The The Delicate Dance Between Rain Evaporation And Convective Organization

Yi-Ling Hwong & Caroline Muller

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Institute of Science and Technology Austria

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Background

- Precipitation extremes increase when convection is more organized (simulations & observations)
- Mesoscale convective organization not properly represented in GCMs

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- Convection self-aggregates in radiative-convective equilibrium (RCE) experiments devoid of external forcings
- Generally mechanism: physical processes that generate a shallow circulation leading to an upgradient transport of MSE from dry to moist region
- Radiative feedback crucial

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- Convection self-aggregates in radiative-convective equilibrium (RCE) experiments devoid of external forcings
- Generally mechanism: physical processes that generate a shallow circulation leading to an upgradient transport of MSE from dry to moist region
- Radiative feedback crucial
- Intriguingly, self-aggregation can also occur *without* radiative feedback if rain evaporation is removed in the boundary layer (Muller & Bony, 2015; Holloway & Woolnough, 2016)
    - "moisture-memory aggregation"

Background

- Are cold pools causing this phenomenon?
  - Cold pools hinder aggregation by increasing mixing between dry and moist areas in the PBL
  - Removing rain evaporation removes cold pools ⇒ aggregation (Jeevanjee & Romps, 2013)
- No clear consensus

Research questions

- How does convective organization change when rain evaporation is removed or reduced in the PBL?
- Which physical processes are involved in the development of this type of organization?

Methods

- 3D RCE simulations in SAM
- Domain size L = 128 km, Δx = 1 km
- Horizontally homogenized radiation and surface fluxes
- Ocean surface, SST = 301 K
- Progressively reduce rain evaporation in lowest 1 km by multiplying $q_{p,evap}$ with a factor α = [1, 0.8, 0.6, 0.4, 0.2, 0]

Aggregation (precipitable water)

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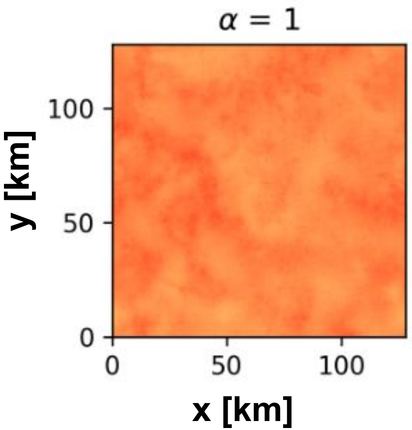
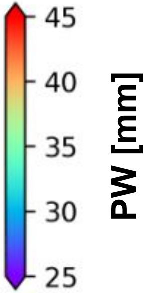
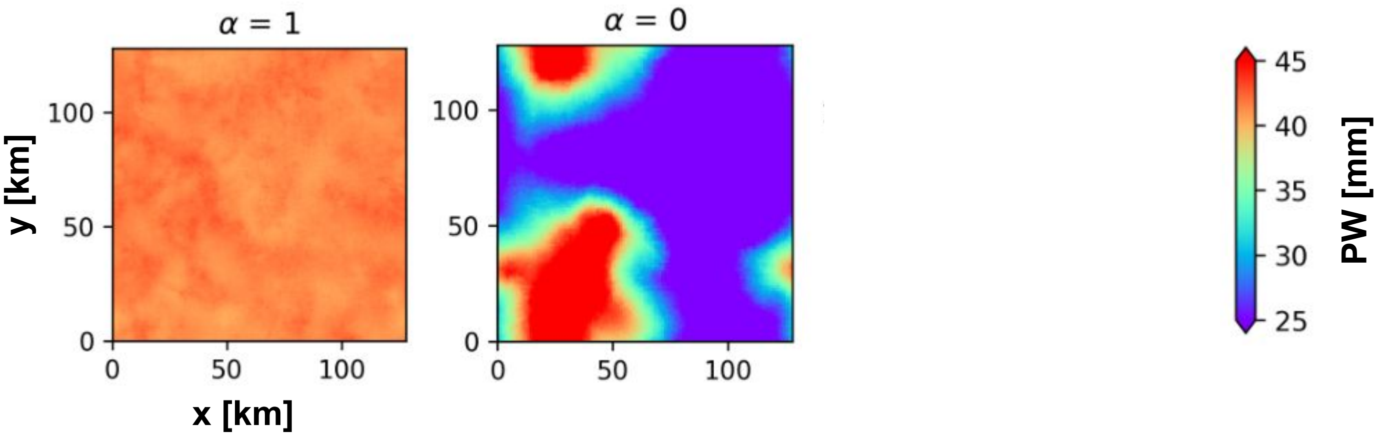


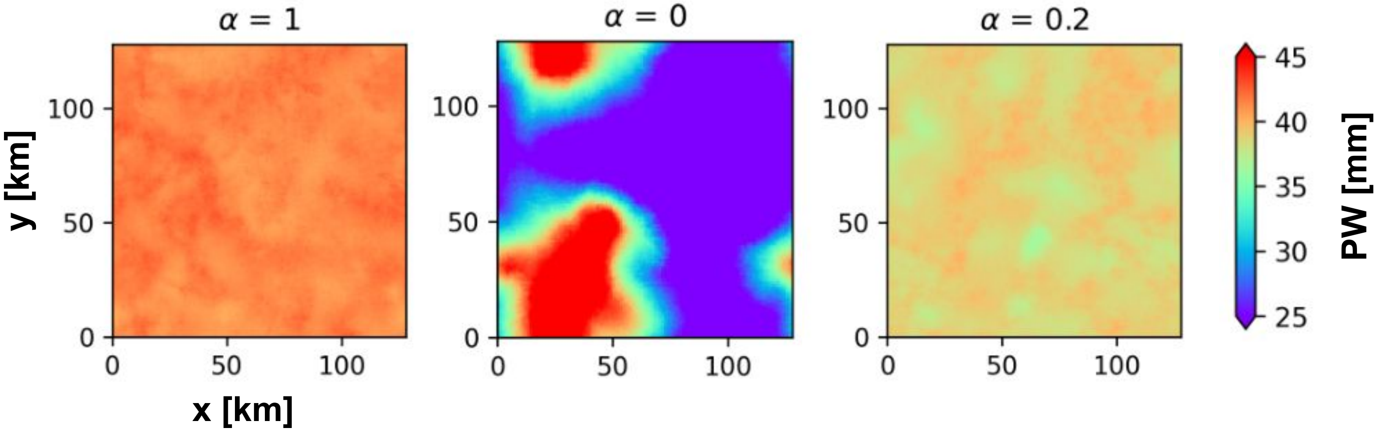


Aggregation (precipitable water)



Aggregation (precipitable water)

Intriguingly …



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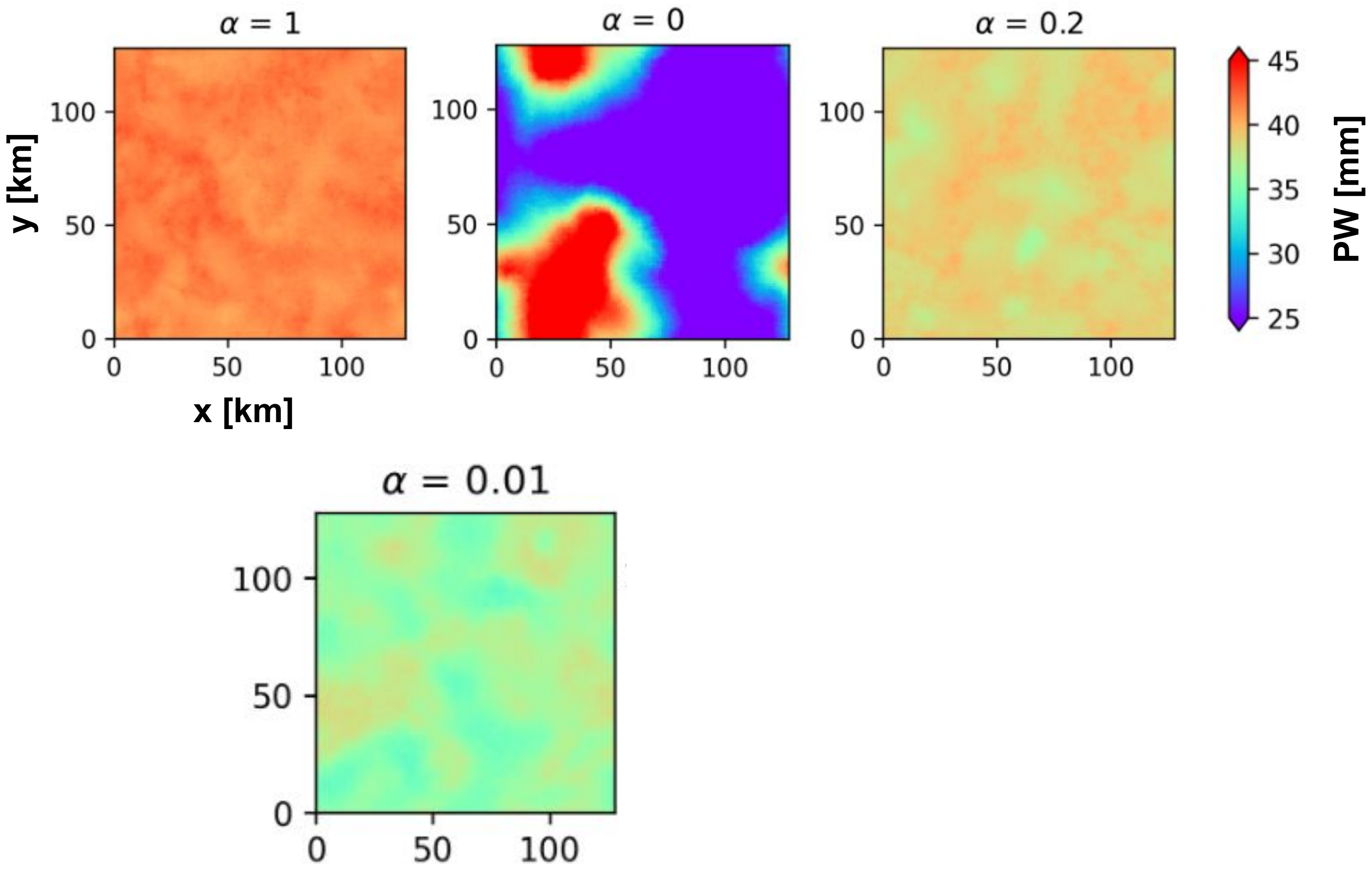
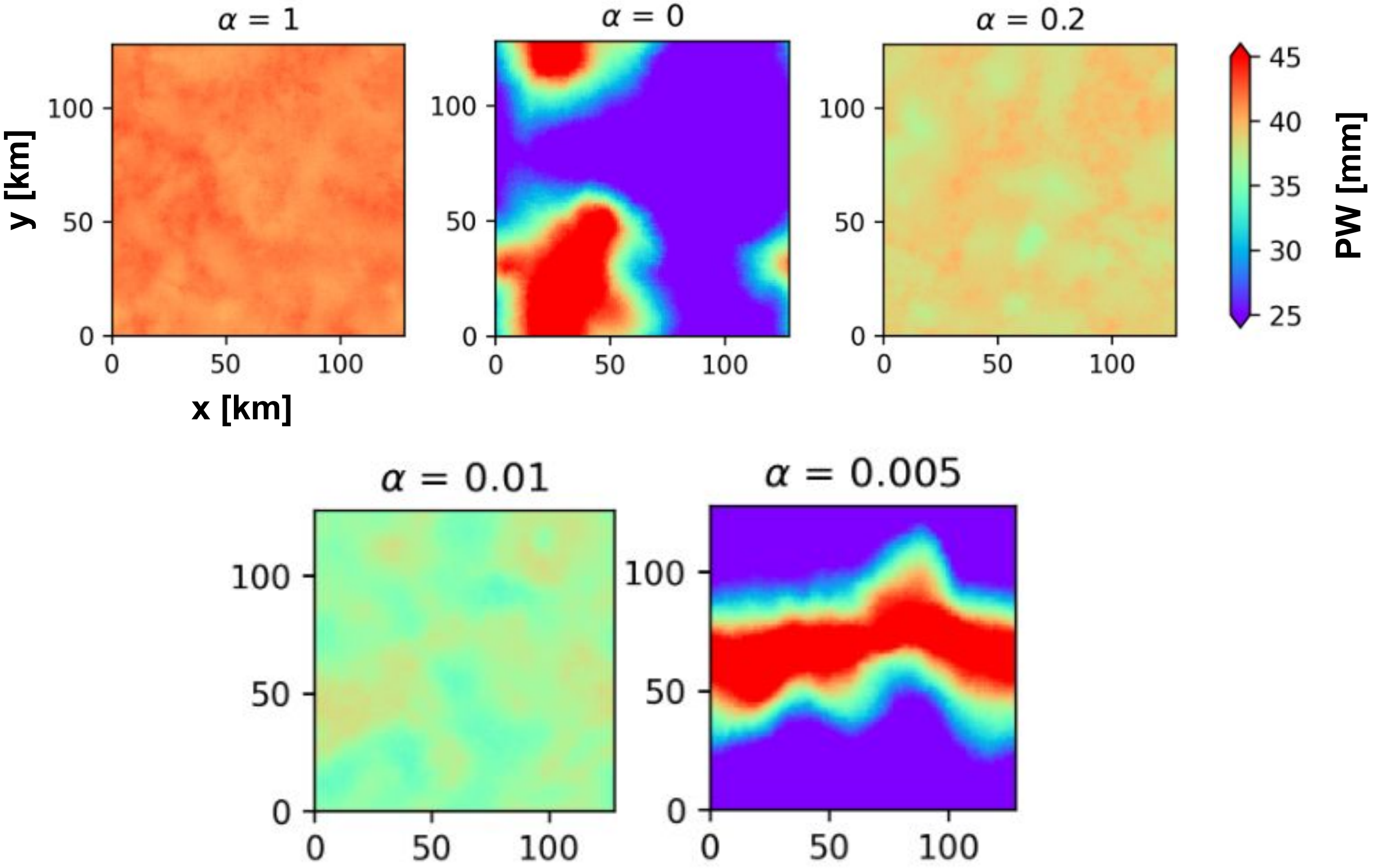


