Small-scale processes and their coupling to radiation in tropical cirrus: A key to anvil climate feedback?

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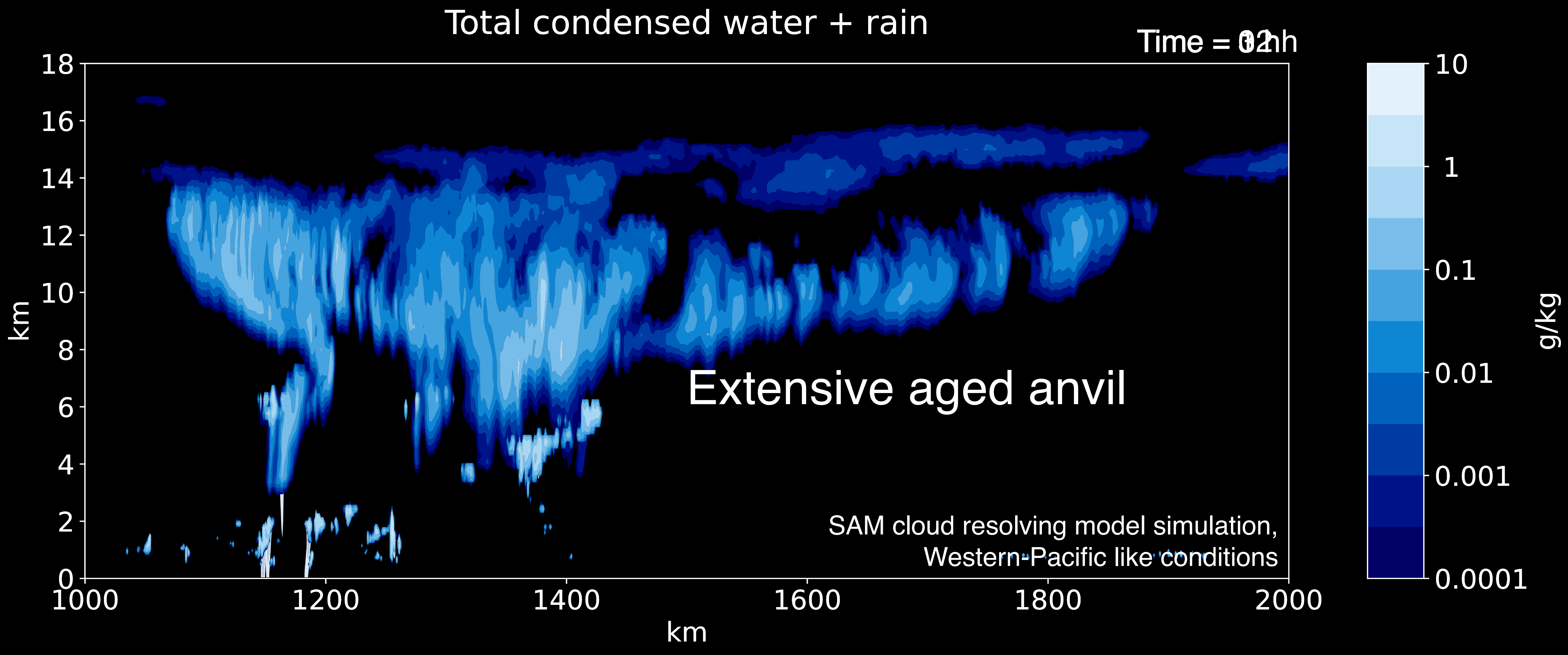
photo: Jurij Struna
@ Piran, Slovenia

Actively convecting & precipitating part covers only a small fraction of the tropics (~1%)

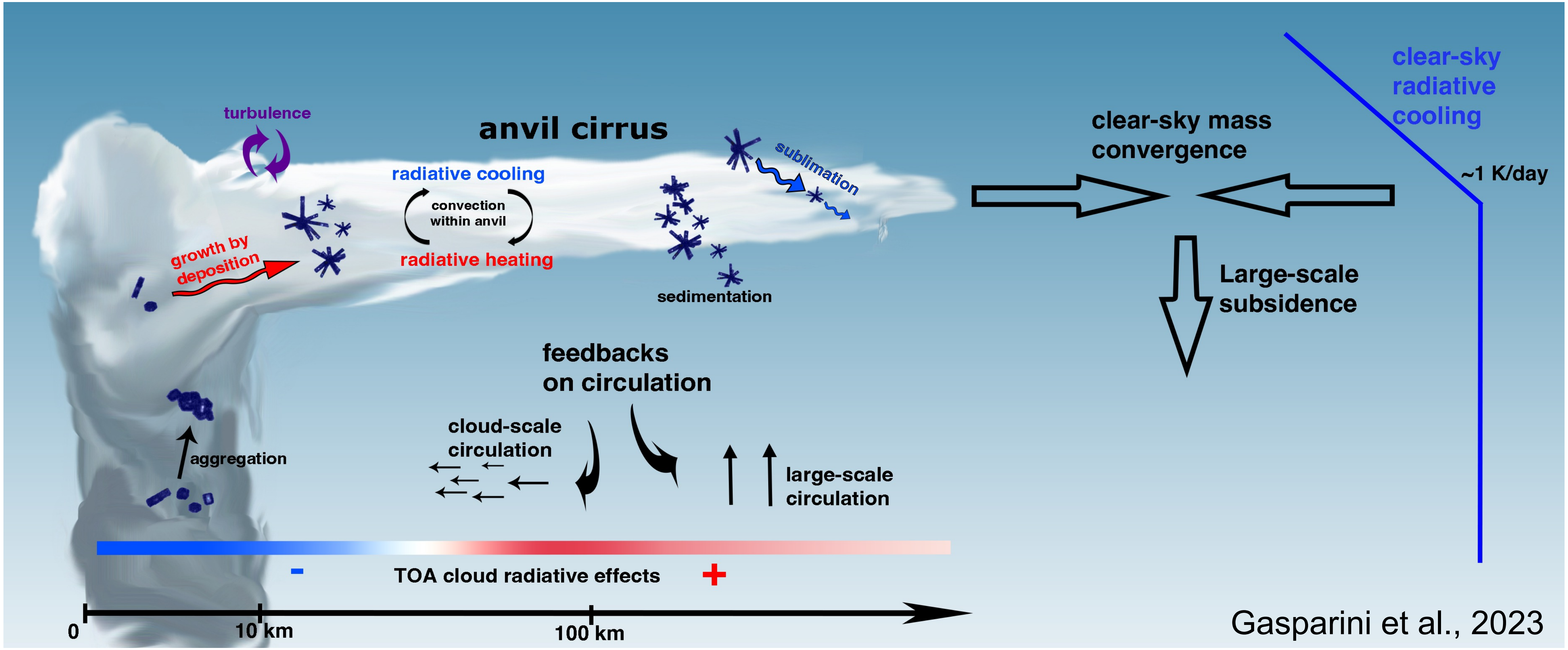
On the other hand, aged clouds spread, thin, and cover about 30% of the area of the tropics

Anvil lifecycle: from reflective, rainy convective cores to long-lived semi-transparent thin cirrus



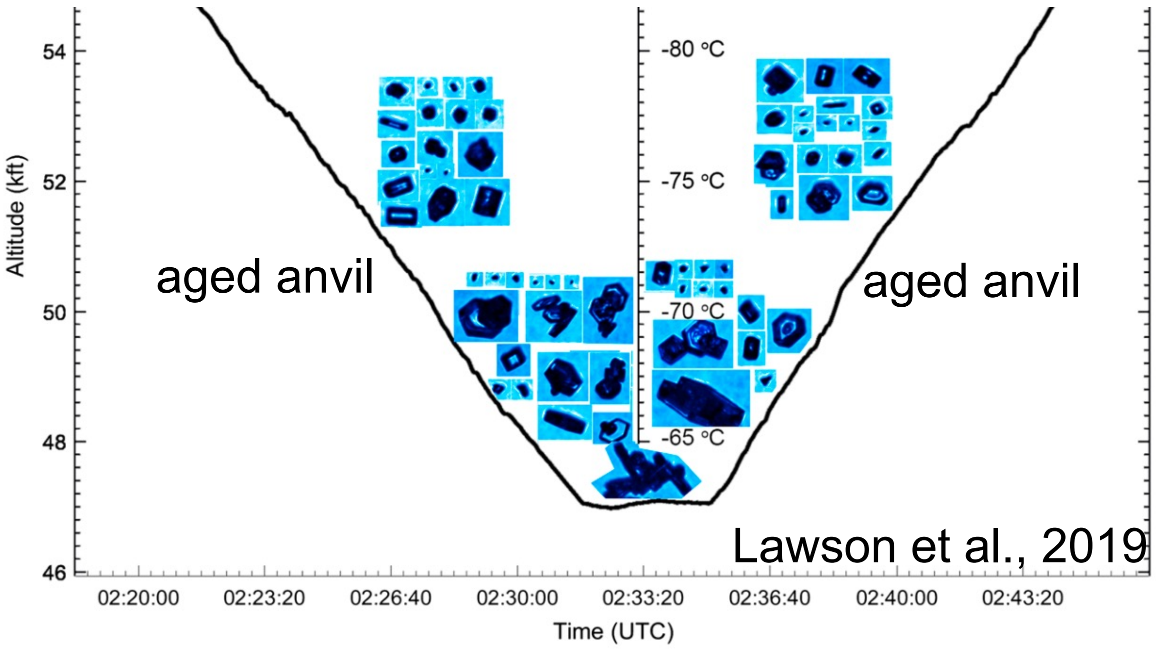
Part 1: What shapes anvil cloud properties?

A number of processes are at work, many interacting with each other and the large-scale environment

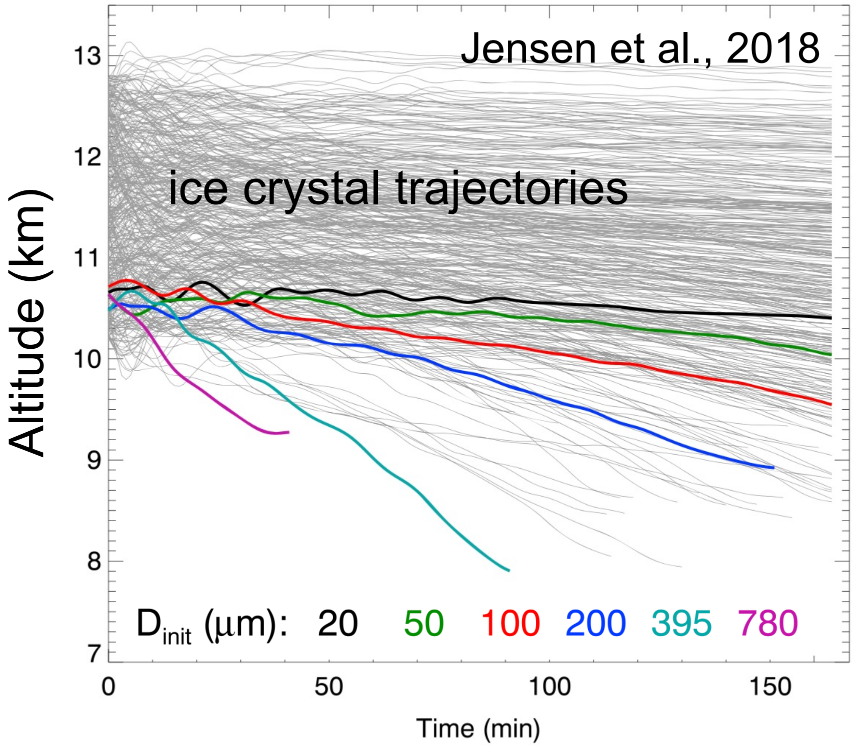


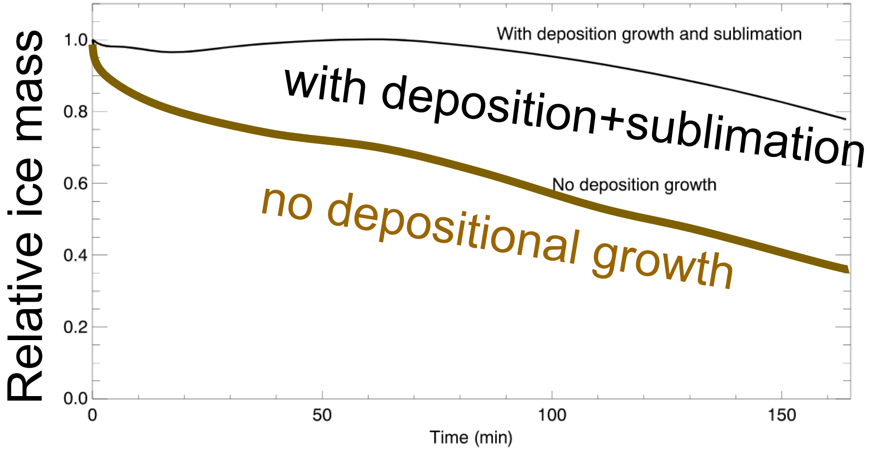
Sedimentation is quick in removing large crystals

