Pacific Northwest
NATIONAL LABORATORY

# Using E3SM to crosscheck other lines of evidence on aerosol–cloud interactions

Johannes Mülmenstädt and many collaborators

Pacific Northwest National Laboratory

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U.S. DEPARTMENT OF ENERGY BATTELLE



Thanks to my collaborators:

Andy Ackerman, Susanne Bauer, Matt Christensen, S. Dipu, Ann Fridlind, Andrew Gettelman, Ed Gryspeerdt, Meng Huang, Ruby Leung, Yi Ming, Johannes Quaas, Florian Tornow, Adam Varble, Hailong Wang, Laura Wilcox, Kai Zhang, Youtong Zheng,

and especially Naser Mahfouz, Susannah Burrows, and Po-Lun Ma

AeroCom/AeroSAT, US Climate Modeling Summit, ACPC, E3SM, EAGLES, NASA, RGMA, ESMD

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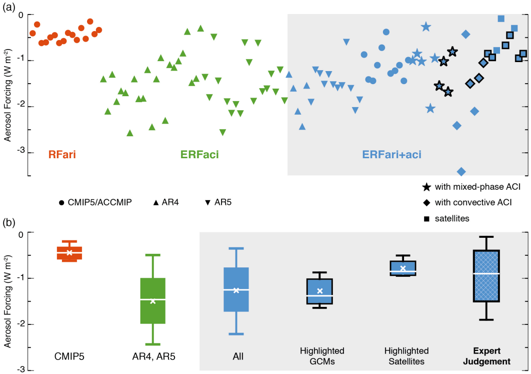
# Global models have had a rough decade




- Cloud physics uncertainties are large contributors to aerosol forcing and climate sensitivity uncertainties
- GCMs have very biased cloud physics, which has caused them to be given little weight in assessments of global mean climate responses (ERF and ECS)

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Boucher et al. (2014); Sherwood et al. (2020); Bellouin et al. (2020)

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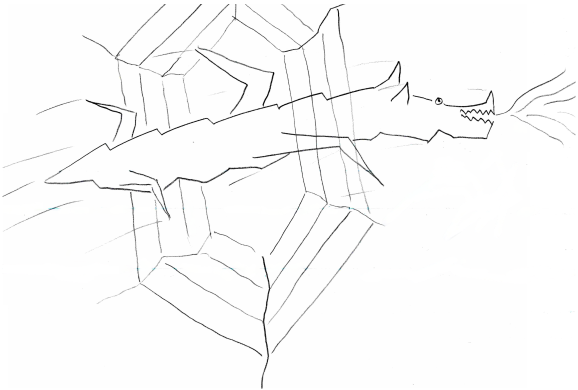
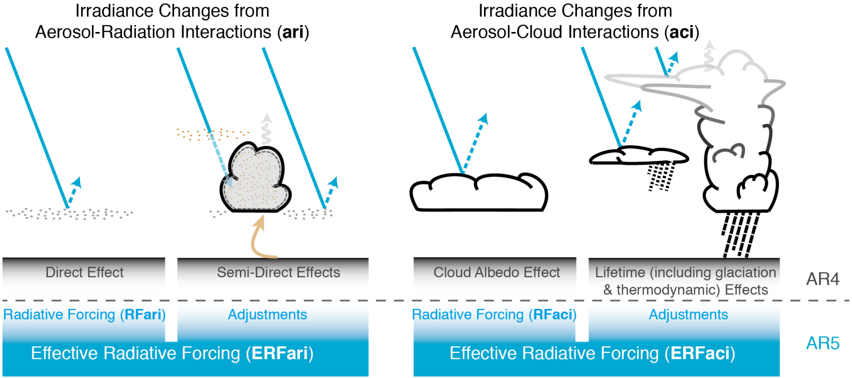


- Cloud physics uncertainties are large contributors to aerosol forcing and climate sensitivity uncertainties
- GCMs have very biased cloud physics, which has caused them to be given little weight in assessments of global mean climate responses (ERF and ECS)
- But discarding global models is a waste of a line of evidence that could be cross-checking the others
- And how do we answer questions society cares about if we don't have a modeling system that can represent scales from cloud processes to the global circulation?

Boucher et al. (2014); Sherwood et al. (2020); Bellouin et al. (2020)

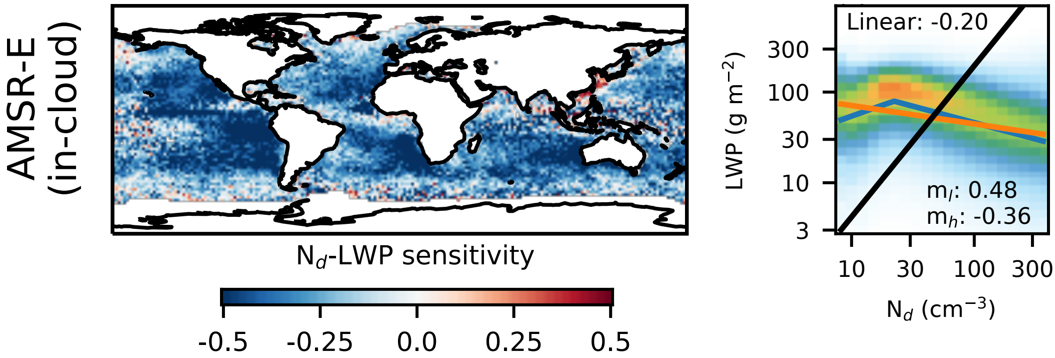
# Effective radiative forcing by aerosol–cloud interactions (ERFaci)




$$\text{ERFaci} = F_{N_d} + F_{\mathcal{L}} + F_{f_c} = \left( \frac{\partial R}{\partial \log N_d} + \frac{\partial R}{\partial \log \mathcal{L}} \frac{d \log \mathcal{L}}{d \log N_d} + \frac{\partial R}{\partial f_c} \frac{d f_c}{d \log N_d} \right) \Delta \log N_d \qquad (1)$$

