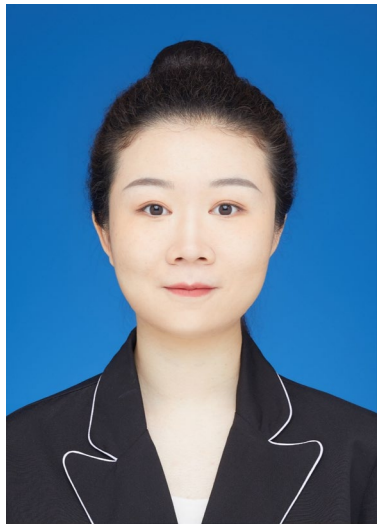
A Global View on Microphysical Discriminations Between Heavier and Lighter Convective Rainfall

Prof. Yali Luo



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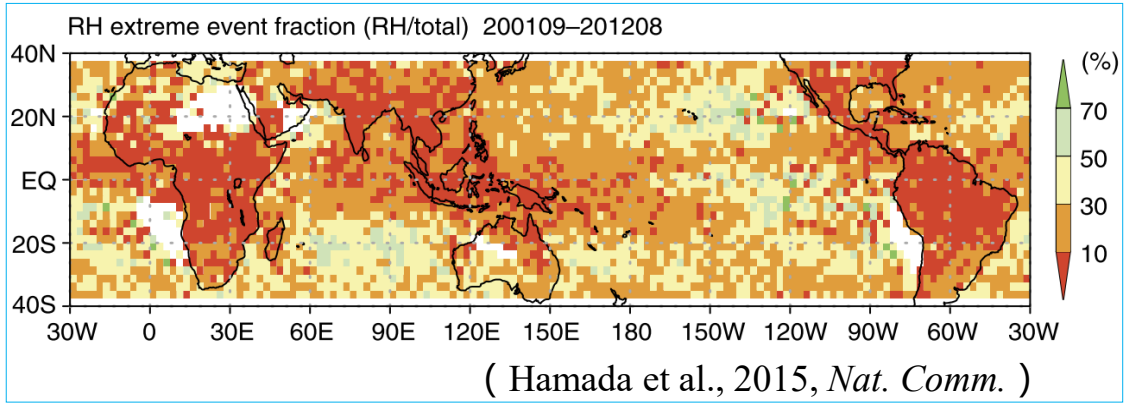
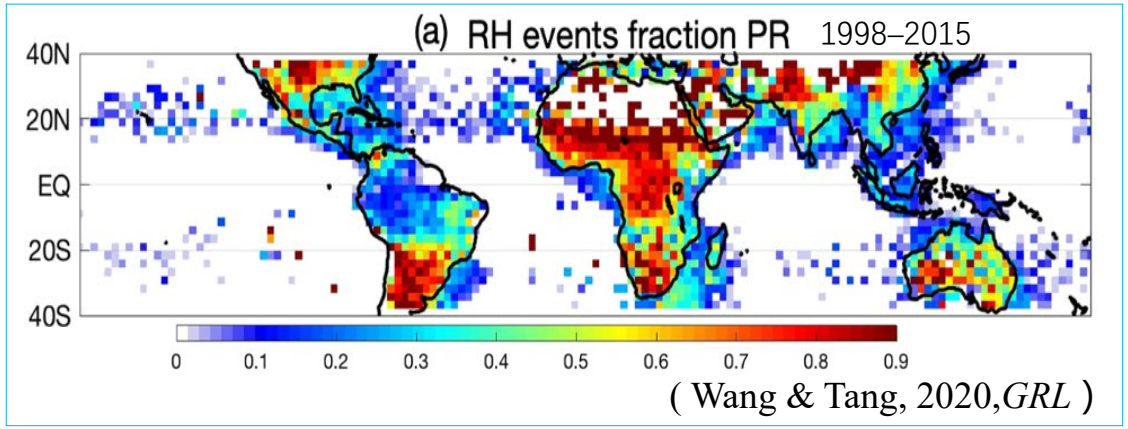
Recent studies emphasize that extreme rainfall can be produced by intense, moderate, or weak convection.

- **The overlapping fraction between extreme precipitation and intense convection varies from < 30% to > 60% globally**
- **The weak and strong convection contributes about 30%, respectively, to global extreme precipitation events** (Xu et al., 2022, *GRL*)



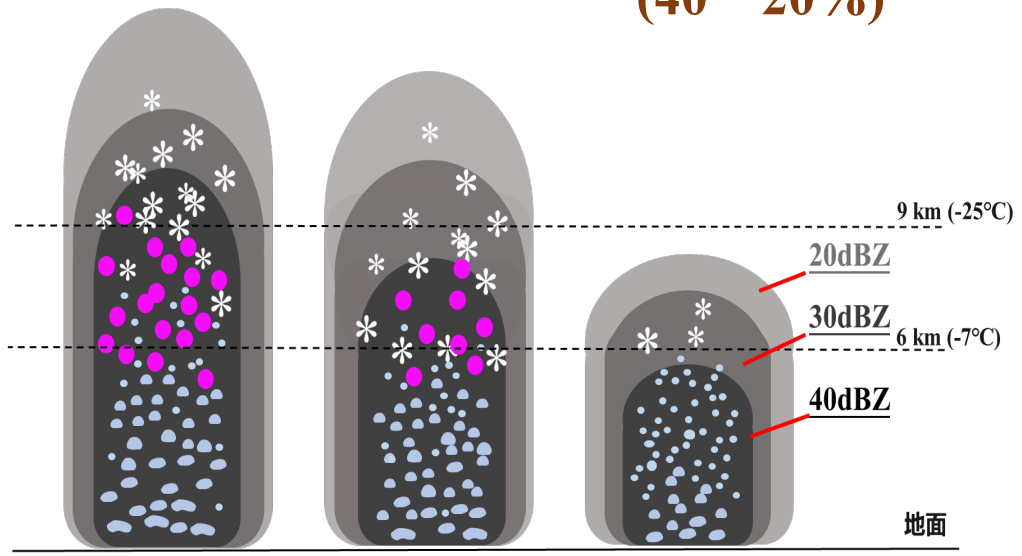
(Hamada et al., 2015, *Nat. Comm.*)



(Wang & Tang, 2020,*GRL*)

Monson coast (South China) (Yu, Luo*, et al., 2022, *GRL*; Gao, Li, Luo*, et al., 2023, *GRL*)

Intense 10 – 30% **Moderate (about 50%)** **Weak convection (40 – 20%)**



Scientific Question & Objectives

Known: Convection can produce both high and low rain rates regardless of convective intensity.

Unknown:

- What happened in convective clouds that results in disparate surface rain rates?

➢ Objectives:

- To identify the microphysical distinctions between “heavier” and “lighter” rainfall in convective precipitation events worldwide.
- To explore key atmospheric conditions driving these differences.

