Idealized modelling of the diurnal cycle of deep convection using the new Met Office Cloud-Resolving Model (MONC)

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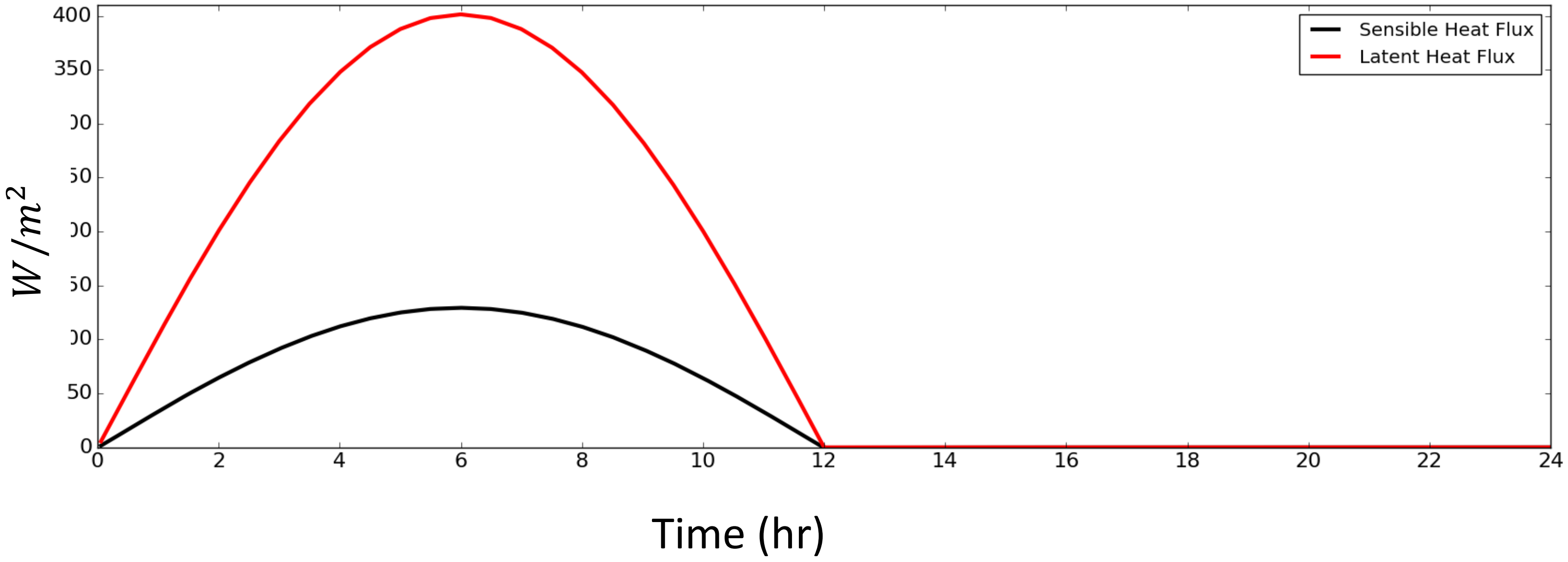
MONC configuration

Model dimensionality	**3D**
Domain size	$100 \times 100\ km$
Horizontal resolution	200 m
Number of vertical levels	99
Vertical resolution	On a stretched grid with more levels near the surface
Model top	20 km
Newtonian damping layer	$\tau = 0.0001, Z_d = 15\ km$ and $H_d = 2.5\ km$
Wind shear imposed	None (u, v relaxed to $0\ m/s$ to with $\tau = 2\ h$)
Coriolis	Zero
Boundary conditions	Bi-periodic, rigid lid

Setup and forcing are based on the EUROCS case study



Control simulation

Peak SHF =130 w/m^2, LHF= 400 w/m^2

RC is prescribed:
$-1.75K/d$ from 0-12km, then decreases linearly with height to $0K/d$ at 15km

Different **strengths of surface forcing**

Strongly forced simulation = 1.5*Control
Peak SHF =195 w/m^2
Peak LHF= 600 w/m^2
RC=$-2.625\ K/d$

Weakly forced simulation = 0.5*Control
Peak SHF =65 w/m^2
Peak LHF= 200 w/m^2
RC=$-0.875\ K/d$

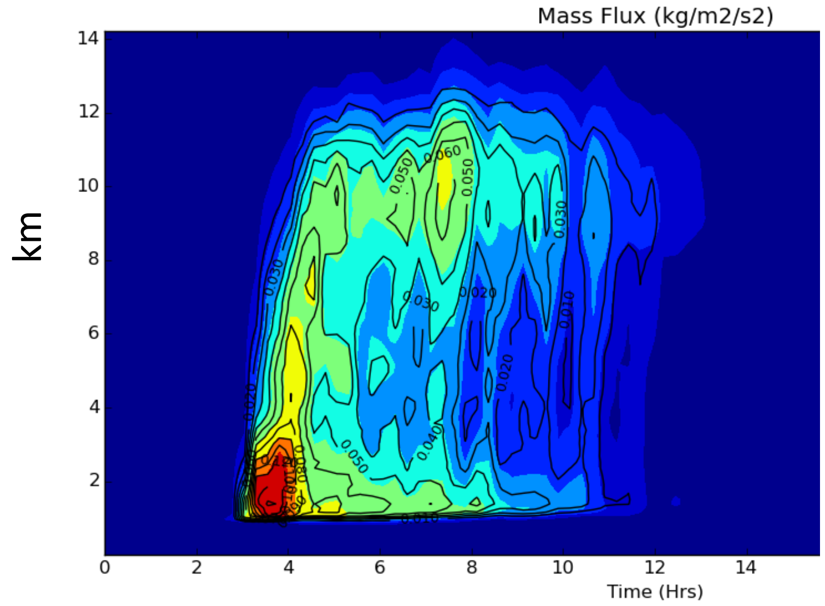
Same Bowen ratio (~0.3) and forcing timescale (24 hrs)

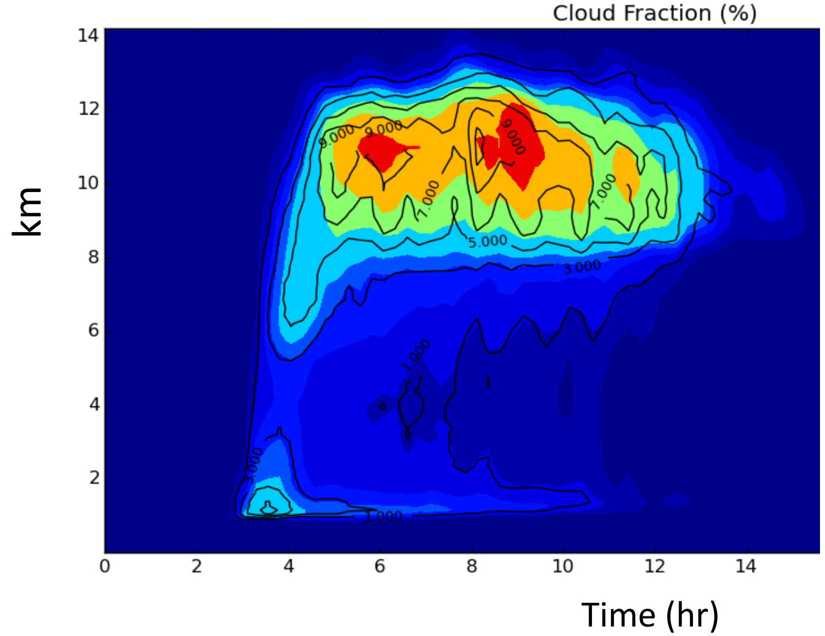
- Most of the simulations are performed over 10 forcing cycles to ensure statically significant results
- Most of the results presented are the composites over 9 forcing cycles, after the first forcing cycle has been removed