Quaas et al. (2008); Boucher et al. (2014); Bellouin et al. (2020)

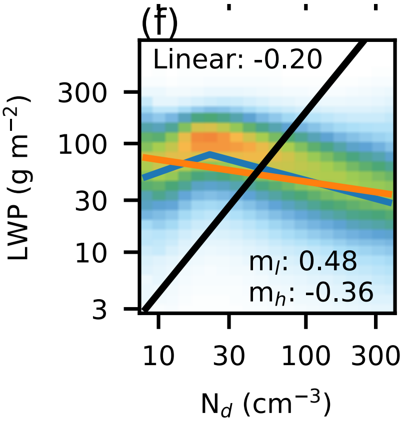
# The "inverted v" in $N_d$–$\mathcal{L}$ space: a tale of two slopes

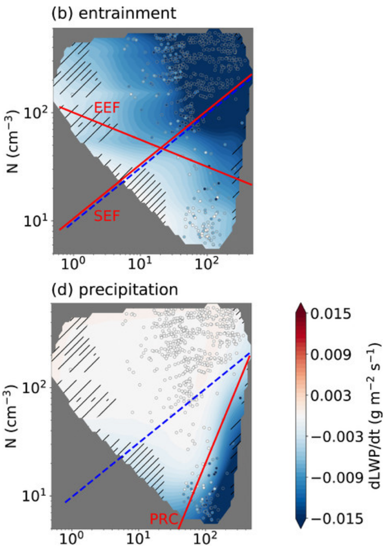



Interpretation: precip suppression at low $N_d$ (Albrecht, 1989), enhanced evaporation at high $N_d$ (Ackerman et al., 2004; Bretherton et al., 2007); partial cancellation, but evaporation wins

Gryspeerdt et al. (2019)

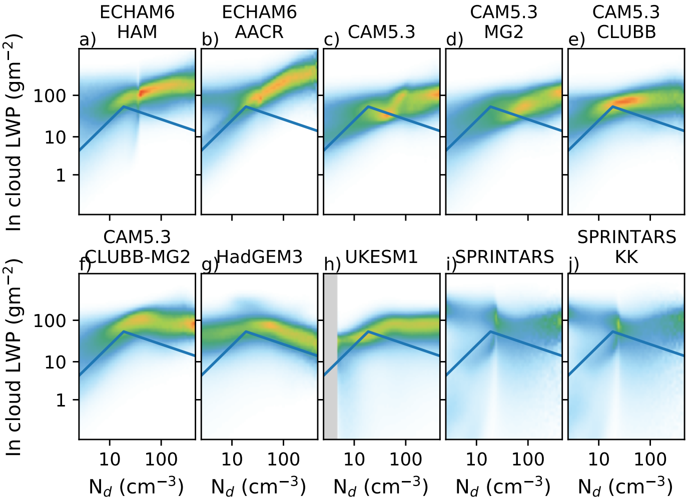
# Process fingerprints in $N_d$–$\mathcal{L}$ space



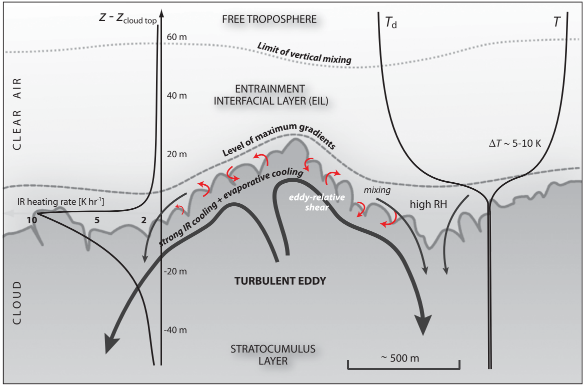

Gryspeerdt et al. (2019); Glassmeier et al. (2019); Hoffmann et al. (2020)

# There's no "v" in "GCM"




Mülmenstädt et al. (2024); see also: Michibata et al. (2016); Zhou and Penner (2017); Sato et al. (2018); Terai et al. (2020)

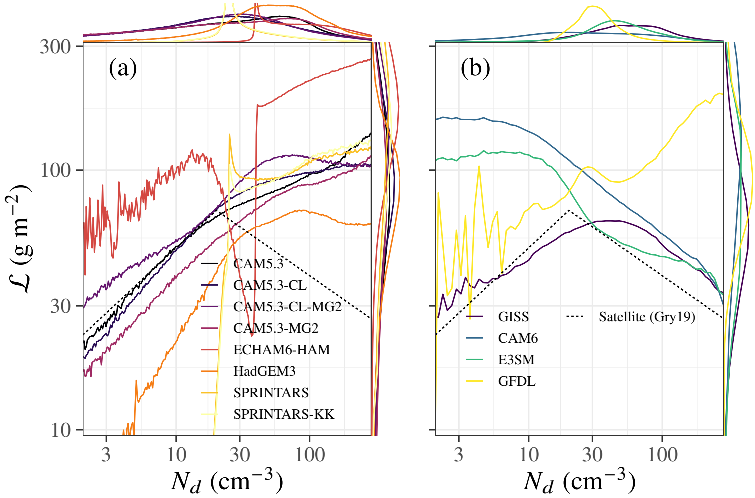
# This is what we should expect, based on process scales




By this argument, all global models are in trouble!

