Diabatic heating of mesoscale convective cloud systems from synergistic satellite data

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Motivation and Strategy

✦ **Latent heat release and its fluctuations are central to the interactions within Earth's water and energy cycles, with radiative heating (RH) of upper-tropospheric (UT) clouds further enhancing this energy reservoir by at least 20%** *[Li et al. JGR, 2013, Stubenrauch et al. ACP, 2021]*.

✦ **What is the relationship between latent heating (LH) and radiative heating in mesoscale convective systems (MCS) ?**

TRMM radar (2004 - 2018)

AIRS (2004-2018)
IASI (2008-2018)
→ IR souder

CALIPSO lidar (2006-2010)

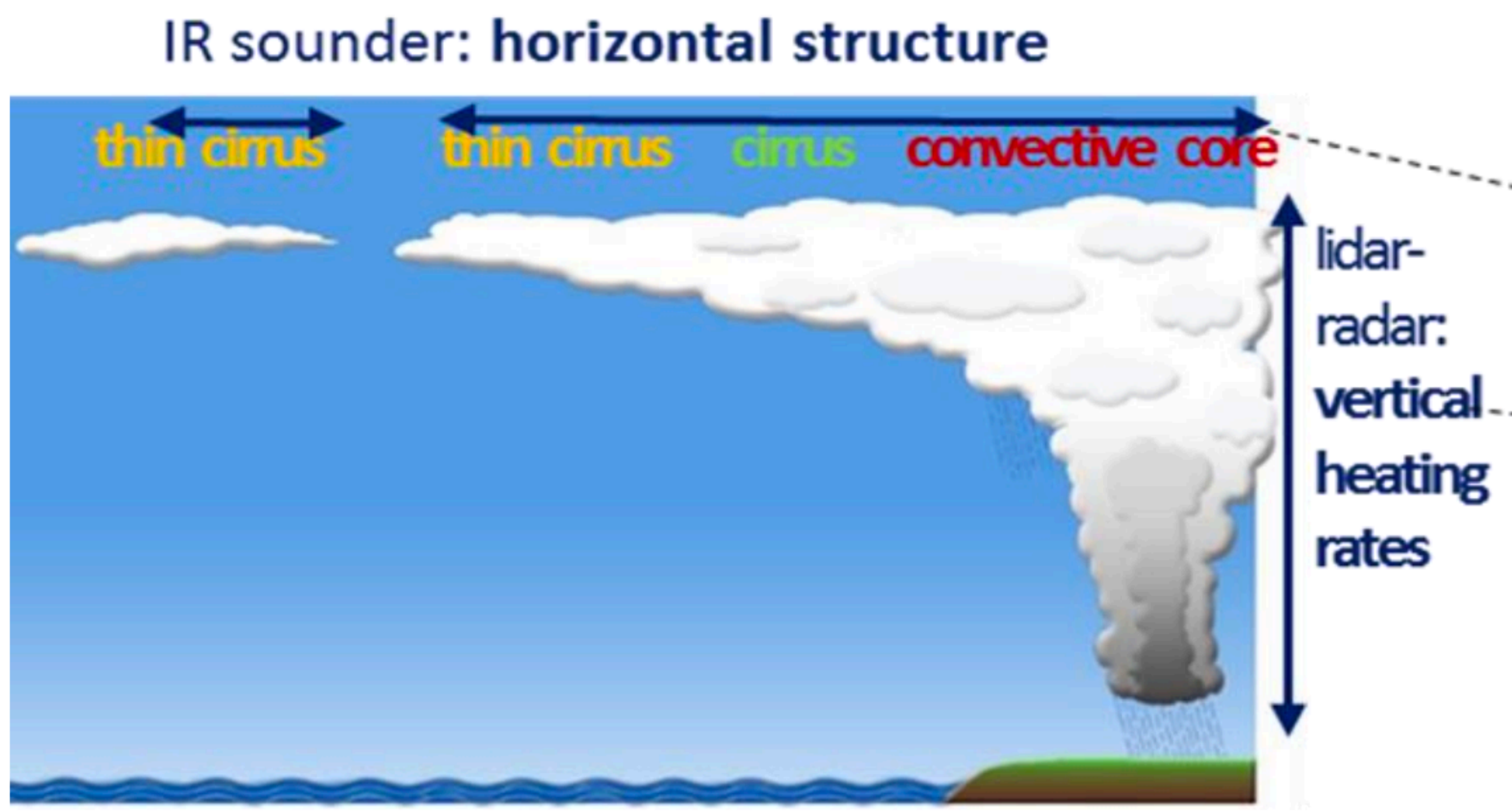
CloudSat radar (2006-2010)