Data

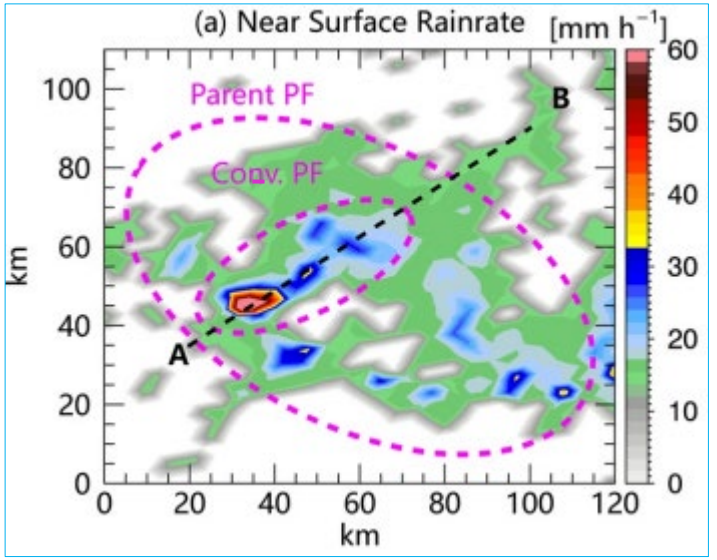
- **The Tropical Rainfall Measuring Mission** (**TRMM**; Kummerow et al., 1998) from 1998 to 2014 (16 warm seasons)
- **The Global Precipitation Measurement** (**GPM**; Hou et al., 2014) from 2014 to 2020 (6 warm seasons)
- **The fifth generation European Centre** for Medium-Range Weather Forecasts **Reanalysis** (**ERA5**; Hersbach et al., 2020)

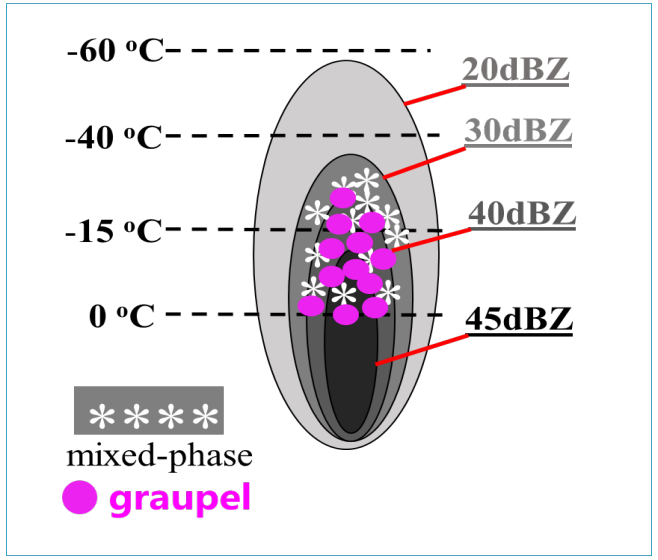
Methods

- **Definition of a CPE (Convective Precipitation Event):**
  A 3D precipitation region composed of at least four convective precipitation pixels (80-100 km^2)

- **CPE Classification by rain rates:**
  - **HR: MAXRR > 60 mm/h**
  - **MR: 30-60 mm/h**
  - **LR: MAXRR < 30 mm/h**

- **CPE Classification by convective intensity:**
  - **InCPE: MAXHT30 > 9 km**
  - **MoCPE: 5.5-9 km**
  - **WeCPE: MAXHT30 < 5.5 km**





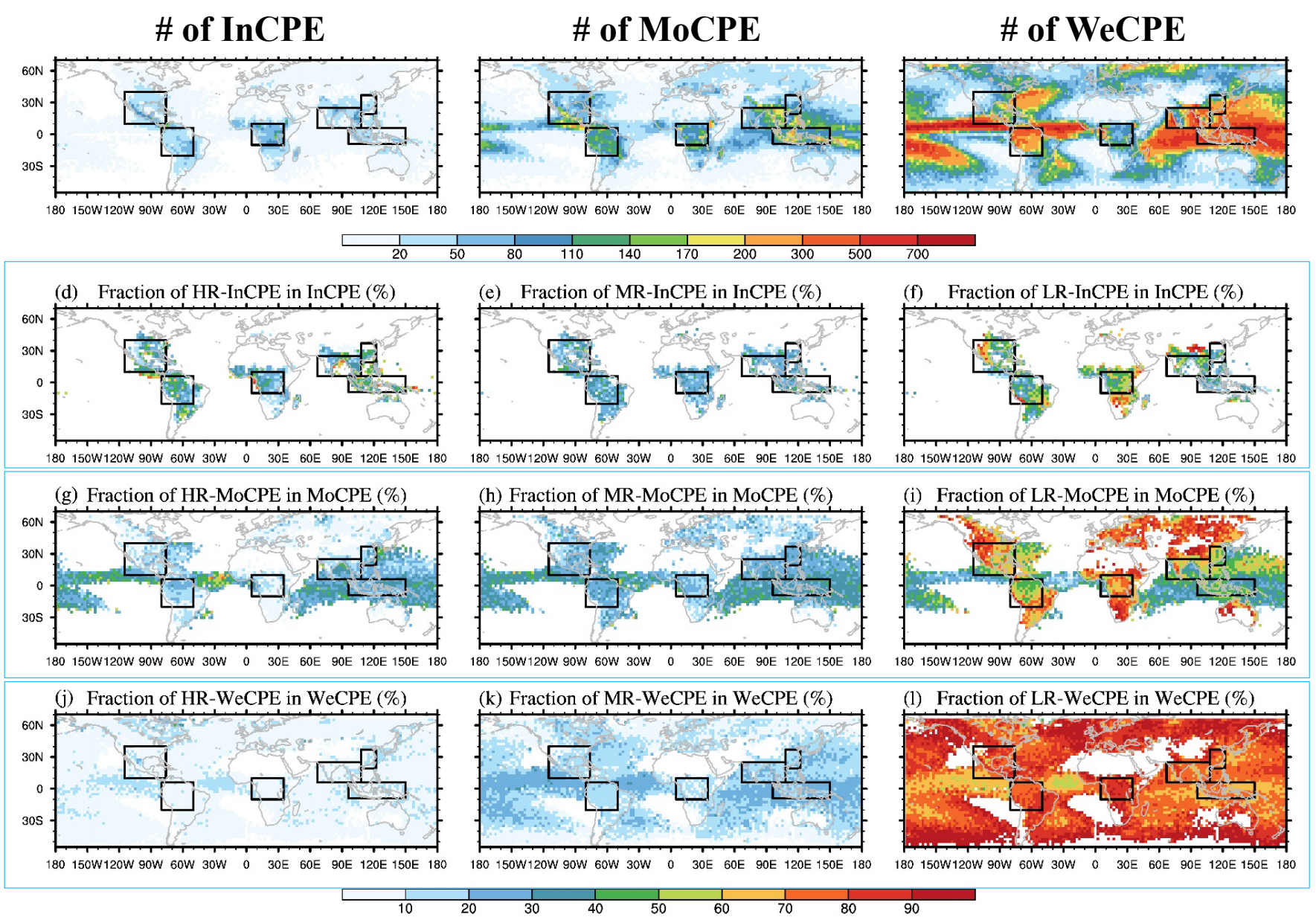
Methods: Cloud-permitting ensemble simulations

