Precipitation extremes, their change with warming & with convective organization

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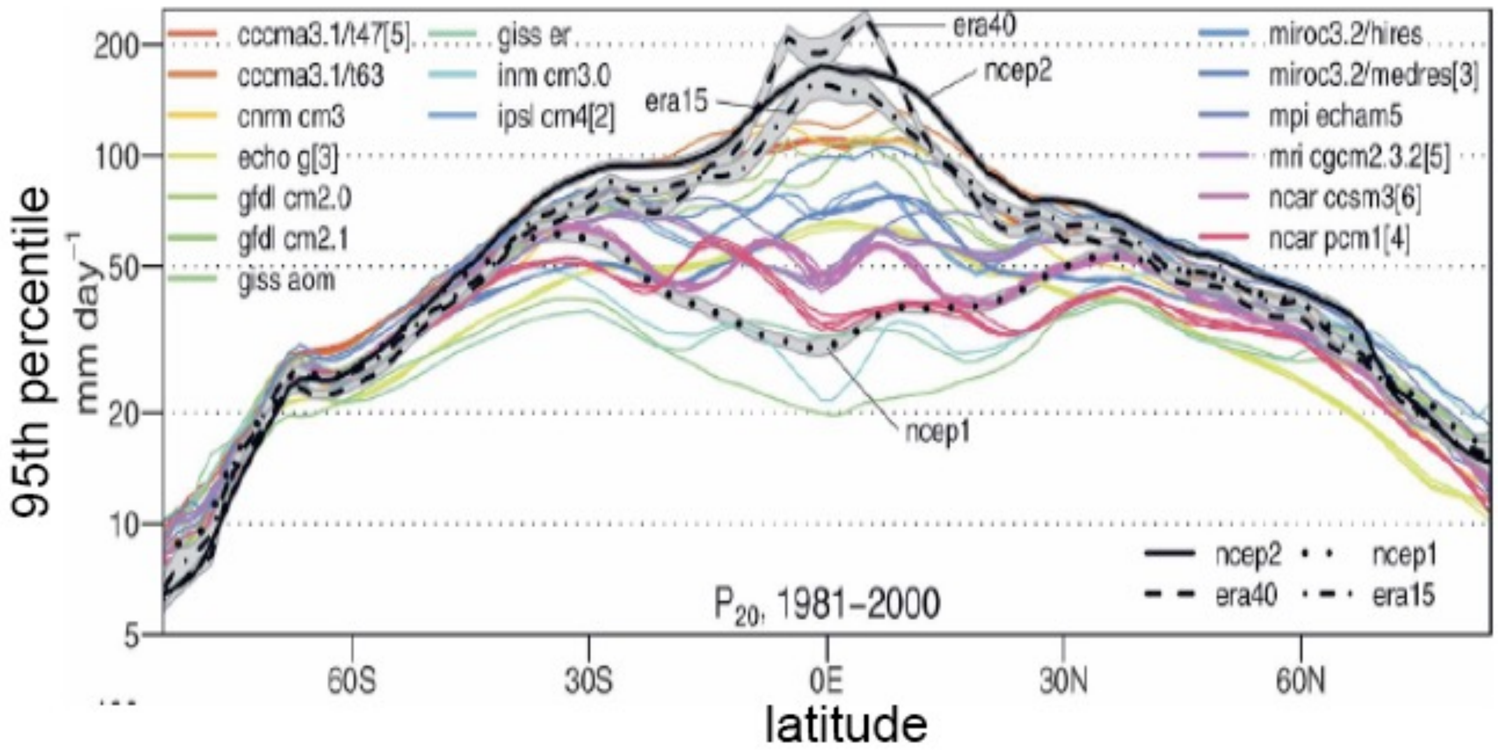
Motivation: Tropical precipitation extremes

Precipitation extremes (95th precipitation percentile) in climate models



⇒ NOT consistent in tropics and subtropics *[Kharin et al, J. Clim. 07]*

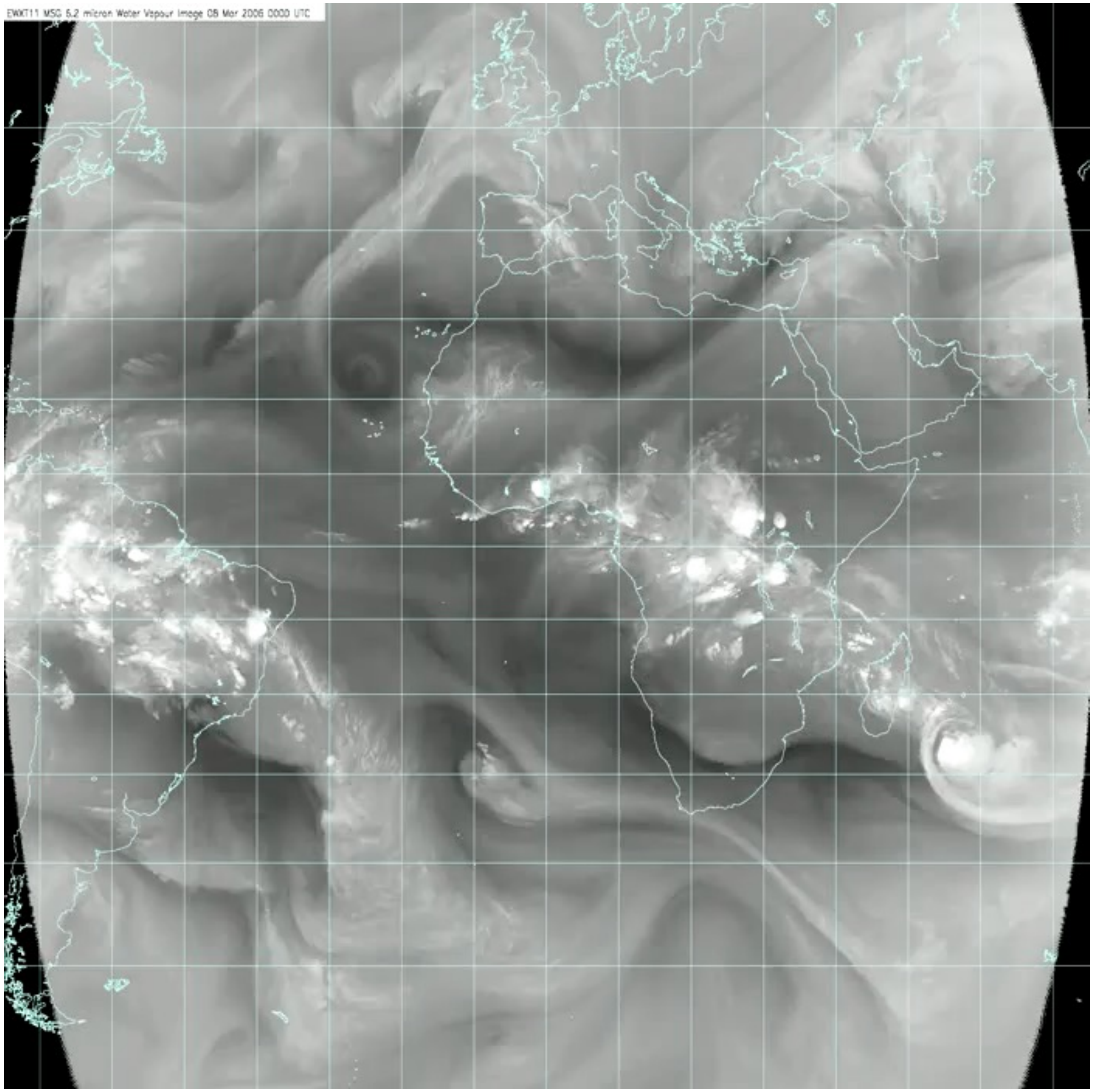
⇒ Not resolution, => due to cloud parametrizations

⇒ Climate models disagree

[O'Gorman&Schneider, 09; Sugiyama,Shiogama,Emori, 10; Pendergrass 2018]

Motivation: Tropical precipitation extremes

Water vapor from satellite

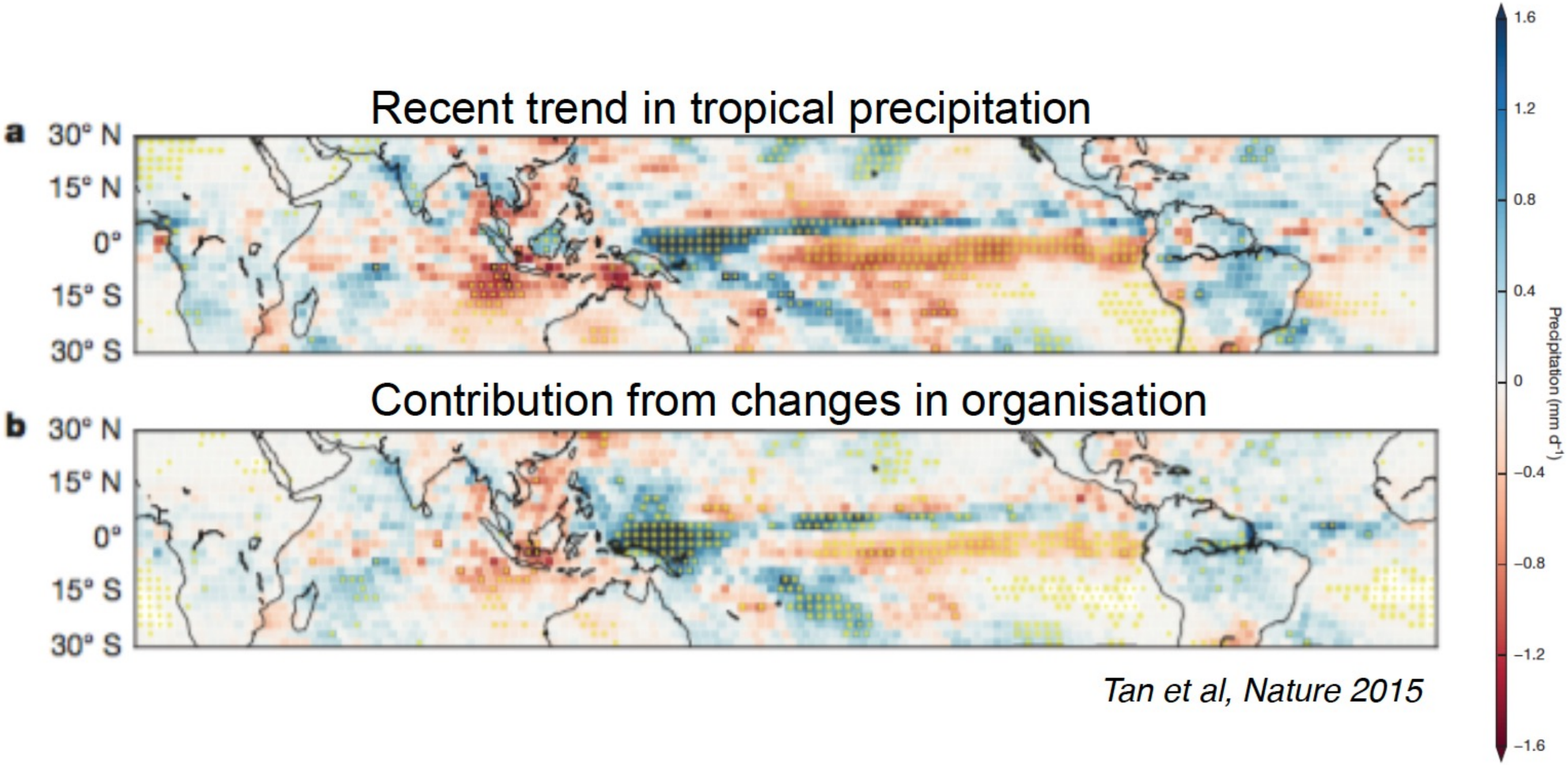


Tropical convection =
« pop corn » convection

Motivation: Tropical precipitation extremes

Extreme precipitation is often associated with organized cloud systems

Increased precipitation is associated with increased organized convection



O'Donnell & Wing: large uncertainty in response of extremes to warming in RCEmip, linked with convective organization

Precipitation extremes, their change with warming & with convective organization

⇒ GOAL HERE:

1) How do precipitation extremes change with **warming?**

2) How do precipitation extremes change with **convective organization?**

3) How does **organization** (& thus extremes) change with **warming**?

Precipitation extremes : theory

Courtesy : Octave Tessiot

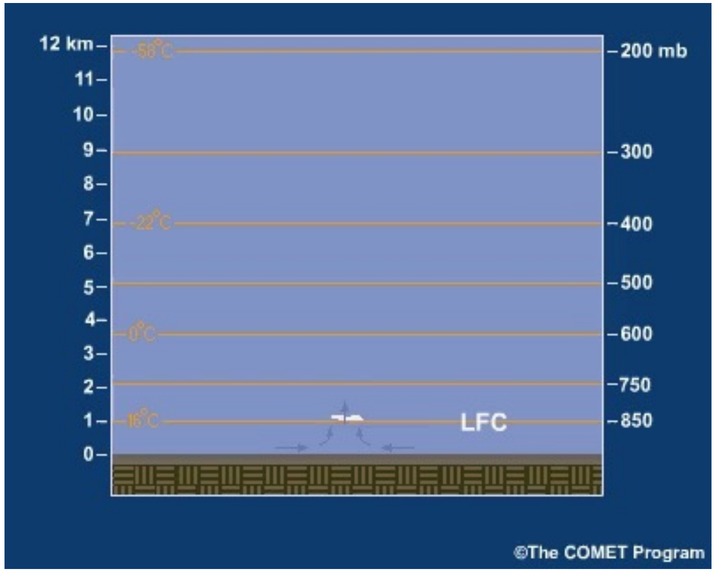
Precipitation extremes : theory

Main balance during precip extremes = "Scaling"

Precipitation efficiency — *Condensation rate*

$$P \sim \underbrace{\varepsilon_p}_{\text{Precipitation efficiency}} \int \underbrace{\rho w \frac{-\partial q_v}{\partial z}}_{\text{Condensation rate}} dz$$

Fraction of condensation that makes it to the ground as surface precip « Microphysic »



[Muller O'Gorman Back 2011; Muller & Takayabu 2020]

Similar to *[Betts&Harshvardhan JGR 87; O'Gorman&Schneider PNAS 09]* but derived from energetics, and at convective scale & with precip efficiency

Precipitation extremes : theory

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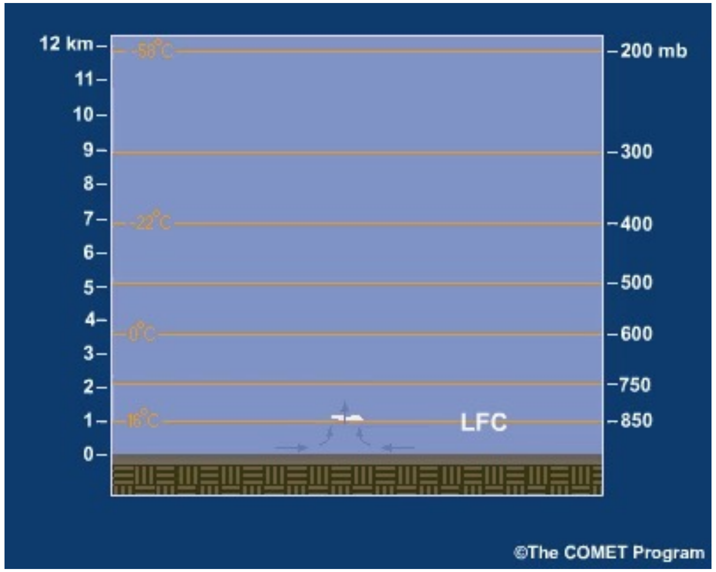
Fraction of condensation that makes it to the ground as surface precip
« Microphysic »

Upward mass flux in the cloud
« Dynamic »

Water vapor profile
« Thermodynamic »



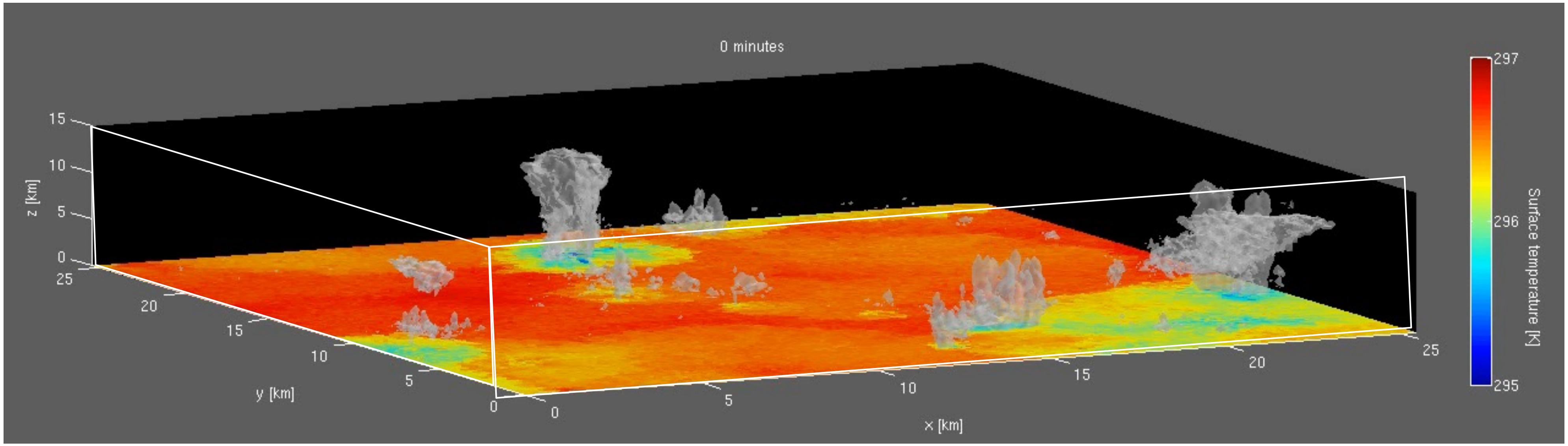
[Muller O'Gorman Back 2011; Muller & Takayabu 2020]

Similar to *[Betts&Harshvardhan JGR 87; O'Gorman&Schneider PNAS 09]* but derived from energetics, and at convective scale & with precip efficiency

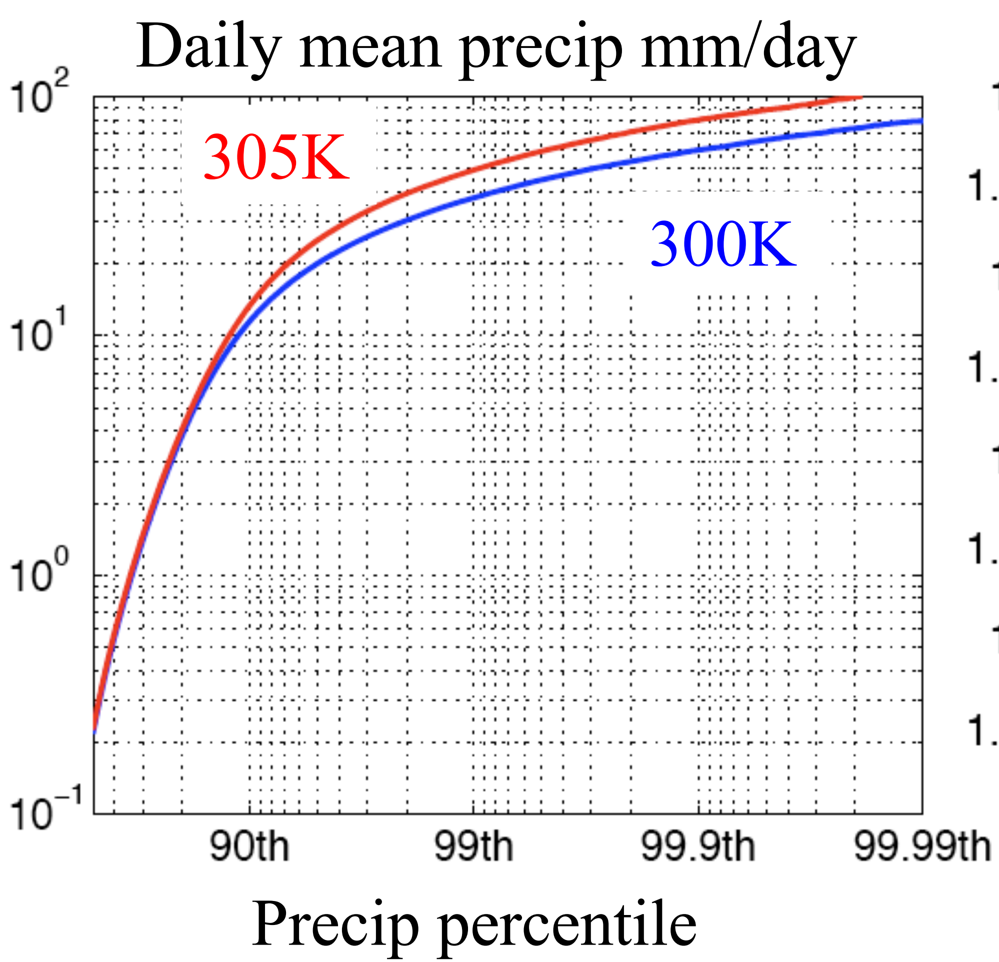
Scaling works in idealized cloud-resolving simulations?