- Large ice crystals sediment (precipitate) out in the first 2-3 hours
- Ice mass loss partially counteracted by **depositional growth**



active convection





Most ice crystals should fall to lower levels after 5-10 hours

Typical ice sedimentation:

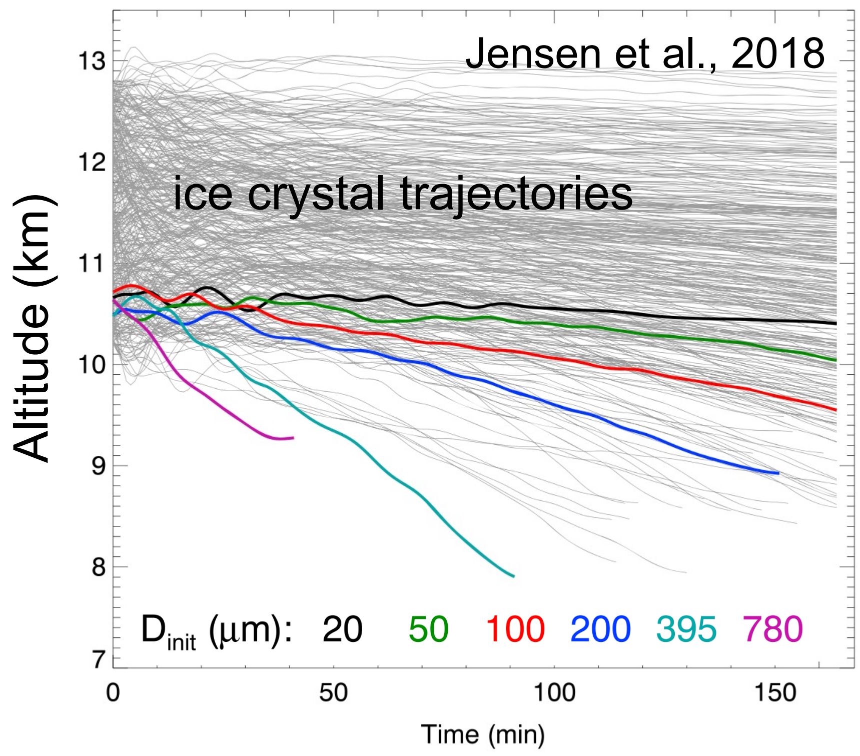
40 μm diameter (very small): 4 cm/s
- **1.5 km/10 hours**

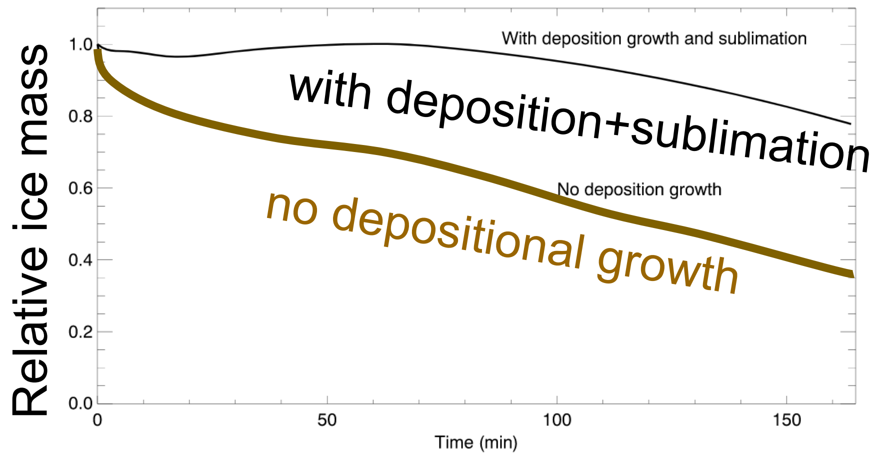
80 μm diameter:
- **3 km/10 hours**

150 μm diameter (large): 15 – 30 cm/s
- **6 – 11 km/10 hours**

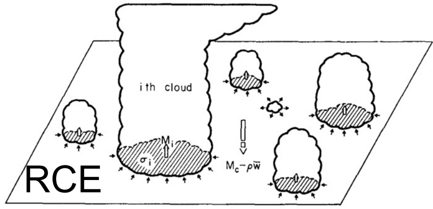
Note: humidity typically quite low below cloud layers (➔ **sublimation**)

But tropical anvil lifetimes are way longer
What keeps them aloft?