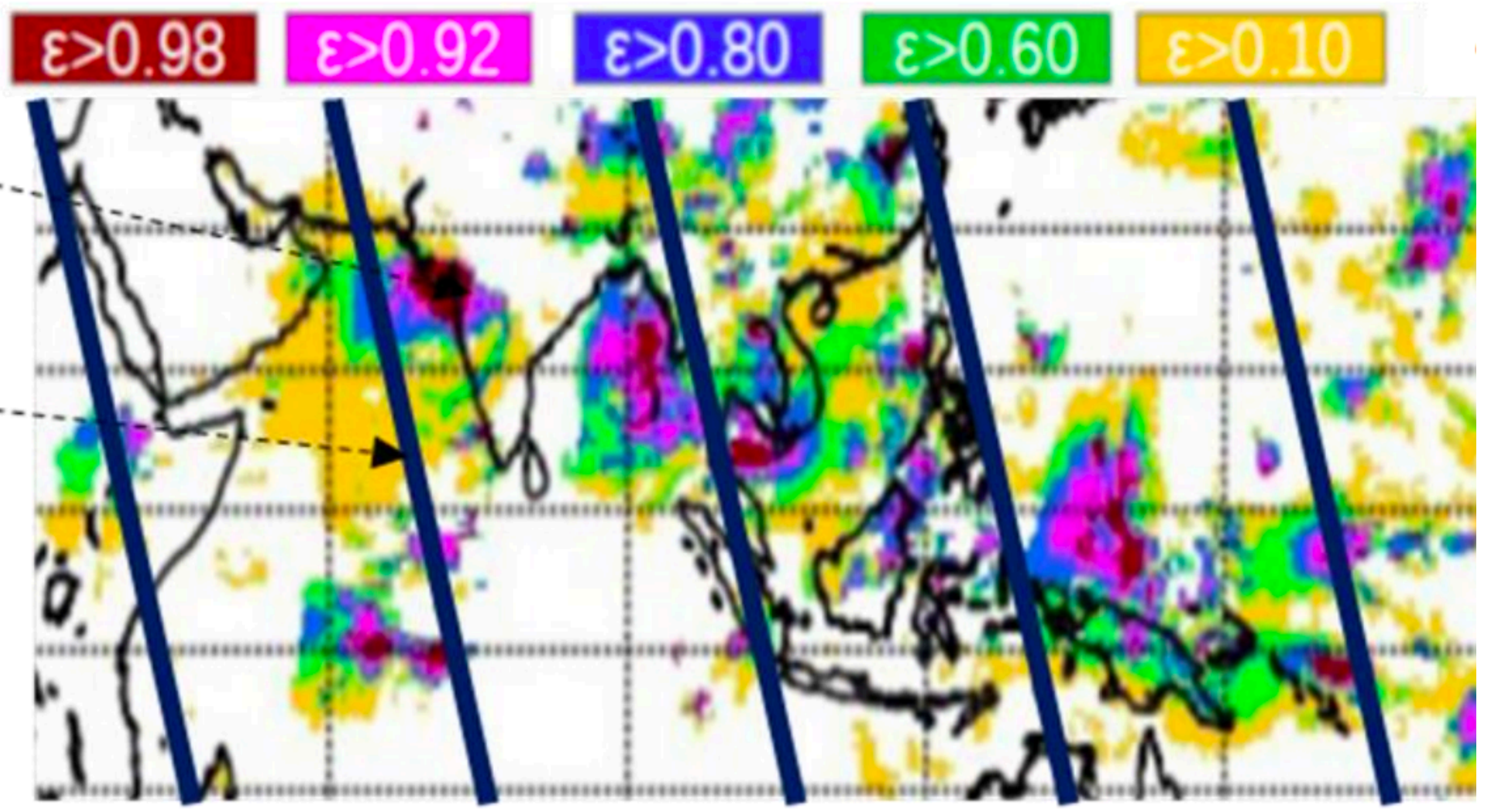
Strategy

Complete picture -> multiple datasets
However, sophisticated measurements constrained by limited sampling density.

- Constructing a more complete dataset by Artificial Neural Network (ANN) techniques.
  - 3D Snapshots at 4 specific observation times
  - Process-oriented analyses

3D snapshot reconstruction using synergistic data & Machine Learning





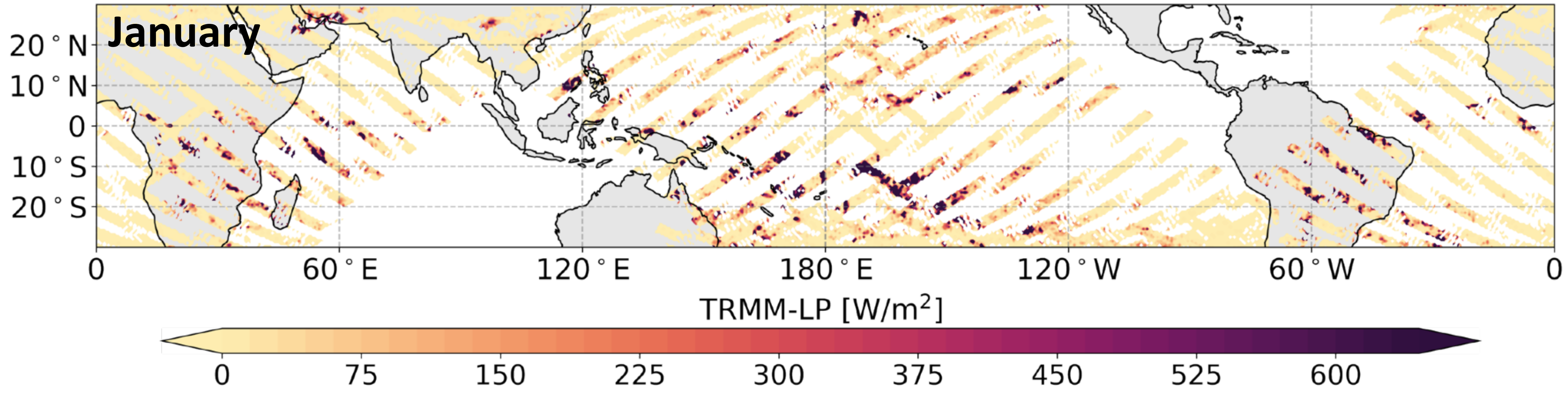
(Stubenrauch et al. 2021)

CIRS (Clouds from IR Sounders) :
only cloud height & emissivity

Vertical structure, radiative heating rate & precipitation:
CloudSat-CALIPSO only on narrow nadir tracks

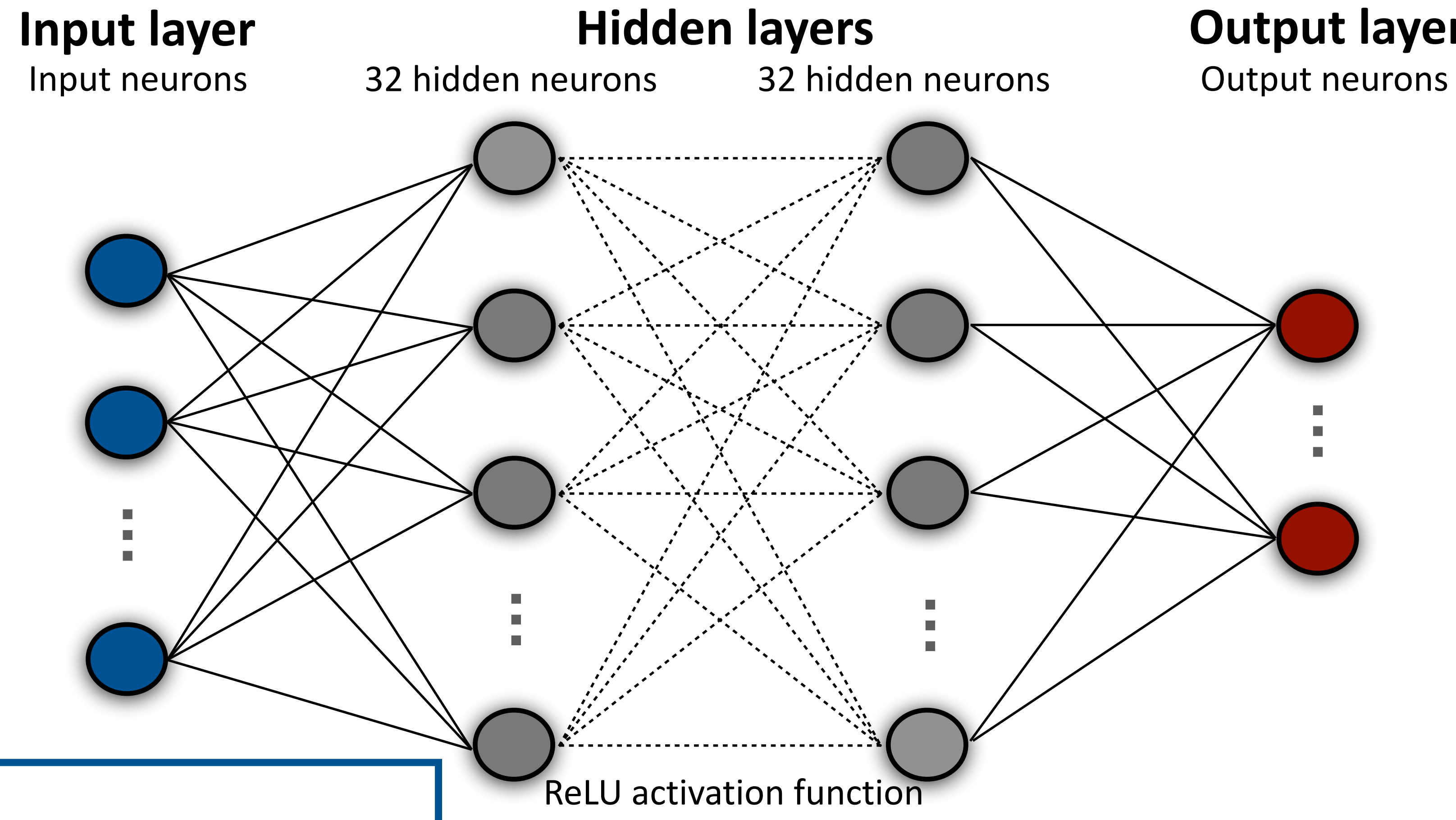
Expanded radiative heating rates are now available: ***https://gewex-utcc-proes.aeris-data/fr***

