On the interplay of tropical clouds, humidity and the energy budget

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Universität Hamburg
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CLUSTER OF EXCELLENCE
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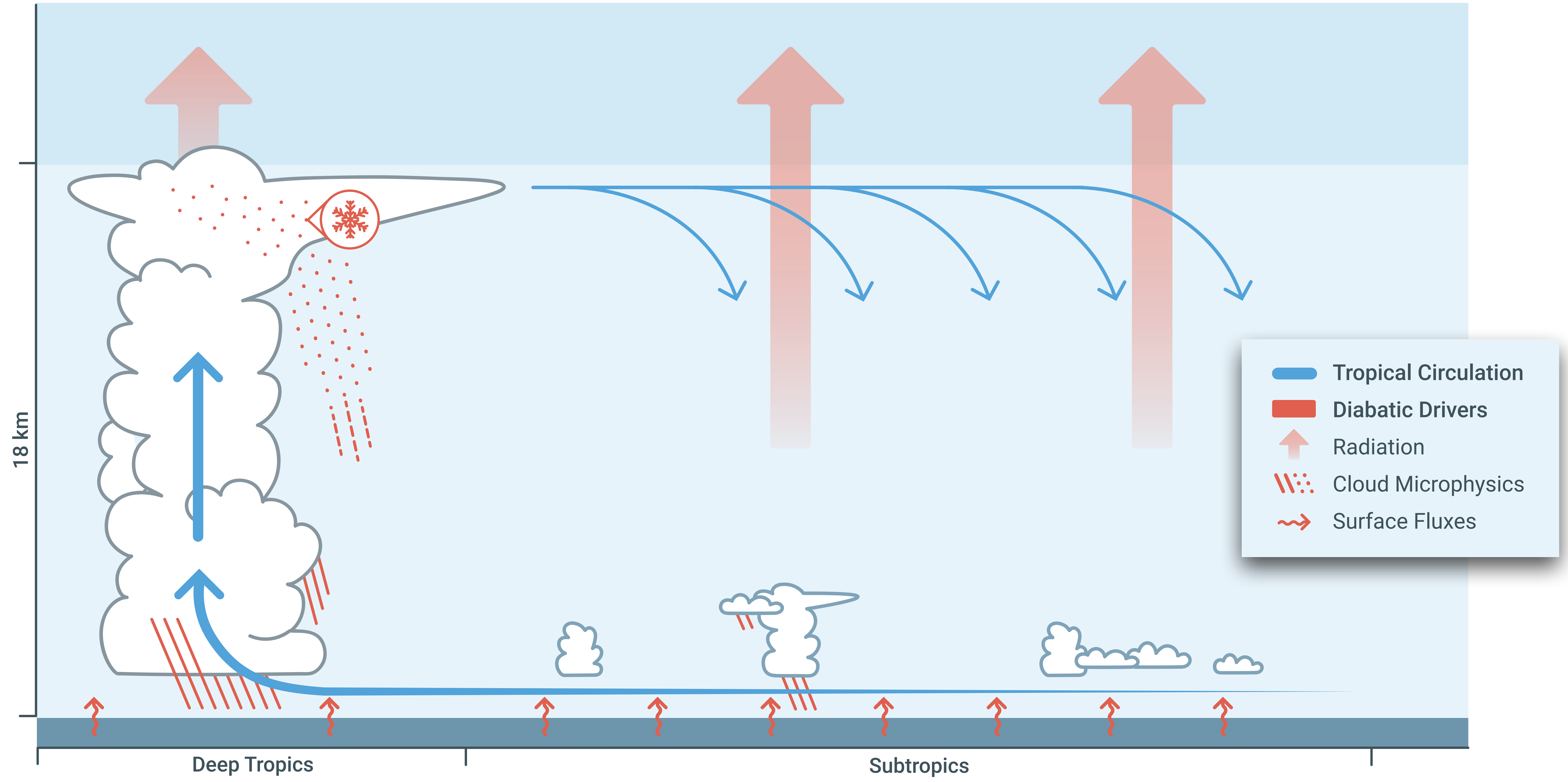
MAX-PLANCK-INSTITUT FÜR METEOROLOGIE

Drivers of tropical circulation and the energy budget

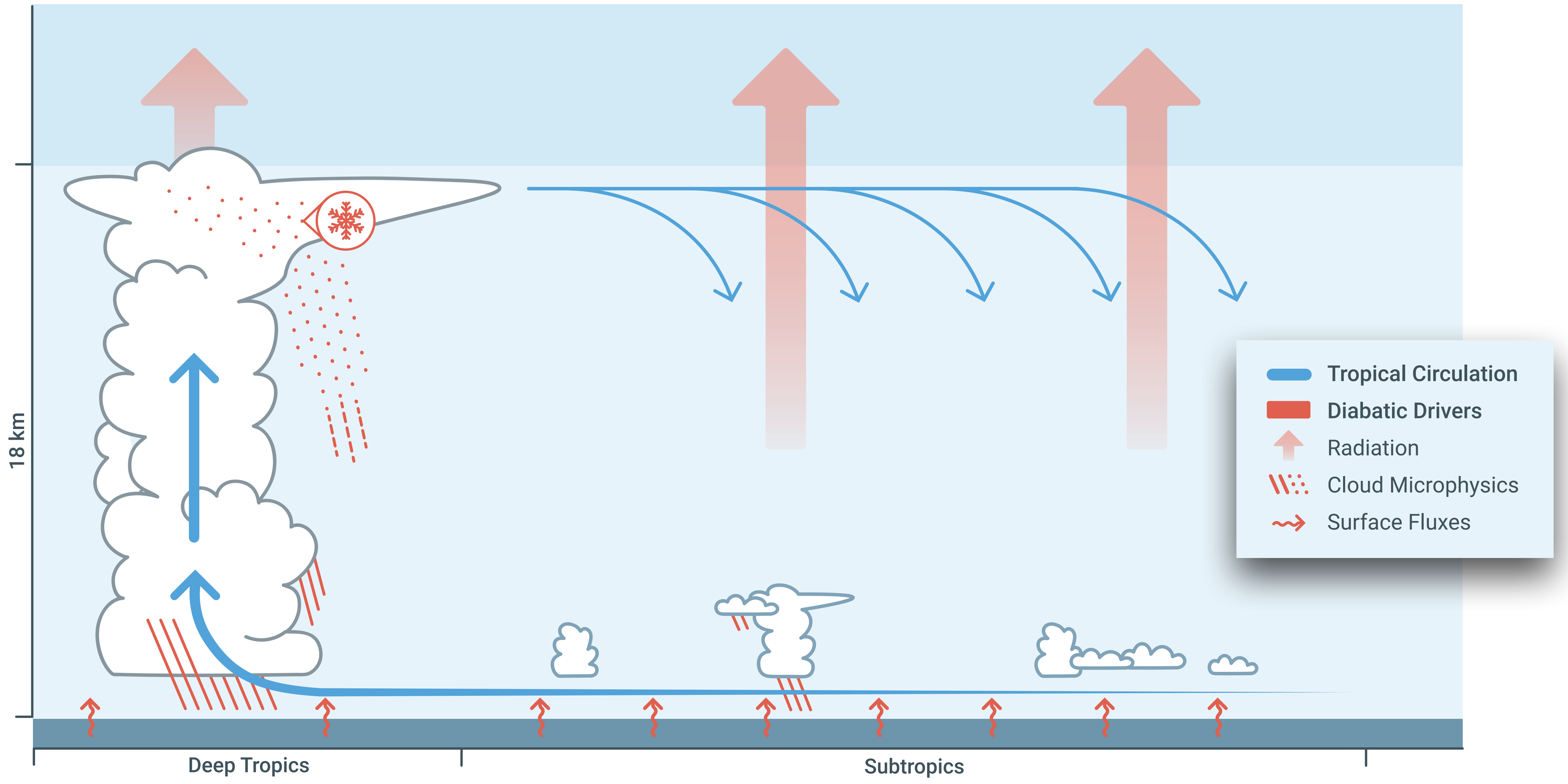
How the tropics respond to forcing dominates Earth's climate sensitivity.



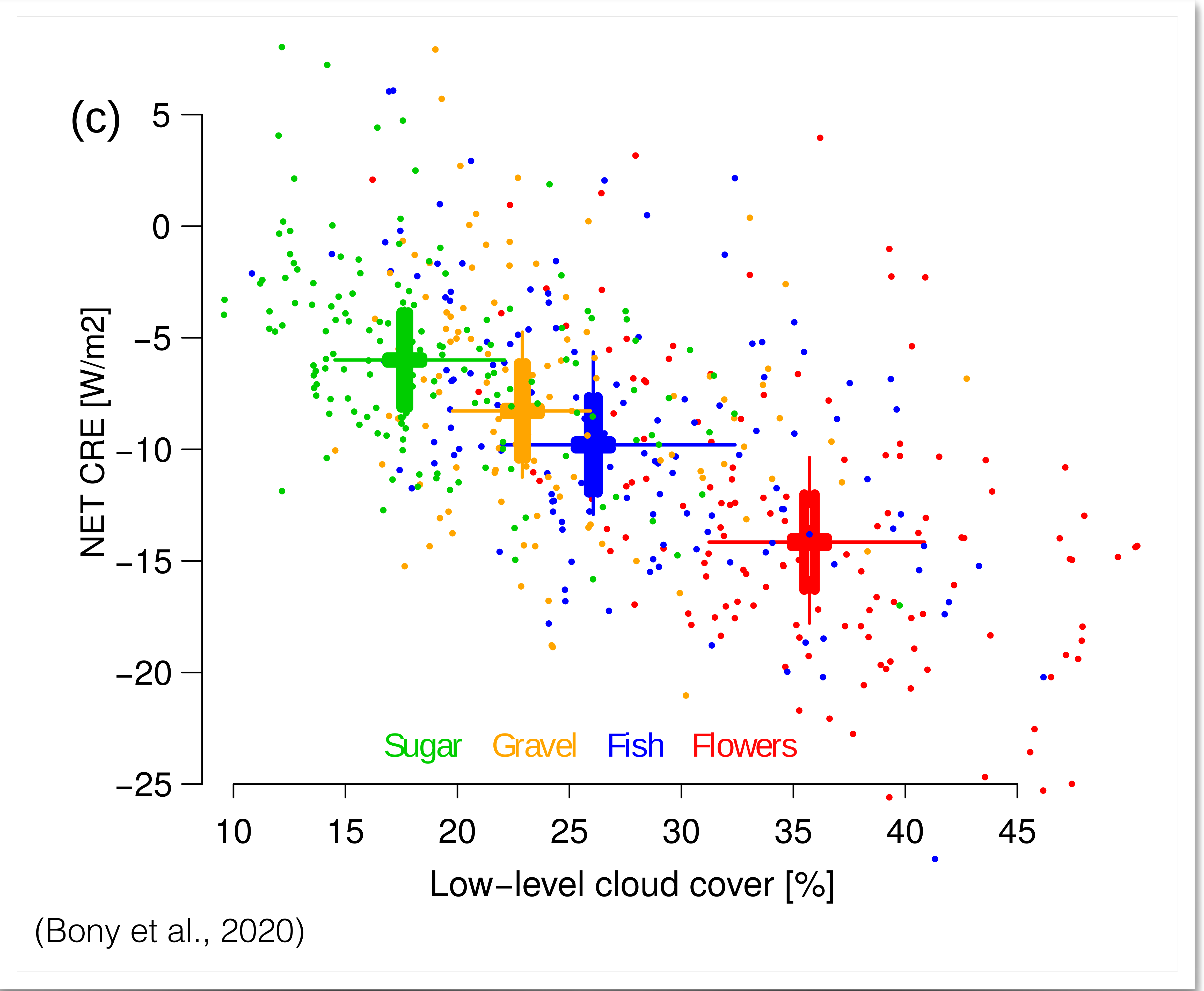
(Graphic: Y. Schrader)

Drivers of tropical circulation and the energy budget

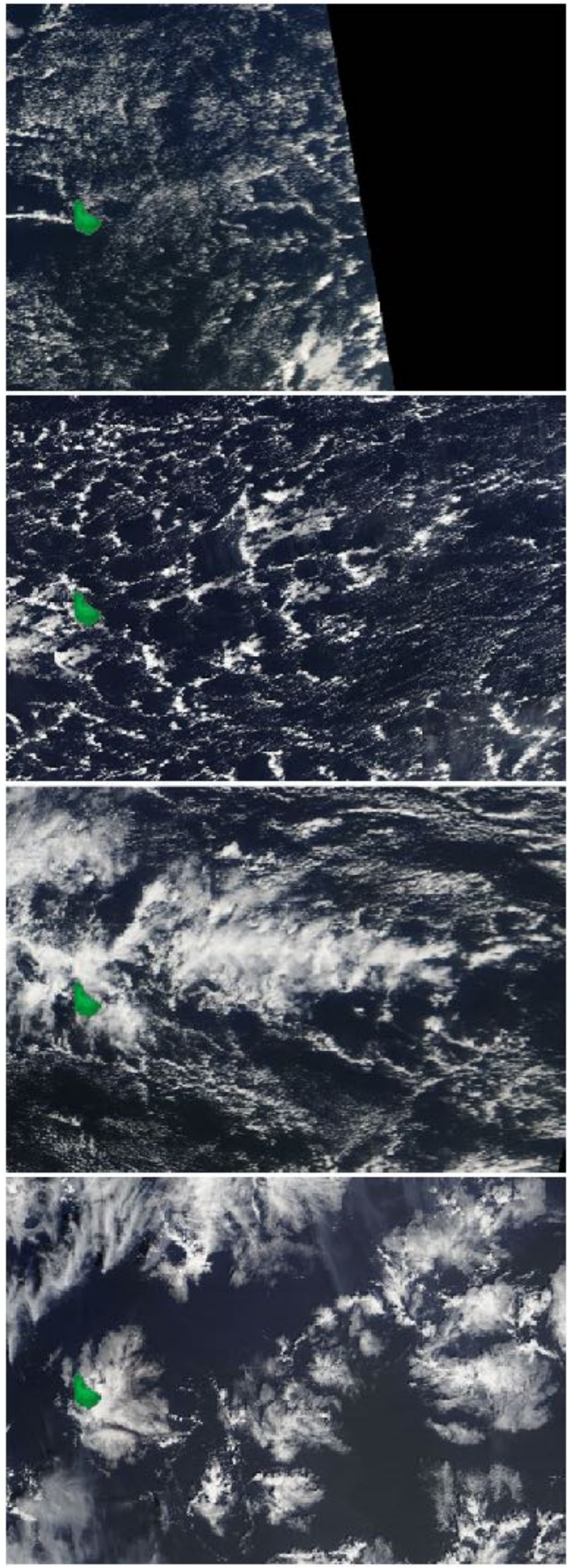
1. Organisation of shallow trade wind convection
2. Modelling the distribution of relative humidity
3. Microphysical uncertainties in global storm-resolving models