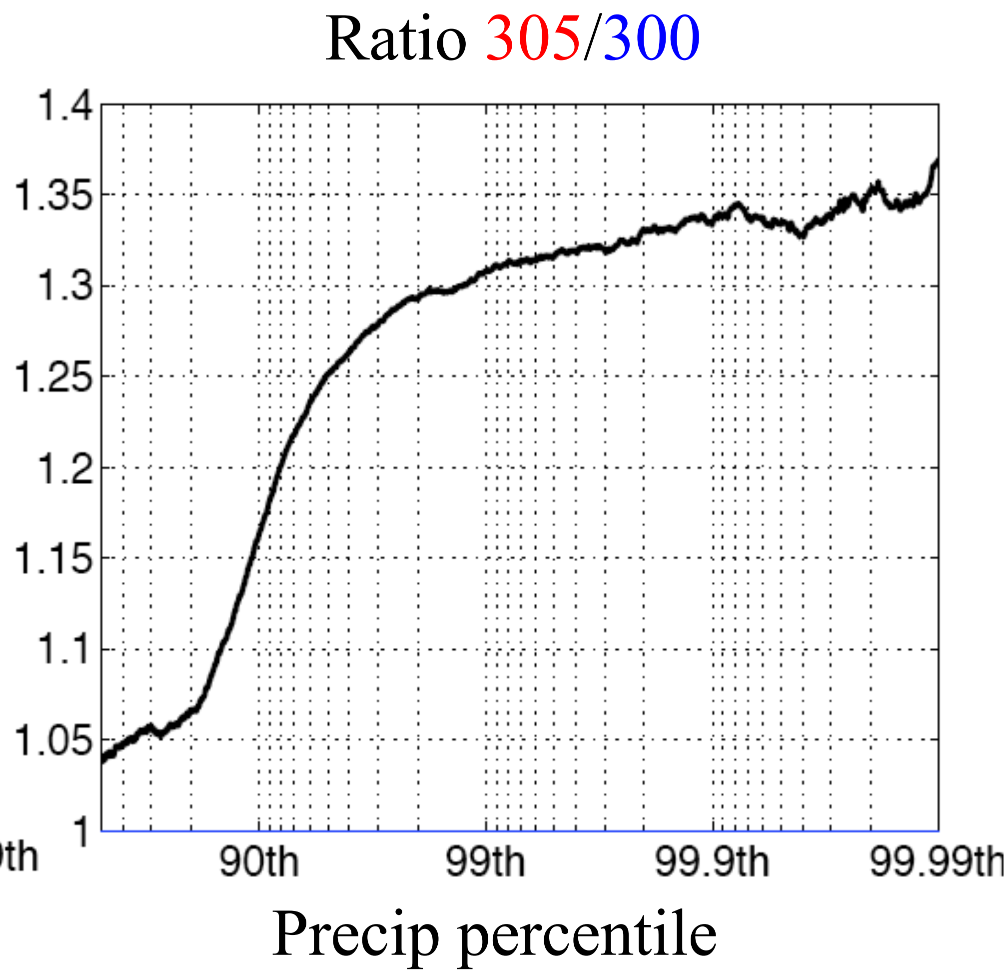
- Cloud-Resolving Model "SAM" *[Khairoutdinov, M.F. and Randall, D.A., JAS 2003]*
  Anelastic momentum, continuity and scalar conservation equations
  Doubly-periodic domain, run to Radiative Convective Equilibrium (RCE)
- Fixed SST: 300K & 305K

Clouds over near-surface temperature



Precipitation extremes in cloud-resolving simulations





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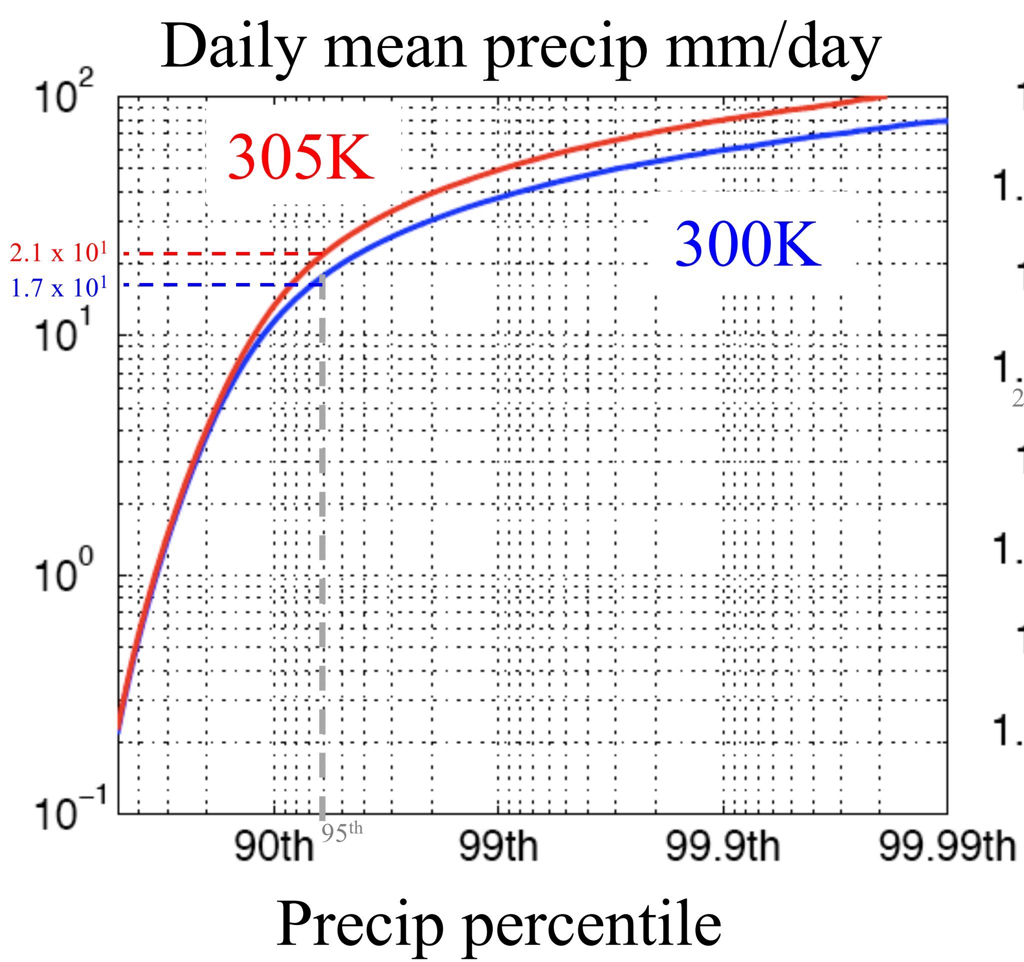
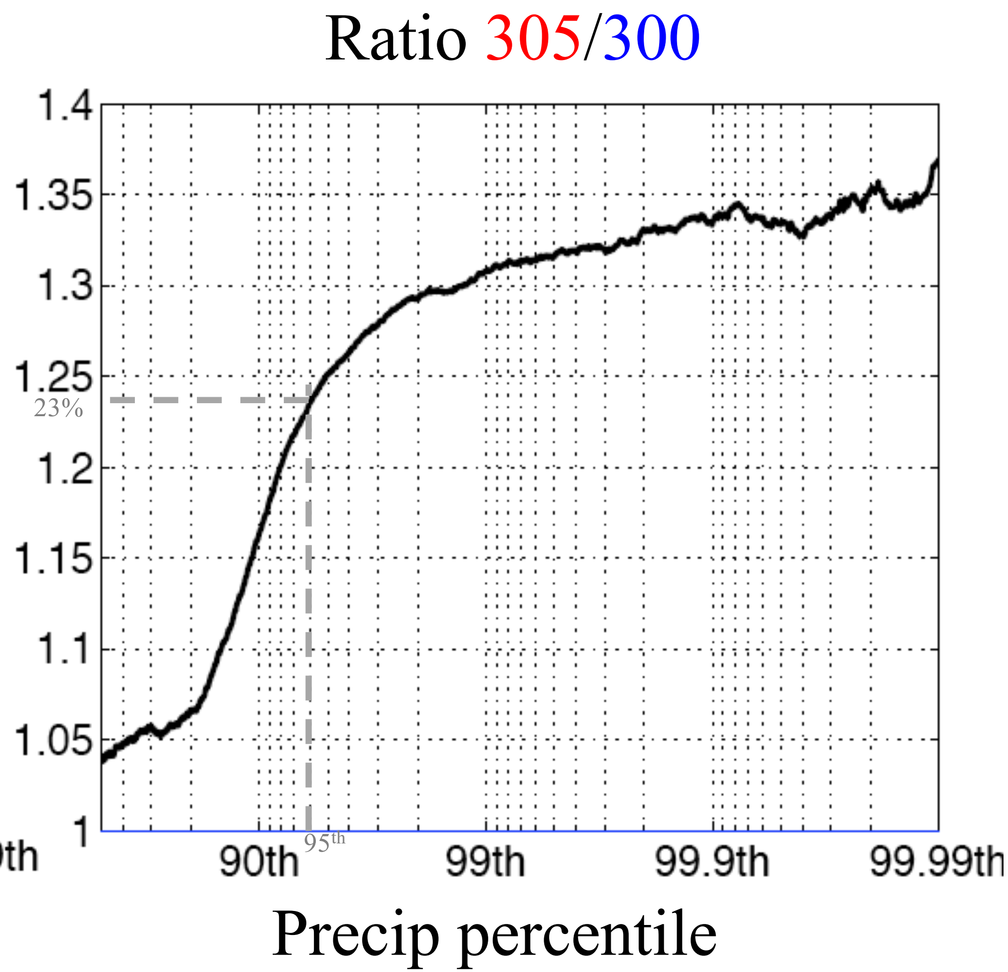
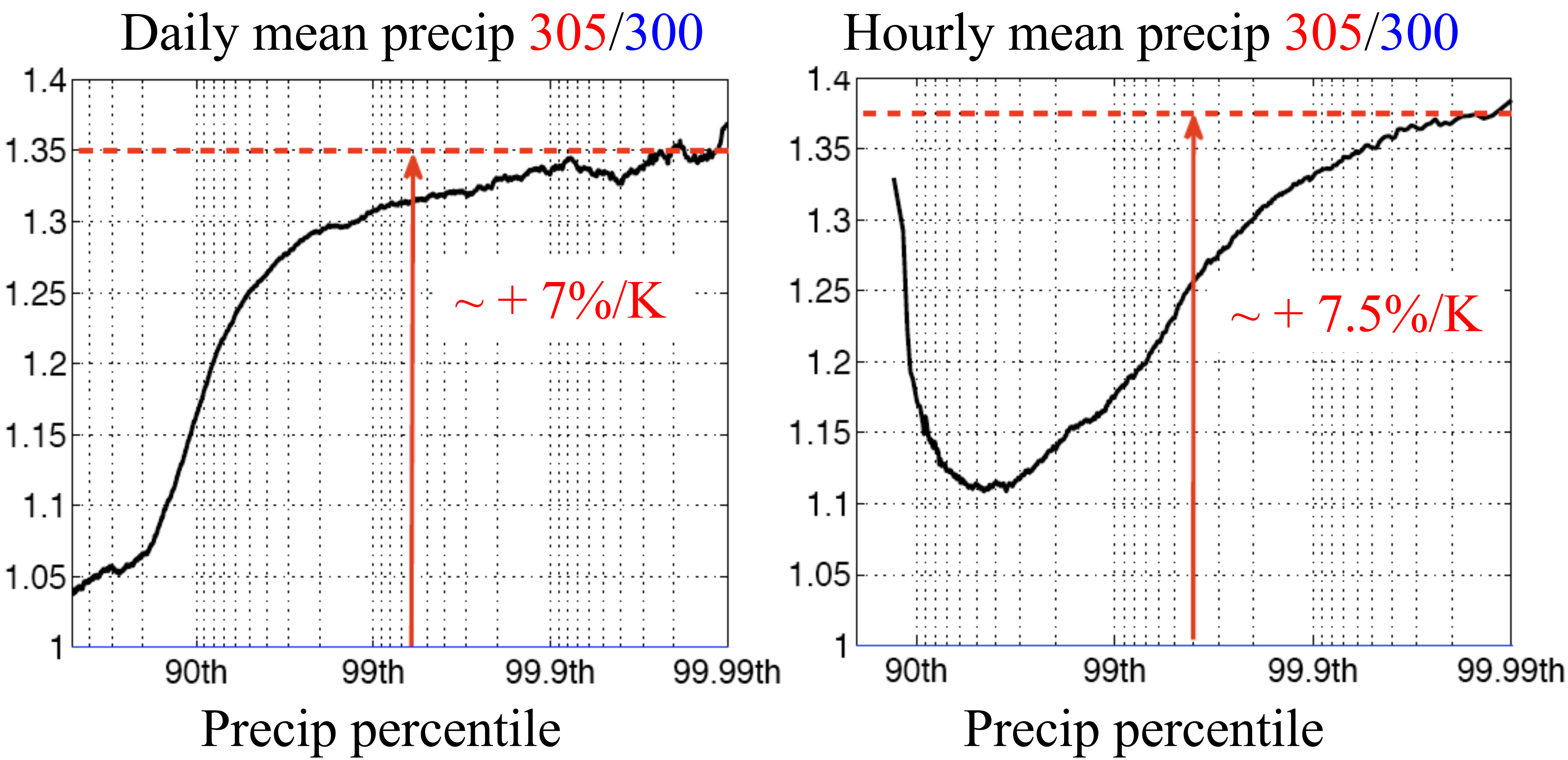




95^{th} percentile = $\begin{cases} 1.7 \times 10^1 \text{ mm/day} \\ 2.1 \times 10^1 \text{ mm/day} \end{cases}$ ⇔ 23 % increase

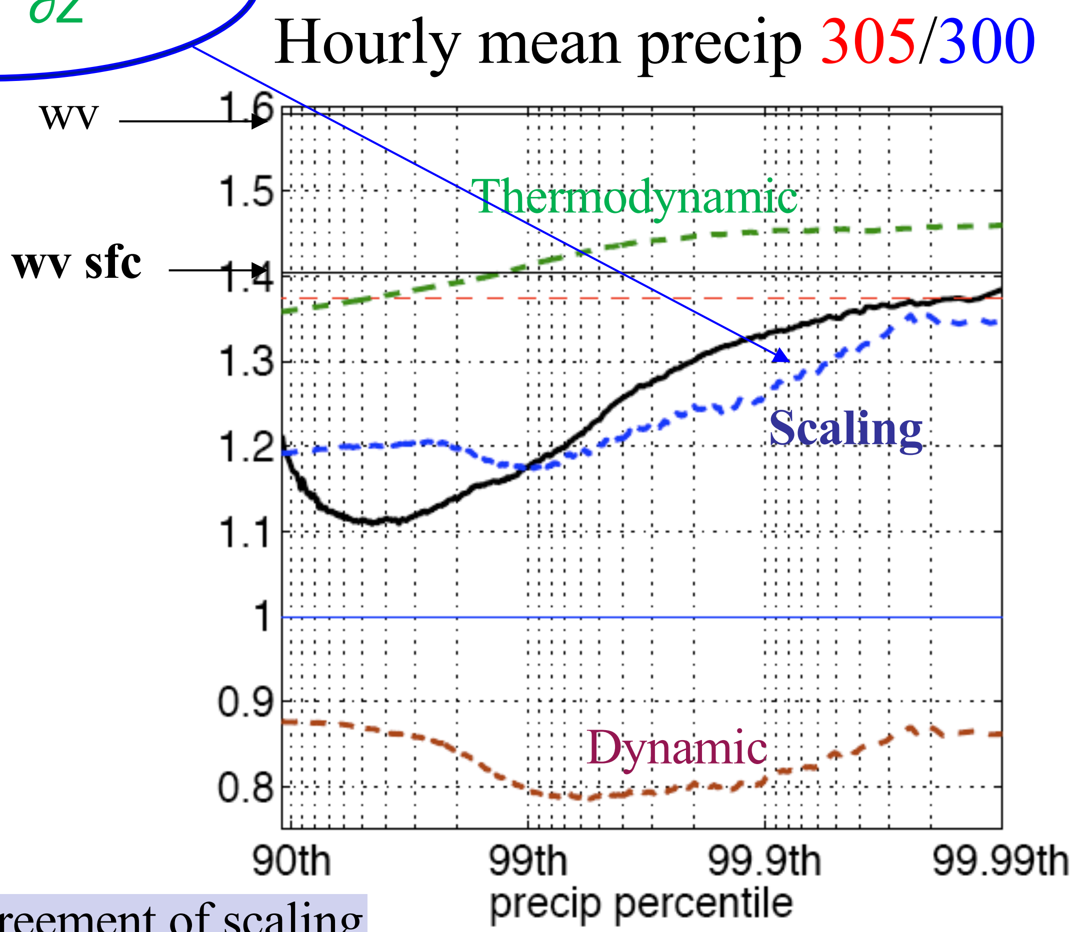
Precipitation extremes in cloud-resolving simulations



=> Why 7%/K?