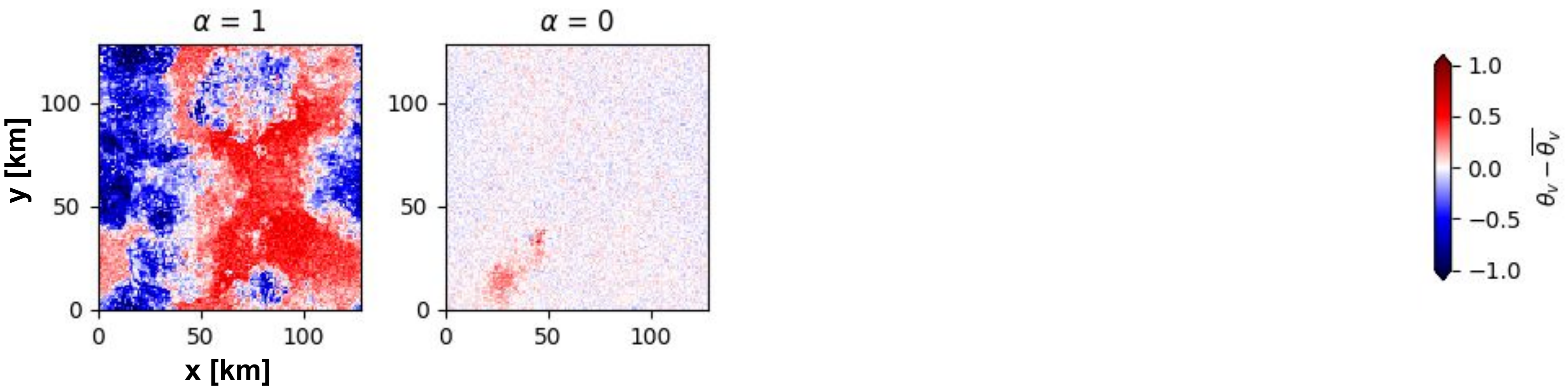
Aggregation (precipitable water)

Intriguingly ...

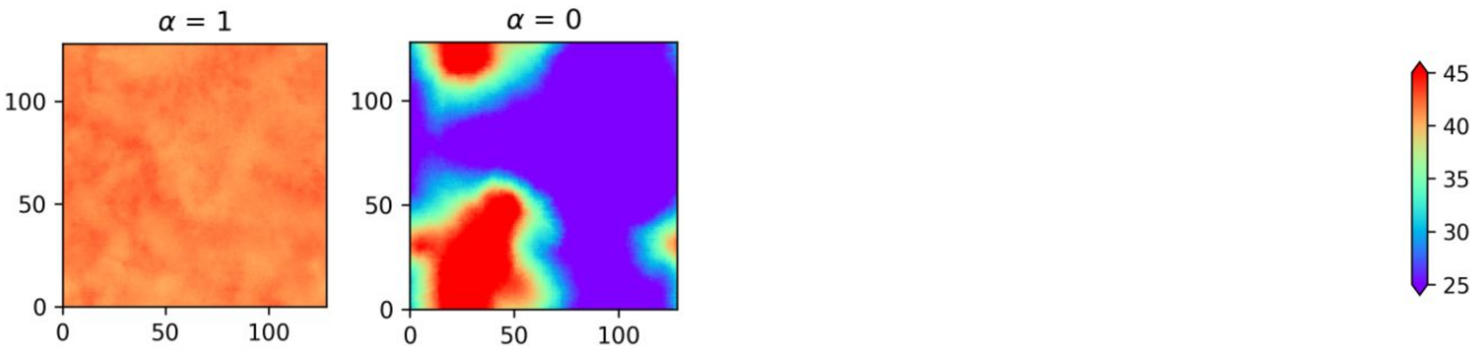


Cold pools?

Cold pools

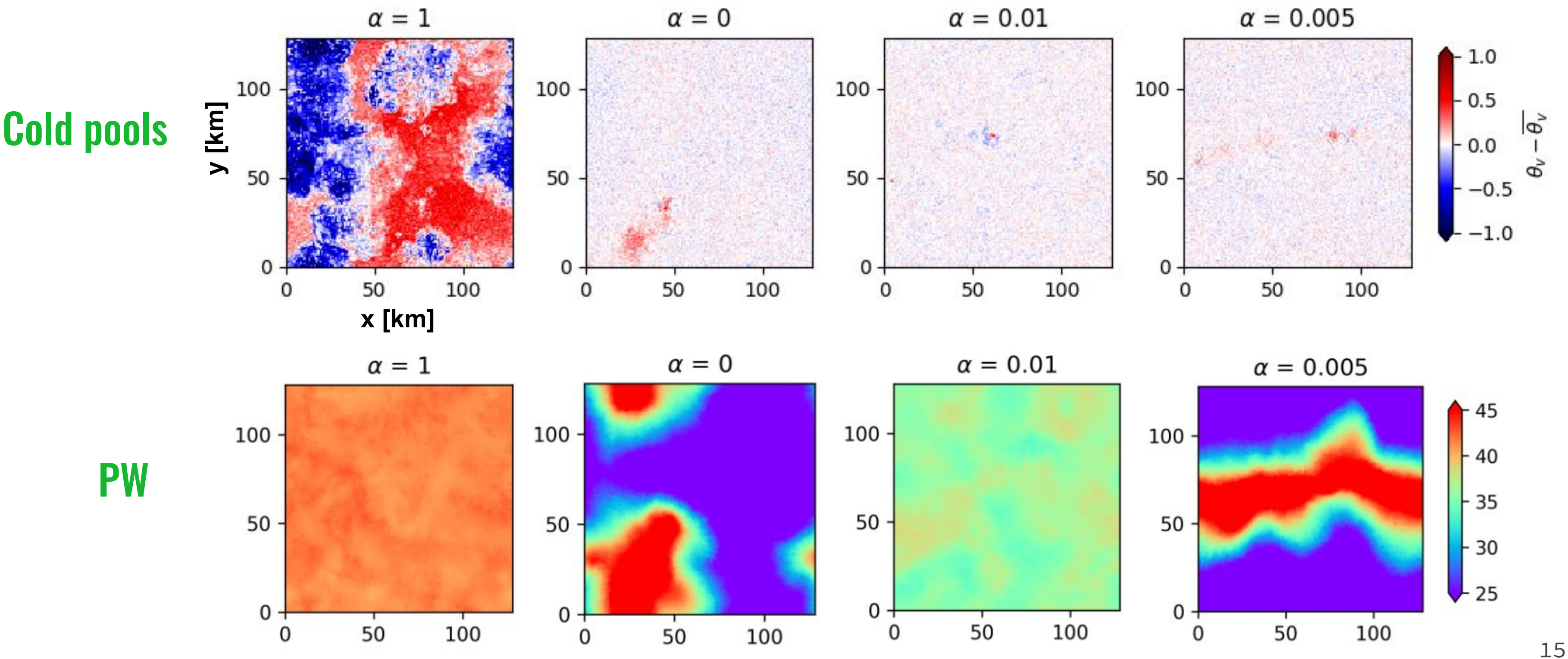


PW



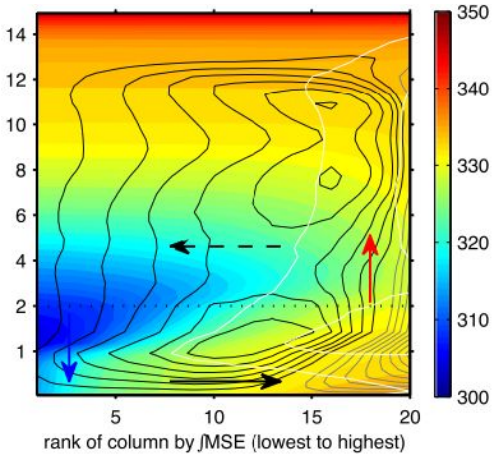
Cold pools?

