Sensitivities of precipitation efficiency and cloud-radiative heating in storm-resolving models

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GEWEX UTCC PROES, 19 May 2025

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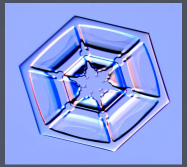
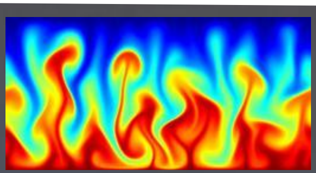
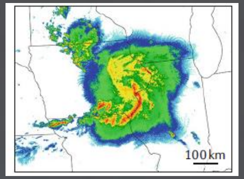
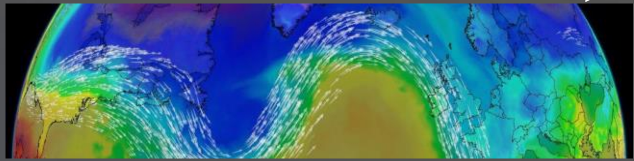
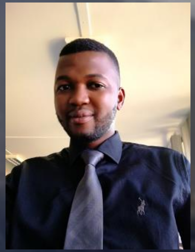
NASA FINESST
80NSSC24K1910
NASA IIP-23 (CHIRP)

Start-up funds
RII IRG 210025

10 µm — 10 mm — 10 m — 10 km — 100 km — 10000 km




Thabo

PART 1: How variable is **precipitation efficiency** across SRMs?

PART 2: How variable is **ice-cloud radiative heating** across SRM settings?


Edgardo

Insets from cmg.soton.ac.uk and www.metoffice.gov.uk NASA, ISS016-E-27426

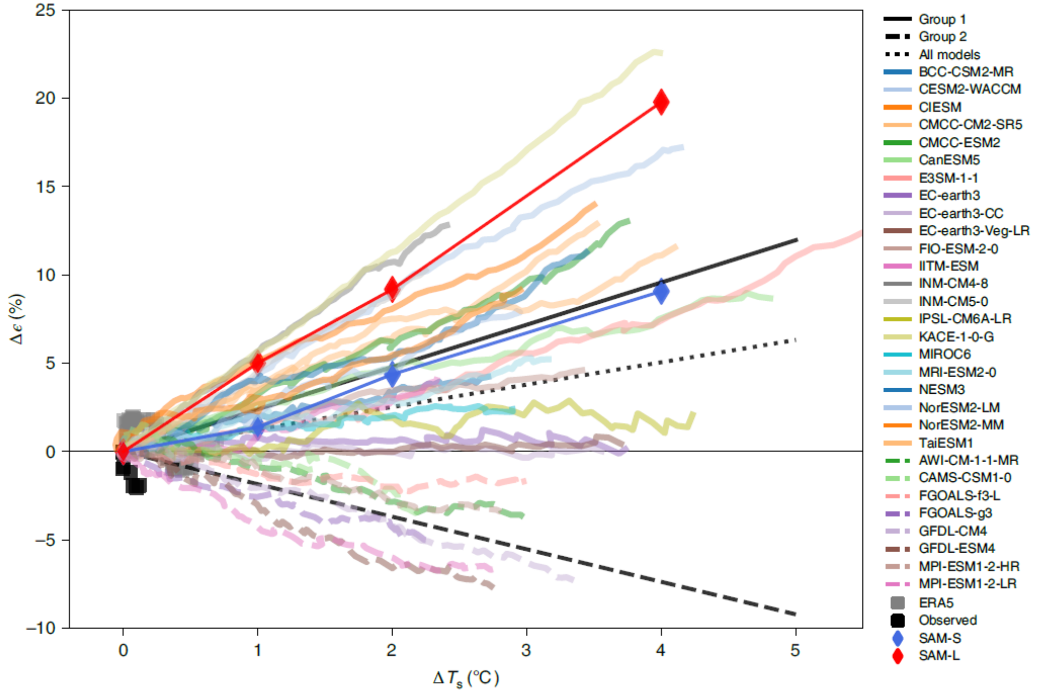
The ratio of surface precipitation and cloud water path can act as a metric of **precipitation efficiency**.

$$\epsilon = \frac{P_s}{\mathrm{CWP}} [\mathrm{units} : \mathrm{s}^{-1}]$$

inverse condensate lifetime

small ϵ^{-1} = short condensate lifetime
large ϵ = high precipitation efficiency

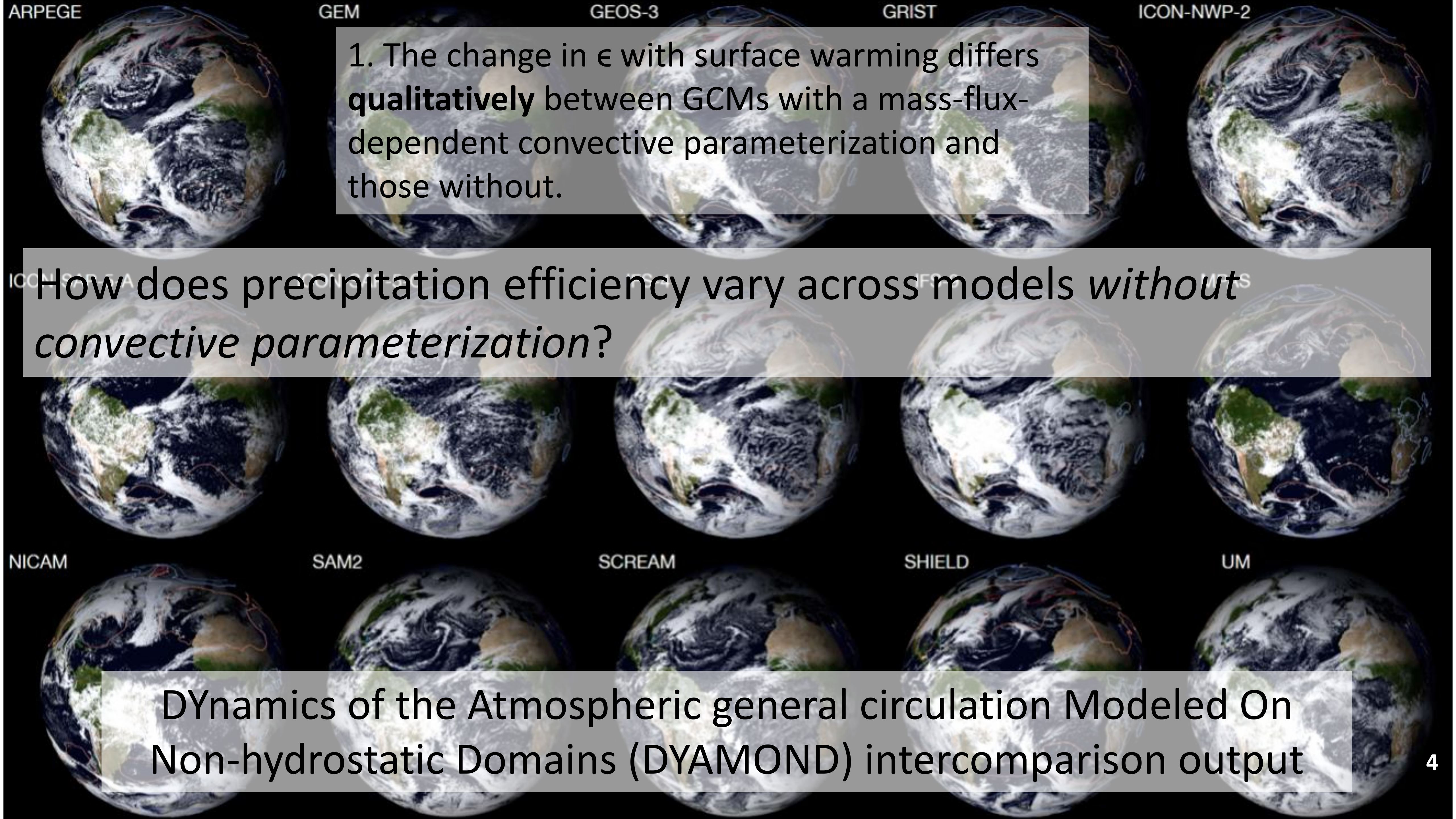
large ϵ^{-1} = long condensate lifetime
small ϵ = low precipitation efficiency



1. The change in ϵ with surface warming differs **qualitatively** between GCMs with a mass-flux-dependent convective parameterization and those without.

2. ϵ can be evaluated from 2D satellite fields (while integrated condensation rates require satellite curtains).

Li et al. (2022) *Nat. Geosci.*

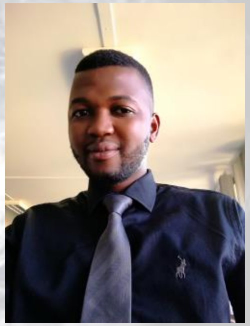


1. The change in ϵ with surface warming differs **qualitatively** between GCMs with a mass-flux-dependent convective parameterization and those without.

How does precipitation efficiency vary across models *without convective parameterization*?

DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains (DYAMOND) intercomparison output

How does precipitation efficiency vary across storm-resolving models?



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DYAMOND summer

1 Aug – 10 Sept 2016

Six models

HadGEM3

FV3

SAM

ICON

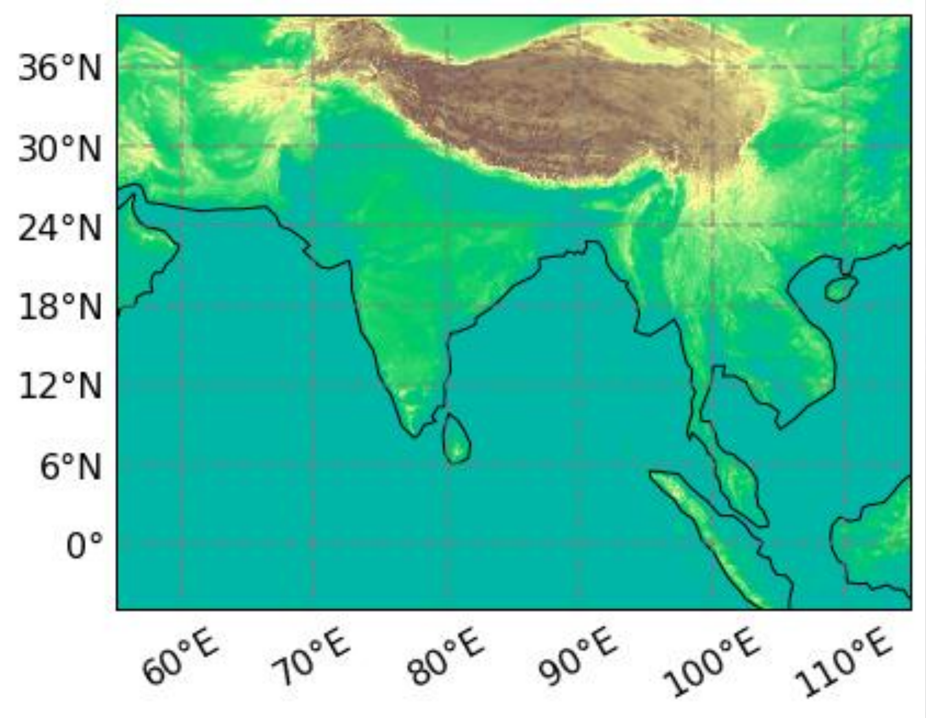
NICAM

GEOS-5

2D output frequency

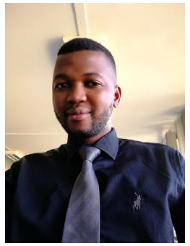
15 min except SAM and ICON (30 min)

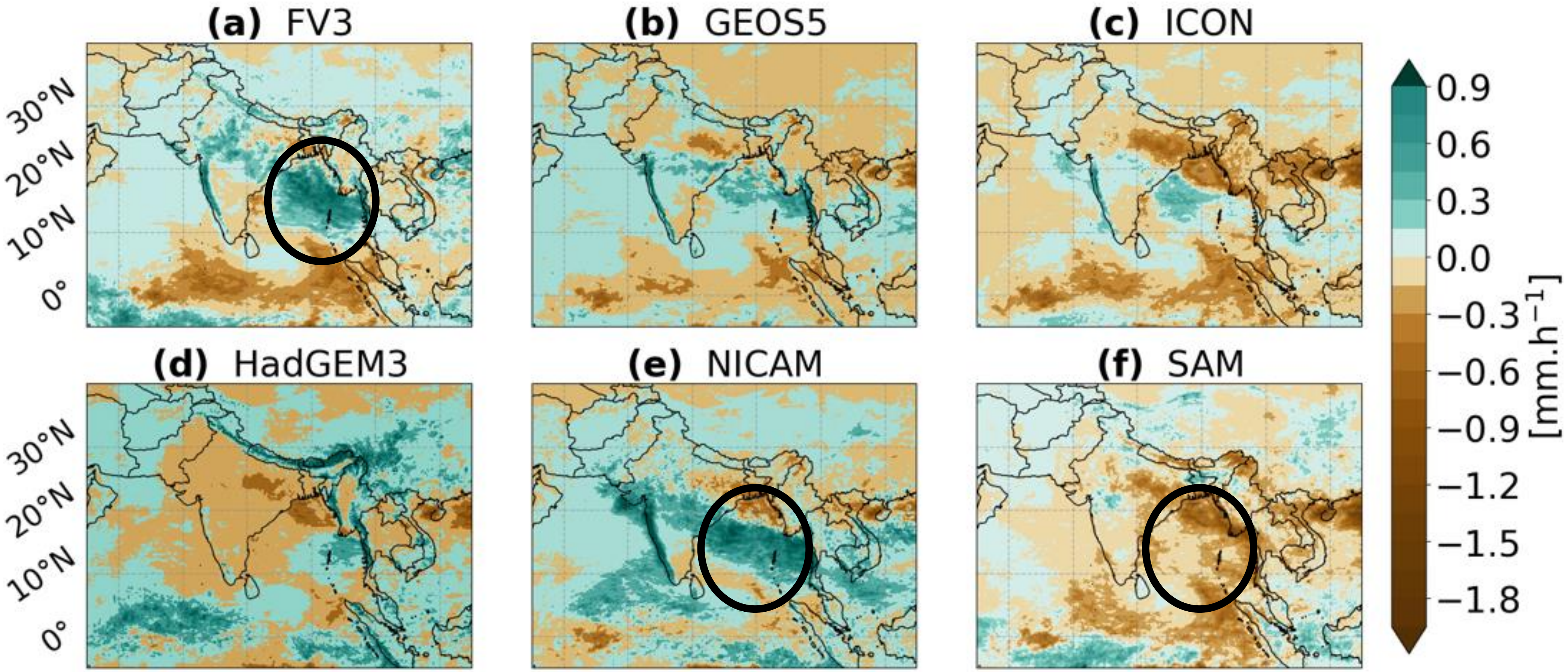
Initial and boundary conditions – ERA5



DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains (DYAMOND) intercomparison output

Precipitation and CWP differences vary widely across the models.





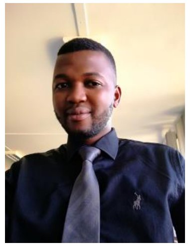
Model-output minus GPM IMERG-observed precipitation intensity

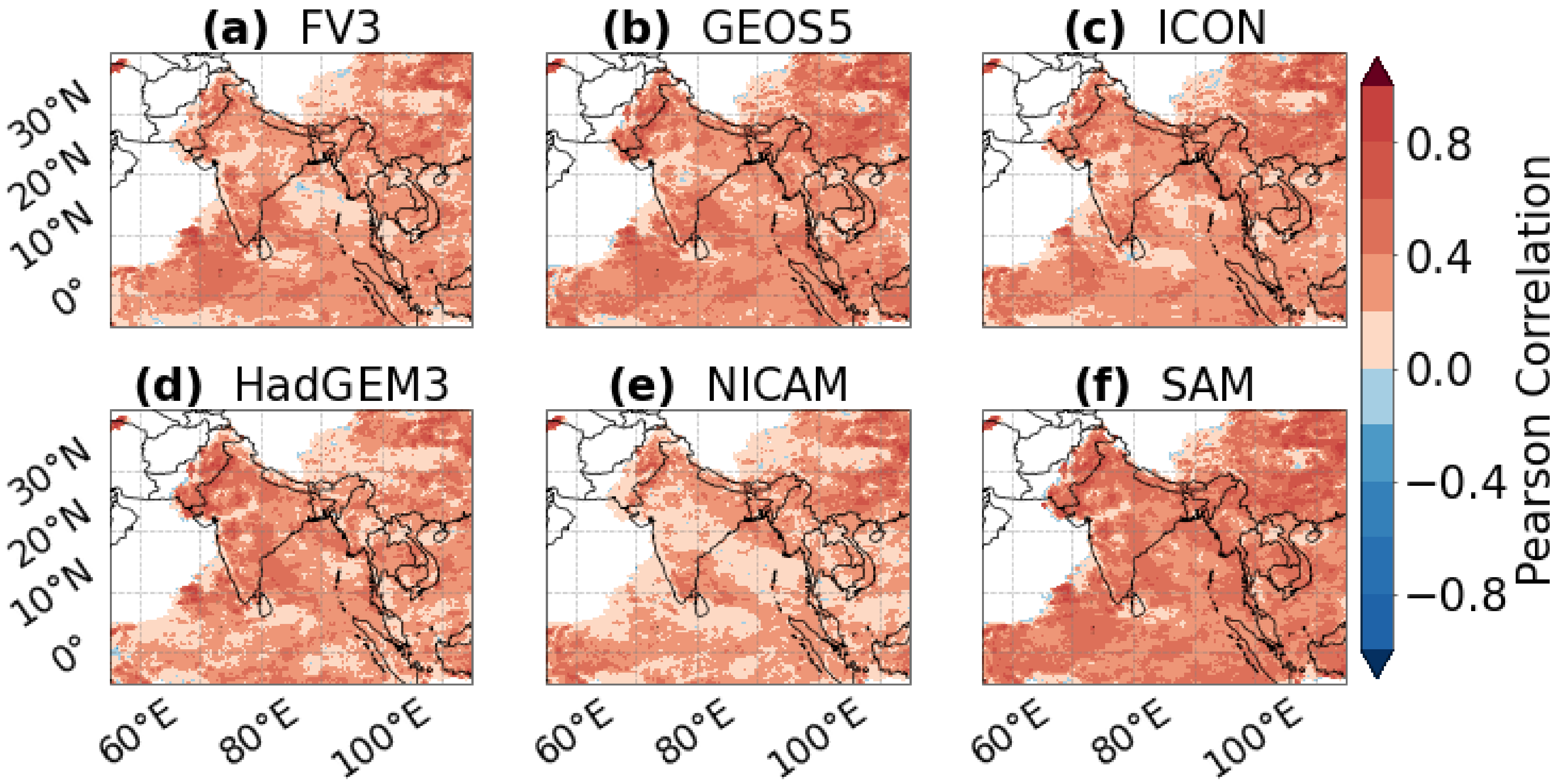
Dry biases are more pervasive in ICON and SAM.