Organisation of shallow cumulus in the trades



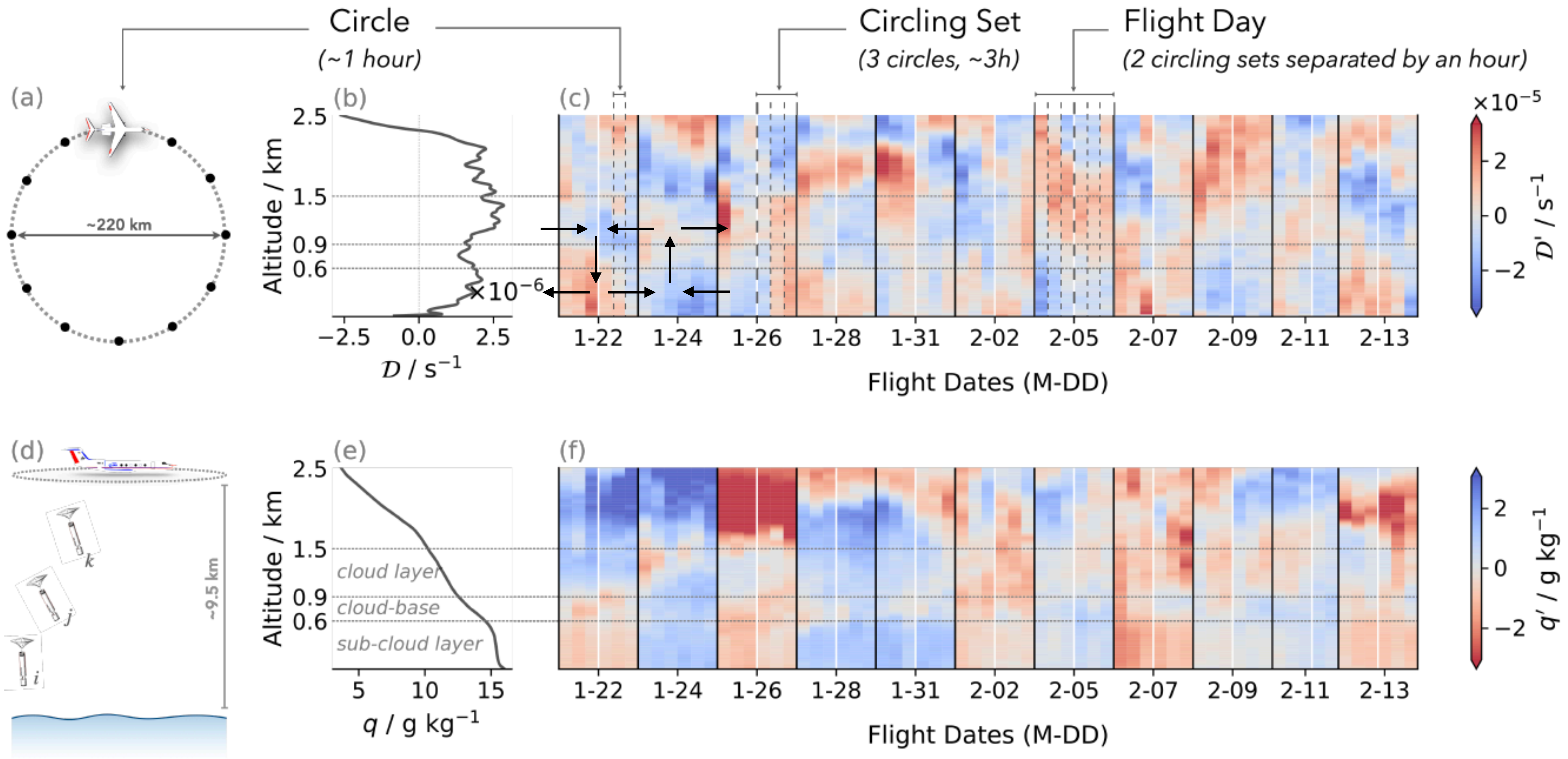
(Bony et al., 2020)



(Stevens et al., 2020)

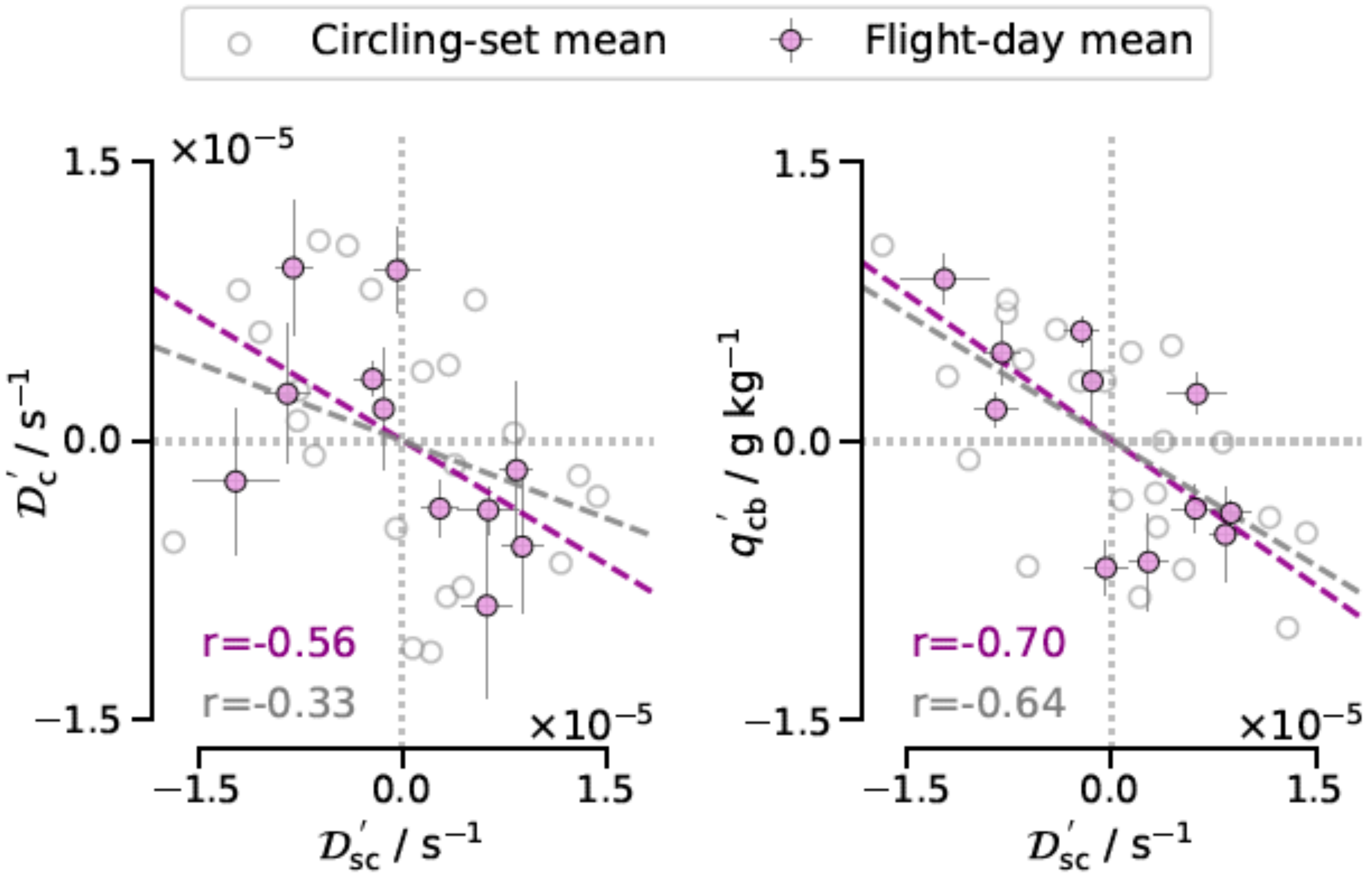
Observational evidence for ubiquity of shallow mesoscale circulations

Shallow mesoscale circulations are thought to play an important role in cloud organization, but they have not been observed yet.



(This study: George et al., accepted; EUREC4A: Stevens et al., 2021)

Coupling of moisture and clouds to shallow circulations



(George et al., accepted)

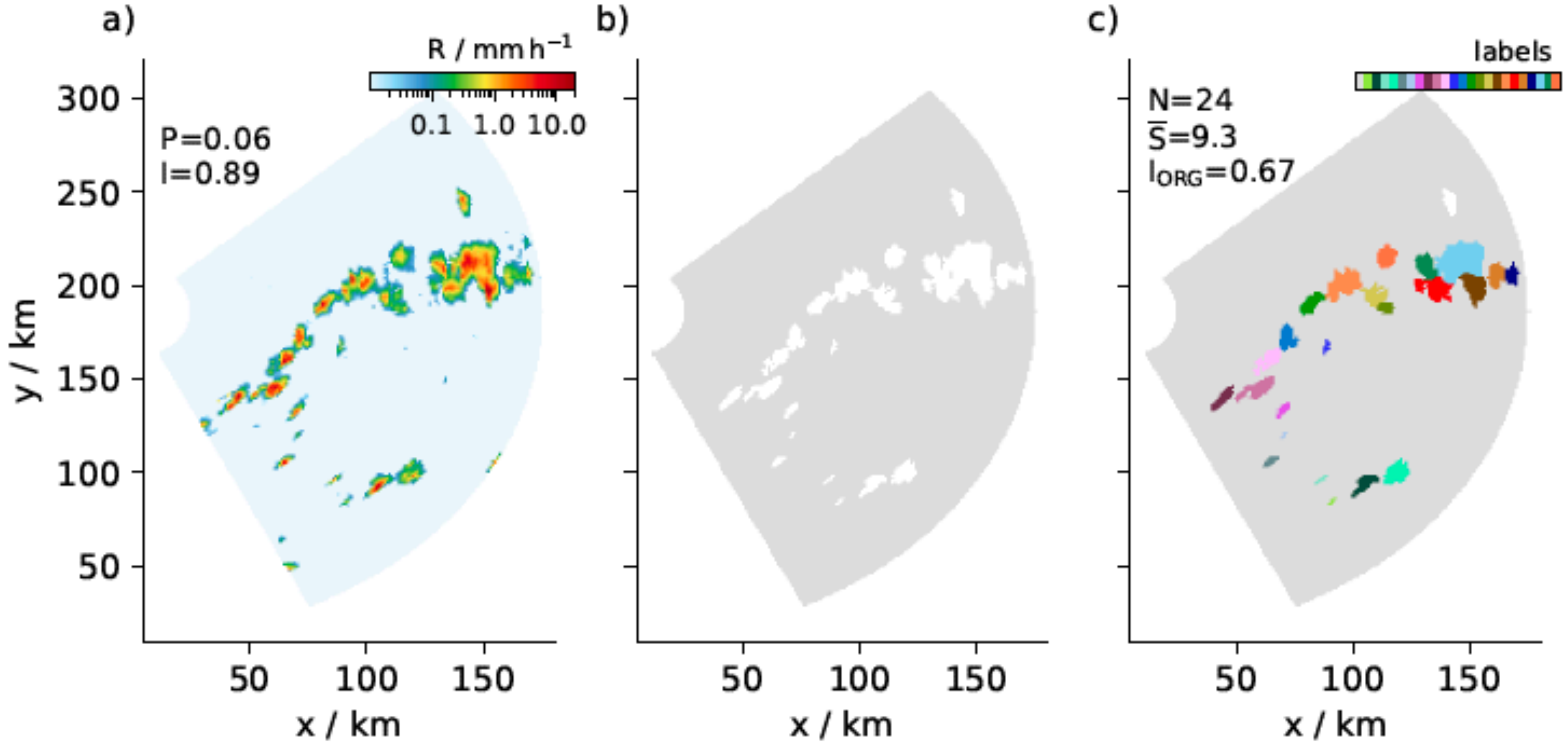
- Mesoscale variability in divergence is five-fold the mean value.
- Modulation of cloud-base moisture affects drying efficiency of entrainment, yielding moist ascending branches and dry descending branches.

What drives shallow mesoscale circulations?

- condensational heating (e.g., Bretherton and Blossey, 2017, Janssen et al., under review)
- radiative cooling differences (e.g., Wing and Emmanuel, 2014, Naumann et al, 2019)
- sea-surface temperature differences (e.g., Foussard et al., 2019, Naumann et al, 2019)
- precipitation (e.g., Bretherton and Blossey, 2017, Radtke et al., 2022)

Spatial patterns of precipitating shallow convection

(Photo by F. Batier)

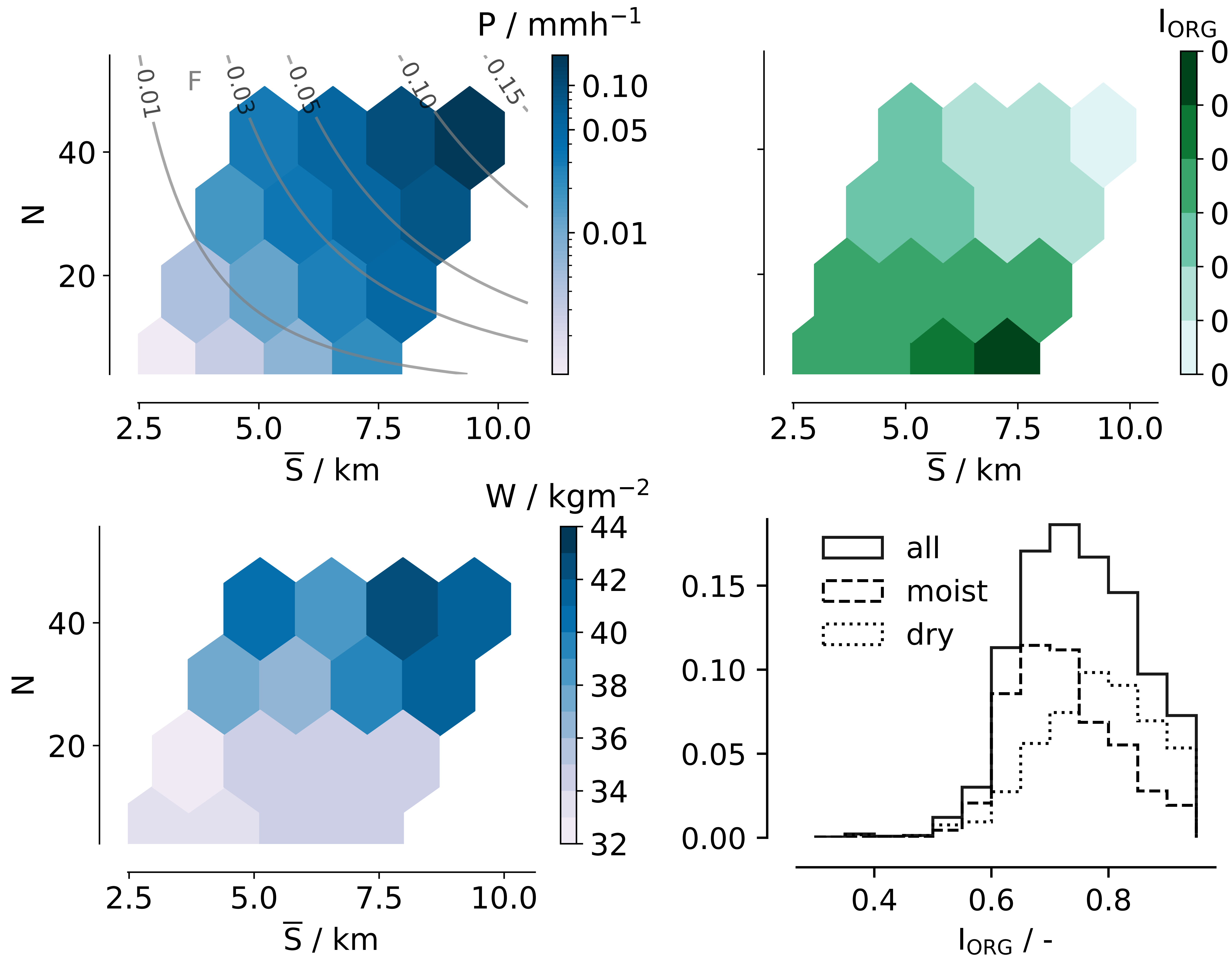


Poldirad:

- mean precipitation, area fraction and intensity
- rain cell segmentation to identify number of cells, their size and organisation

(This study: Radtke et al., 2022; EUREC4A: Stevens et al., 2021; Poldirad: Hagen et al., 2021)

Does spatial patterning matter for precipitation characteristics?