- **Cloud Model 1** (**CM1;** Bryan and Rotunno, 2009)
- **Three groups of ensemble simulations** in 60-min periods
  - **CASE1: HR-InCPE; CASE2: LR-to-MR-InCPE; CASE3: HR-We-to-MoCPE**

Setup	
Domain size	100 km*100 km*17.475 km
Horizontal grid spacing	200 m
Vertical grid spacing	150 m
Initial large time step	2.5 s
Lateral boundary conditions	Open radiative
Top and bottom boundary conditions	Free slip
Governing equation	Filtered Navier–Stokes equations
Initiation method (ensemble)	2±0.5 K warm bubble, located 1.5 km AGL with a horizontal radius of 10 km, vertical radius of 1.5 km
Microphysics	Morrison double moment
Pressure solver	Compressible, Klemp-Wilhelmson time-splitting, vertically implicit
Radiation	the NASA-Goddard scheme
Surface fluxes	None
Coriolis acceleration	None
Topography	Land with grass
3D output frequency	60 s

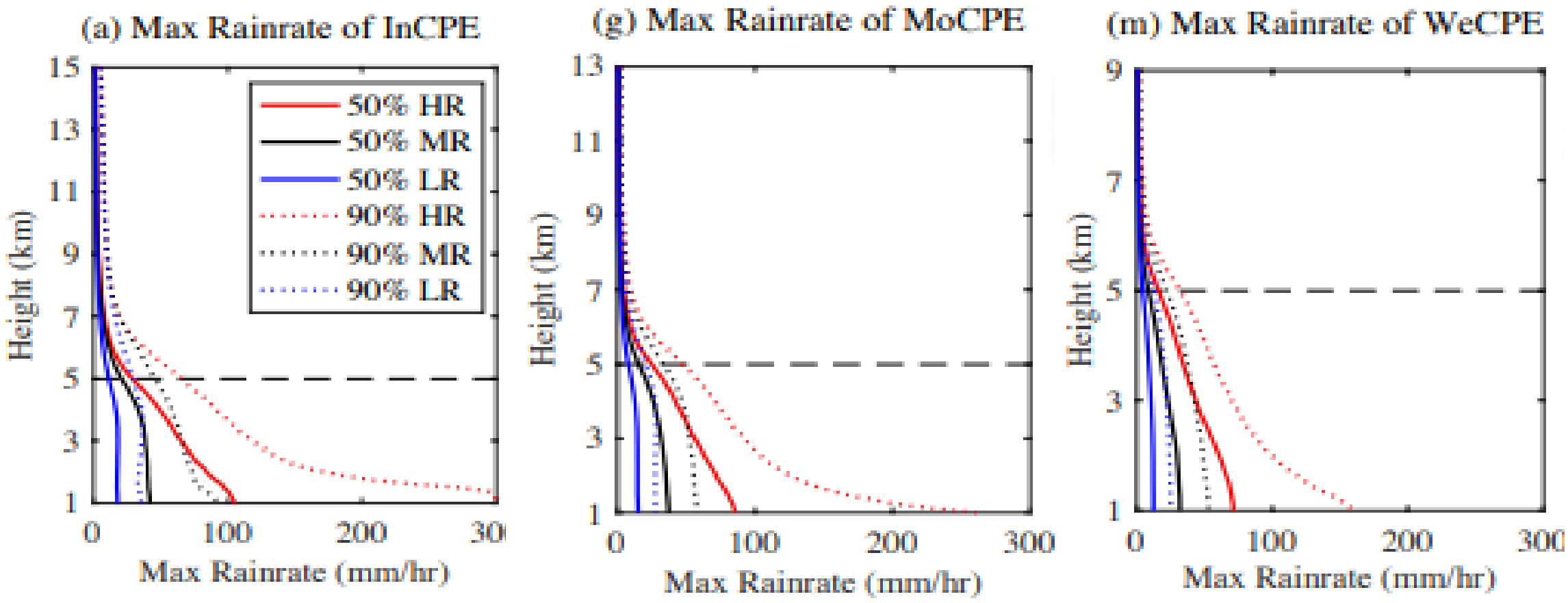
Results: Spatial distribution of CPEs

- InCPEs are mostly land-based, while MoCPEs and WeCPEs are mainly in the ITCZ and monsoon regions.
- Six convective hotspots on land: Southern North America, the Amazon, Central Africa, South Asia, southeastern China, the Maritime Continent islands.
- In these regions, InCPEs produce HR or LR events in roughly equal proportion (30-50%). As convection weakens, the proportion of HR decreases & LR increases.



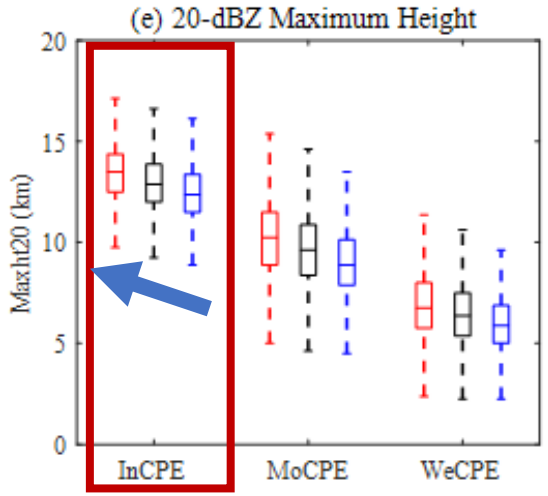
Comparison of Rainfall Intensity

Compared to WeCPEs, InCPEs not only have a much higher probability of producing the high rain rate (HR) **but also can generate more extreme HR.**