Do not have cold pools, but one aggregates and the other does not



Shallow circulation

- Radiatively-driven aggregation (i.e., with interactive radiation) is driven by a shallow circulation that transports MSE upgradient
  - differential radiative cooling ⇒ dry region gets drier ⇒ dry region expands ⇒ aggregation



Muller & Bony (2015)

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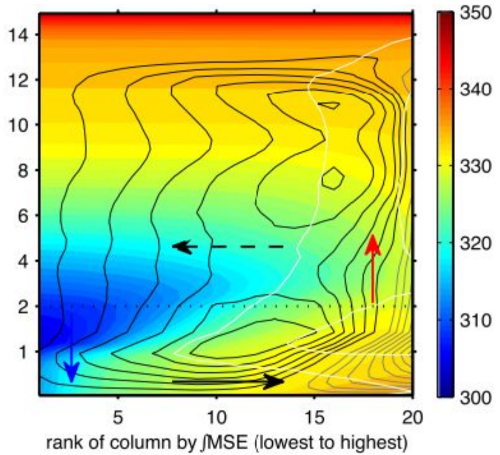
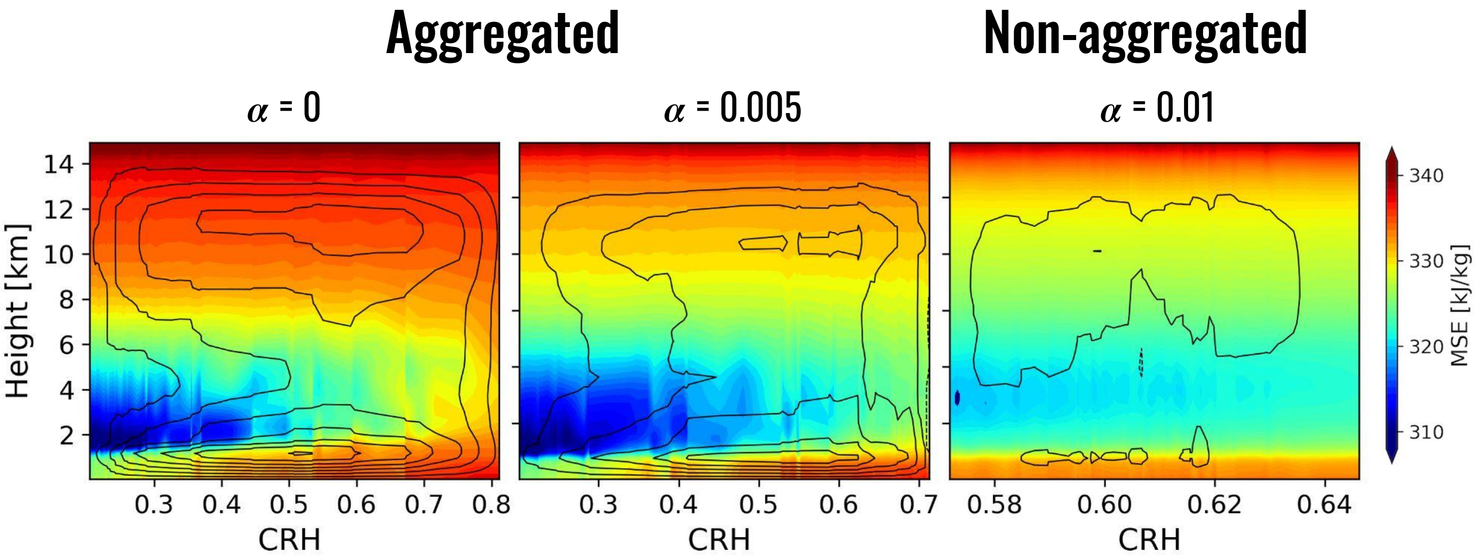


Muller & Bony (2015)

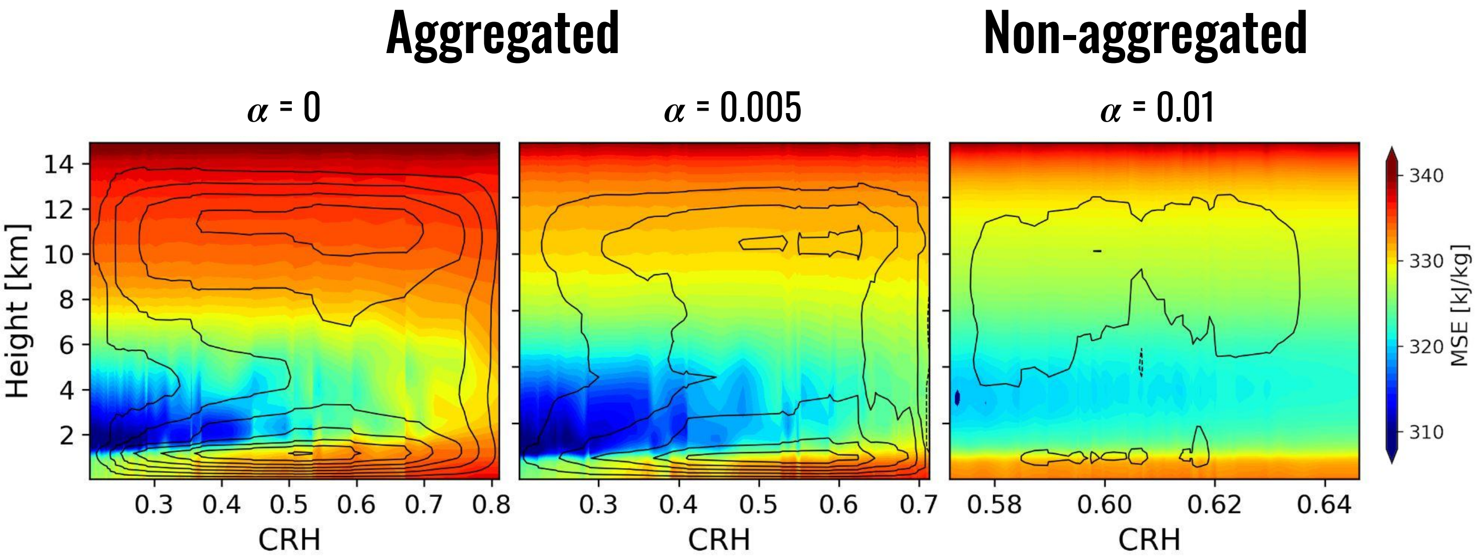
In our case radiation is horizontally homogenized, is this shallow circulation still present?

Yes it is …



** averaged over final 5 days*

Yes it is …



** averaged over final 5 days*

What is driving this shallow circulation, if not radiation?

Buoyancy

- High surface pressure (P_{sfc}) anomaly of dry region builds up a divergent flow that drives the shallow circulation required for aggregation to occur (Yang, 2018; Shamekh et al., 2020)
- Assuming weak temperature gradient in the FT, P_{sfc} anomaly is related to the boundary layer buoyancy (density) anomaly (Yang, 2018):

$$b = g\frac{\theta_v'}{\overline{\theta_v}} = g\left(\frac{\theta'}{\overline{\theta'}} + \frac{\epsilon q'}{1+\epsilon\bar{q}}\right)$$

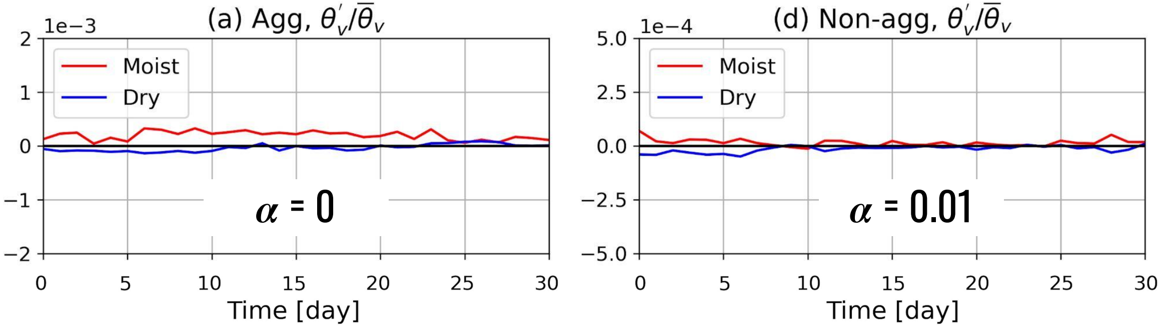
Temperature contribution

Moisture contribution

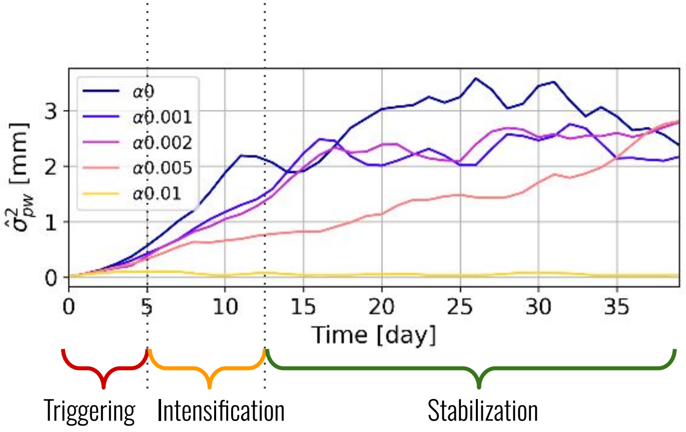
Buoyancy

- Reducing rain evaporation:
  - reduce evaporative cooling (net heating effect)
  - reduce evaporative moistening (net drying effect)
- Two opposing buoyancy effects, which one plays a dominant role in self-aggregation?

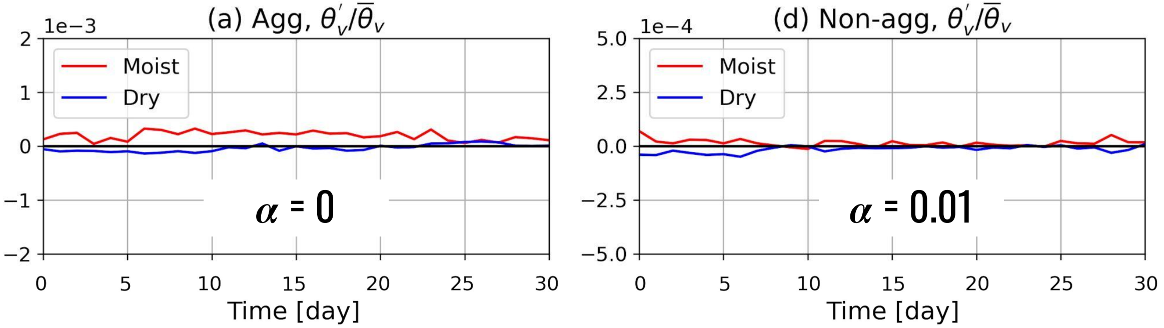
Buoyancy ($\theta_v{}'$)