Theoretical scaling in cloud-resolving simulations

$$P \sim \varepsilon_p \int \rho w \, \frac{-\partial q_{sat}}{\partial z} \, dz$$



⇒ Fairly good agreement of scaling

⇒ To first order, thermodynamic, closer to wv sfc than wv

⇒ Dynamics play 2ndary role, and tend to reduce P extremes

[Muller O'Gorman Back 2011]

Approx scaling for precip extremes – relationship to water vapor

If further assume that representative value of mass flux is its value at 500hPa,

scaling becomes:

$$\int \rho\, w \frac{-\partial q_v}{\partial z} dz \quad \sim \quad (\rho\, w)_{500} \int \frac{-\partial q_v}{\partial z} dz \quad \sim \quad (\rho\, w)_{500}\, q_{v,BL}$$

$$\Rightarrow \quad P_e \sim (\rho\, w)_{500}\, q_{v,BL}$$

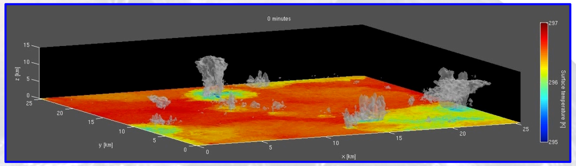
shows link to wv_{sfc}

[Muller 2013; Abbott et al 2020]

Precipitation extremes, their change with warming & with convective organization

1) How do precipitation extremes change with **warming?**

⇒ Precipitation extremes increase



⇒ Follow Clausius-Clapeyron (near-surface humidity increase)

$$P \sim \varepsilon_p \int \rho w \, \frac{-\partial q_v}{\partial z} \, dz$$

Precipitation extremes, their change with warming & with convective organization

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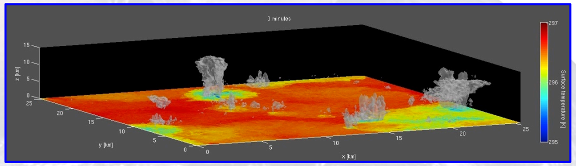


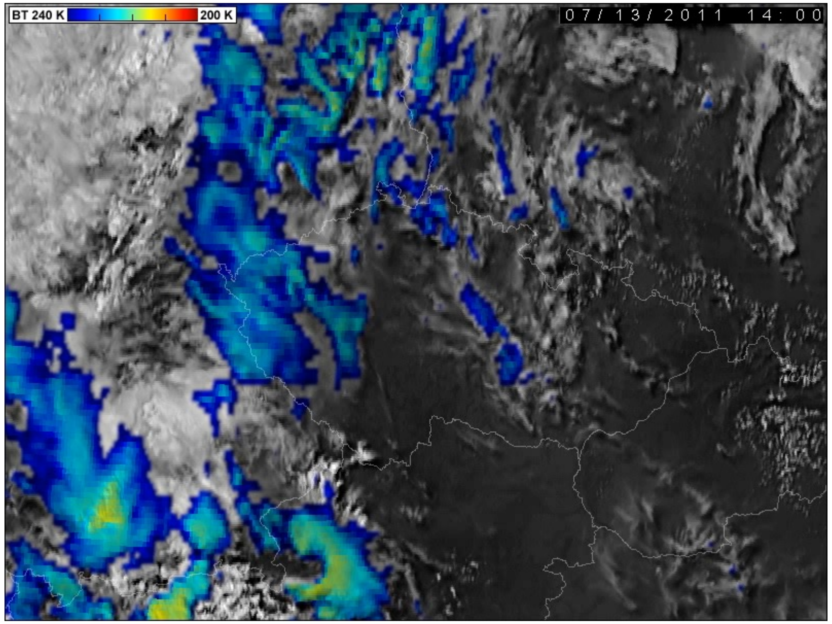
⇒ Follow Clausius-Clapeyron (near-surface humidity increase)

$$P \sim \varepsilon_p \int \rho w \frac{-\partial q_v}{\partial z} dz$$

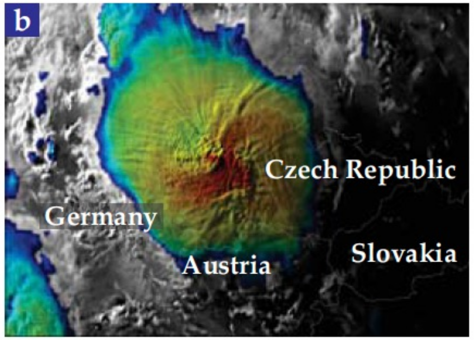
2) How do precipitation extremes change with **convective organization?**

3) How does **organization** (& thus extremes) change with **warming**?

Will look at 2 types of organization:

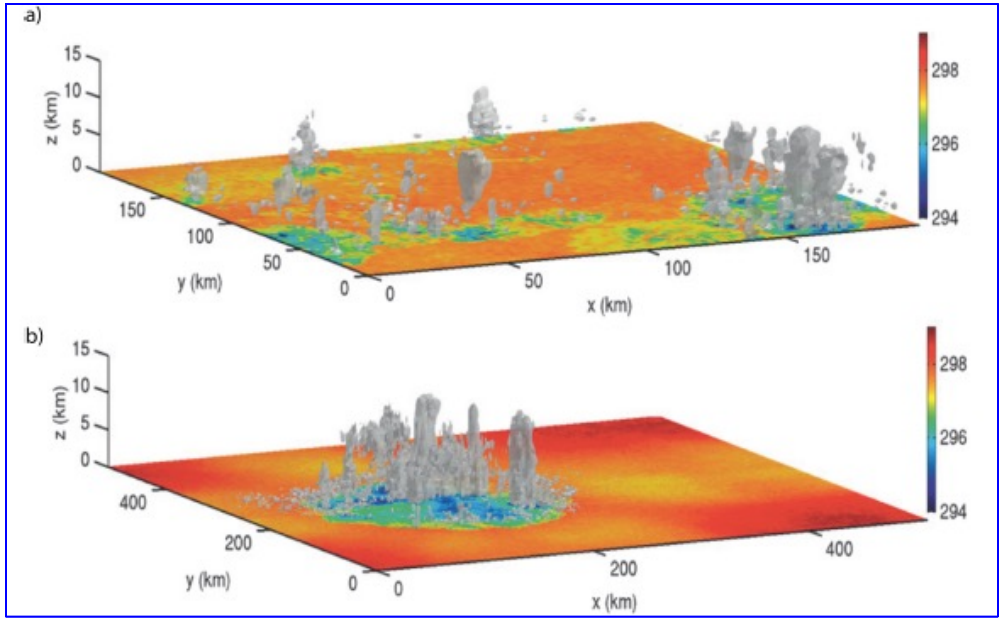


MCCs



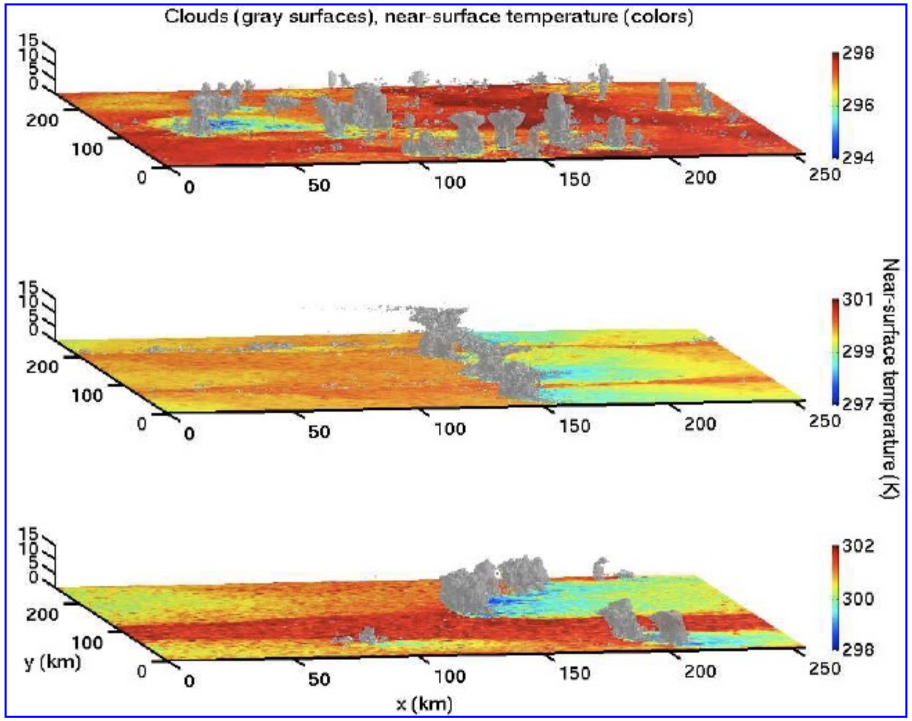
Squall lines

Will look at 2 types of organization:



Self-aggregation

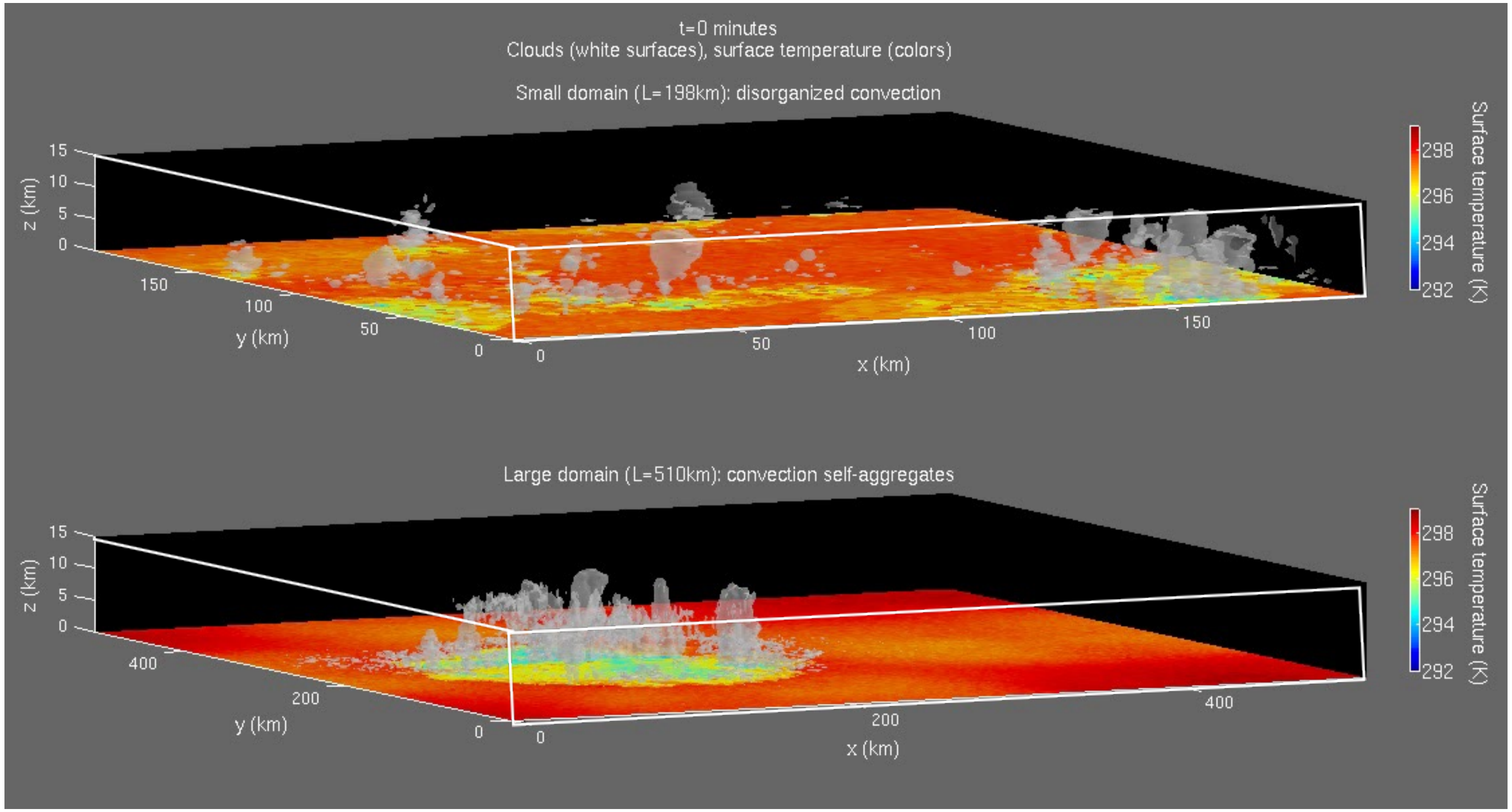
Squall lines



- SAM [Khairoutdinov & Randall 03]
- SST=300K uniform
- No Coriolis (f=0)
- Doubly periodic
- In RCE (dx~1 km; Lx~100s km)

How do precipitation extremes change with self-aggregation?

Clouds over near-surface temperature in cloud-resolving model SAM



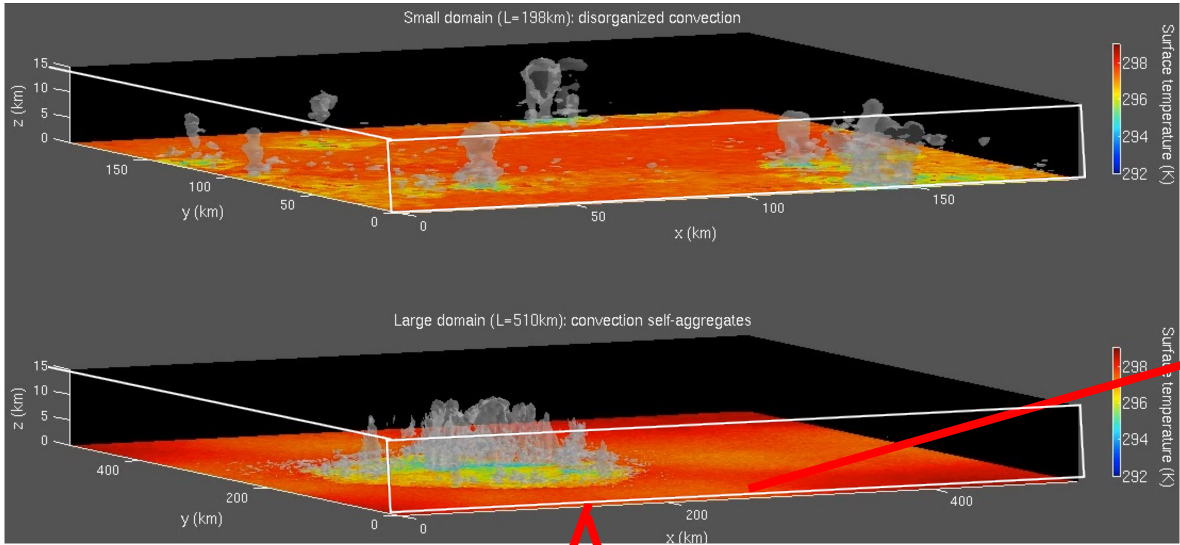
« pop corn » convection

Self-aggregates

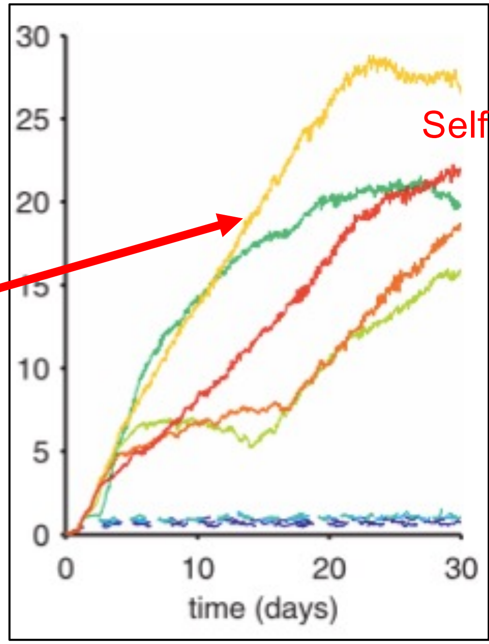
Self Aggregation = Instability of disorganized Radiative-Convective Equilibrium “pop corn” state

[Bretherton, Blossey, Khairoutdinov, 2005; Sobel, Bellon, Bacmeister 2007; Muller, Held 2012; Emanuel, Wing, Vincent 2013; Jeevanjee Romps 2013; Khairoutdinov Emanuel, 2013; Wing Emanuel 2014; Shi Bretherton 2014; Tobin, Bony, Roca, 2012; Tobin et al, 2013; Muller Bony 2015; Arnold Randall 2015; Coppin Bony 2015; Mapes 2016; Holloway Woolnough 2016; Tompkins Semie 2017; ***Wing Holloway Emanuel Muller 2017****; Becker Bretherton Hohenegger Stevens 2018; Yang 2018; Muller Romps 2018;* ***Wing 2019****;* ***Muller et al 2022****; ….]*

How do precipitation extremes change with self-aggregation?