Expand *latent heating rate* across AIRS/IASI swath by ANNs



TRMM radar statistically samples diurnal cycle, but…
at specific local time (1h30 AM), only covers 3%

AIRS swath 70% **IASI** swath 77%



Input (27 variables)
- AIRS/IASI:

CIRS cloud properties
- Grid cell structure (0.5° x 0.5°):
  Fractions of cloud type, clear sky, rainy area and heavy rain area.
- Re-analysis:

ERA-interim atmospheric & surface properties

Training: 60%
Validation: 20%
Test: 20%

Output
- Latent heating rates on 20 pressure layers

Machine learning - Artificial Neural Networks (ANNs)

Relationship: rain intensity-cloud properties

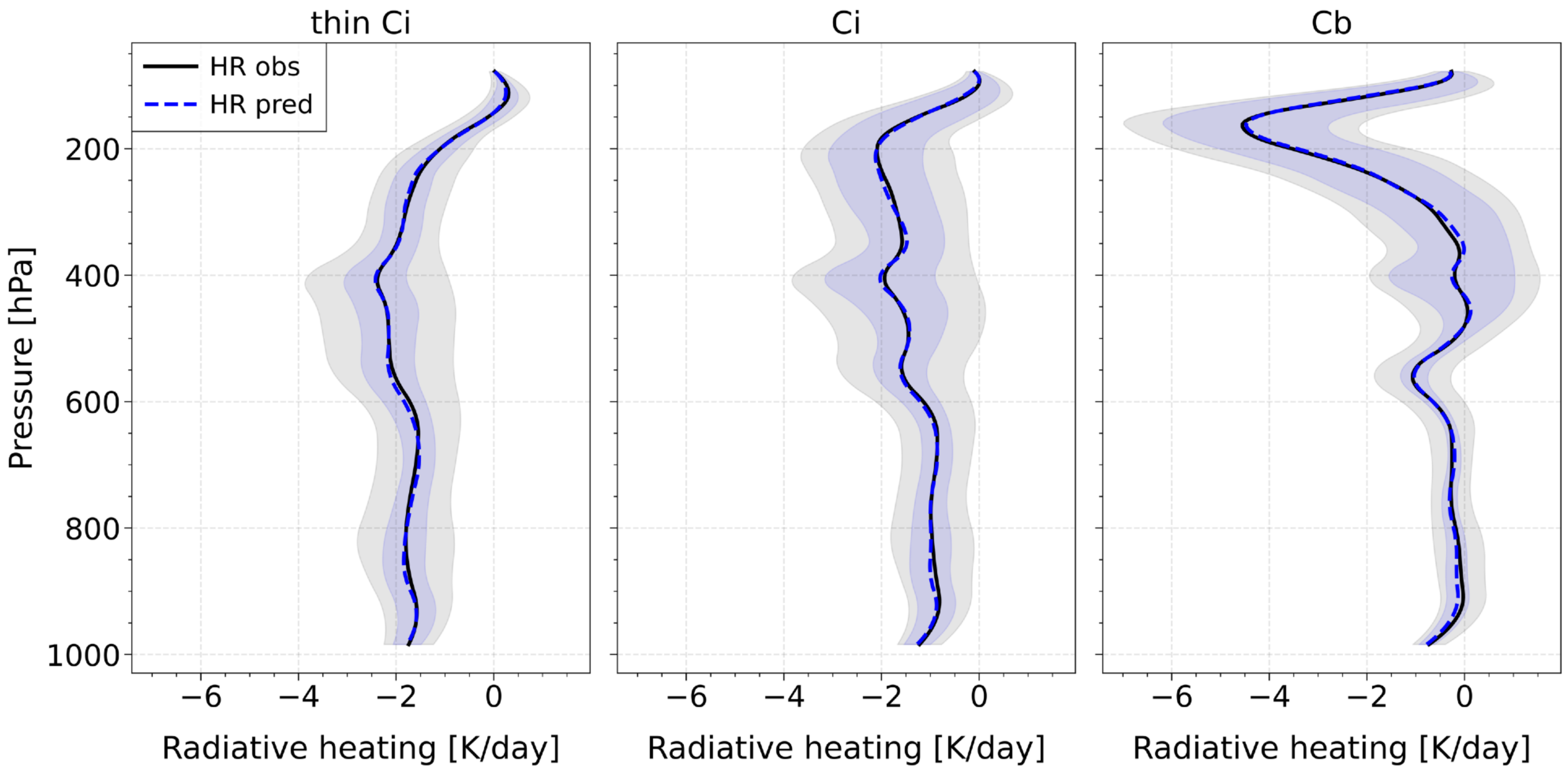
Rain rate intensity is largest for opaque, thickest and highest clouds!

Rain rate classification from AIRS ML-CloudSat for scene identification: no rain, light rain, heavy rain