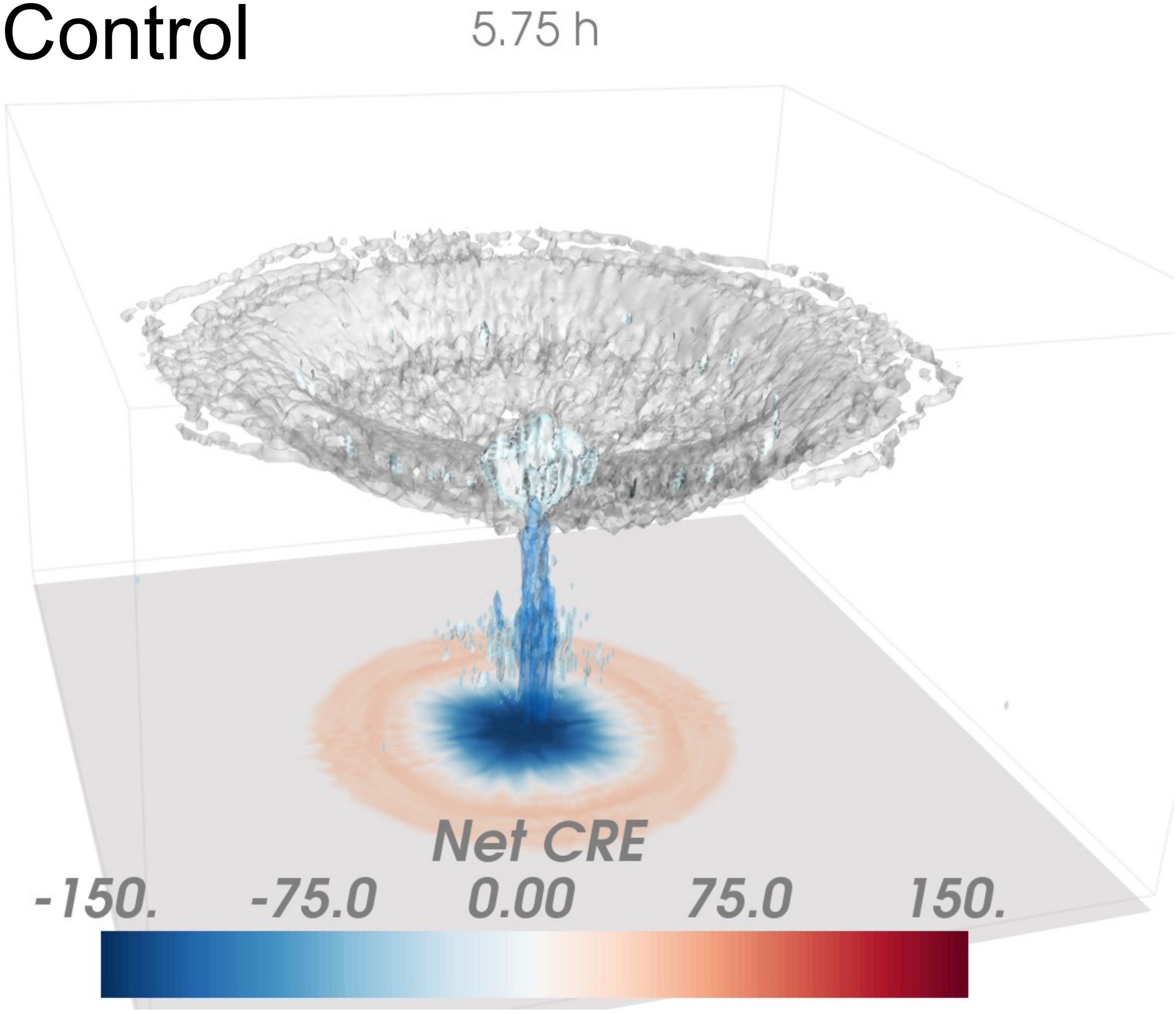


Cloud radiative heating (CRH) thins and spreads the anvil

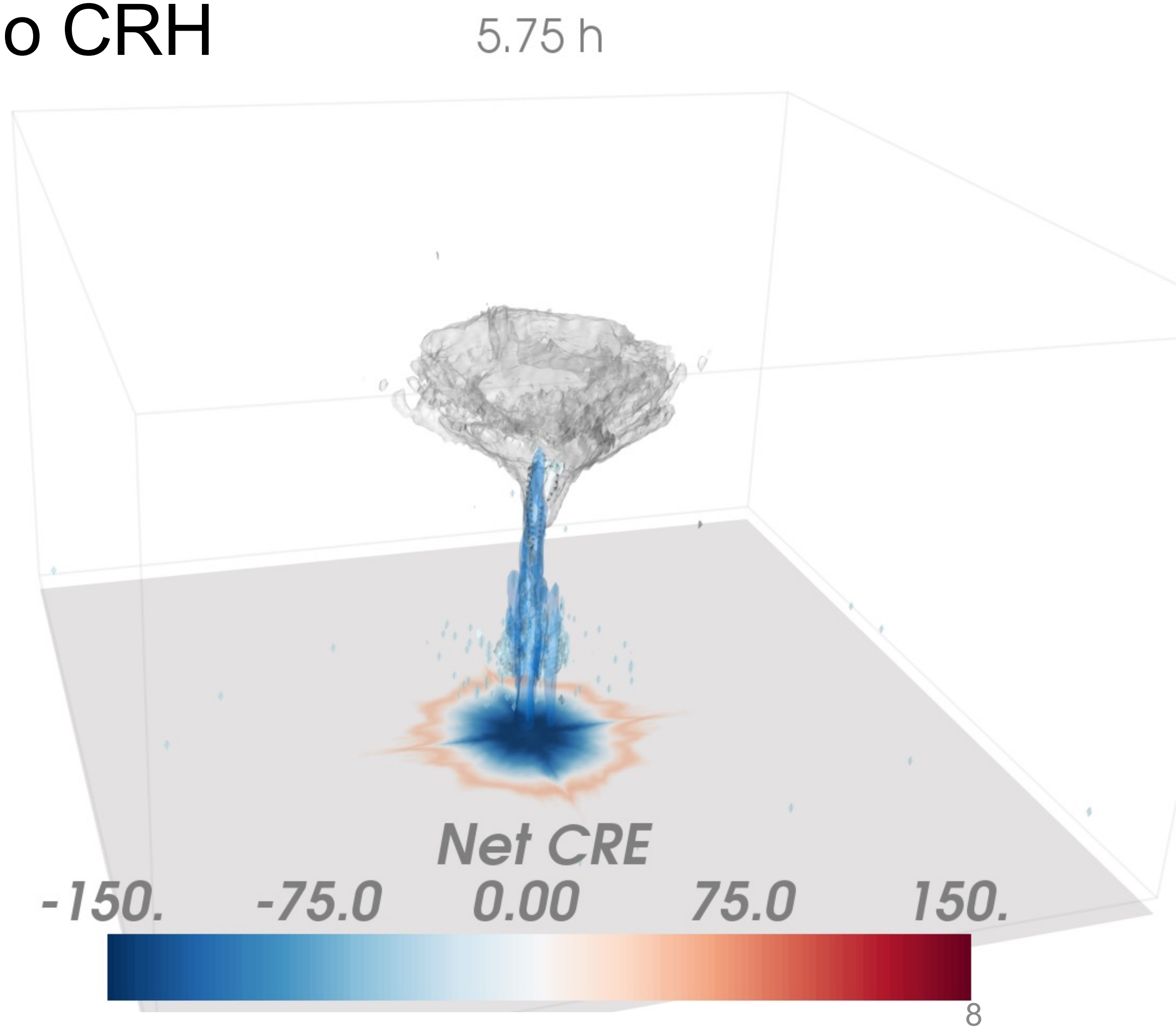


SAM cloud resolving model simulation, “convection in a box” setup

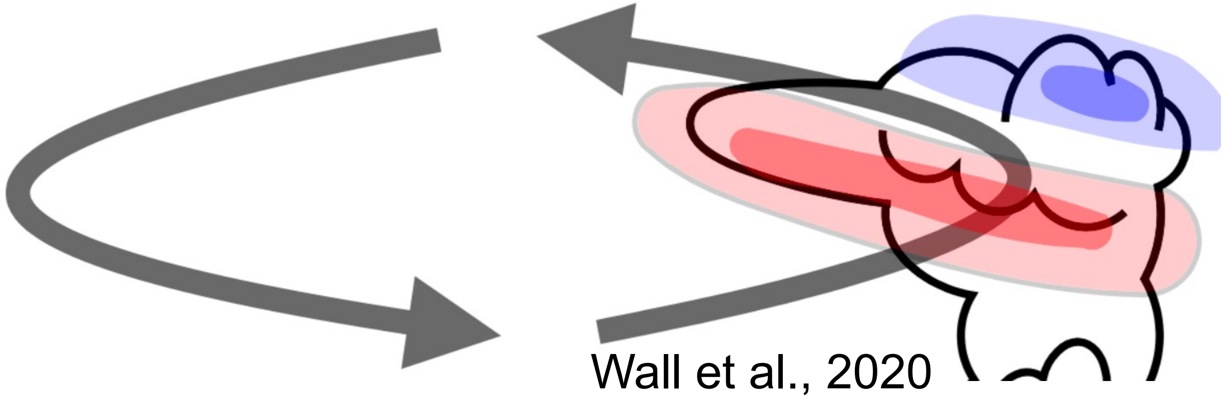
Control



No CRH



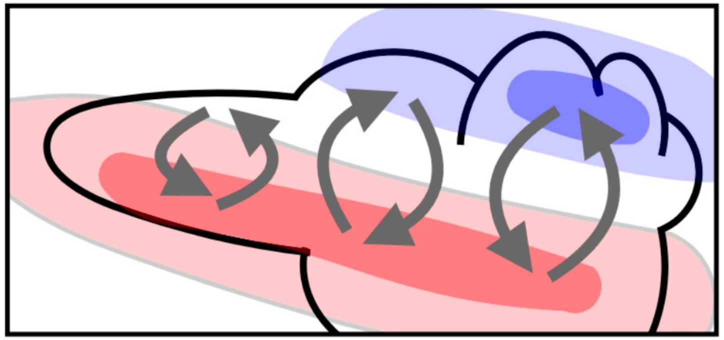
Anvil spreading


Wall et al., 2020

How does cloud radiative heating influence the spreading?

- Radiatively-driven circulation **counteracts sedimentation**
- Also drives cloud spreading
- Supported based on idealized & realistic modeling (e.g. Ruppert et al., 2019) + observations (Deng and Mace, 2008, Wall et al., 2020)

Microphysical cycling



Wall et al., 2020

How does cloud radiative heating influence the spreading?

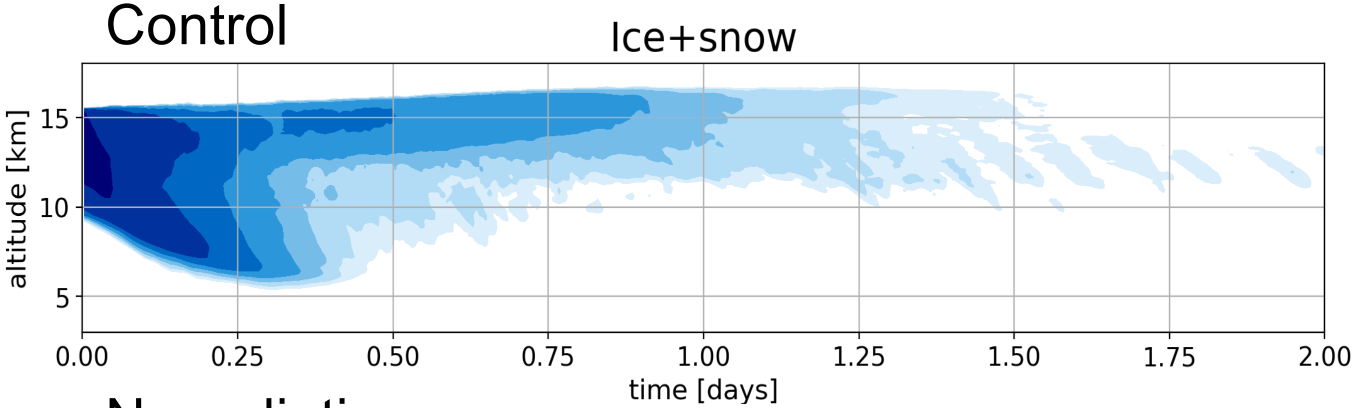
- Heating dipole drives convection within anvils
- Strong enough to nucleate ice crystals
- Small, stay up for very long

Hartmann et al., 2018, Sokol and Hartmann, 2020

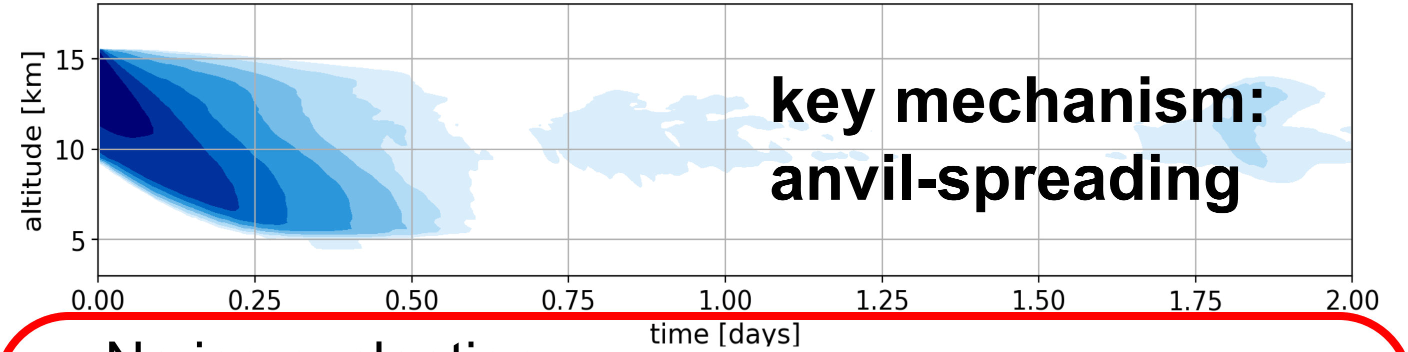
➔ **disputed, hard to veryify**

Radiation and ice nucleation play important roles in anvil lifecycle

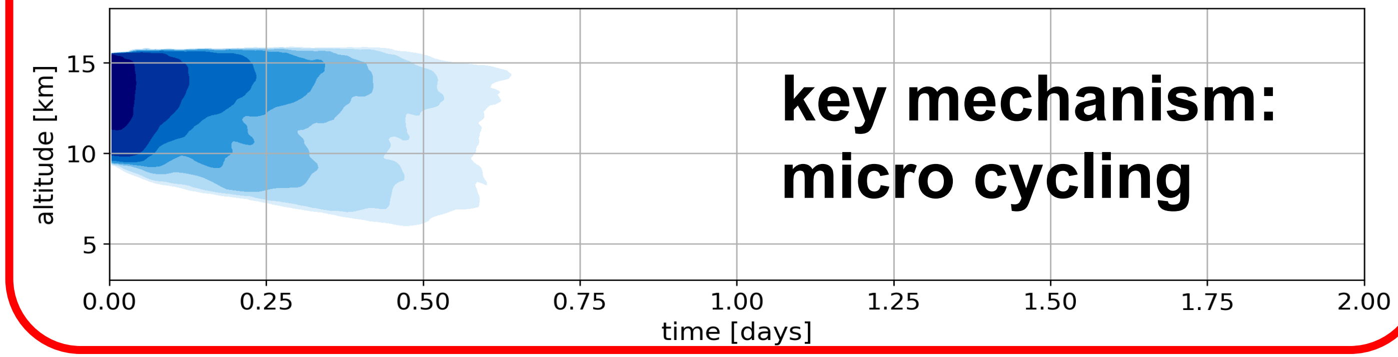
Control

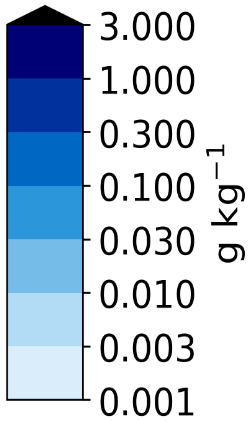


No radiation



No ice nucleation





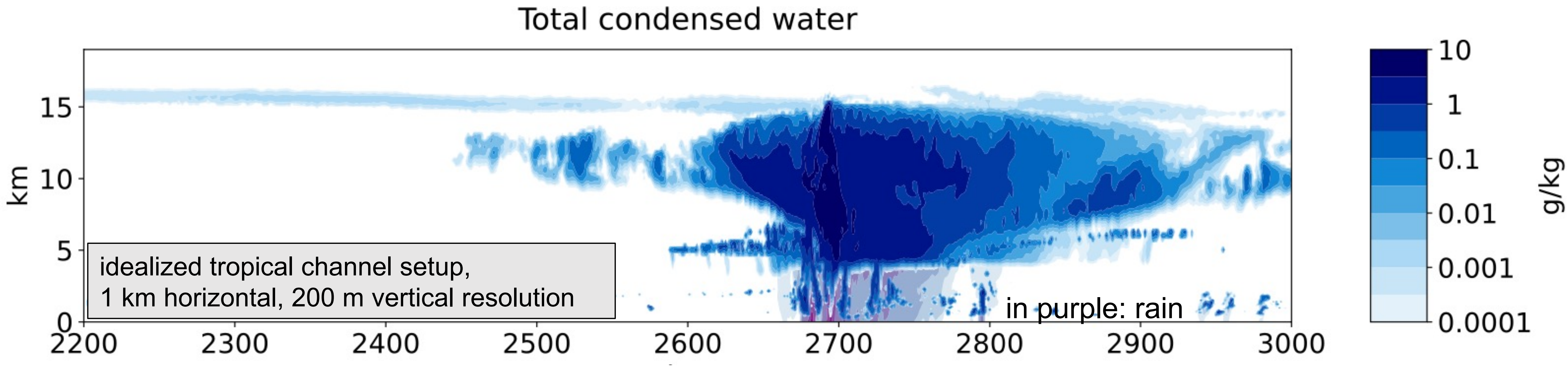
Ice nucleation (driven by radiation-generated turbulence) is crucial in prolonging the anvil cloud lifetime.

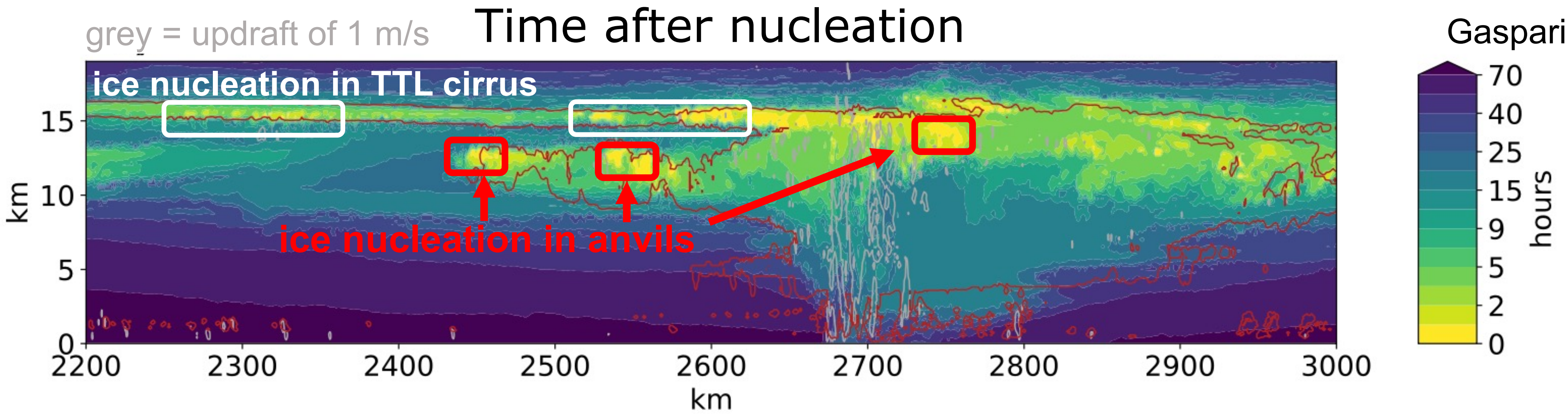
Hartmann et al., 2018

Beware:
very idealized modeling!

Ice nucleation occurs quite frequently within aged anvils

SAM model tropical channel simulations ➔ **much more realistic modeling**





Gasparini et al., 2025

Part I: What shapes anvil properties?

