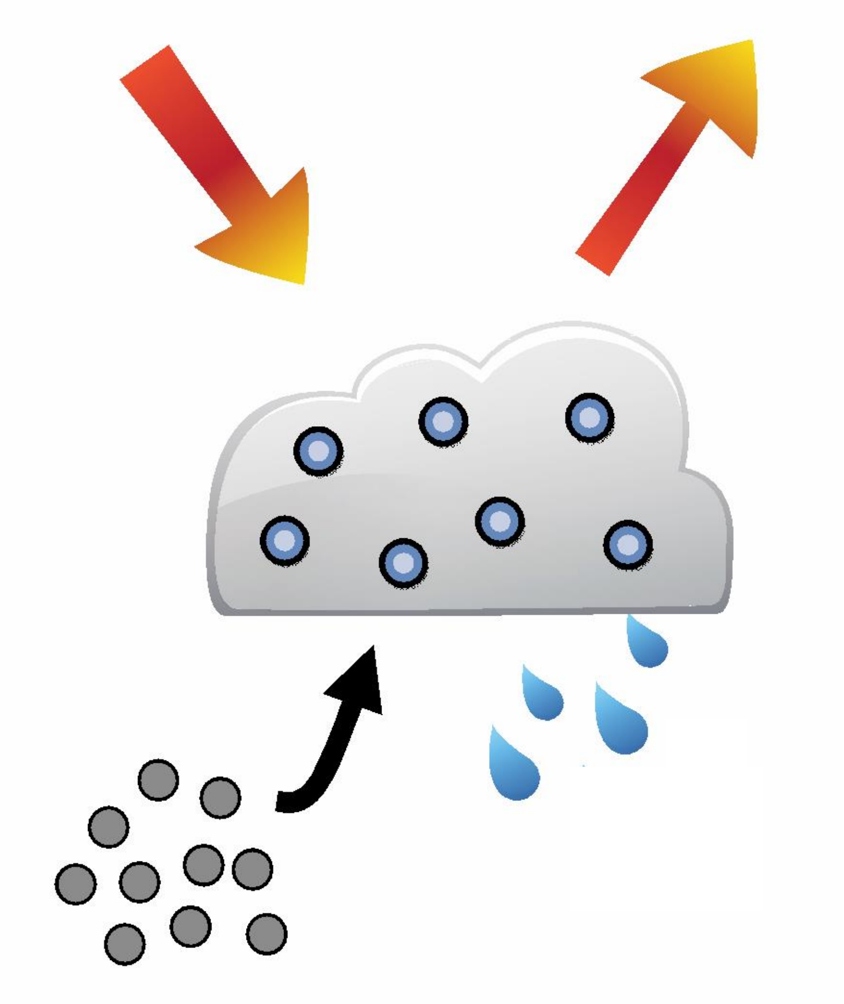
Radiative Forcing: Aerosol-Cloud Interactions



clean cloud
fewer large
drops



polluted cloud
many small
drops

IPCC, 2013, Fig. FAQ7.2

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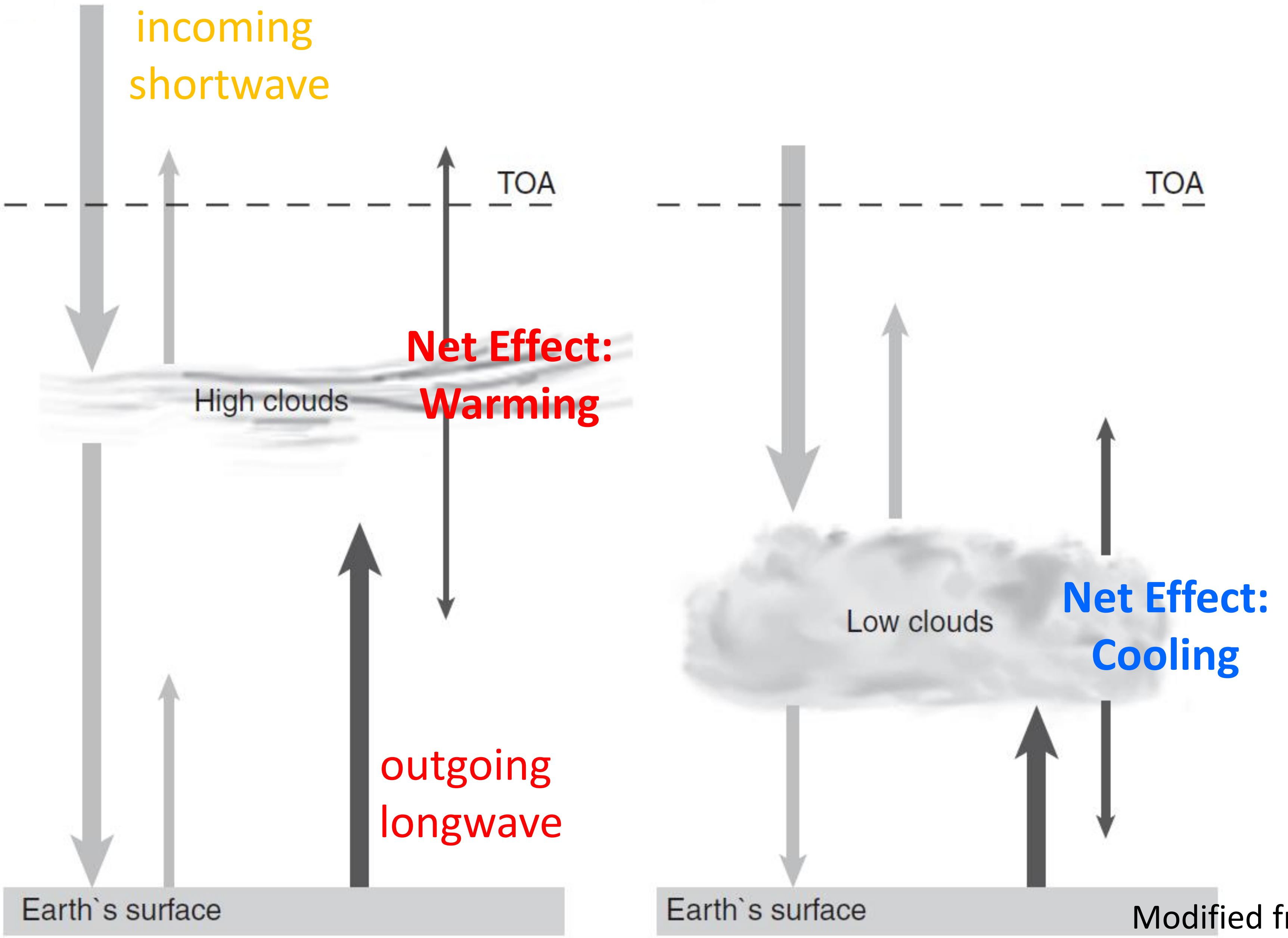
Radiative Effect: Cloud Altitude