Evaluation of ANN radiative and latent heating

Good predicted mean,
Good predicted variability

LW Ocean

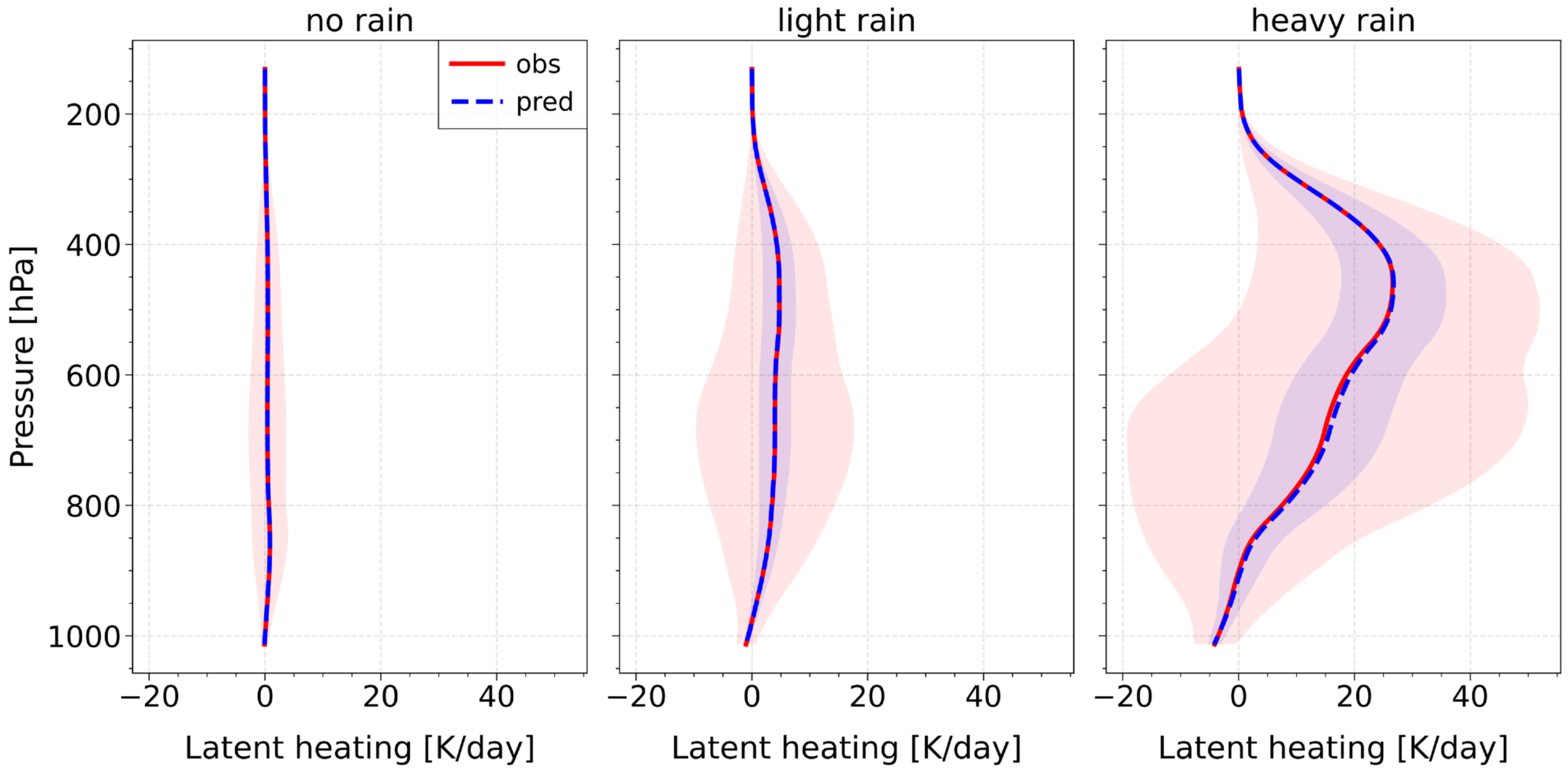


LW radiative heating rates from Calipso-CloudSat

LW radiative heating rates from ANN prediction

Good predicted mean,
Underestimated predicted variability

LH Ocean

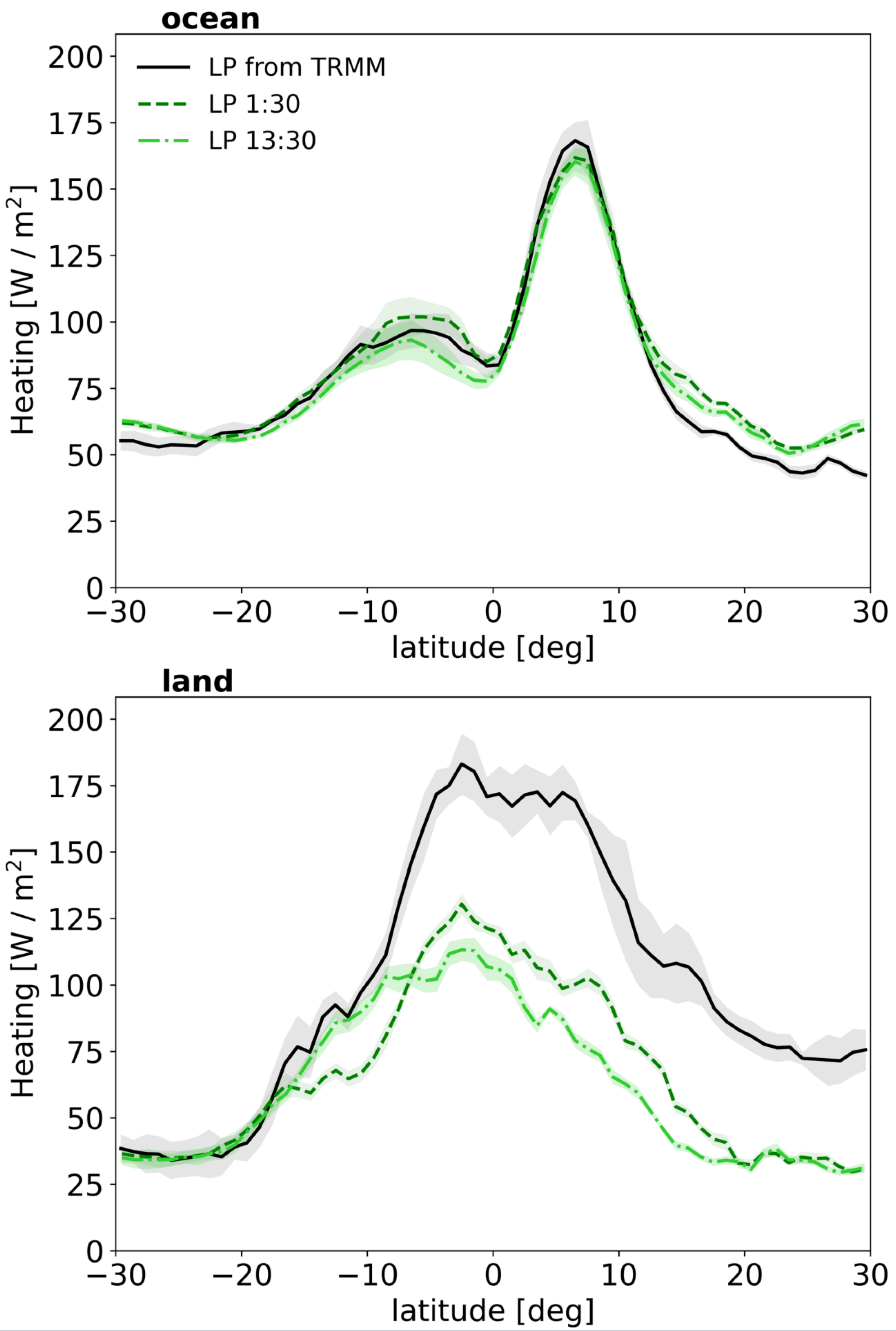