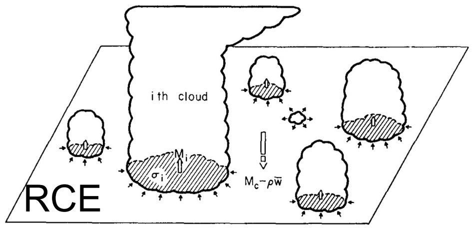
Anvils results from interactions of multiple processes:

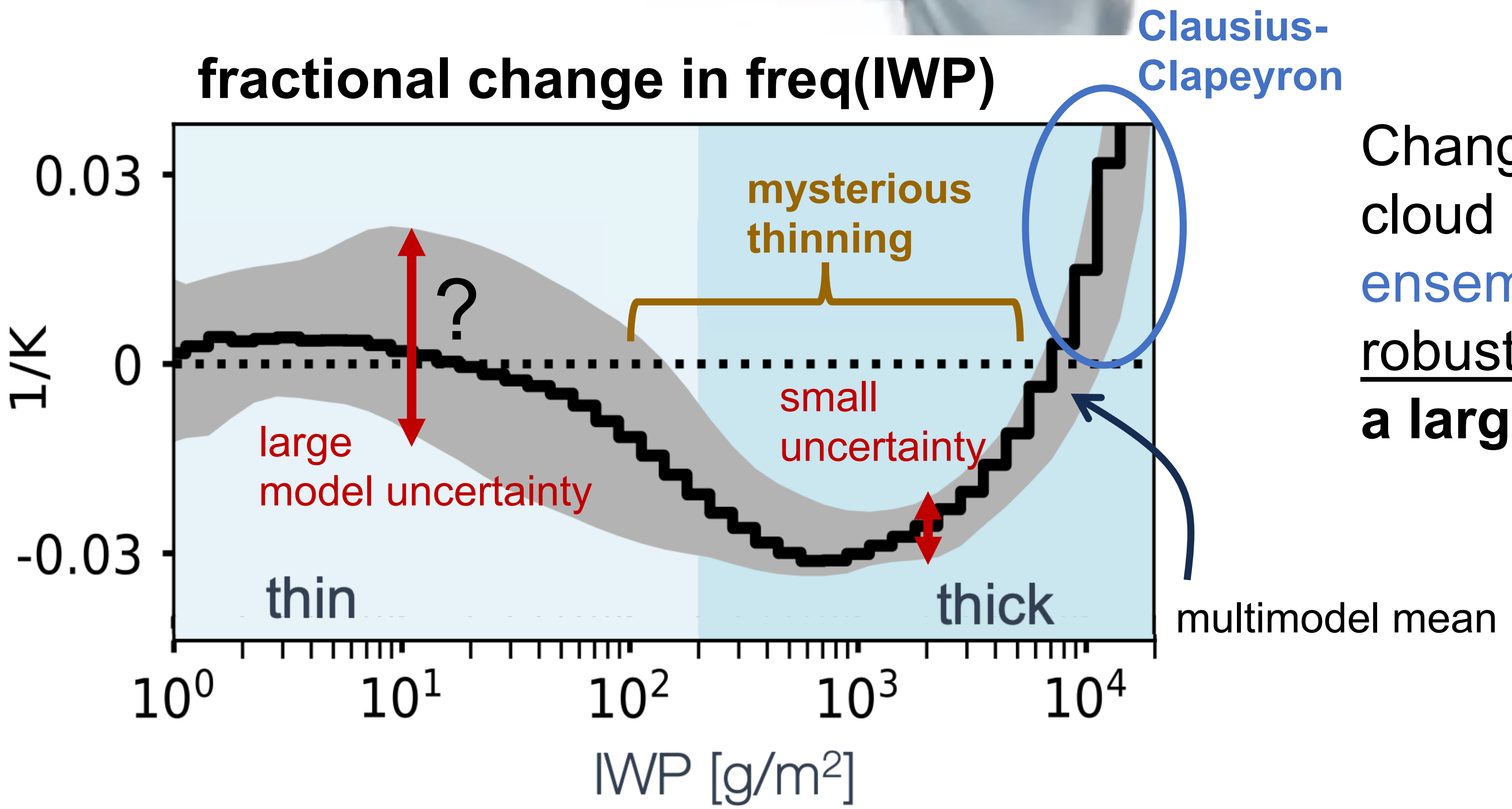
- **sedimentation/precipitation formation**
- **deposition/sublimation**
- **ice nucleation (?)**

➔ Cloud radiative heating as an "impact multiplier"

Part II: Anvil responses to global warming

Uncertainties in anvil responses to warming largest for thin anvils

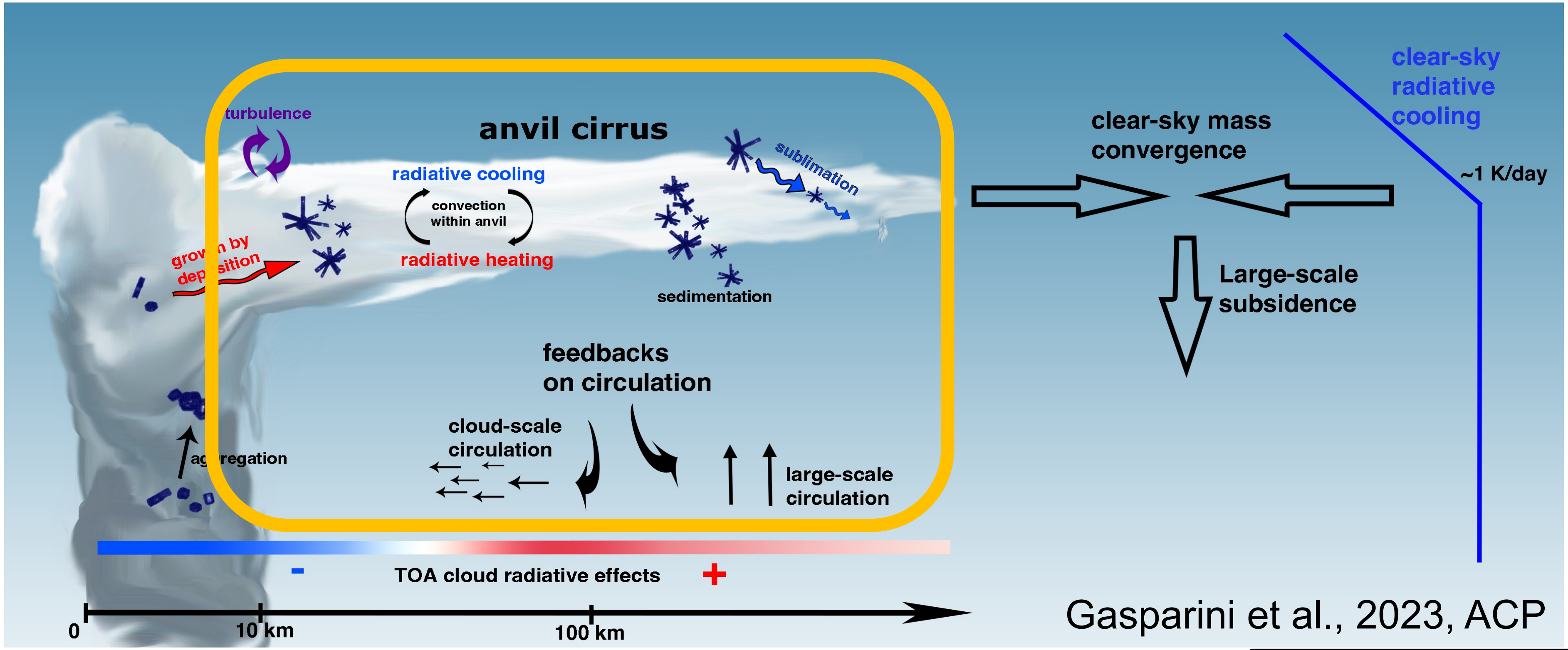




Changes in the amount of anvil cloud ice from a multimodel ensemble:
robust response for thick anvils,
a large spread for thin anvils

Sokol et al., 2024

Uncertainties in anvil responses to warming largest for thin anvils

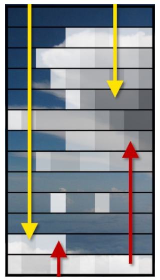


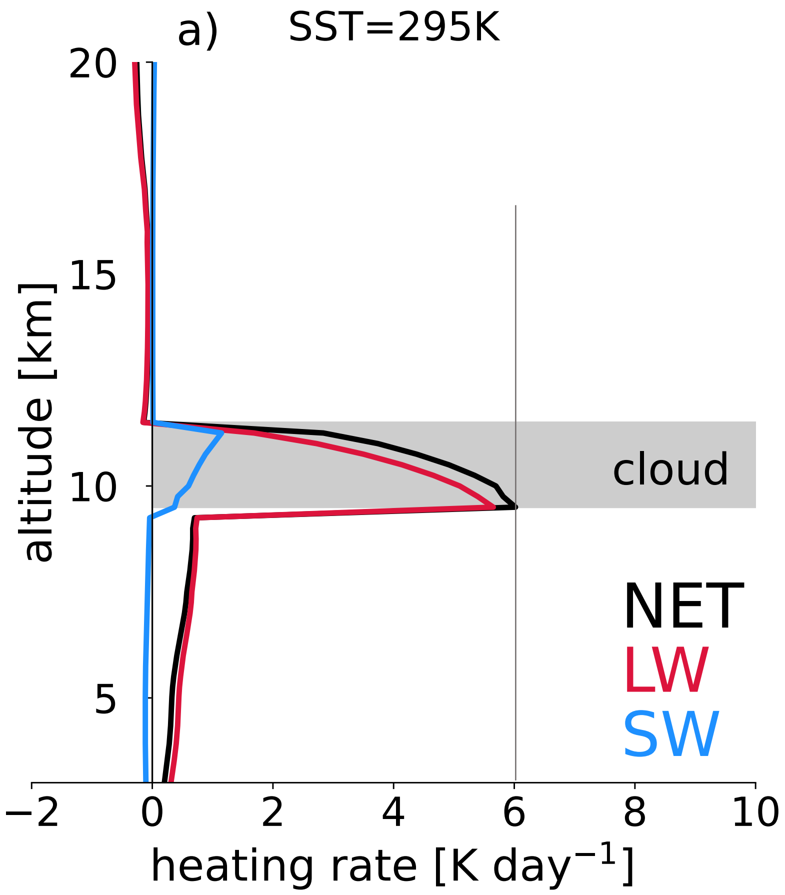
Known (convection): more of intense convection, stronger updrafts

Unknown: Microphysics and its interaction with radiation

Known (large-scale environment): more stable upper troposphere, unfavorable for anvil clouds

Radiative transfer calculations show an increase in CRH





Cloud with **FIXED** properties

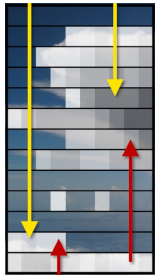
(cloud optical depth = 1,

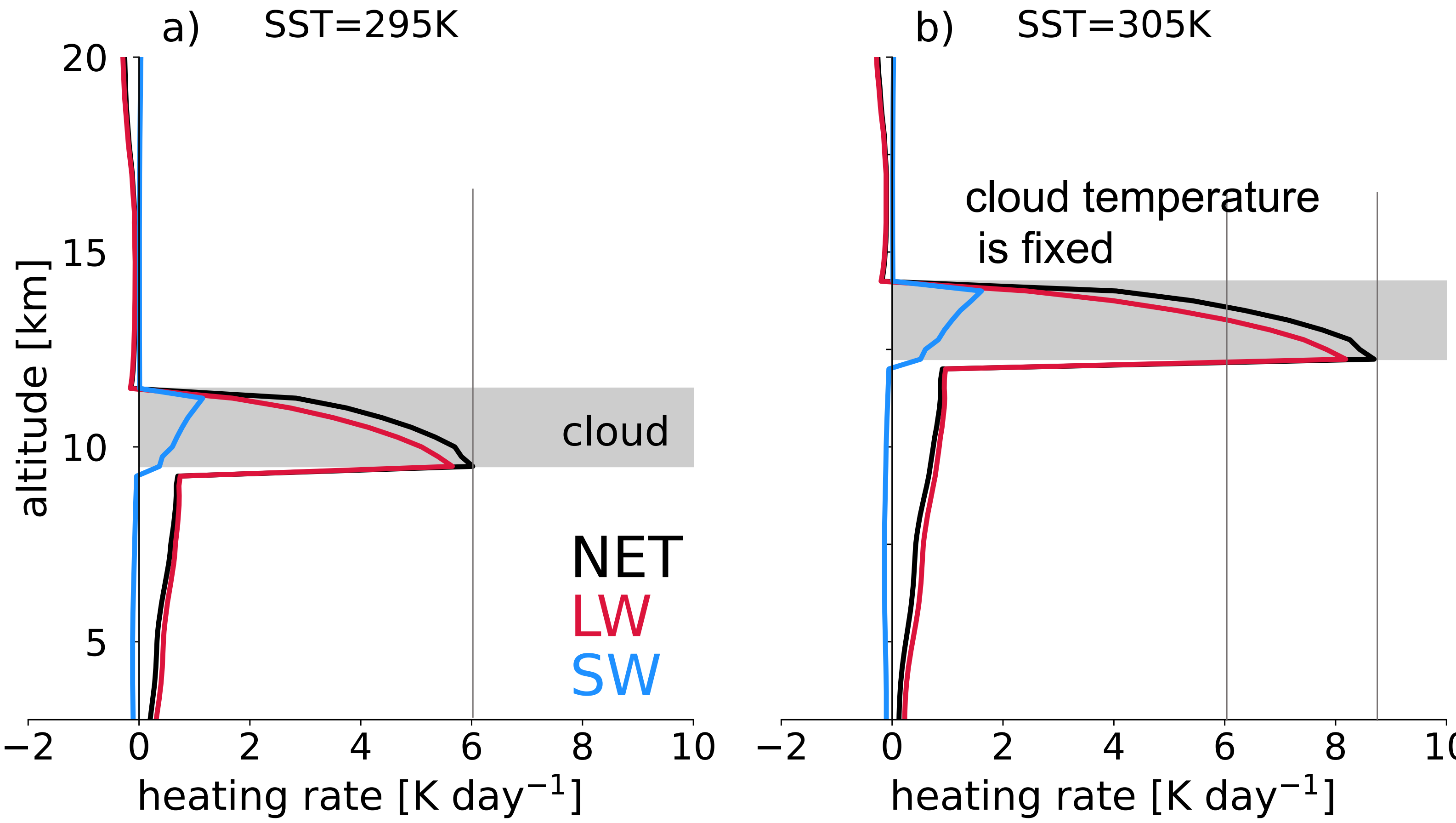
ice water path = constant)