Modified from Lohmann et al. (2016), *Cambridge University Press*

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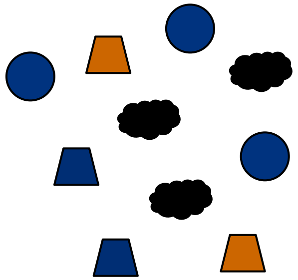
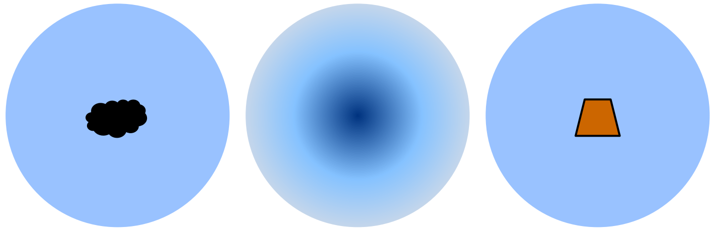
Aerosol Droplet Activation



Köhler Theory

Deliquescence/
Hygroscopic growth



Droplet Activation
Cloud Condensation Nuclei **(CCN)**

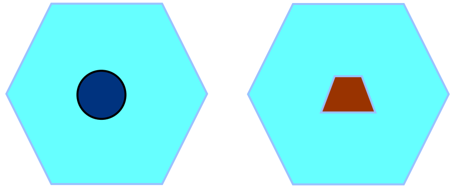
Activated Particles = 3

$$AF = \frac{3}{10}$$

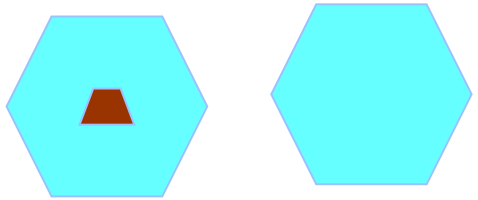
Heterogeneous
Ice Nucleation
$RH_w < 100\%$

Droplet freezing
Heterogeneously or homogenously
$RH_w \cong 100\%$

Aerosols:
Ice Nucleating Particles **(INP)**



Activated Particles = 2



Activated Particles = 2

Active (frozen) Fraction (AF)

$$\frac{N_{ice/drops}}{N_{aerosol}} = \frac{2}{10}$$

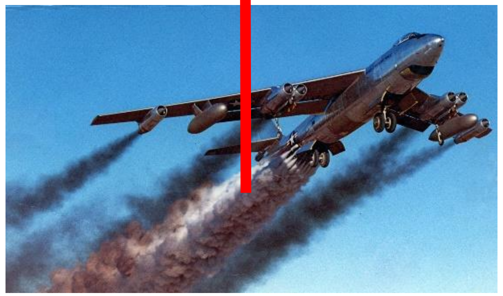
Why Soot (Black Carbon)?

- Major anthropogenic pollutant ~7500 Gg y^{-1} (Bond et al., 2013) and can account for 10% (by mass) of PM in troposphere

- Previous studies report freezing temperatures of up to -22°C for carbonaceous particles (see summaries in Murray et al., 2012; Hoose and Möhler, 2012; Kanji et al., 2017)

- Unconstrained ice forming properties of soot/BC
- Dependent on comp., size, (surface) and morphology

- Freshly emitted soot particles are hydrophobic, not CCN active



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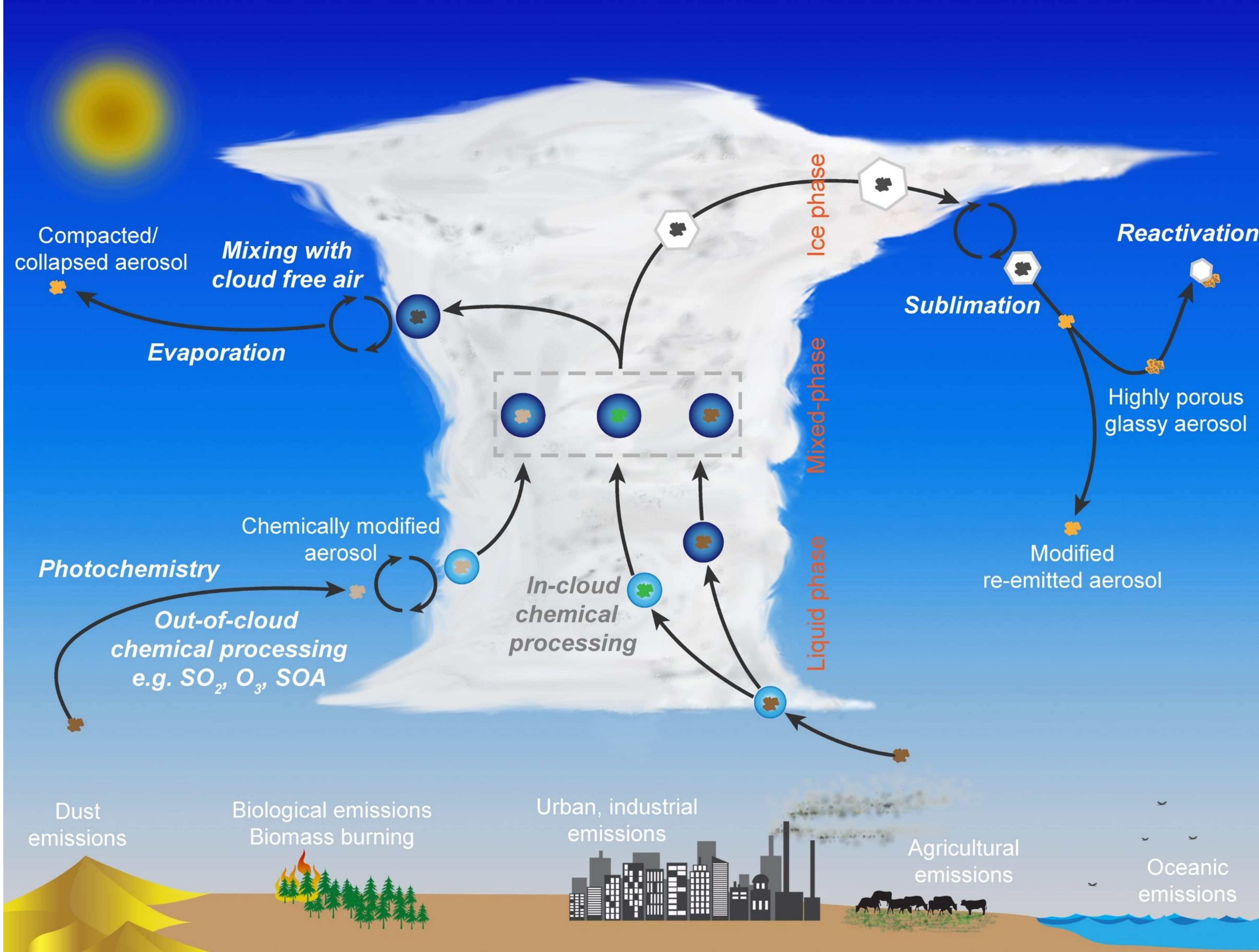
Aging Impacts on cloud formation