Some of the largest $\dot{P}$ biases occur over the Bay of Bengal, where MCS frequency is high.

Makgoale and Sullivan (2025) *under review*

$\Delta\dot{P}$ correlates strongly with MCS occurrence.

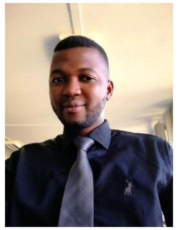


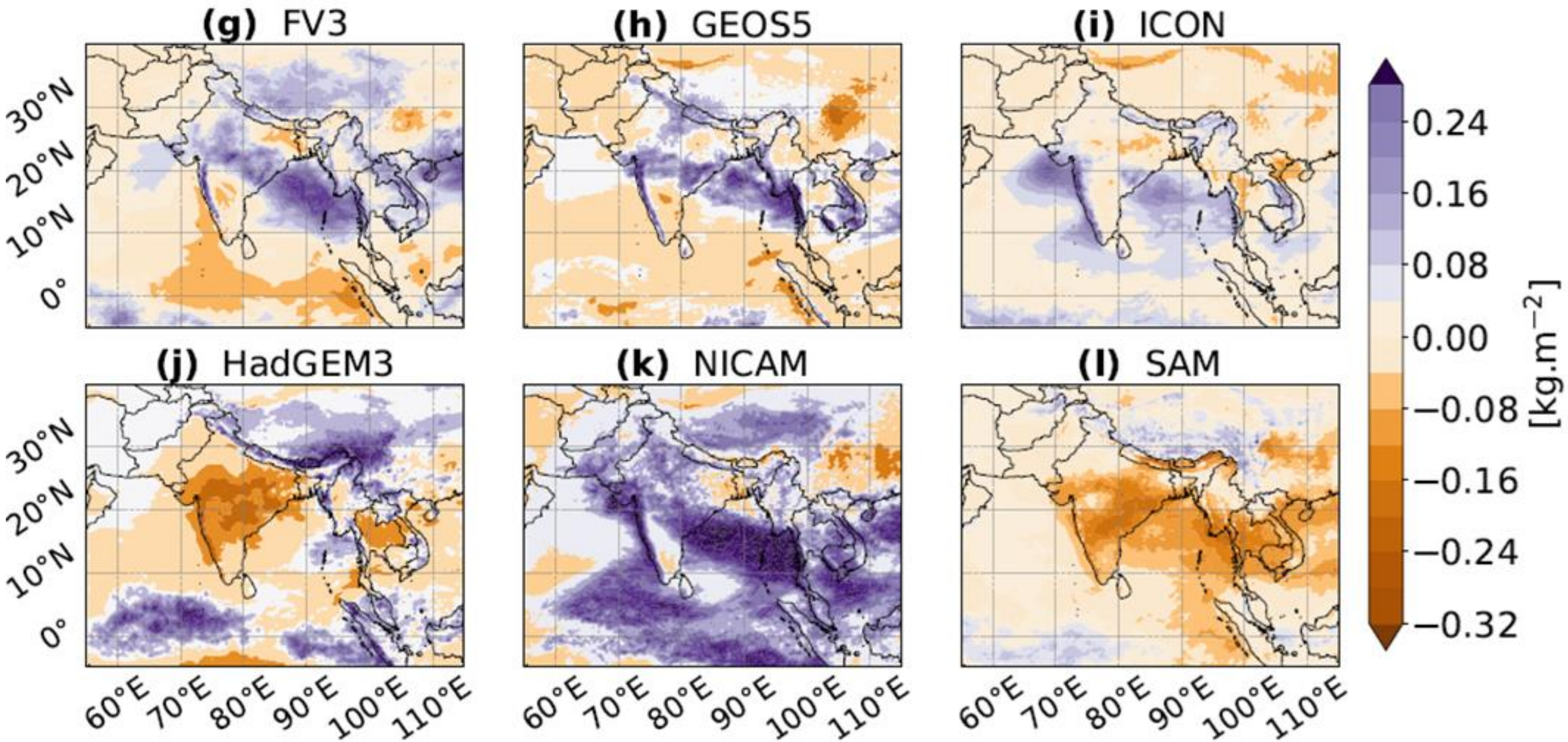


$\Delta\dot{P}$ $\equiv$ Model-output minus GPM IMERG-observed precipitation intensity

MCS occurrence taken from the FLEXTRKR convective tracking dataset

Precipitation and CWP differences vary widely across the models.





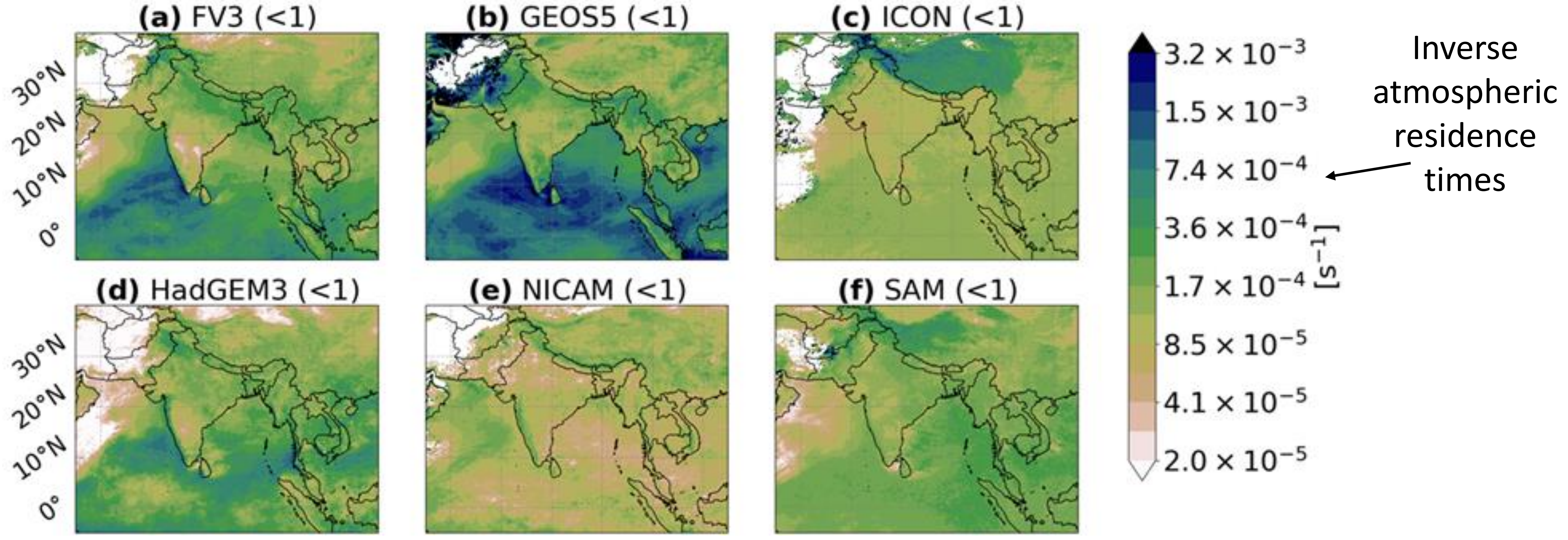
Model-output minus ERA-5 reanalysis CWP

Differences in CWP correlate weakly with those in $\dot{P}$ (*r* = 0.062).

But models with smaller $\dot{P}$ differences also have smaller CWP differences.

Makgoale and Sullivan (2025) *under review*

Models also show very different conversion rates of condensate to $\dot{P}$.



$$\epsilon = \frac{< \dot{P} >}{< \mathrm{CWP} >} \qquad \frac{[\mathrm{kg\ m^{-2}\ s^{-1}}]}{[\mathrm{kg\ m^{-2}}]}$$

Construct this ratio from time-averaged data and for moderate rainfall events $\dot{P} < 1$ mm h^{-1}

Makgoale and Sullivan (2024) *under review*

Li et al. 2022 *Nat. Geosci.*

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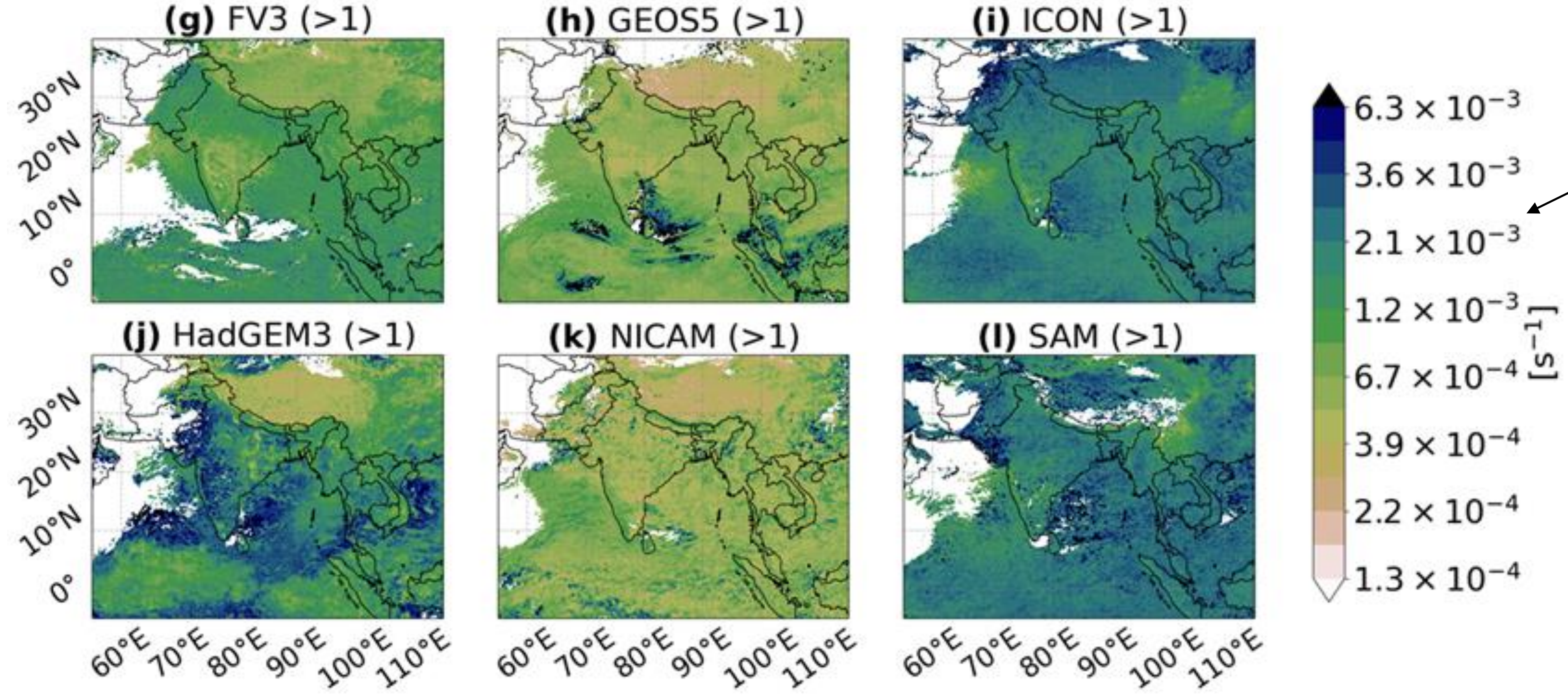


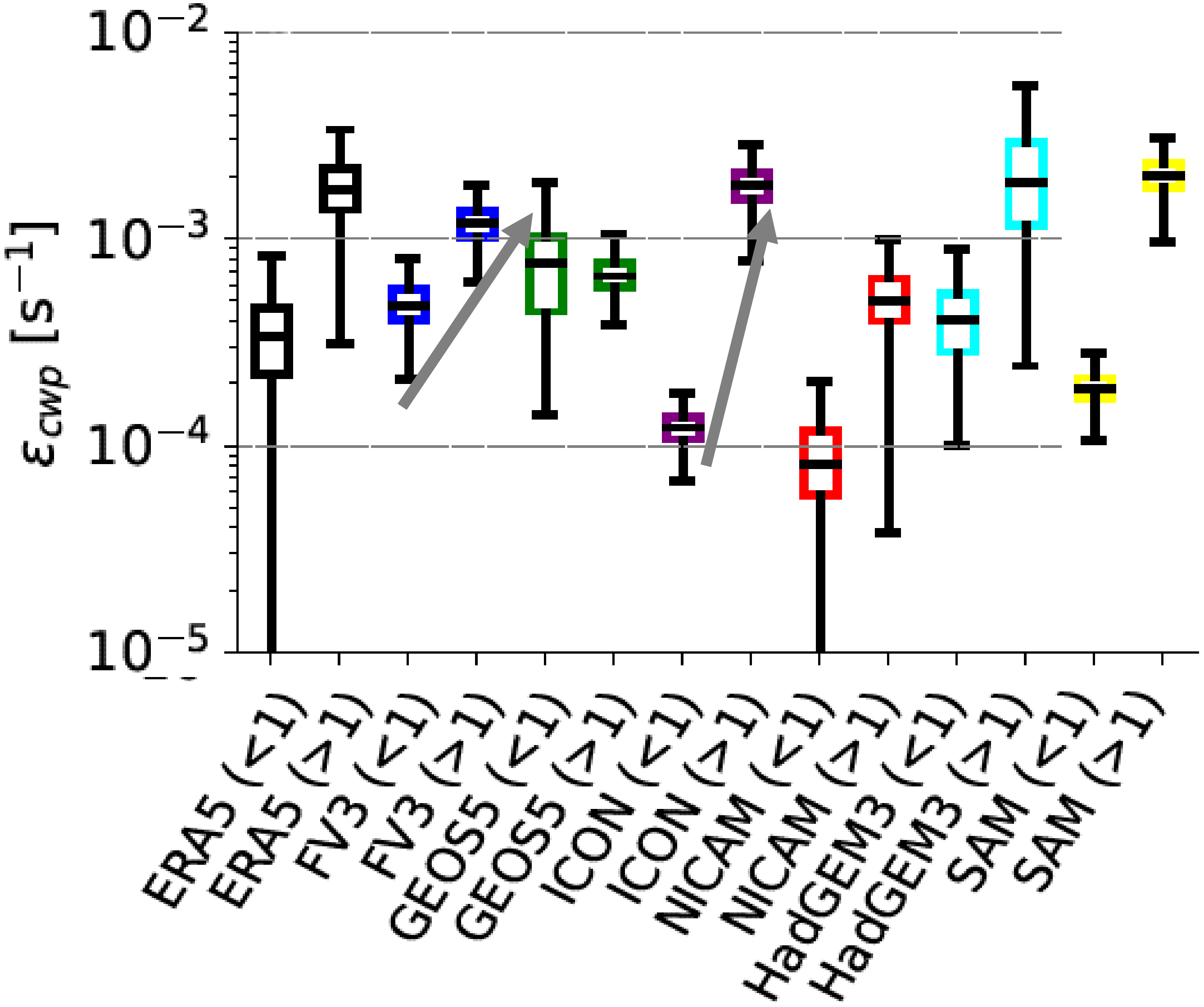
Much shorter condensate lifetimes

$$\epsilon = \frac{< \dot{P} >}{< \mathrm{CWP} >}$$

rainfall events $\dot{P} > 1$ mm h^{-1}

- Somewhat less spatial variability in ϵ for intense events
- Much more *intermodel* variability than *intramodel* variability in ϵ for intense events

Somewhat less spatial variability in ϵ for intense events.
Much more intermodel spread than intramodel spread.