Latent heating rates from TRMM

Latent heating rates from ANN prediction

Coherence between TRMM-SLH and ANN predicted LH

Vertically integrated LH over all scenes

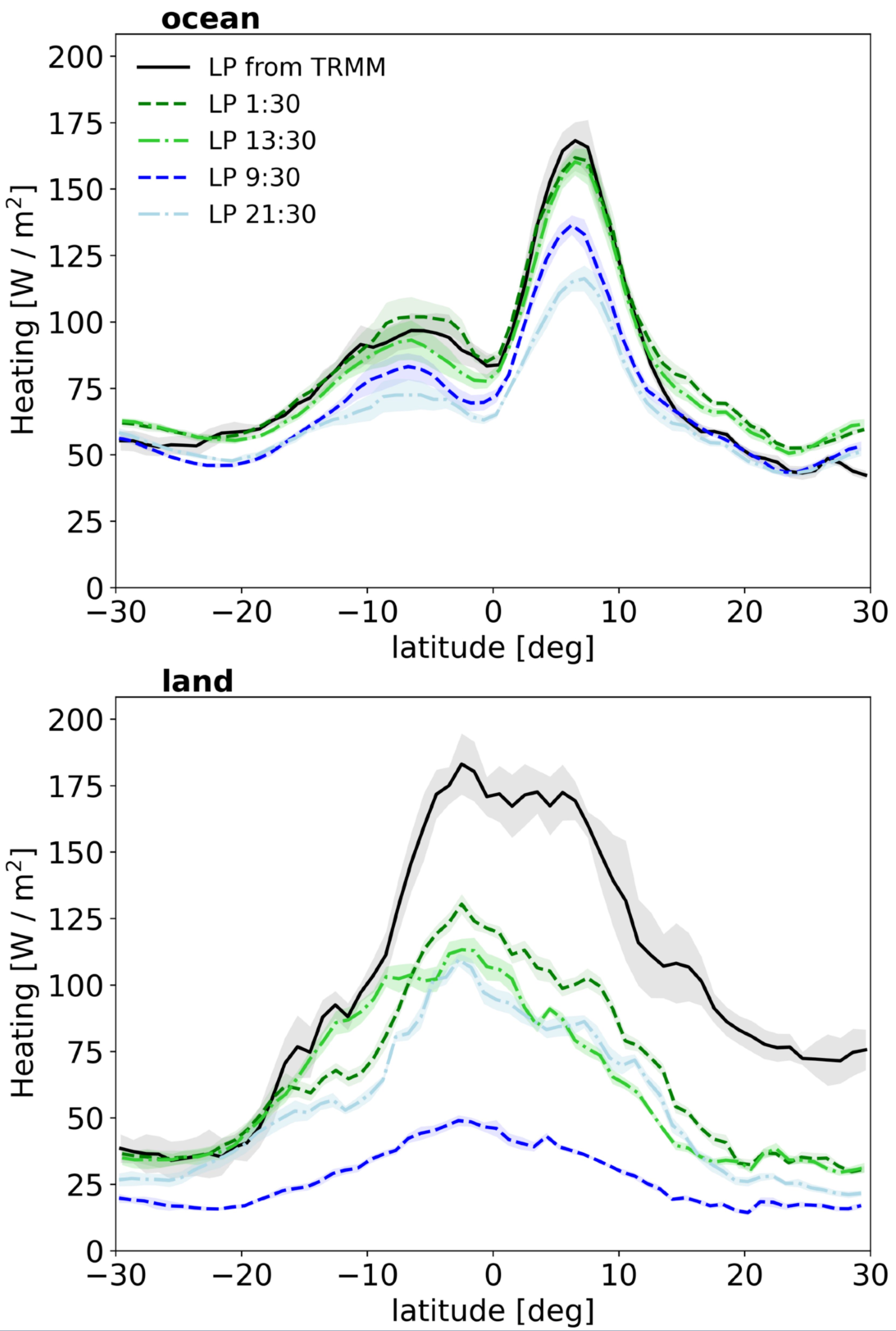


Over ocean, the zonal averages of LH at 1:30 AM&PM agree well with TRMM-SLH complete diurnal sampling.

Over land, we miss strong convection of late afternoon.