<u>approx. fixed cloud temp.</u>

Gasparini et al., 2024

Radiative transfer calculations show an increase in CRH





Cloud with **FIXED** properties

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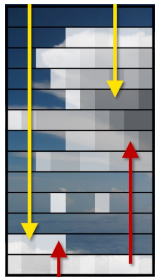
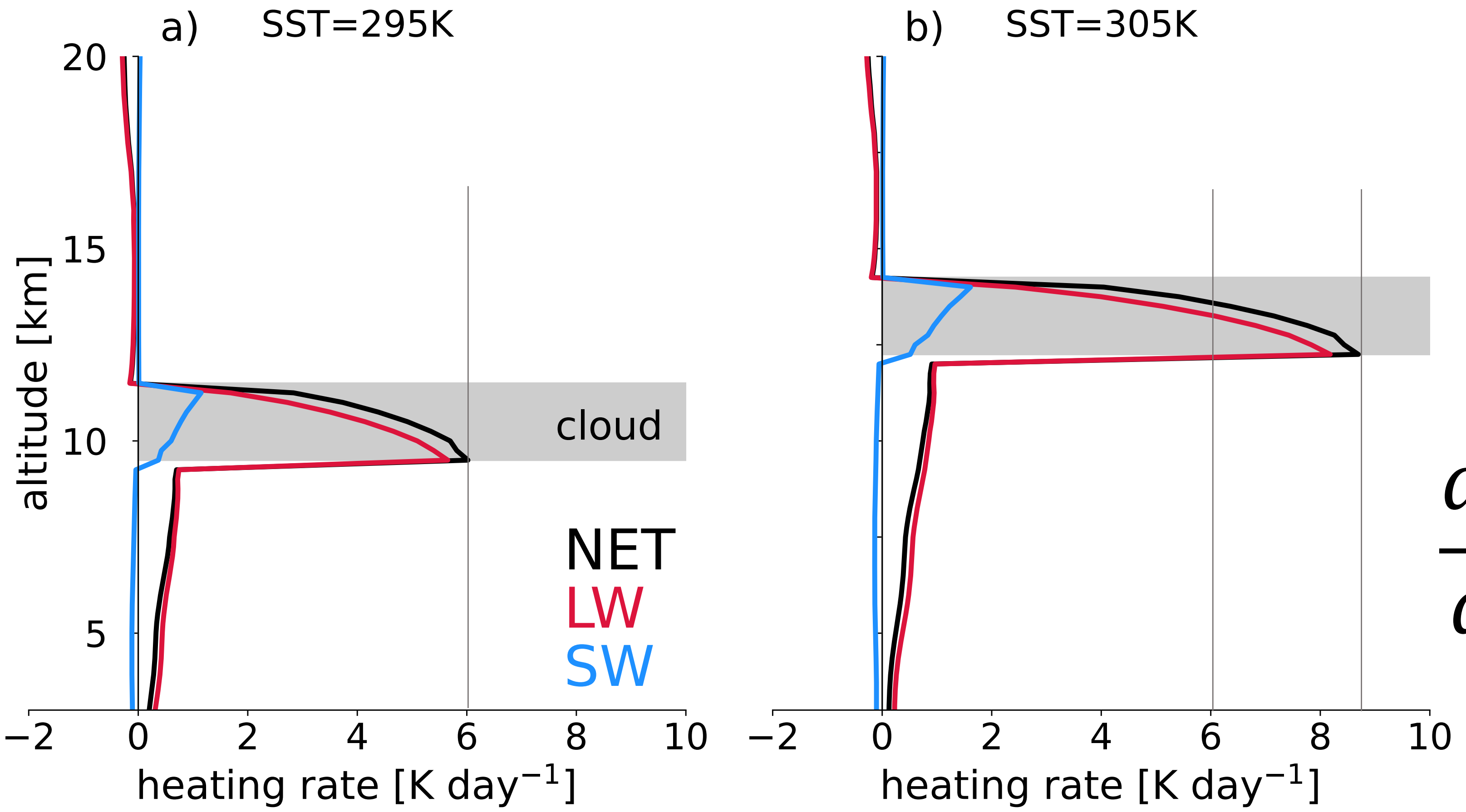
Gasparini et al., 2024

The increase in CRH is explained by a decrease in density





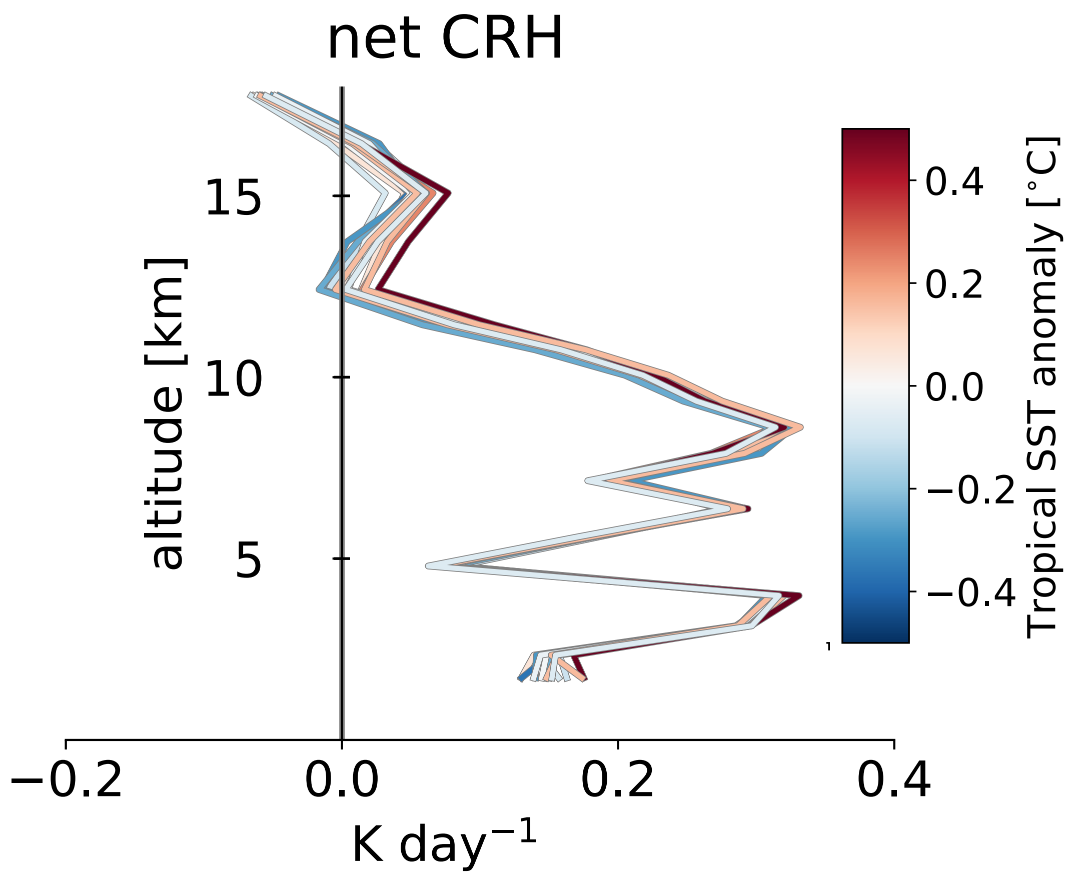
Cloud properties fixed
➔ radiative fluxes approximately fixed

$$\frac{dT}{dt} = g\frac{1}{\rho c_p}\frac{dF_{cloud}}{dz}$$

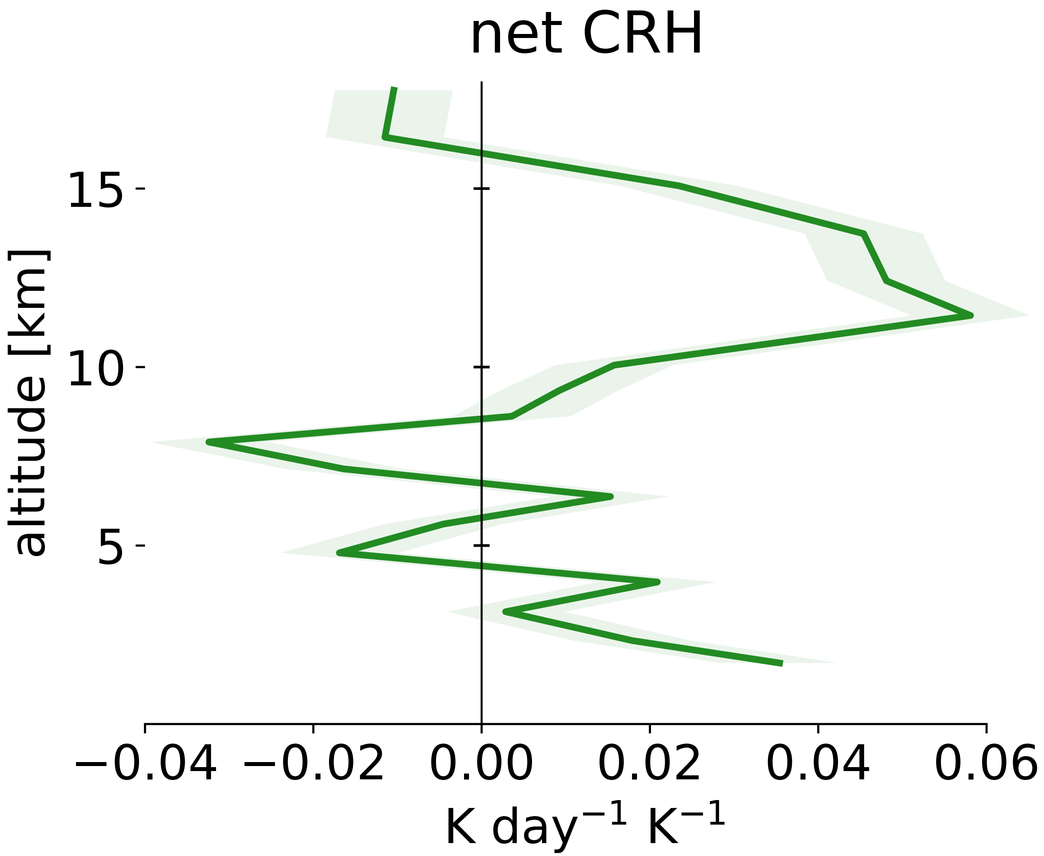
Shift in altitude: density decreases

Gasparini et al., 2024

Satellite data also show an increase in CRH in warmer years



15-year satellite dataset based on infrared sounder data trained on 2B-FLXHR (Stubenrauch et al., 2021)