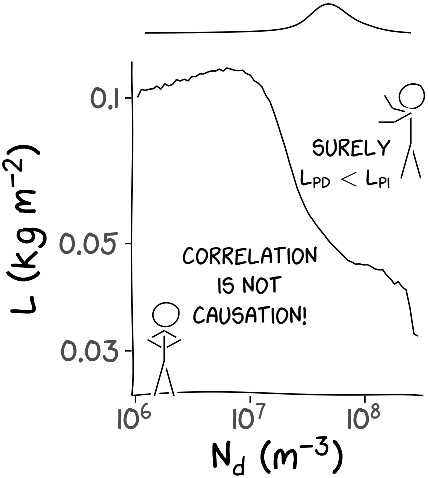
Wood (2012); Michibata et al. (2016); Zhou and Penner (2017); Sato et al. (2018); Terai et al. (2020)

# CMIP5 $\longrightarrow$ CMIP6: several models now have an inverted v!

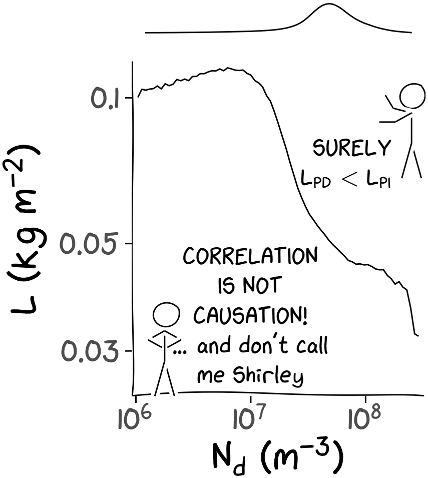


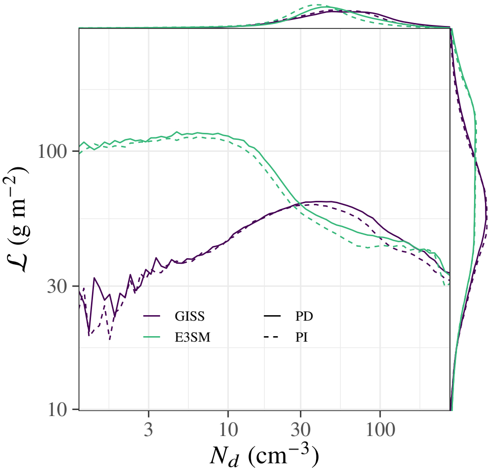

Mülmenstädt et al. (2024)

# Is the $N_d$–$\mathcal{L}$ relationship causal?



# Is the $N_d$–$\mathcal{L}$ relationship causal? No!




Actual LWP adjustment (PI⟶PD):

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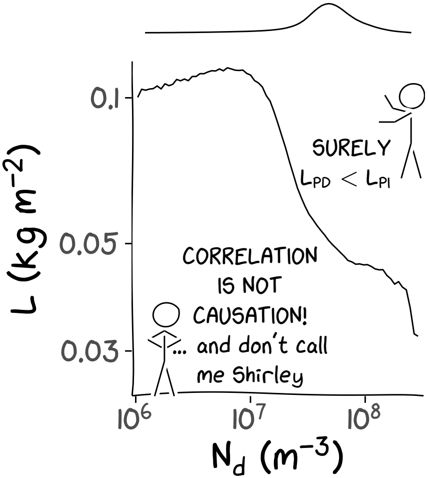
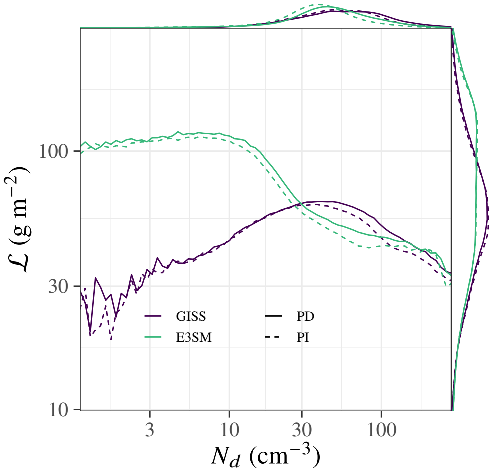
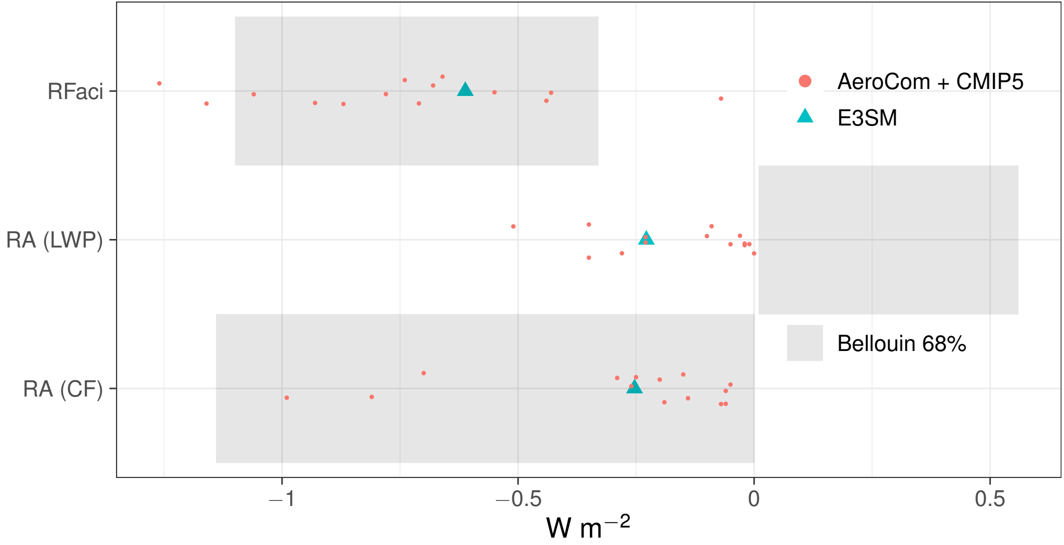