Coherence between TRMM-SLH and ANN predicted LH

Vertically integrated LH over all scenes

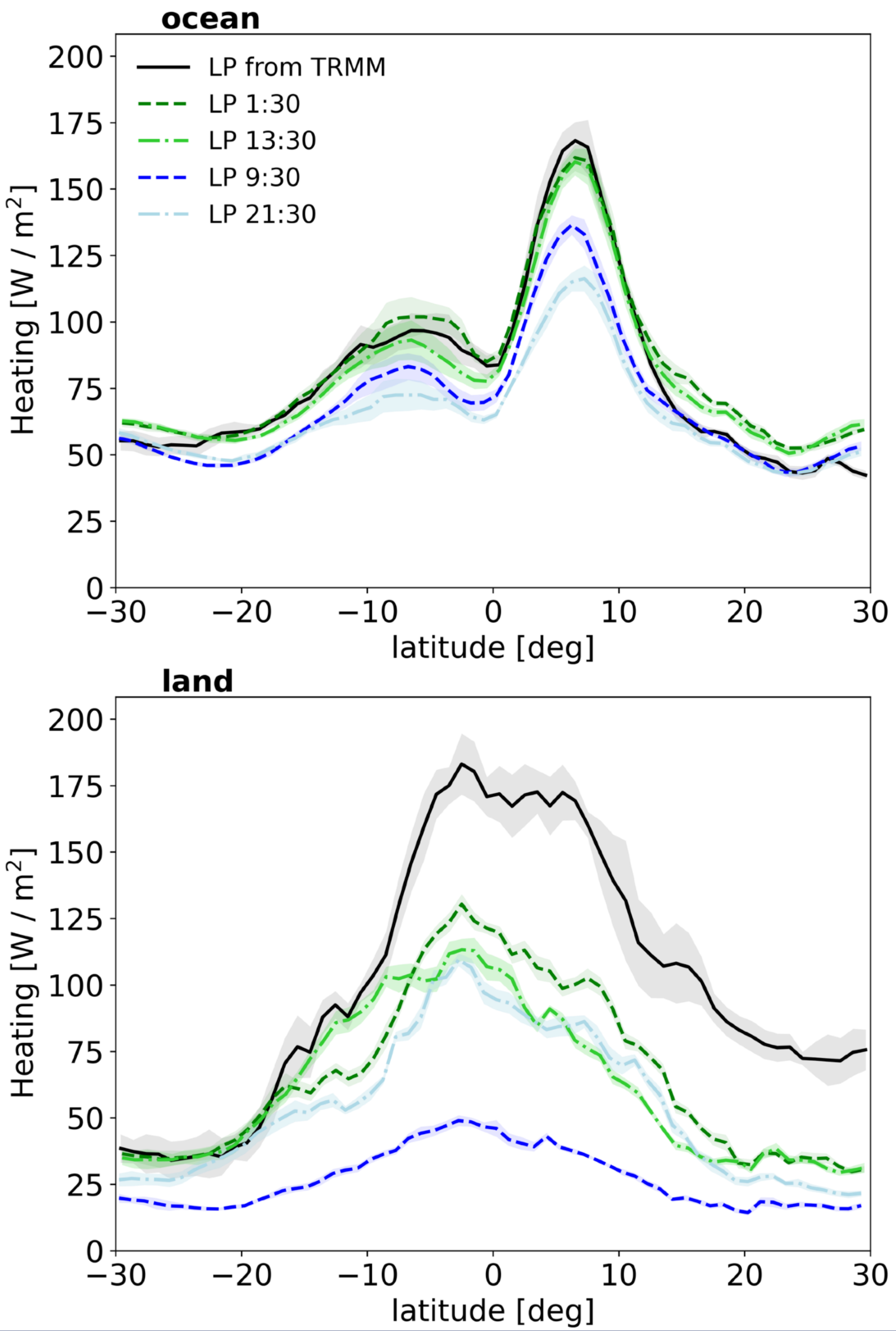


Over ocean, the zonal averages of LH at 1:30 AM&PM agree well with TRMM-SLH complete diurnal sampling.

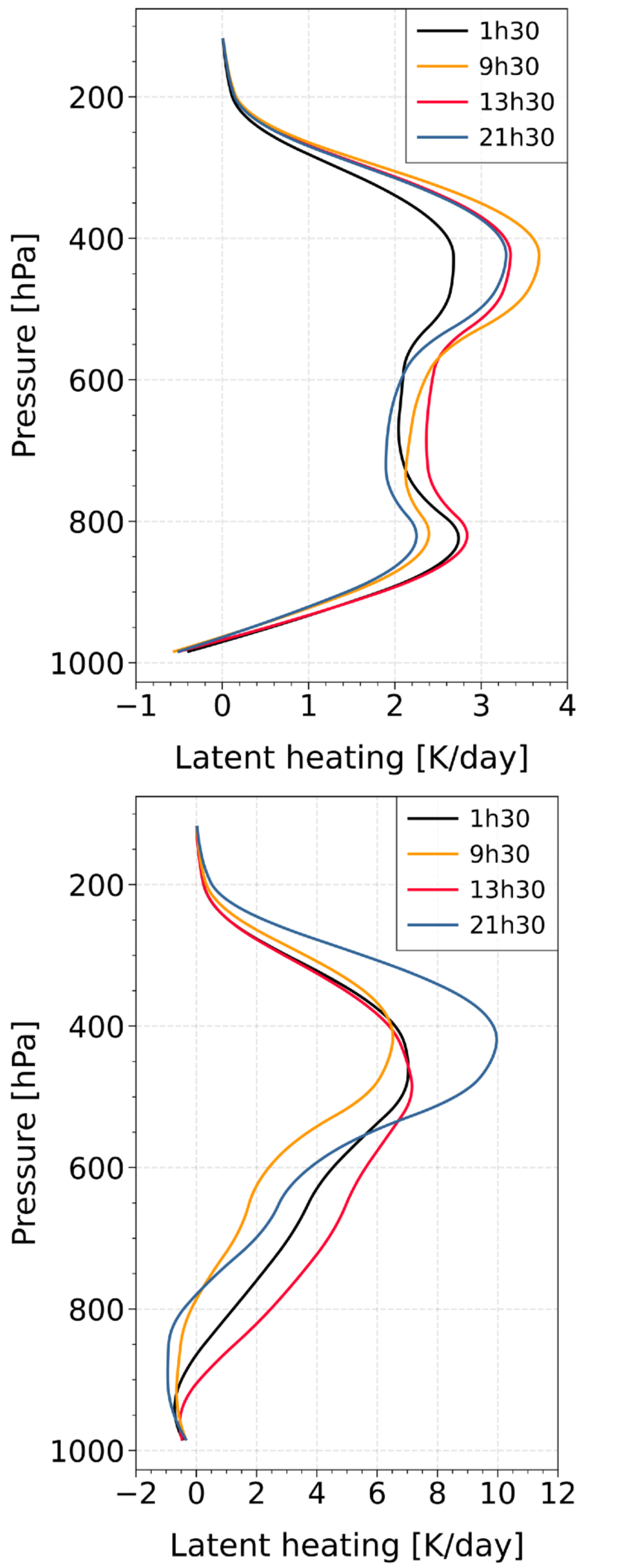
While the sampling at 9:30 slightly underestimates LH

Coherence between TRMM-SLH and ANN predicted LH

Vertically integrated LH over all scenes



LH profiles of rainy scenes



Over ocean, the zonal averages of LH at 1:30 AM&PM agree well with TRMM-SLH complete diurnal sampling.

While the sampling at 9:30 slightly underestimates LH

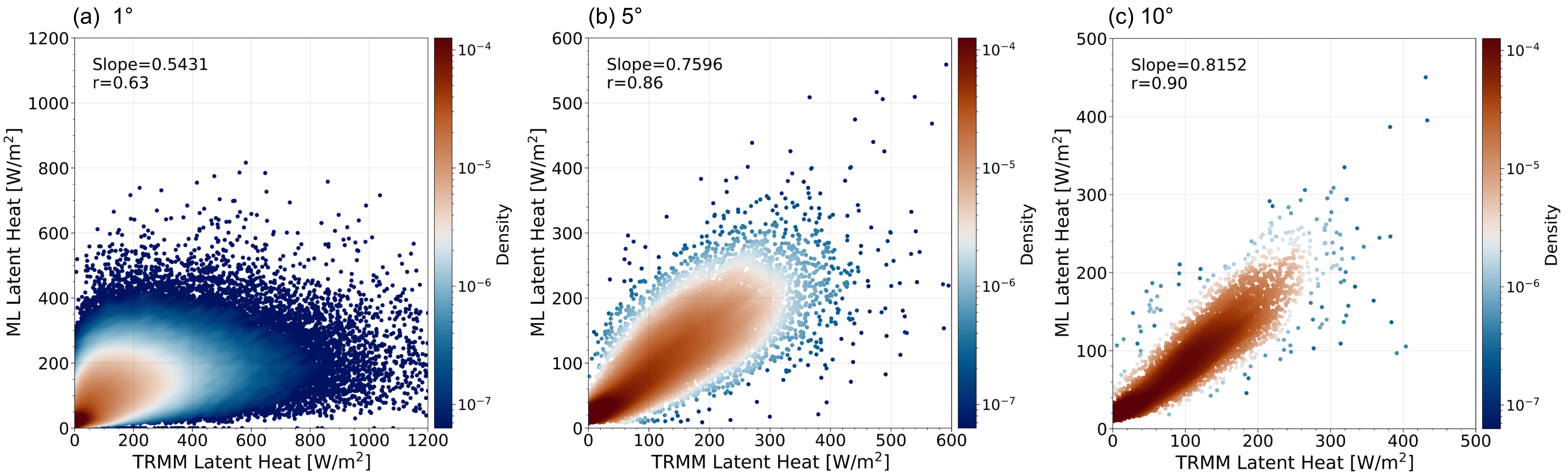
Shapes of ocean/land profiles are different, as expected with a larger contribution of low level clouds over ocean.