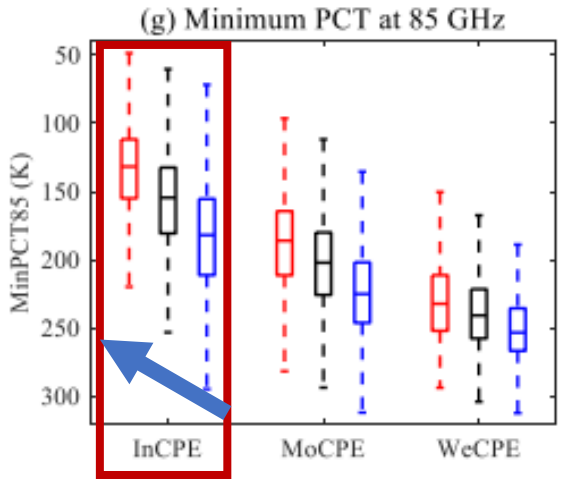


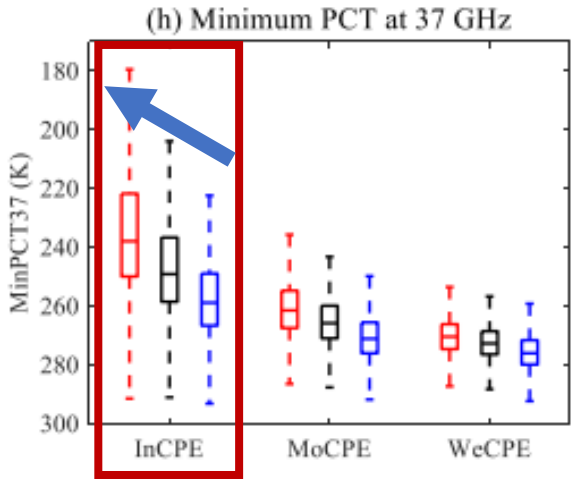
Convective Intensity of InCPE

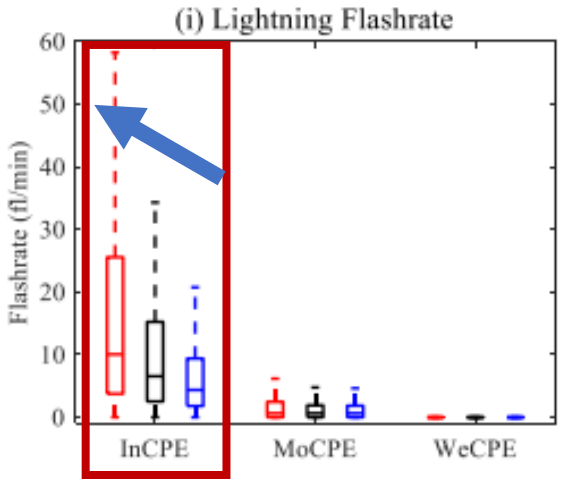
Over global land, InCPEs producing HR tend to have stronger convective intensity than InCPEs producing LR.