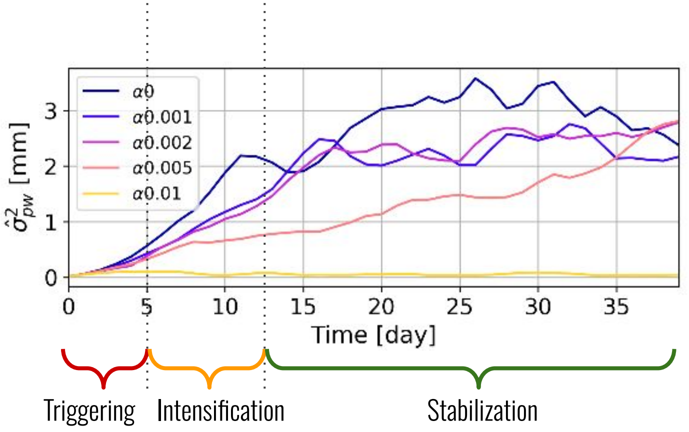
Aggregation index



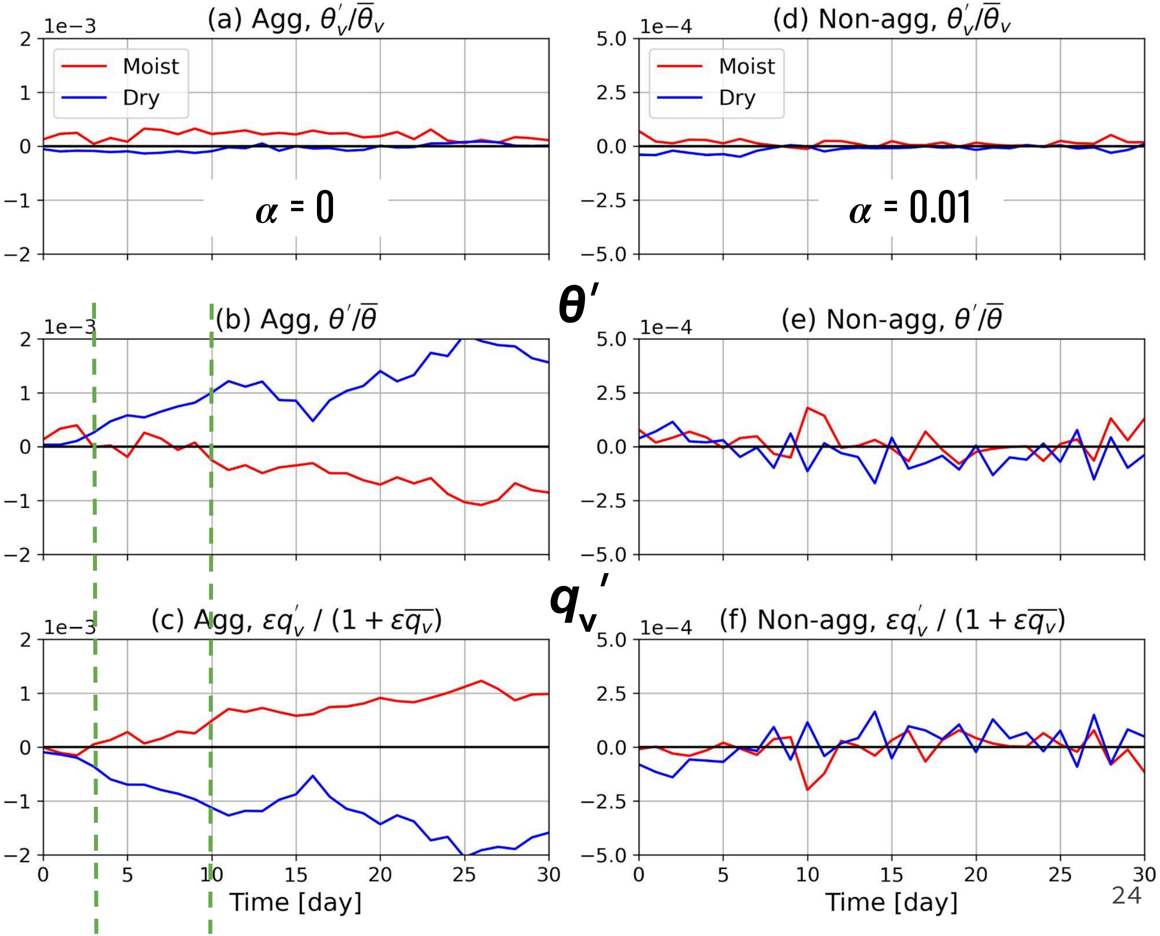
Buoyancy (θ_v')



Aggregation index



Buoyancy ($\boldsymbol{\theta_v}'$)



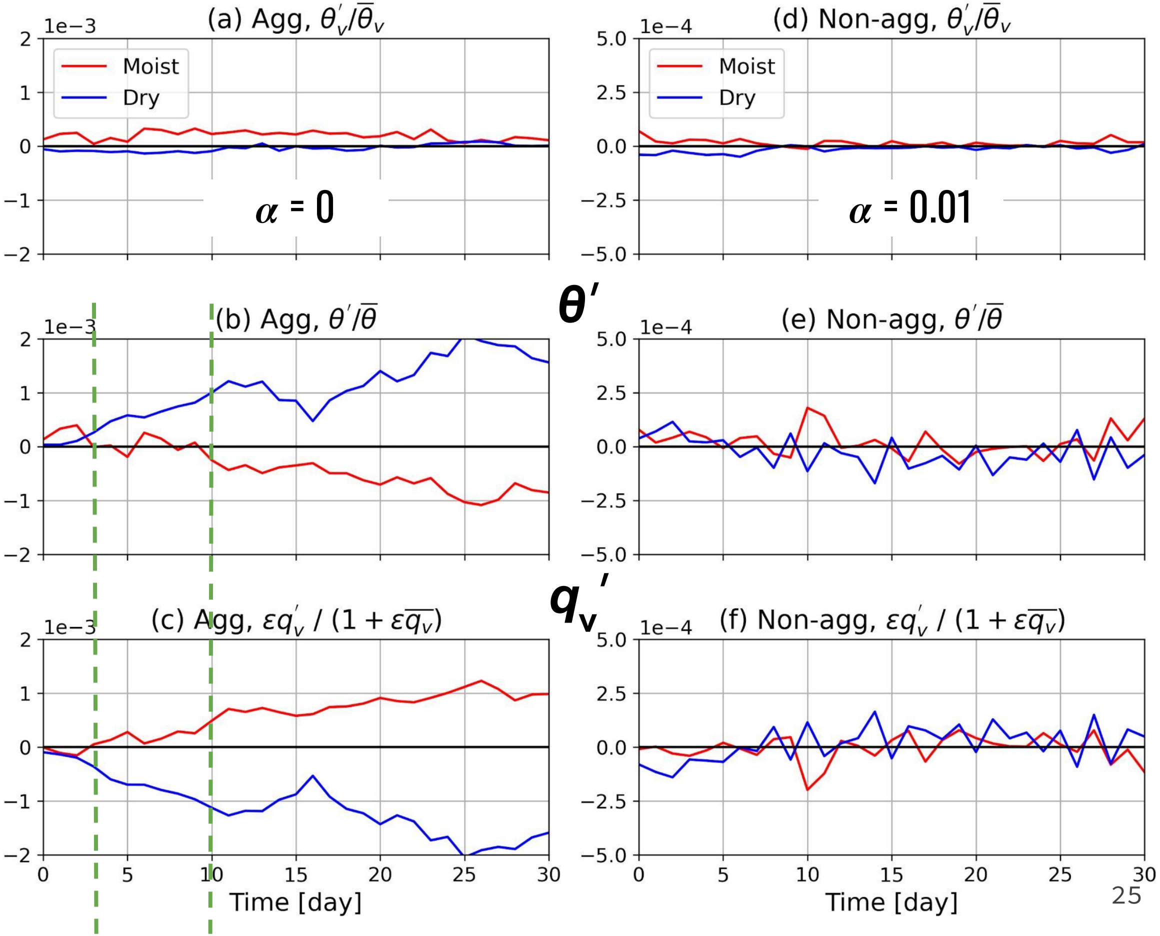
Convective **heating** of **moist** patch triggers aggregation

Dry **subsidence** intrusion into PBL of dry region **intensifies** aggregation

Competing T and q_v effects in **mature** phase of aggregation

Very small α required (almost **total** rain evap. removal)

Buoyancy (θ_v')



Convective heating of moist patch triggers aggregation

↓

Dry subsidence intrusion into PBL of dry region intensifies aggregation

↓

Competing T and q_v effects in mature phase of aggregation

↓

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- Moisture-memory aggregation ⇒ convectively-driven aggregation?

Convective heating of moist patch triggers aggregation

↓

Dry subsidence intrusion into PBL of dry region intensifies aggregation

↓

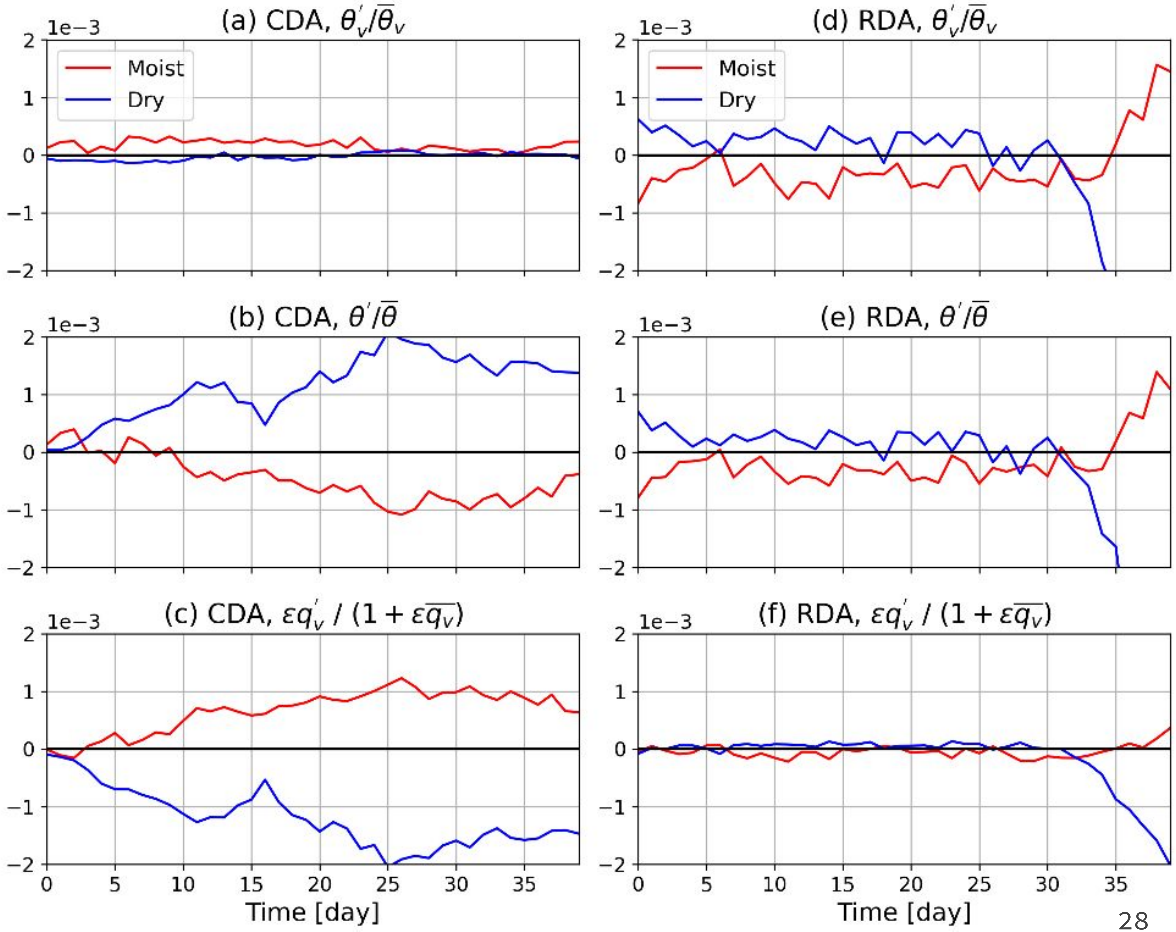
Competing T and q_v effects in mature phase of aggregation

↓

Very small α required (almost total rain evap. removal)

- Moisture-memory aggregation ⇒ convectively-driven aggregation?
- How is it different from radiatively-driven aggregation?