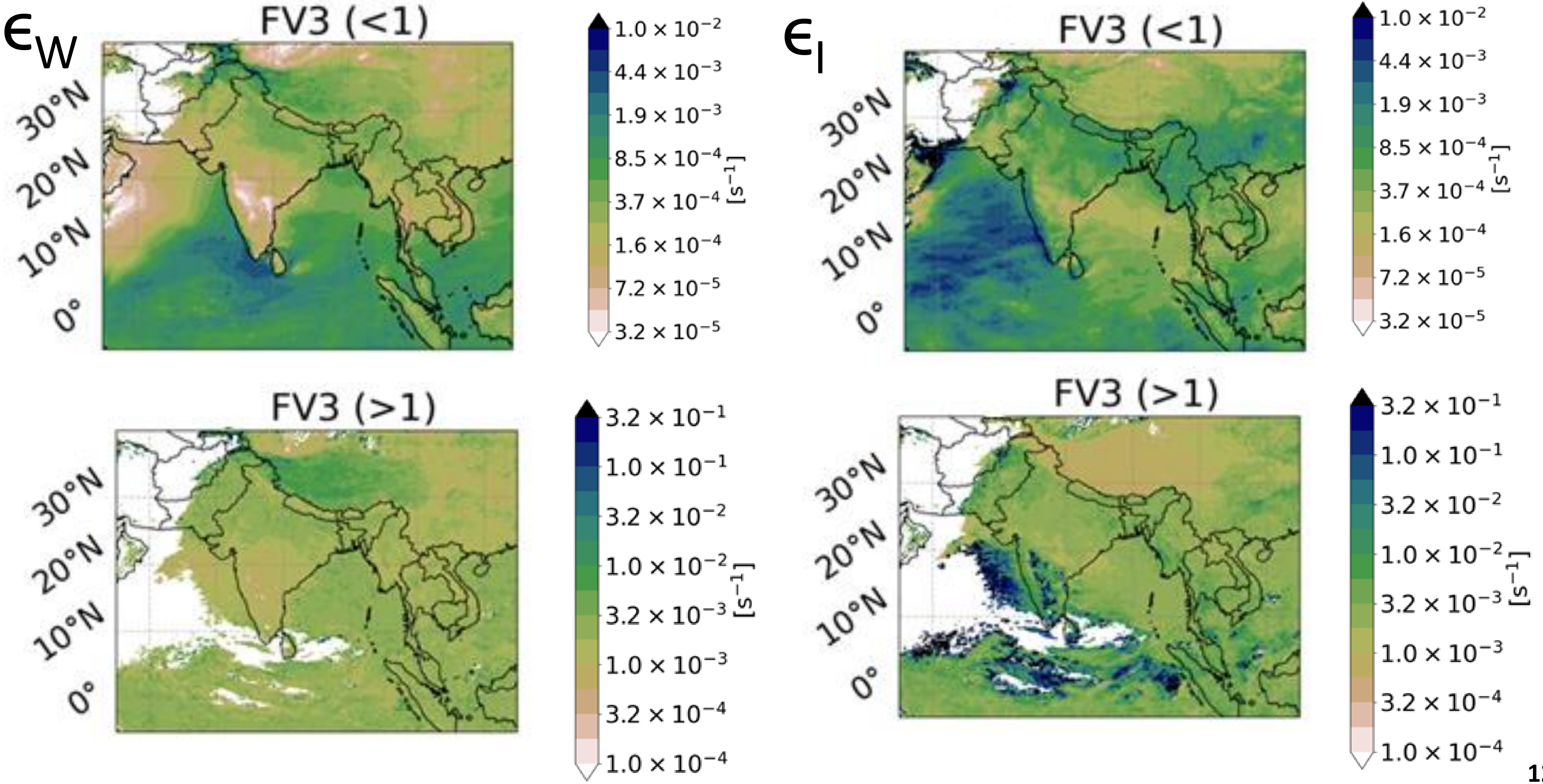


Large variation in how much ϵ changes with event intensity.

Factor of 5 – FV3
Factor of 15 - ICON

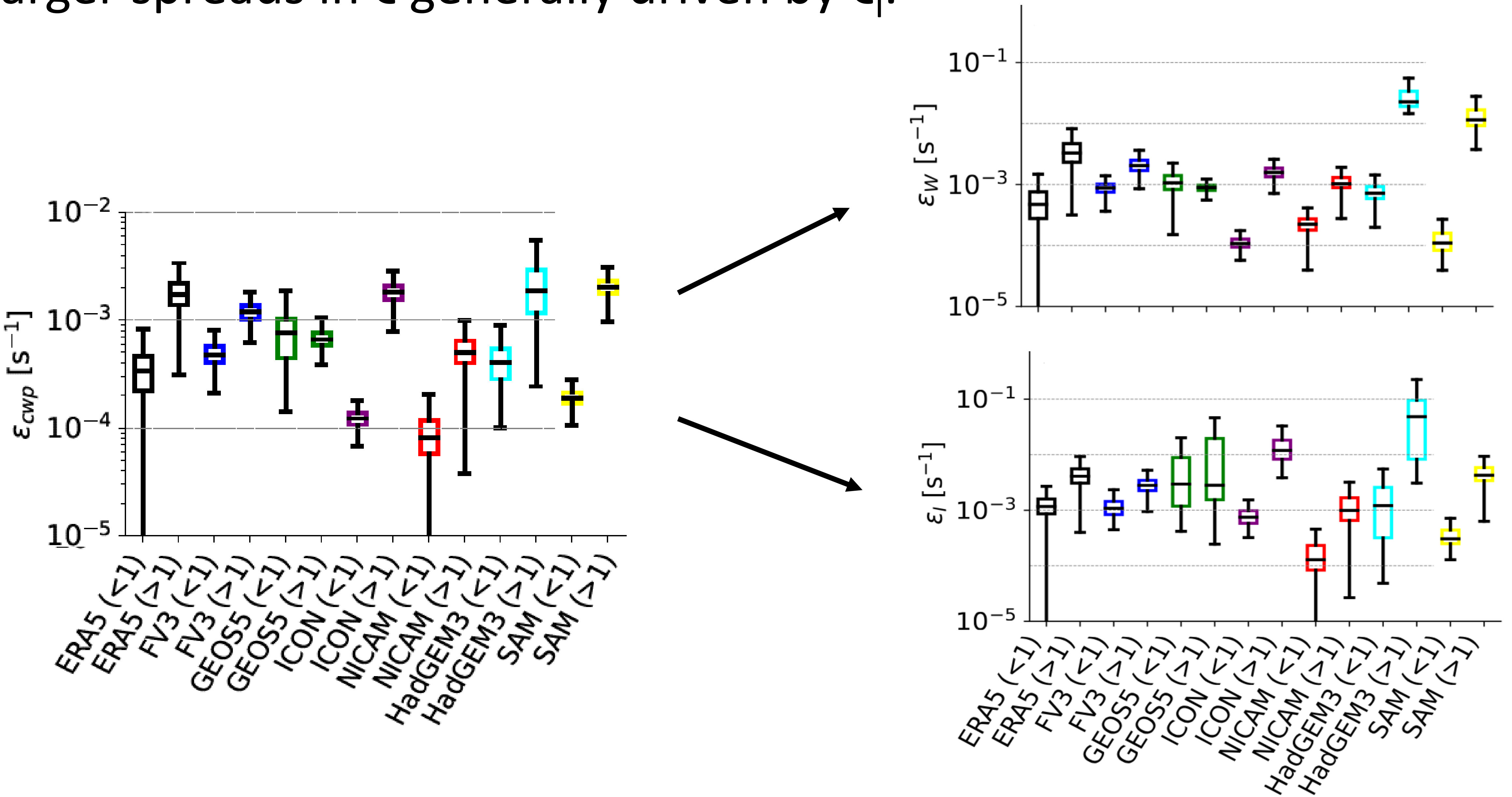
Continued impact of uncertain subgrid-physics even when deep convection is resolved

We also **phase partition** the precipitation efficiency metric.



Mean values of ϵ and the shift with event intensity generally follow ϵ_w.

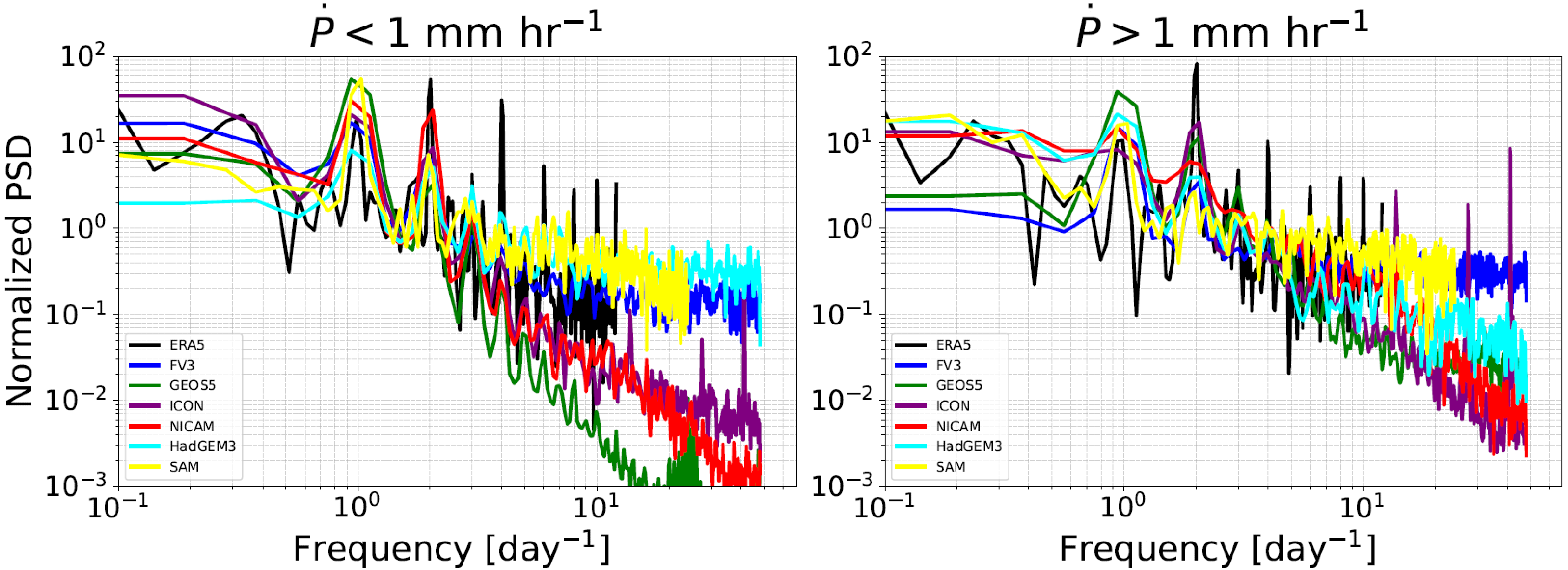
Larger spreads in ϵ generally driven by ϵ_l.



We can also consider time variability in ϵ.

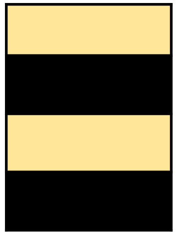
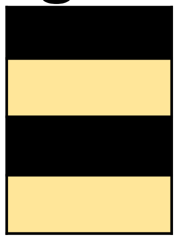
We calculate ϵ over different time scales.

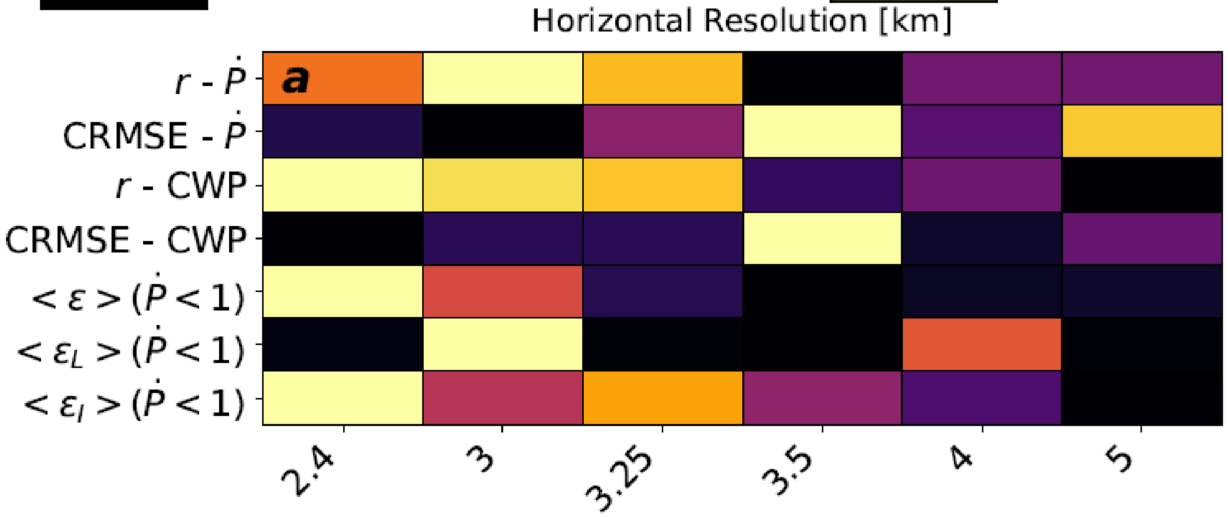
We construct power spectra of ϵ.

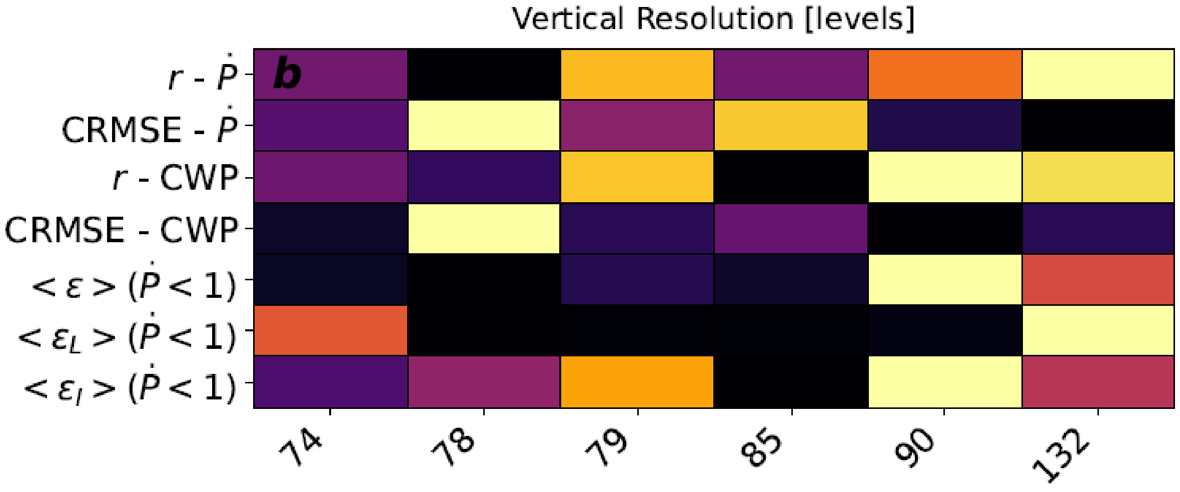


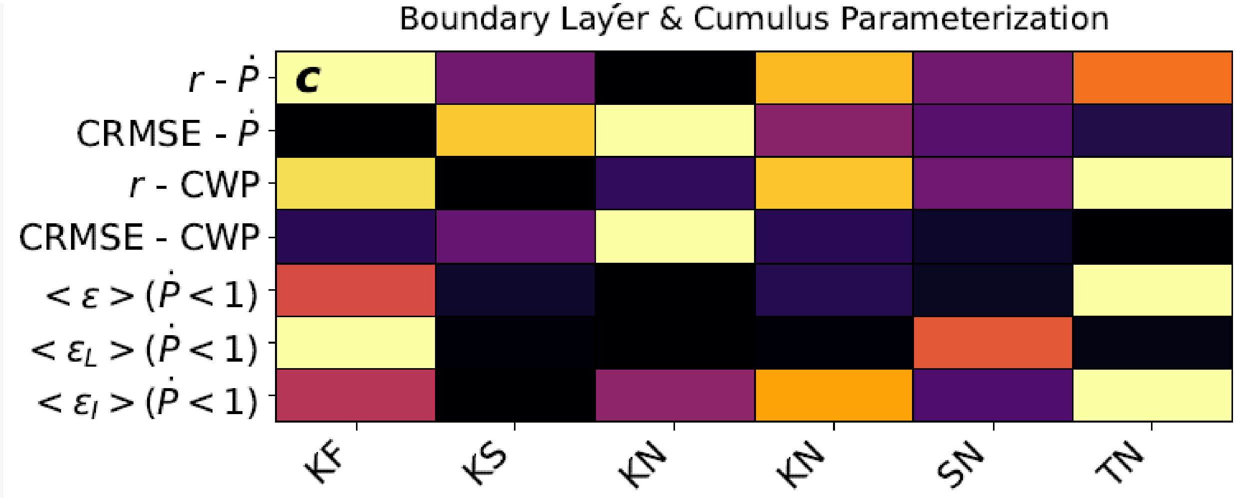
Large differences between the SRMs in their spectral roll-off, especially for moderate events.