- **HR (High Rain)**
- **MR (Medium Rain)**
- **LR (Lighter Rain)**

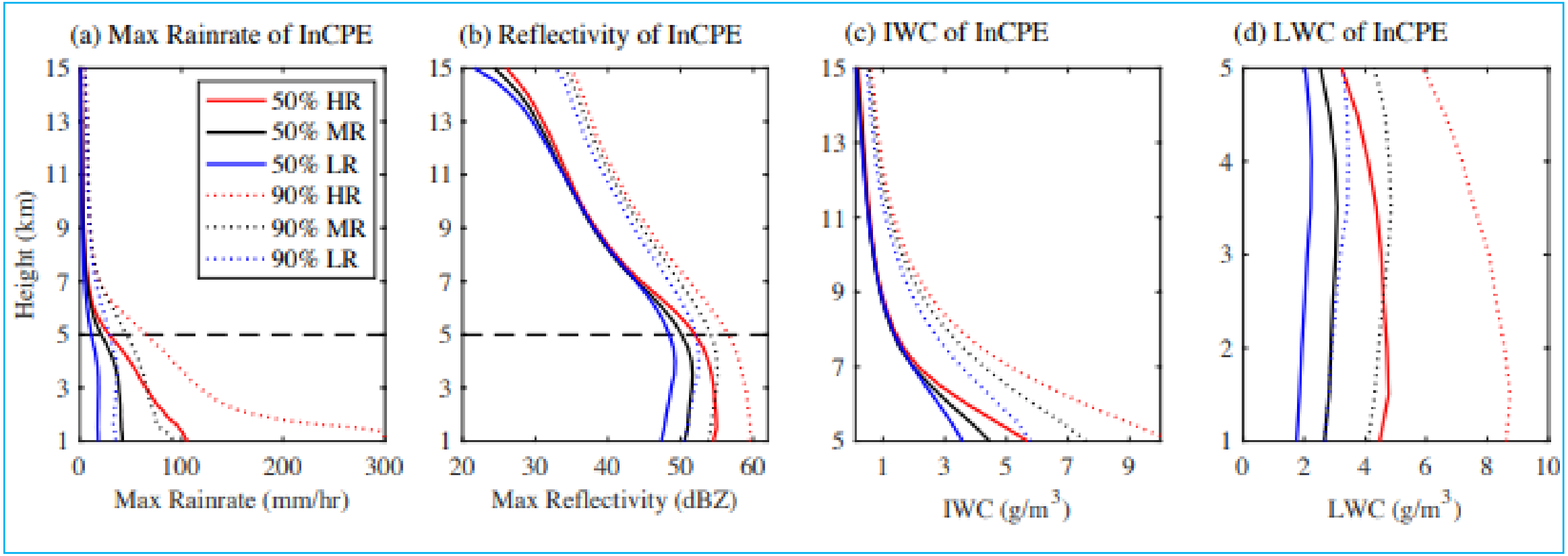






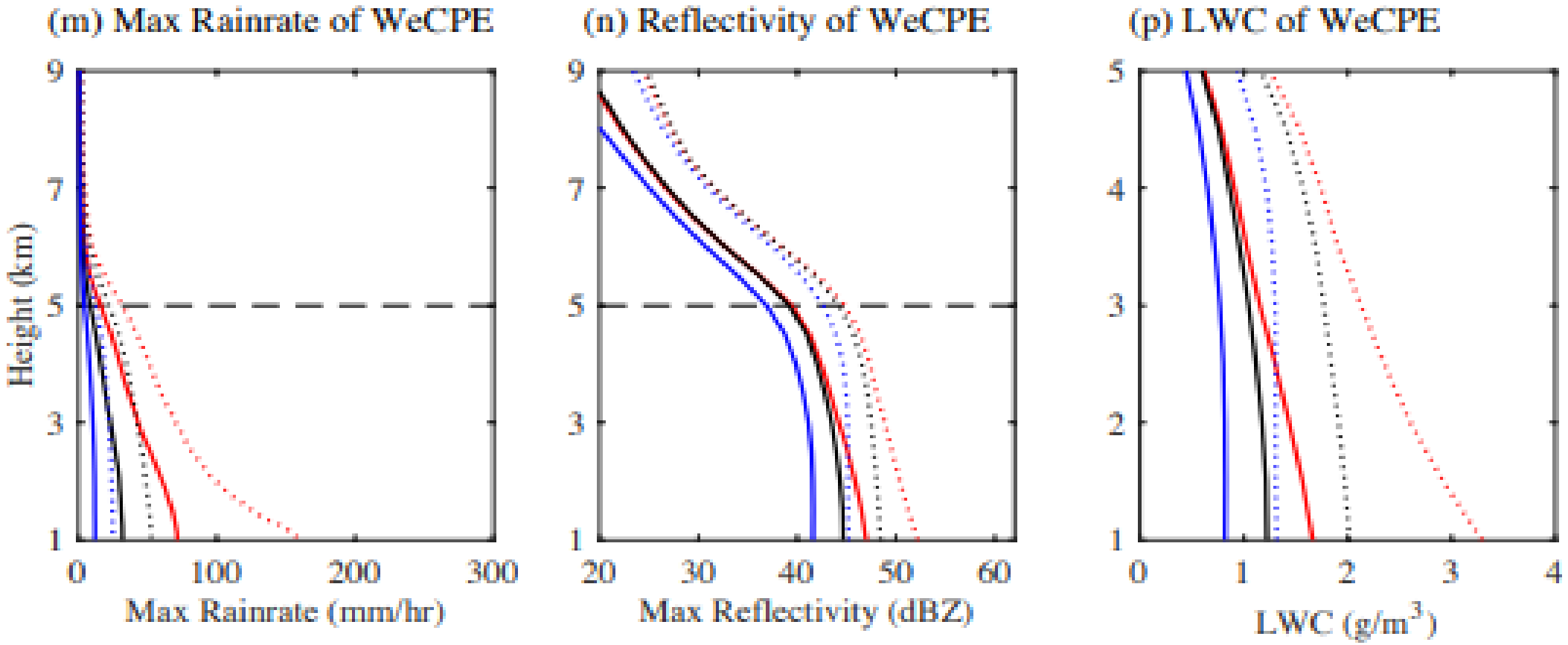
Microphysical processes of InCPE

- HR-InCPEs show faster increases in rain rate, reflectivity, and ice water content, from 7 to 5 km indicating stronger riming. This results in higher liquid water content just below the melting level, which can enhance raindrop coalescence downward and intensify surface rainfall.
- Differences between HR- and LR-InCPEs become larger with decreasing height.



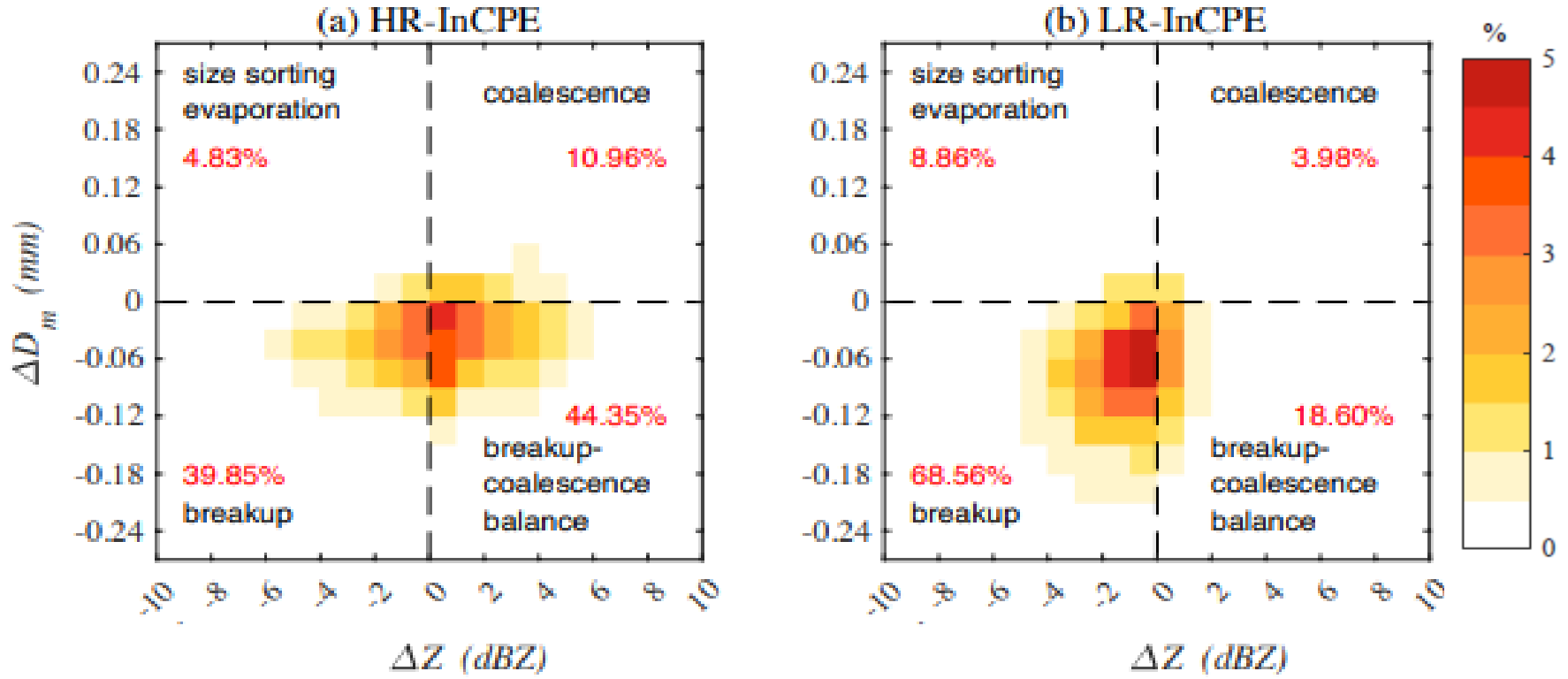
Microphysical processes of WeCPE

- The differences between HR- and LR-WeCPEs also become more pronounced with decreasing height below the melting level.
- Liquid-phase microphysical processes play a crucial role in determining surface rain rate for both InCPE and WeCPE.



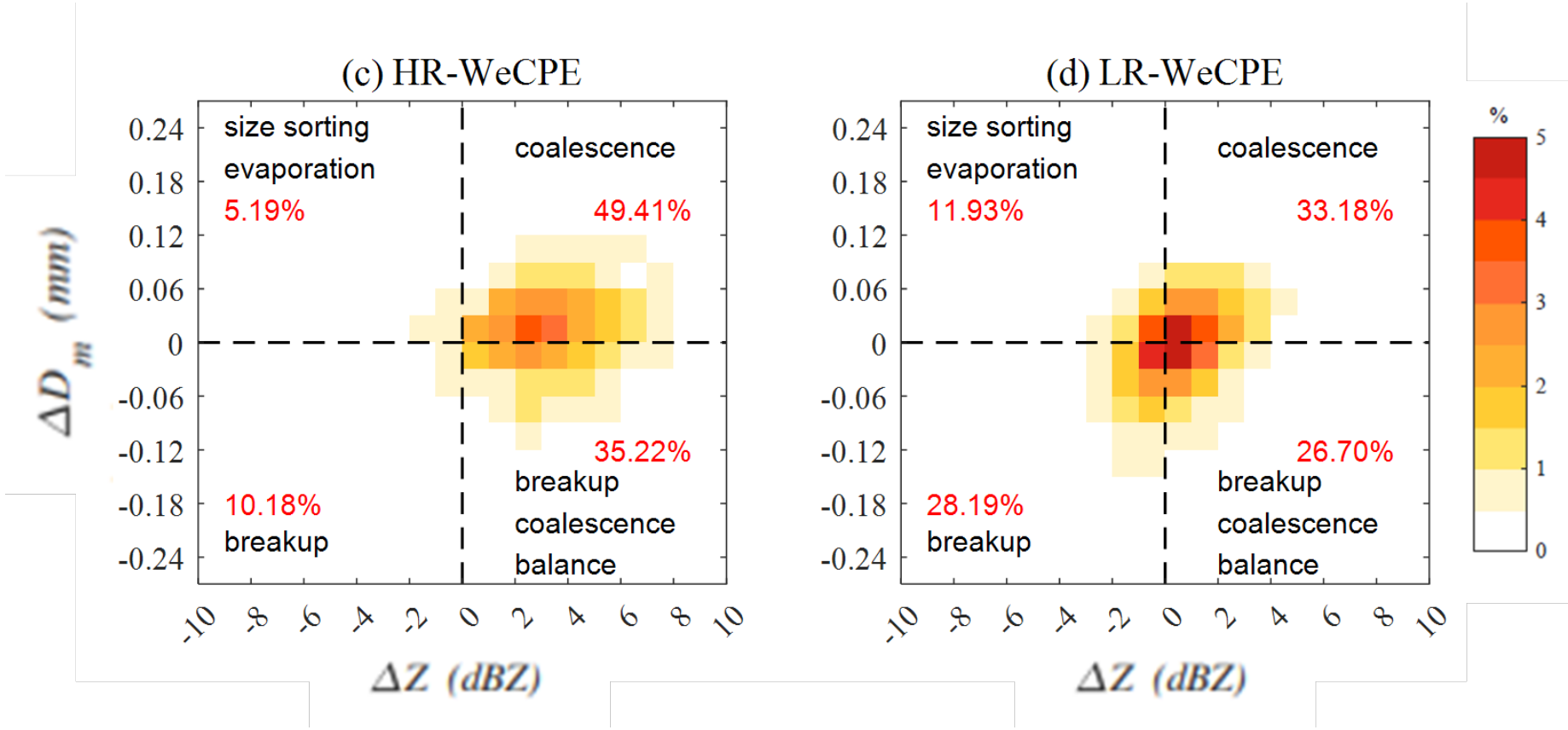
Liquid-phase microphysical processes in InCPE