Convectively-driven agg (CDA) **Radiatively-driven agg (RDA)**



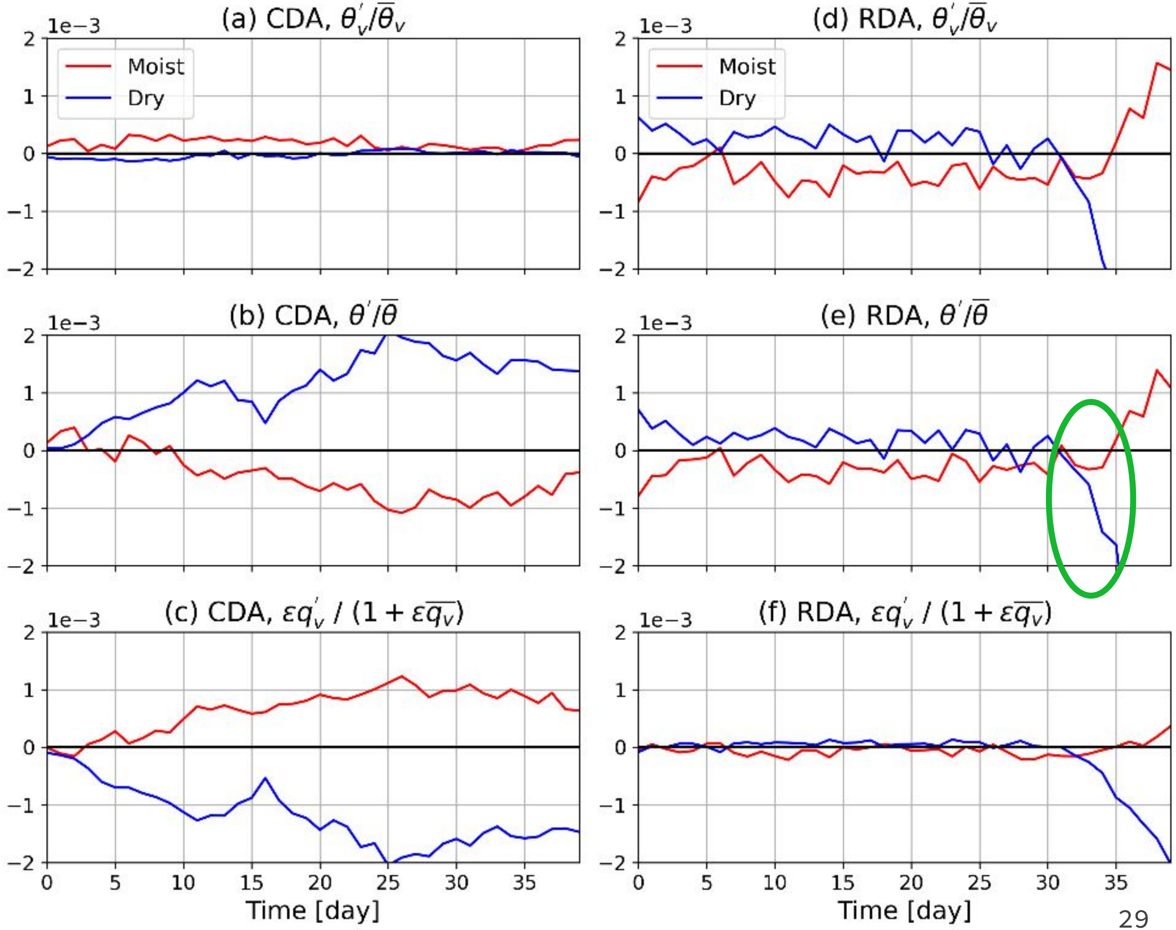
Radiative **cooling** of **dry** patch triggers aggregation

Dry **subsidence** intrusion into PBL of dry region **intensifies** aggregation

T and q_v effects both **support** aggregation in **mature** phase

Convectively-driven agg (CDA)

Radiatively-driven agg (RDA)



Summary

Convectively-Driven Aggregation (CDA)	Radiatively-Driven Aggregation (RDA)
Convective heating of moist patch triggers aggregation	Radiative cooling of dry patch is the first-mover of aggregation
Dry subsidence (virtual effect) intrusion into PBL of dry patch intensifies aggregation	Dry subsidence (virtual effect) intrusion into PBL of dry patch intensifies aggregation
Moist and dry patches work in tandem	Dry patch driven
Aggregation occurs quickly	Aggregation occurs slowly
T and q_v effects oppose each other in mature phase	T and q_v effects work together in mature phase

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Moist and dry patches work in tandem	Dry patch driven
Aggregation occurs quickly	Aggregation occurs slowly
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(almost) total rain evaporation removal needed as ignition during triggering phase, and to counter the opposing T and q_v effects in mature phase

Thank you!

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Geophysical Research Letters

RESEARCH LETTER

10.1029/2023GL106523

The Unreasonable Efficiency of Total Rain Evaporation Removal in Triggering Convective Self-Aggregation

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[1]Institute of Science and Technology Austria, Klosterneuburg, Austria

Key Points:

- When rain evaporation is removed in the PBL, convective self-aggregation (CSA) is triggered by convective heating of the moist regions
- Surprisingly, CSA only occurs when rain evaporation is almost totally removed in the PBL, due to opposing temperature and moisture effects
- CSA occurs more easily in a larger domain due to stronger radiatively induced subsidence, while cold pools play a less significant role

Supporting Information:

Supporting Information may be found in the online version of this article.

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Citation:

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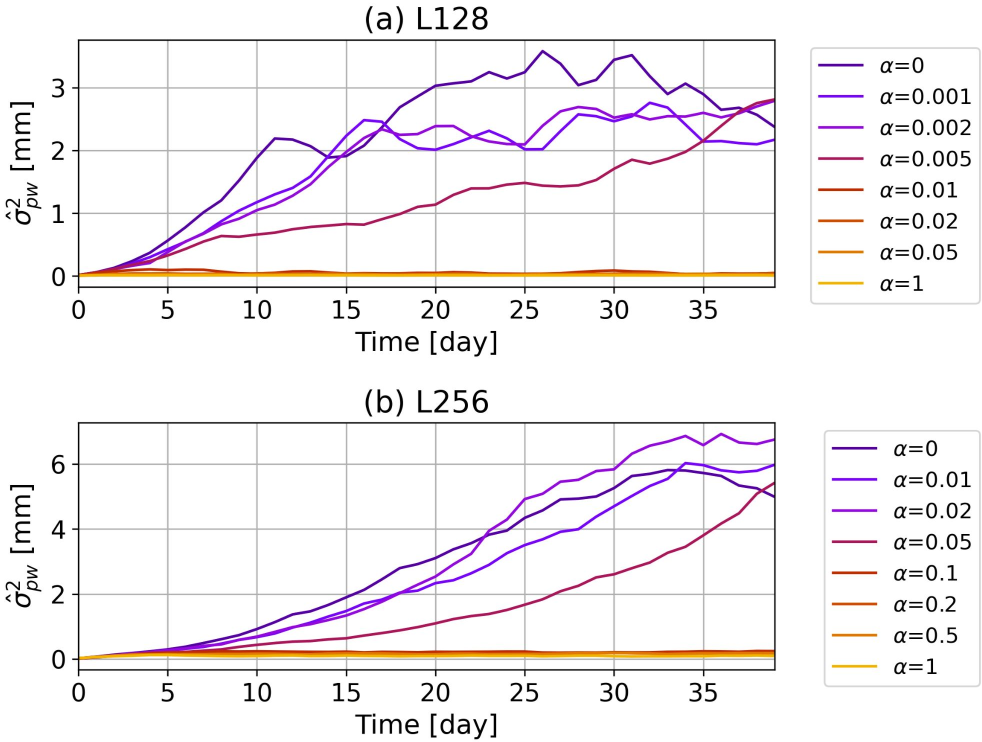
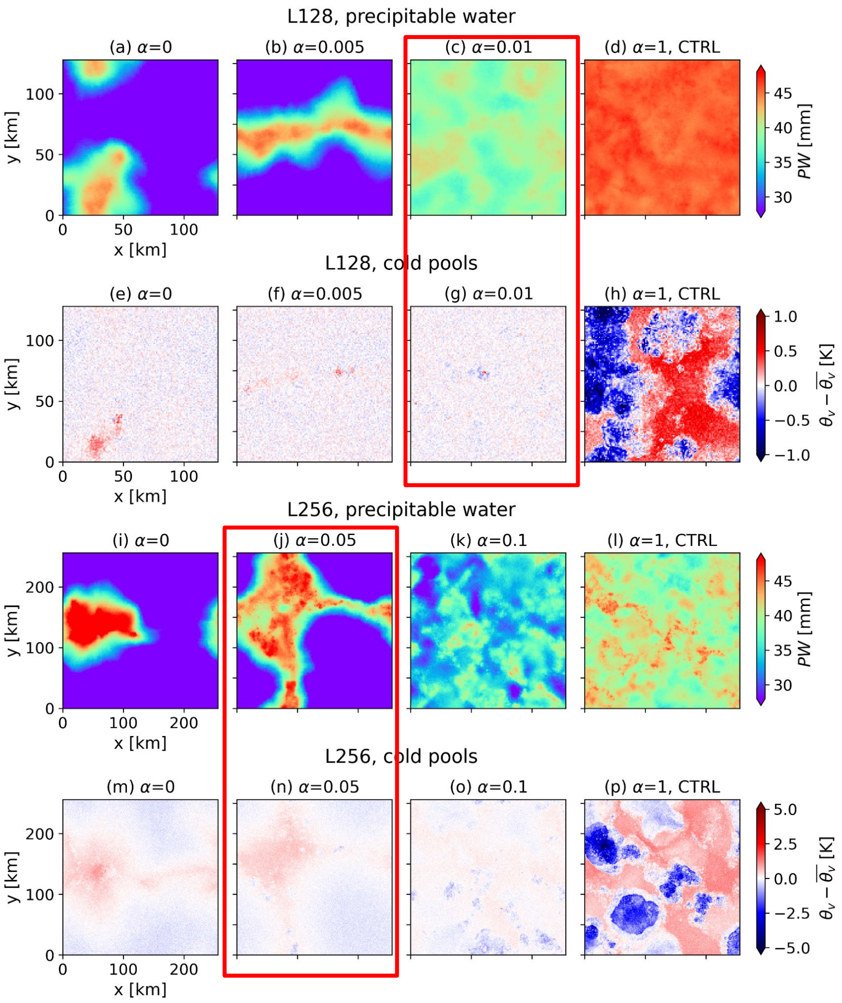
Abstract The elimination of rain evaporation in the planetary boundary layer (PBL) has been found to lead to convective self-aggregation (CSA) even without radiative feedback, but the precise mechanisms underlying this phenomenon remain unclear. We conducted cloud-resolving simulations with two domain sizes and progressively reduced rain evaporation in the PBL. Surprisingly, CSA only occurred when rain evaporation was almost completely removed. The additional convective heating resulting from the reduction of evaporative cooling in the moist patch was found to be the trigger, thereafter a dry subsidence intrusion into the PBL in the dry patch takes over and sets CSA in motion. Temperature and moisture anomalies oppose each other in their buoyancy effects, hence explaining the need for almost total rain evaporation removal. We also found radiative cooling and not cold pools to be the leading cause for the comparative ease of CSA to take place in the larger domain.