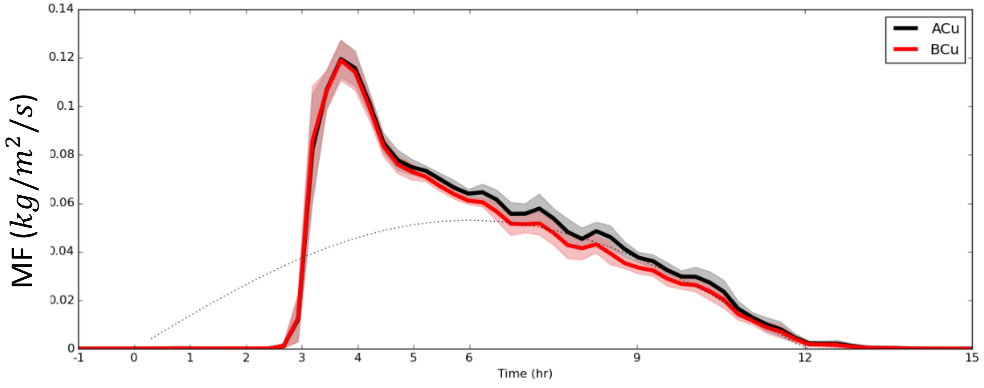
Evaluation on multi forcing cycles

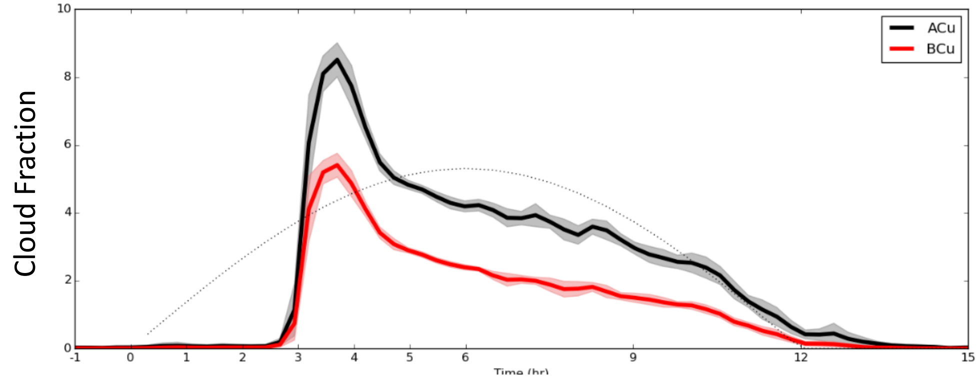
Control simulation ACu (q_l or $q_i > 10^{-5} kg/kg, w > 0\ m/s$)

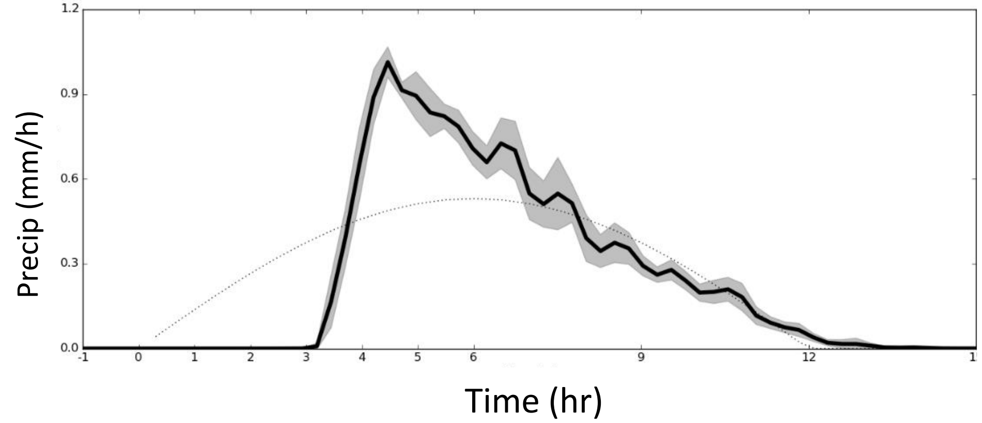
BCu or Cloud cores (ACu, $\theta_v' > 0\ K$)











Triggering = sharp increases of cloud base MF and cloud fraction.

The details (e.g., timing) of the triggering varies from one forcing cycle to the other.

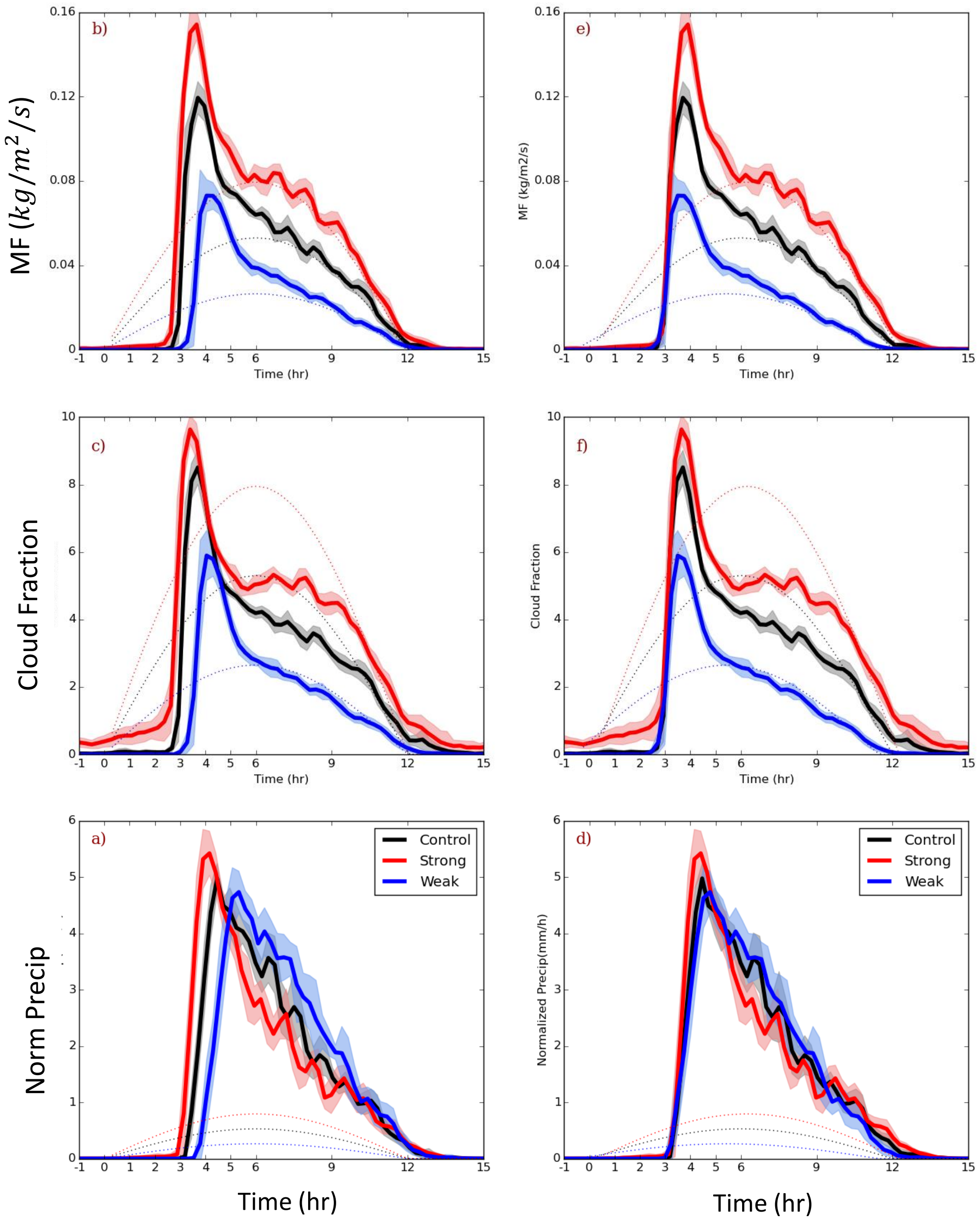
For all 9 simulations triggering =rapid intensification of convection with deep convective cloud top emerging rapidly into the upper troposphere

- drives a sharp increase in surface precipitation rates

Rainfall occurs too early after triggering

- Early morning precipitation peak
- More stable BL at dawn delays the onset of precipitation but the afternoon or evening precipitation peak is not achieved

Timing of convection for different strengths of surface forcing



- Convection intensity increases consistent with the RC applied
  - MRR=0.1mm/h (weak), 0.2mm/h (control), and 0.3 mm/h (strong)

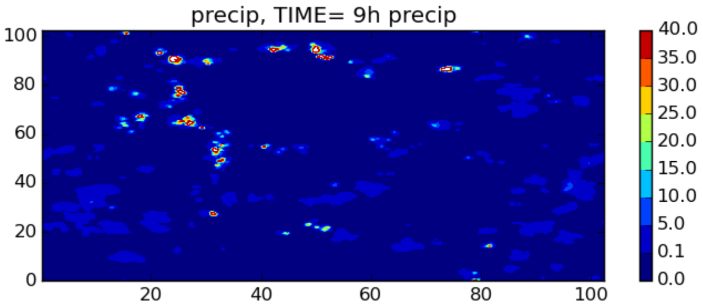
- MF and cloud fraction increases with the strength of surface forcing
- Time of triggering increases with decreasing forcing
  - Strong forcing, triggering at 2.75h, 15min earlier than in the control and 45 min earlier than in the Weak forcing (3.5h) .