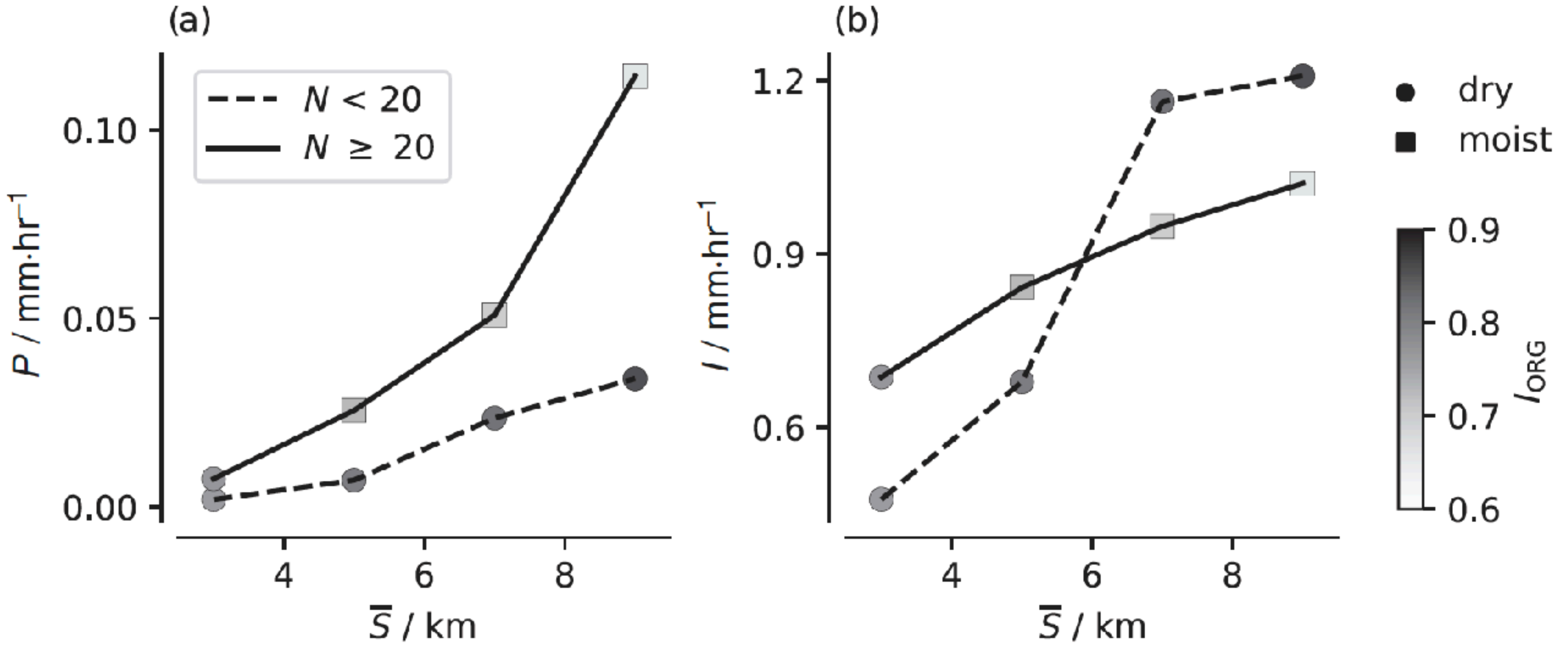


(Radtke et al., 2022)

Weak correlations indicate that organisation of rain cells is of second order importance for precipitation characteristics.

Dry environments are associated with more strongly clustered cells, which is similar to deep convection.
(Bretherton et al., 2005; Tobin et al., 2012)

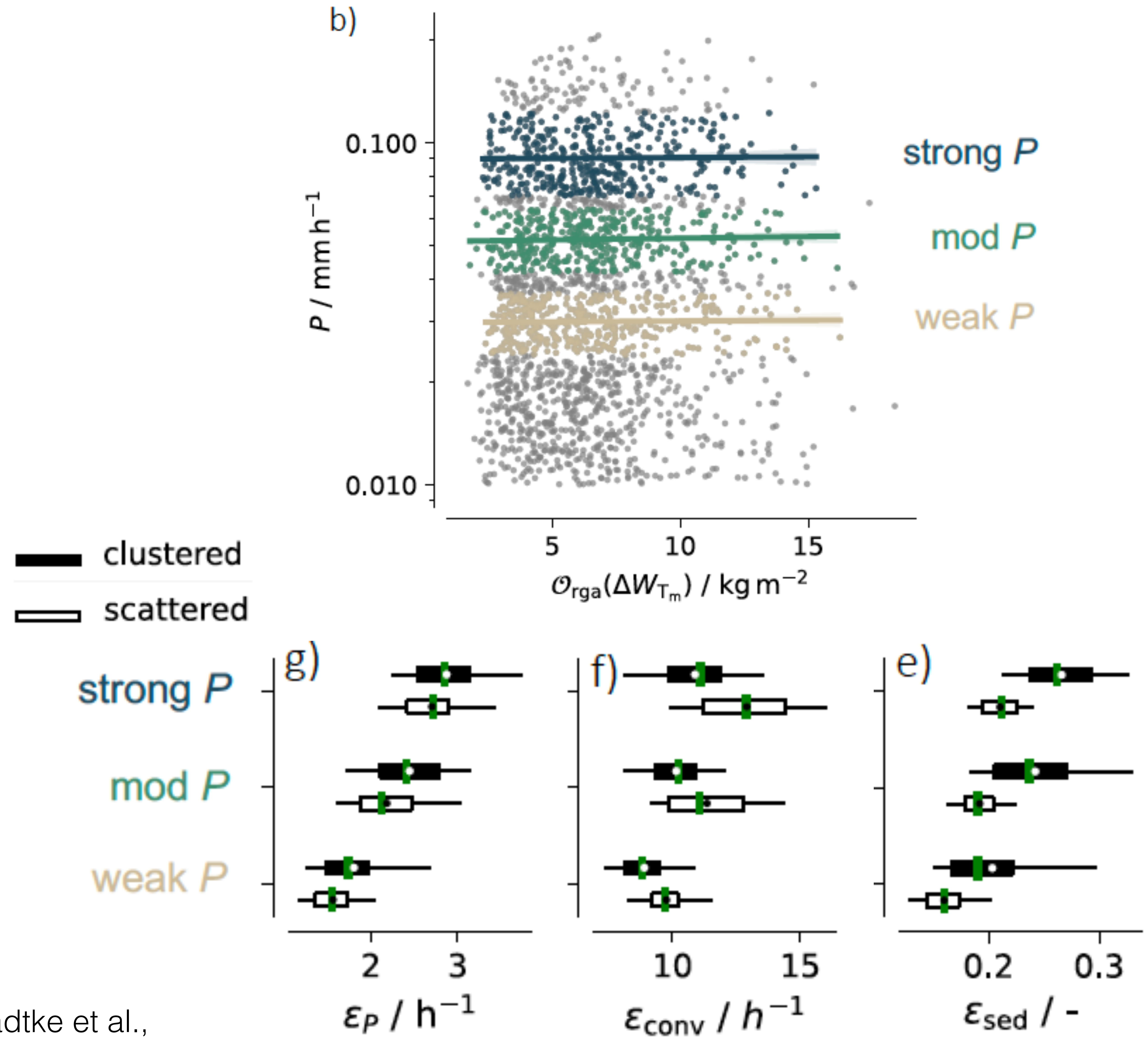
Can clustering maintain precipitation in dry environments?



Clustering may be important for high precipitation intensities and to maintain precipitation amounts in dry environments.

(Radtke et al., 2022)

Organisation affects rain production and sedimentation



(Radtke et al., in preparation)

$$\epsilon_p = \frac{\text{precipitation}}{\text{cloud water path}}$$

$$= \epsilon_{\text{conv}} \cdot \epsilon_{\text{sed}}$$

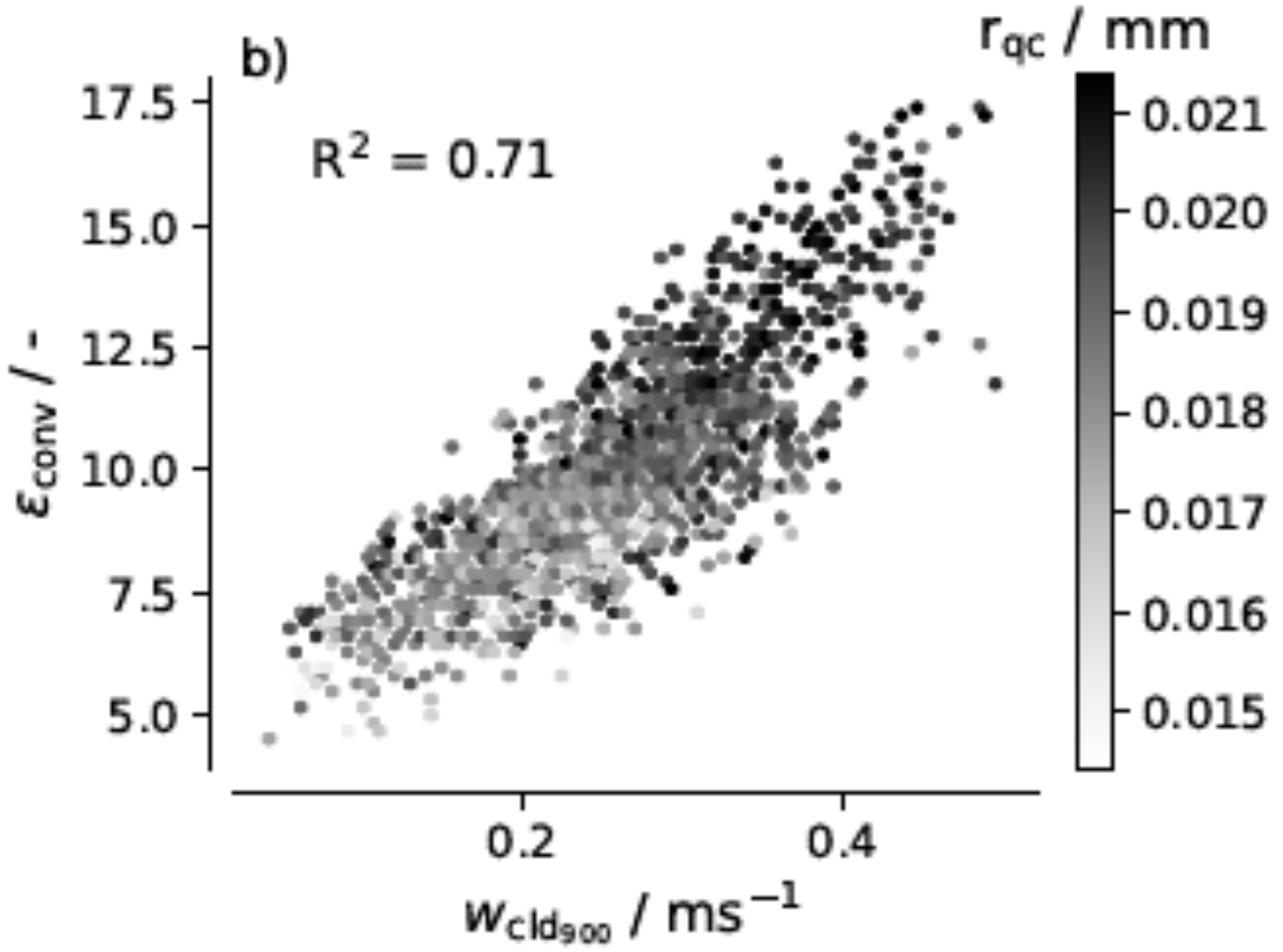
$$= \frac{\text{production of rain}}{\text{cloud water path}} \cdot \frac{\text{precipitation}}{\text{production of rain}}$$