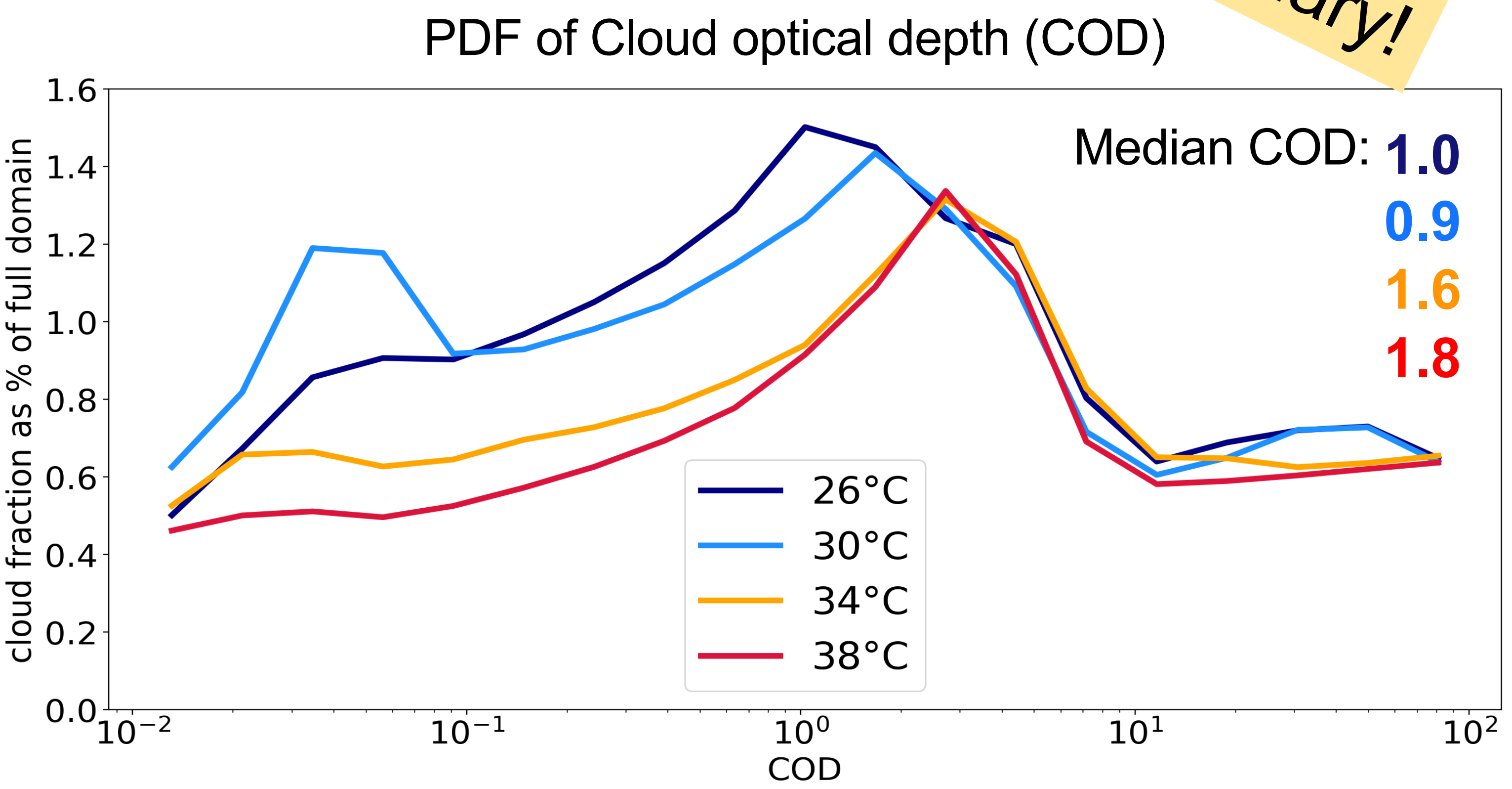


Response of satellite retrieval to warming comparable to CRH changes in models

Gasparini et al., 2024

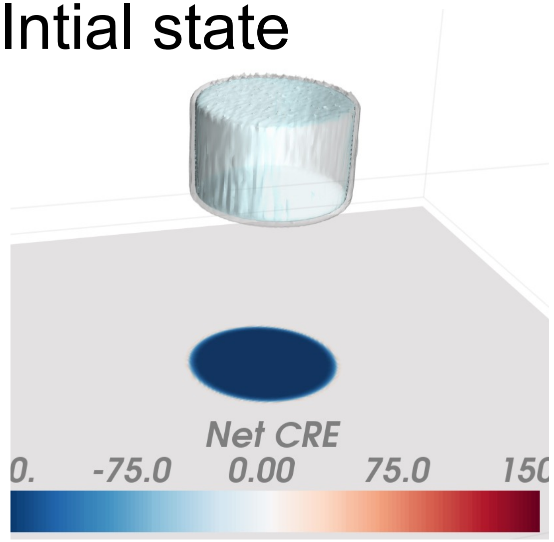
Implication 1: CRH increase leads to more opaque and shorter-lived clouds

Preliminary!

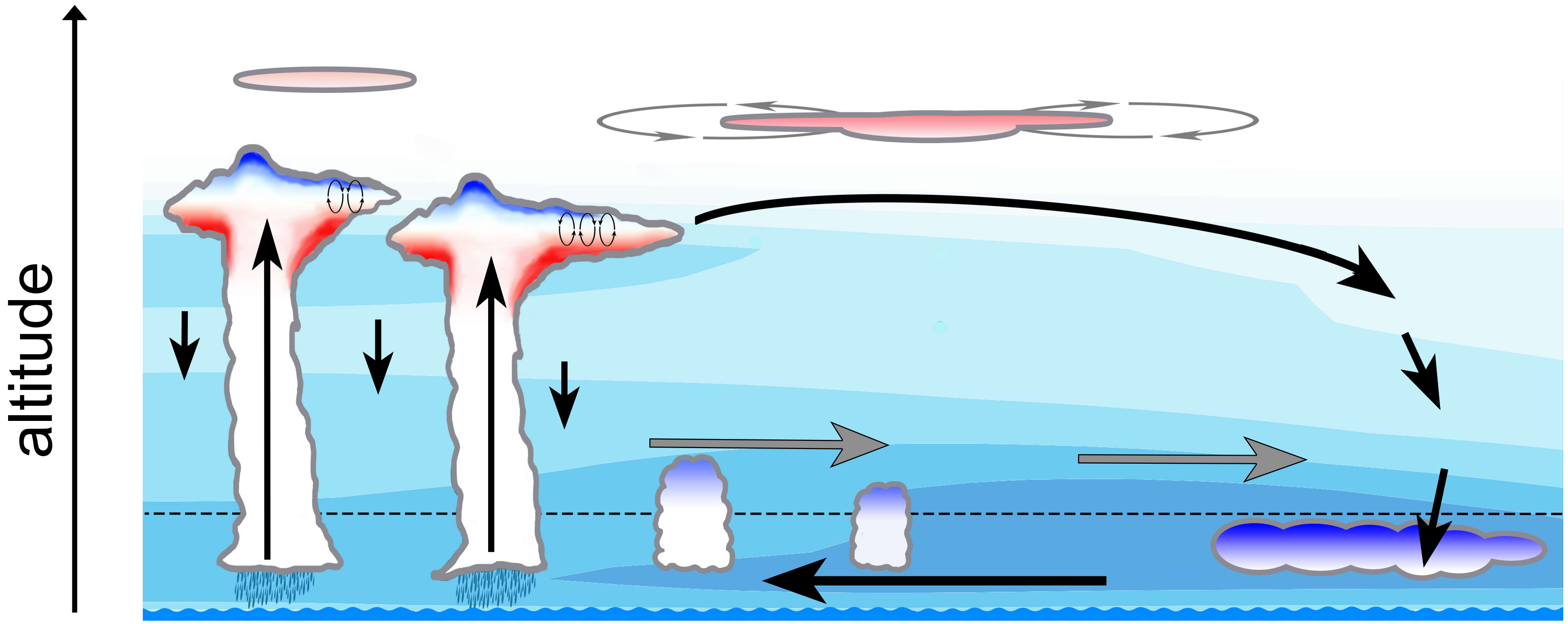


Idealized cloud evolution pathways initialized with same cloud in SAM RCE simulations

Intial state



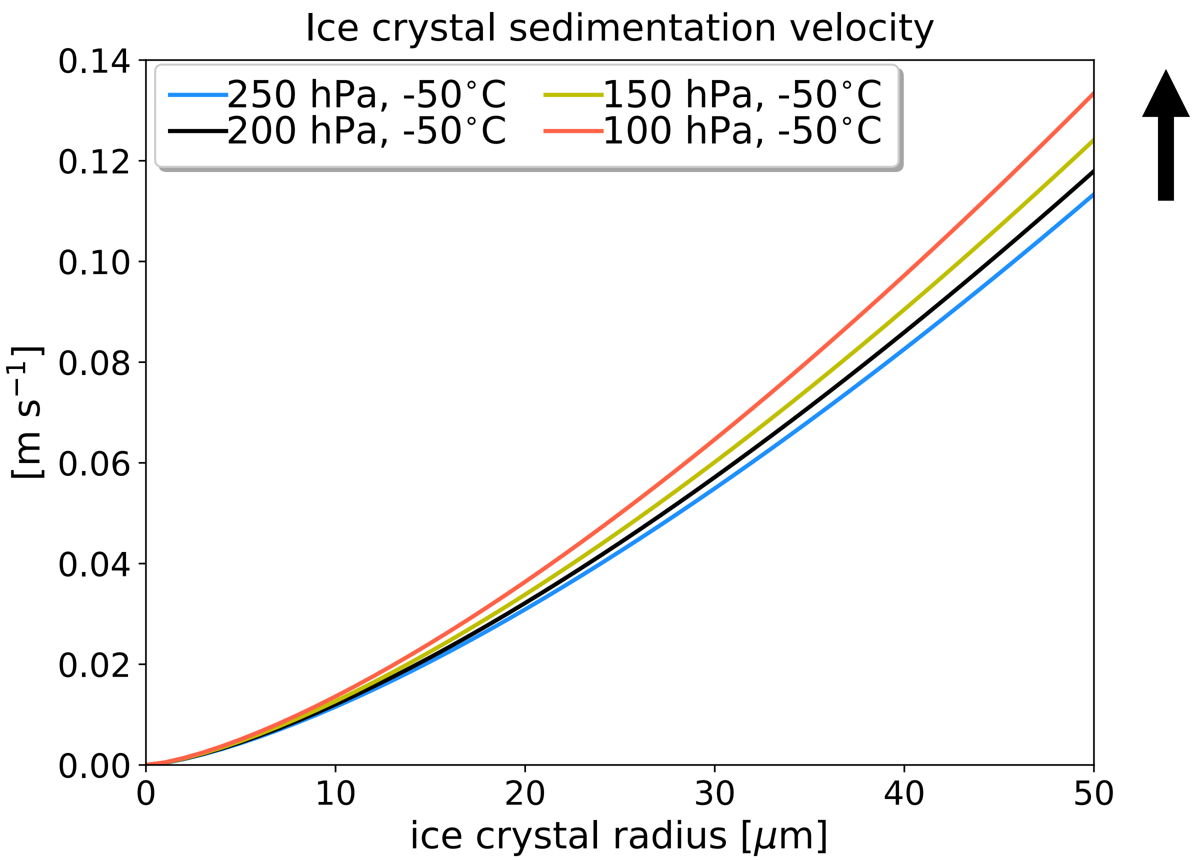
Implication 2: The importance of high clouds in driving circulations increases in warmer world



Dinh et al., 2023

Cloud radiative heating drives **large-scale dynamics and its response to global warming** (e.g. Voigt et al., 2021, Dinh et al., 2023).