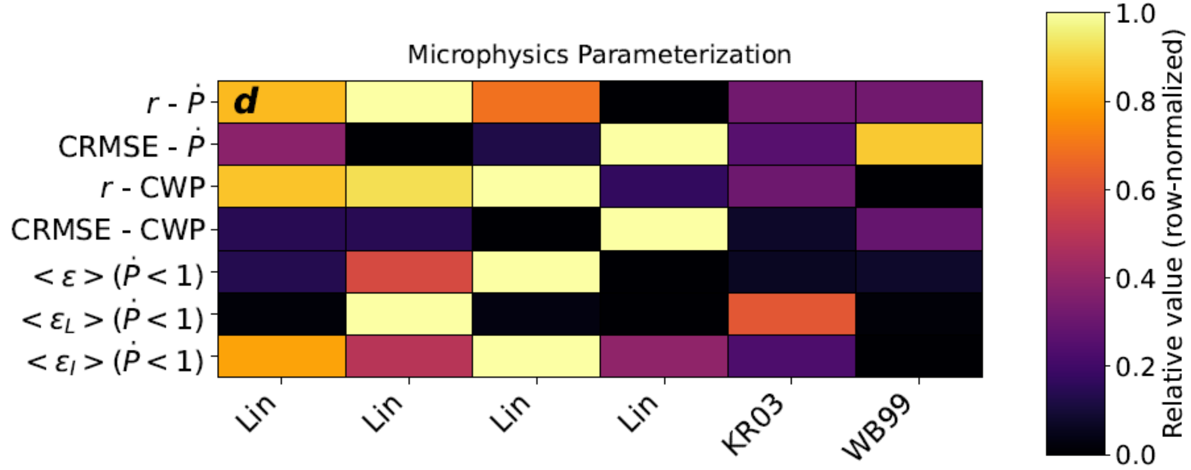
We summarize our findings in heatmaps of model performance and settings.

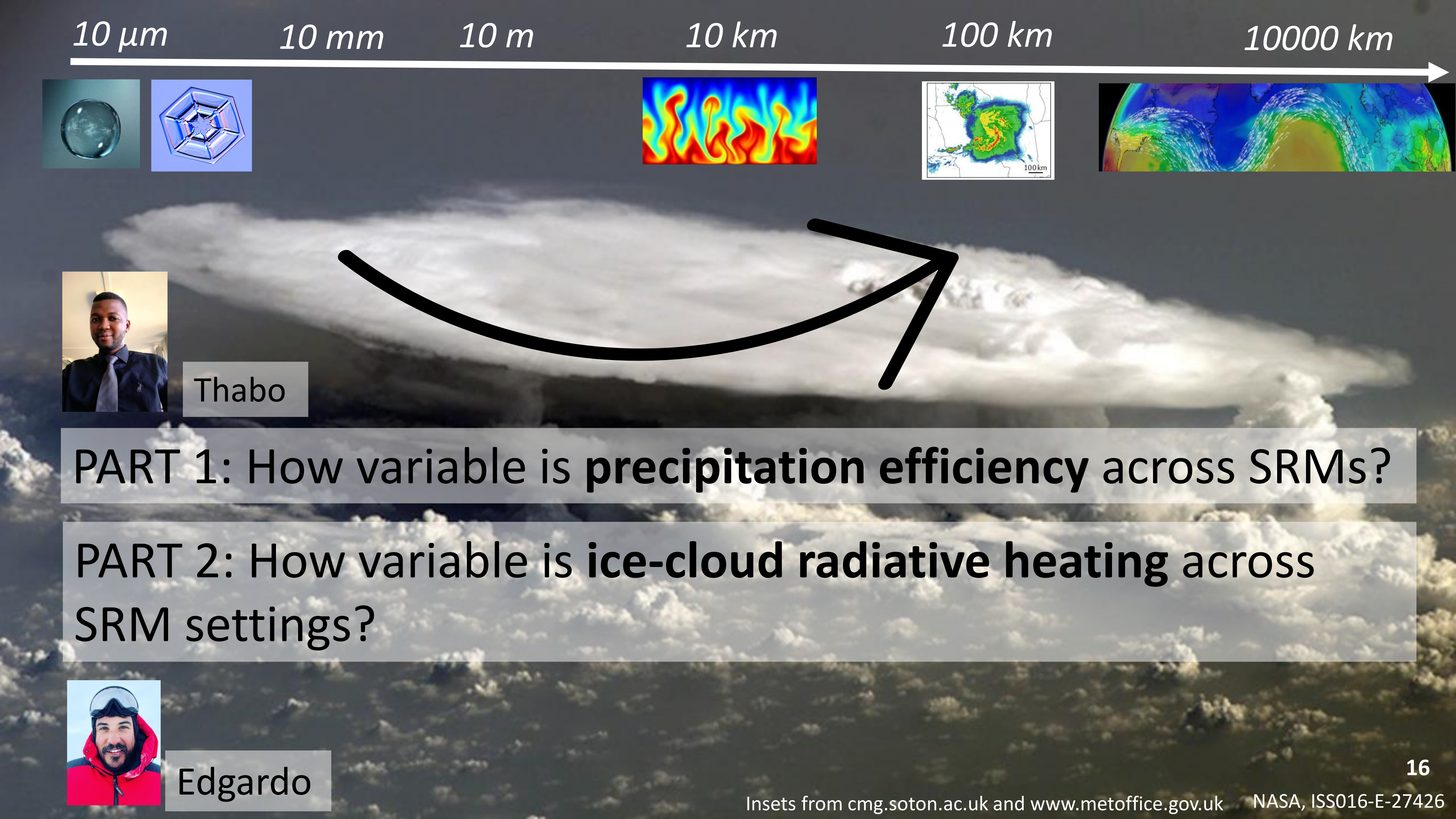
 = good performance  = poor performance










10 µm
10 mm
10 m
10 km
100 km
10000 km
100 km
Thabo
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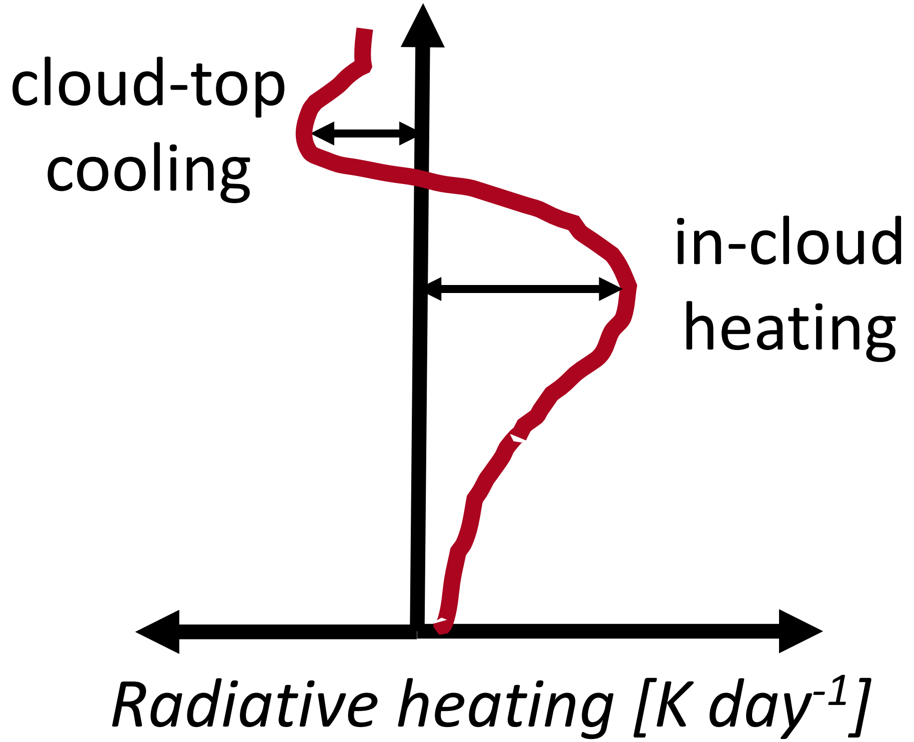
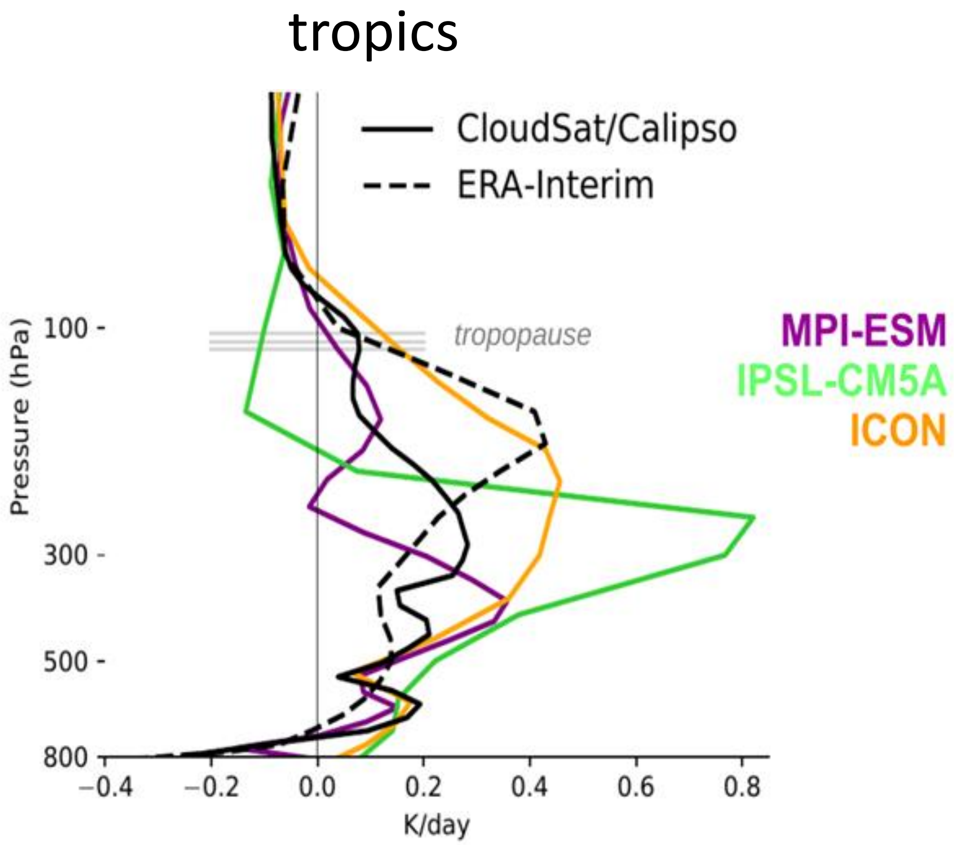
PART 2: How variable is **ice-cloud radiative heating** across SRM settings?
Edgardo
16
Insets from cmg.soton.ac.uk and www.metoffice.gov.uk
NASA, ISS016-E-27426

Tropical upper-level cloud-radiative heating is not well-constrained.

$$\mathrm{CRH} = \frac{g}{c_p}\frac{\partial F}{\partial p}$$

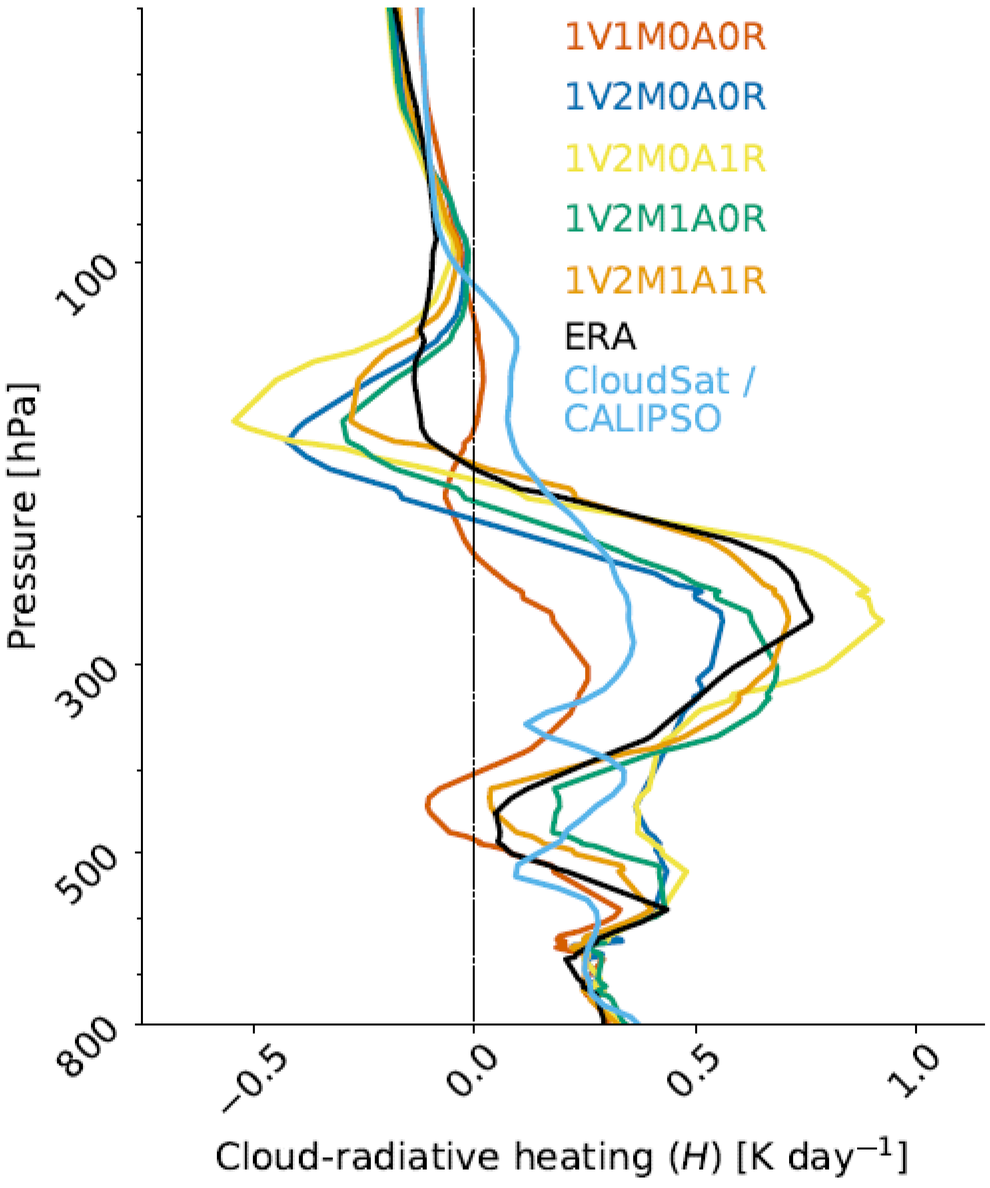




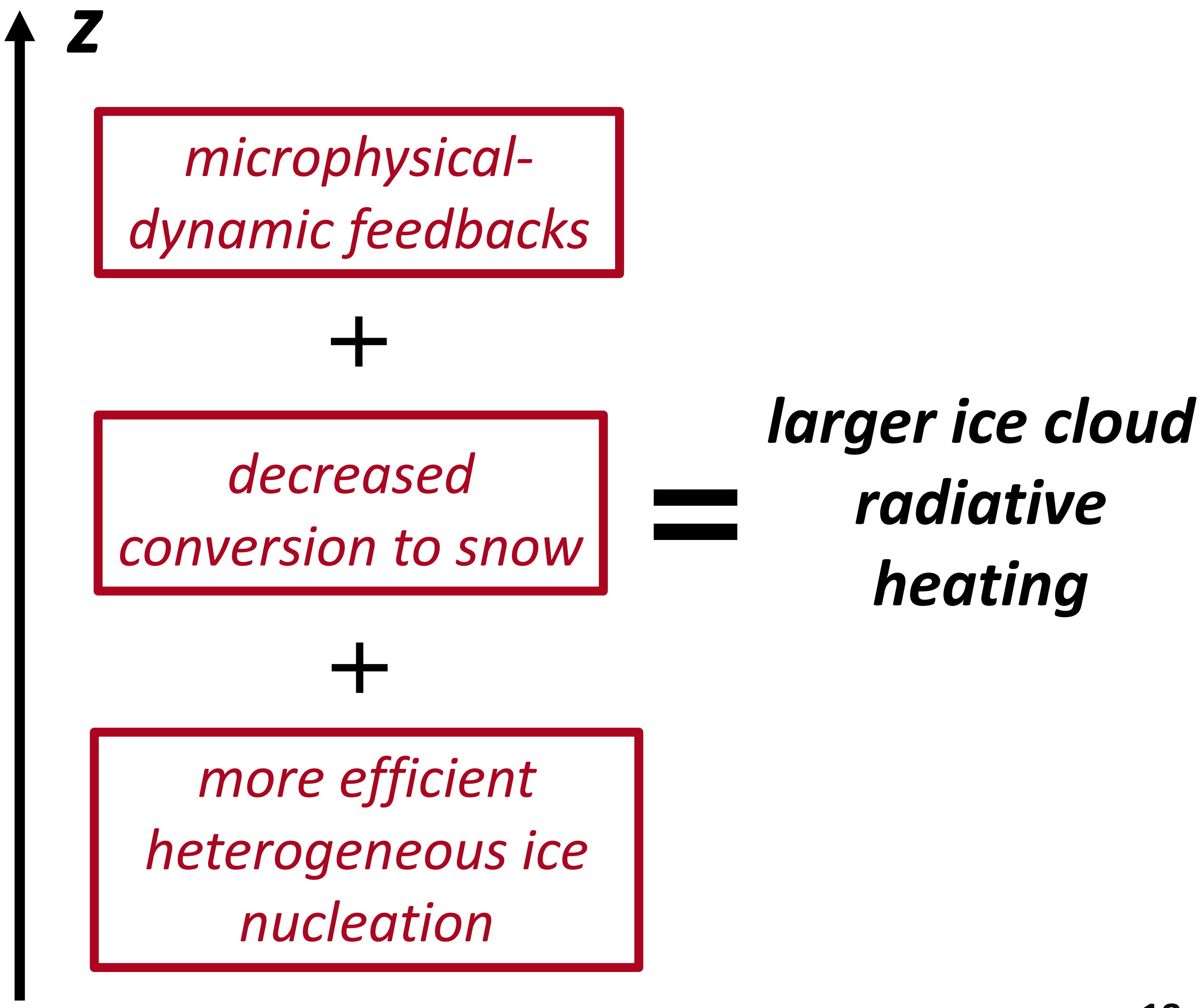
Voigt et al. 2019

How sensitive is this cloud-radiative heating to the parameterization of ice (physics / optics) in the model?