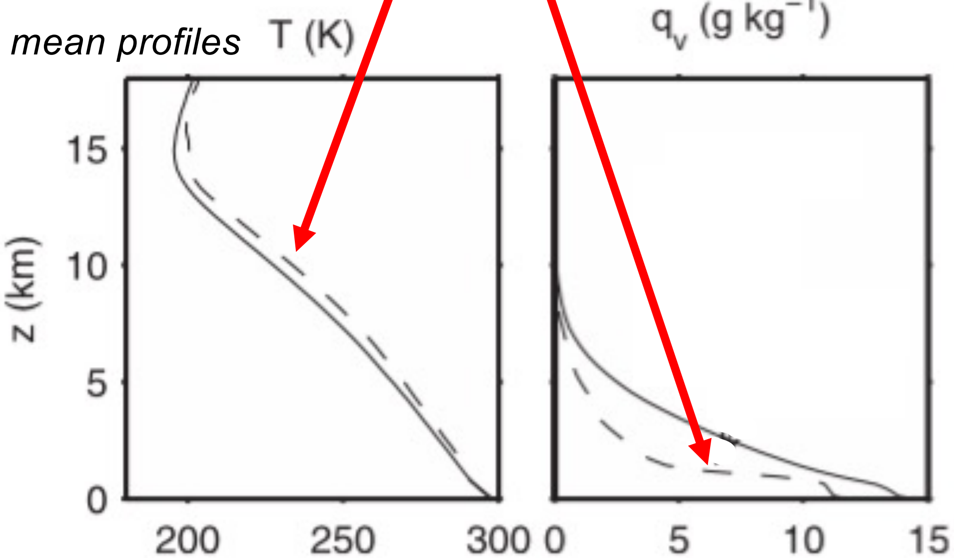


Variance of precipitable water (mm) in simulations



Self-aggregation leads to enhanced moisture variability (moister moist region, drier dry region)

Domain mean profiles



- Overall drying
- Overall warming (warmer moist adiabat)

How do precipitation extremes change with convective organization?

What can we expect?

Microphysic

$$\delta P \sim \delta\left[\varepsilon_p \int \rho w \left(-\frac{\partial q_{sat}}{\partial z} \right) dz \right]$$

Dynamic *Thermodynamic*

- Increased water vapor, as more moisture is confined to the moist region with aggregation

⇒ **Increased thermodynamic** contribution ?

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Dynamic *Thermodynamic*

- Increased water vapor, as more moisture is confined to the moist region with aggregation
⇒ **Increased thermodynamic** contribution ?

- Increased precipitation efficiency, less rain evaporation in moister near-cloud conditions.
⇒ **Increased microphysic** contribution ?

How do precipitation extremes change with convective organization?

What can we expect?

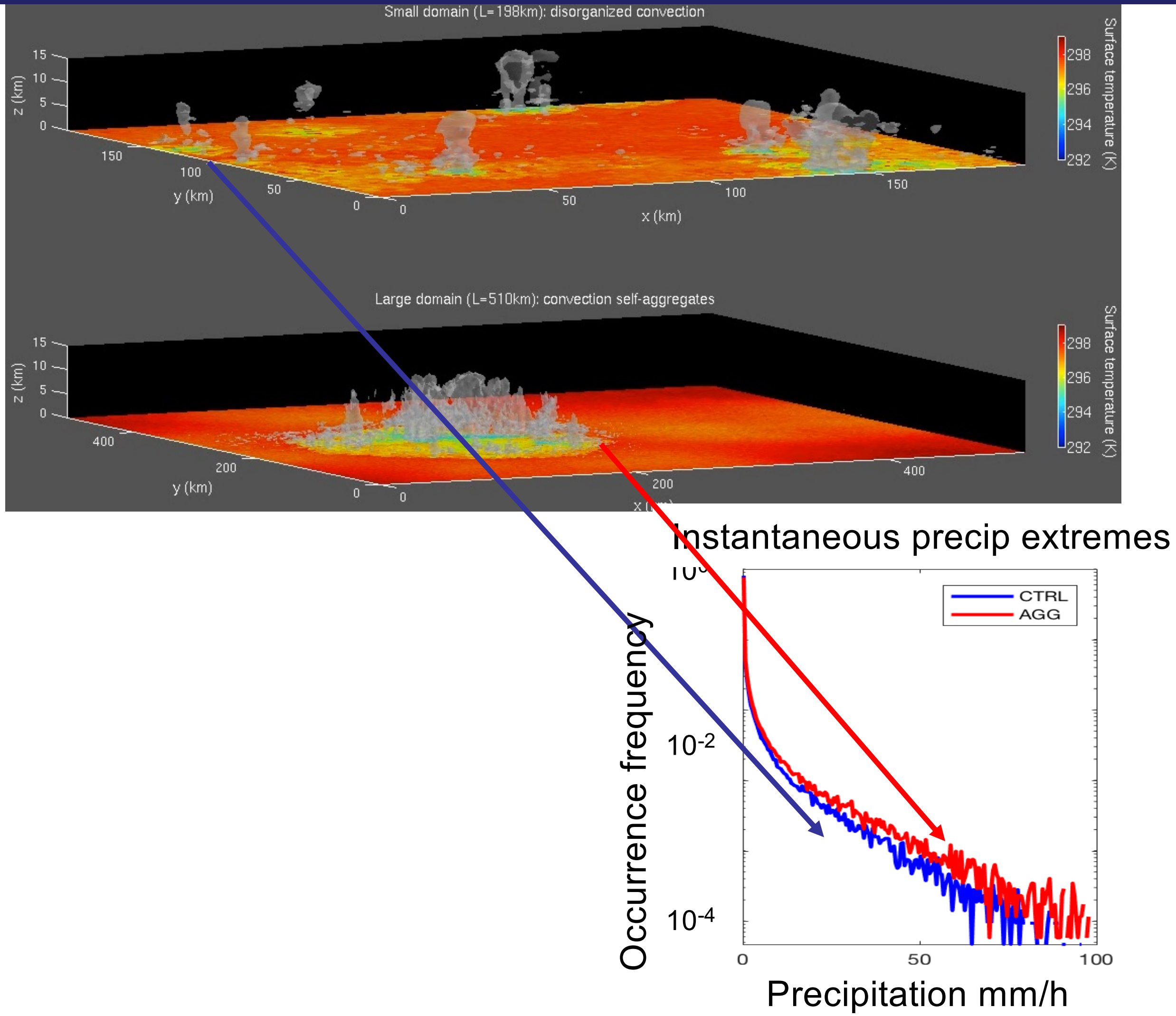
$$\delta P \sim \delta\left[\underbrace{\varepsilon_p}_{\text{Microphysic}} \int \underbrace{\rho w}_{\text{Dynamic}} \underbrace{\left(-\frac{\partial q_{sat}}{\partial z}\right)}_{\text{Thermodynamic}} dz\right]$$

- Increased water vapor, as more moisture is confined to the moist region with aggregation
⇒ **Increased thermodynamic** contribution ?

- Increased precipitation efficiency, less rain evaporation in moister near-cloud conditions.
⇒ **Increased microphysic** contribution ?

- Decreased atmospheric instability (CAPE), as frequent convection in organized systems consumes CAPE, thus instability does not have time to grow (low CIN in the moist convecting region => instability is removed fast), leading to less CAPE and weaker updrafts.
⇒ **Decreased dynamic** contribution ?

Precipitation extremes with self-aggregation



Self-aggregation => more rain accumulation => stronger 3-hourly precip *[Bao Sherwood 2019]*

⇒ BUT increased instantaneous precipitation extremes as well +30%!

Why 30%?

[Da Silva, Muller, Shamekh, Fildier 2021]

How do precipitation extremes change with self-aggregation?

Precip efficiency

Condensation rate « CR » = Dynamic + Thermodynamic

+30%

$$\delta P \sim \delta \left[\varepsilon_p \int \rho w \frac{-\partial q_{sat}}{\partial z} dz \right]$$

[Da Silva, Muller, Shamekh, Fildier 2021]

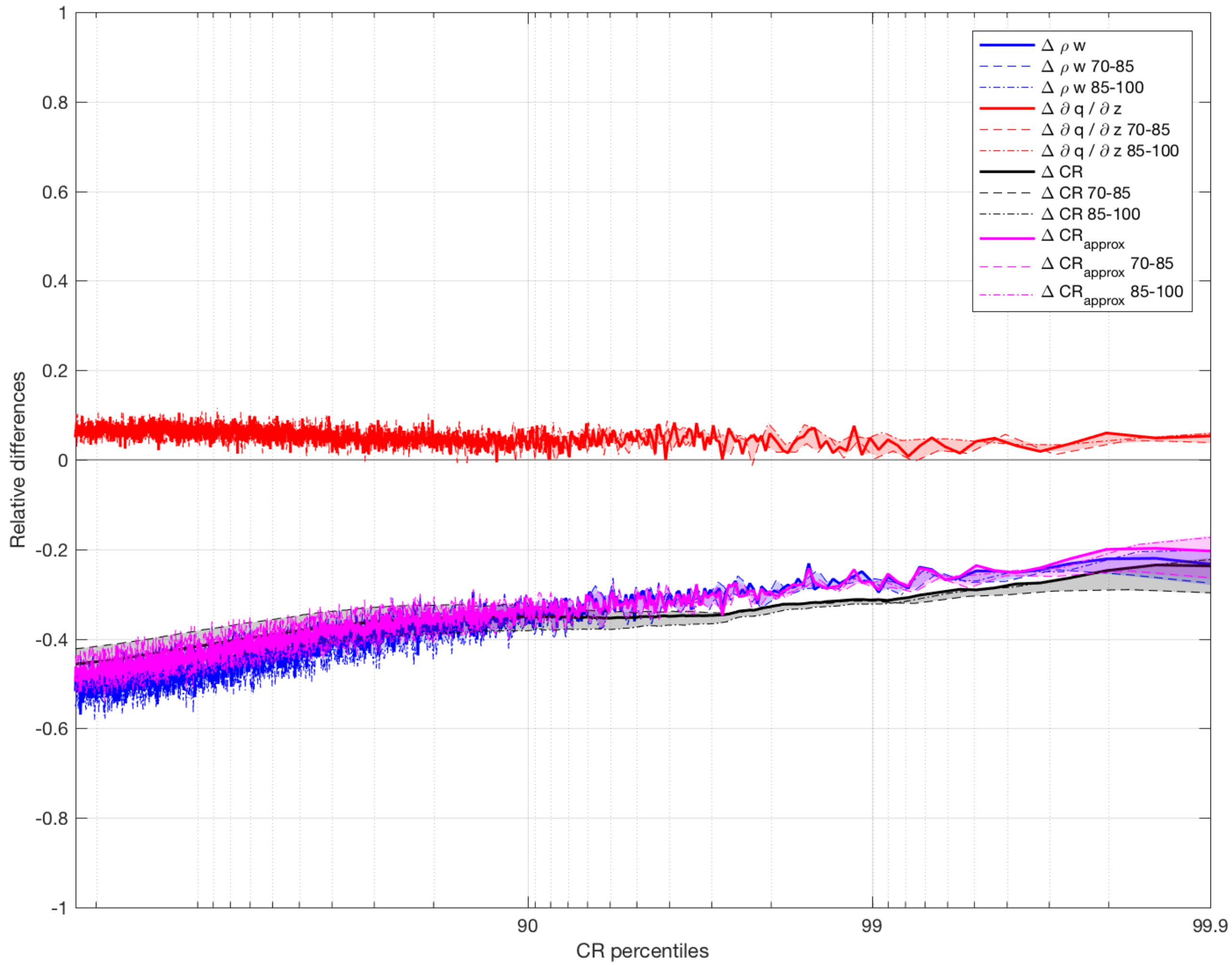
How do precipitation extremes change with self-aggregation?

Precip efficiency

Condensation rate « CR » = Dynamic + Thermodynamic

+30% $\quad \delta P \sim \delta\left[\epsilon_p \int \rho w \frac{-\partial q_{sat}}{\partial z} dz \right]$

-20% = -25% + +5%



Thermodynamic + 5%

Condensation rate -20%

Dynamic -25%

[Da Silva, Muller, Shamekh, Fildier 2021]

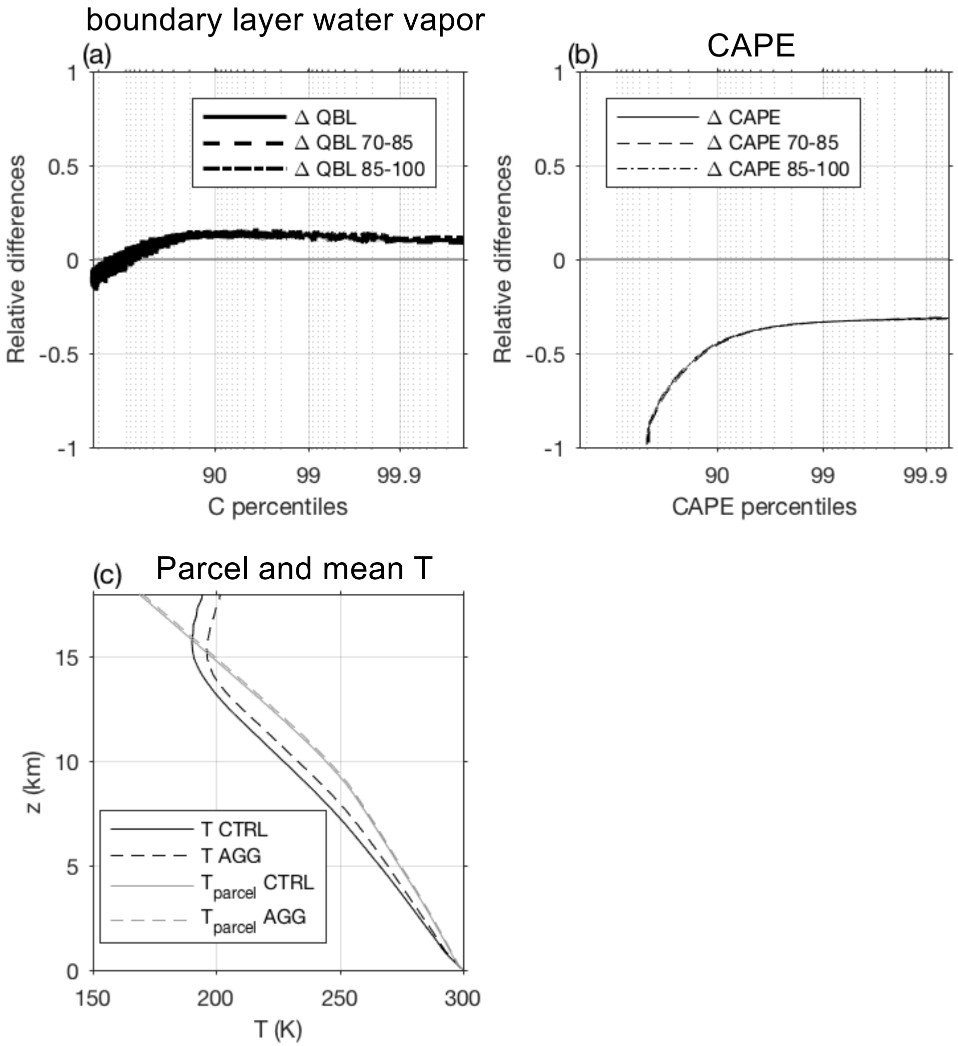
How do precipitation extremes change with self-aggregation?

Precip efficiency

Condensation rate « CR » = Dynamic + Thermodynamic

$$\underbrace{+30\%}\quad \delta P \sim \delta\left[\varepsilon_p \int \rho w \frac{-\partial q_{sat}}{\partial z}\, dz\right]$$

CR: -20% = -25% + +5%



Thermodynamic:

Increase due to moister boundary layer water vapor in cloudy regions

Positive but small contribution

Dynamic:

Decrease due to decreased instability
-30% CAPE <=> -15% w

Qualitatively consistent with dynamic decrease -25%

[Da Silva, Muller, Shamekh, Fildier 2021]

How do precipitation extremes change with self-aggregation?

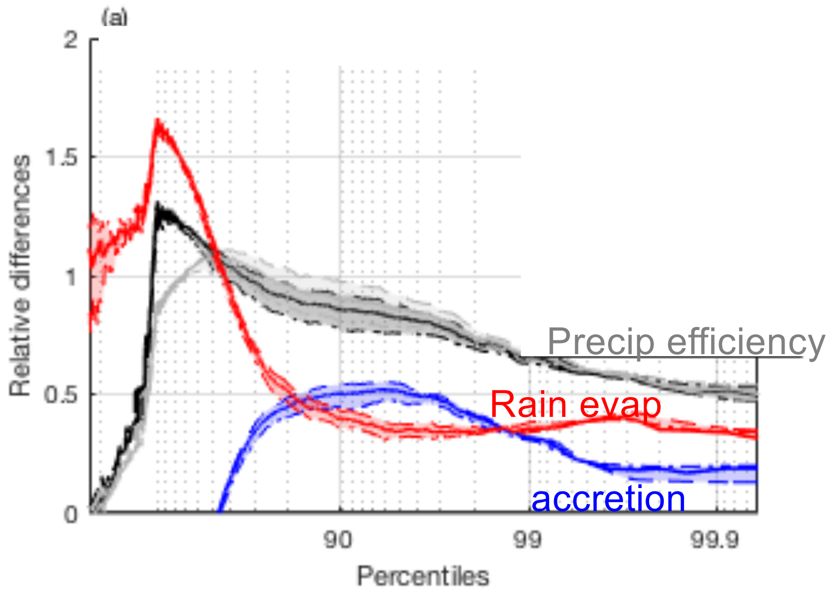
+50%!! *Precip efficiency* *Condensation rate « CR » = Dynamic + Thermodynamic*

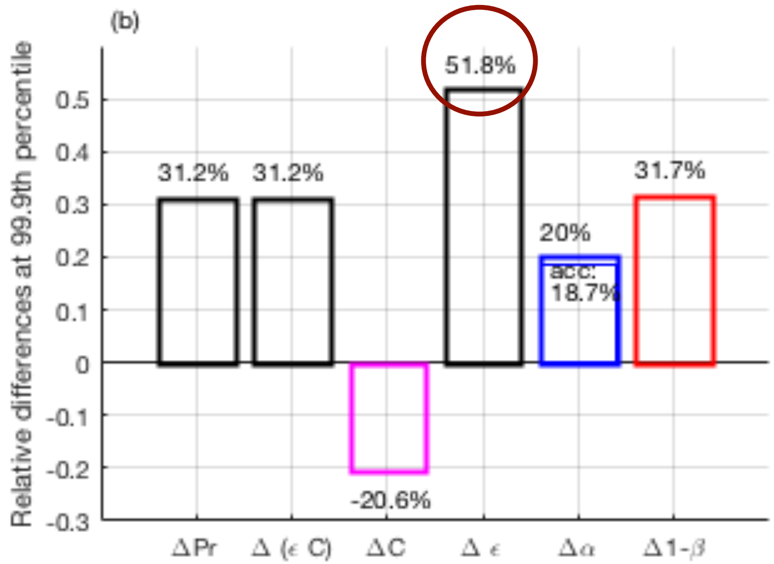
-20% = -25% + +5%

+30%

$$\delta P \sim \delta\left(\varepsilon_p \int \rho w \frac{-\partial q_{sat}}{\partial z} dz \right)$$

Split further into microphysical processes *[Lutsko Cronin 2018]*





accr (collection of cloud into precip)
+ (autoconversion) (cloud into precip)

evaporates (fraction β)
or reaches surface

Cloud condensate → Precipitating condensate → Surface precip

⇒ Mainly reduced rain evaporation (due to moister conditions)

[Da Silva, Muller, Shamekh, Fildier 2021]

How do precipitation extremes change with convective organization?