- Compared to LR-InCPEs, HR-InCPEs show a higher combined fraction of coalescence and coalescence-breakup balance (55% vs. 23%), a lower fraction of raindrop breakup (69% vs. 40%), and much larger increase in MAXREF from 3km to 1km altitude.
- For InCPE to produce high rain rates, strong riming requires the support of warm rain processes, i.e., more coalescence & less breakup.



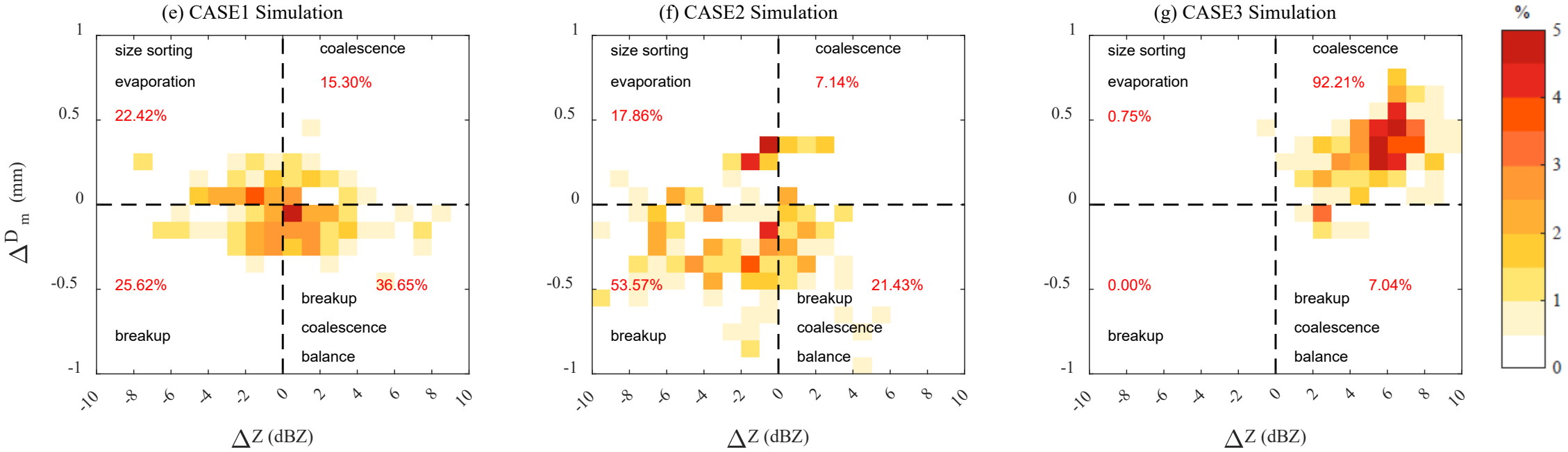
Liquid-phase microphysical processes in WeCPE

- **Compared to LR-WeCPEs, HR-WeCPEs have a much larger fraction of coalescence and coalescence-breakup balance combined (85% vs. 60%) and a much smaller fraction of breakup (10% vs. 28%). During raindrops' descent, the increases in D_m and MAXREF are significantly larger, indicating more active coalescence.**



Liquid-phase microphysical processes in CM1 simulations

- **CASE1 (HR-InCPE) vs. CASE2 (LR-to-MR-InCPE): Coalescence and coalescence-breakup balance rise from 28% to 52%, while breakup drops from 54% to 25% with smaller reduction of D_m in HR-InCPE.**
- **CASE3 (HR-We-to-MoCPE): Coalescence dominates (92%) with minimal breakup.**