Diurnal cycle as expected:

Over ocean: maximum convection over early morning

Over land: maximum convection in the evening

Coherence between TRMM-SLH and ANN predicted LH



- ❖ **The TRMM's revisit cycle strongly varies across regions**, with 23 days at the equator and up to 46 days at the highest latitudes (Negri et al., 2002).
- ❖ From **1° to 10°** averaging, slopes between TRMM-LP and ML-LP increase: **0.54 to 0.82 (10°N-10°S)**,
  0.44 to 0.77 (20°N/S-30°N/S, not shown)
- ❖ Strong bias reduction and noise reduction when averaging over more observations. For larger grid cell sizes the agreement is much better

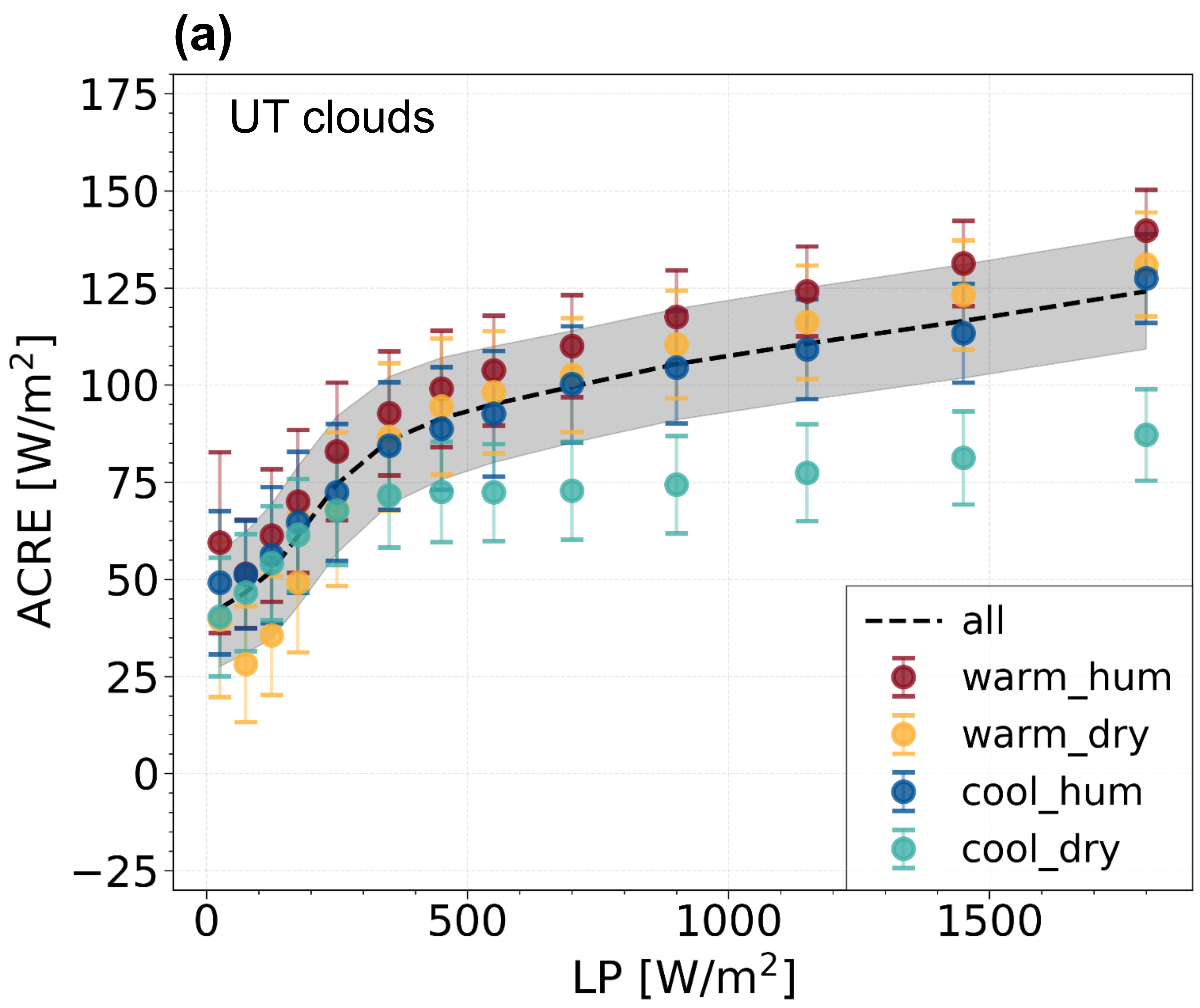
Contrasting La Niña and El Niño events

Atmospheric Cloud Radiative Effect (ACRE): the difference in cloud radiative effects between the TOA and the surface