The lower the pressure, the larger the sedimentation velocity

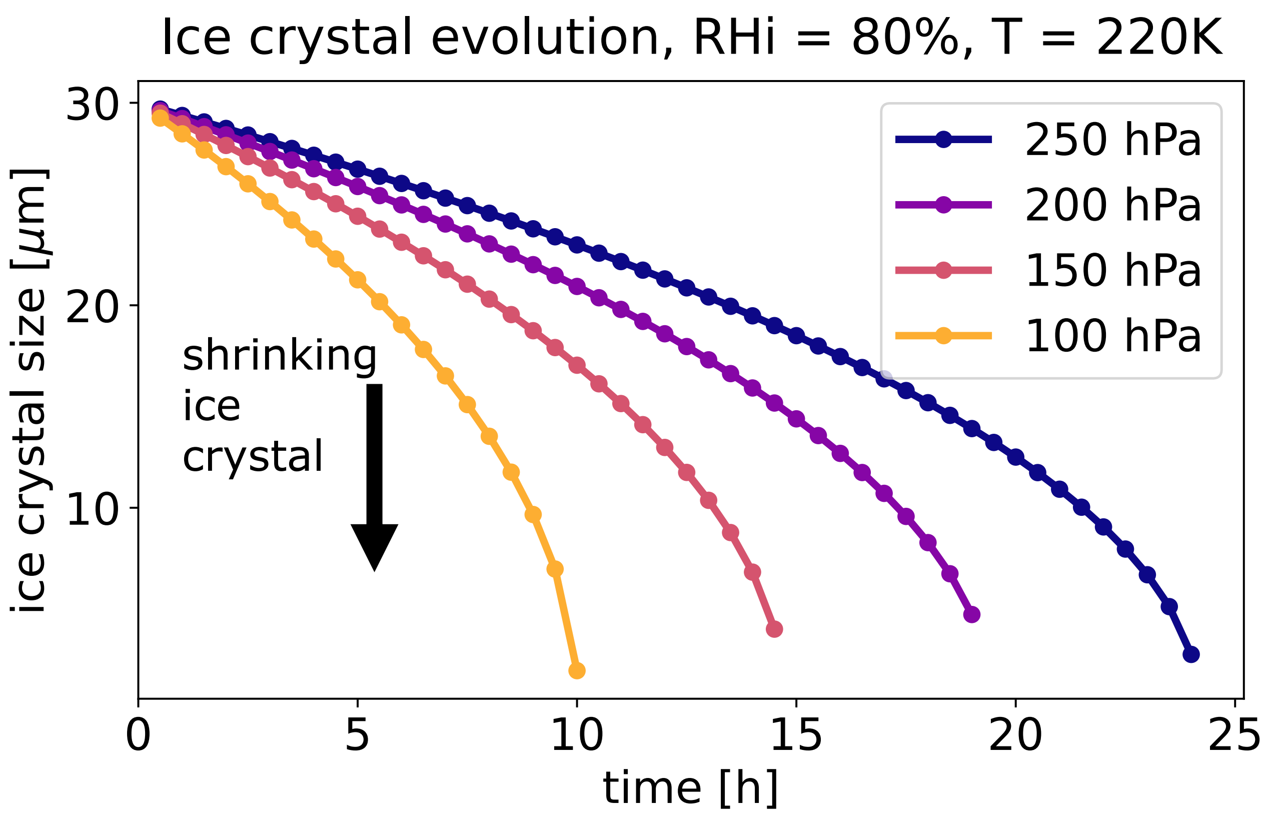


Ice crystal sedimentation **increases** when clouds move upward to **lower pressures**

$$v_{terminal} \propto \frac{1}{mean\ free\ path\ of\ air}$$

see also Ohno et al., 2021: impact on anvils in idealized simulations
partially Sokol and Hartmann, 2022: impact on atmospheric ice

Pressure dependence of the depositional growth equation



Sublimation of an ice crystal at fixed RH and temperature but **varying pressure**.

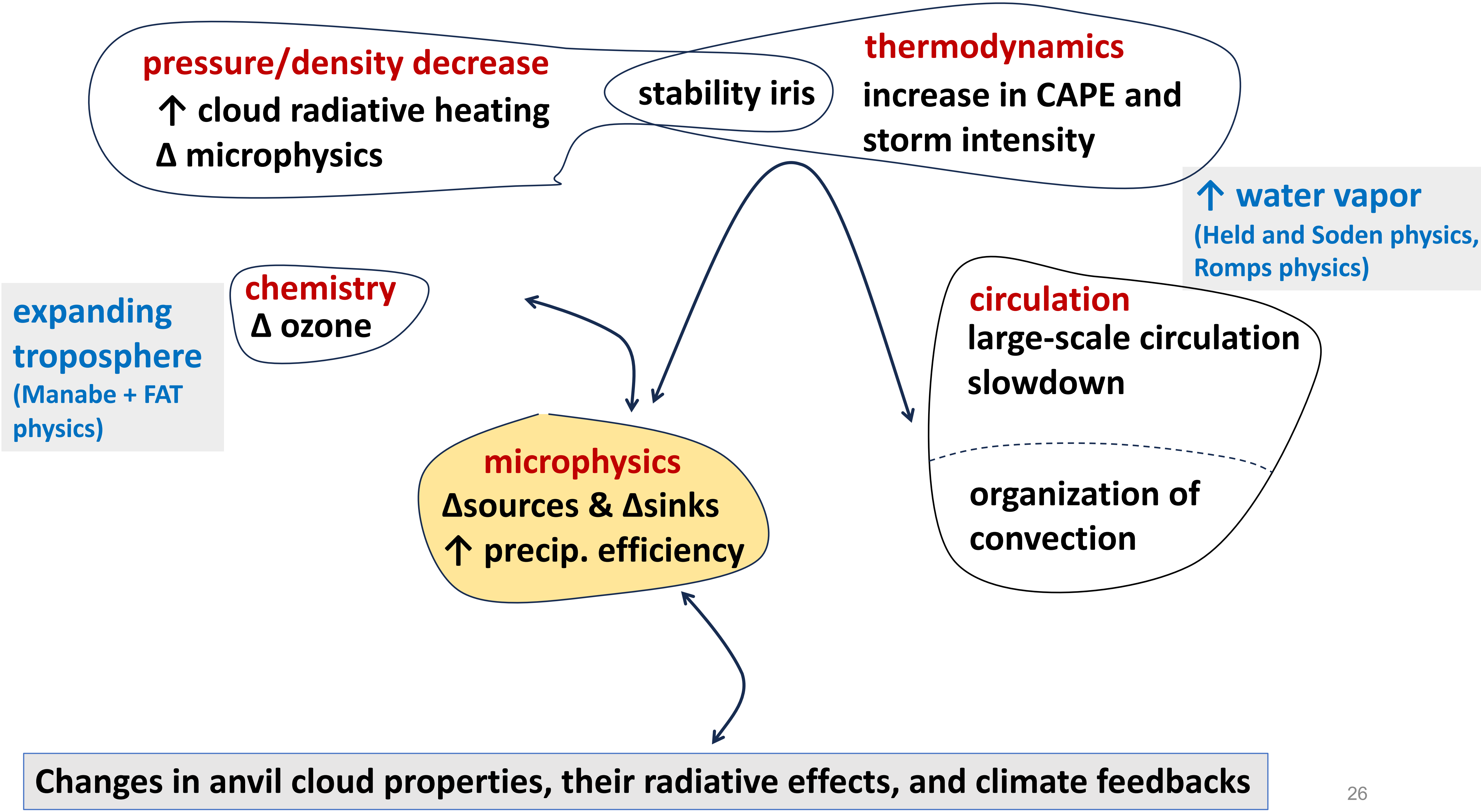
Ohno et al., 2021: impact in idealized simulations
Gasparini et al., 2021 impact in a high-res GCM

The **diffusivity** of water vapor **increases** as pressure decreases because the **mean free path of molecules becomes larger**

➔ water vapor can leave the ice crystal surface more easily, enhancing shrinking

Quantifying feedback based on their mechanisms: still a long way to go!

		Change per K surface warming			Feedback
Quantity	Mechanisms	Theory	Simulations	Observations	W m^{-2} K^{-1}
cloud fraction	expanding troposphere: stability iris; circulation & microphysics	-1 to -4 % |[a]	-2 ± 4% |[b,c,d]	-7 ± 2% |[a]	0.03 ± 0.1 |[a]
optical depth	unknown	\	0 to -4% |[e,f]	11± 5 % |[a]	0.08 ± 0.1 |[a,e,f]
sedimentation	expanding troposphere: pressure-dependence	~1 % |[g]	0.6 % |[h]	\	\
deposition	expanding troposphere: pressure-dependence, circulation change	~5 % |[i]	small |[j]	\	\
cloud radiative heating	expanding troposphere: pressure-dependence	~3 % |[k]	0 to 5% |[k]	\	\
temperature	expanding troposphere: stability change; ozone change	\	unclear |[l]	0.58-0.86 K |[m]	< 0 |[n,o]

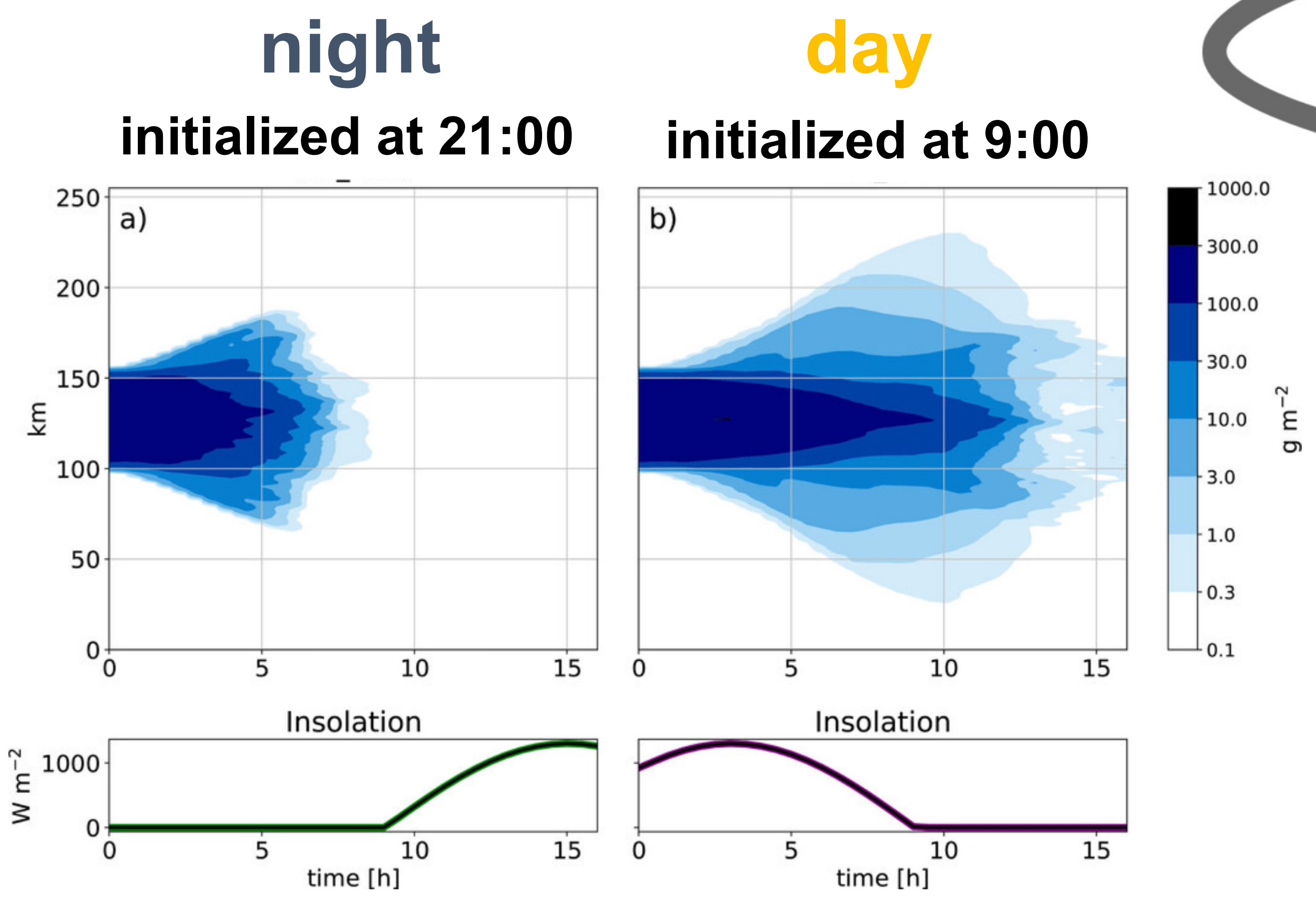

pressure/density decrease
↑ cloud radiative heating
Δ microphysics
stability iris
thermodynamics
increase in CAPE and storm intensity
↑ water vapor
(Held and Soden physics, Romps physics)
expanding troposphere
(Manabe + FAT physics)
chemistry
Δ ozone
circulation
large-scale circulation slowdown
organization of convection
microphysics
Δsources & Δsinks
↑ precip. efficiency
Changes in anvil cloud properties, their radiative effects, and climate feedbacks

Conclusion

At the process level, the feedback mechanisms of high clouds, especially opacity, remain poorly

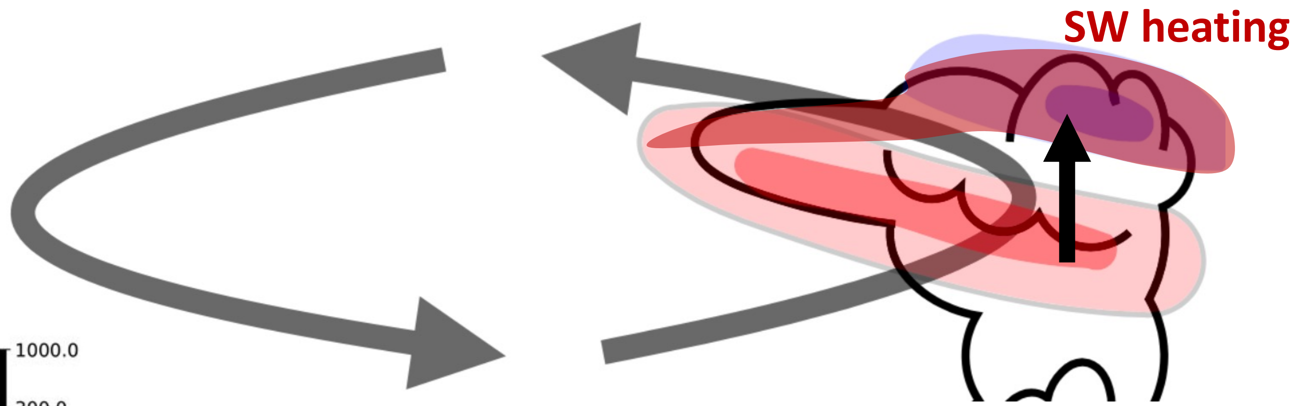
How can they be included in the broader context of tropical climate responses to warming?