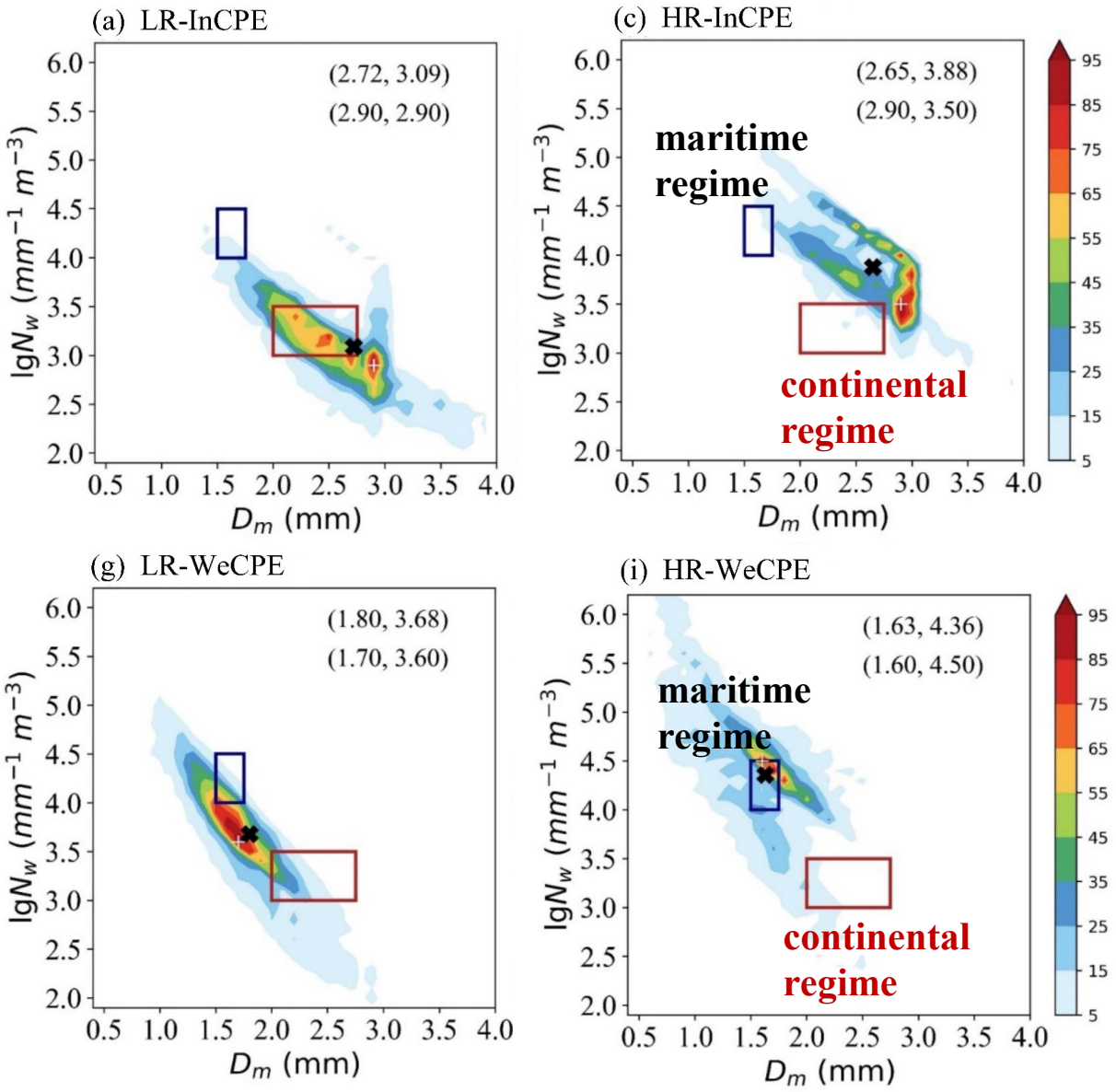


HR-InCPE **LR-to-MR-InCPE** **HR-We-to-MoCPE**

Frequency in the 2-D space of D_m- lgN_w at 1 km

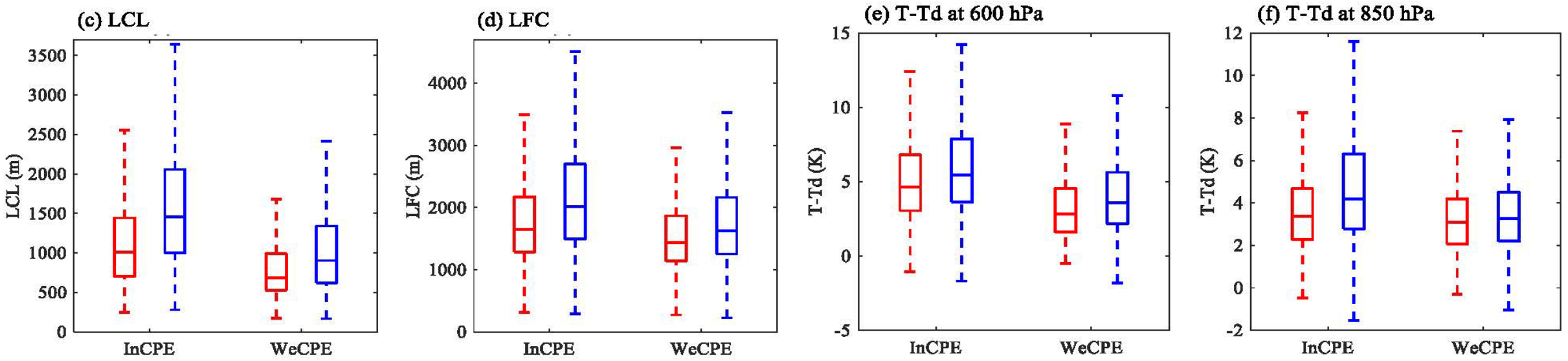
- For CPEs with the same convective intensity, the key difference between HR and LR is the significantly higher raindrop concentration in HR.
- HR-InCPE: Higher concentration and larger size than the continental regime
- HR-WeCPE: Highest concentration (far above HR-InCPE), with a maritime-like characteristic with concentration in the upper portion.

N_w: the normalized drop size distribution (DSD) scaling parameter for concentration
D_m: the mass-weighted mean diameter