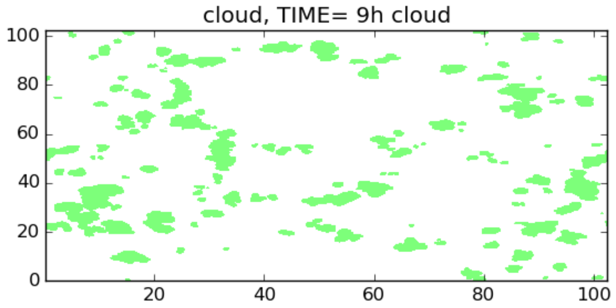
After triggering:

Regardless of the strength of surface forcing

- deep convective cloud top emerges rapidly into the upper troposphere
- The rate of growth of cloud top is very similar
  - Rainfall occur too early after triggering
  - Precipitation peaks almost at the same time: about 1.5h after triggering

Evolution of rainfall events



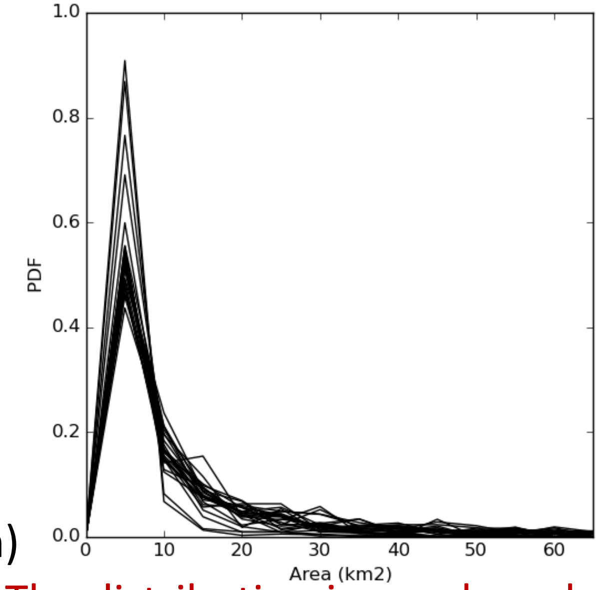


For each 2D surface precipitation field, a grid point (i, j) is masked as cloudy if $precip_{i,j} \geq 0.5 \times \overline{< precip >}$

Cloudy grid points are classified in clusters (rainfall events)

Number of rainfall events is N

Area of each event $A_i = n_i \Delta x \Delta y$



PDF of A_i (4-12h)

The distribution is very broad.

Average radius $\bar{R} = \sqrt{\bar{A}/\pi}$ and standard deviation of radii σ_R

Evolution of rainfall events

Evolution of $\bar{R} = \sqrt{\bar{A}/\pi}$ can be divided into three stages:

Growing stage(3-5h):

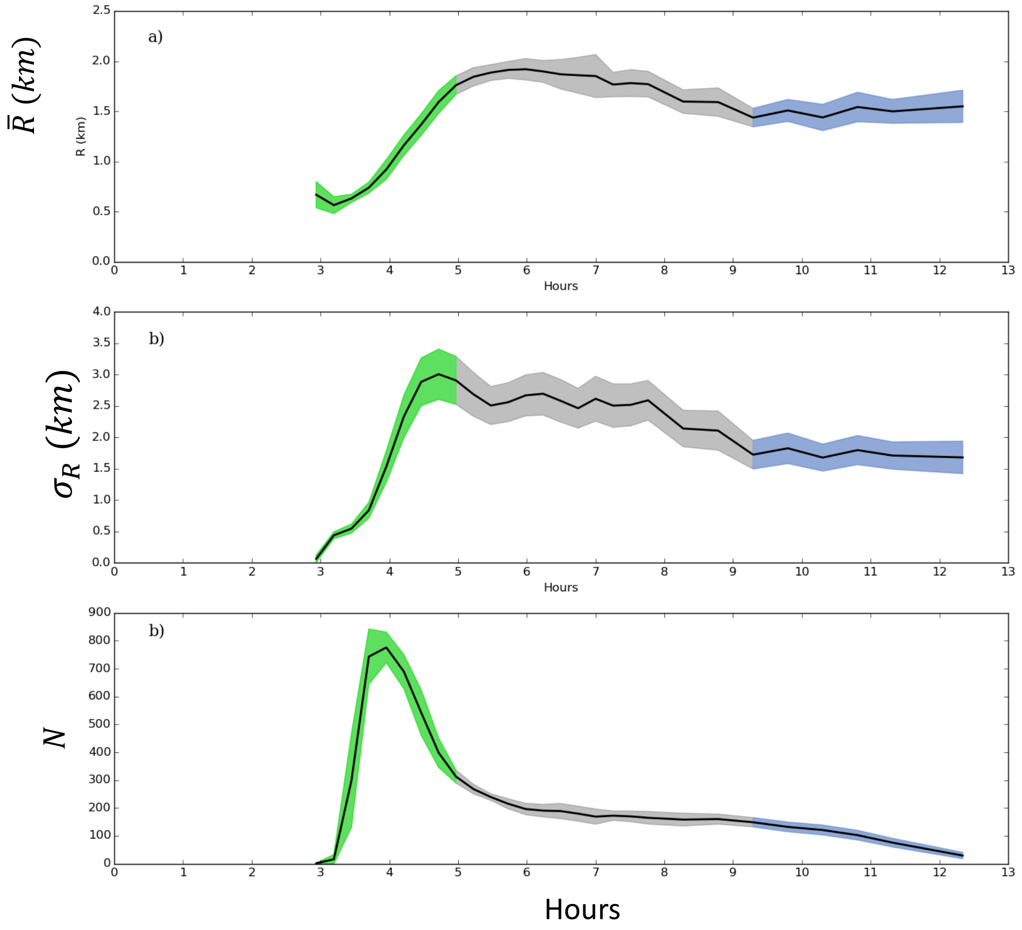
- marked with a gradual growth of $\bar{R}$
- Few clouds with average radius ~0.7km
- Peak value of N at 4h (~1h after triggering)
- Between 4-5h N decreases rapidly while $\bar{R}$ is increasing
    - Smaller events are getting sucked into larger ones

Mature stage(5-9h):

- $\bar{R}$ adjusts from its peak value to a smaller value
- N is decreasing

Steady stage (9-12h):

- $\bar{R}$ almost constant
- N continues to decrease and reaches 0 when precipitation stops



$\bar{R}$ does not vary substantially with time, away from triggering
Time-evolution of the total MF is mainly caused by variations in the cloud statistics (number, cloud fraction), rather than changes in the characteristics of the clouds (radius).

Sensitive to the strength of the forcing?

The mean MF per cloud increases with the strength of SF

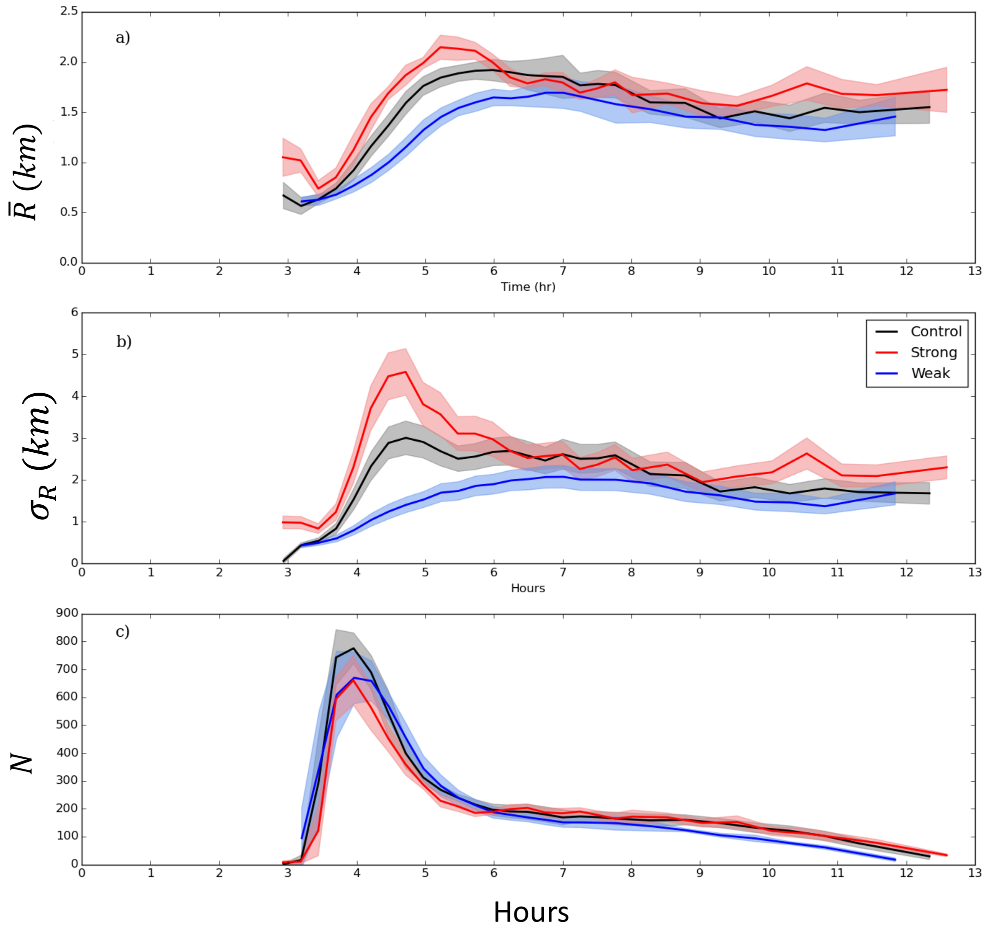
Growing stage:

- Clear size dependence
  - $\bar{R}$ and σ_R increase with the strength of surface forcing
- N reaches it peak value 1 hour after triggering (for all cases)

Mature and steady stages

- No clear separations in the evolution of $\bar{R}$ and σ_R
- From hour 5 after triggering N in the Weak is the smallest

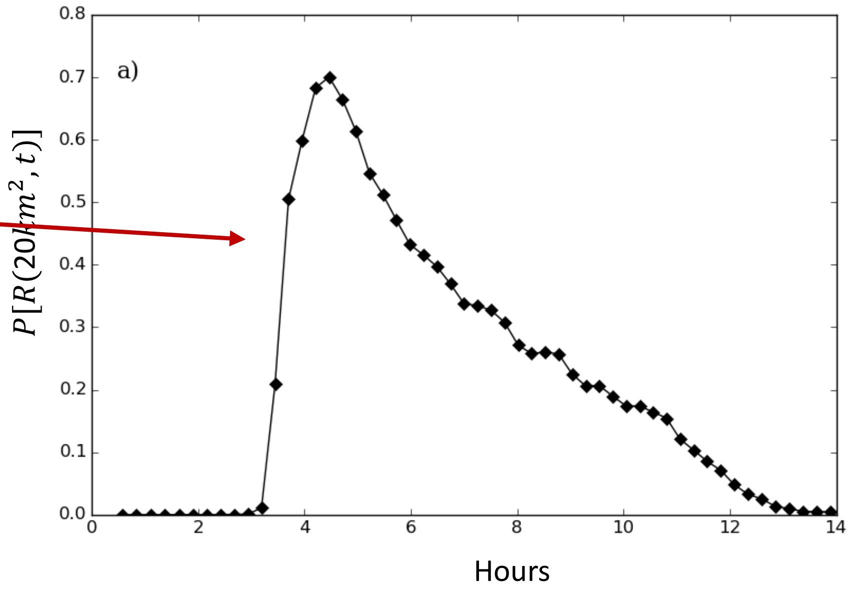
$\bar{R}$ does not vary substantially with time, away from triggering
Time-evolution of the total MF is mainly caused by variations in the cloud statistics (number, cloud fraction), rather than changes in the characteristics of the clouds (radius).



Convection depends on its own history?

Evaluation of convection within a given area A
Each area A is considered to have rain if its precip is $\geq 0.5 \times \overline{< precip >}$

Conditional probability of finding rain within a $20km^2$, $P[R(20km^2, t)]$



Persistence of rainfall events: $P[R(A,t)/R(A,t-\Delta t)]$
Varies between 0 and $P[R(A,t)]$

For random distributions, the conditional probability of finding persistent rainfall by random chance:
$P^2[R(A,t,\Delta t)]$=$P[R(A,t)] \times P[R(A,t-\Delta t)]$

No convective memory if $P[R(A,t)/R(A,t-\Delta t)] \sim P^2(R(A,t,\Delta t)$

There is memory if $P[R(A,t)/R(A,t-\Delta t)] \neq P^2(R(A,t,\Delta t)$

Memory function $M[R(A,t,\Delta t)]= \frac{P[R(A,t)/R(A,t-\Delta t)] - P^2[R(A,t,\Delta t)]}{P[R(A,t)]}$

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Convection depends on its own history?

$P[R(20km^2,t)]$

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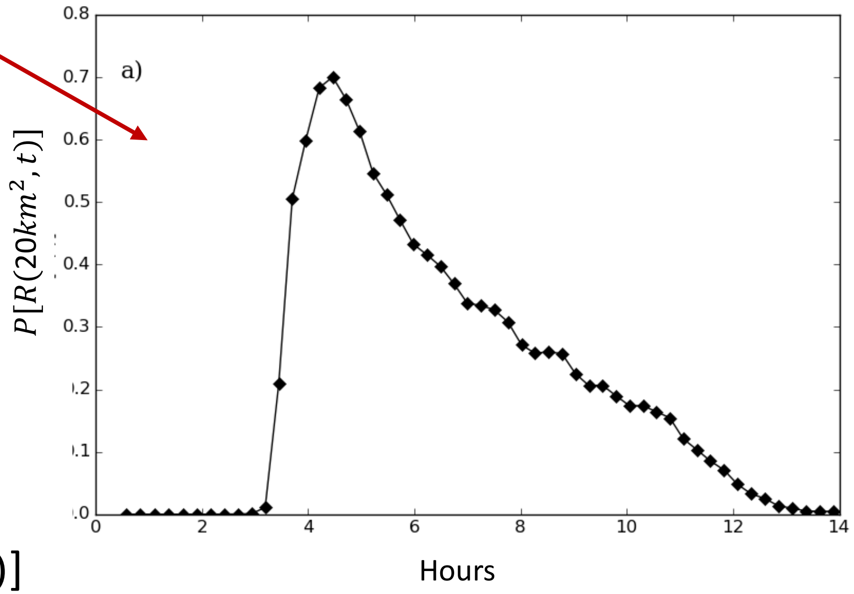
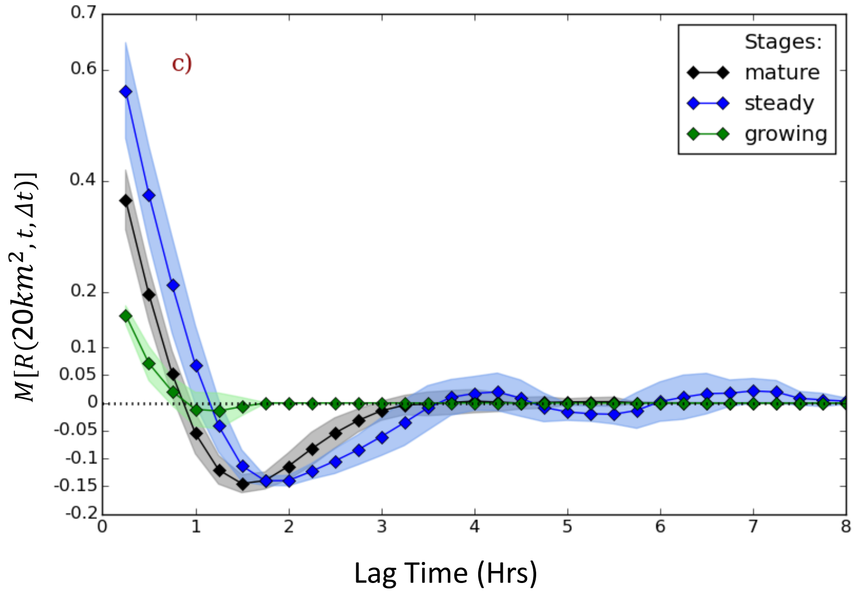


Growing stage (3-5h):

- Newly developing rainfall events are more likely to persist for half an hour or so
- The amplitudes of $M[R(A,t,\Delta t)]$ reduce with increasing A

$M[R(20km^2,t,\Delta t)]$



Mature (5-9h) and steady (9-12h) stages:

- Very similar memory functions
- Convection depends its history over the previous 3 hours
- Depending on the most recent history:
  - *it may be more likely to rain where it was already raining*
  - *rainfall events are more likely to be suppressed*

Sensitivity to A

- The amplitudes of $M[R(A,t,\Delta t)]$ decrease with increasing A.
- $M[R(A,t,\Delta t)] \sim 0$ for $A \geq 25 \times 25\ km^2$