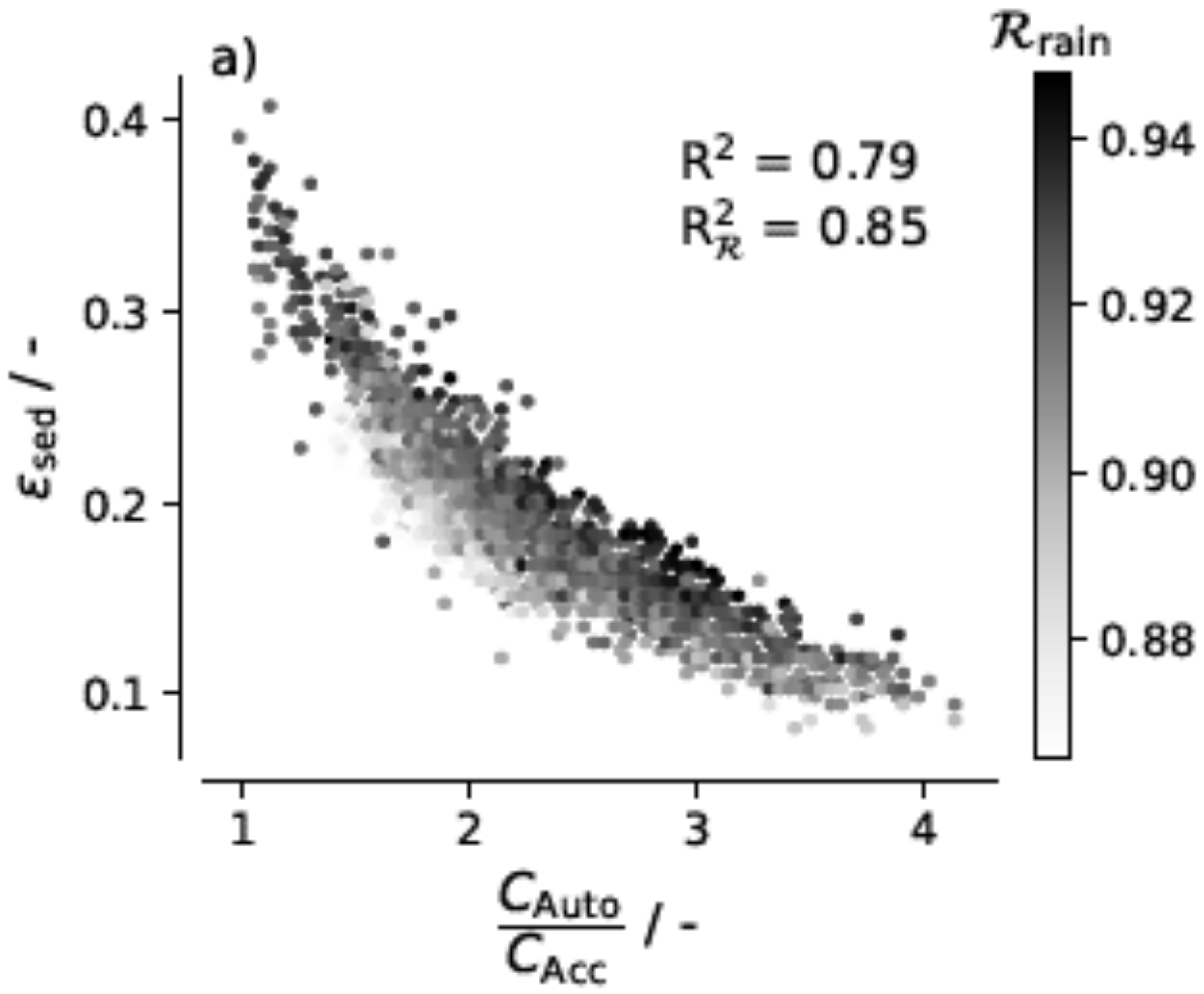
(Langhans et al., 2015)

Precipitation efficiency varies with mean precipitation. The effect of organisation is minor.

As organisation strengthens, cloud condensate is less efficiently converted to rain, but rain sediments more efficiently.

Organisation affects conditions of rain production





As organisations strengthens, rain already forms in weaker updrafts.

Increasing contribution from accretion and a more humid environment lead to less evaporation.

(Radtke et al., in preparation)

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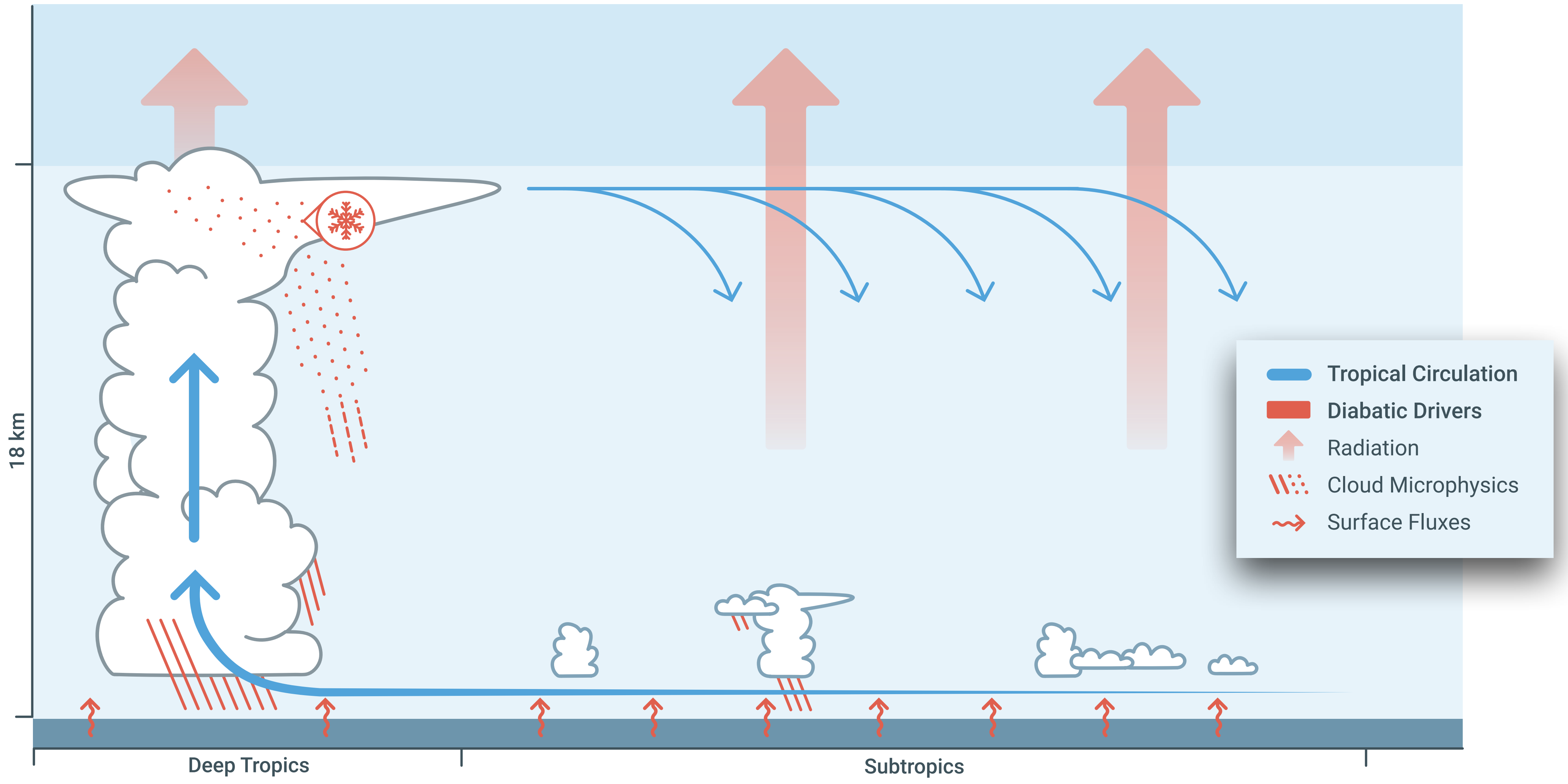
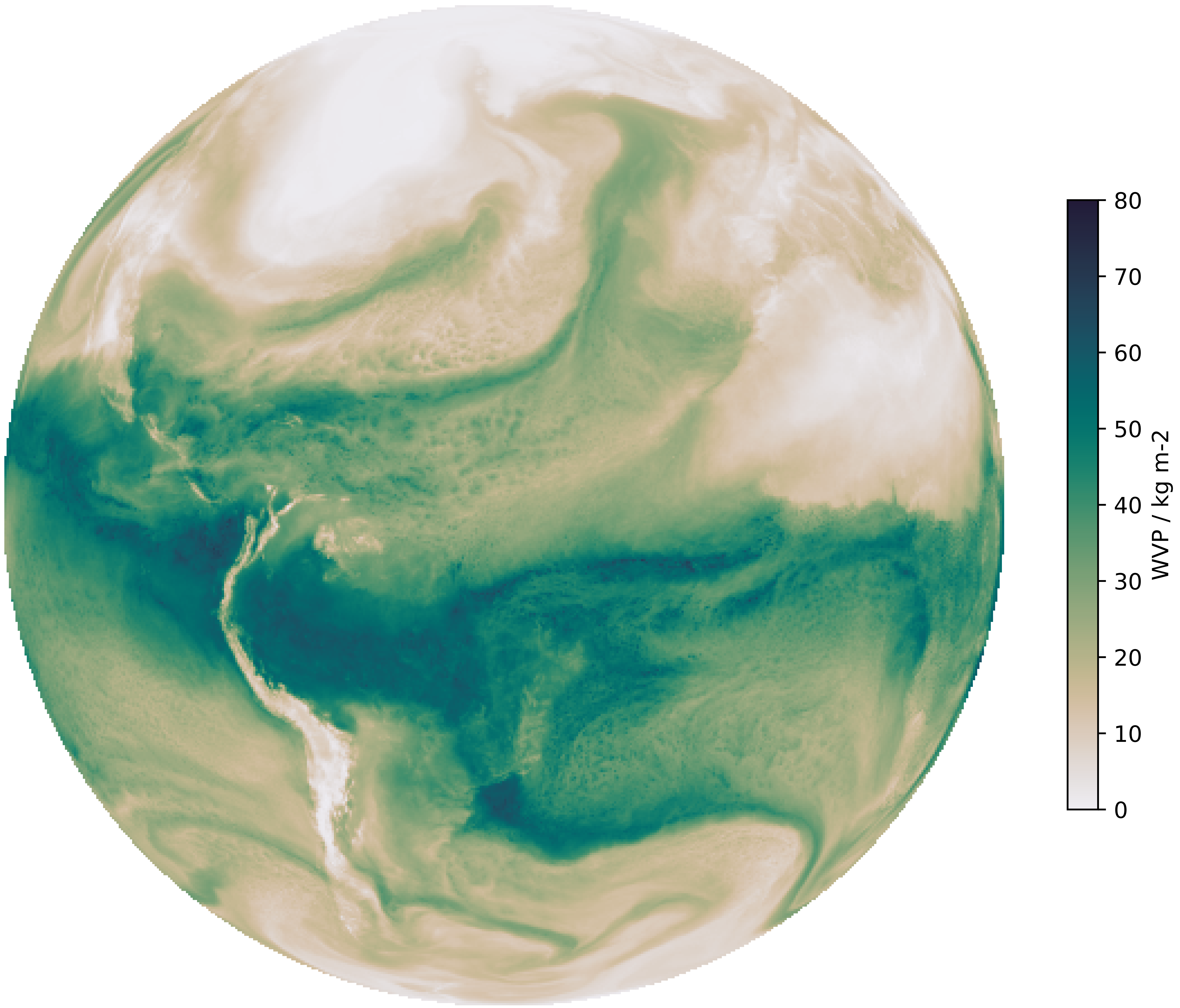


Simulating the tropical heat budget at kilometre-scale resolution

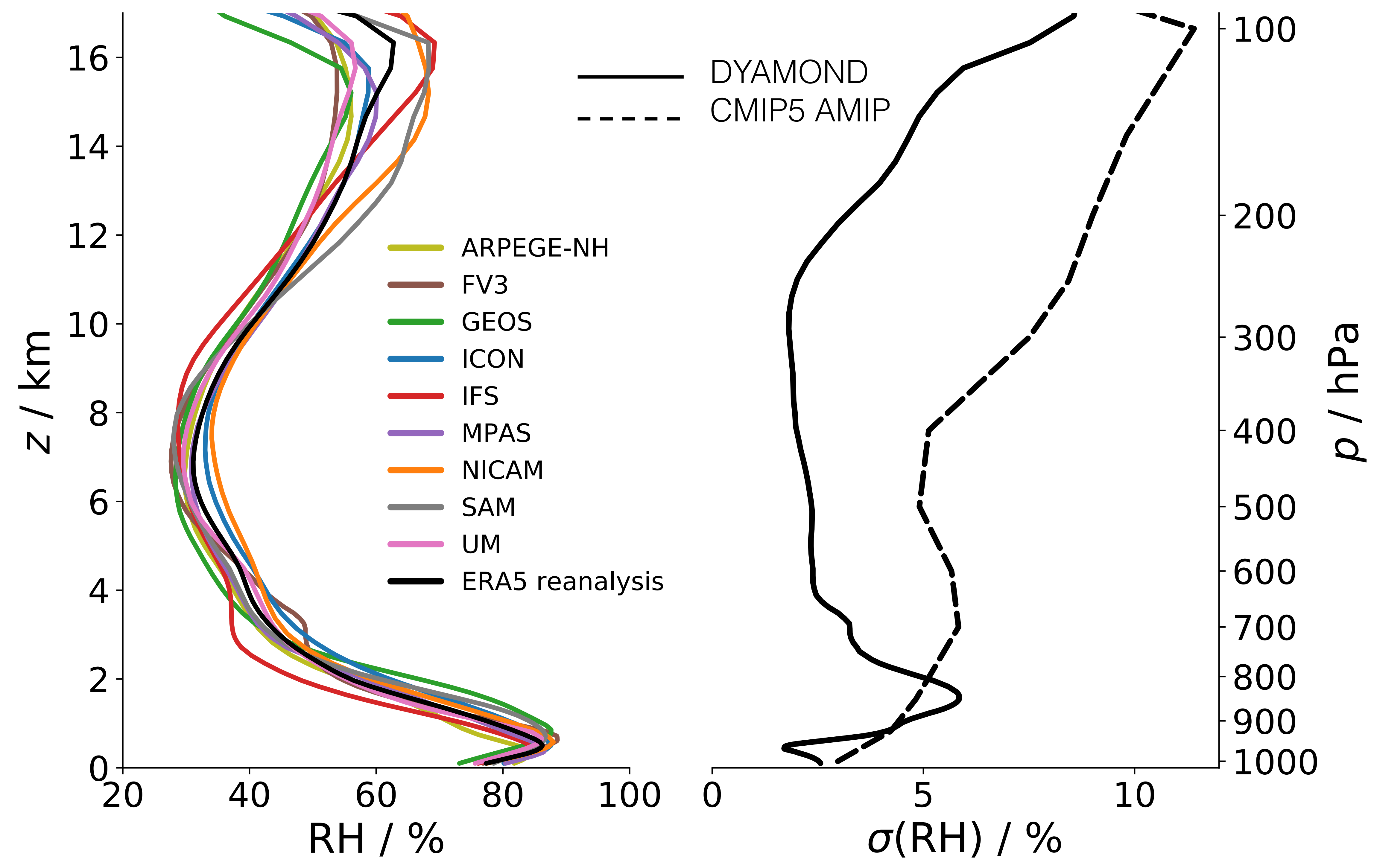
reduced number of poorly constraint processes:

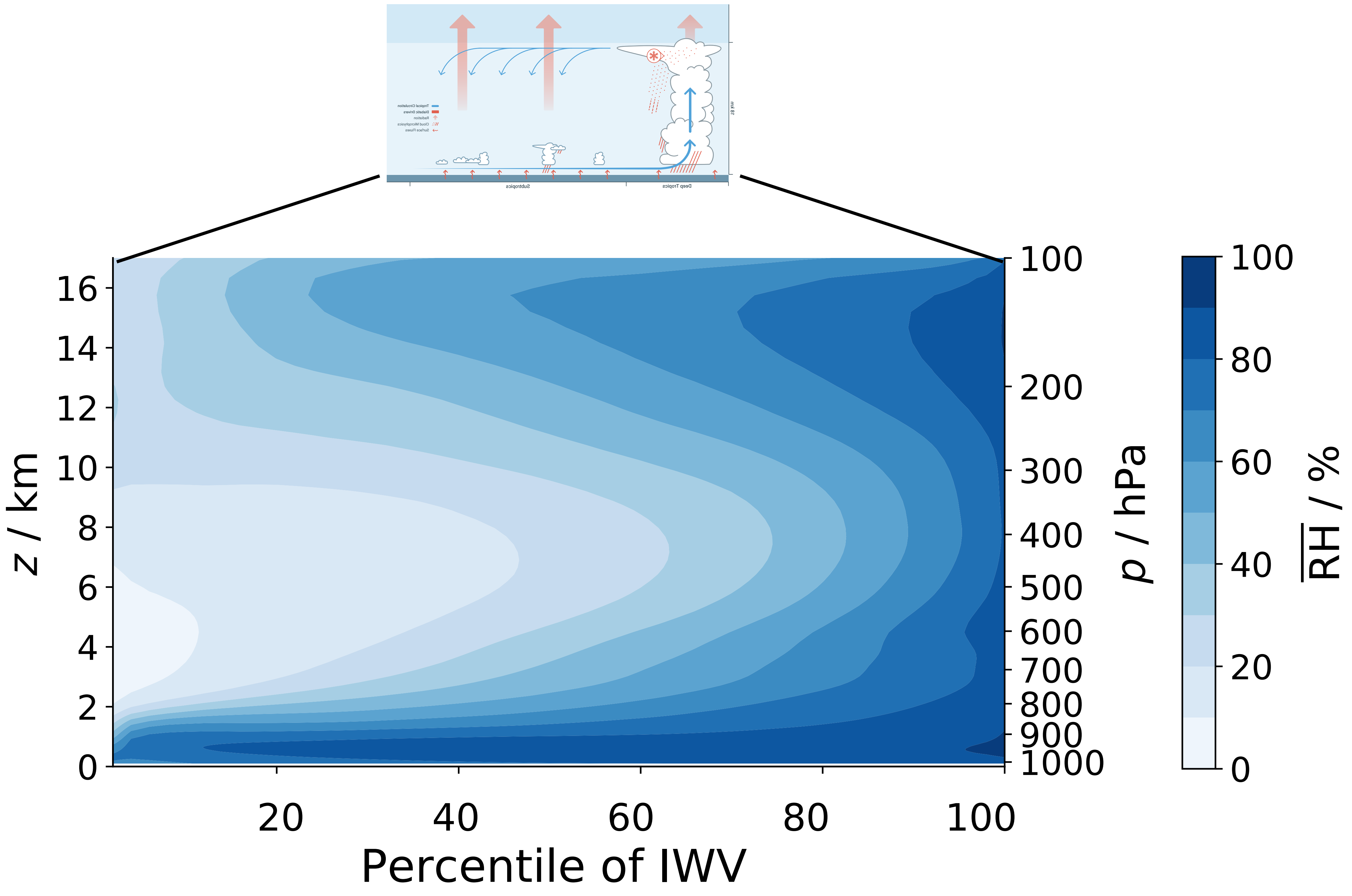
microphysics
turbulence

How much of the tropical heat budget is controlled by circulation and dynamics as compared to microphysical and turbulent processes?



Distribution of free-tropospheric humidity in a multi-model ensemble





The inter-model spread of RH in GSRMs is about half as large as in the AMIP ensemble.

(This study: Lang et al., 2021; DYAMOND ensemble: Satoh et al., 2019, Stevens et al., 2019)

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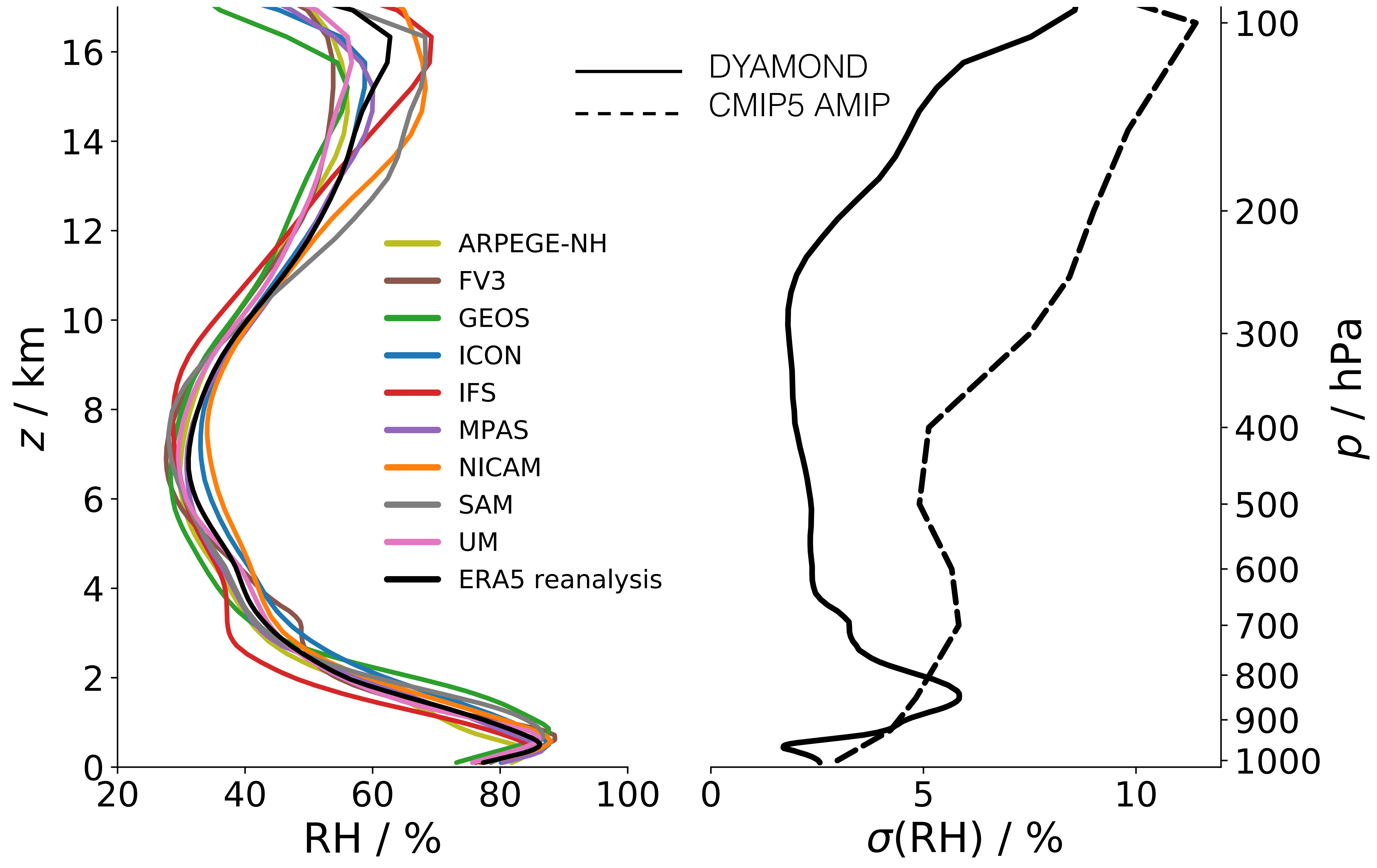