Ice microphysics strongly modulates upper-level CRH.

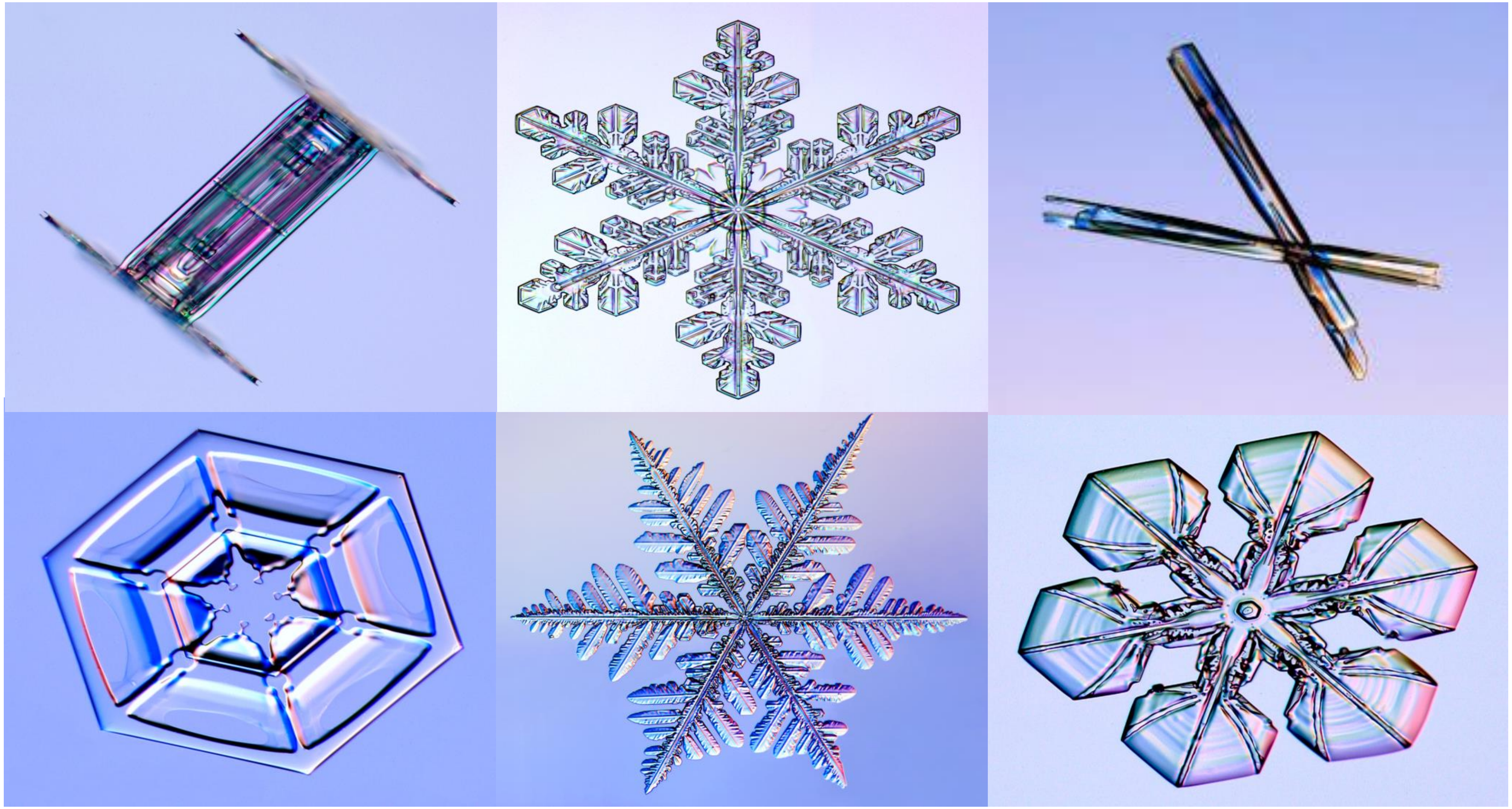


Sullivan and Voigt (2021). *Comms. Earth & Env.*



Ice microphysics strongly modulates upper-level CRH.

What about the model formulation of ice optics?



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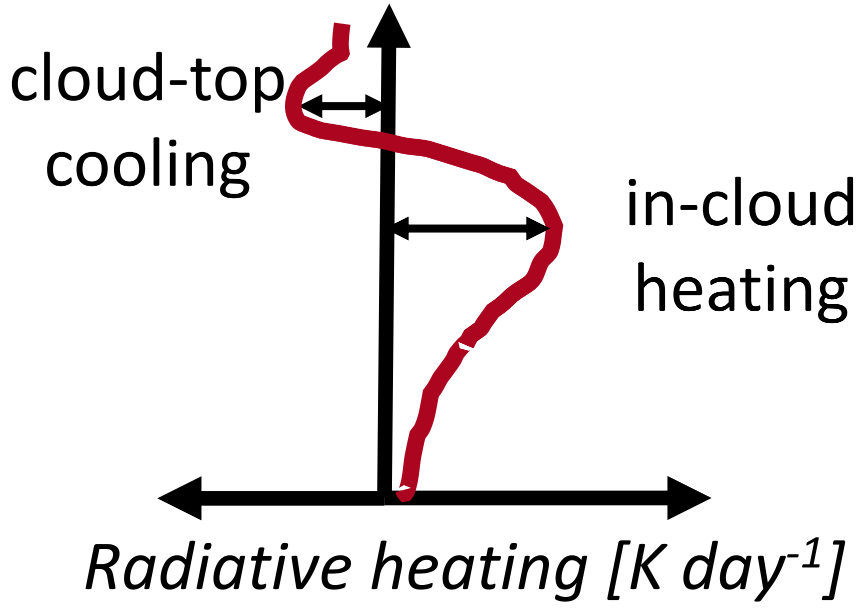
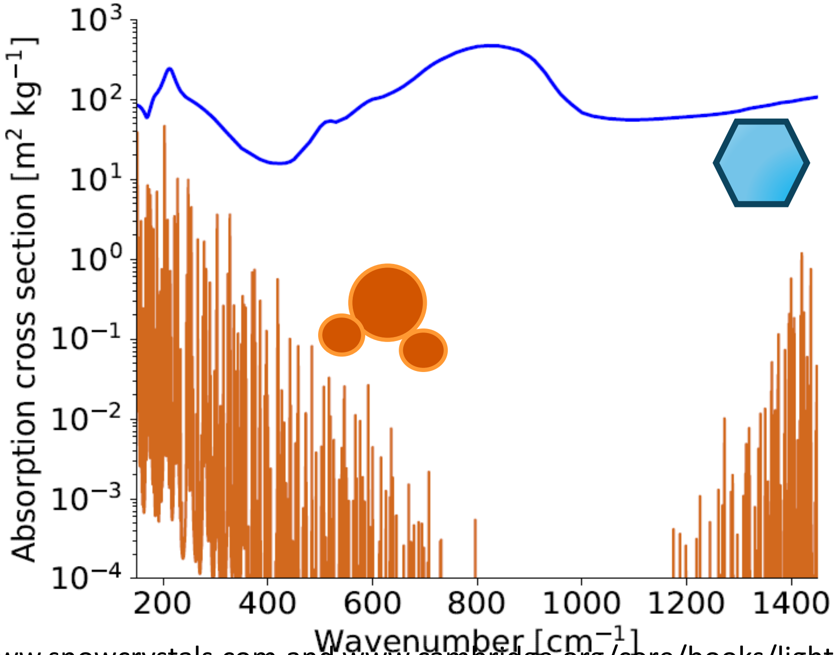
Images from www.snowcrystals.com

How sensitive is cloud-radiative heating to ice optical properties?





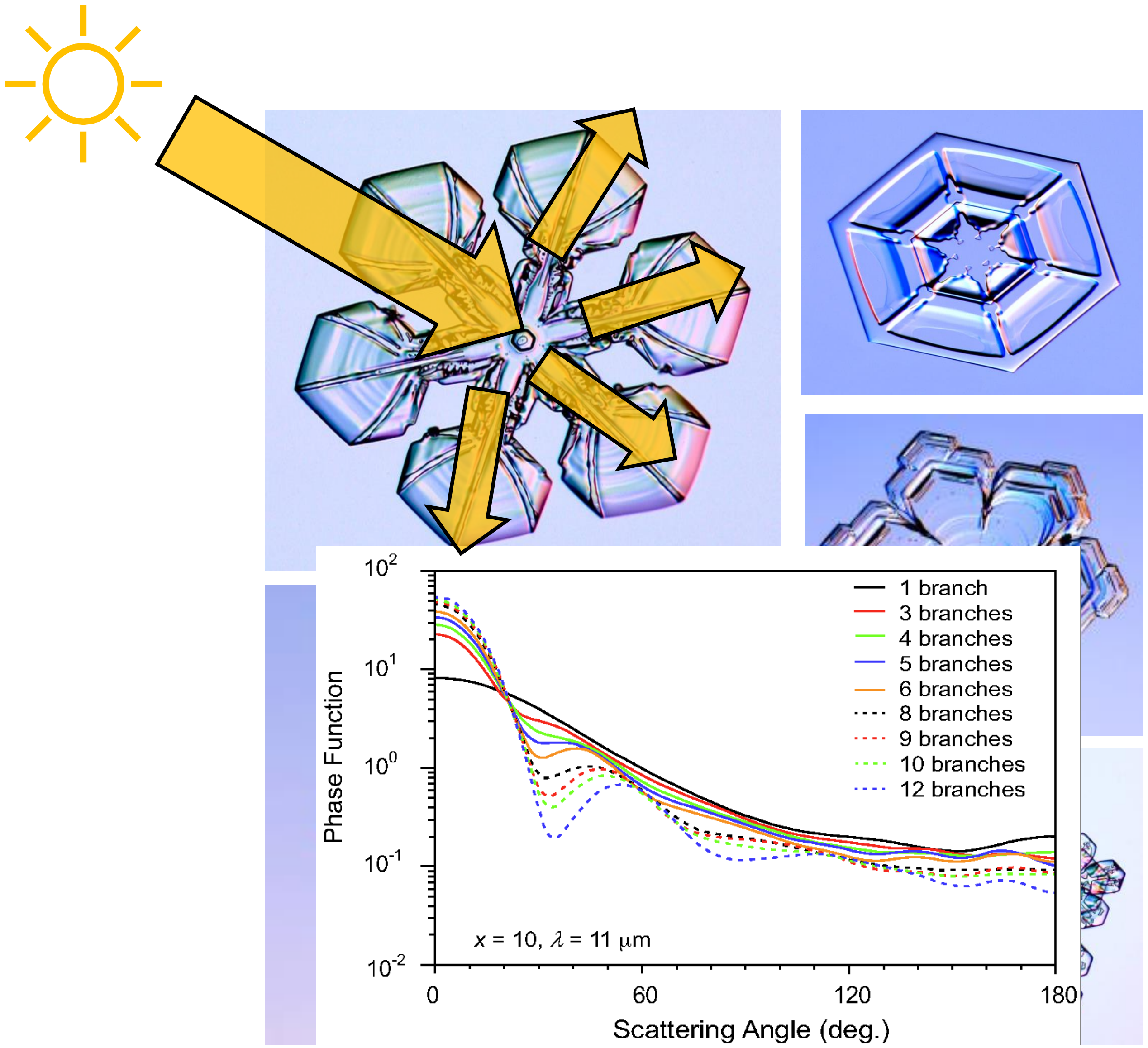
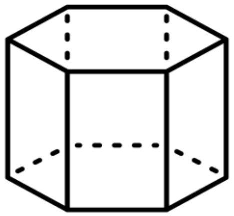


Image from wwww.snowcrystals.com and www.cambridge.org/core/books/light-scattering-by-ice-crystals

How sensitive is cloud-radiative heating to ice optical properties?

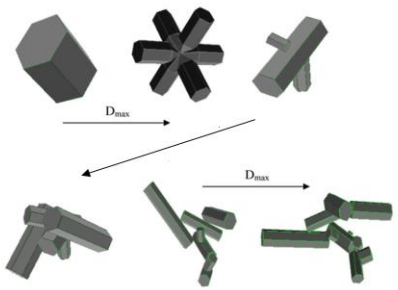
“hierarchy” of optical schemes

(a)



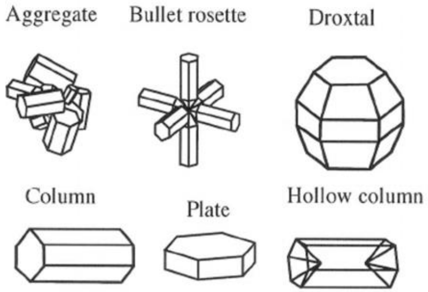
Fu 1996 (SW) and Fu, Yang & Sun 1998 (LW)

(b)



Baran et al. 2016

(c)



Yi et al. 2013

\+

ecRad radiative transfer scheme

idealized ice clouds

IWP r_eff T_top

T_bottom T_mid

F_LW,up,clr F_SW,up,clr

F_LW,down,clr F_SW,down,clr

F_LW,up,cld F_SW,up,cld

F_LW,down,cld F_SW,down,cld

$$\mathrm{CRH} = \frac{g}{c_p}\frac{\partial F}{\partial p}$$

How sensitive is cloud-radiative heating to ice optical properties?