Sensitivity to the strength of surface forcing

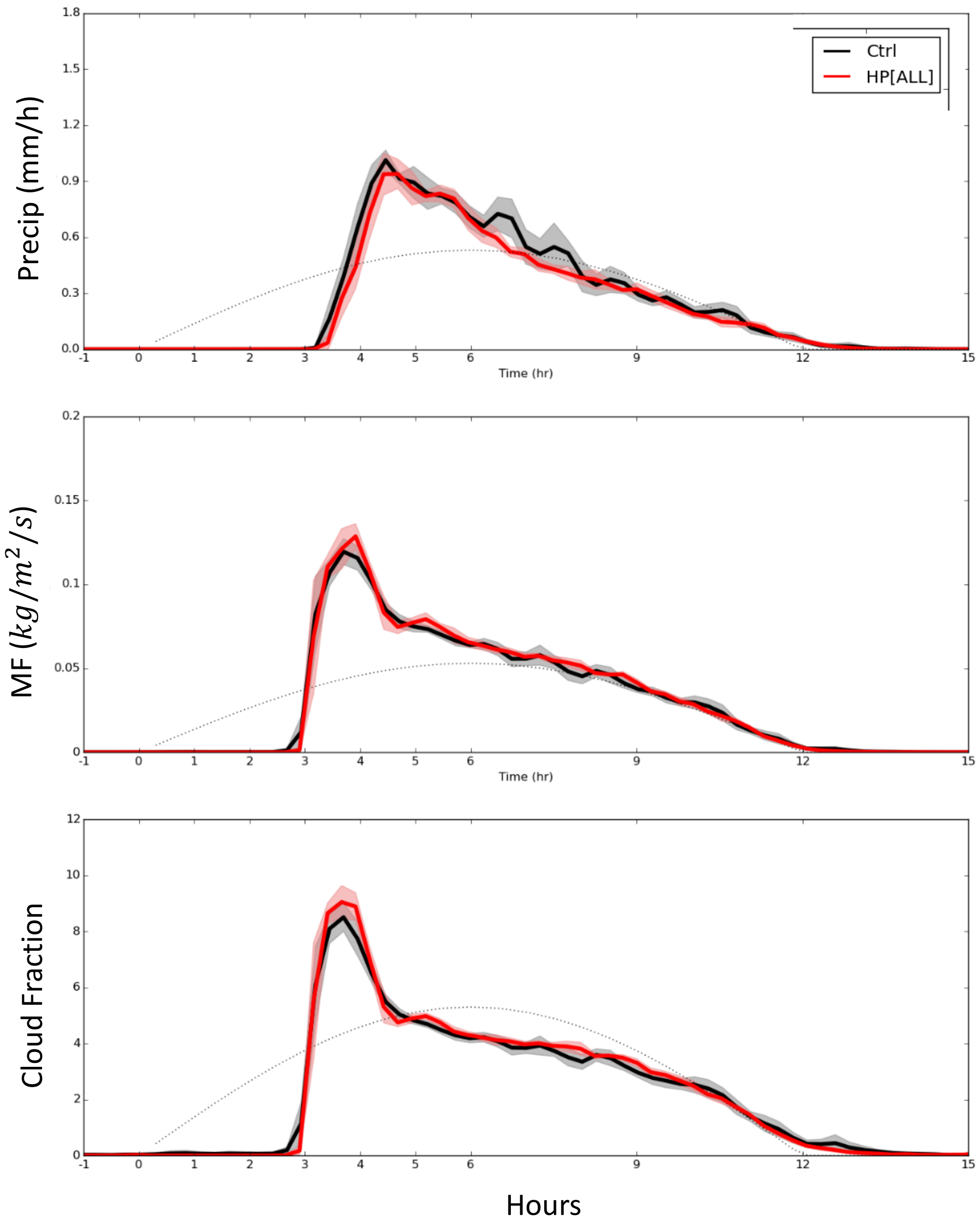
- $M[R(A,t,\Delta t)]$ shows a very weak sensitivity to the strength of surface forcing
- Weak: rainfall events decay less rapidly and are suppressed more strongly

Memory attributed to the initial thermodynamic fluctuations

1- We applied “homogenization perturbations” of θ and q_v (without changing the domain mean state) at all vertical levels between 15-24h

Following “homogenization perturbations”:

- precipitation peaks at the same time
- Convection intensity is reduced by 10%
  (MRR is 0.18mm/h compared to 0.2mm/h in the control simulation)



Memory attributed to the initial thermodynamic fluctuations

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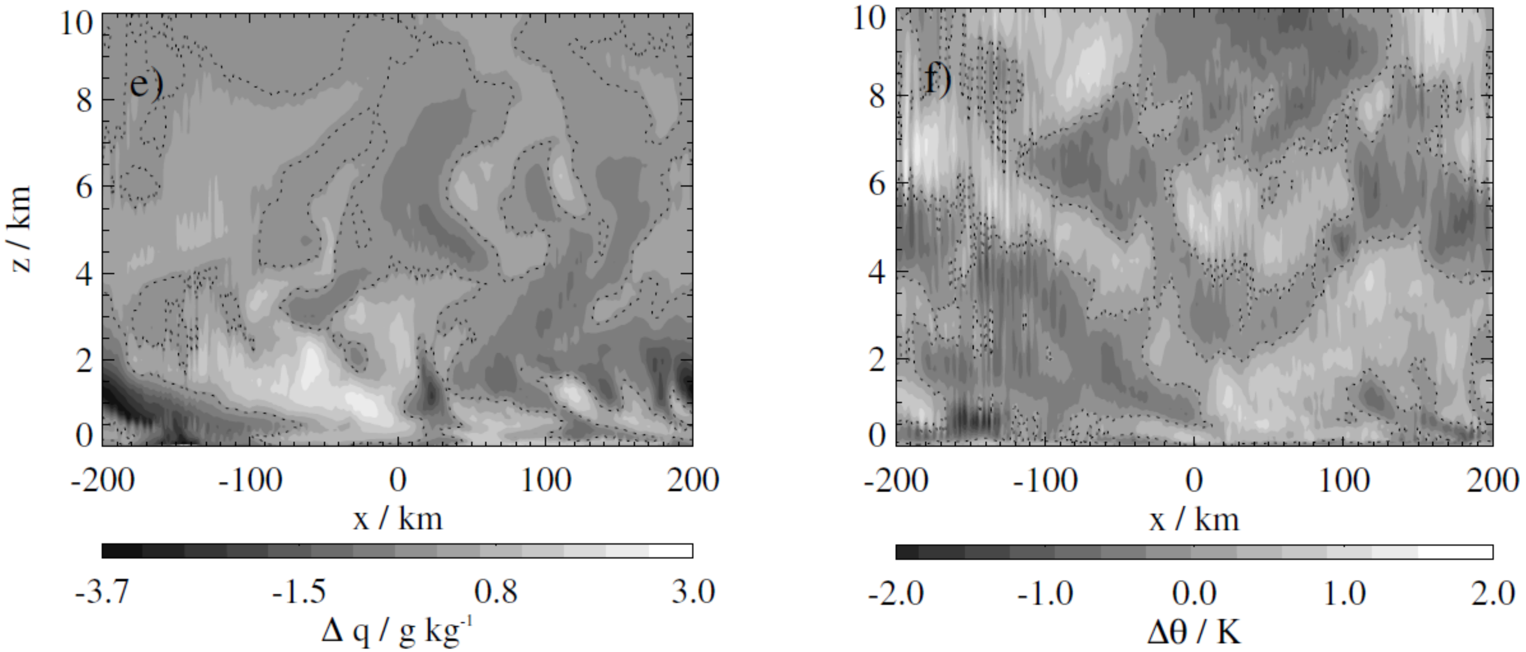
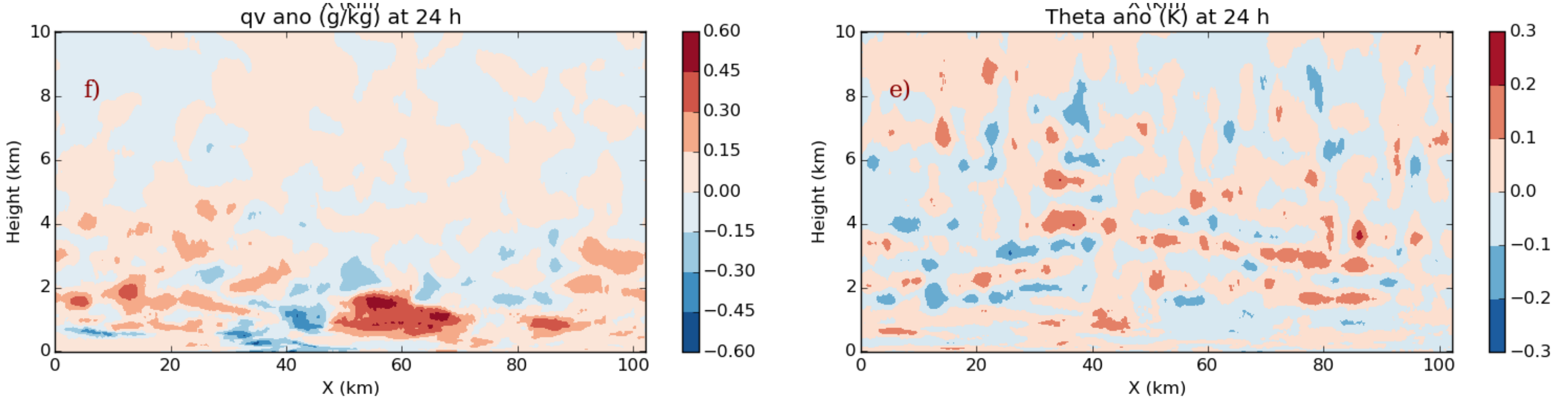
Study of Stirling and Petch [2004]
Onset of precip changes by several hours
And rainfall amount is increased by 70 %

- Thermodynamic fluctuations generated from simulations of 24 hours of deep convection



In our study:
No clouds and convection between15-24h

Thermodynamic fluctuations 12 hours after a decaying day time deep convective events.