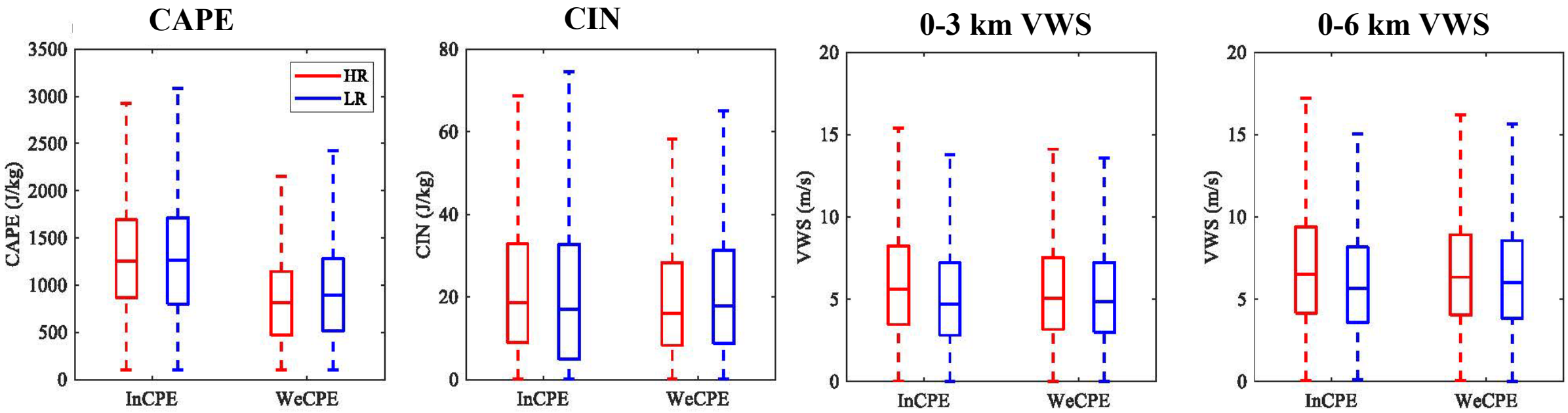
Environmental conditions

Red: High Rain Rate **Blue: Low Rain Rate**



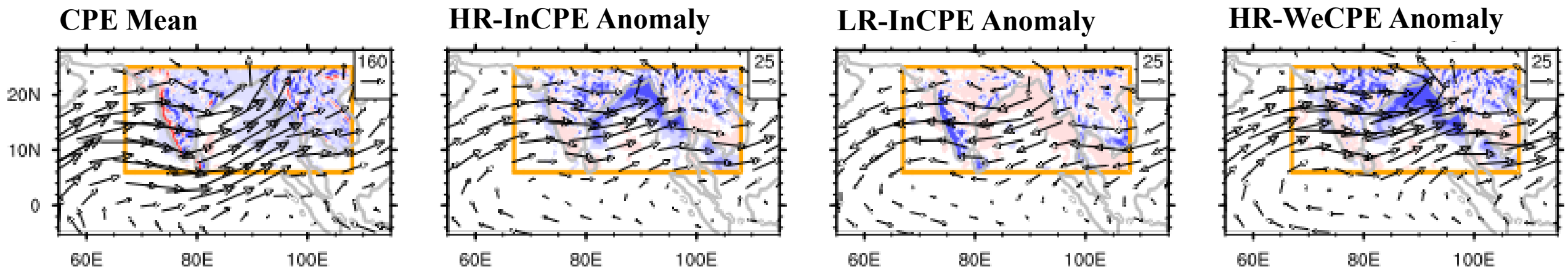
- Compared to LR-CPEs, HR-CPEs have lower LCL (lower cloud bases, thicker warm cloud layers), and a more humid mid-to-lower troposphere.
- Compared to HR-InCPEs, HR-WeCPEs feature even lower cloud bases, thicker warm cloud layers, and a more humid mid-troposphere, facilitating more active and efficient droplet coalescence, which could compensate for the absence of mixed-phase microphysical processes.

Environmental conditions



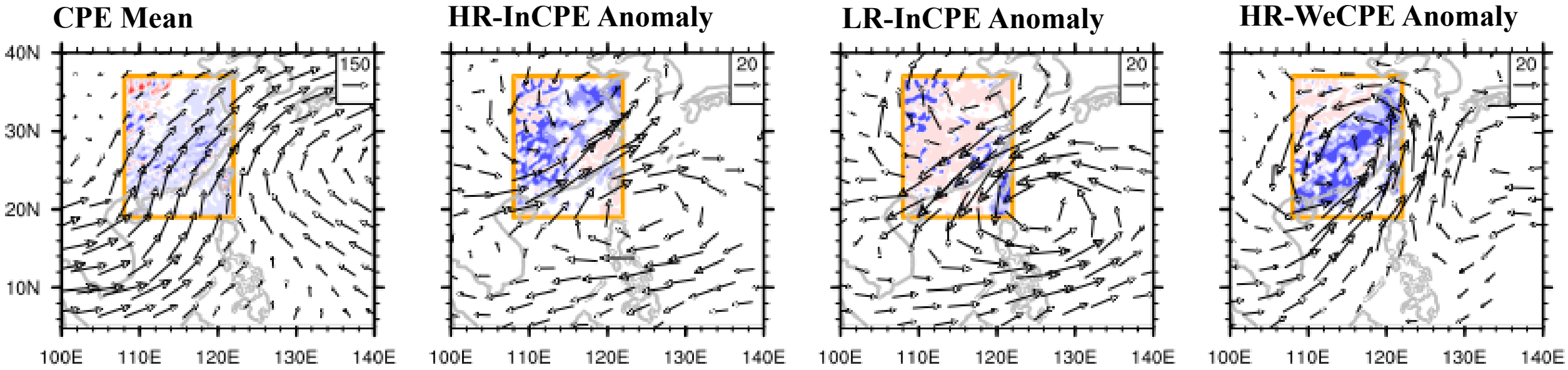
- **Other atmospheric parameters, such as CAPE, CIN, and vertical wind shear, show insignificant differences between HR- and LR-producing CPEs, partially due to the limitations of the reanalysis data.**

Vertically integrated moisture flux & its convergence



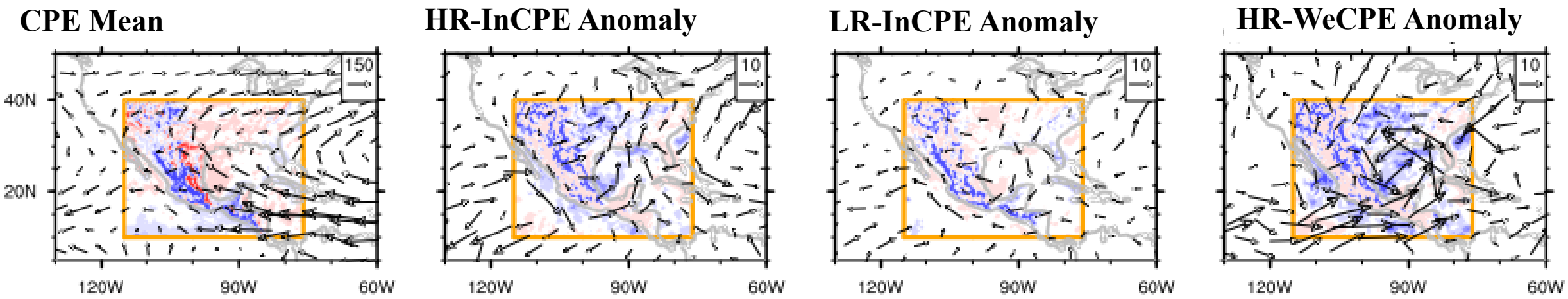
- When HR-producing InCPEs are observed in the Amazon, South Asia, and Maritime Continent islands, the monsoonal flow from the ocean intensifies, enhancing moisture flux convergence.
- At LR-InCPE moments, the monsoonal flow relatively weakens with reduced moisture flux convergence.
- For HR-WeCPEs, the monsoonal flow is even stronger than that with HR-InCPEs.

Vertically integrated moisture flux & its convergence



- With HR-InCPE in the southeastern China, an anticyclonic moisture flux anomaly appears over the Philippine Sea, while LR-InCPE is accompanied by a cyclonic anomaly, leading to stronger (weaker) moisture convergence in HR-InCPE (LR-InCPE).
- With HR-WeCPE, the southeastern China experiences a cyclonic moisture flux anomaly, resulting in even stronger moisture convergence than in HR-InCPE.

Vertically integrated moisture flux & its convergence



- For HR-producing InCPE over southern North America, an anticyclonic moisture flux anomaly off Mexico's west coast and southerly flow anomaly over the Gulf strengthen moisture flux convergence, which is aided by anomalous northerly transport from the northwest Atlantic. LR-producing InCPE shows the opposite.

- For HR-producing WeCPE, anomalous westerly moisture transport from the tropical eastern Pacific forms a cyclonic anomaly over the Gulf, intensifying moisture convergence.

Conclusions

- **Intense convection** involves vigorous mixed-phase microphysical processes with **stronger riming**, leading to larger rain rates at and above the melting level compared to weak convection and **possibly more extreme rainfall at the surface**.
- Warm-rain processes are important in determining the rain rates. InCPEs (WeCPEs) are dominated by breakup (coalescence). With comparable convective intensity, HR-producing CPEs correspond to **much enhanced coalescence (reduced breakup) and substantially larger raindrop concentration.**
- The higher rain rates result from **more humid mid-to-lower troposphere and thicker warm-cloud layers** due to significant variations in water vapor channels. HR-WeCPEs at the convective hotspots on land are accompanied by the strongest large-scale moisture flux convergence among the various CPEs.

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Thanks!

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