Plain Language Summary Convective clouds are not randomly scattered across the sky but tend to clump together, a phenomenon known as convective self-aggregation (CSA). The interaction between clouds and radiation is a key mechanism for CSA to occur. Curiously, CSA can still take place without this radiative feedback, provided that rain is prohibited from evaporating in the lowest layers of the atmosphere (~1 km), called the planetary boundary layer (PBL). To investigate the physical processes behind this type of CSA (no-evaporation CSA, or "NE-CSA"), we ran high resolution atmospheric model simulations and reduced rain evaporation in steps in the PBL. We found that the additional heat resulting from the reduction of evaporative cooling is crucial in triggering NE-CSA, thereafter the invasion of dry air into the PBL in the dry region takes over and intensifies aggregation. Surprisingly, allowing even a minuscule amount of rain to evaporate prevents NE-CSA from taking place. This is because removing rain evaporation has two opposing effects on convection: heating and drying. The former aids convection while the latter hinders it. Only when rain evaporation is almost completely eliminated can the heating effect be powerful enough to overcome the drying effect and kick-start NE-CSA.

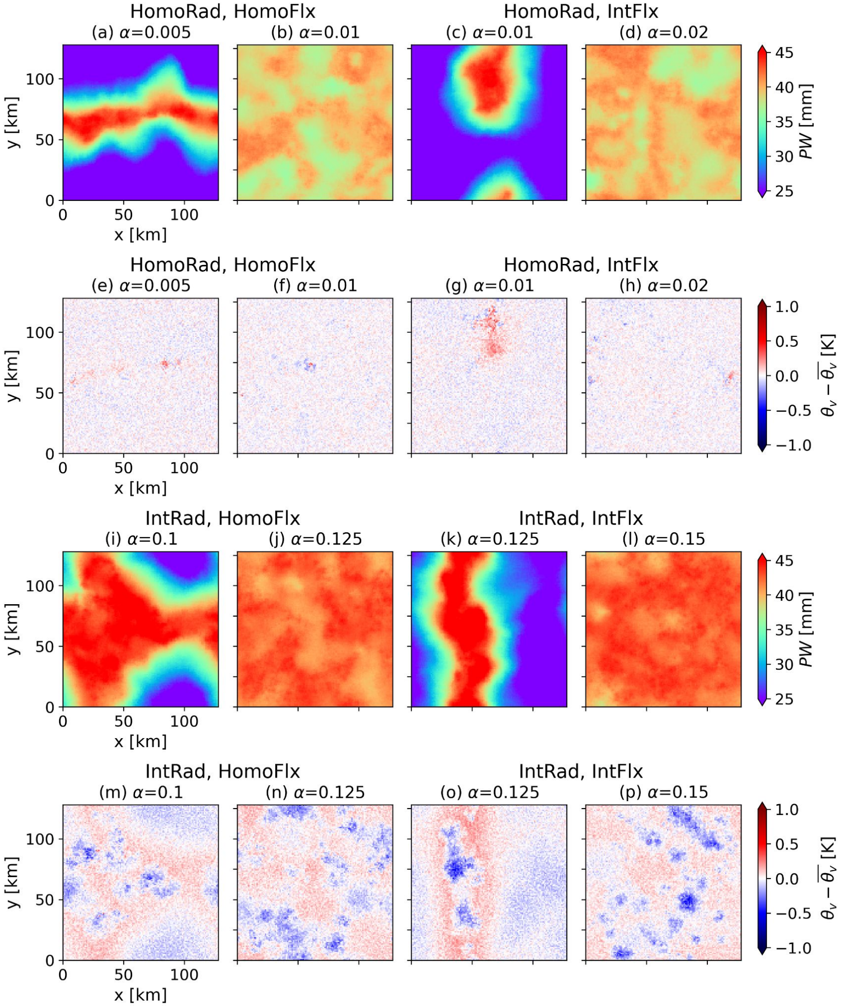
Additional slides



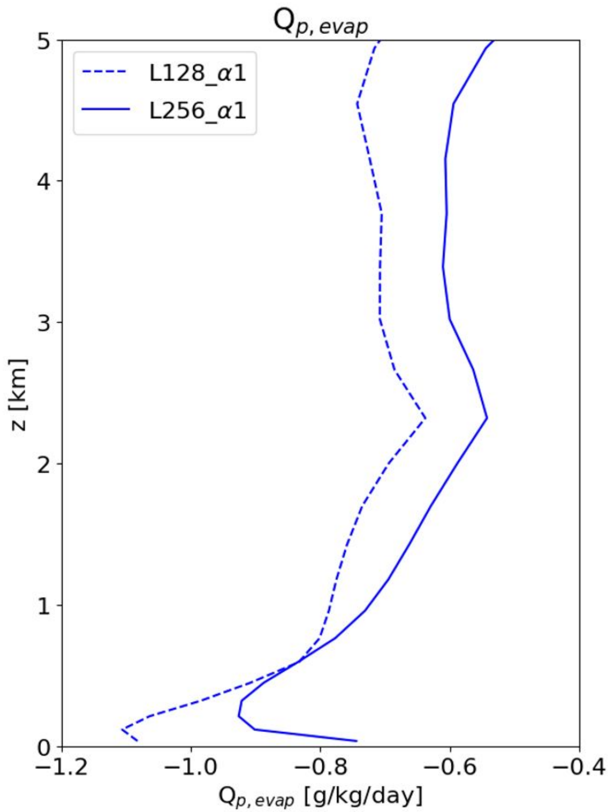
(a) L128
$\hat{\sigma}^2_{pw}$ [mm]
Time [day]
α=0
α=0.001
α=0.002
α=0.005
α=0.01
α=0.02
α=0.05
α=1
(b) L256
$\hat{\sigma}^2_{pw}$ [mm]
Time [day]
α=0
α=0.01
α=0.02
α=0.05
α=0.1
α=0.2
α=0.5
α=1



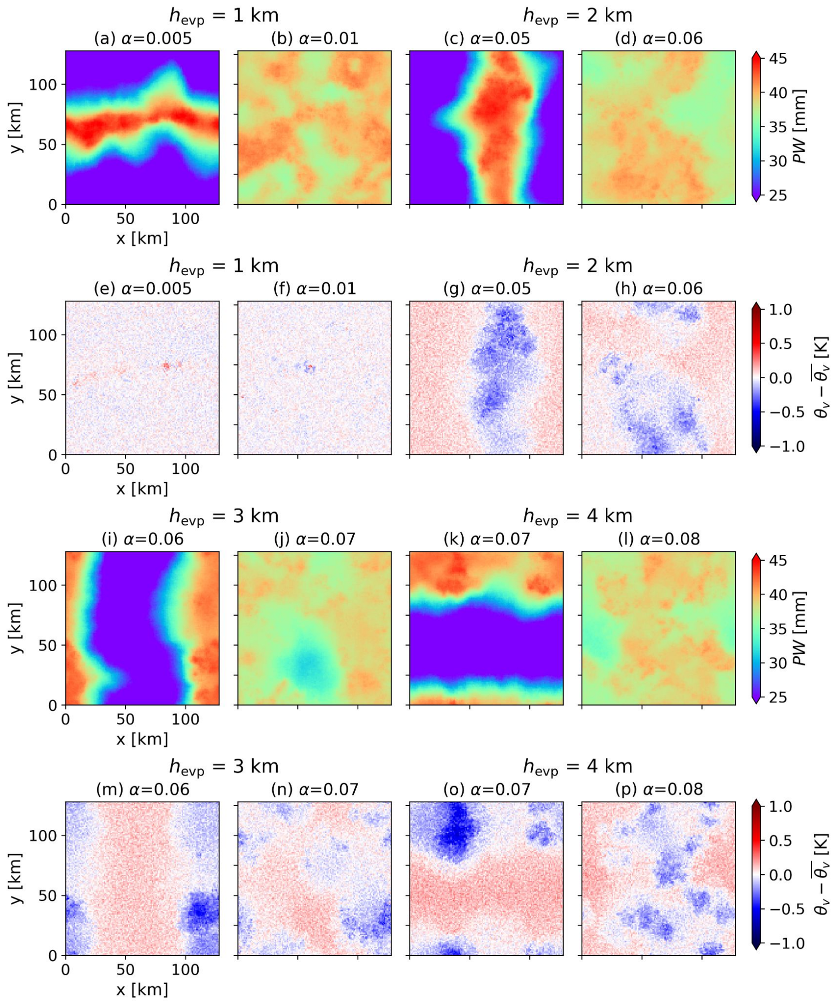
L128, precipitable water
(a) α=0
(b) α=0.005
(c) α=0.01
(d) α=1, CTRL
PW [mm]
L128, cold pools
(e) α=0
(f) α=0.005
(g) α=0.01
(h) α=1, CTRL
$\theta_v - \overline{\theta_v}$ [K]
L256, precipitable water
(i) α=0
(j) α=0.05
(k) α=0.1
(l) α=1, CTRL
PW [mm]
L256, cold pools
(m) α=0
(n) α=0.05
(o) α=0.1
(p) α=1, CTRL
$\theta_v - \overline{\theta_v}$ [K]
y [km]
x [km]



HomoRad, HomoFlx
HomoRad, IntFlx
(a) α=0.005
(b) α=0.01
(c) α=0.01
(d) α=0.02
PW [mm]
HomoRad, HomoFlx
HomoRad, IntFlx
(e) α=0.005
(f) α=0.01
(g) α=0.01
(h) α=0.02
$\theta_v - \overline{\theta_v}$ [K]
IntRad, HomoFlx
IntRad, IntFlx
(i) α=0.1
(j) α=0.125
(k) α=0.125
(l) α=0.15
PW [mm]
IntRad, HomoFlx
IntRad, IntFlx
(m) α=0.1
(n) α=0.125
(o) α=0.125
(p) α=0.15
$\theta_v - \overline{\theta_v}$ [K]
y [km]
x [km]



$Q_{p,evap}$
L128_α1
L256_α1
z [km]
$Q_{p,evap}$ [g/kg/day]