The amplitudes of θ' and q_v' are smaller
Do they influence the evolution of rainfall events on the next diurnal cycle?

Thermodynamic fluctuations have a significant impact of the evolution of rainfall events

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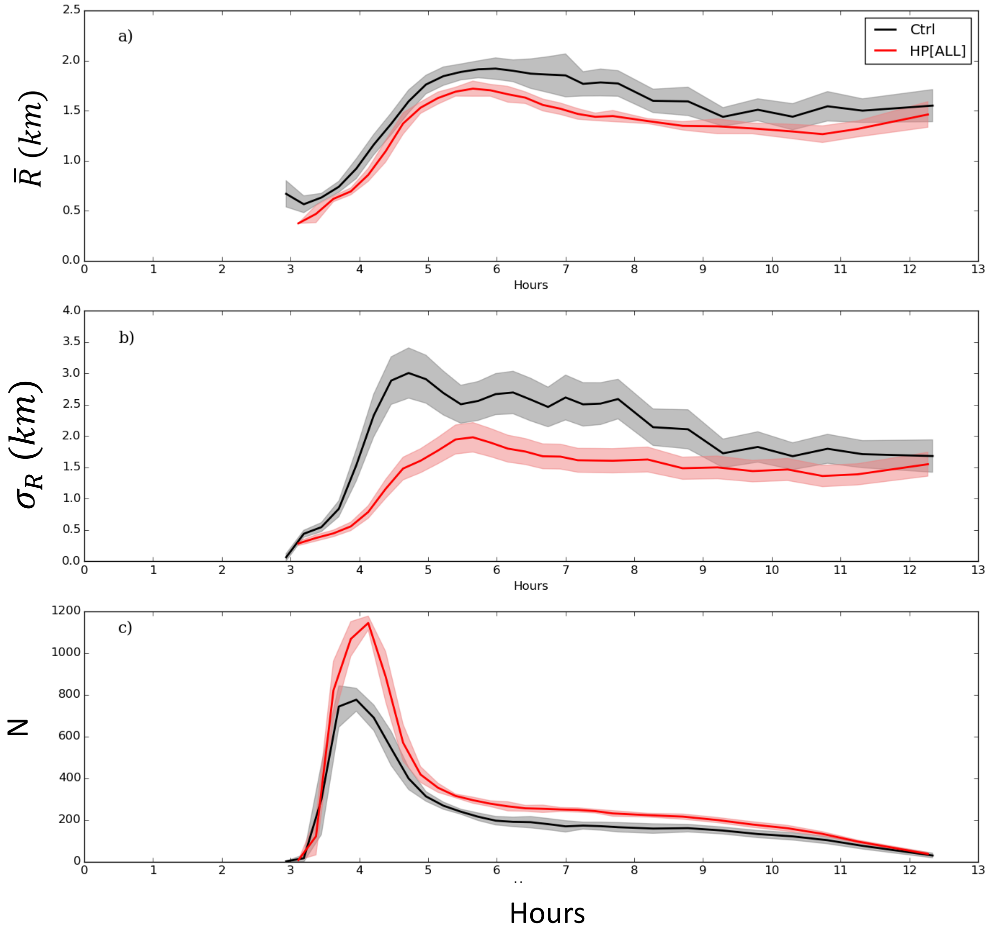
Following homogenization perturbations

- Clear separations in the evolution of rainfall events
- σ_R is narrower and $\bar{R}$ is smaller
- N is increased (up to 450)
- Recovery time is over 6hours (3-9h)
- Convection intensity is reduced by 10% and N is increased
    - Rainfall events are less intense