Kanji et al. (2017), *Met. Mono, AMS*

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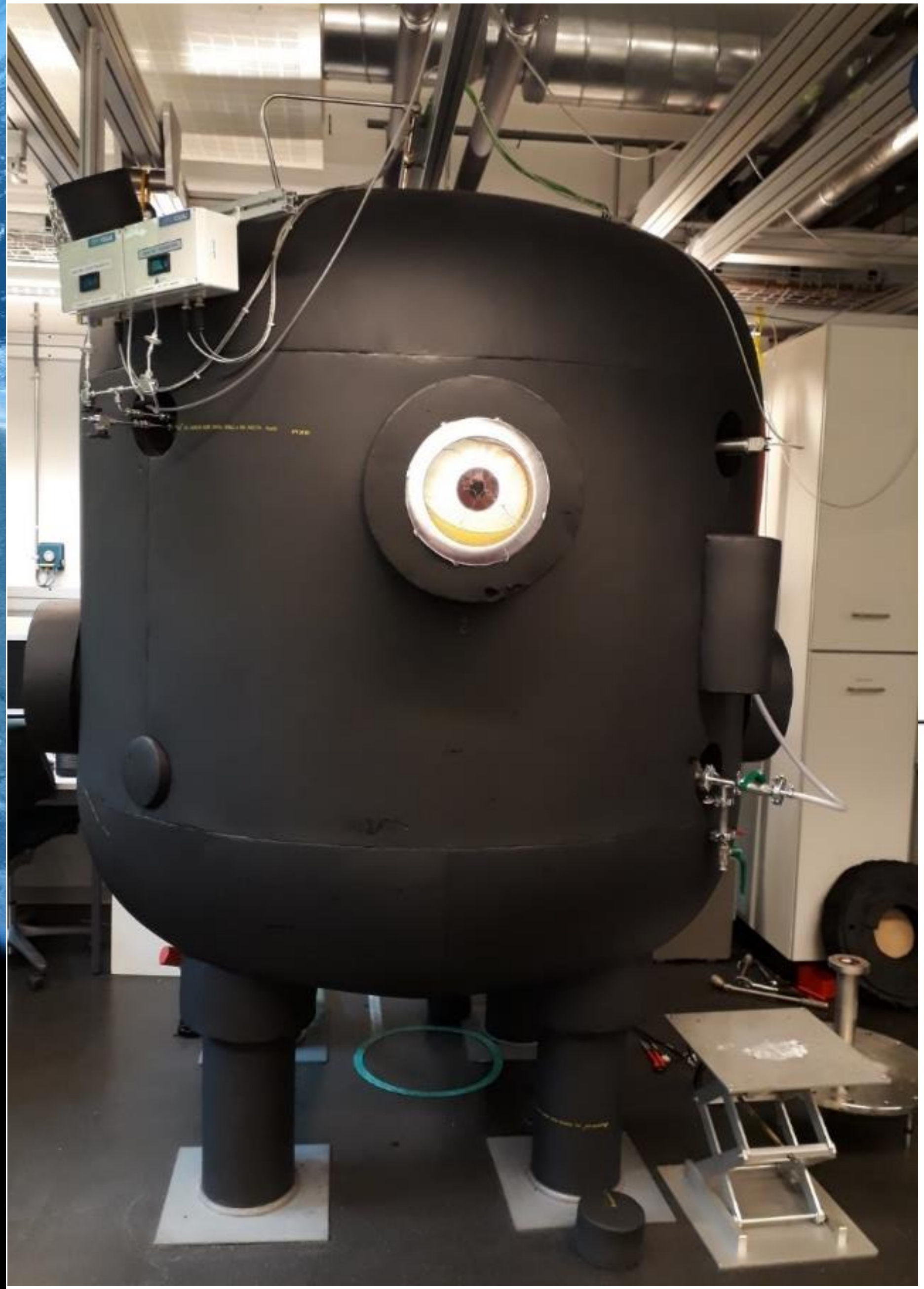
Research Questions

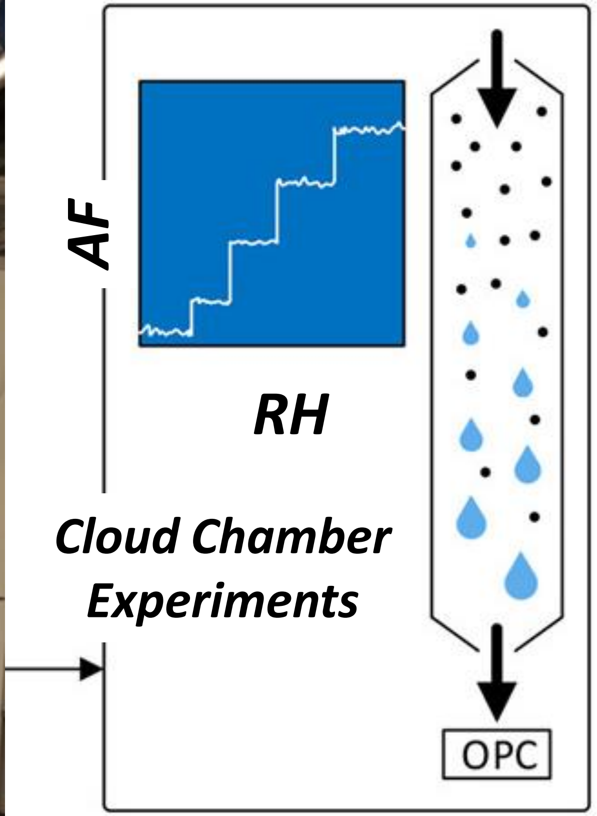
1) Does the liquid and ice cloud forming potential of soot particles change with aging or cloud processing during its atmospheric lifetime?