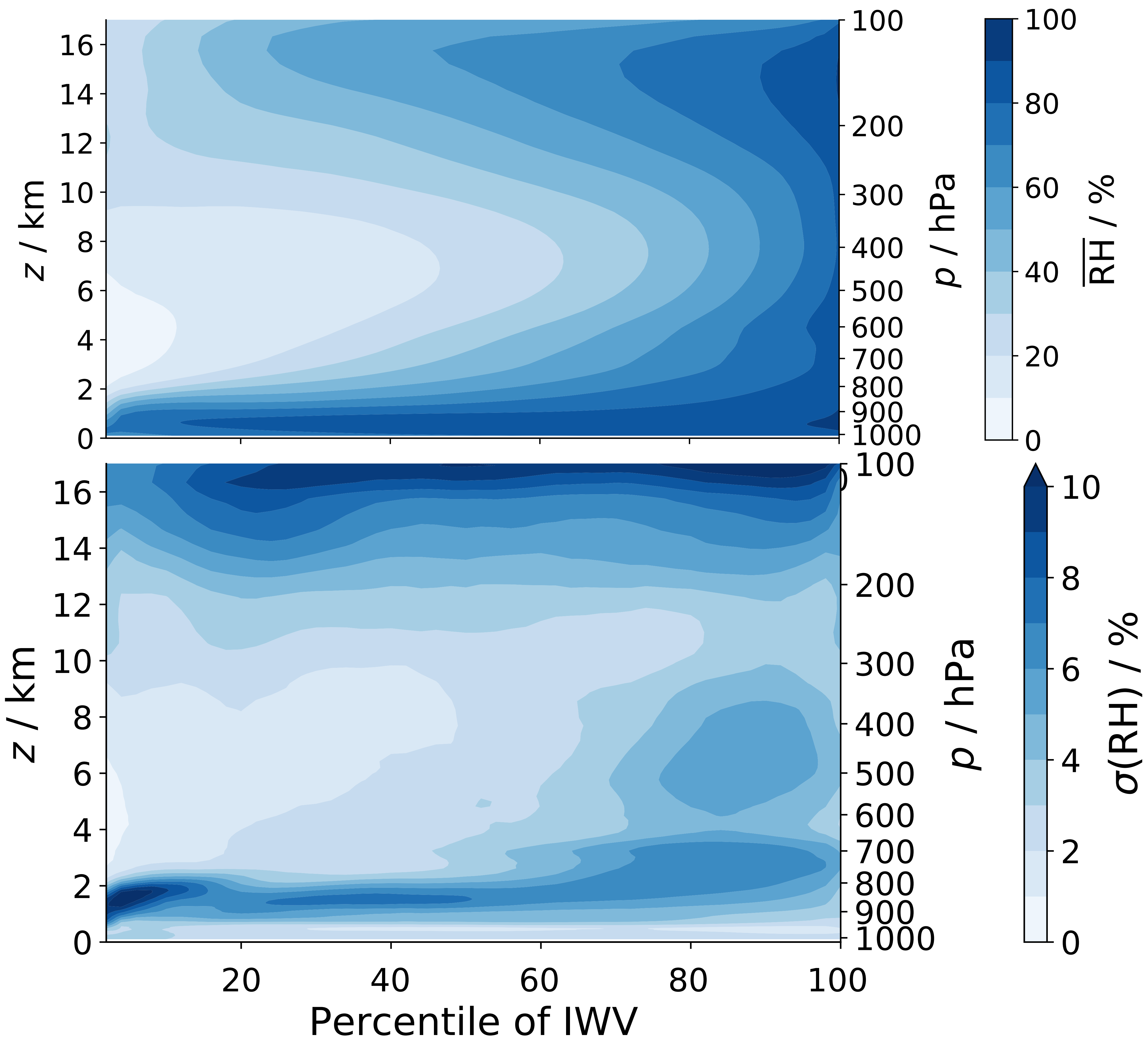

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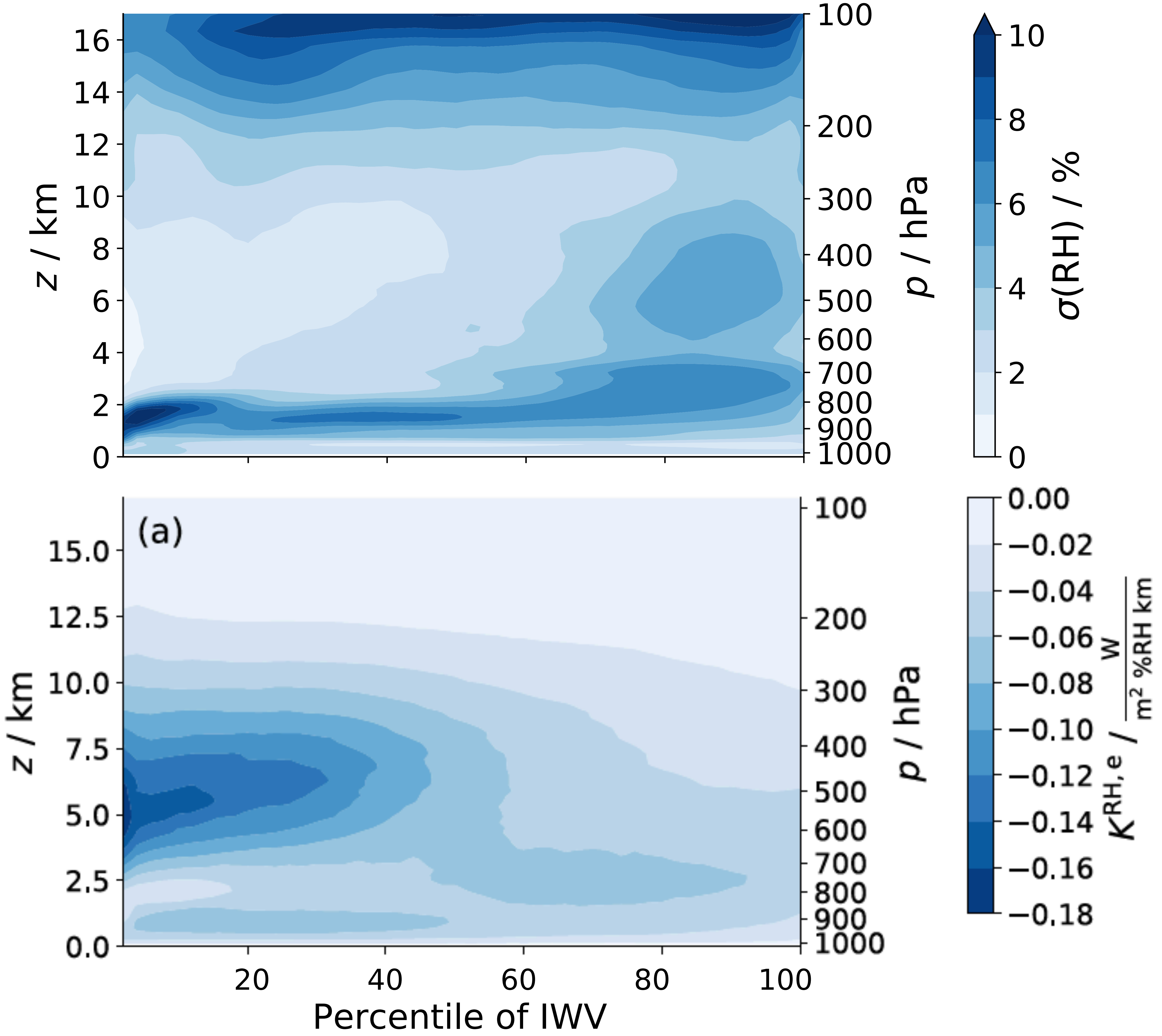
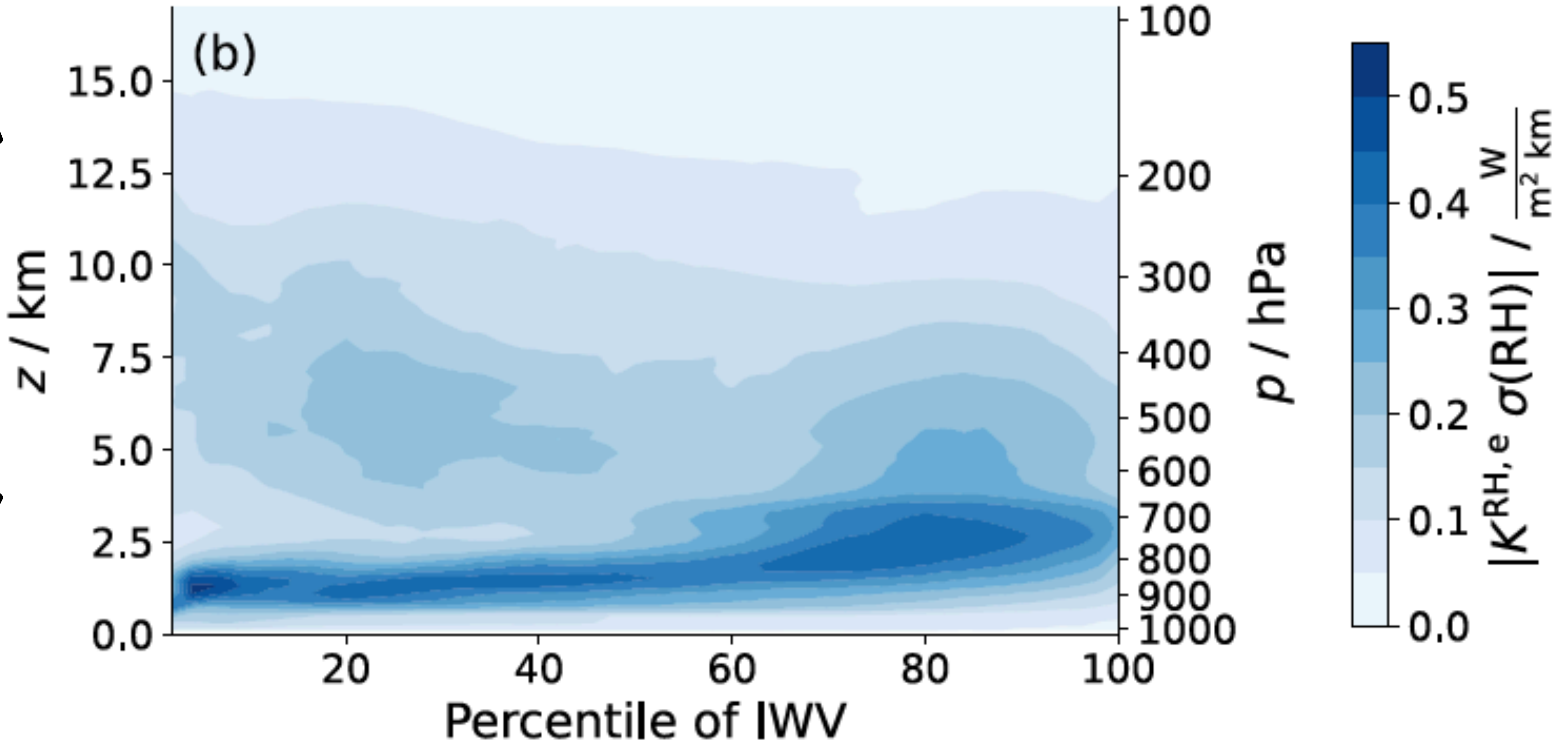
Effect of humidity spread on clear-sky outgoing longwave radiation



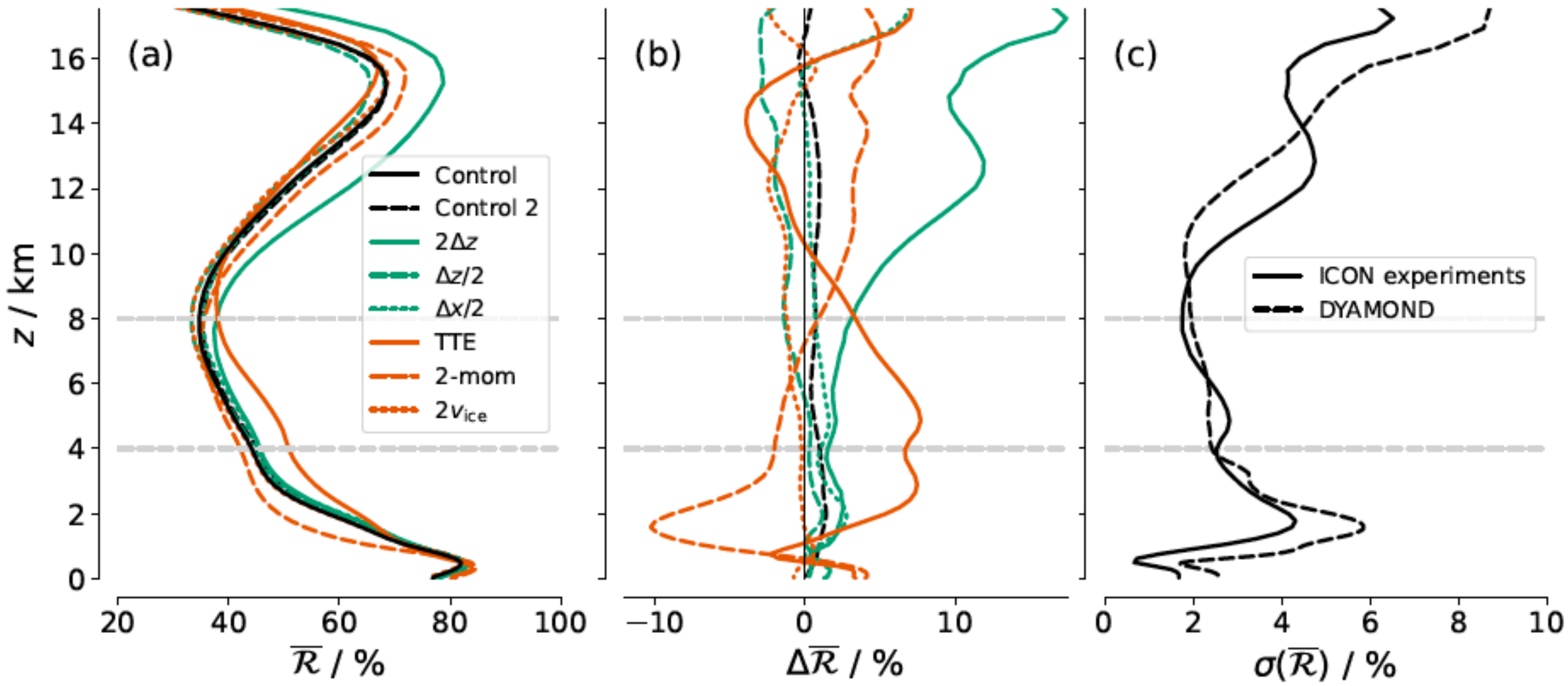
X



The remaining humidity differences still cause a non-negligible (~1.2 Wm^{-2}) spread in tropical mean clear-sky outgoing longwave radiation.

(Lang et al., 2021)

Parameterizations are major source for relative humidity spread



Tropical relative humidity in a global storm-resolving model is robust to changes in model resolution and parameterizations.

(Lang et al., in review)

Which physical processes control the humidity distribution?

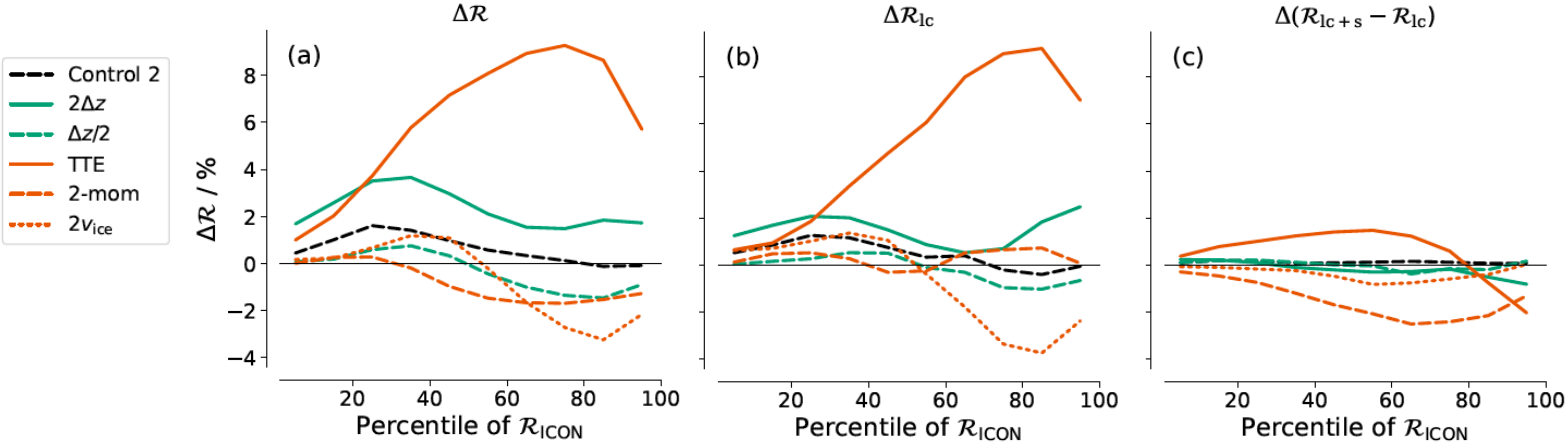
last-saturation model:
(e.g., Pierrehumbert et al., 2006; Sherwood et al., 2010)

$$\mathcal{R} = \frac{q_{\mathrm{lc}}}{q_{\mathrm{t}}^{*}}$$

simulated RH difference

reconstructed RH difference due to last-saturation model

effect of moisture sources and sinks after last saturation



Mid-tropospheric humidity differences are well-explained by differences in their last saturation points, except for a change in the microphysics scheme.

(Lang et al., in review)