What can we expect?

Microphysic

$$\delta P \sim \delta \left(\varepsilon_p \int \rho w \left(-\frac{\partial q_{sat}}{\partial z} \right) dz \right)$$

Dynamic *Thermodynamic*

⇒ **Increased thermodynamic** contribution ?

⇒ **Increased microphysic** contribution ?

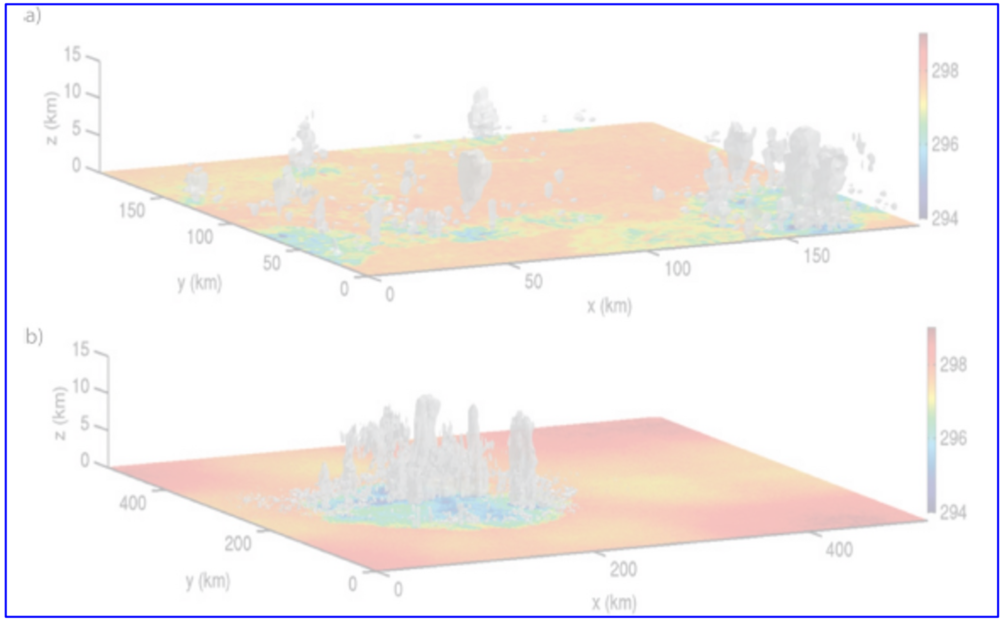
⇒ **Decreased dynamic** contribution ?

With Aggregation: Microphysic contribution dominates amplification of precipitation extremes

Due to less rain evaporation, higher precipitation efficiency

[Da Silva, Muller, Shamekh, Fildier 2021]

Will look at 2 types of organization:

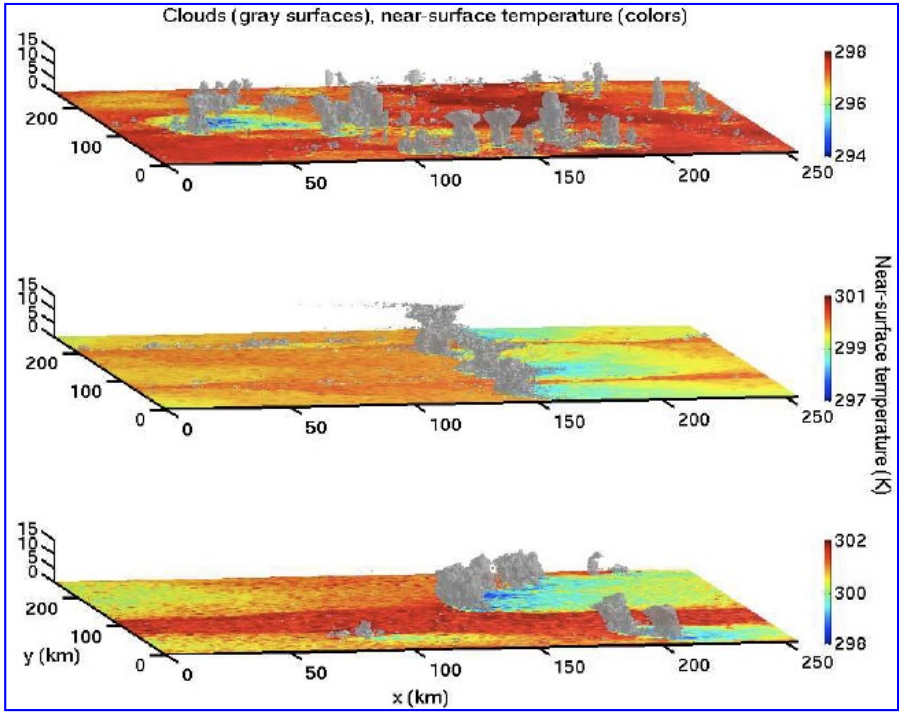


Self-aggregation

Microphysic contribution dominates amplification of precipitation extremes

Due to less rain evaporation => higher precipitation efficiency

Squall lines

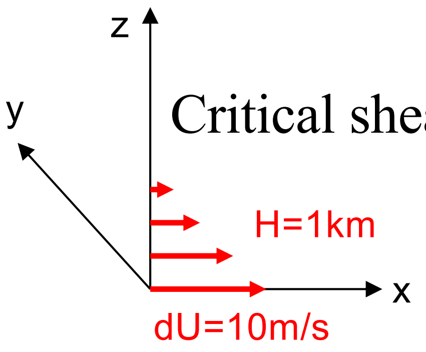


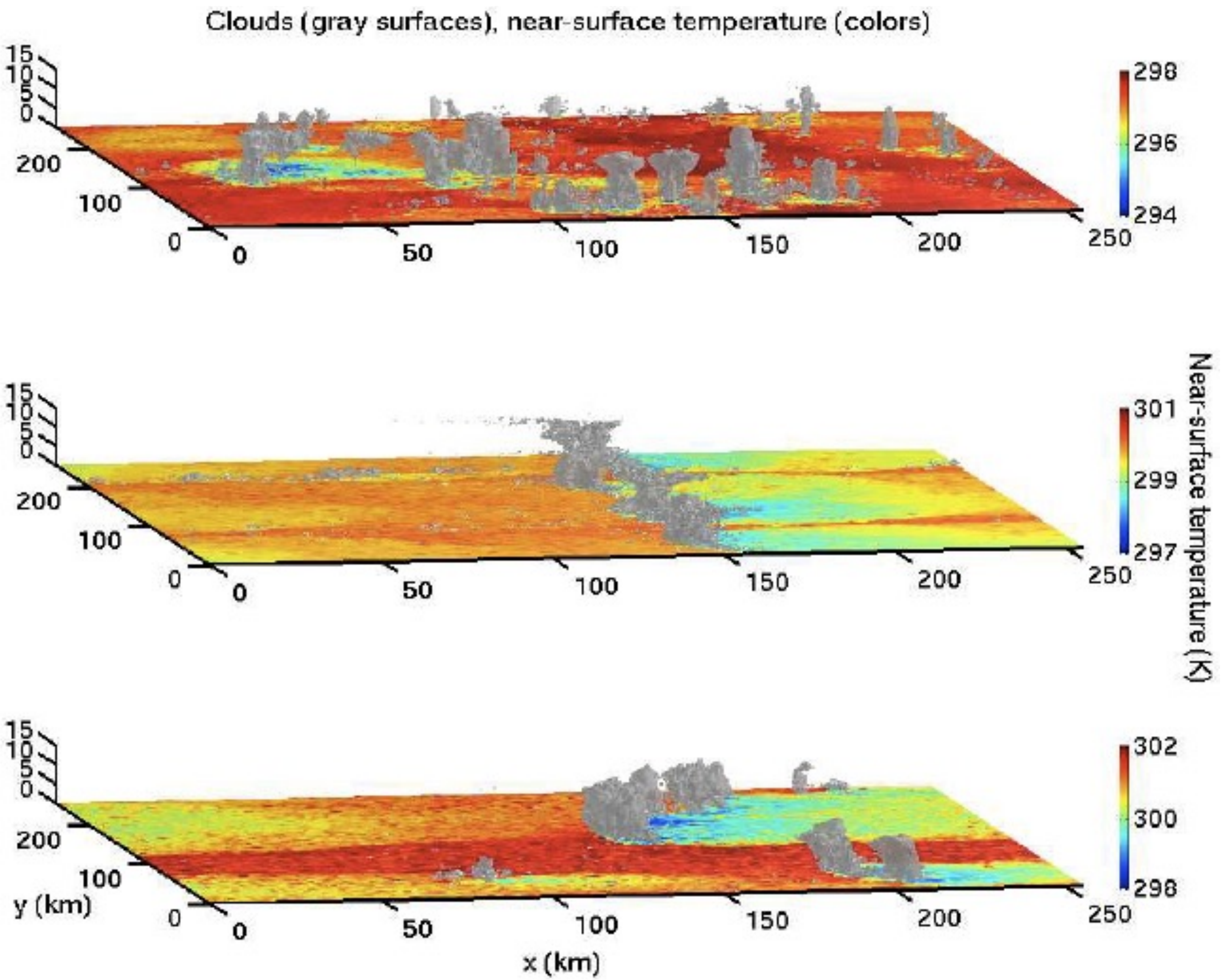
Precipitation extremes in squall lines?

Squall lines (use vertical shear to organize the convection into arcs)

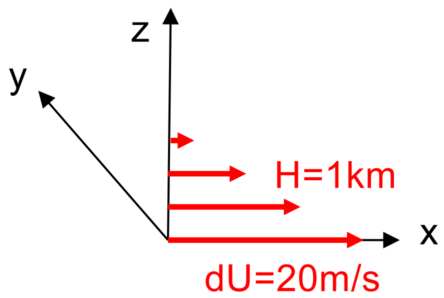
No shear:

Critical shear:





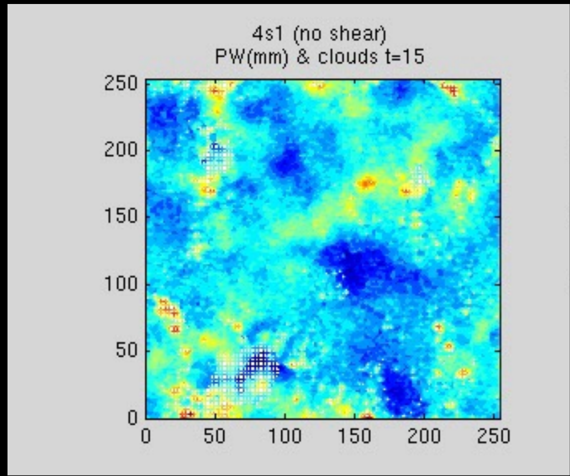
Supercritical shear:



Precipitation extremes in squall lines?

Top view

Color: PW



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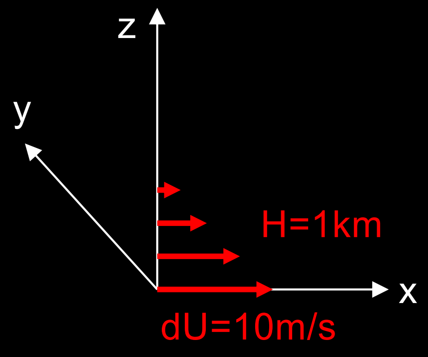

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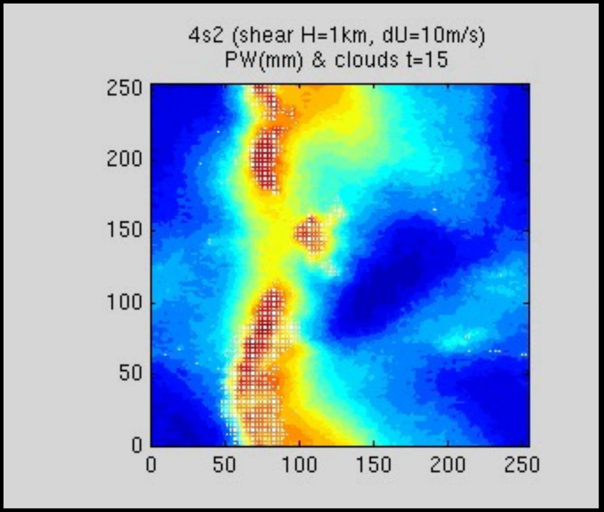
Top view



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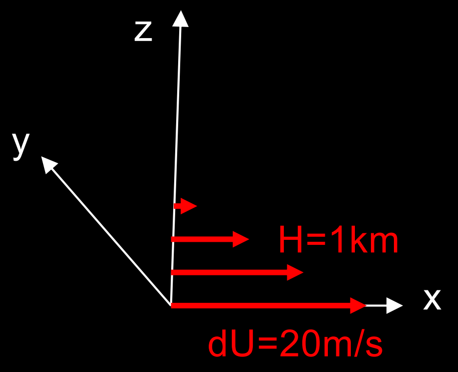

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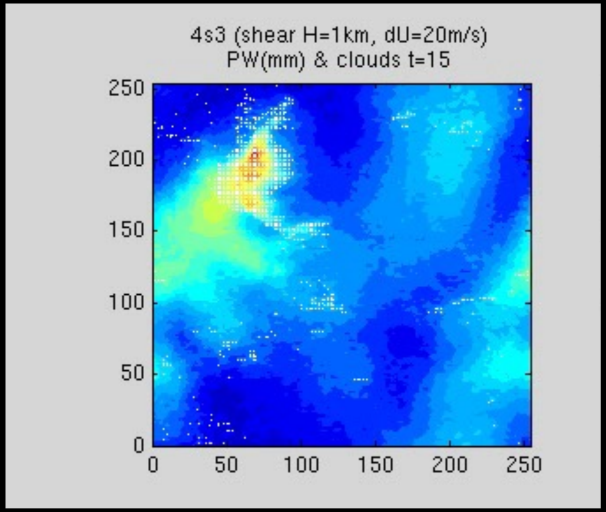
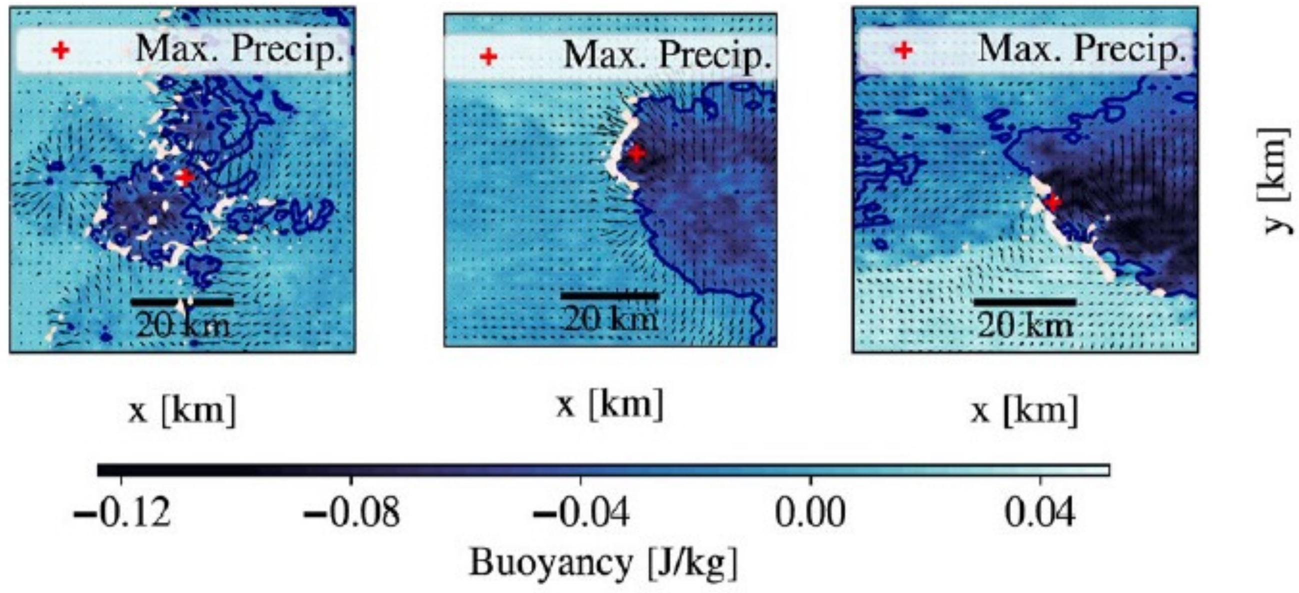
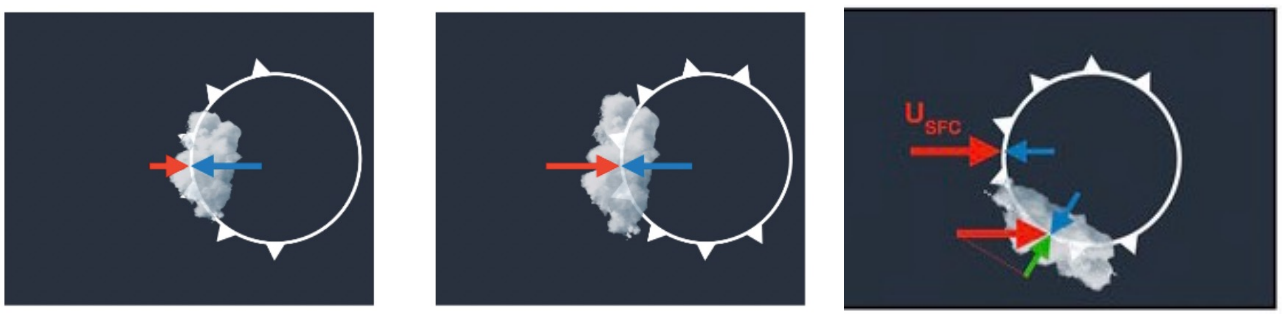