2) Do the changes in cloud forming potential affect climate globally?

Soot Aging and Cloud Formation (ice and liquid clouds)



Mahrt, Kanji et al. (2020), *ESPI and JGR*
Friebel and Mensah (2019), *AMT*



- Brown and Black (organic rich and poor) soot
- 100 - 400 nm soot
- 16 h aging time in O_3
- Cloud cycling and acid exposure
- Fraction of soot forming cloud droplets or ice crystals (***AF***)

Liquid cloud formation (CCN)

Temperature 5 - 35 °C ⟷ Ozone 0 - 200 ppb

Ice cloud formation (INP)

Temperature -40 to -55 °C ⟷ Cloud cycling H_2SO_4 aging

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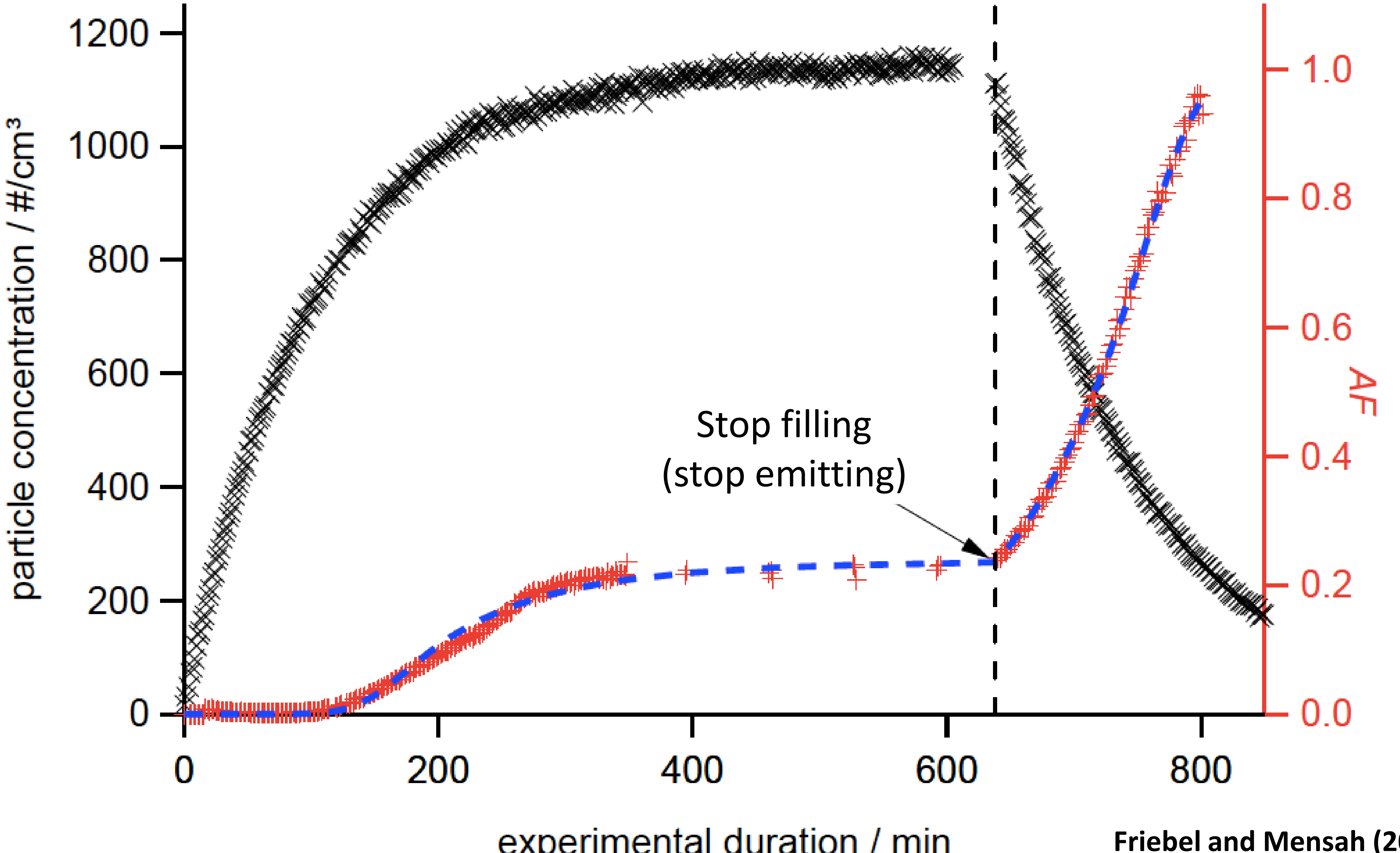
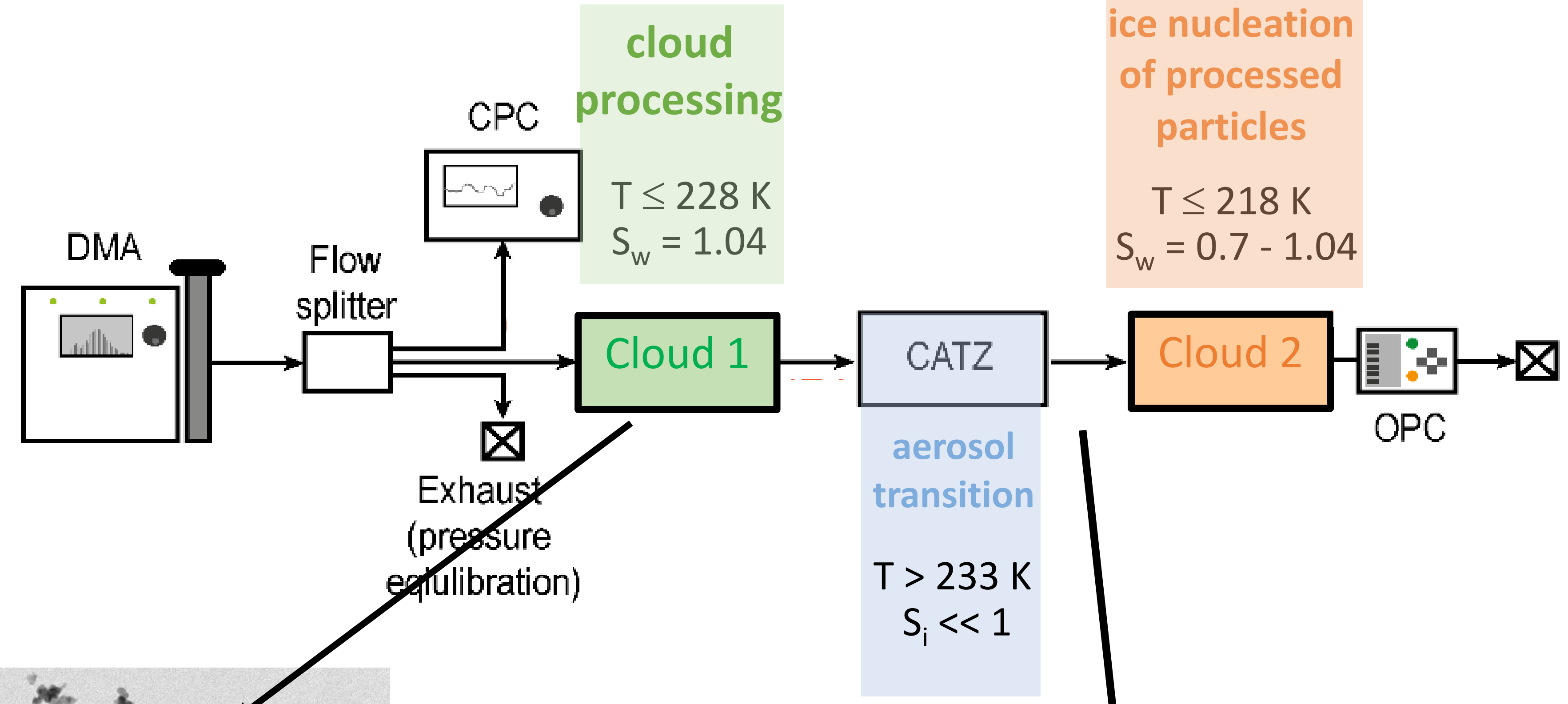
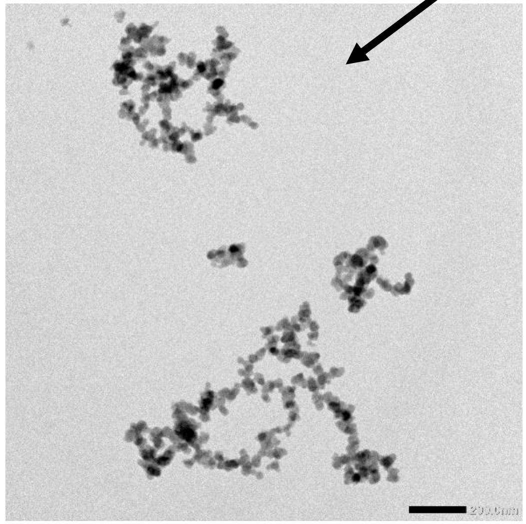
O_3 (200 ppb) Ageing of 100 nm Soot in Aerosol Tank