Actual LWP adjustment (PI⟶PD): $+3\%$

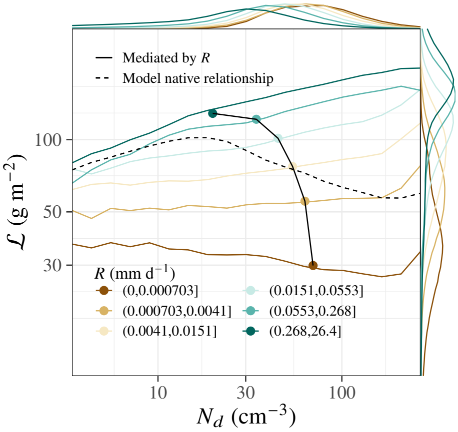
# GCM $\mathcal{L}$ adjustment is still the opposite of the other lines of evidence




Gryspeerdt et al. (2020); Bellouin et al. (2020)

# What confounds the $N_d$–$\mathcal{L}$ relationship?

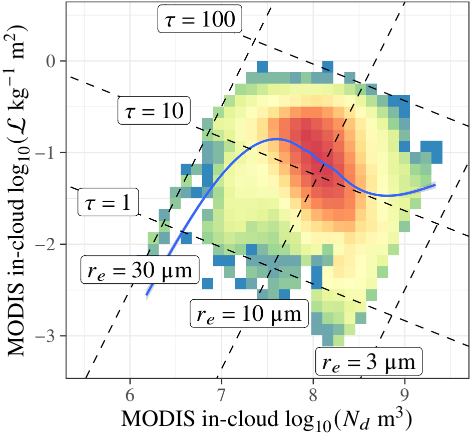
Regimes? Process dependence on base state? Thence, parameters?




Mülmenstädt et al. (2024)

# What confounds the $N_d$–$\mathcal{L}$ relationship?

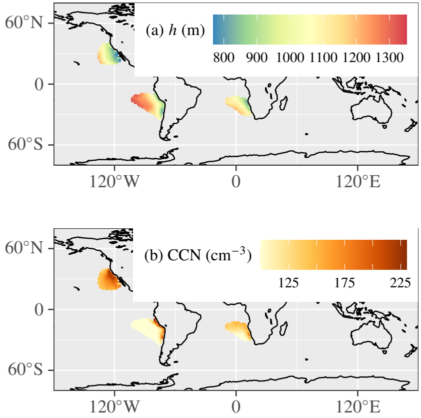
Artifacts?




Mülmenstädt et al. (2024)

# What confounds the $N_d$–$\mathcal{L}$ relationship?

Scales?




Mülmenstädt et al. (2024)

# Weave lines of evidence into a tight net for this multiscale problem

Atmos. Chem. Phys., 24, 7331–7345, 2024
https://doi.org/10.5194/acp-24-7331-2024


Atmospheric Chemistry and Physics
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Research article

**General circulation models simulate negative liquid water path–droplet number correlations, but anthropogenic aerosols still increase simulated liquid water path**

Johannes Mülmenstädt[1], Edward Gryspeerdt[2], Sudhakar Dipu[3], Johannes Quaas[3],
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- GCMs can reproduce the observed negative correlation between $N_d$ and $\mathcal{L}$, but they still produce higher $\mathcal{L}$ in PD than PI

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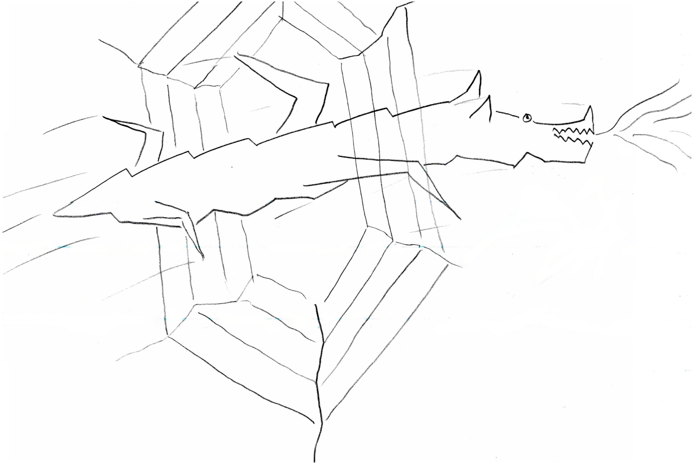
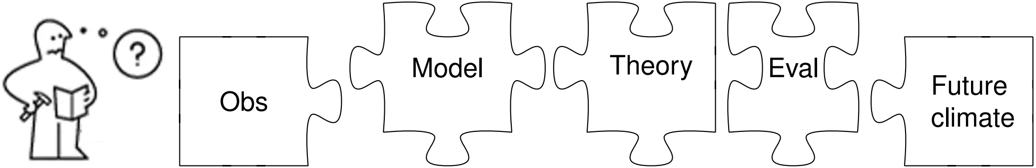
- GCMs can reproduce the observed negative correlation between $N_d$ and $\mathcal{L}$, but they still produce higher $\mathcal{L}$ in PD than PI
- Why this disagreement in sign? Points to a covariation rather than causal relationship between $N_d$ and $\mathcal{L}$

# Weave lines of evidence into a tight net for this multiscale problem



- GCMs can reproduce the observed negative correlation between $N_d$ and $\mathcal{L}$, but they still produce higher $\mathcal{L}$ in PD than PI
- Why this disagreement in sign? Points to a covariation rather than causal relationship between $N_d$ and $\mathcal{L}$
- We need to be really careful about interpreting PD variability as a proxy for secular change