We know anvil spreading is important because day anvils have longer lifetimes



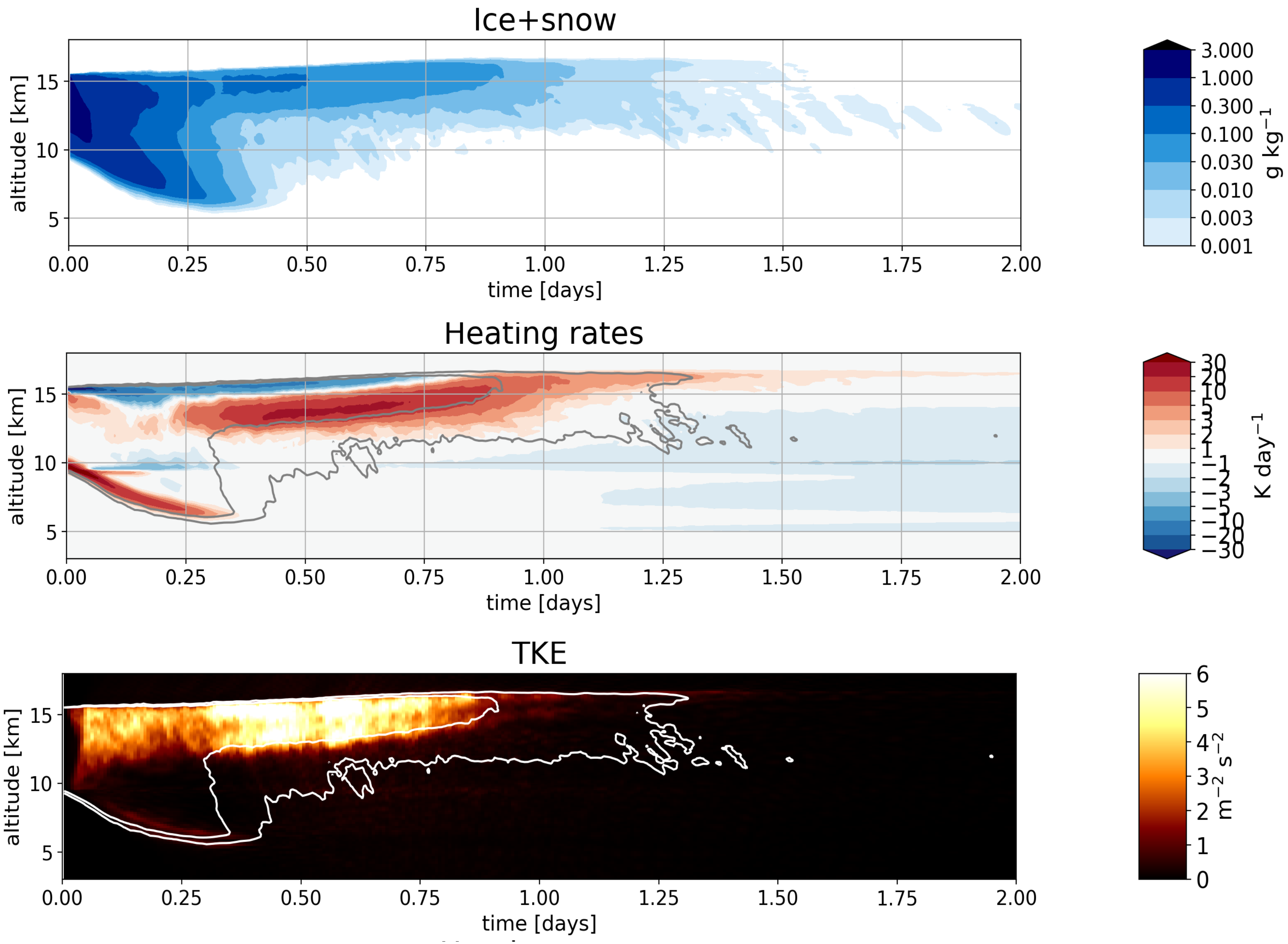
Gasparini et al., 2022

Anvil spreading



- Radiatively-driven circulation **counteracts sedimentation**
- Also drives cloud spreading
- Supported based on idealized & realistic modeling (e.g. Ruppert et al., 2019) + observations (Deng and Mace, 2008, Wall et al., 2020)

Another possible effect of radiation on the anvil lifecycle



1. Cloud top cooling and cloud base warming dipole

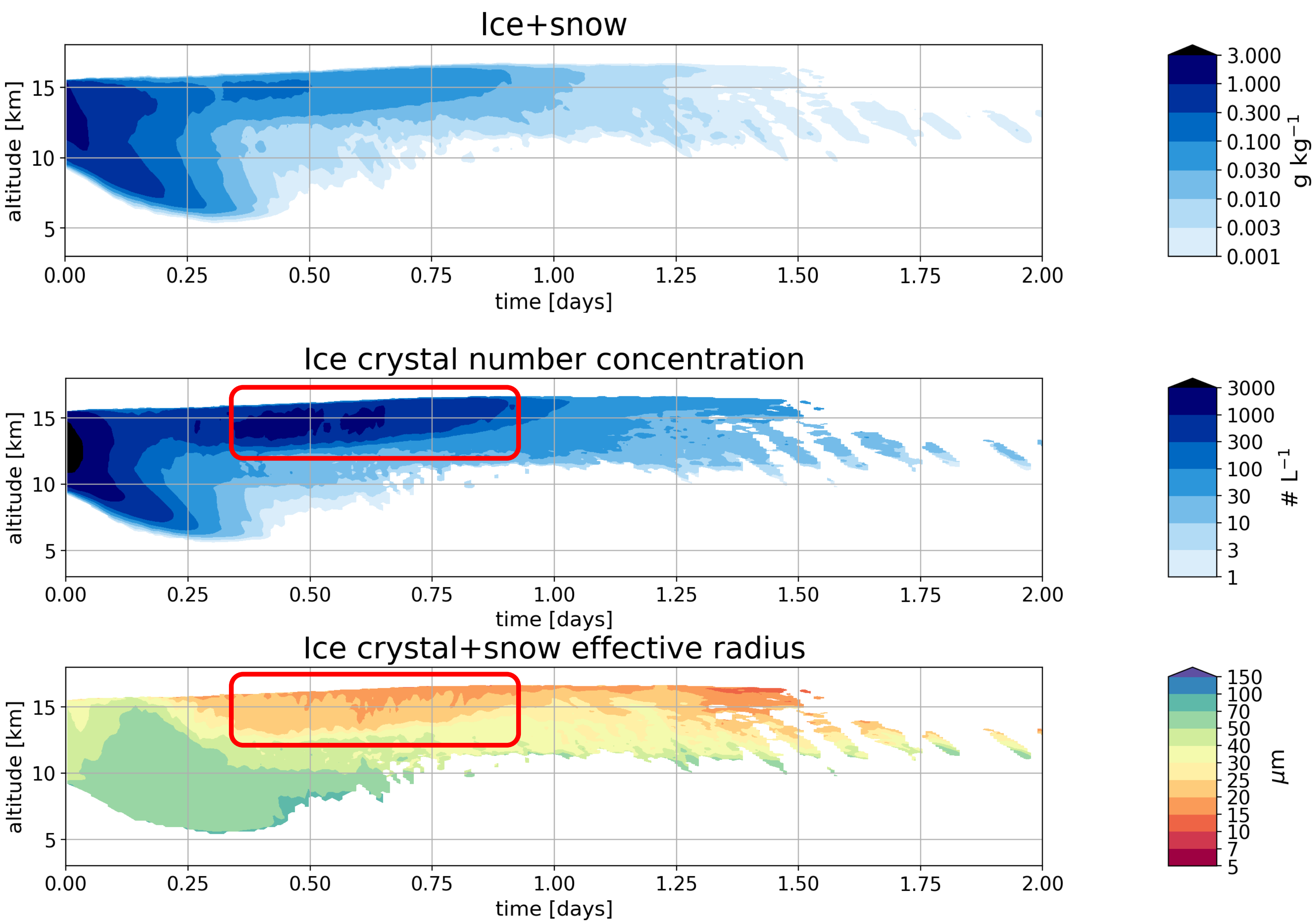
1. Driving turbulent kinetic energy (TKE) and in-cloud convective motions

1. In-cloud convection leads to the formation of numerous small ice crystals

Hartmann et al., 2018

Beware:
very idealized modeling!

Radiative turbulence nucleates ice crystals, prolonging anvil lifetime



1. Cloud top cooling and cloud base warming dipole
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1. In-cloud convection leads to the formation of numerous small ice crystals

Hartmann et al., 2018

Beware:
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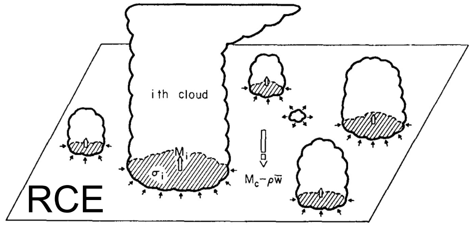
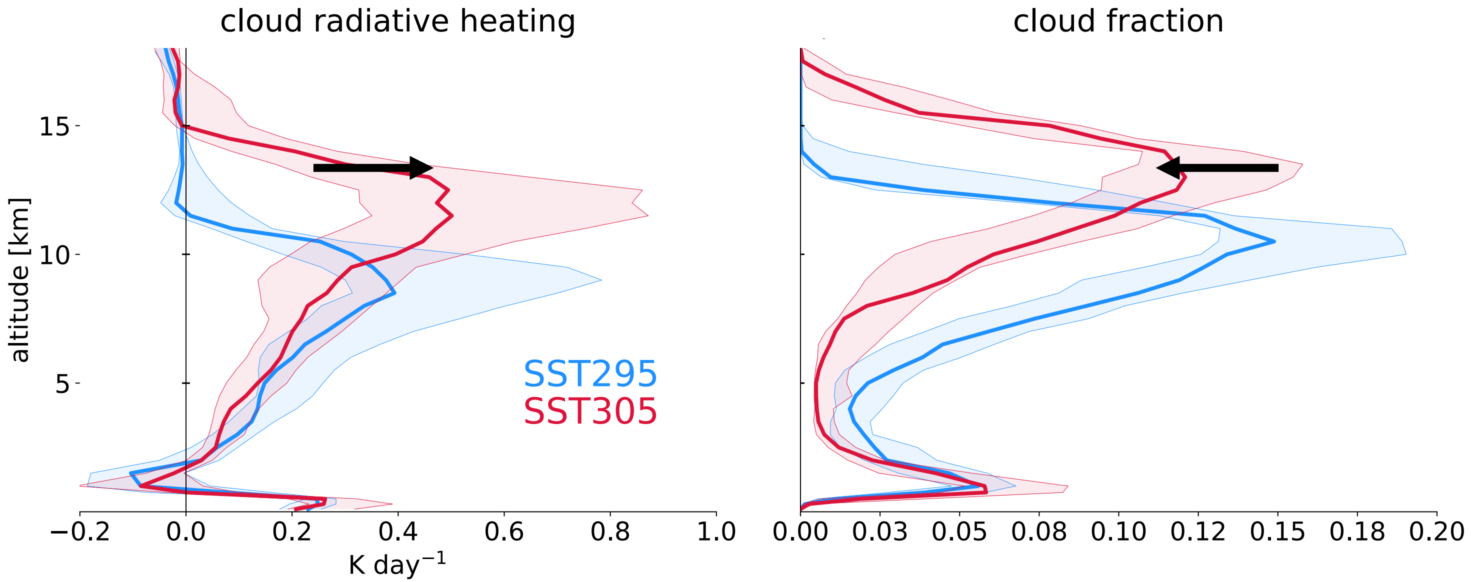
The mechanism is robust across models





RCEMIP data

RCE_large domain simulations from 13 cloud resolving models (Wing et al., 2020)

Despite a mean cloud fraction decrease, cloud radiative heating increases!

Gasparini et al., 2024