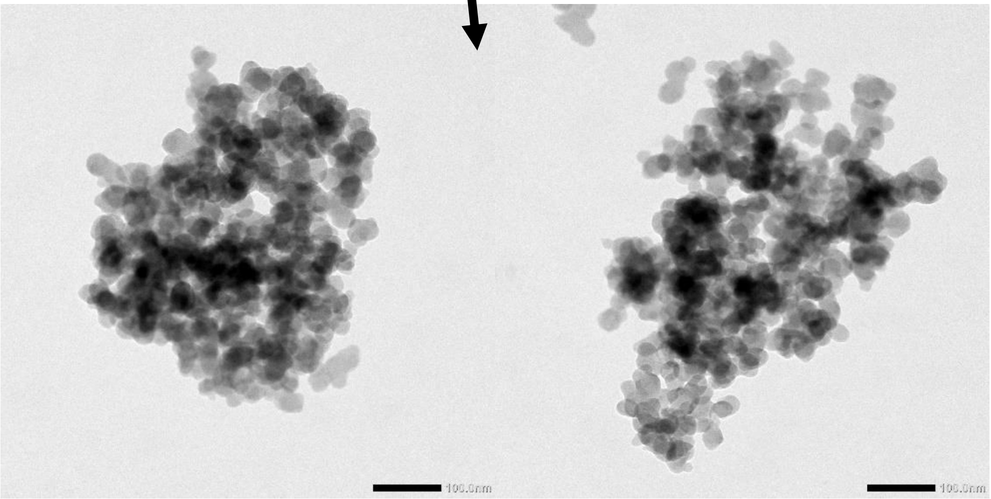


Friebel and Mensah (2019), *AMT*

Cloud Processing of Soot (CAST Black)