Squall line regimes



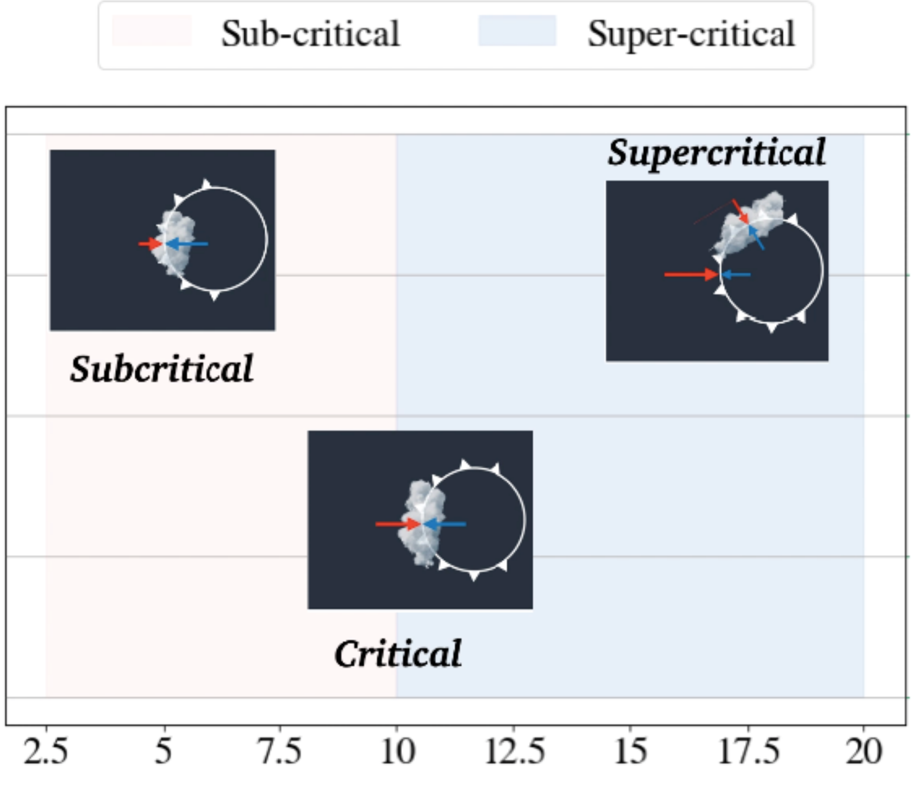
Cold Pool wins | *Equality* | *Shear wins*

Subcritical | *Critical* | *Supercritical*

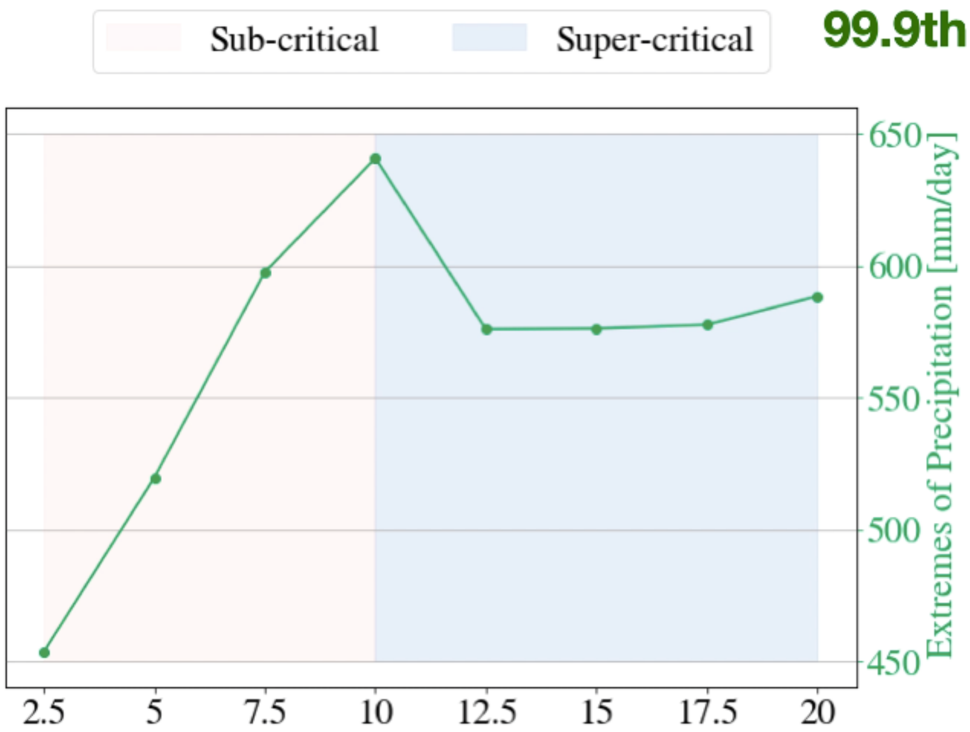


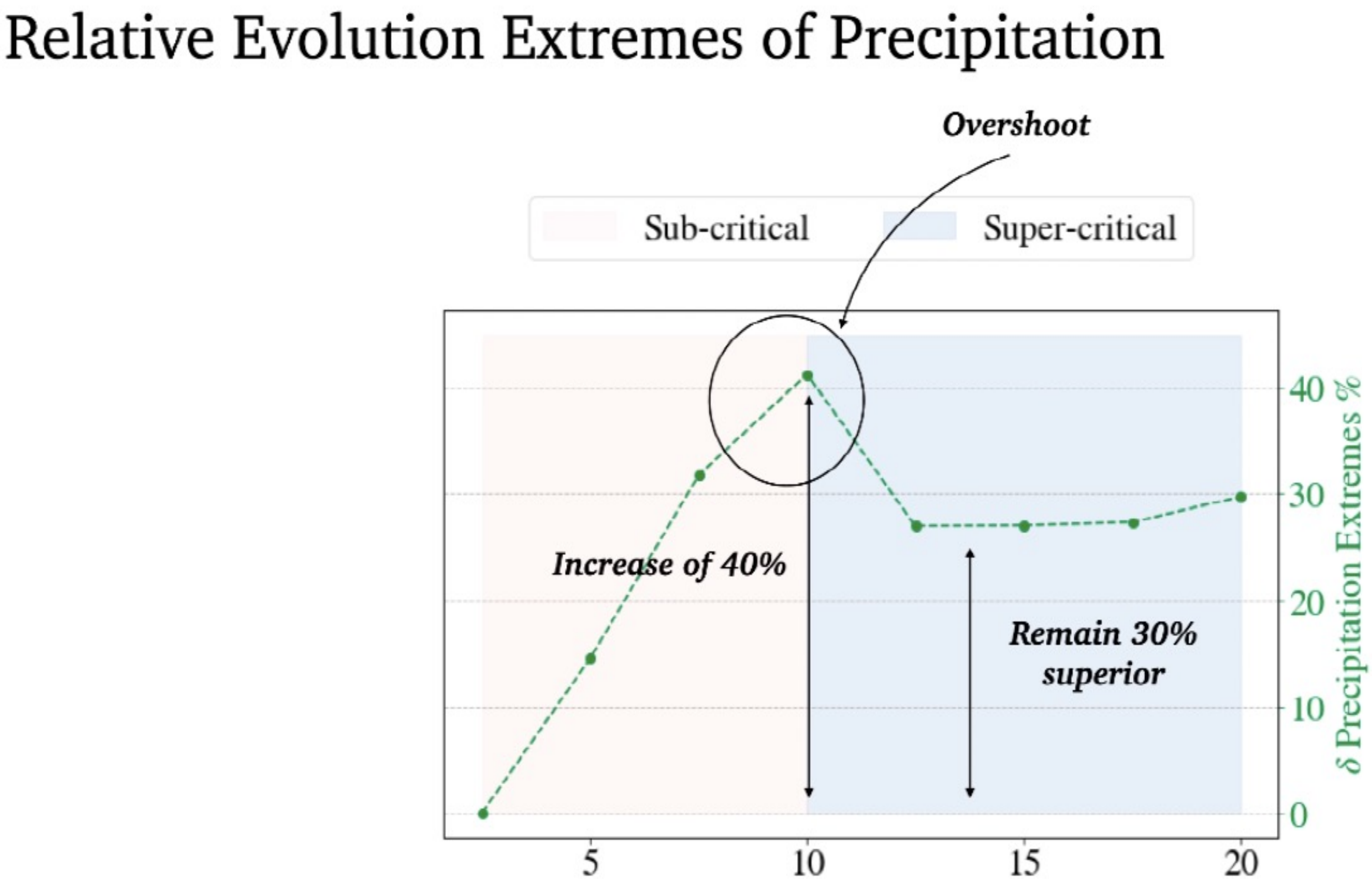
[Rotunno Klemp Weisman 1988;
Robe Emanuel 2011;
Abramian Muller Risi 2021]

How do Extremes of Precipitation evolve with Squall Lines regime ?

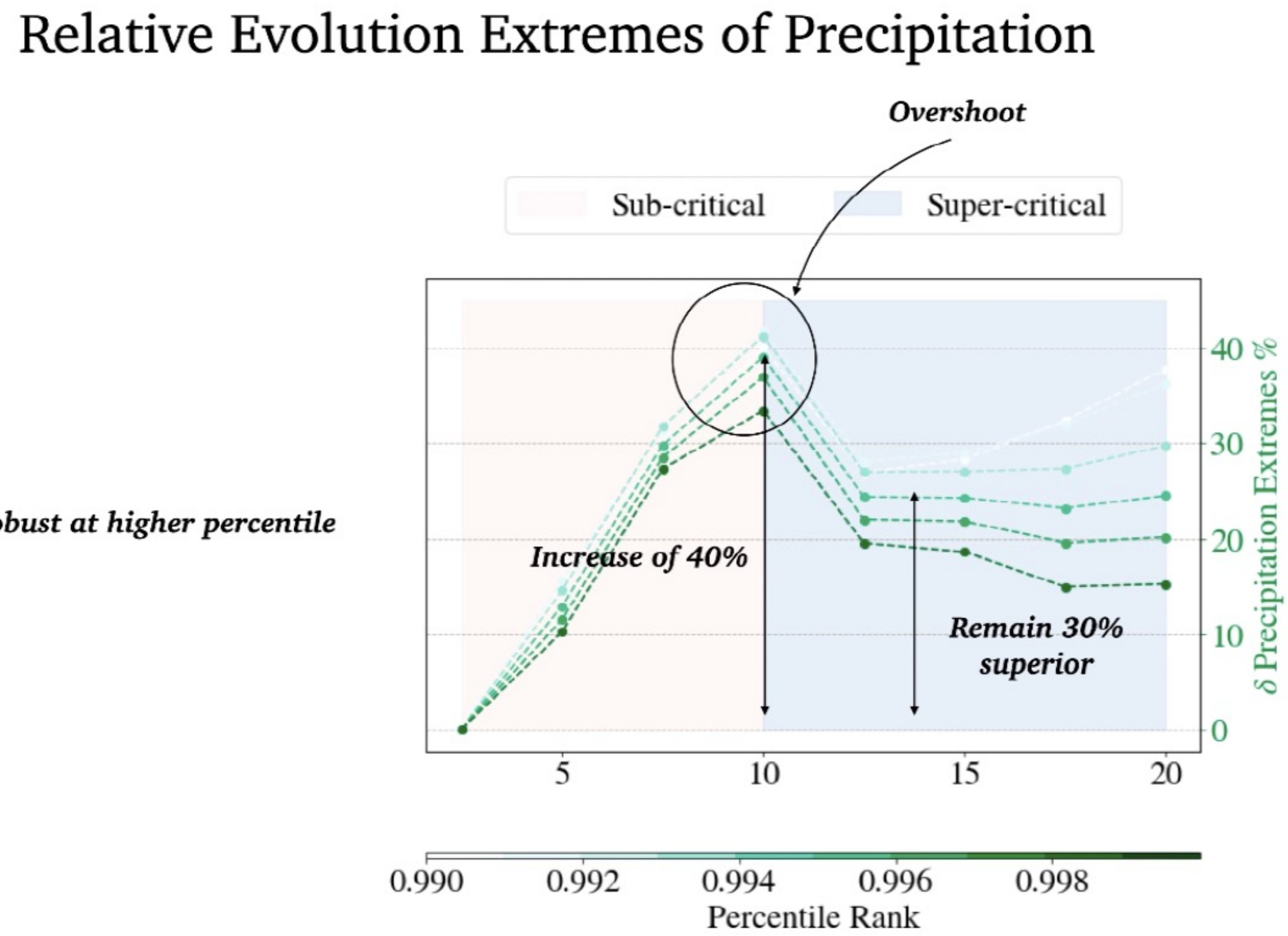


How do Extremes of Precipitation evolve with Squall Lines regime ?




Relative Evolution Extremes of Precipitation
Overshoot
Sub-critical
Super-critical
Increase of 40%
Remain 30%
superior
40
30
20
10
0
δ Precipitation Extremes %
5
10
15
20

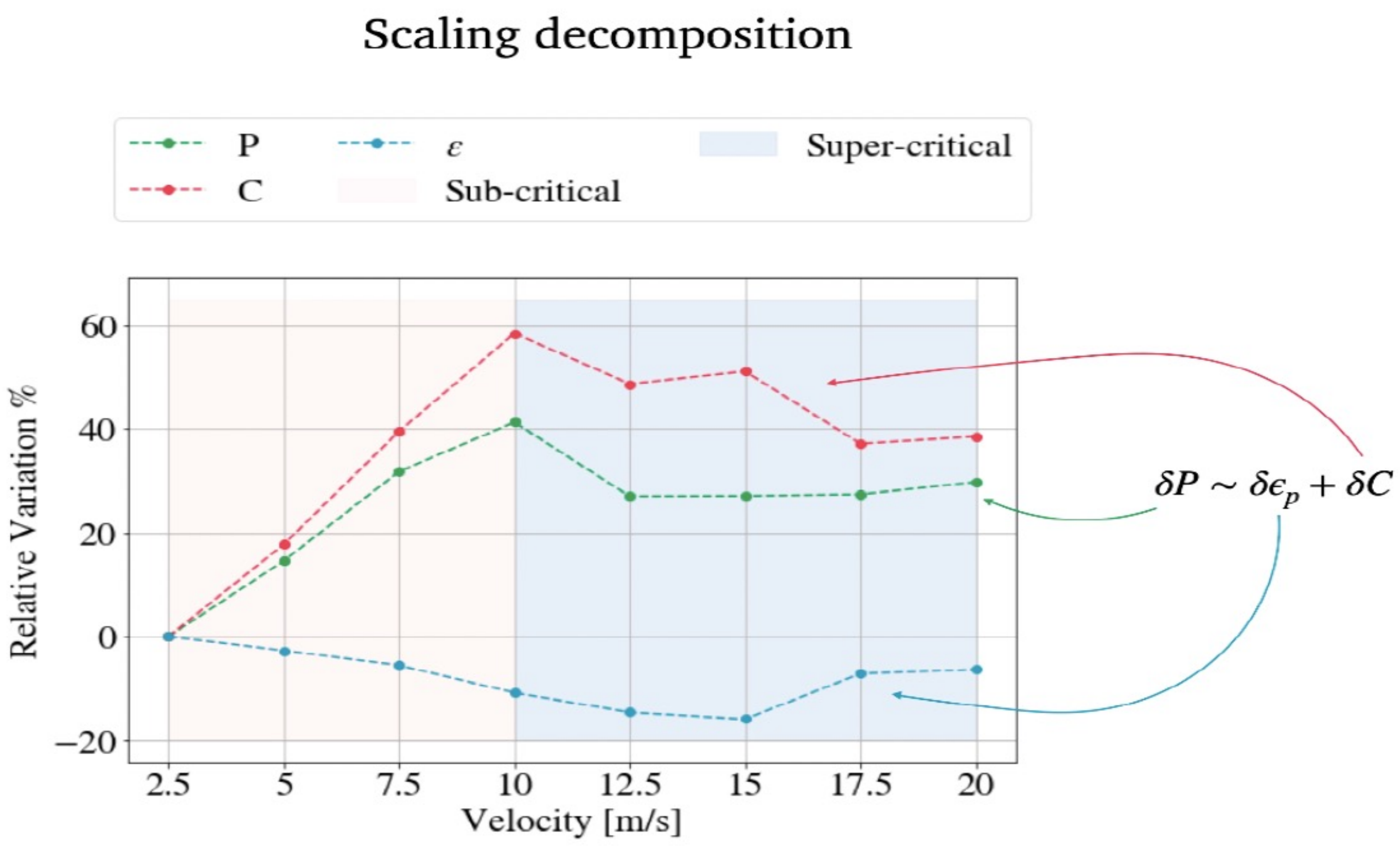
Precipitation extremes in squall lines?



Robust at higher percentile

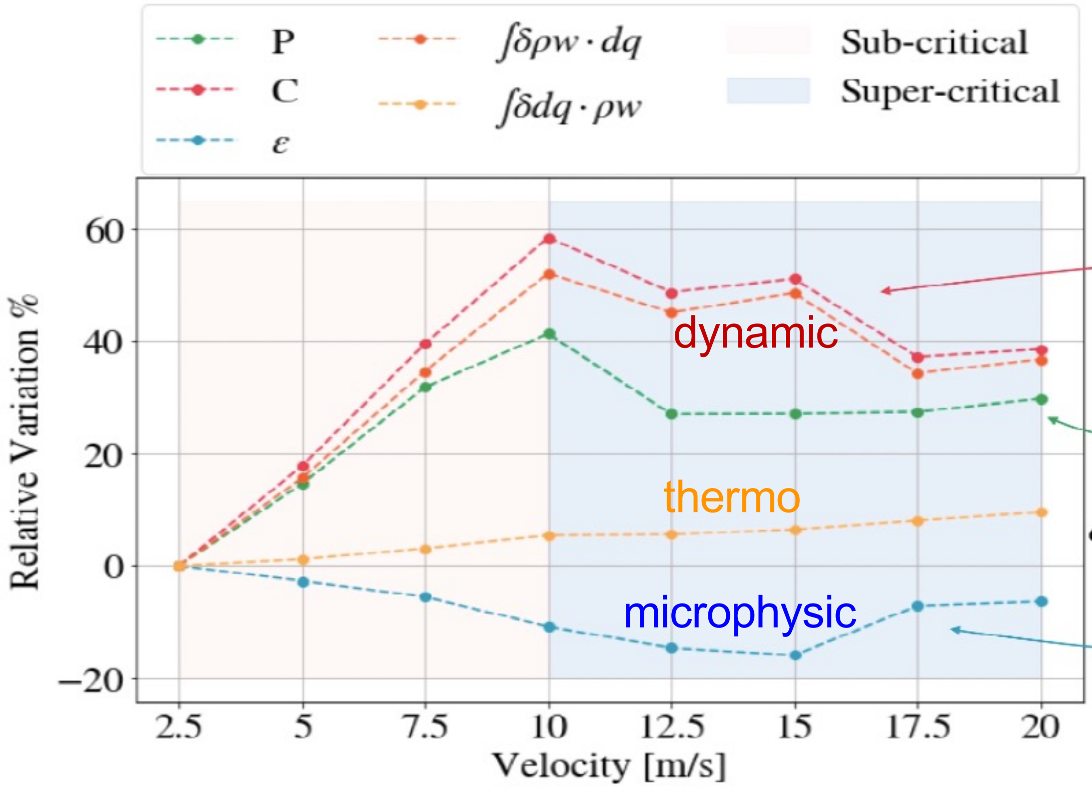
→ Why ?