# The puzzle only comes together if all the pieces are right



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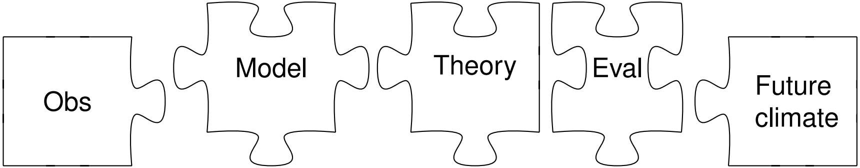
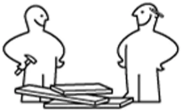
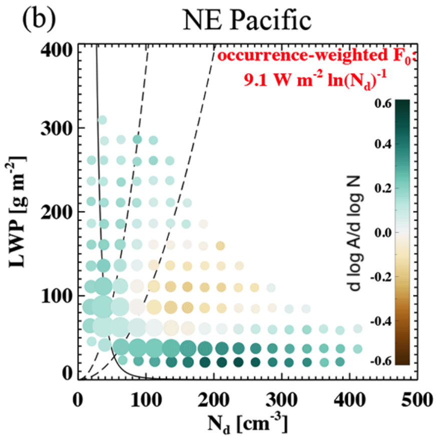


# Does aerosol make clouds darker or brighter?




Zhang and Feingold (2023)

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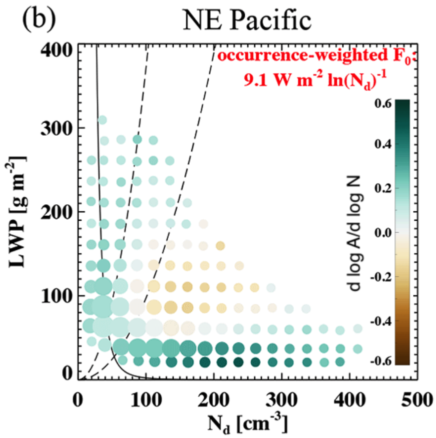


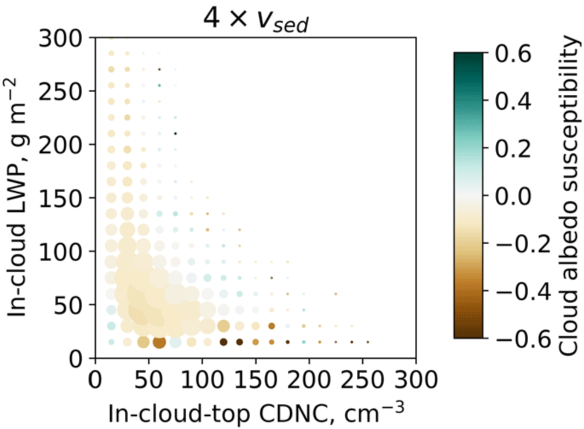


Zhang and Feingold (2023); Mahfouz et al. (2024)

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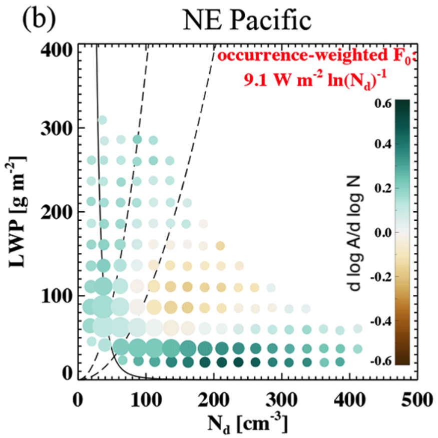


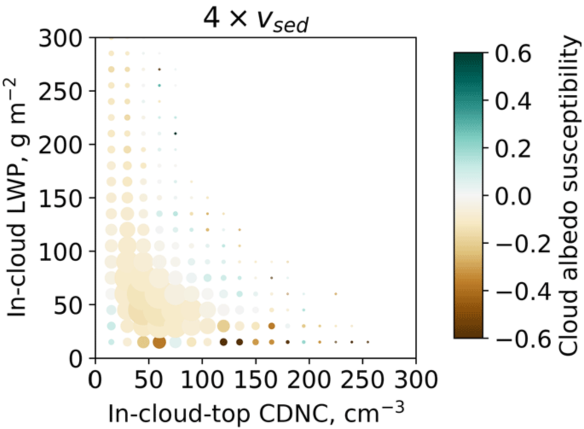


Actual PI⟶PD cloud albedo change:

Zhang and Feingold (2023); Mahfouz et al. (2024)

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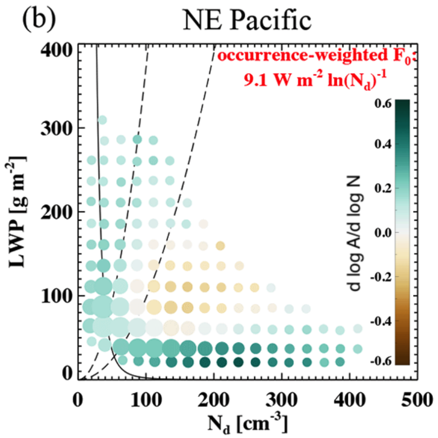