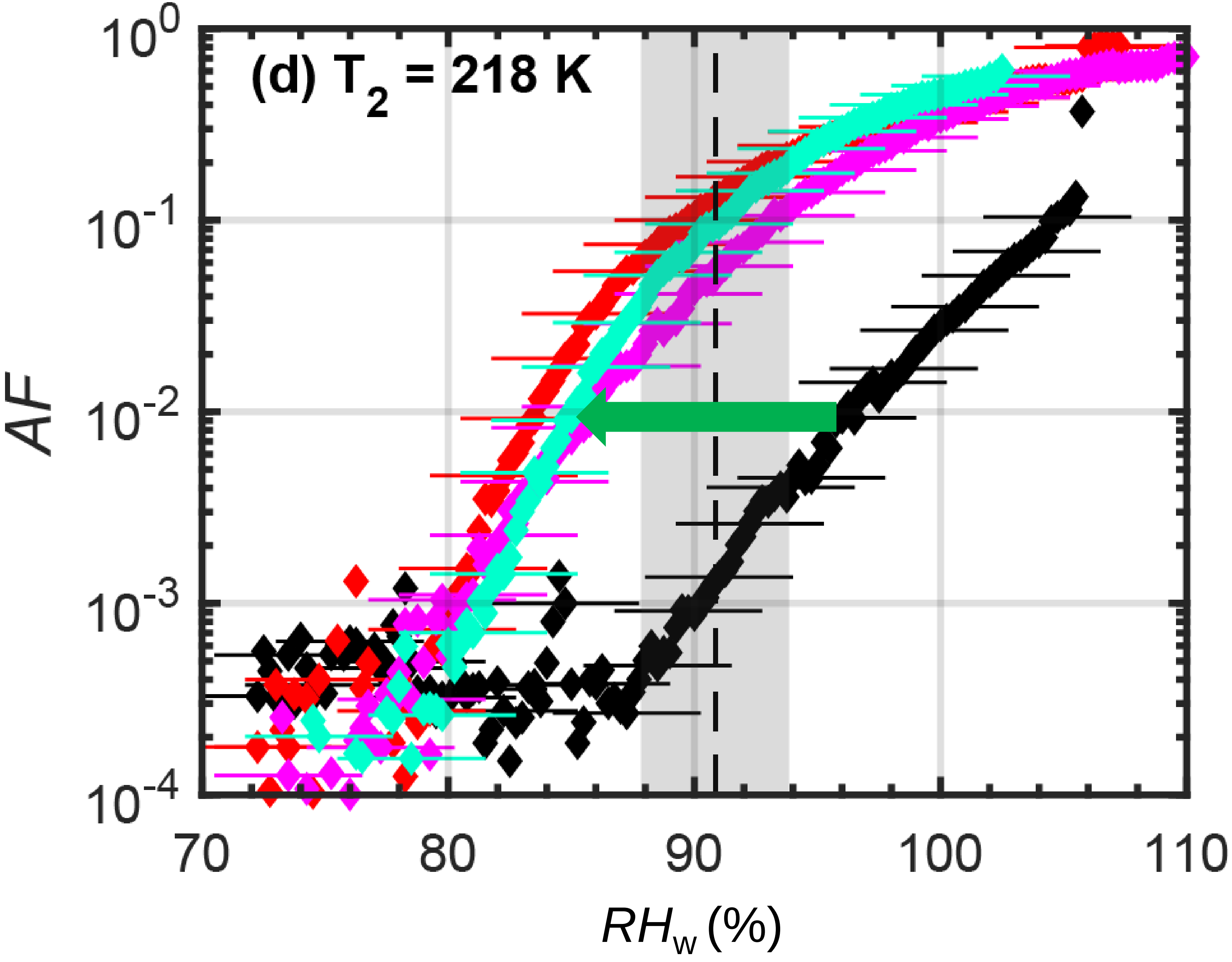






Mahrt, Kanji et al. (2020), *JGR*

Cloud Processing



Increase in water uptake

Increase in ice cloud forming potential

Mahrt, Kanji et al. (2020), *JGR*

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Higher CCN potential (liquid cloud) due to aging

Increased INP potential (cirrus cloud) due to aging and cloud processing

Impacts on Climate?

Lohmann, Friebel, Kanji, Mensah, Mahrt, Neubauer (2020), *Nat. Geos.*

Accounting for Ageing in Climate Model

Climate Model ECHAM-HAM (Neubauer et al., 2019)

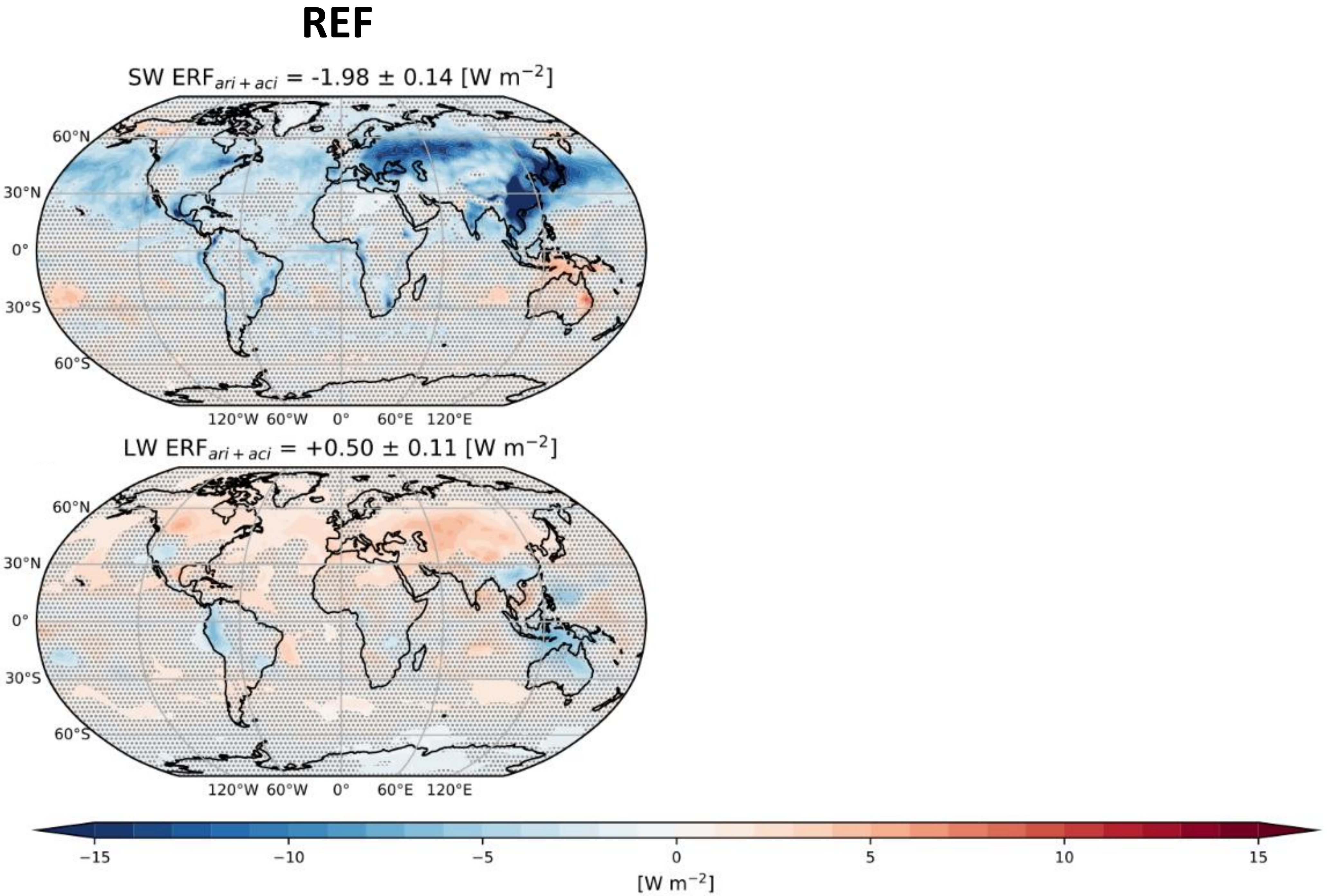
1. **REF** (present day 2008 – preindustrial 1850) not accounting for ageing
2. **SOOT-CCN** (as REF but accounting for O_3 aged soot as CCN)
3. **SOOT-CCN-INP** (as SOOT-CCN and with aged soot acting as INP in the cirrus regime)