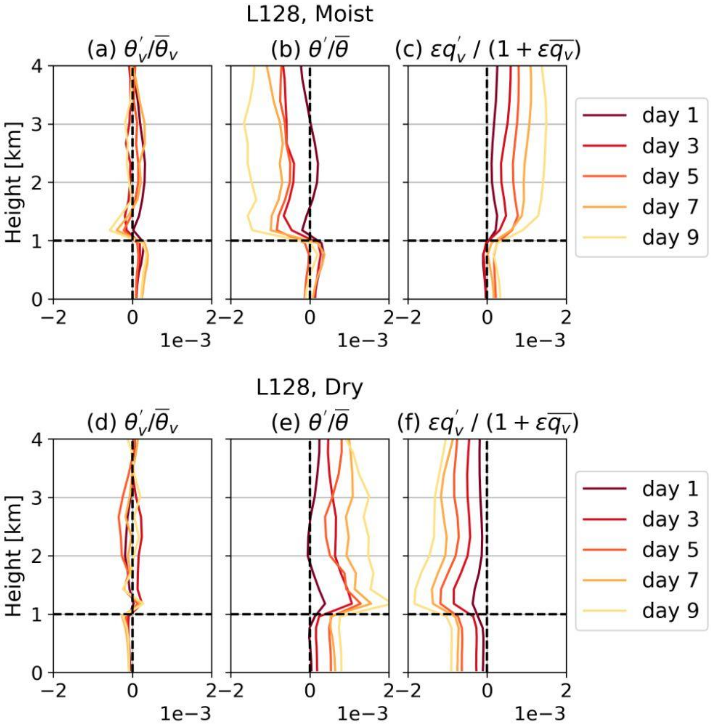
h_{evp} = 1 km
h_{evp} = 2 km
(a) α=0.005
(b) α=0.01
(c) α=0.05
(d) α=0.06
(e) α=0.005
(f) α=0.01
(g) α=0.05
(h) α=0.06
h_{evp} = 3 km
h_{evp} = 4 km
(i) α=0.06
(j) α=0.07
(k) α=0.07
(l) α=0.08
(m) α=0.06
(n) α=0.07
(o) α=0.07
(p) α=0.08
y [km]
x [km]
PW [mm]
$\theta_v - \overline{\theta}_v$ [K]