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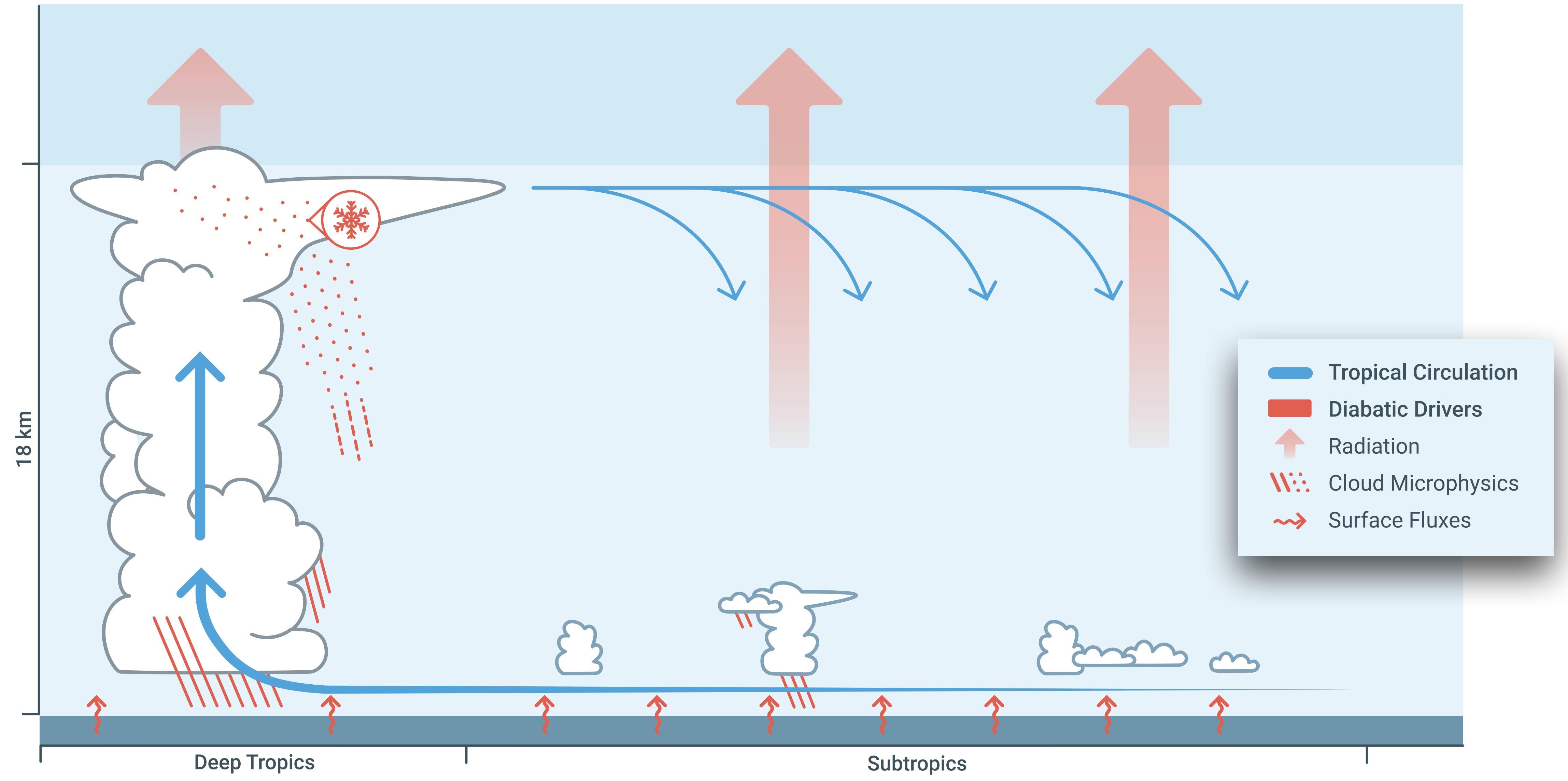
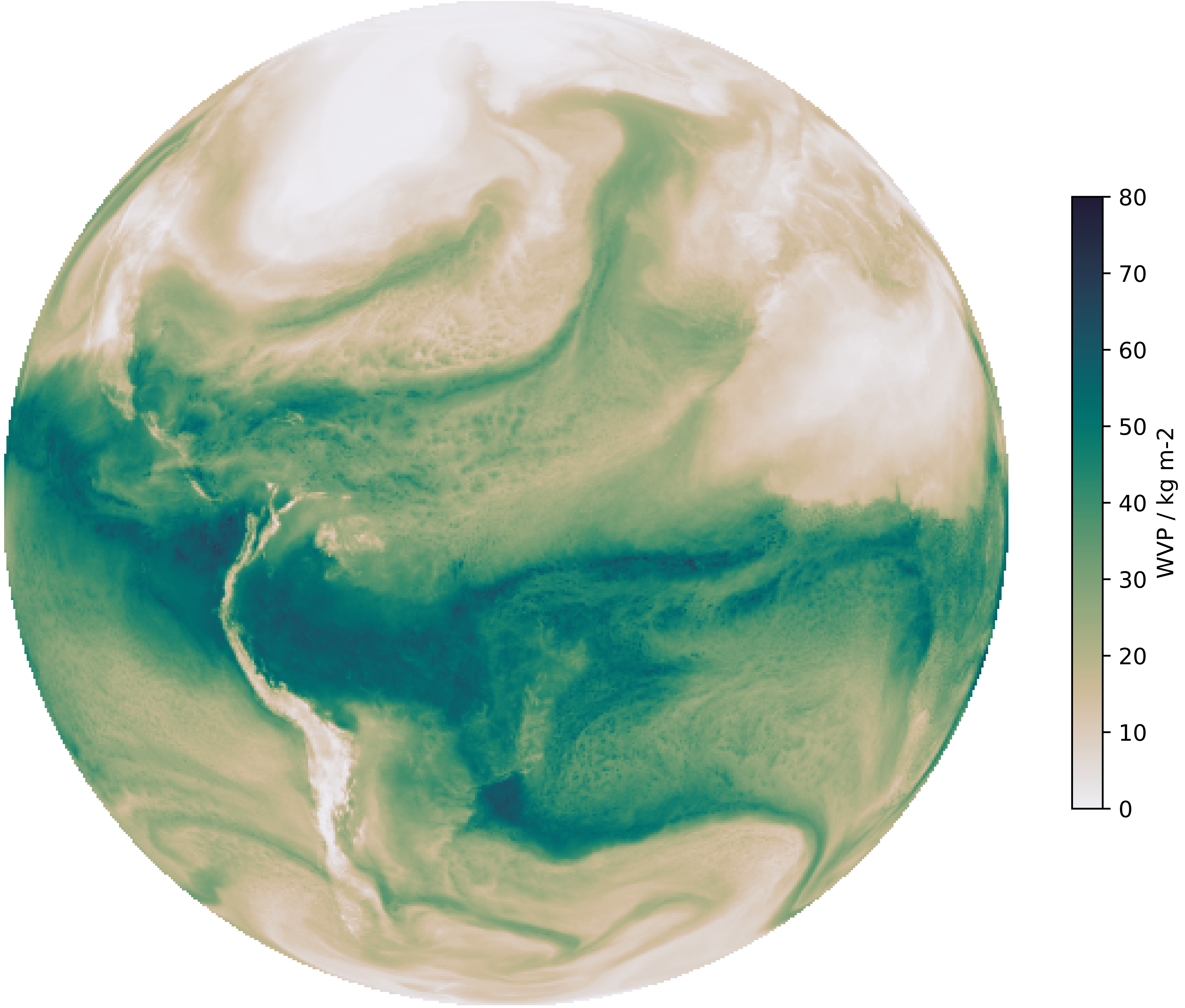


How do microphysical choices affect the energy budget of the tropics?

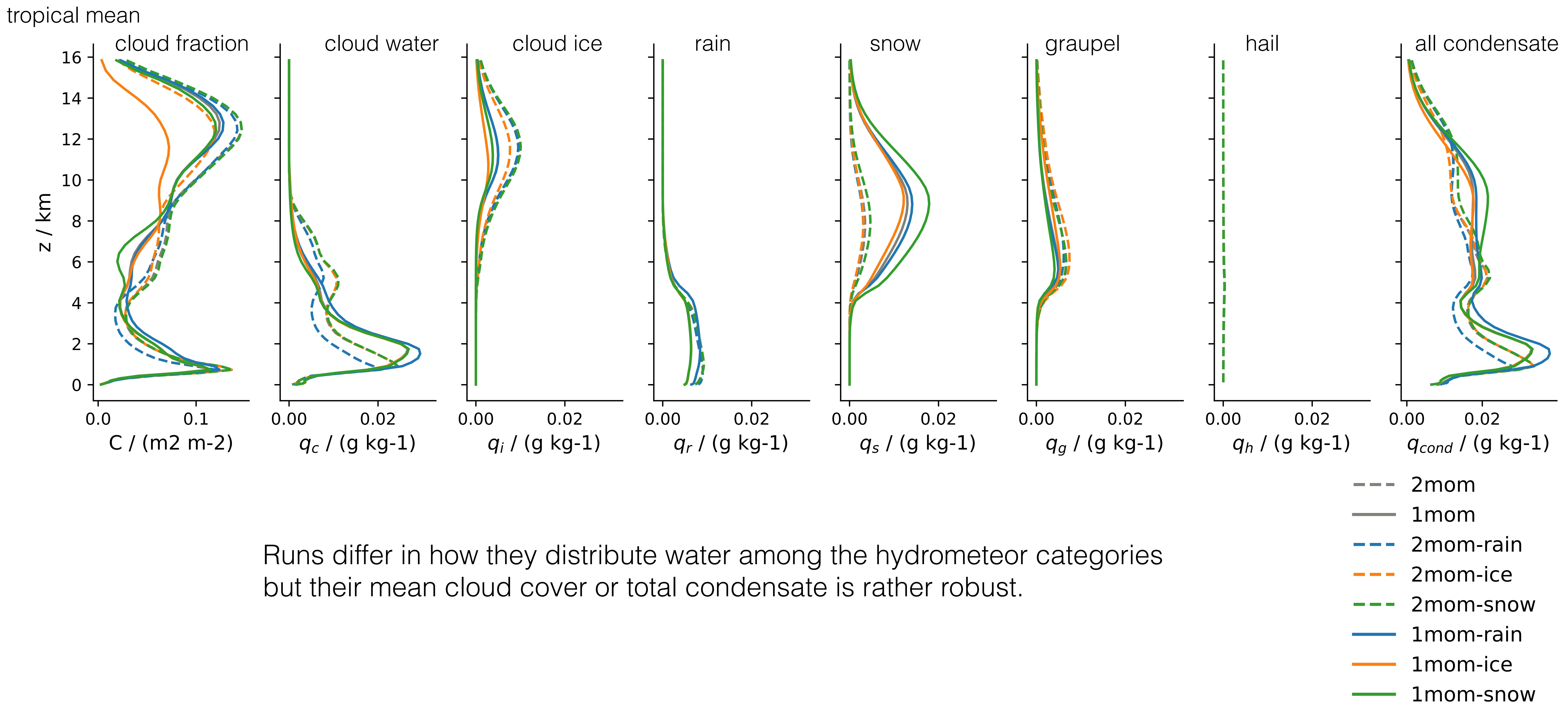
global simulation with ICON at 5 km grid spacing

- with a one- and a two-moment microphysics scheme (Baldauf et al., 2011; based on Seifert and Beheng, 2006)
- perturbing one parameter of one hydrometeor category

8 simulations: 1mom
1mom-rain
1mom-ice
1mom-snow
2mom
2mom-rain
2mom-ice
2mom-snow

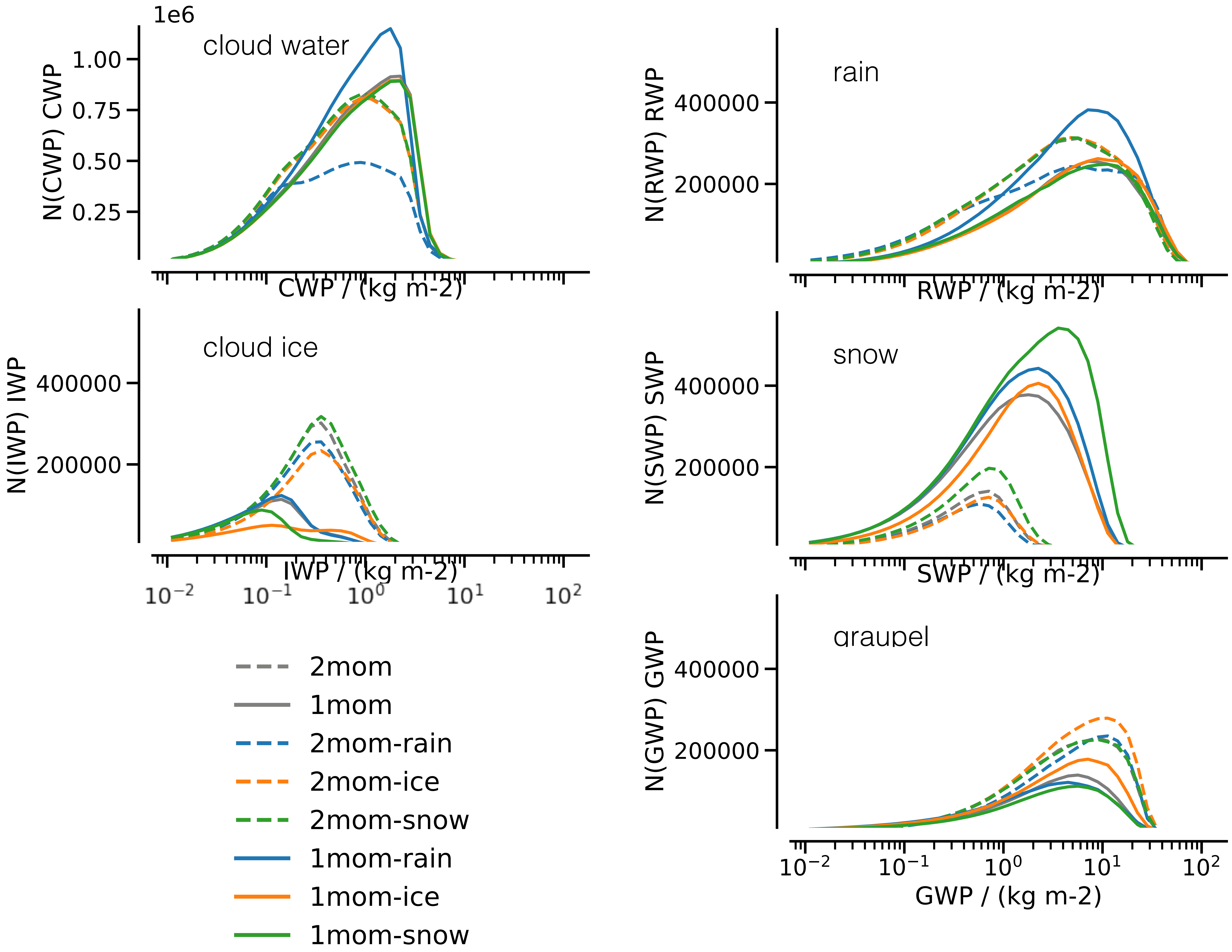


The two-moment scheme less easily converts ice to snow



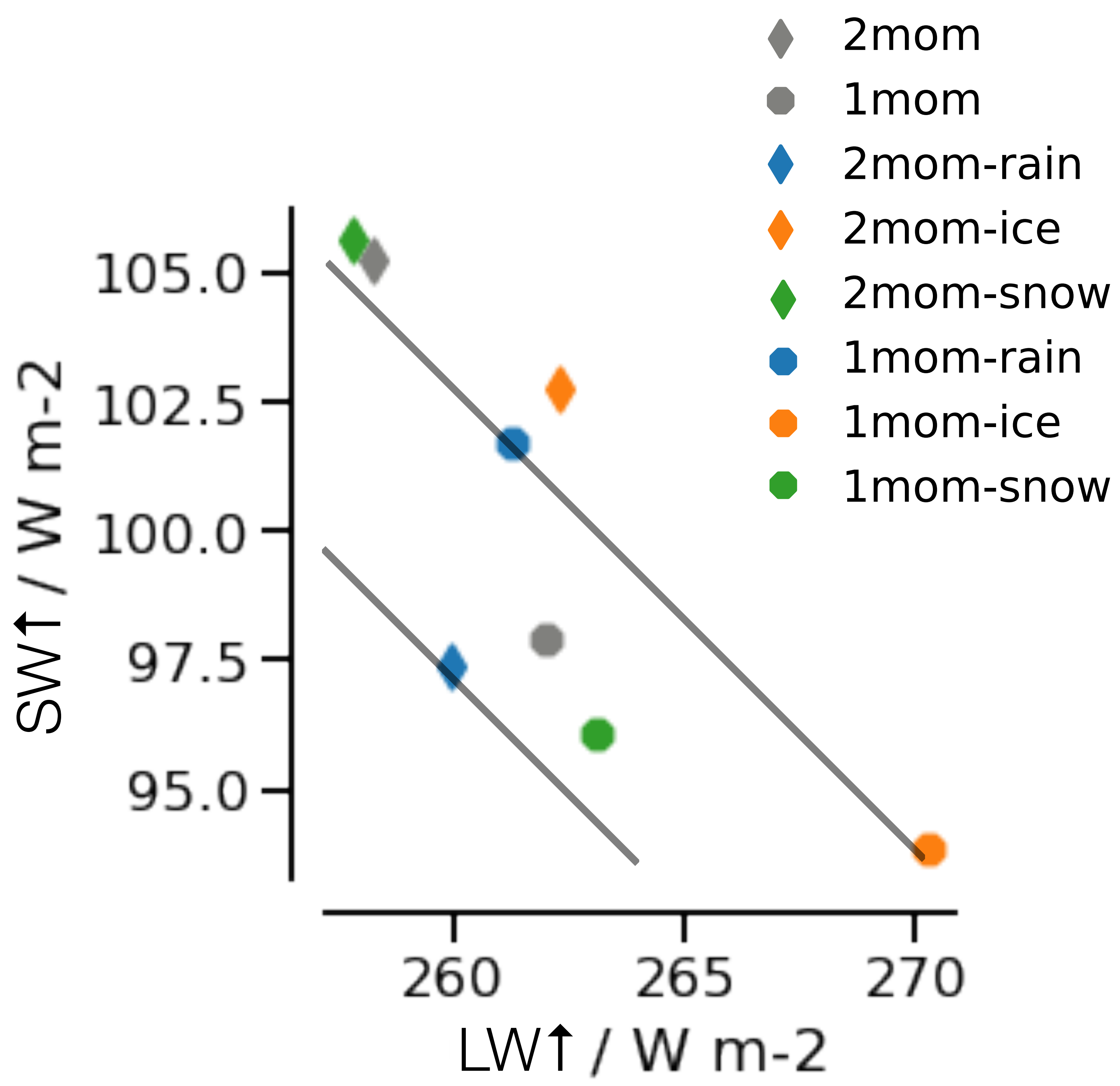
Runs differ in how they distribute water among the hydrometeor categories but their mean cloud cover or total condensate is rather robust.