Effective Short/Long-wave Radiative Impact

SW anthropogenic aerosol effect reduced

Due to increased pre-industrial CCN

Regionally largest impact over China

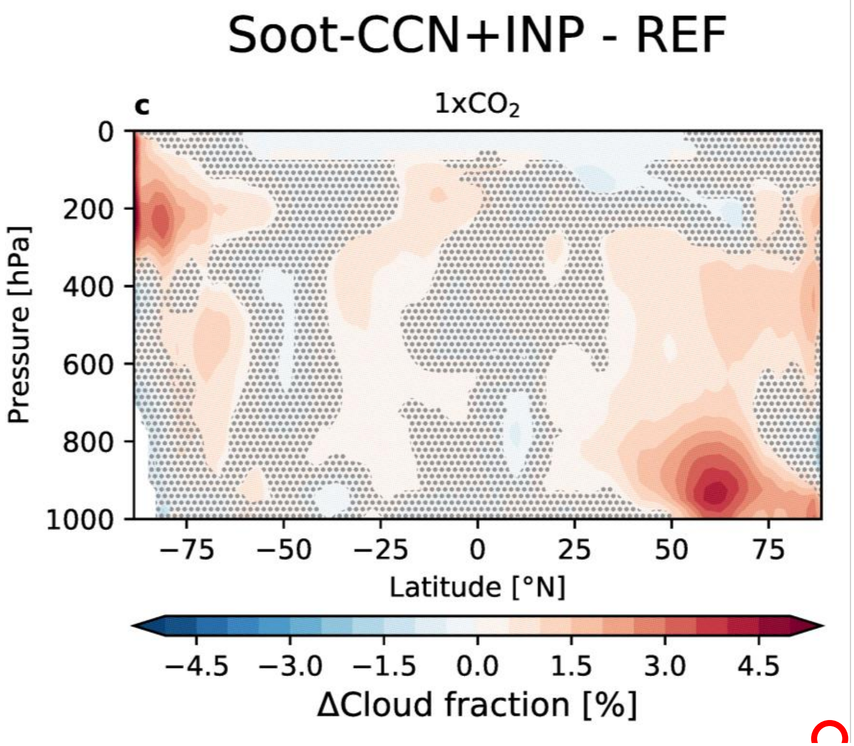


Changes in Cloud Cover: Preindustrial ($1\times CO_2$) and Future ($2\times CO_2$)

Increase in low level cloud fraction

Some increase in high level cloud fraction

Reduced cooling effect than previously thought



Increase in high level cloud fraction

Decrease in low-mid level cloud fraction

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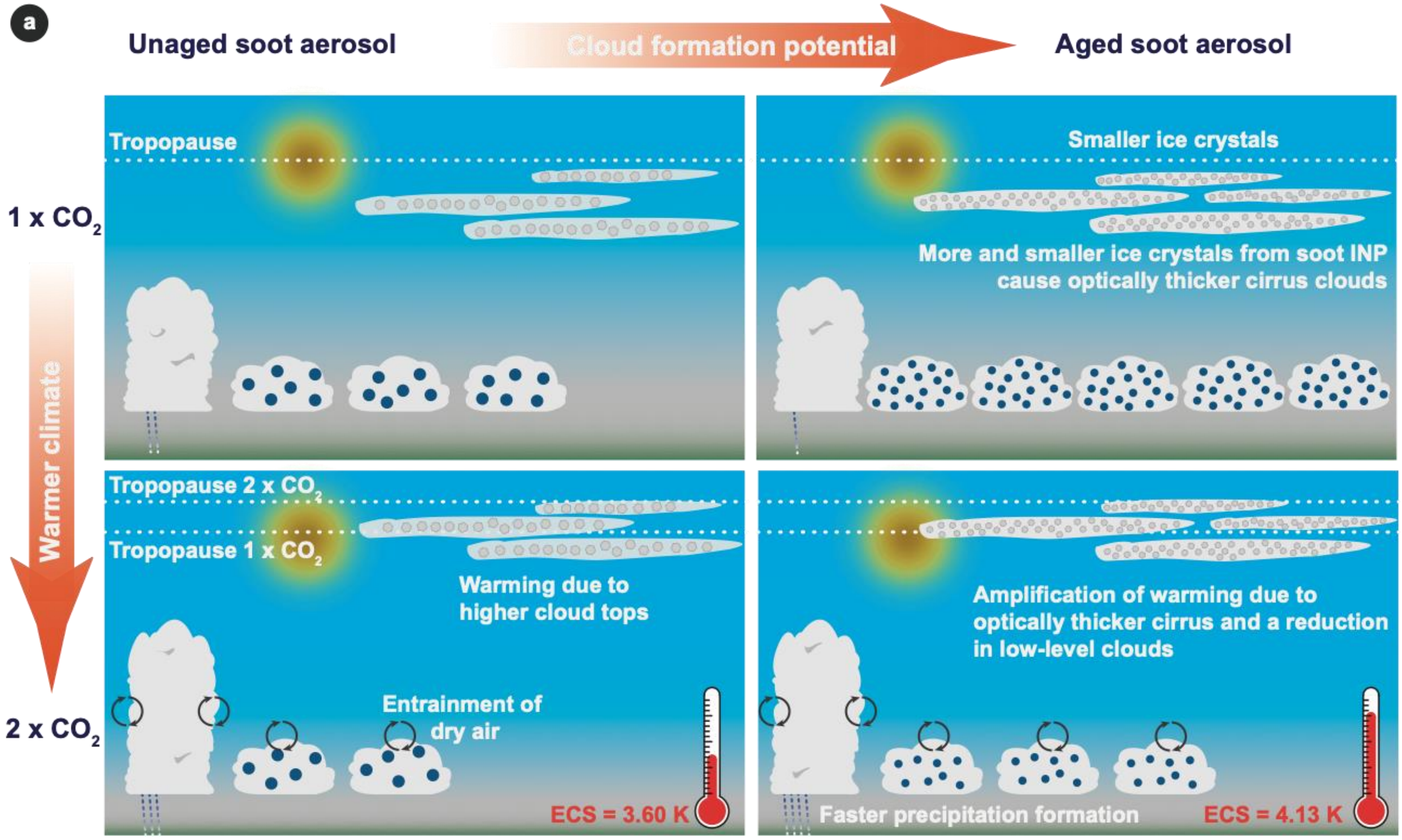
Results: Climate Forcing