Precipitation extremes in squall lines?



⇒ Condensation is sensitive to squall line regime

Scaling decomposition



$$\delta P \sim \delta \epsilon_p + \delta C$$

$$\delta P \sim \delta \epsilon_p + \int \delta\rho w dq + \int \delta dq \rho w$$

⇒ Dominated by dynamic contribution!

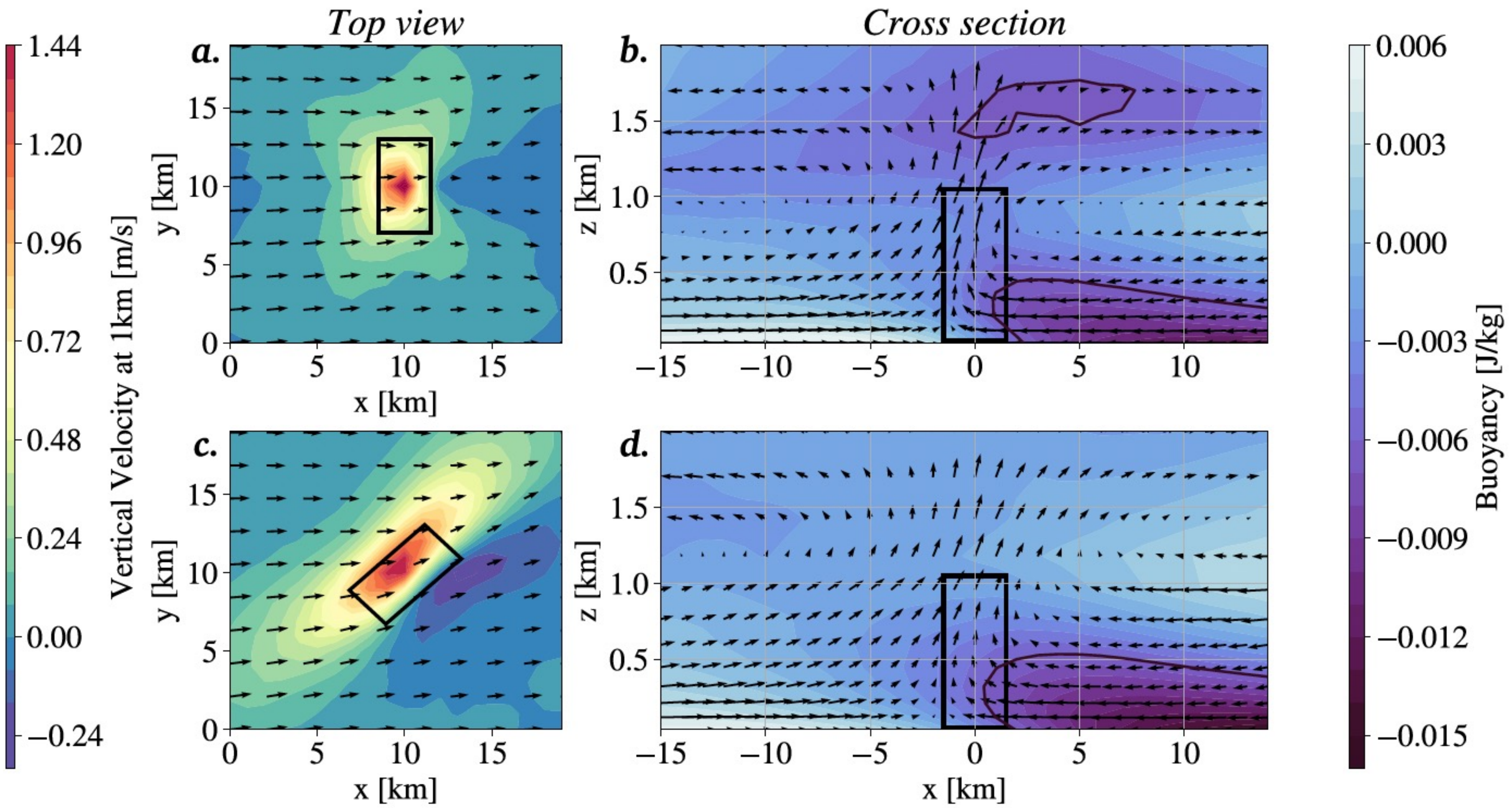
Precipitation extremes in squall lines?

Why? CAPE changes are small…

[Abramian Muller Risi 2023]

Precipitation extremes in squall lines?

Why? CAPE changes are small…

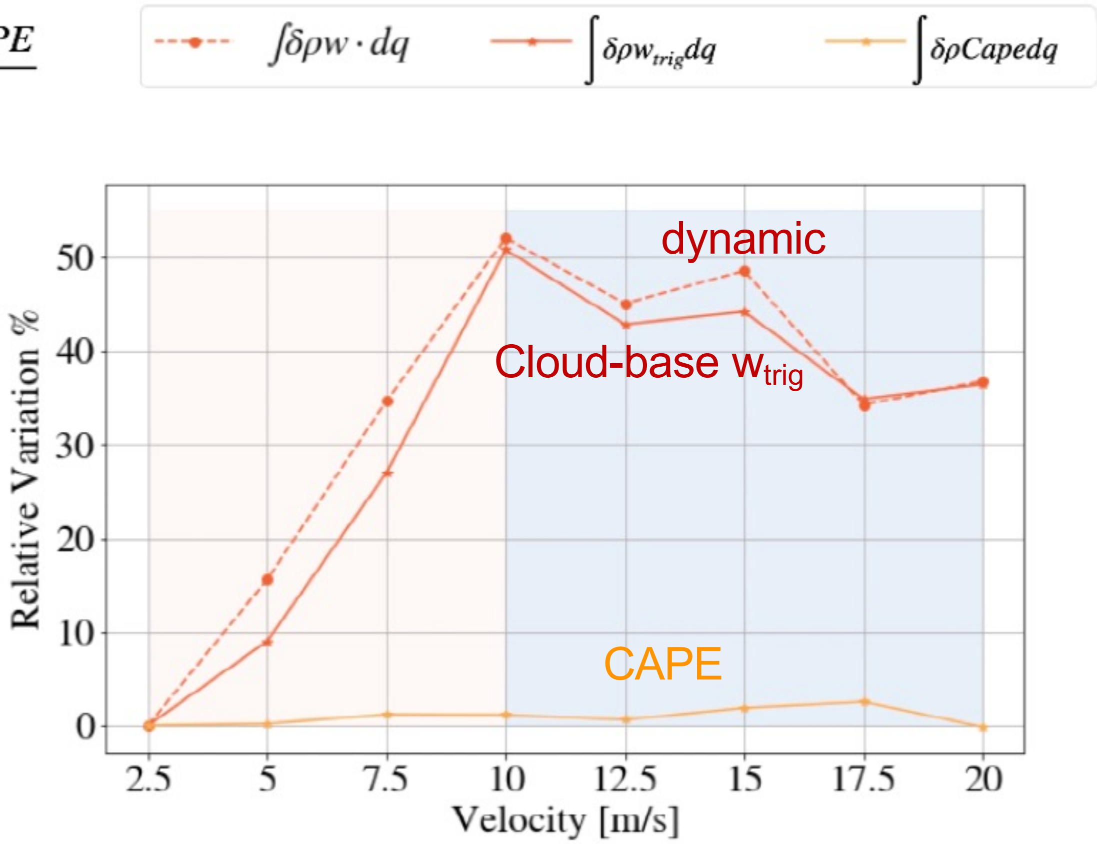


[Abramian Muller Risi 2023]

Precipitation extremes in squall lines?

Convective triggering dominates dynamics

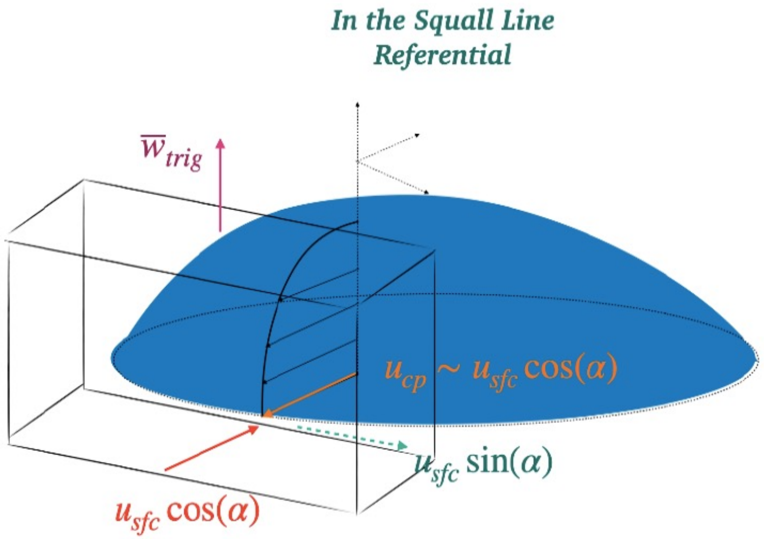
$$dw \sim \int w_{trig} \frac{\Delta w_{trig}}{w} + \int \frac{\Delta CAPE}{w}$$



[Abramian Muller Risi 2023]

Precipitation extremes in squall lines?

A model for convective triggering ?

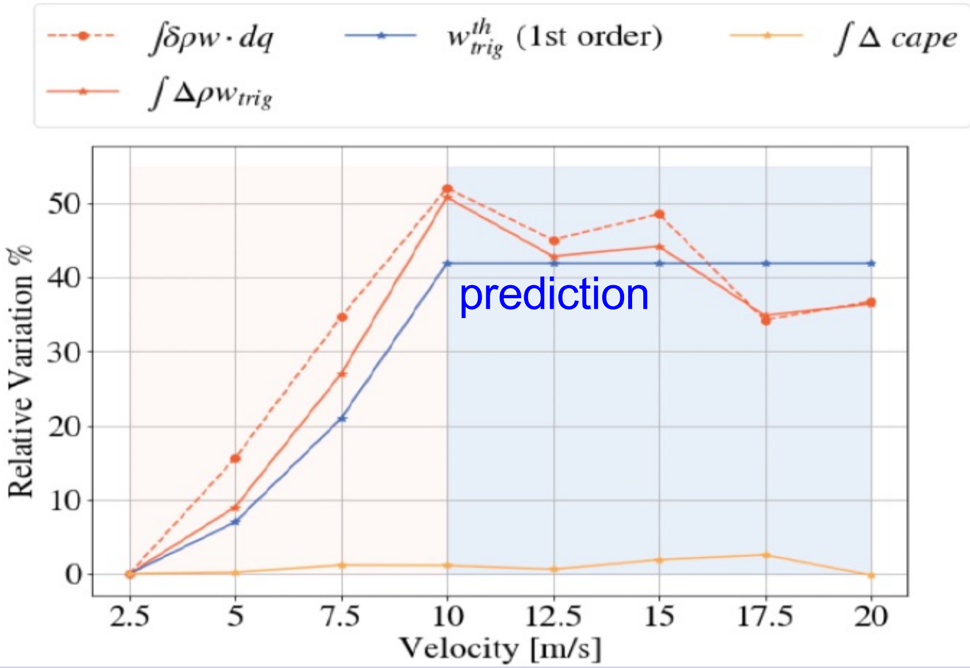


Mass Balance

$$div(\rho\vec{u}) = 0$$

1st order

$$\overline{w}_{trig} \sim r\frac{u_{sfc}\cos(\alpha)}{6}$$



[Abramian Muller Risi 2023]

Precipitation extremes in squall lines?

⇒ Extremes of precipitation are sensitive to squall line regime

⇒ Explained by a change in dynamics with the orientation of the line

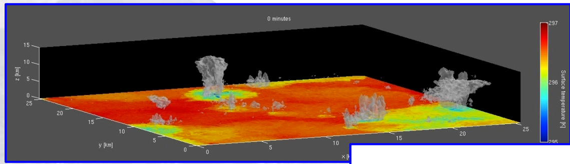
⇒ In particular, the triggering vertical velocity depends on convergence between cold pool spreading and projected wind shear

⇒ We derive a simple model for triggering velocity that fits the variation of the dynamic term

[Abramian Muller Risi 2023]

Precipitation extremes, their change with warming & with convective organization

1) How do precipitation extremes change with **warming?**



⇒ Precipitation extremes increase with warming

⇒ Following Clausius-Clapeyron (near-surface humidity increase)

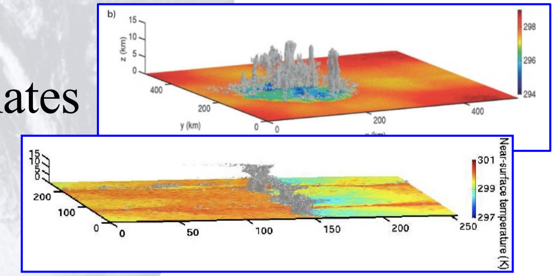
$$P \sim \varepsilon_p \int \rho w \, \frac{-\partial q_v}{\partial z} \, dz$$

2) How do precipitation extremes change with **convective organization?**

⇒ Precipitation extremes increase in organized convection

⇒ With self-aggregation, increased precipitation efficiency dominates

⇒ In squall lines, increased updraft velocities dominate



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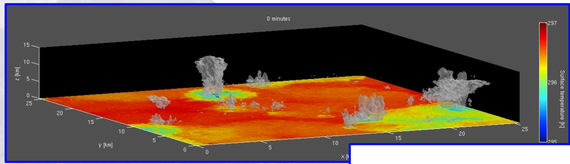

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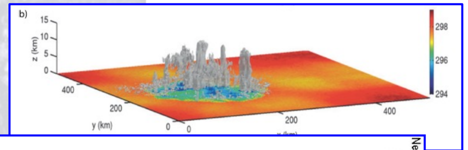

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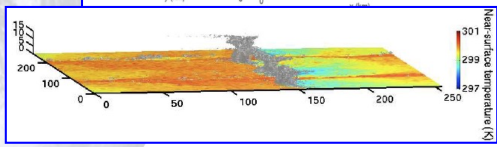


⇒ In squall lines, increased updraft velocities dominate

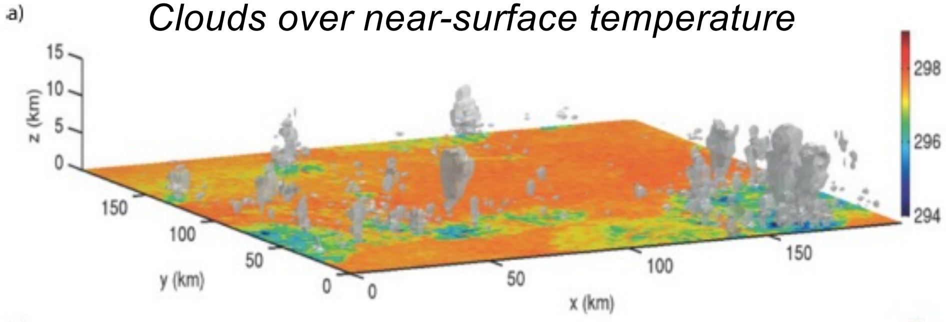
3) How does **organization** (& thus extremes) change with **warming**?

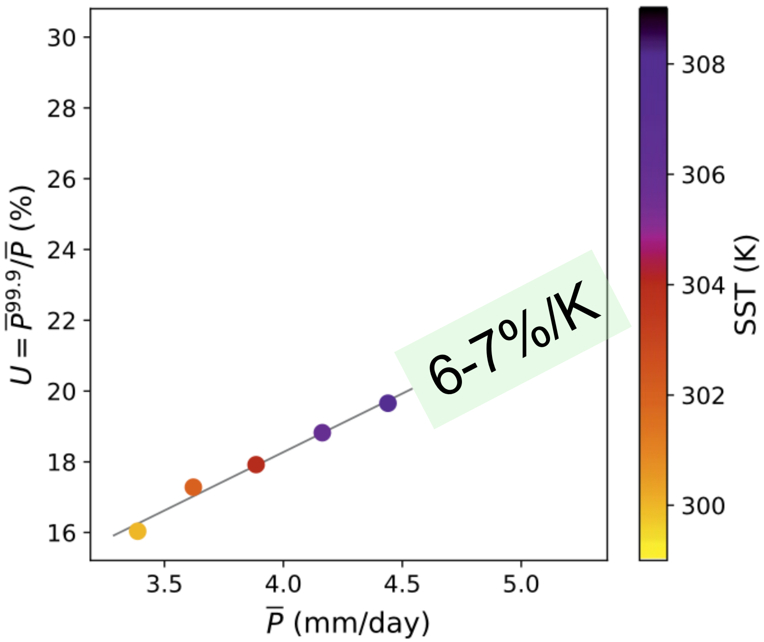
Precipitation extremes, organization and warming

Local (convective scale) precipitation extremes increase
following surface water vapor ~6-7%/K

Cloud-Resolving Model (CRM) "SAM" *[Khairoutdinov, M.F. and Randall, D.A., JAS 2003]*