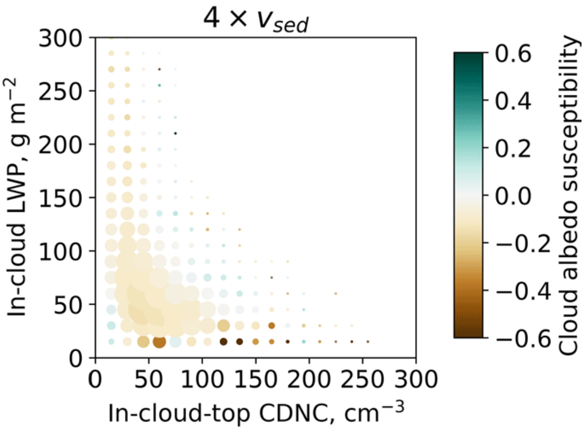


Actual PI$\longrightarrow$PD cloud albedo change: $+3\%$

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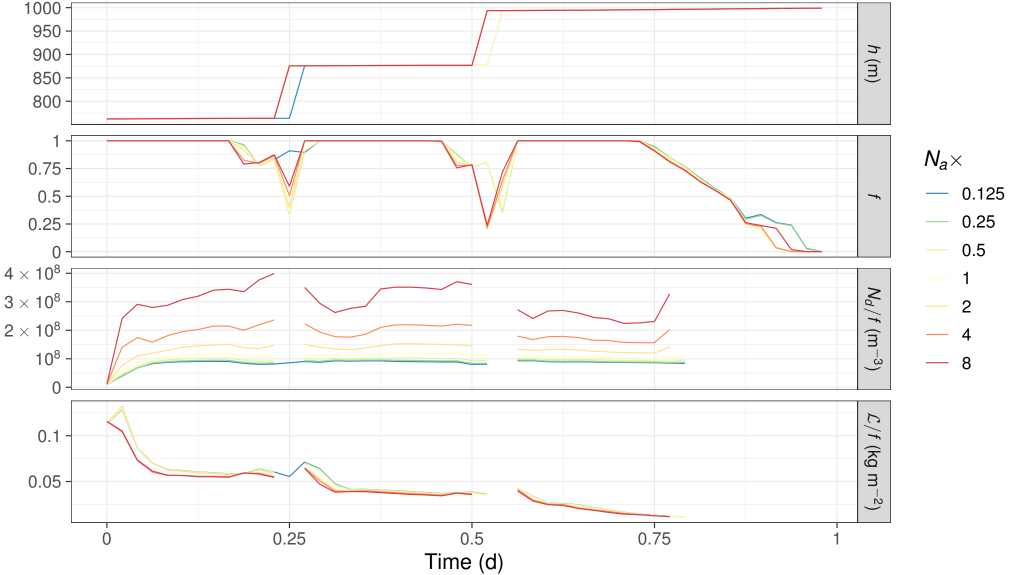
# Diagnosing the entrainment process – in a well studied LES case



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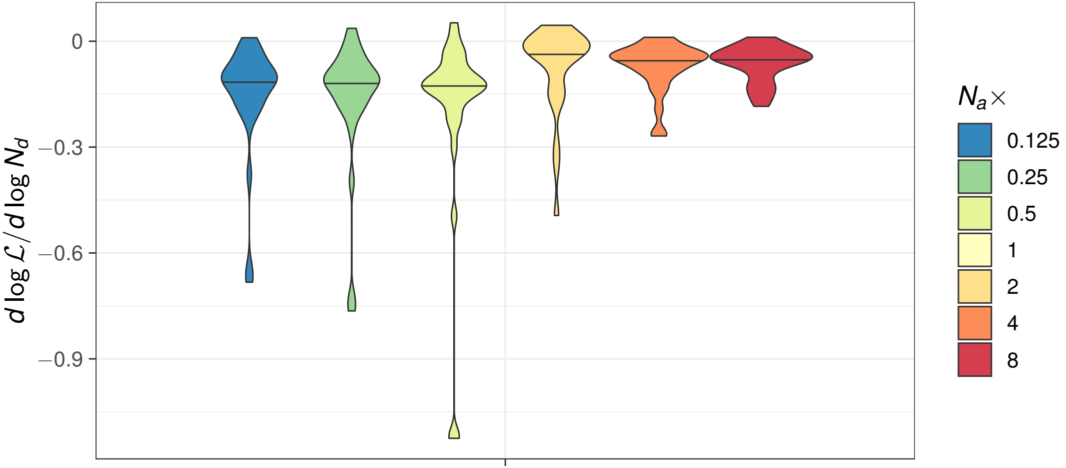

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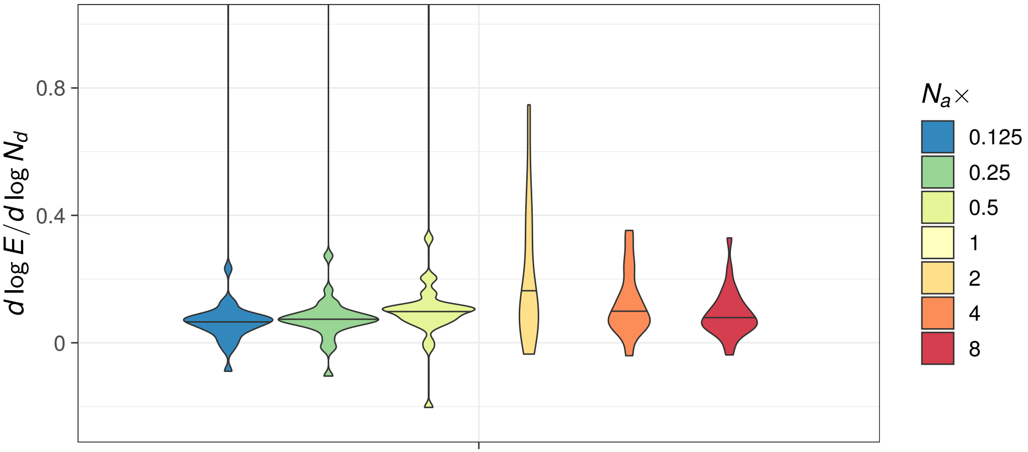