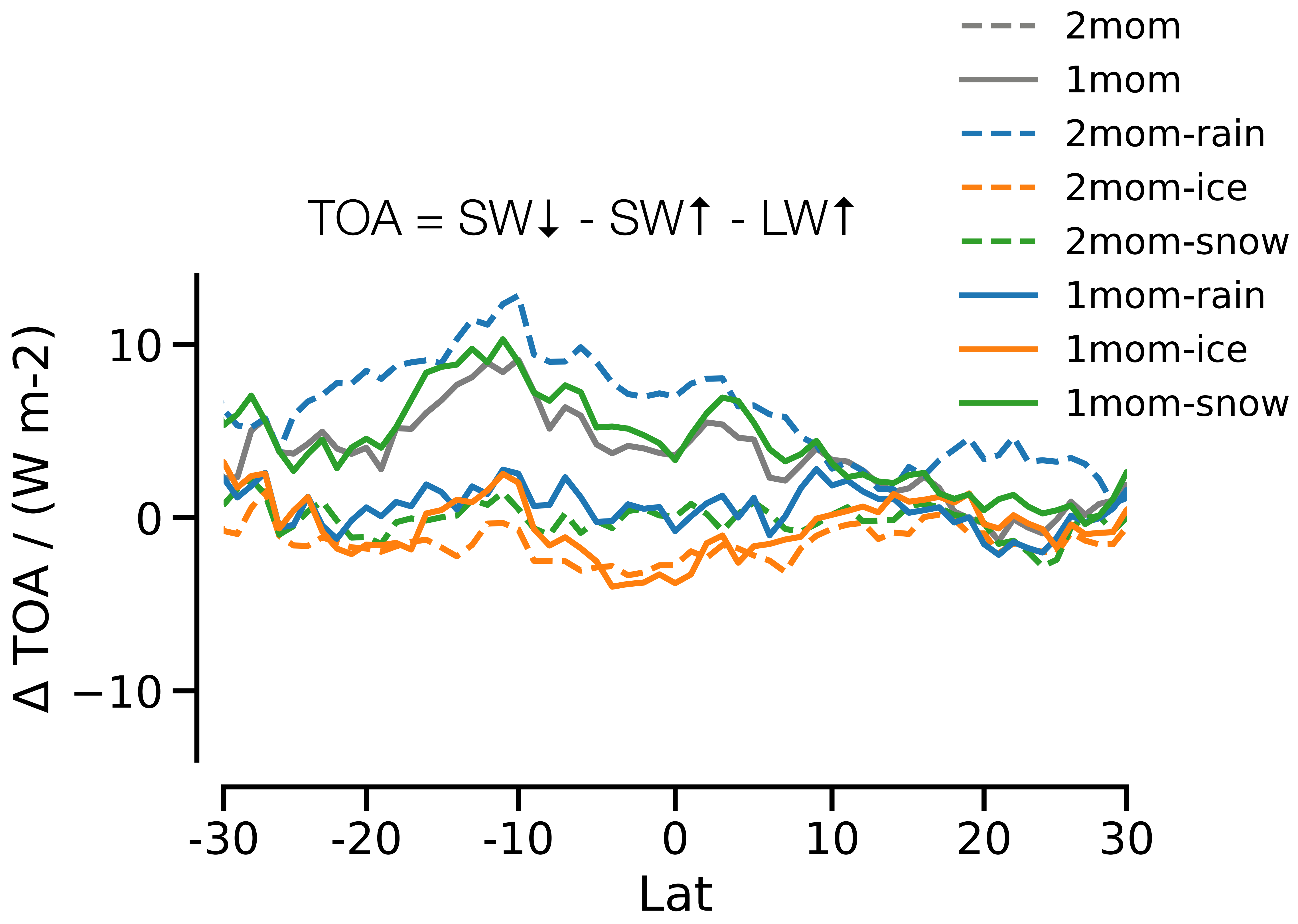
Cloud ice occurs in higher concentrations in the two-moment scheme



We expect an effect on the heat budget because in ICON ice is radiatively active while snow is not.

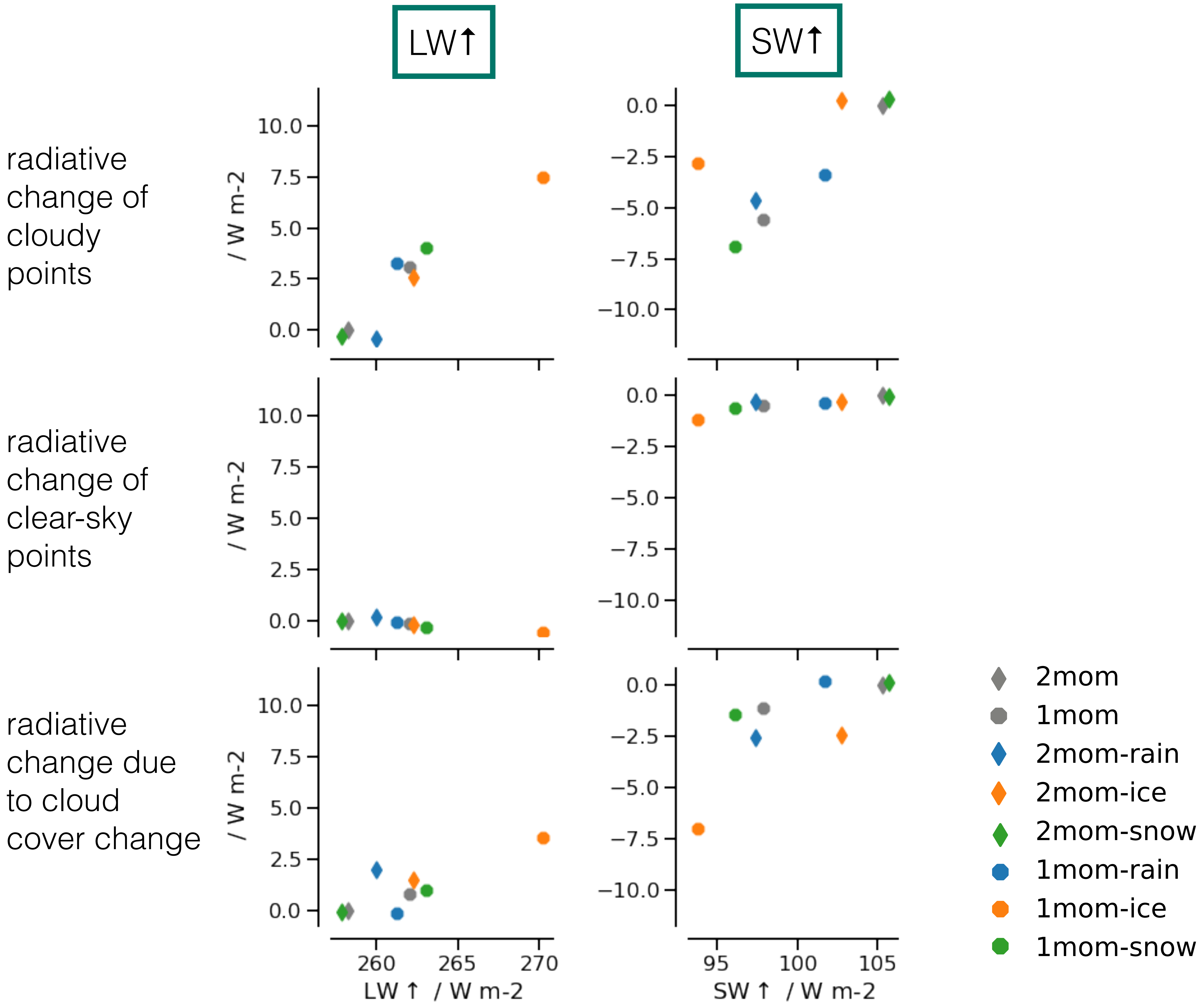
Radiation balance at the top of the atmosphere (TOA)





While microphysical effects largely balance for the net TOA flux, differences of a few W m-2 remain.

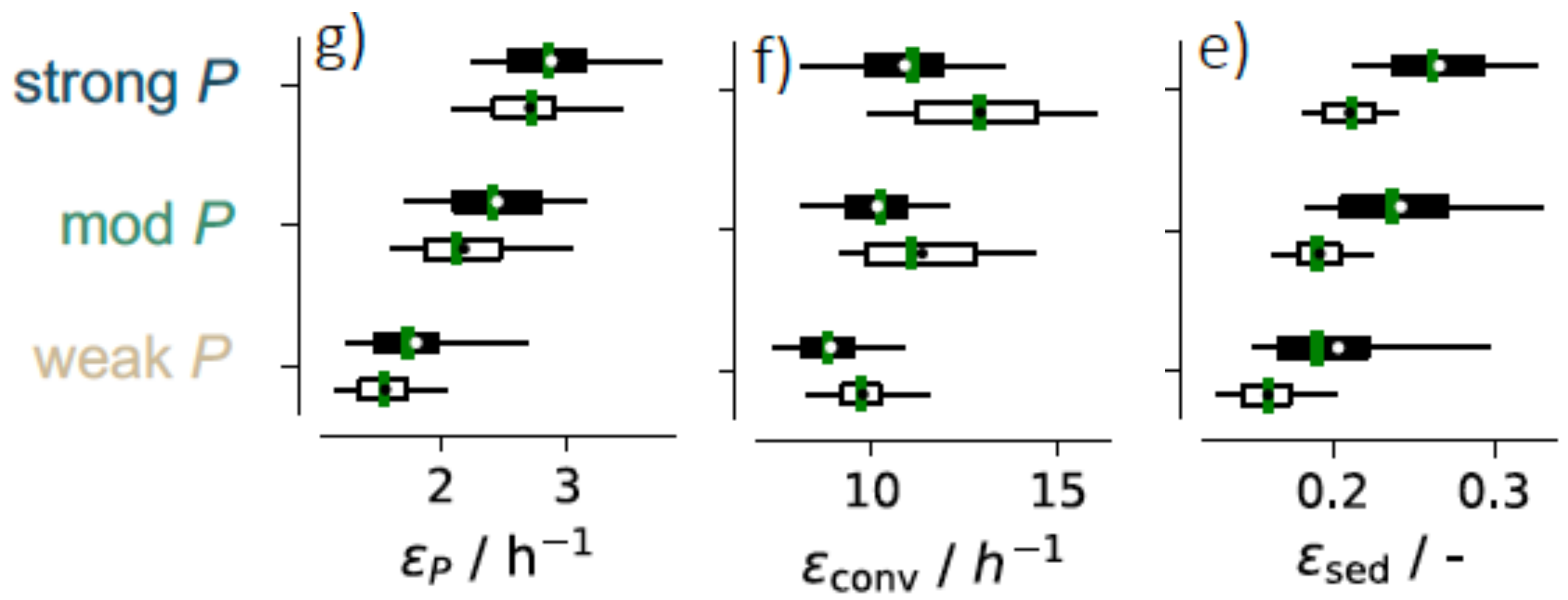
Decomposition of radiative changes at TOA



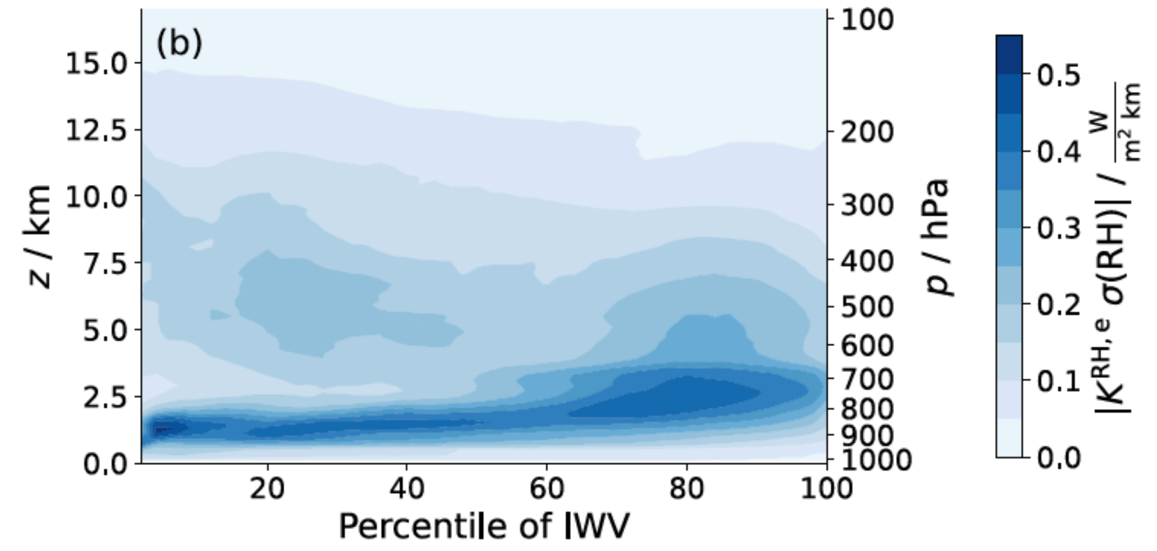
Changes in radiative properties of cloudy points dominate changes in the radiative balance at TOA.

On the interplay of tropical clouds, humidity and the energy budget

Organisation of shallow trade wind convection is of second order importance for precipitation amount but affects the pathway to precipitation: as organisation strengthens, less efficient conversion from cloud condensate to rain is compensated by more efficient sedimentation.



In global storm-resolving models the spread in tropical humidity is substantially reduced but still causes a non-negligible (~1.2 Wm^{-2}) spread in tropical mean clear-sky outgoing longwave radiation. Sensitivity experiments suggest that parameterizations are the major source of relative humidity spread.



Tropical cloud cover and total condensate are robust to changes in microphysical parameters but a shift from ice to snow affects the radiative properties of cloudy grid points.