Simulation	REF	Soot-CCN+INP
$ERF_{ari+aci}$ – SW [W m^{-2}]	-1.98 ± 0.14	-1.66 ± 0.17
$ERF_{ari+aci}$ – LW [W m^{-2}]	0.50 ± 0.11	0.39 ± 0.10
$ERF_{ari+aci}$ – net [W m^{-2}]	-1.47 ± 0.15	-1.27 ± 0.16
ECS [K]	3.60 ± 0.03	4.13 ± 0.02
Cloud effects (net) [W m^{-2}]	-1.64 ± 0.13	-1.32 ± 0.14
Δ Precipitation (mm d^{-1})	0.194 ± 0.002	0.238 ± 0.002

- Reduced cooling from shortwave due to soot as CCN and INP
- Reduced warming from longwave
- Net: Non-negligible warming (global) with stronger regional effects
- ECS increases, future warmer climate exacerbated from soot ageing

Summary of Impacts



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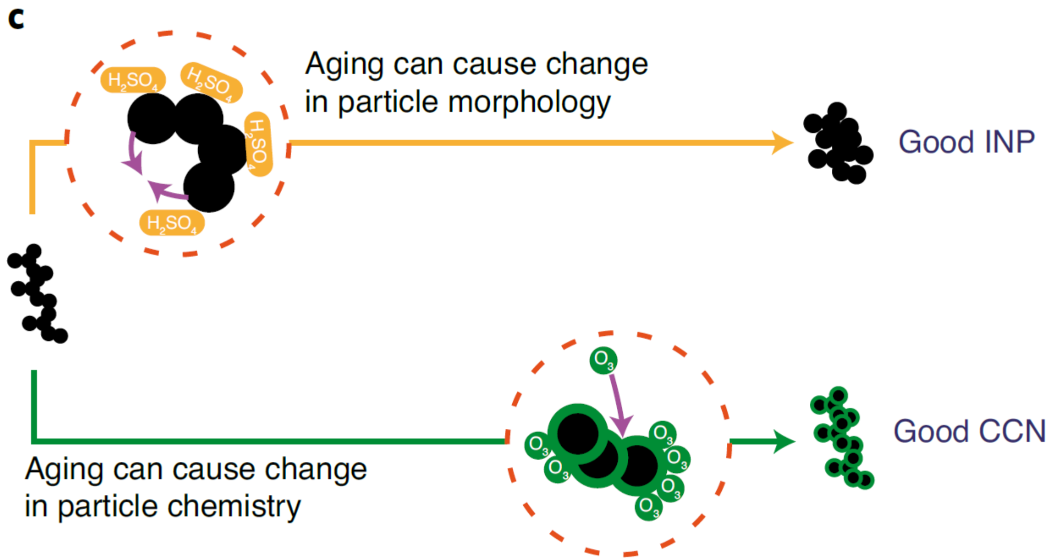
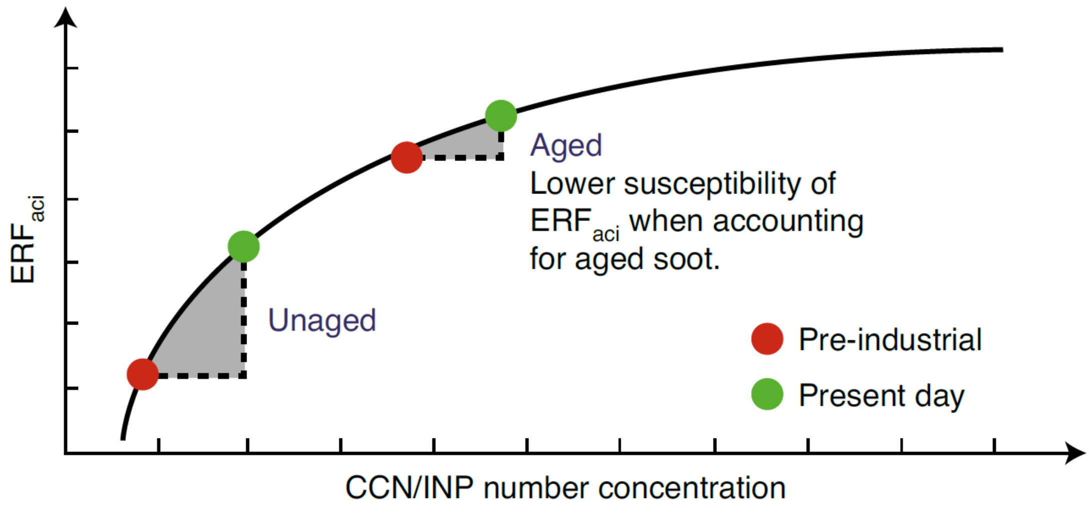
Conclusions

- Soot particles can be chemically and physically aged
  - Increasing (CCN) warm cloud potential
  - Increasing (INP) cirrus cloud potential
- Smaller shortwave indirect aerosol effect compared to pre-industrial
- Warming amplification
  - due to denser cirrus at higher altitudes
  - Reduction in low level clouds
- Amplification in global mean precipitation





Lohmann, Friebel, Kanji, Mensah, Mahrt, Neubauer (2020), *Nat. Geos.*