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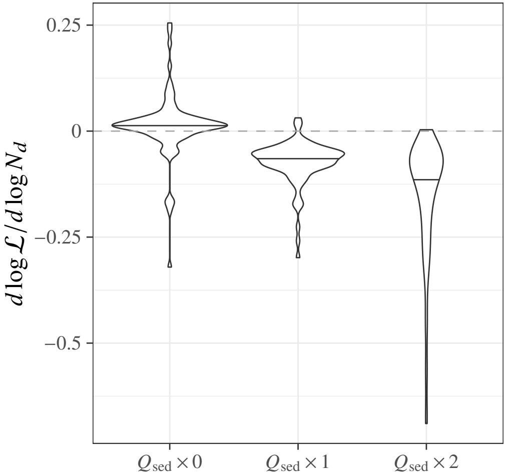
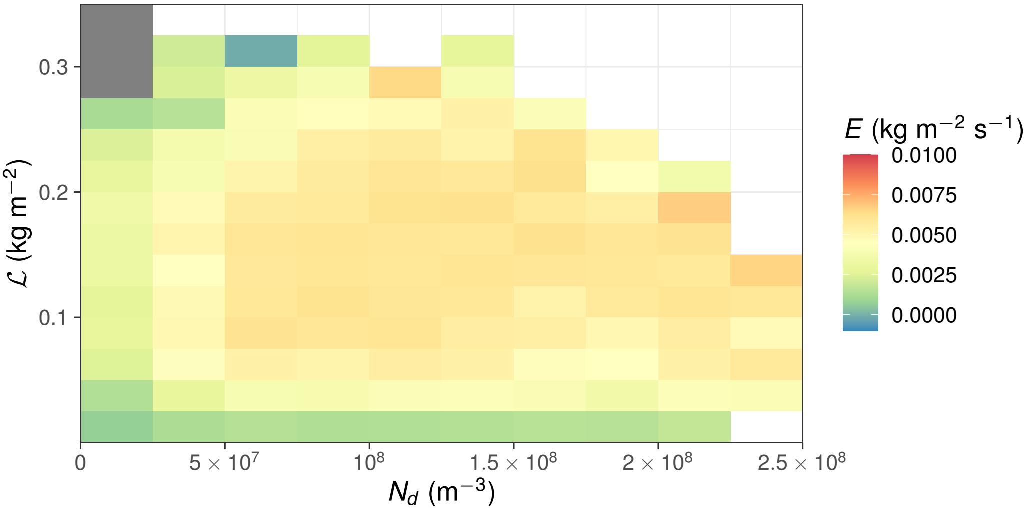



Mülmenstädt et al. (revised)

# Diagnosing the entrainment process – in stratocumulus diversity



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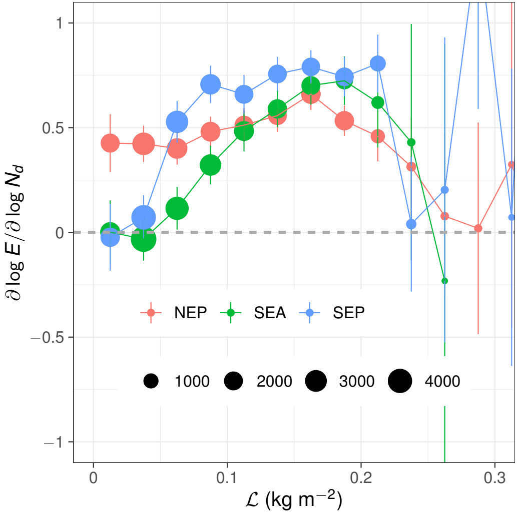

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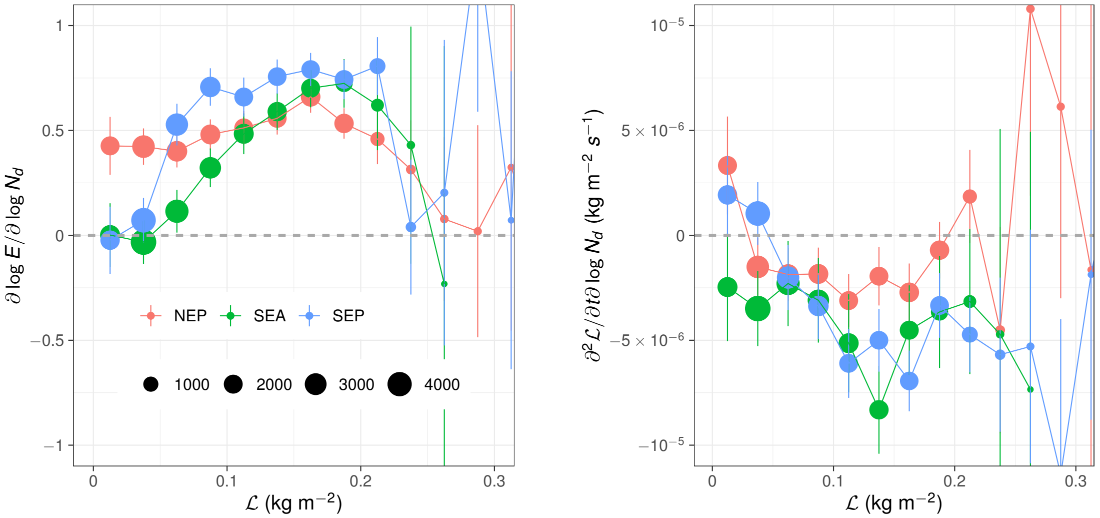