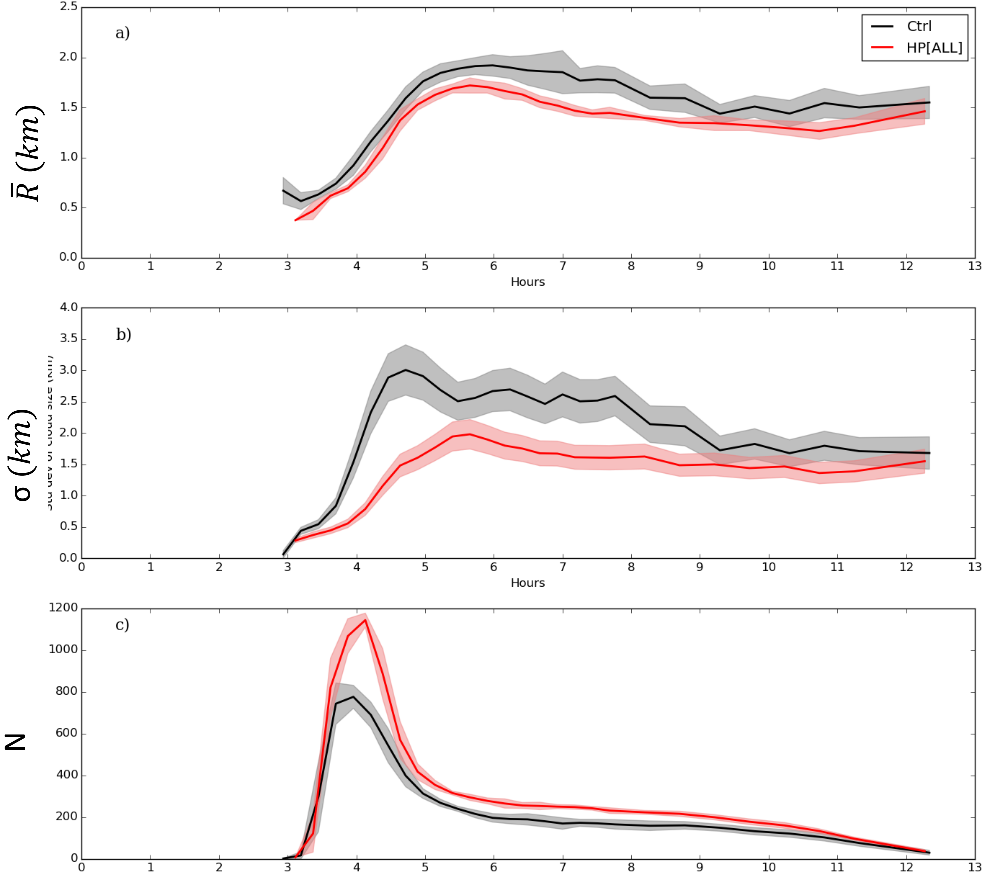
Following homogenization perturbations

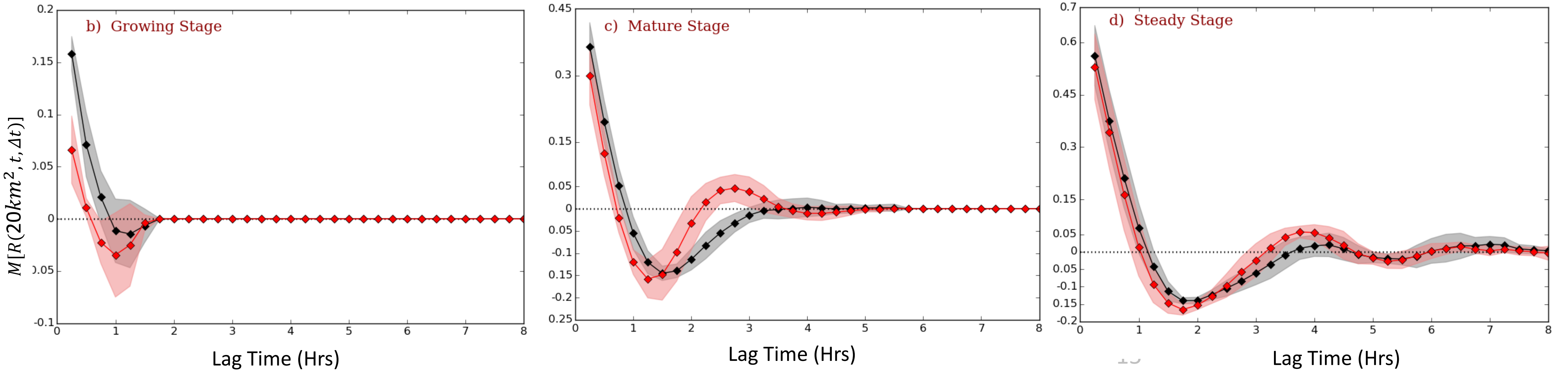
- Clear separations in the evolution of rainfall events
- σ_R is narrower and $\bar{R}$ is smaller
- N is increased (up to 450)
- Recovery time is over 6hours (3-9h)
- Convection intensity is reduced by 10% and N is increased
  - Rainfall events are less intense
    - Decay more rapidly
    - Recover more rapidly (an hour earlier)

Homogenization perturbations below 4km or above 4km

- θ' and q_v' below 4km appear to contribute as a primary storage of convective memory

(Confirms the results of Stirling and Petch [2004] and Colin et al. [2019])





Summary

- We produced the Diurnal cycle experiment that focuses on the triggering of deep convection.
- Morning precipitation maxima regardless of the strength of surface forcing (*rainfall occurs too early after triggering*)

- Rainfall events become relatively larger with increasing strength of surface forcing
- Cloud-size does not vary substantially with time, away from triggering (regardless of the strength of surface forcing)
    - Time-evolution of convection is mainly caused by variations in the cloud statistics, rather than changes in the characteristics of the clouds (independent on the strength of the forcing.

The memory function depends on the size of the area within which convection is evaluated.
Within a 20 kilometre square area

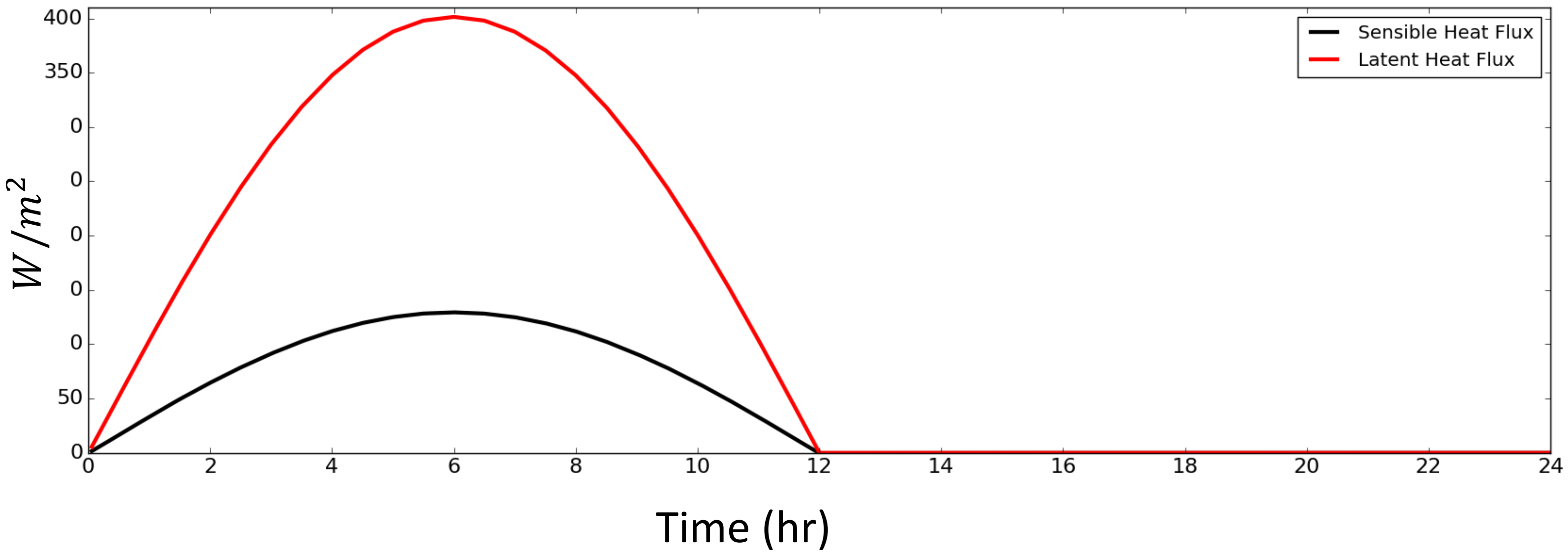
- During the growing stage: newly developing rainfall events are more likely to persist for an half and hour or so.
- During the mature or steady stages: depending on the most recent history of convection, it might be more likely to precipitate where it was already precipitating or rainfall events might be more likely to be suppressed if they have been active for few hours already

Thermodynamic fluctuations generated (*via diffusion and advection*) about 12 hours after deep convective activity have

- A little impact on the timing and intensity of convection
- A significant impact of the evolution of rainfall events
    - N decreases (up to 450 reduction), R increases, and σ_R is wider
    - Rainfall events are more intense, thus decay and recover more slowly
- Further sensitivity experiments revealed that convective memory resides in the lower 4 km.

Questions

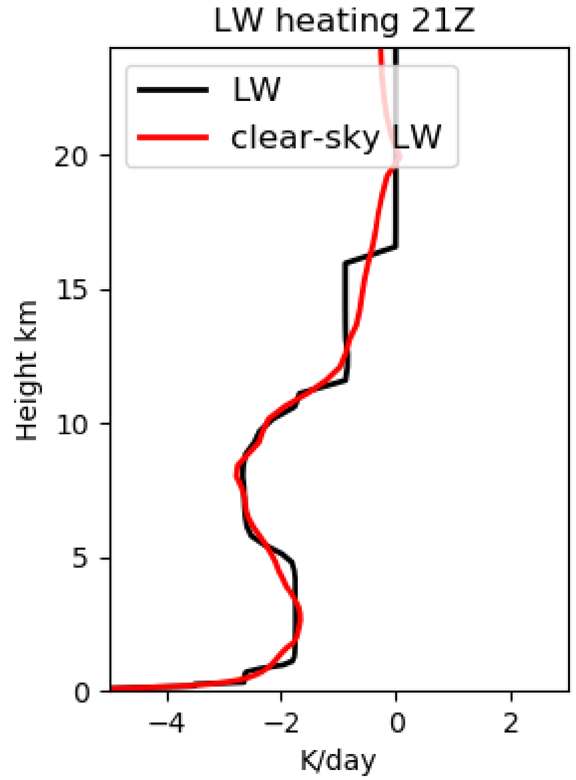
Setup and forcing are based on the EUROCS case study