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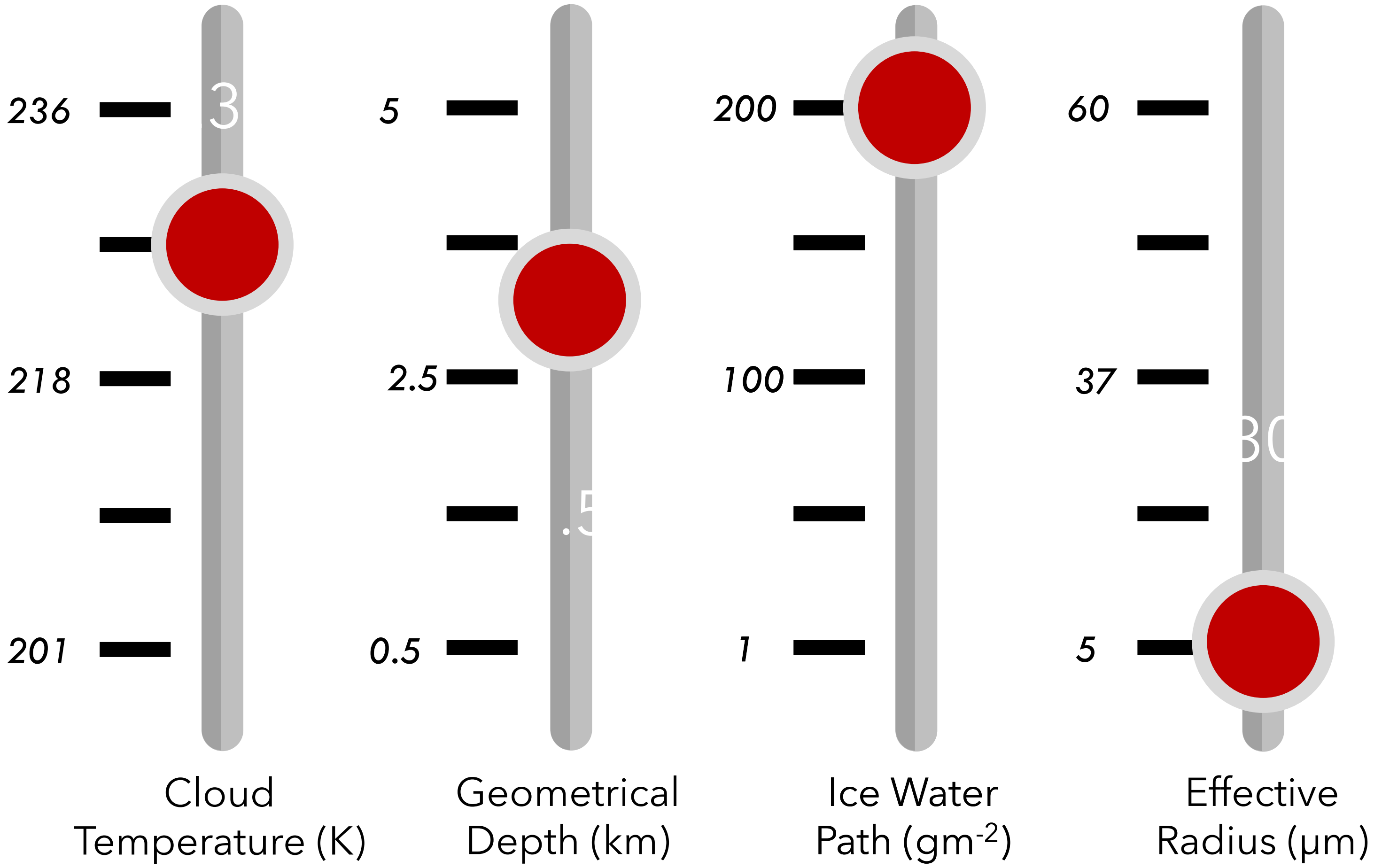
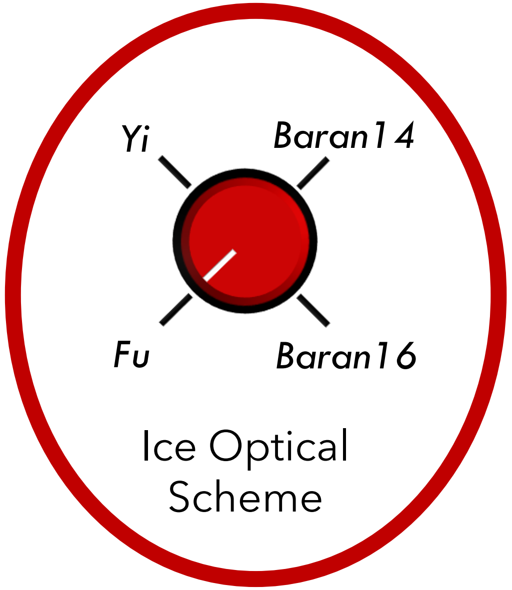
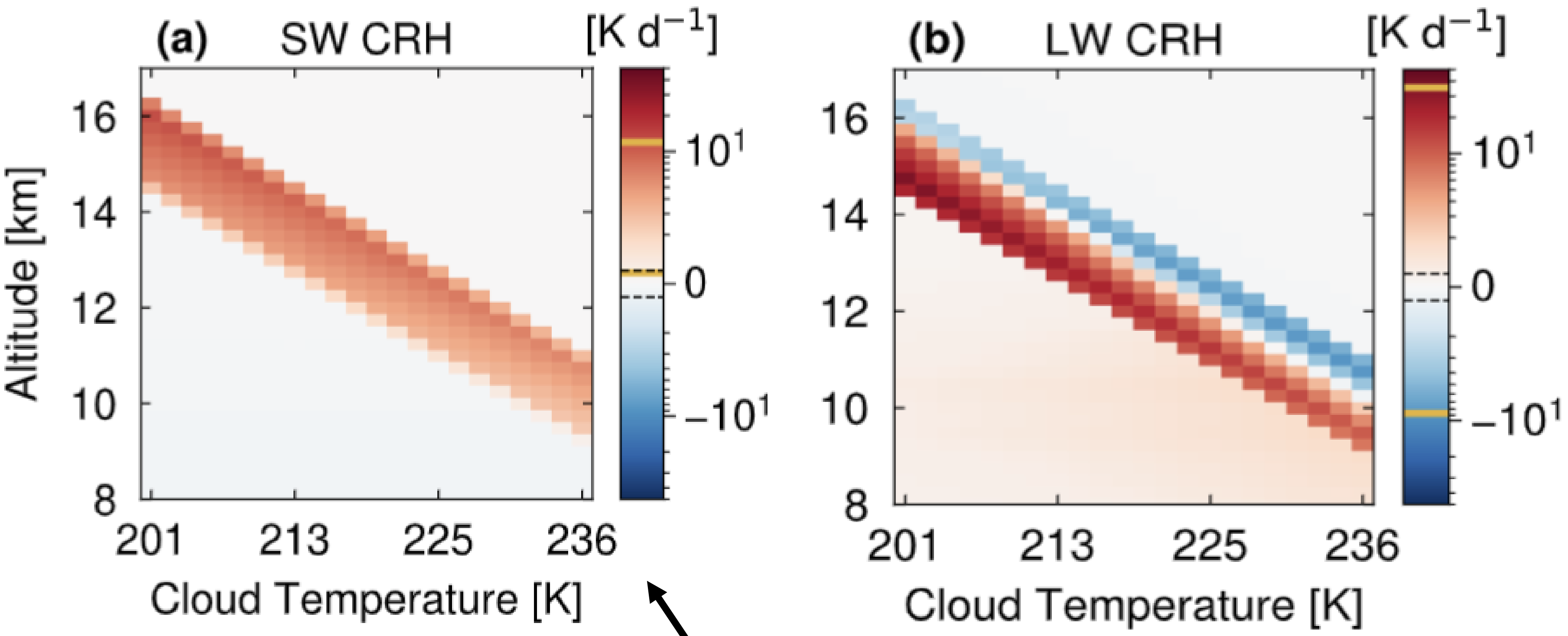
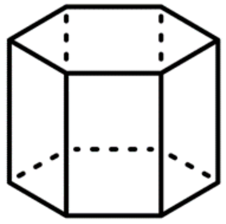




We visualize the output cloud-radiative heating with a *heating rate matrix*.



Height of cloud "injection" with fixed ice water path



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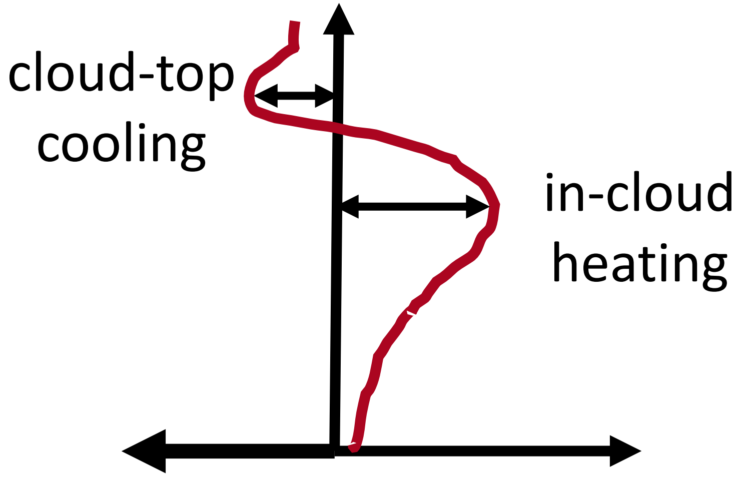

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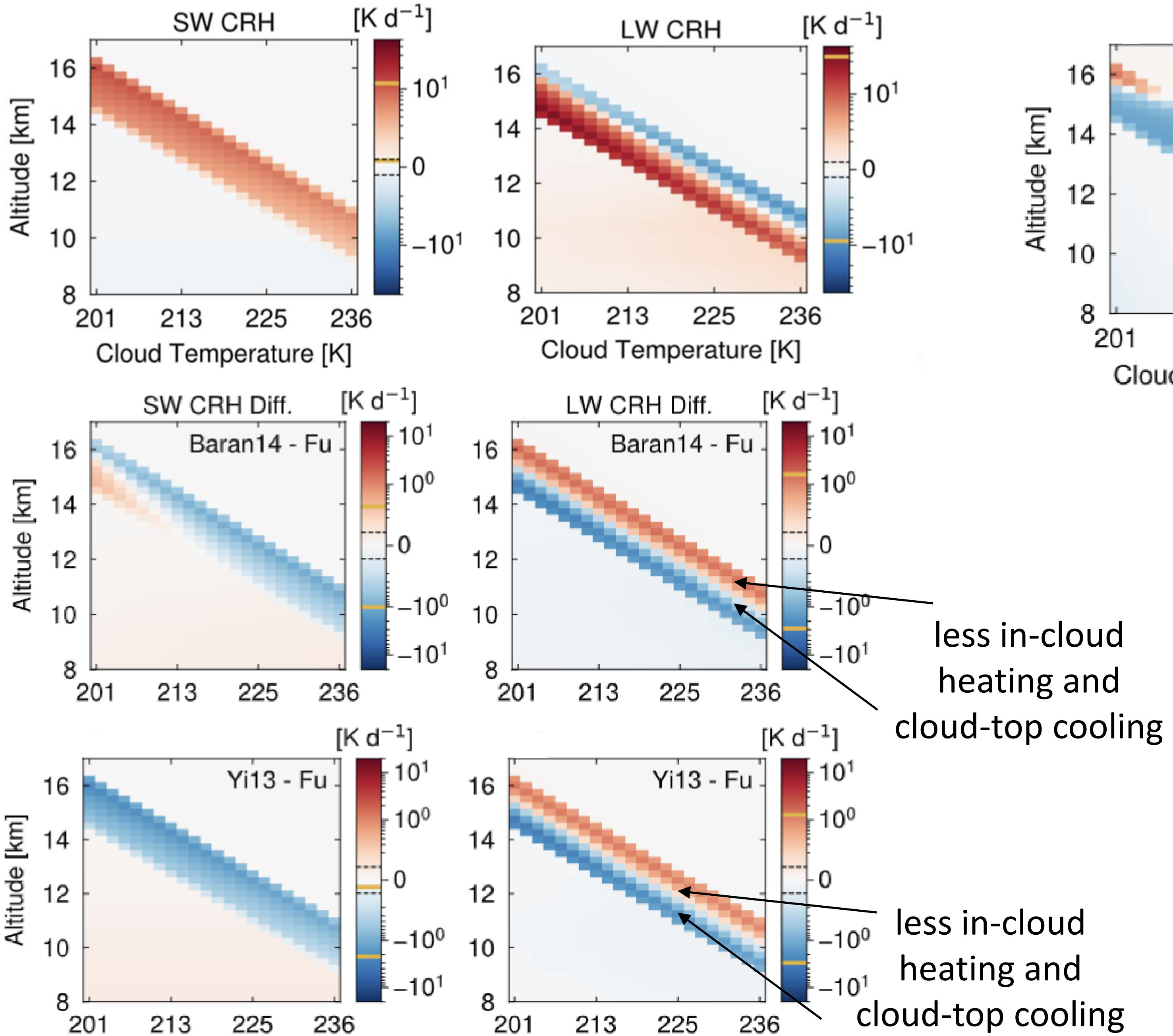
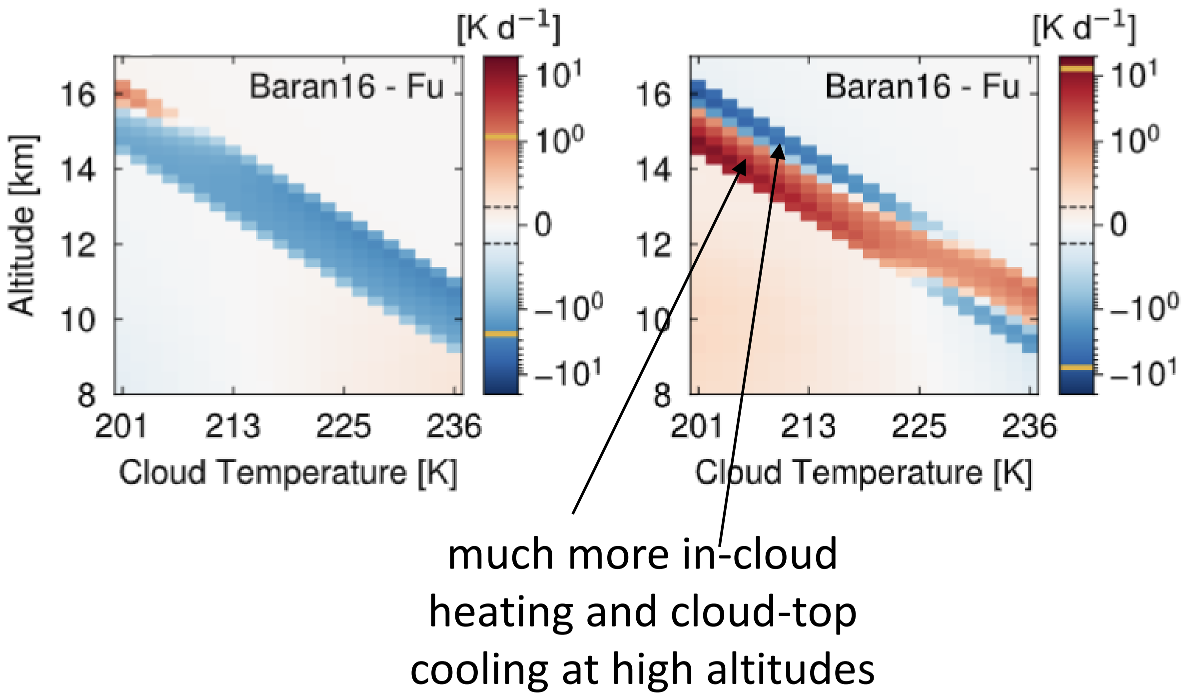


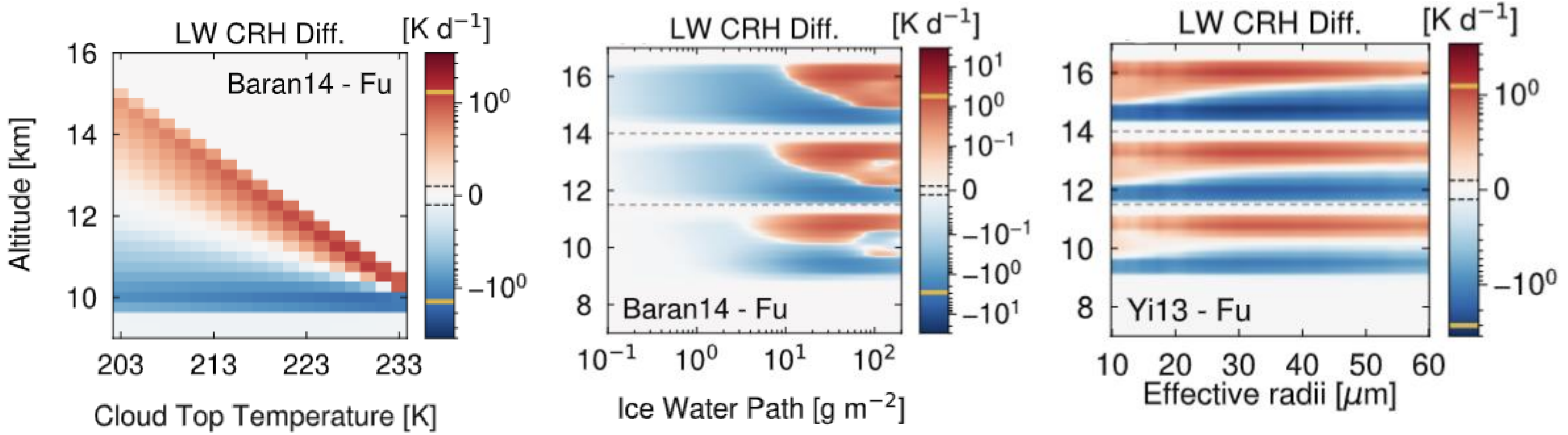


Including temperature dependence in the optical scheme intensifies CRH at high altitudes.

Including ice complexity in the optical scheme weakens CRH across all altitudes.

Sepúlveda Araya, Sullivan, and Voigt (2025) Accepted at *ACP*

We visualize the output cloud-radiative heating with a *heating rate matrix*.



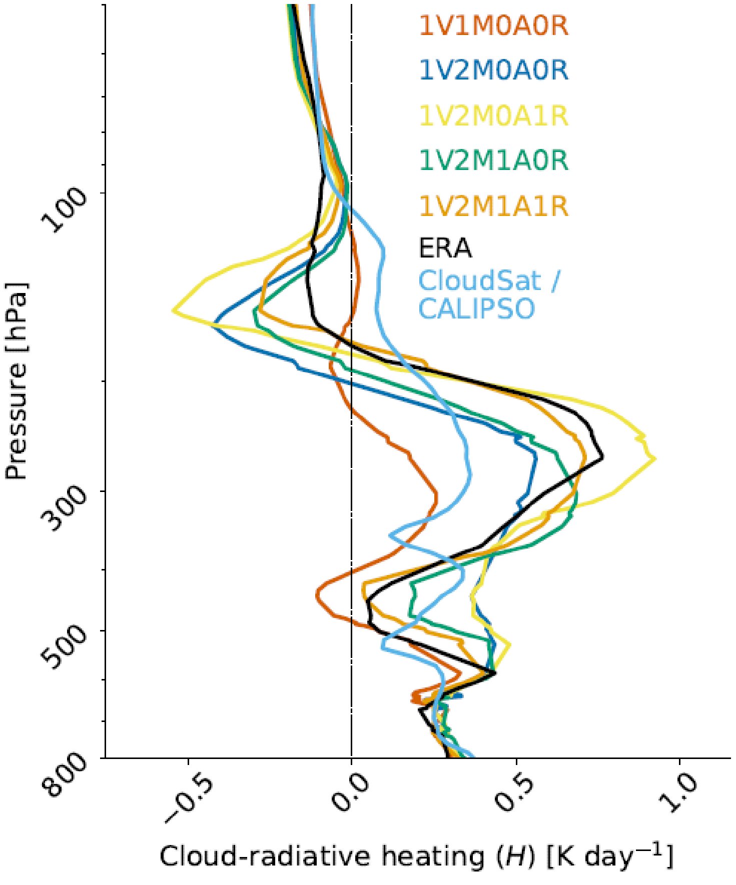
Including temperature dependence in the optical scheme intensifies CRH at high altitudes.