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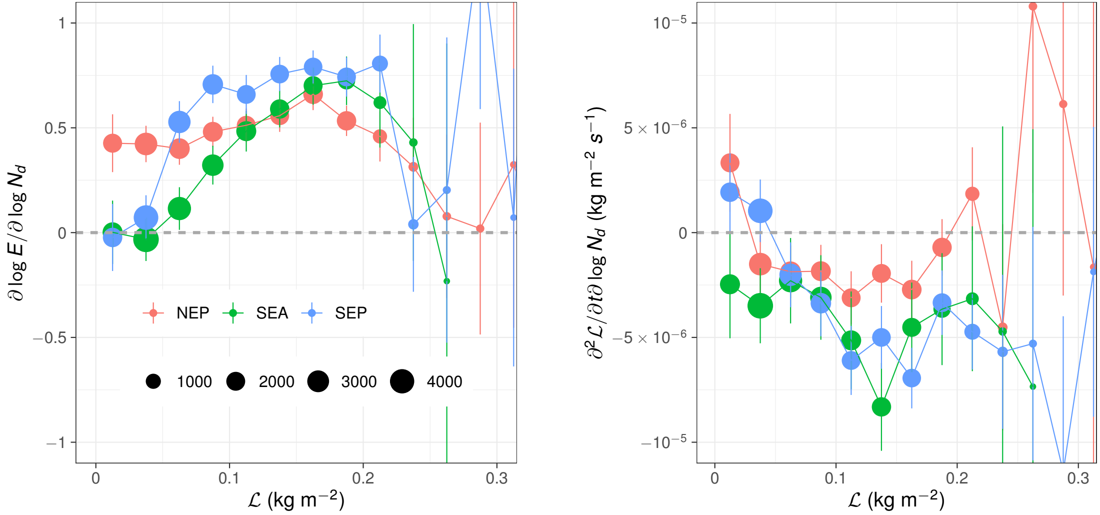


Actual LWP adjustment (PI⟶PD):

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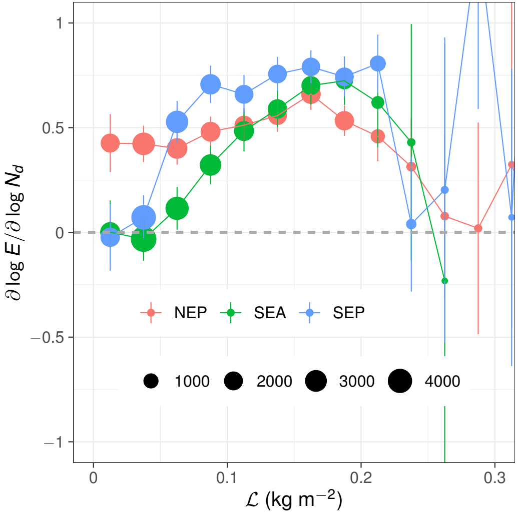
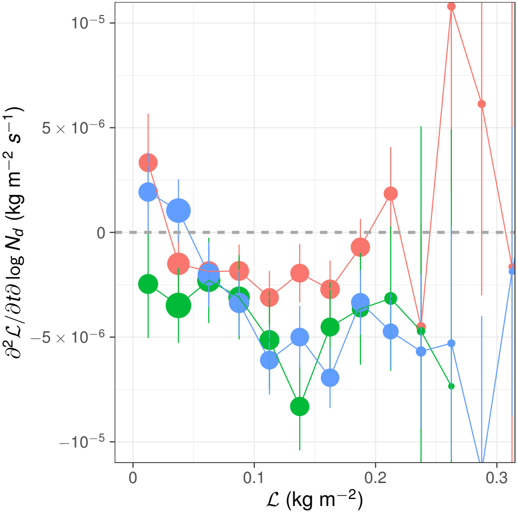
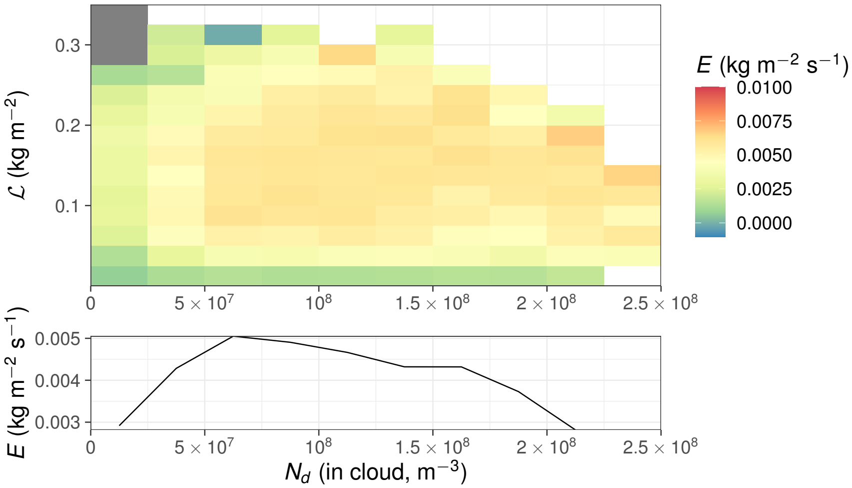


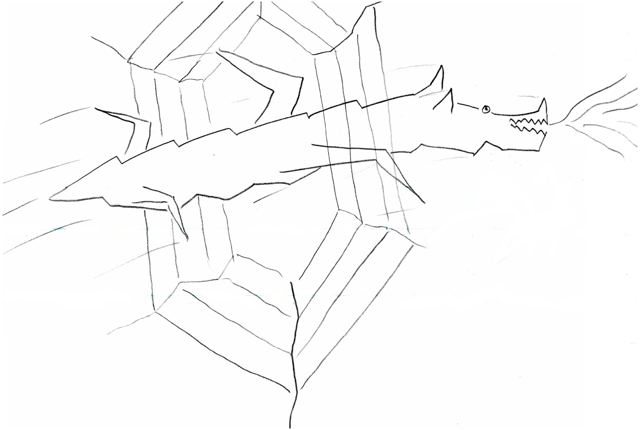

Actual LWP adjustment (PI⟶PD): 0

# Enhanced entrainment begets its own demise (buffering)




Mülmenstädt et al. (revised)

# Global models provide a crosscheck on observations, LES



- Present-day correlation is not climatological causation
- Well studied LES cases may not represent the entire diversity even of subtropical subsidence stratocumulus
- Climate is the mother of all multiscale problems – we need a multiscale way of understanding its behavior

See also: Goren et al. (2024); Mülmenstädt and Wilcox (2021)

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