Control simulation

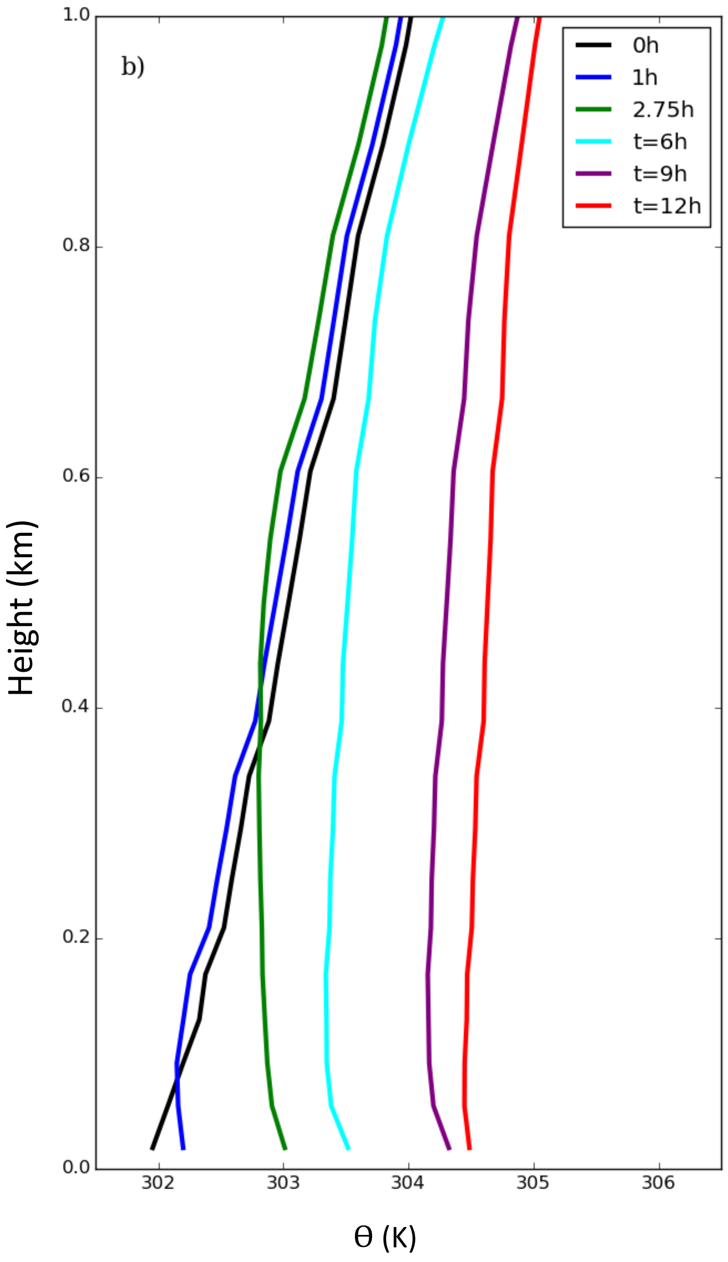
Peak SHF =130 w/m^2, LHF= 400 w/m^2

RC is prescribed:
$-1.75K/d$ from 0-12km, then $0K/d$ at 15km
Additional cooling at night (12-24h)
$-3K/d$ at 0 km decreases to 0 K/d at 1 km



Evolution of the boundary layer

Control simulation



Evolution of the BL

- At sunrise: the near surface is at its coolest state and the BL is stable
- Near surface temperature is increasing
- BL depth is increasing: 100m at 1h to 800m at 12h
- Warmest state at sunset
- Surface forcing is off between 12-24h
  - Free troposphere cools down uniformly
  - Below 1km: the column cools more rapidly
- At 24h
  - Stability structure of the free troposphere is maintained close to that at 0h
  - The BL is stable

Convection depends on its own history?

Does $M[R(A,t,\Delta t)]$ sensitive to the A?

The amplitudes of $M[R(A,t,\Delta t)]$ decrease with increasing A

Growing stage:

- No convective memory when $A \geq 15 \times 15\ km^2$

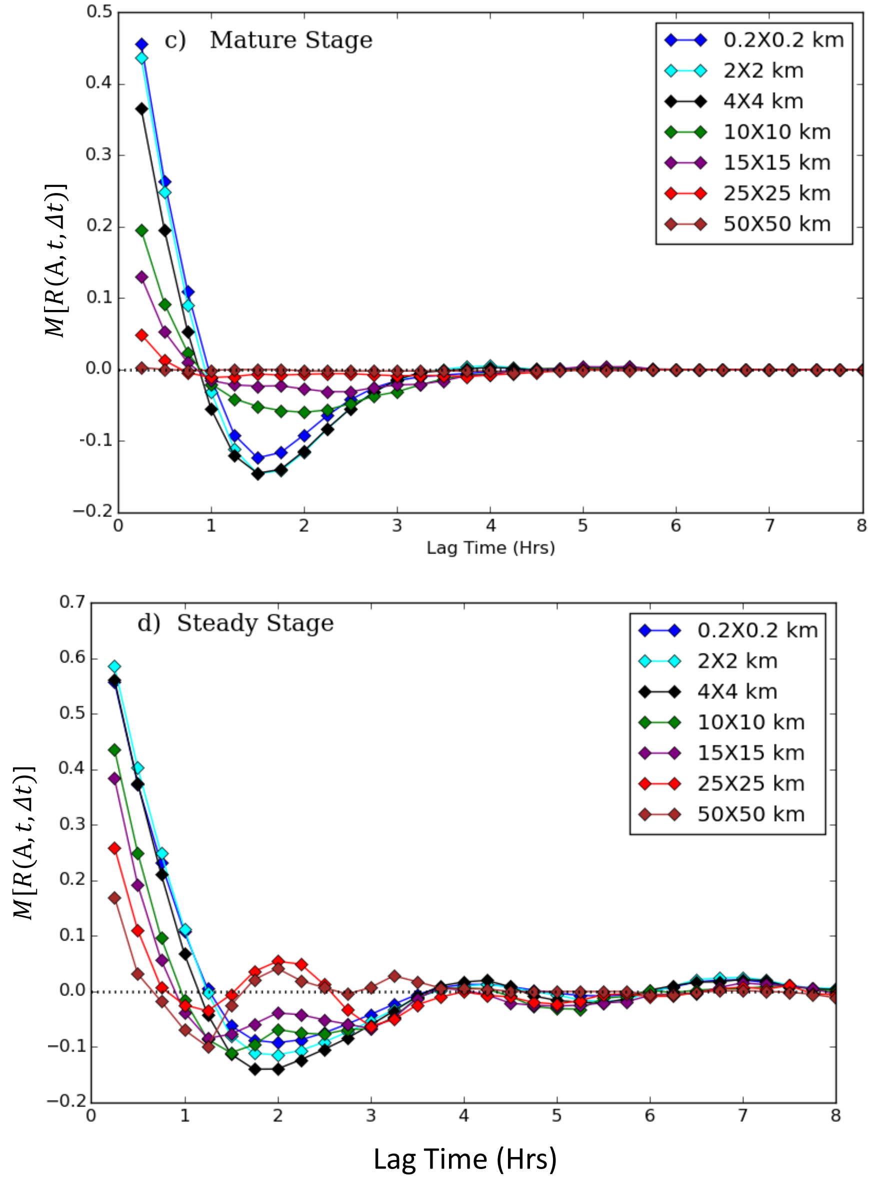
Mature stage:

- Very similar memory functions for $A < 10 \times 10\ km^2$
- A significant reduction when $A \geq 10 \times 10\ km^2$ and
- No convective memory when $A \geq 25 \times 25\ km^2$

Steady stage

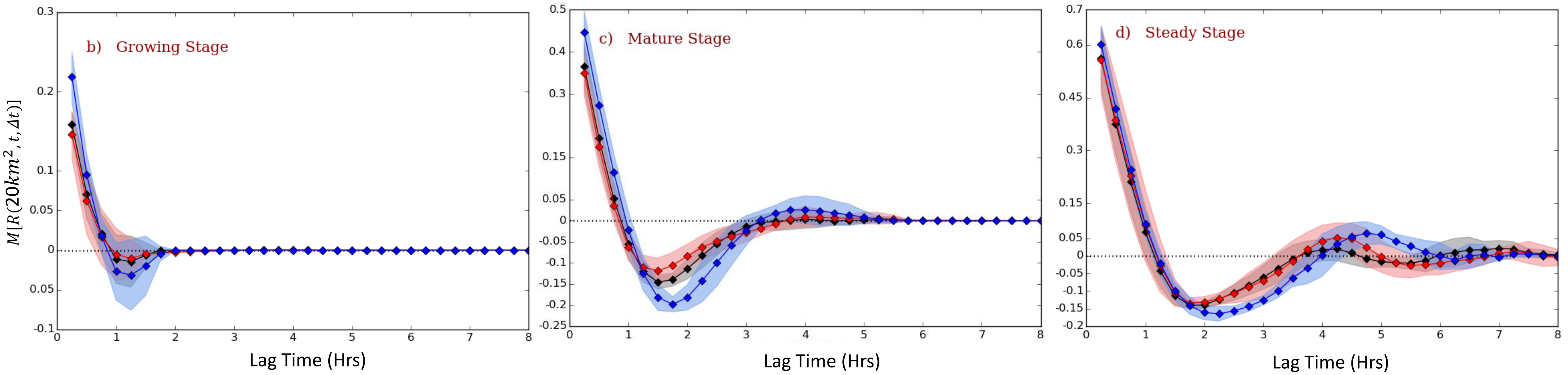
- $M[R(A,t,\Delta t)]$ shows different sensitivity for $A \geq 15 \times 15\ km^2$
    - Rainfall events are a little bit enhanced and
    - There is convective memory even within area $\geq 25 \times 25\ km^2$

Analysis of $M[R(A,t,\Delta t)]$ reveals to evaluate current convection using information from previous behaviour of convection we needs to know the size of the area within which convection is evaluated and its life cycle are



Convection depends on its own history?

Does $M[R(A, t, \Delta t)]$ sensitive to the strength of surface forcing?



Very similar memory functions but in the weakly forced simulation
Rainfall events decay less rapidly
They are also suppressed more strongly during the mature and steady stages