Clouds over near-surface temperature



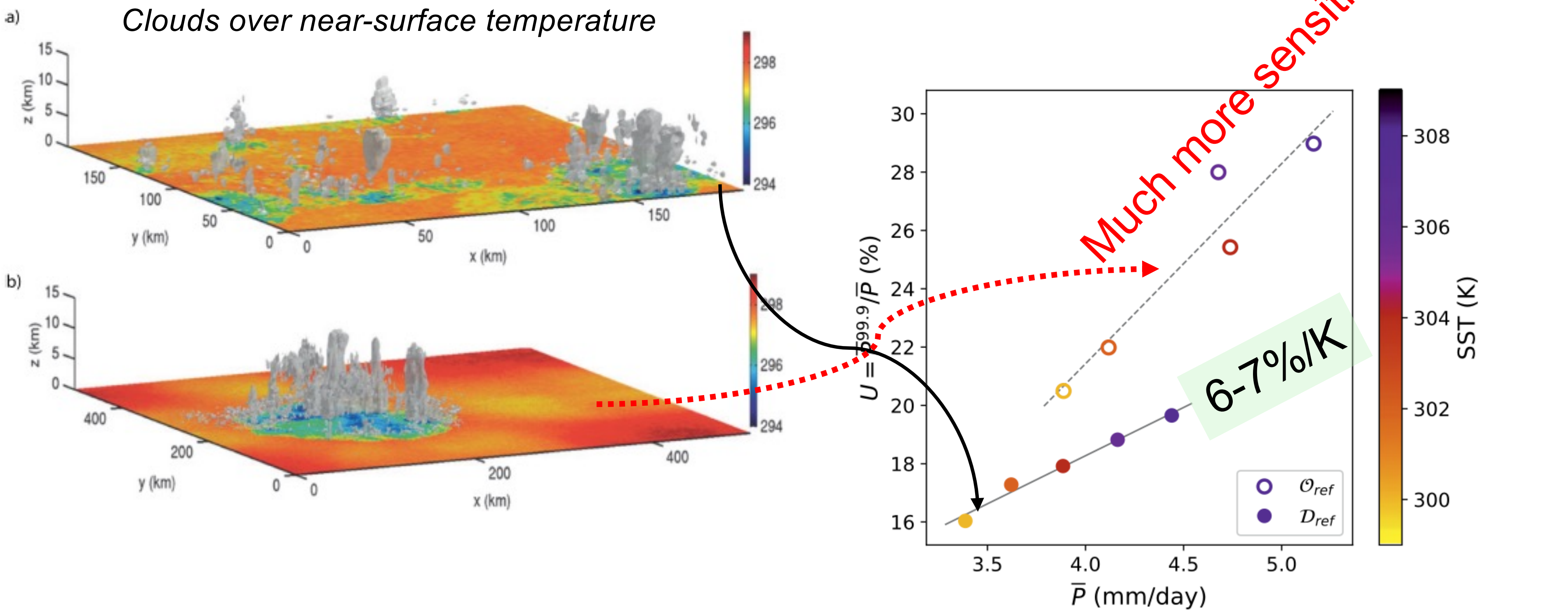


Precipitation extremes, organization and warming

Local (convective scale) precipitation extremes increase
following surface water vapor ~6-7%/K

⇒ BUT more sensitive to warming if organized
⇒ Need to understand mesoscale systems & link with precip extremes

Cloud-Resolving Model (CRM) "SAM" *[Khairoutdinov, M.F. and Randall, D.A., JAS 2003]*



[Fildier Collins Muller 2021]

Precipitation extremes in GSRMs

Global storm resolving models (GSRMs)

- High resolution (<5km), global domain
- Realistic conditions (forcing, with rotation)
- With large-scale circulation

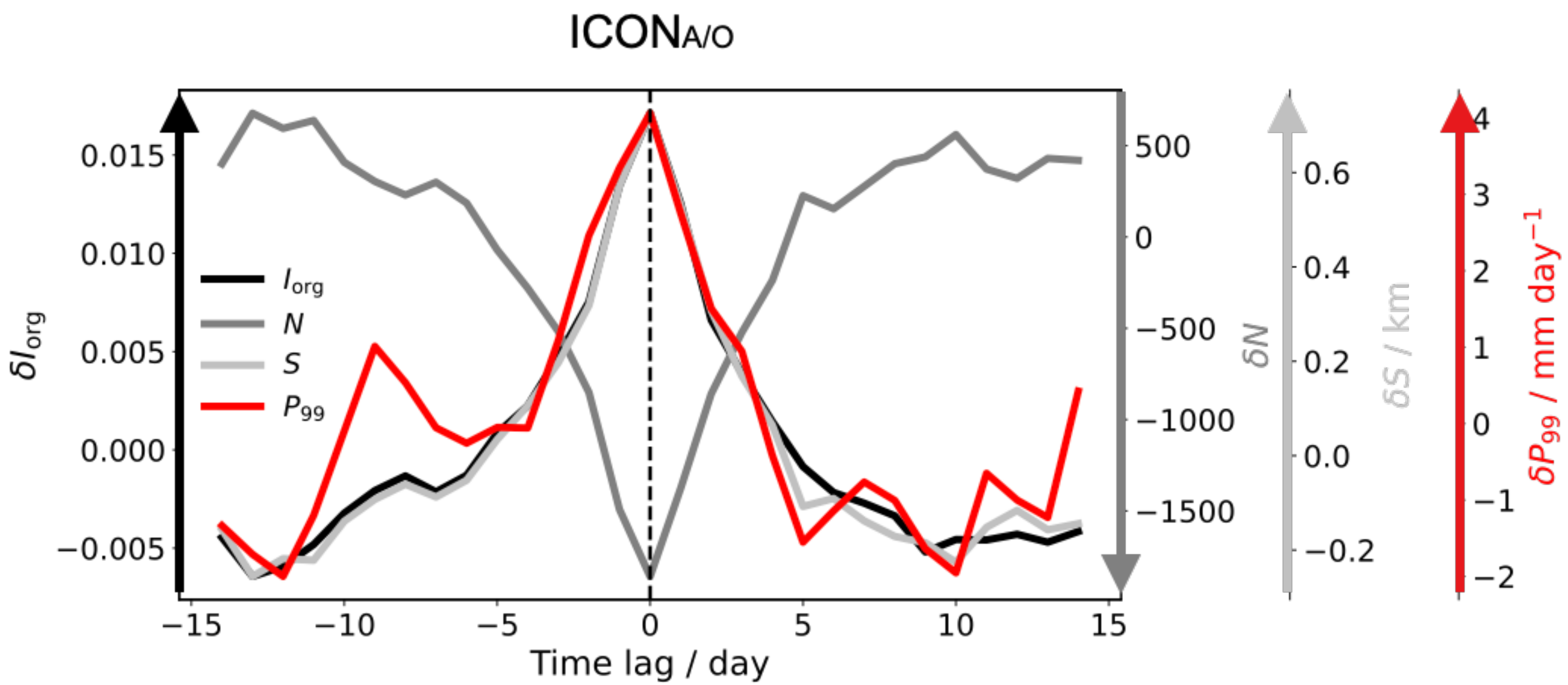
next GEMS

ICON 1 km visualization (MPI-M&DKRZ)
Hohenegger et al. 2023

Precipitation extremes in GSRMs

In current climate:

Time evolution of organisation and precipitation extremes during the composite peak organization events



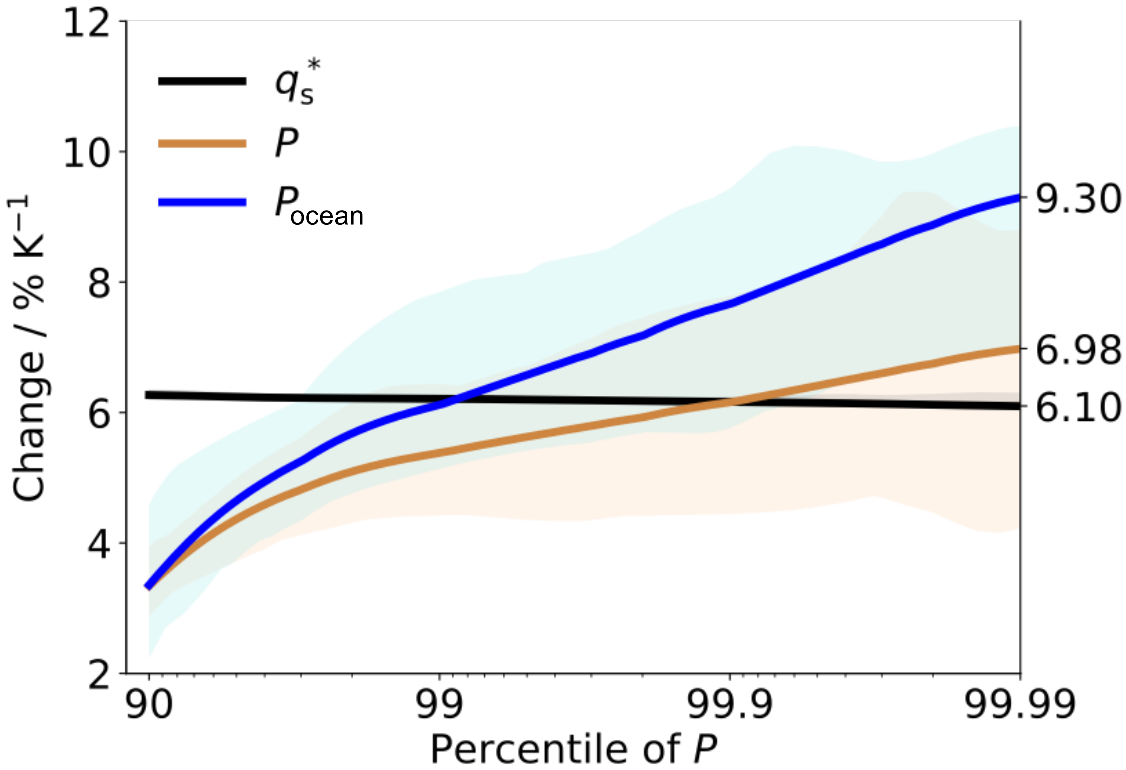
⇒ Precipitation extremes & Iorg related

Bao Stevens Kluft Muller, *Science Advances* (2024)

Precipitation extremes in GSRMs

In future climate:

Change in daily precipitation extremes in 2070 relative to 1850 from $ICON_A$



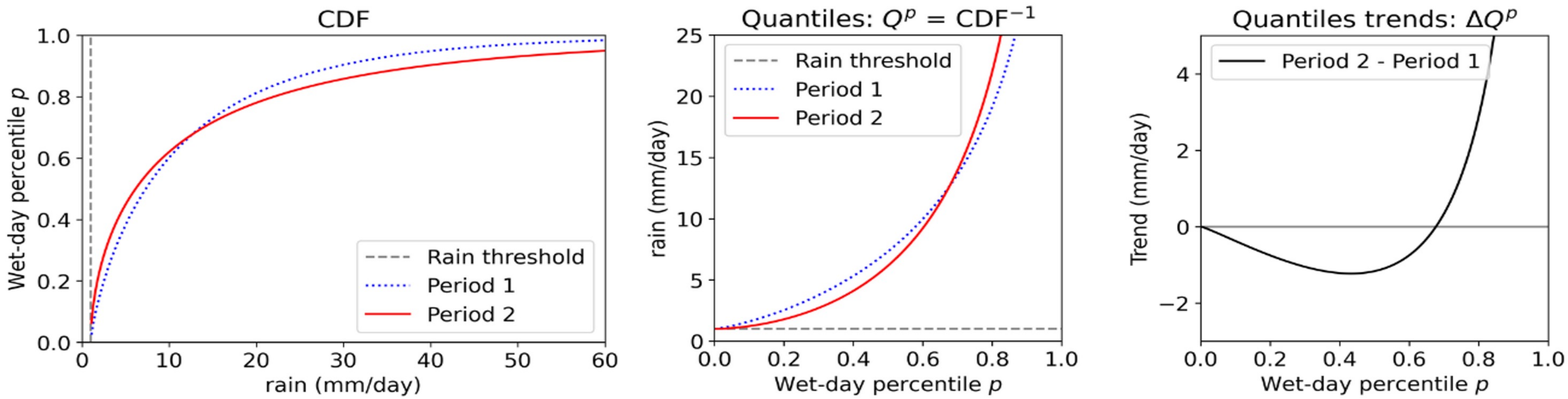
⇒ Precip extremes amplify beyond CC

⇒ Due to increased organization

Bao Stevens Kluft Muller, *Science Advances* (2024)

Precipitation extremes projects

Project : Framework to look at whole precip pdf (not just mean or extremes)



Andre et al 2024

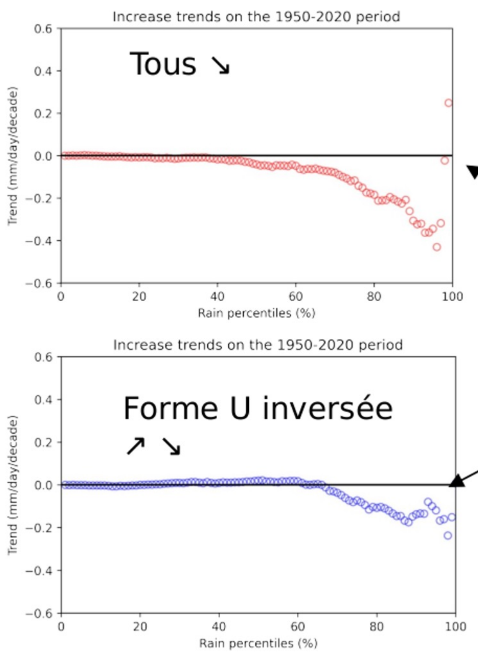
Precipitation extremes projects

A distribution approach on ERA5 data

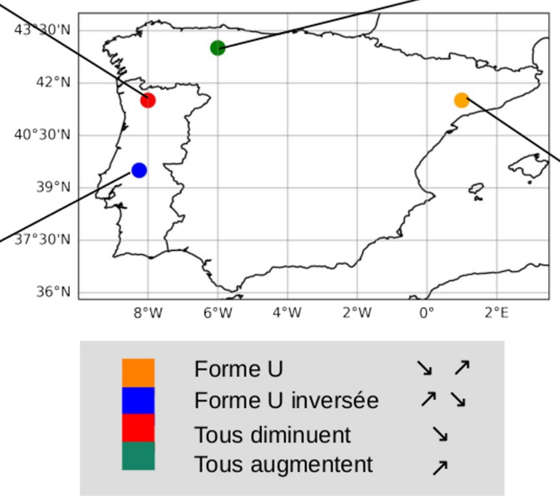
Dataset = ERA5 precipitation, 0.25°, daily

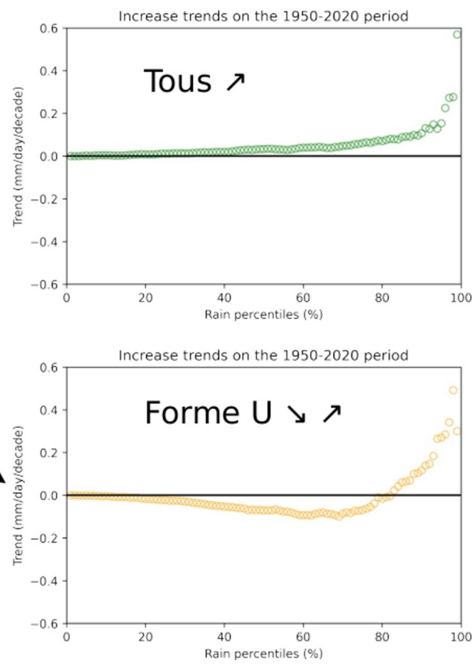
Wet-days = if more than 1 mm/day (recommendation ETCCDI)

Trends = change between periods 1950-1980 and 1990-2020.



4 types of quantile trends curve :





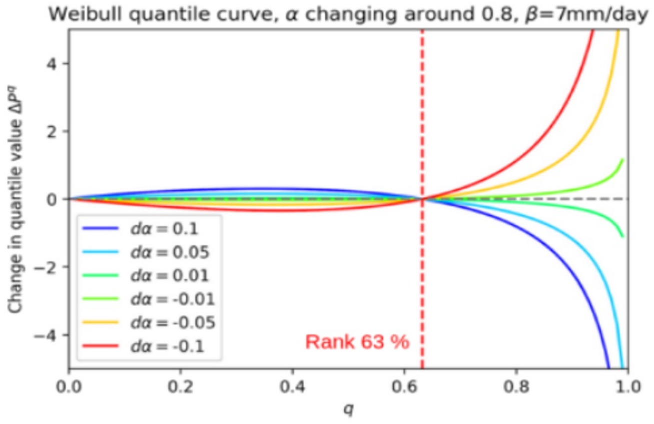
Andre et al 2024

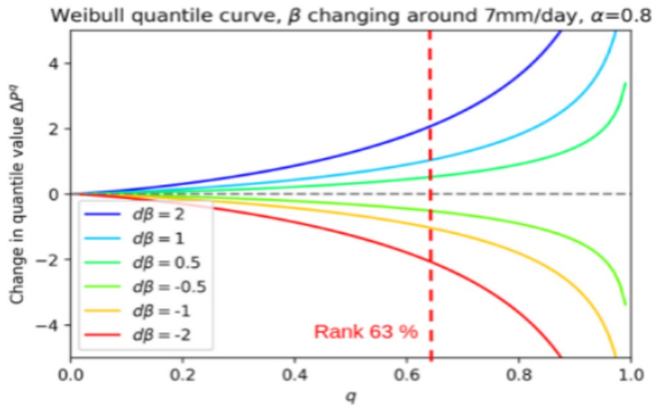
Precipitation extremes projects

Approximate pdf: a Weibull model (β ~ median, $1/\alpha$ ~ variance)

<u>Theoretical change of quantile:</u>

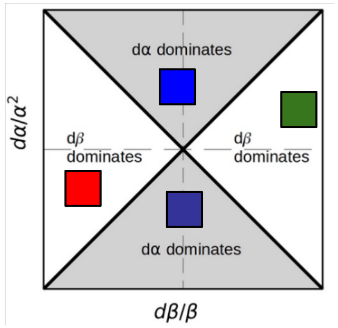
$$\forall p \in (0,1),\ \Delta Q(p) \approx \underbrace{\frac{\partial Q}{\partial \alpha}(p)}\ \Delta\alpha + \underbrace{\frac{\partial Q}{\partial \beta}(p)}\ \Delta\beta$$





⇒ U-shape iif $\Delta\alpha$<0 and if: $\left|\frac{\Delta\alpha}{\alpha^2}\right| \gg \left|\frac{\Delta\beta}{\beta}\right|$

⇒ Theoretical limits for the 4 regimes



⇒ (α, β) and their changes are key !

Andre et al 2024

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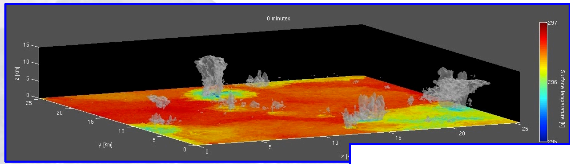

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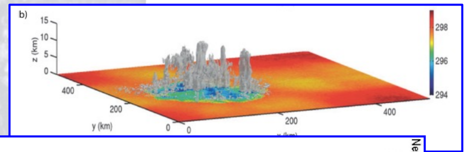

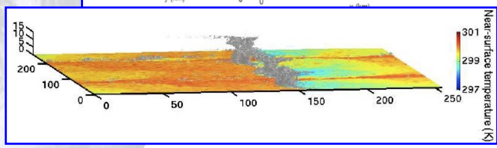

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