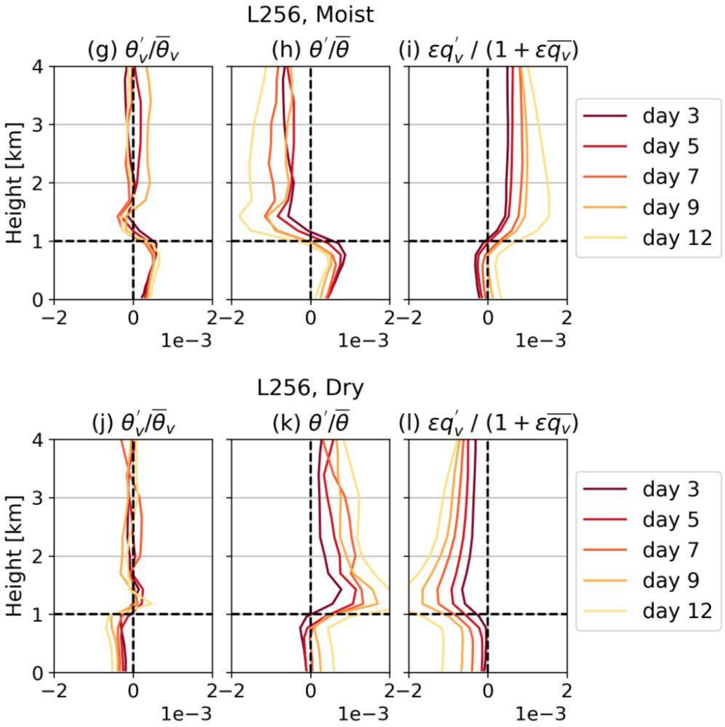
L128

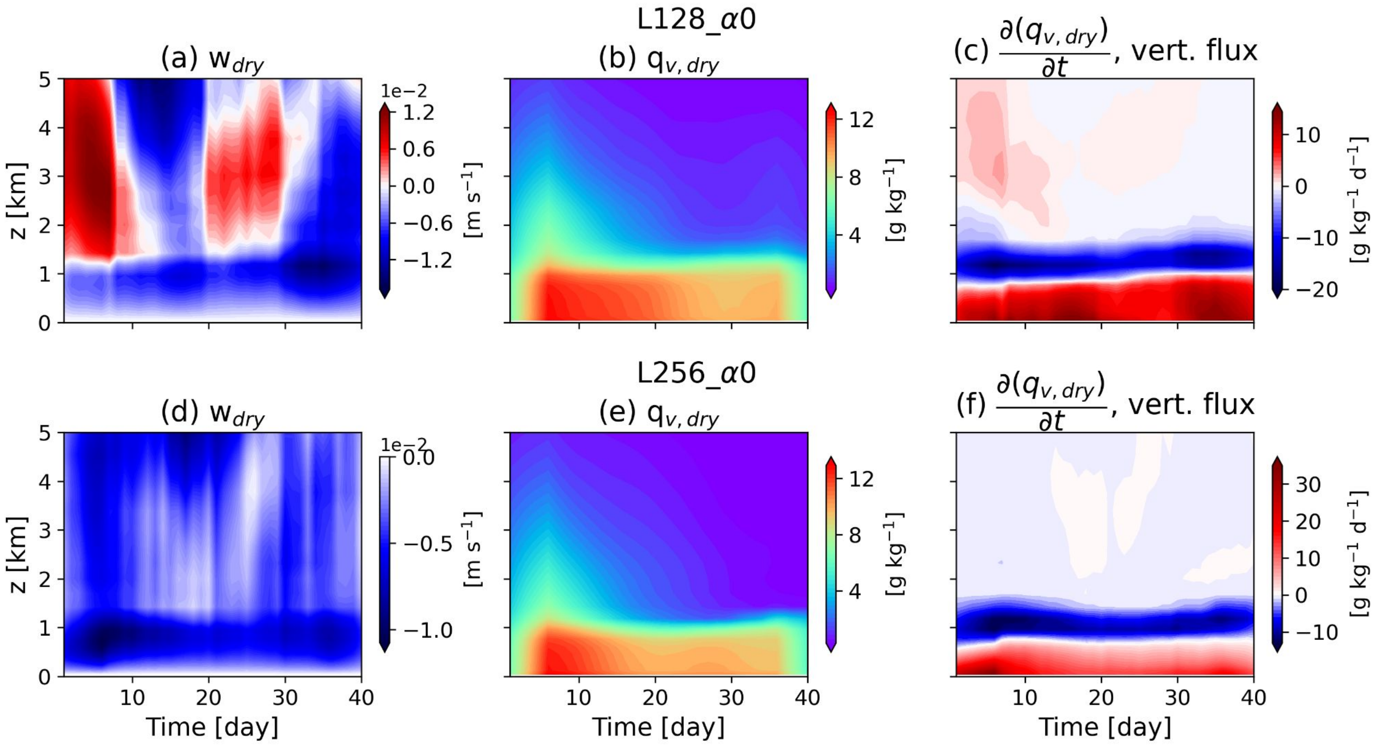
L256

Moist

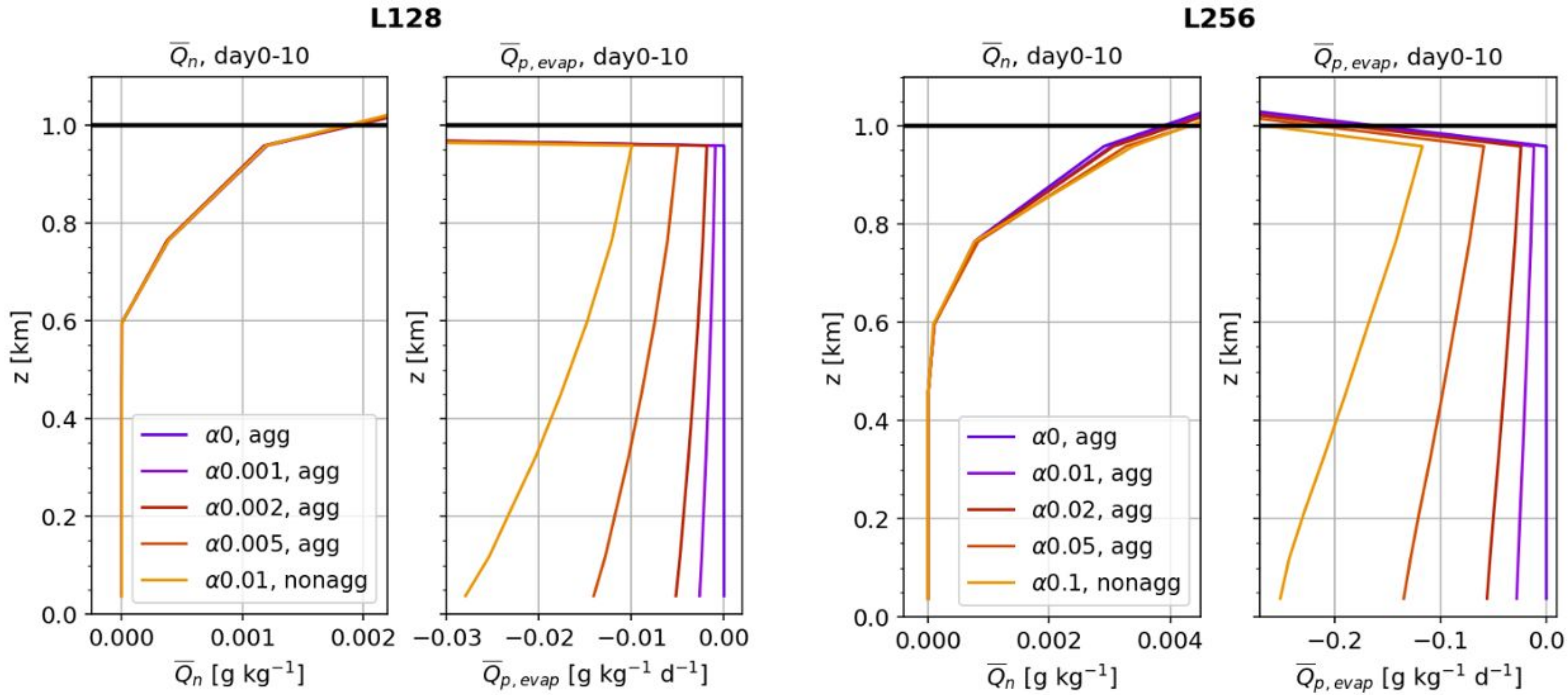
Dry

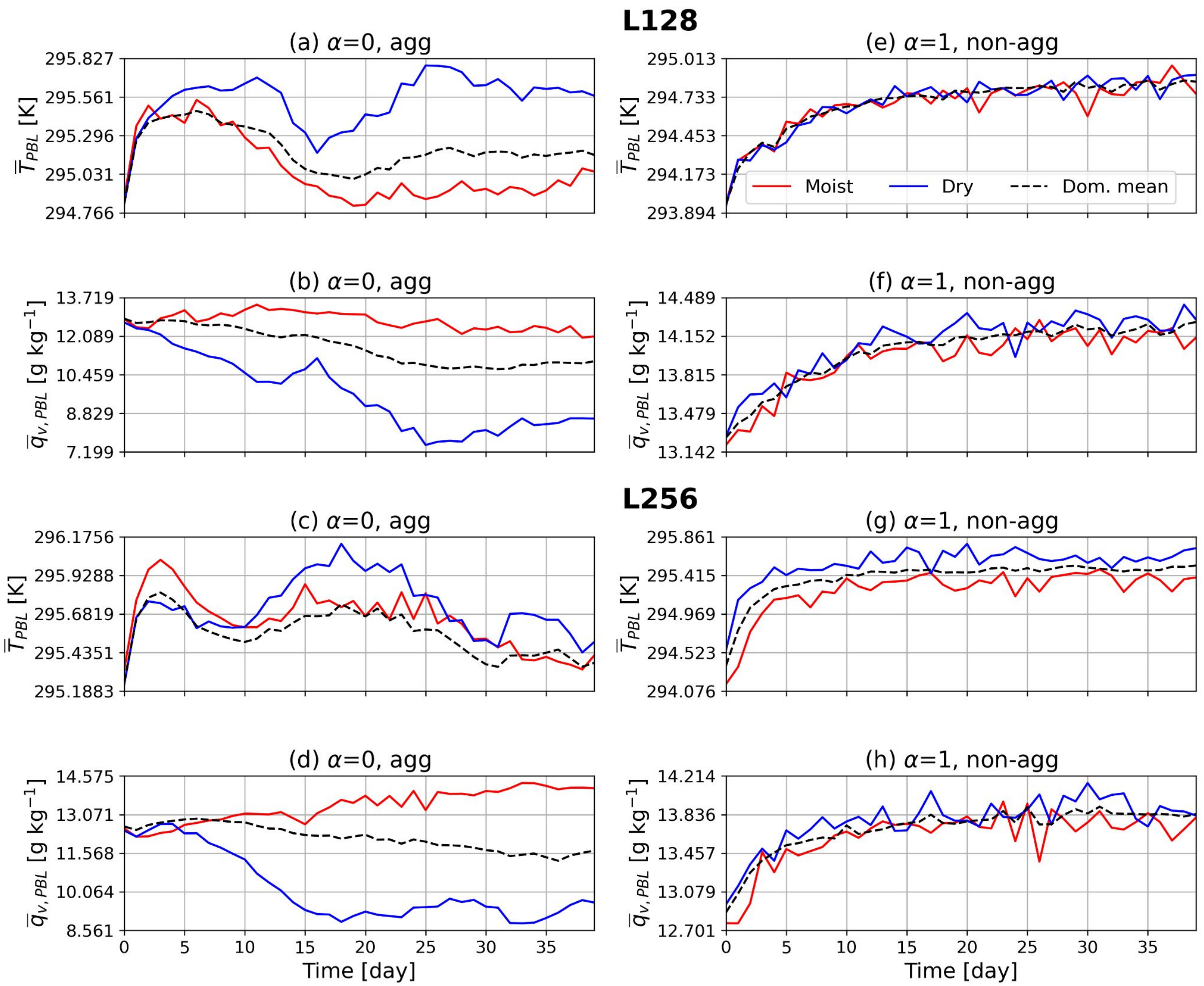






L128_α0
(a) w_dry
(b) q_v,dry
(c) ∂(q_v,dry)/∂t, vert. flux
1e−2
1.2
0.6
0.0
−0.6
−1.2
[m s⁻¹]
12
8
4
[g kg⁻¹]
10
0
−10
−20
[g kg⁻¹ d⁻¹]
z [km]
L256_α0
(d) w_dry
(e) q_v,dry
(f) ∂(q_v,dry)/∂t, vert. flux
1e−2
0.0
−0.5
−1.0
[m s⁻¹]
12
8
4
[g kg⁻¹]
30
20
10
0
−10
[g kg⁻¹ d⁻¹]
z [km]
Time [day]
Time [day]
Time [day]

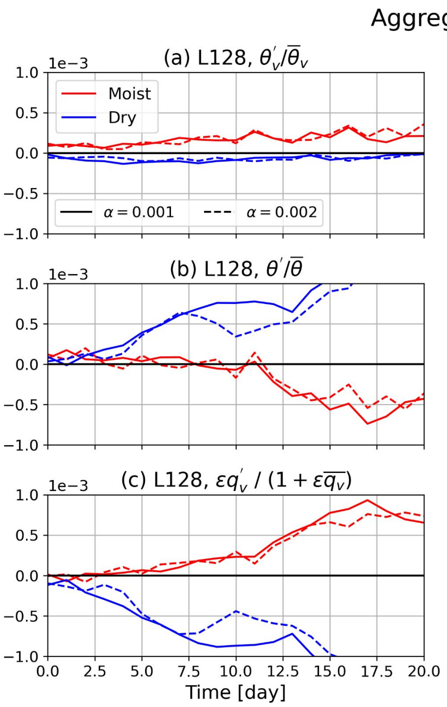

L128
L256
$\overline{Q}_n$, day0-10
$\overline{Q}_{p,evap}$, day0-10
$\overline{Q}_n$, day0-10
$\overline{Q}_{p,evap}$, day0-10
z [km]
1.0
0.8
0.6
0.4
0.2
0.0
0.000
0.001
0.002
$\overline{Q}_n$ [g kg^{-1}]
−0.03
−0.02
−0.01
0.00
$\overline{Q}_{p,evap}$ [g kg^{-1} d^{-1}]
α0, agg
α0.001, agg
α0.002, agg
α0.005, agg
α0.01, nonagg
0.000
0.002
0.004
−0.2
−0.1
0.0
α0, agg
α0.01, agg
α0.02, agg
α0.05, agg
α0.1, nonagg

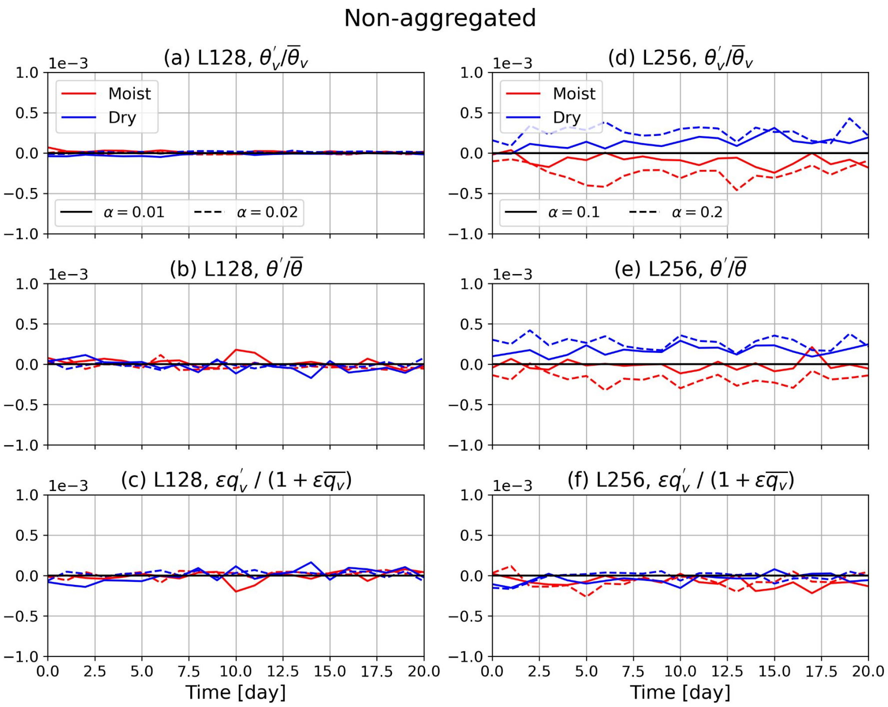


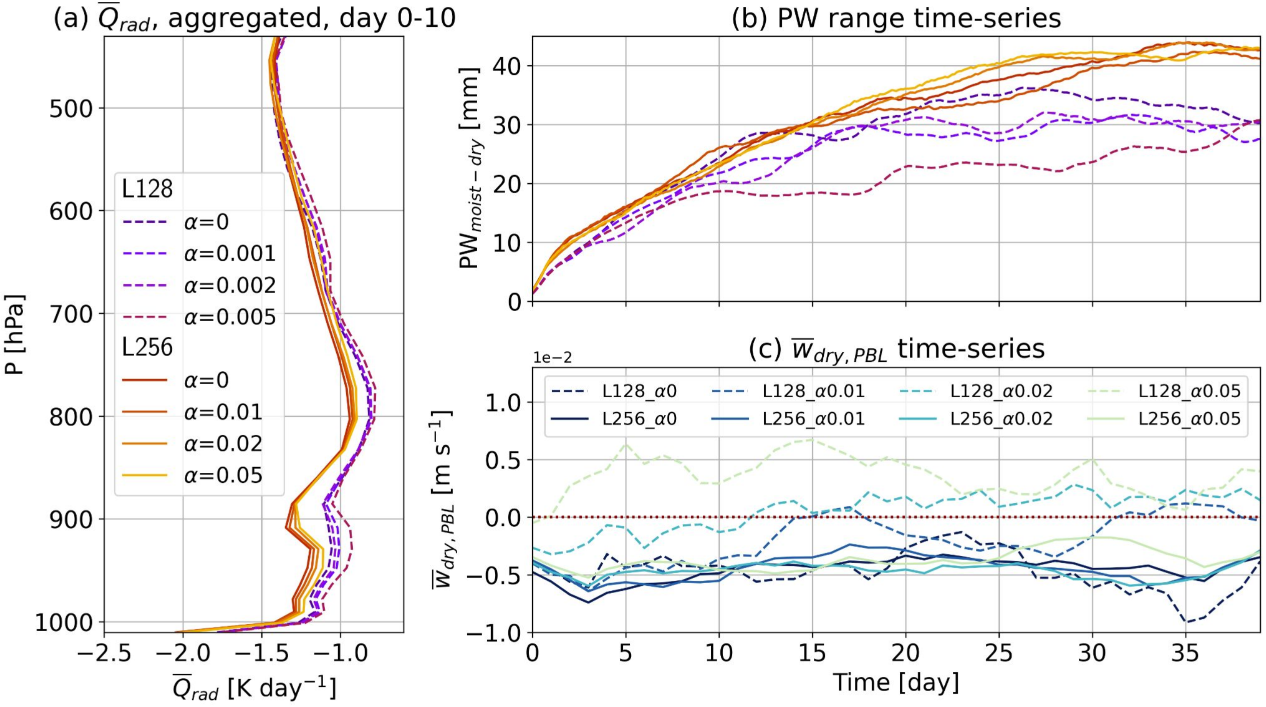
L128
(a) α=0, agg
(e) α=1, non-agg
(b) α=0, agg
(f) α=1, non-agg
L256
(c) α=0, agg
(g) α=1, non-agg
(d) α=0, agg
(h) α=1, non-agg
$\overline{T}_{PBL}$ [K]
$\overline{q}_{v,PBL}$ [g kg^{-1}]
Time [day]
Moist
Dry
Dom. mean
295.827
295.561
295.296
295.031
294.766
295.013
294.733
294.453
294.173
293.894
13.719
12.089
10.459
8.829
7.199
14.489
14.152
13.815
13.479
13.142
296.1756
295.9288
295.6819
295.4351
295.1883
295.861
295.415
294.969
294.523
294.076
14.575
13.071
11.568
10.064
8.561
14.214
13.836
13.457
13.079
12.701
0
5
10
15
20
25
30
35

Aggregated

Non-aggregated







(a) $\overline{Q}_{rad}$, aggregated, day 0-10
P [hPa]
$\overline{Q}_{rad}$ [K day^{-1}]
L128
α=0
α=0.001
α=0.002
α=0.005
L256
α=0
α=0.01
α=0.02
α=0.05
(b) PW range time-series
$PW_{moist-dry}$ [mm]
(c) $\overline{w}_{dry,PBL}$ time-series
$\overline{w}_{dry,PBL}$ [m s^{-1}]
1e−2
L128_α0
L128_α0.01
L128_α0.02
L128_α0.05
L256_α0
L256_α0.01
L256_α0.02
L256_α0.05
Time [day]