Including ice crystal complexity in the optical scheme weakens CRH across all altitudes.

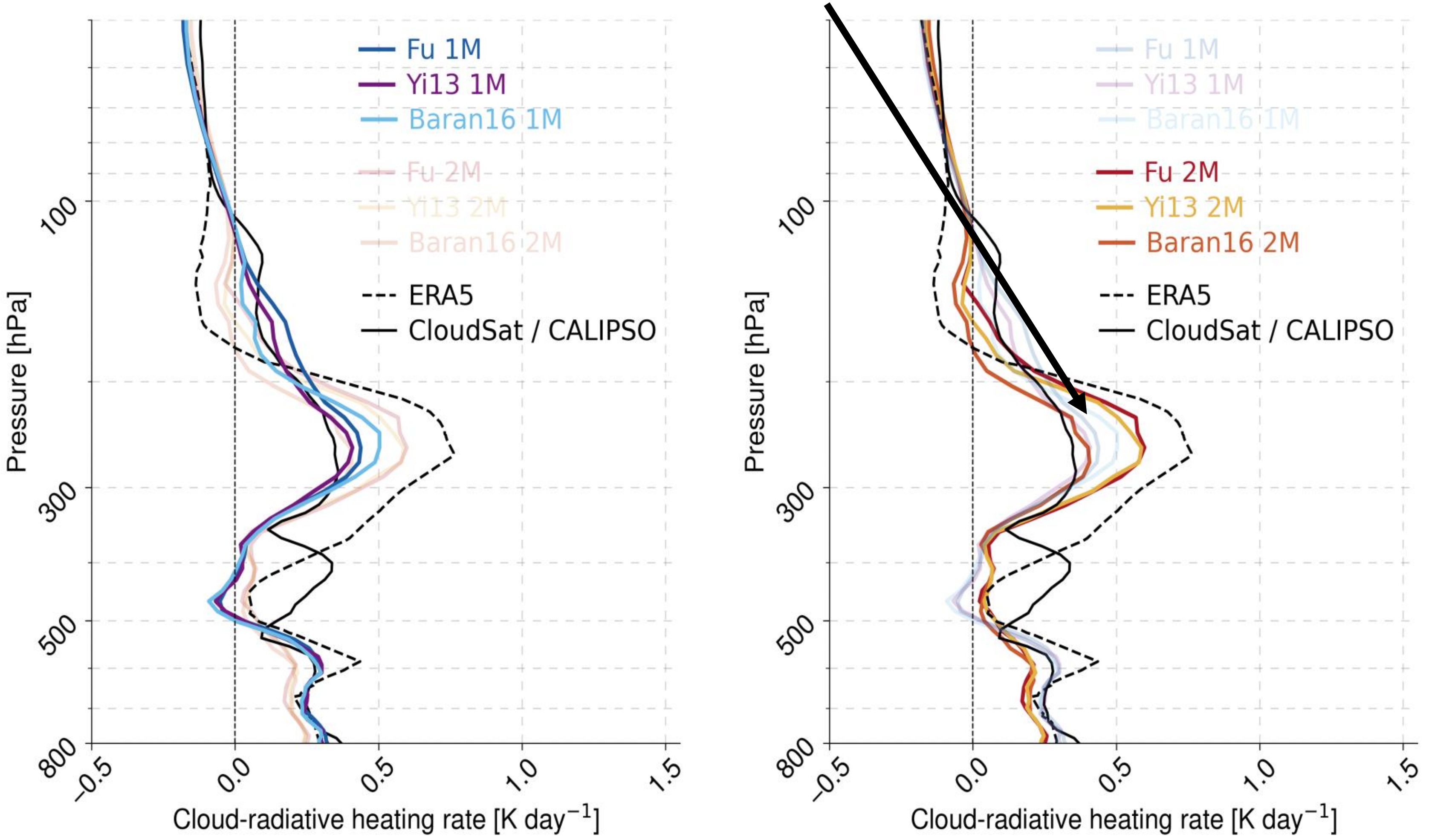
The largest sensitivities to optical schemes are for (geometrically) thin ice clouds at high altitudes.

What about optical sensitivites of CRH in a full-complexity model?

Optical sensitivities are stronger when coupled to a two-moment scheme.



Sullivan and Voigt (2021). *Comms. Earth & Env.*



Sepulveda Araya et al. (2025). *In prep.*

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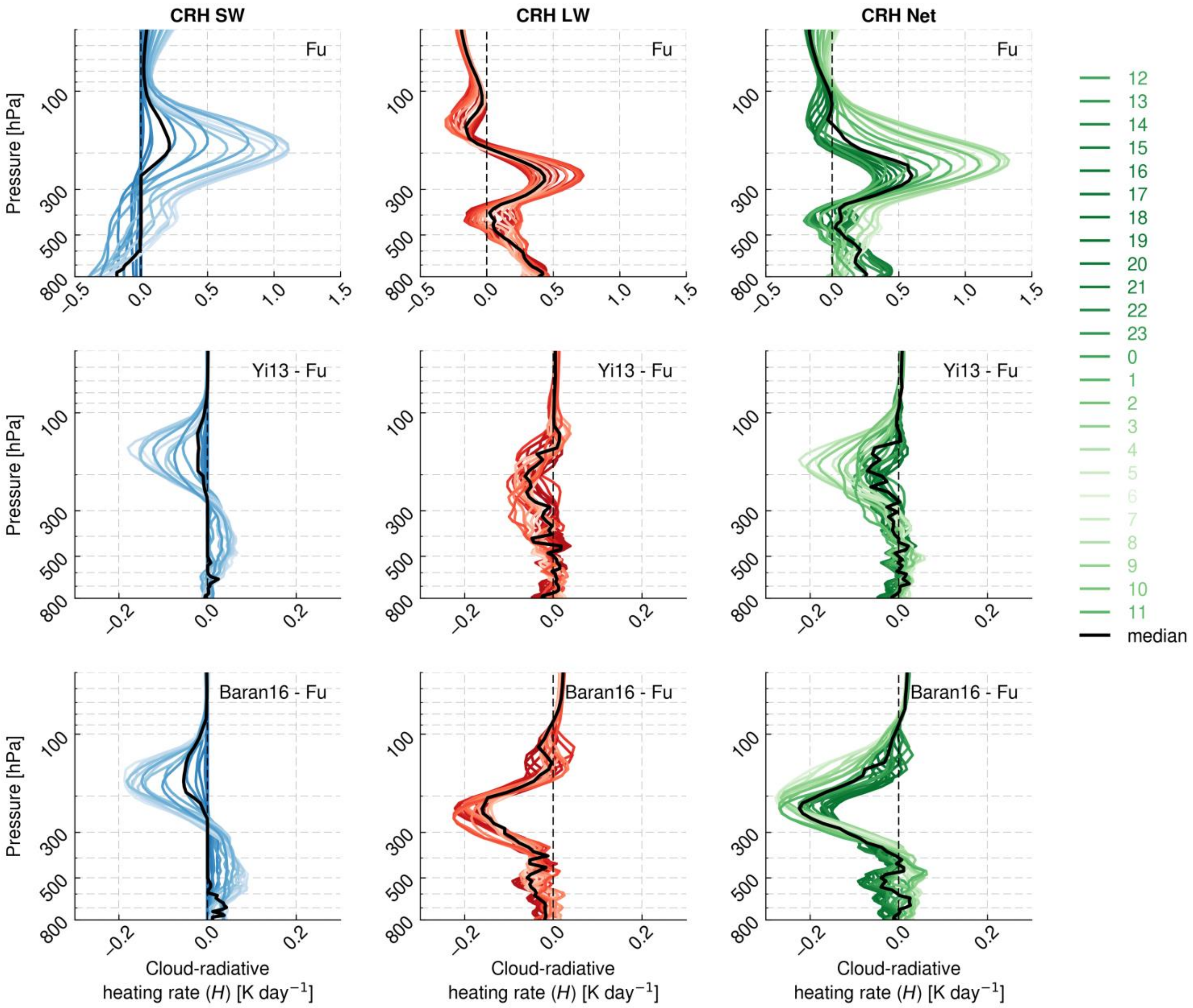


Important differences across the diurnal cycle for the different optical schemes.

Weaker SW heating at low solar zenith angles when including complexity.

Weaker SW *and* LW heating when using temperature-dependent properties.

Optical properties may be most important in the more detailed spatiotemporal distribution of CRH.

TAKEAWAYS

PART 1: a) $\dot{P}$, CWP, and ϵ still vary greatly from one SRM to the next.

→ Continued importance of subgrid-physics even when deep convection is resolved

b) Mean ϵ influenced more by liquid microphysics but spread in ϵ more by ice.

c) Strong correlation of $\Delta\dot{P}$ and underestimation of ϵ at higher frequencies point to importance of MCSs.

PART 2: a) Ice microphysics strongly modulated upper-level CRH.

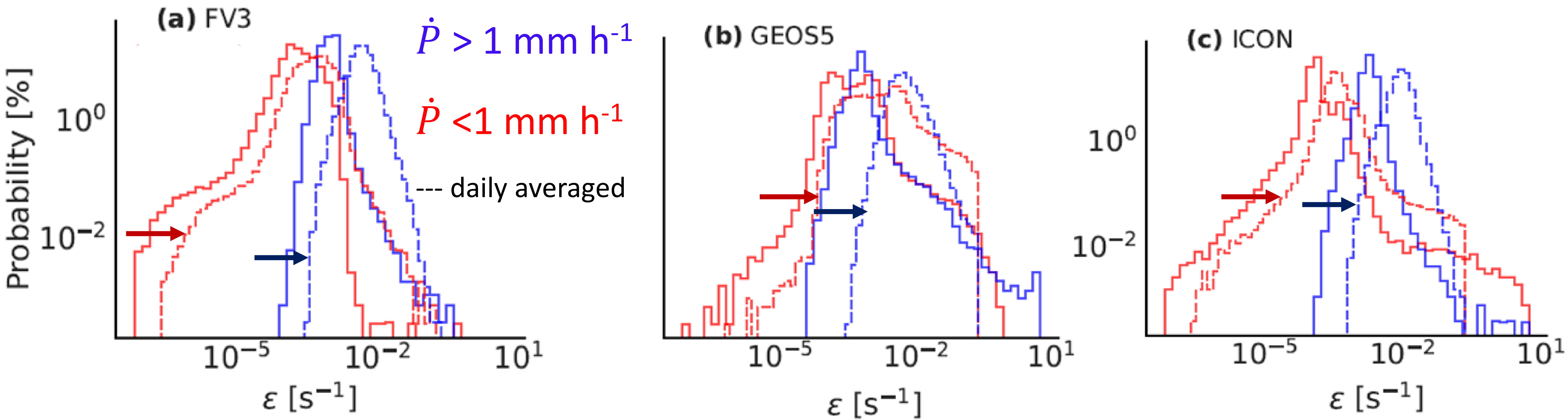
→ Ice optics have a secondary but non-negligible impact, especially when coupled to two-moment schemes.

b) Inclusion of ice complexity weakens CRH; *T*-dependent optics strengthens CRH.

c) Optical sensitivities are particularly large for thin, high-altitude cirrus *and* when considering the diurnal cycle of CRH.

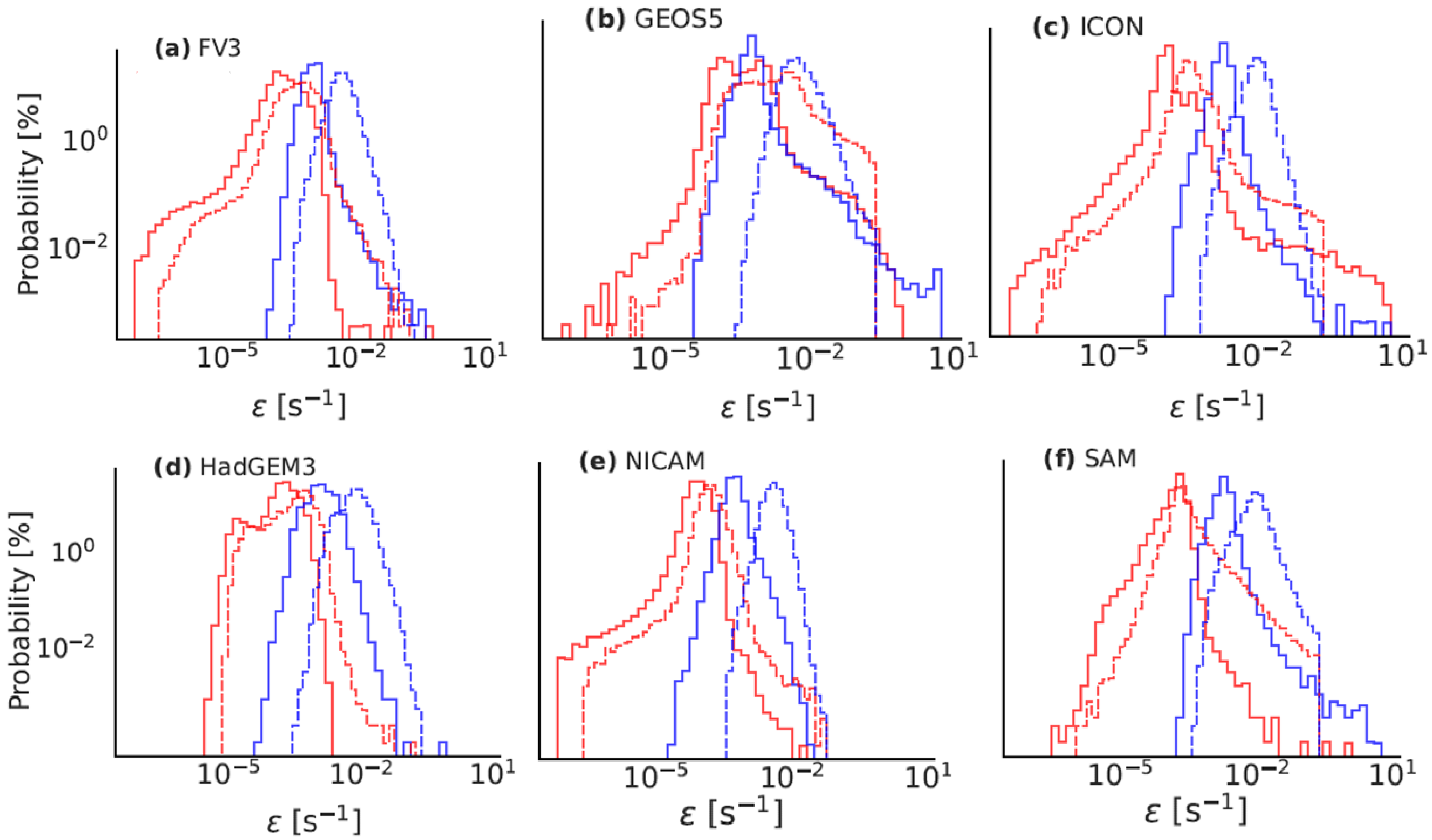
Supplemental Slides

Sensitivity of ϵ to averaging duration is consistent across models.

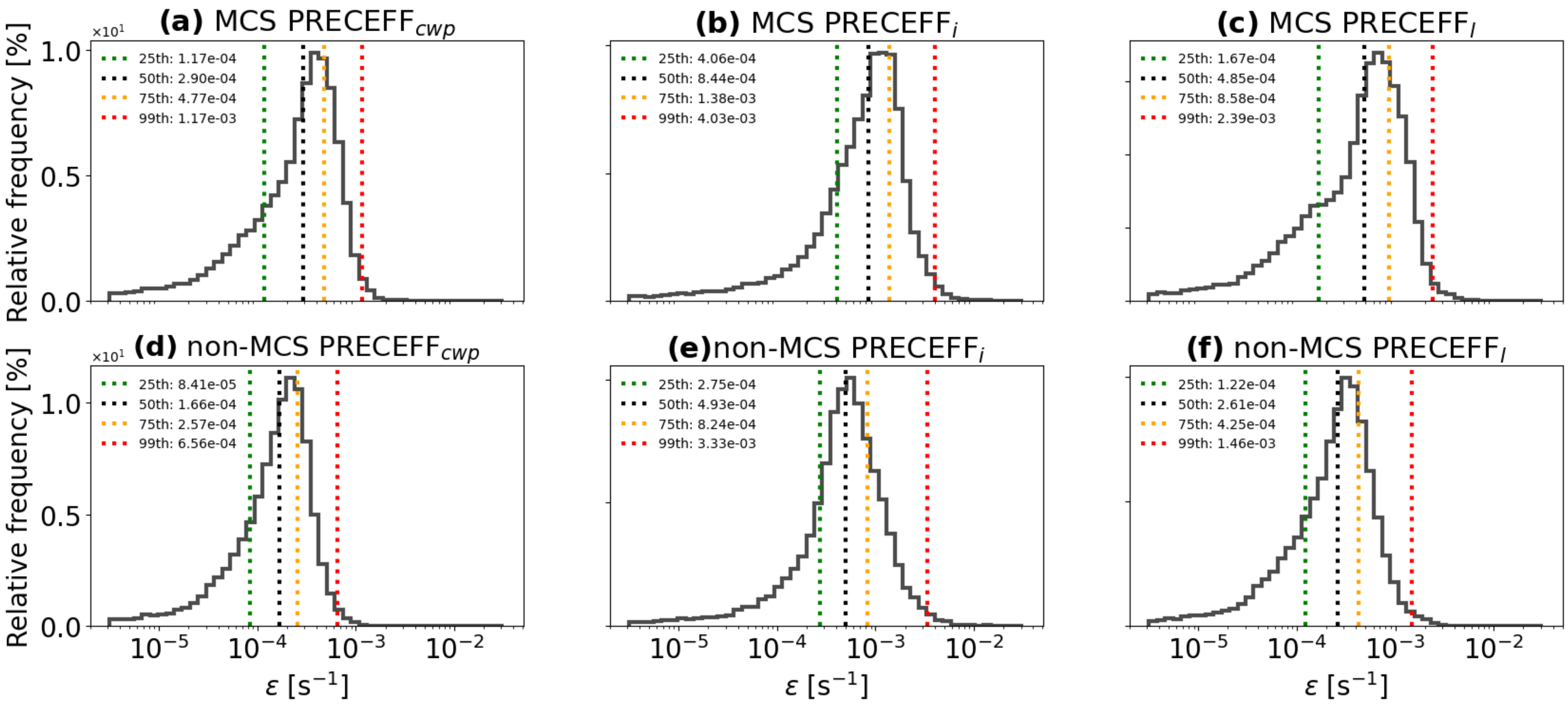


- With a shorter averaging duration and across the distribution, ϵ shifts to higher values.
  by a factor of 2-6
- With a shorter averaging duration and across the models, ϵ shifts to higher values.
  by a factor of 2-6

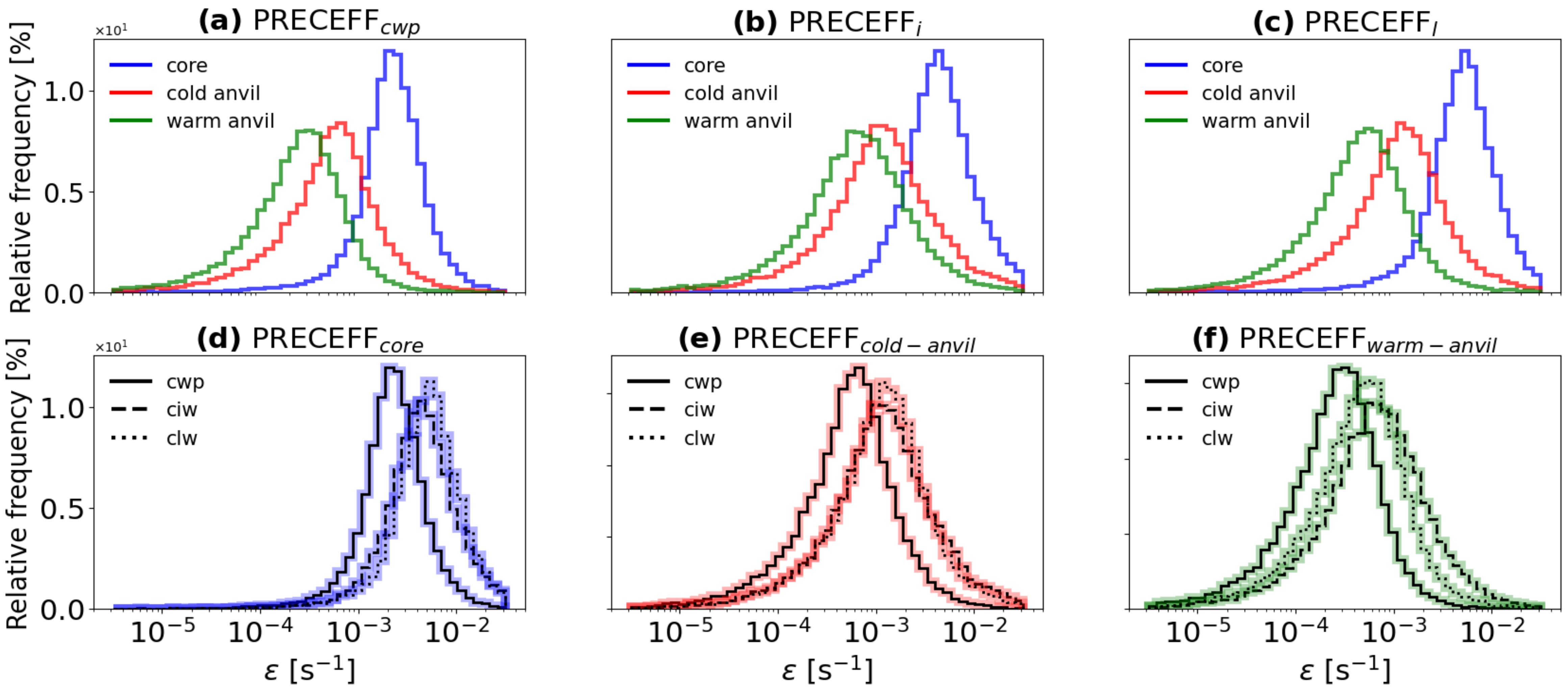
Sensitivity of ϵ to averaging duration is consistent across models.



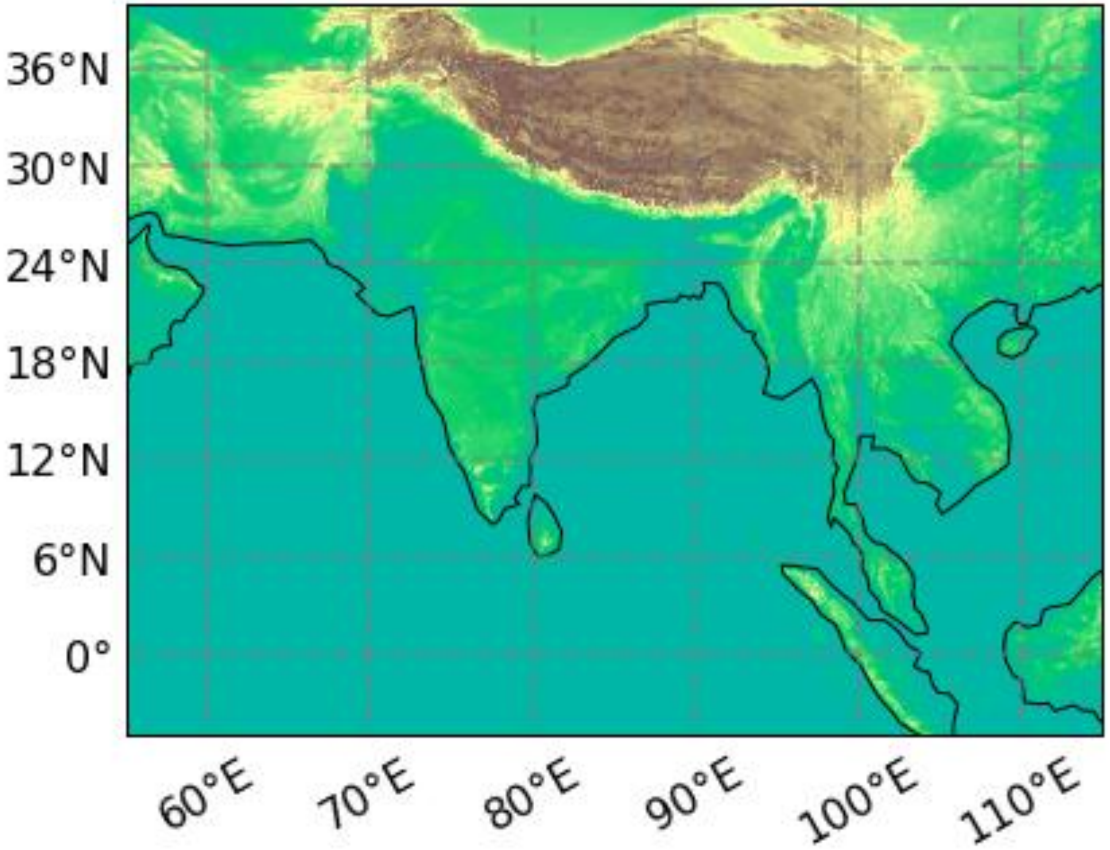
MCS ϵ metrics are 50-75% larger than the non-MCS values



MCS ϵ metrics across different parts of the system and for liquid, ice, and total condensate



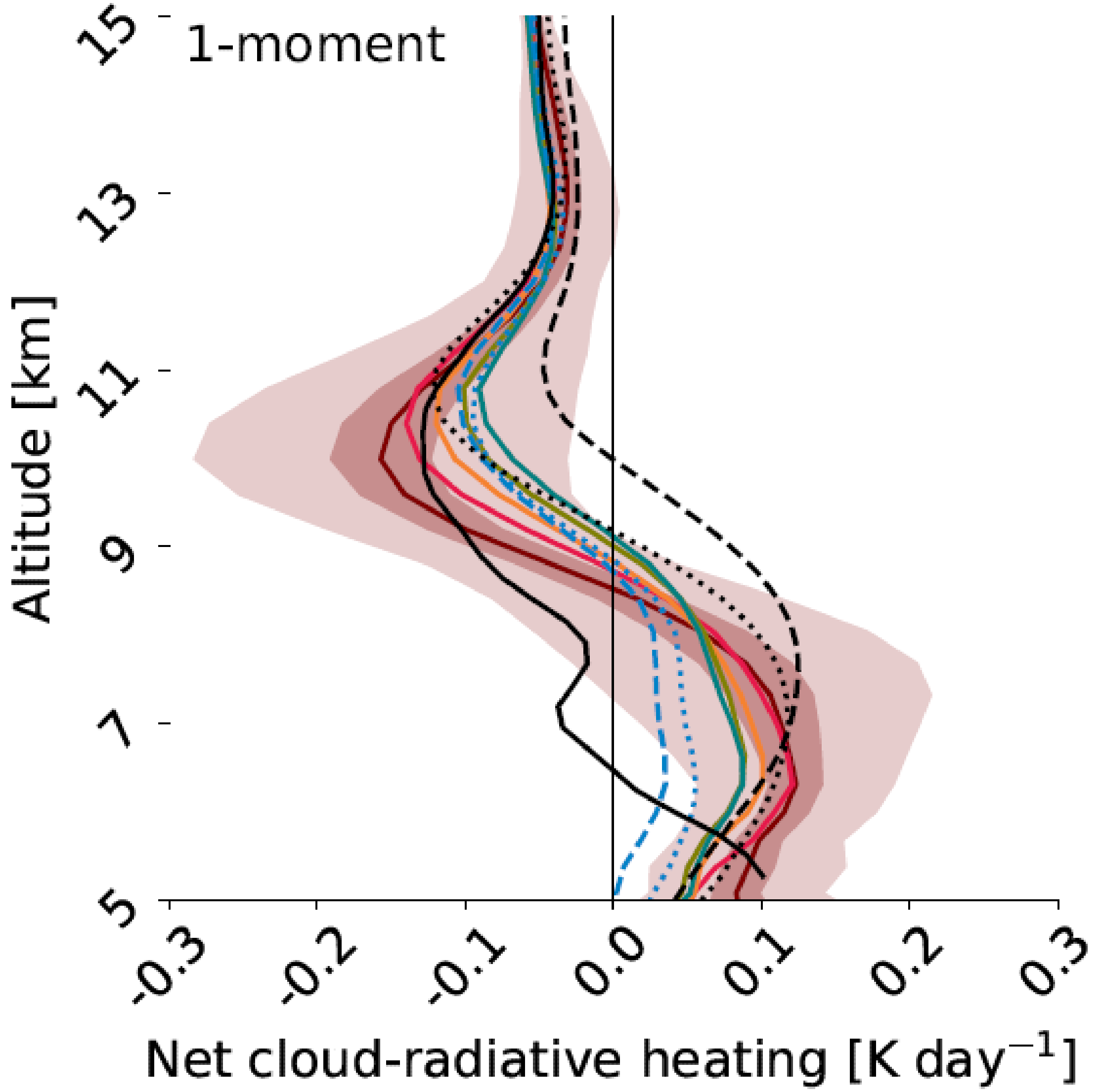
We “flip” four switches in a storm-resolving model.

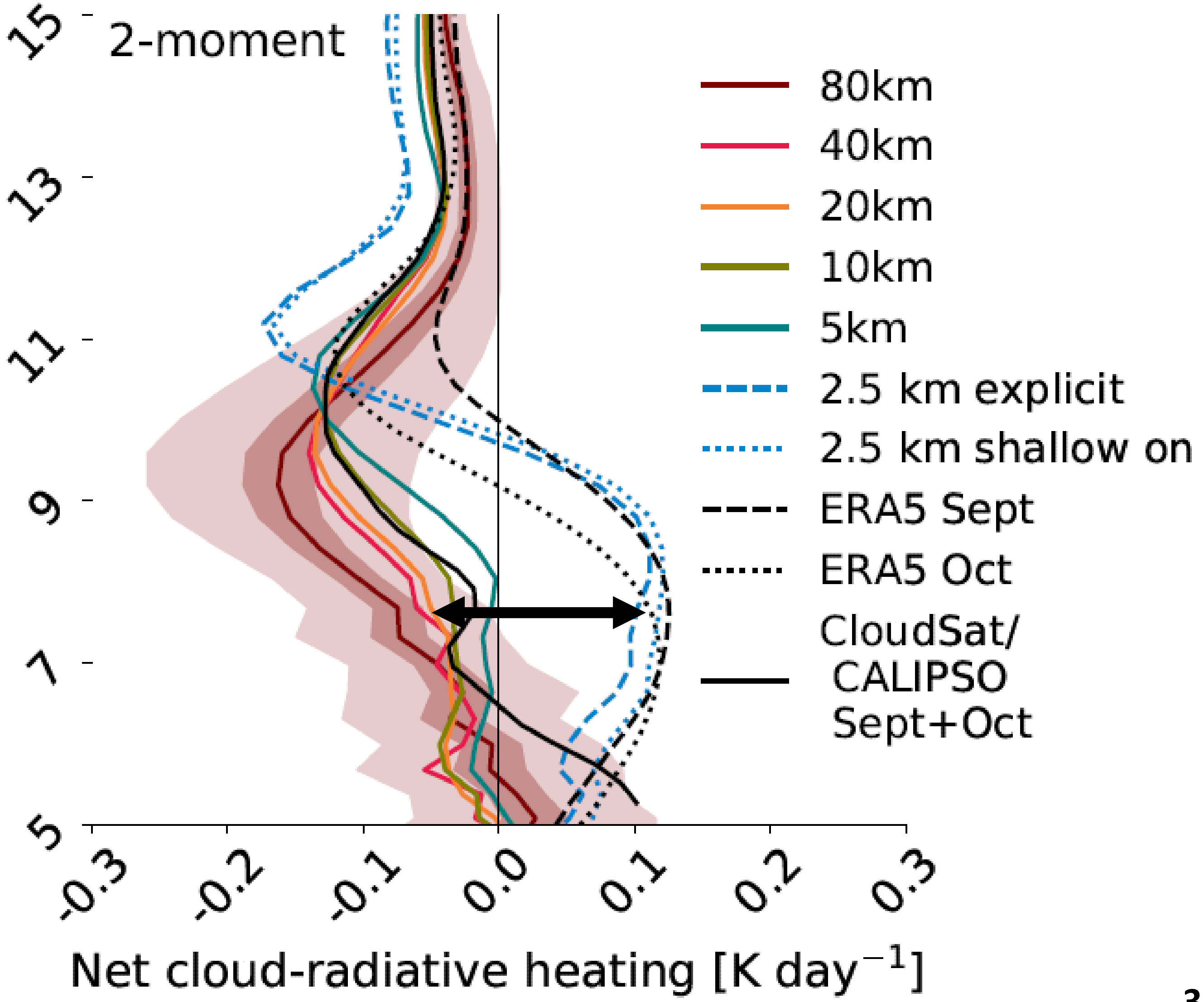


M q_i or N_i	One-**M**oment or two-moment microphysics scheme
V	Default or higher **V**ertical resolution
A	**A**erosol dependence or not in nucleation
R	Consistent size (effective **R**adius) of crystals between microphysics and radiation or not

Icosahedral Nonhydrostatic Model (ICON), 2.5-km equivalent resolution, 3 days of simulation (StratoClim Flight 7 - August 2017), 24-second time step

dependence on microphysics + convection >> dependence on horizontal resolution





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