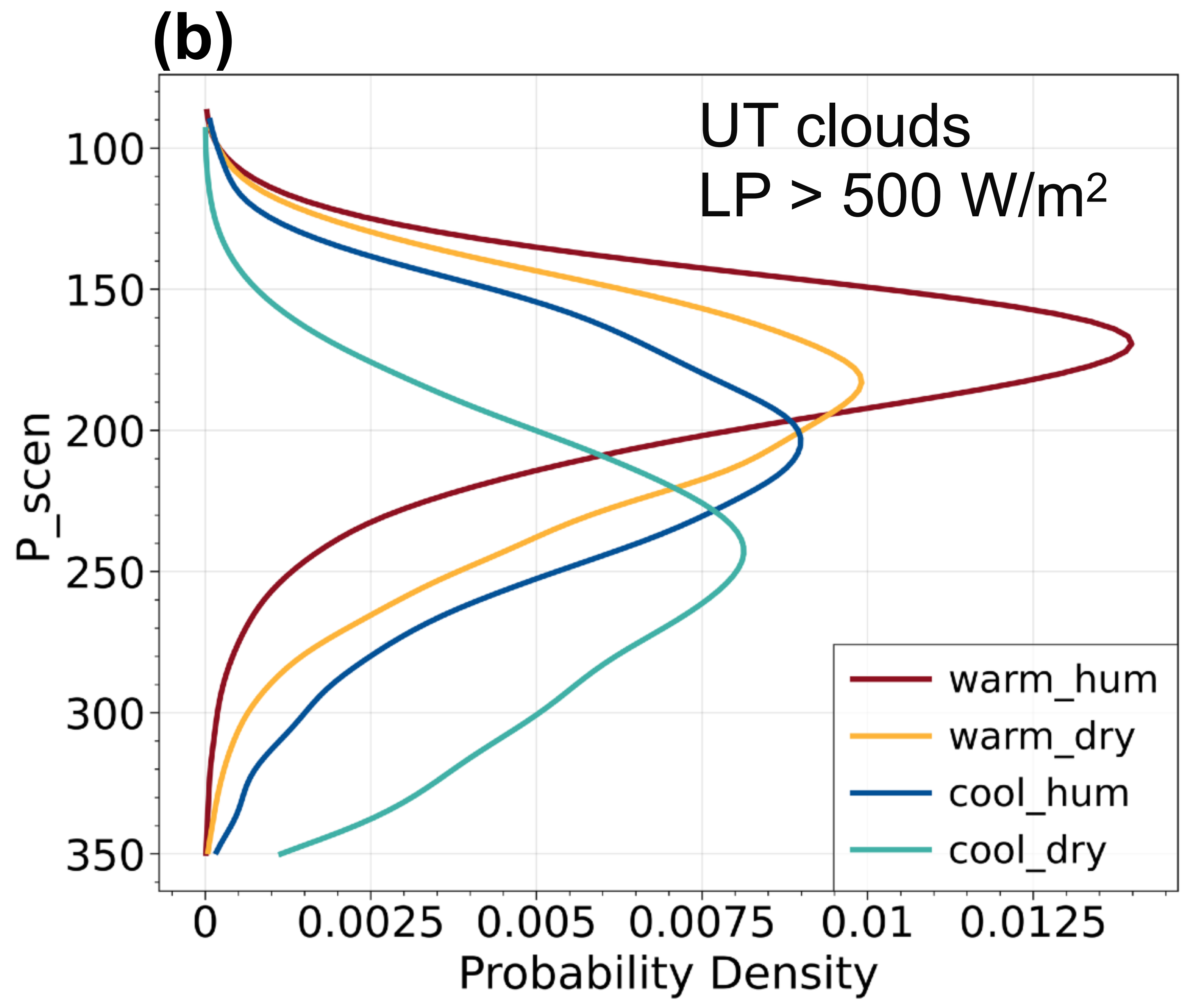
$$\mathrm{ACRE} = \int \mathrm{HR}\, dp - \int \mathrm{HRclr}\, dp$$

Relationship between LP, ACRE and environment

Different environments characterized by sea surface temperature (SST) and column water vapour (CWV):

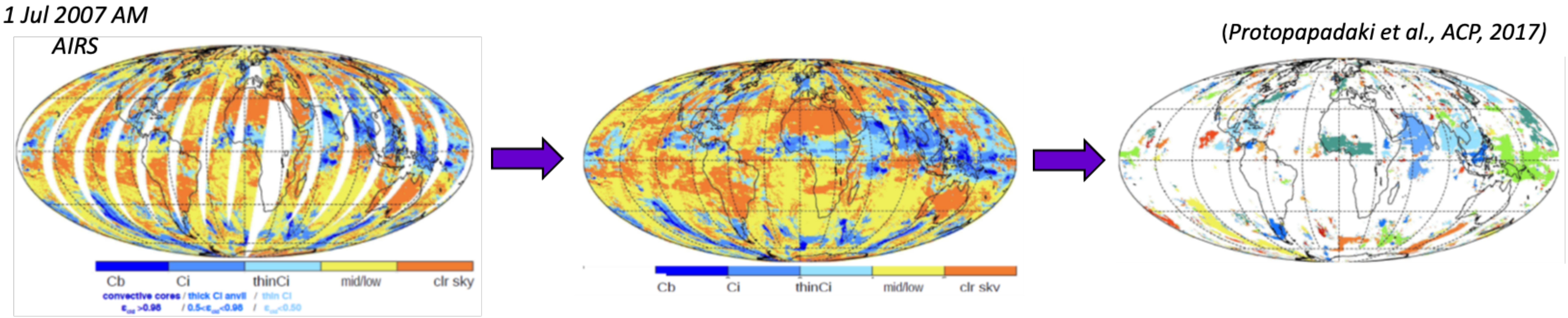


- For a given LP, **ACRE** is generally **largest** in **warm-humid** and **smallest** in **cool-dry** conditions.
- **SST** plays a **larger role** in **dry** environments.
- **Humidity** plays a **larger role** in **cool** environments.
- **Larger ACRE** is linked to **higher cloud height** (lower cloud top pressure).

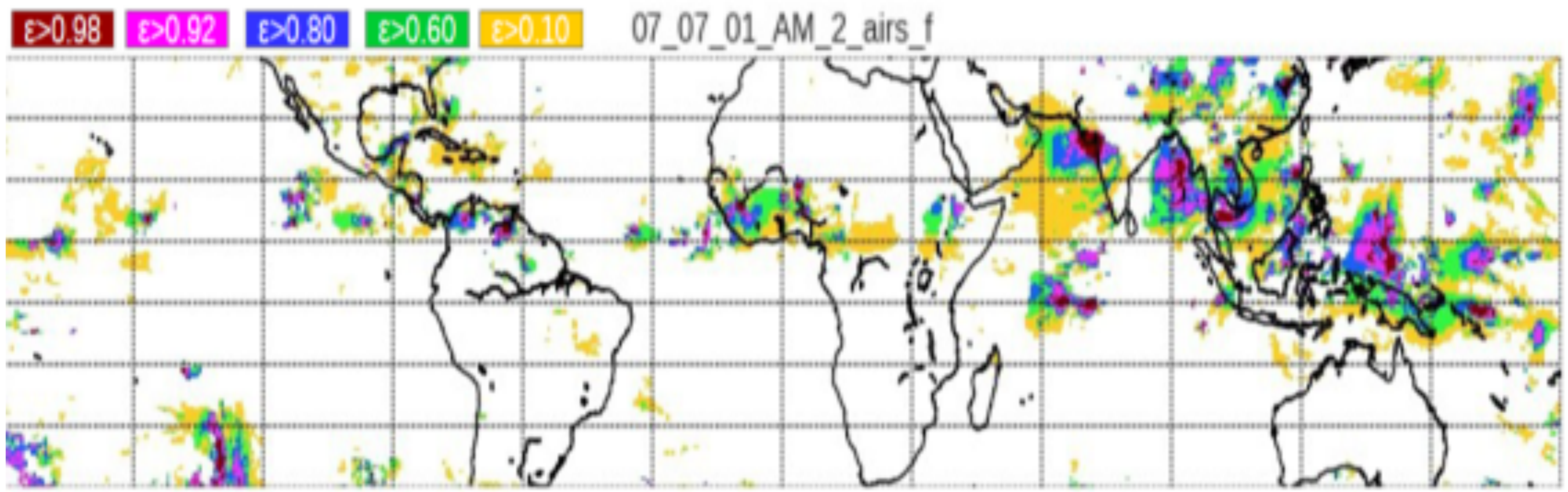


Reconstruction of mesoscale convective systems (MCS)

UT cloud systems built from adjacent grid cells with similar $\boldsymbol{P_{cld}}$



(Protopapadaki et al., ACP, 2017)



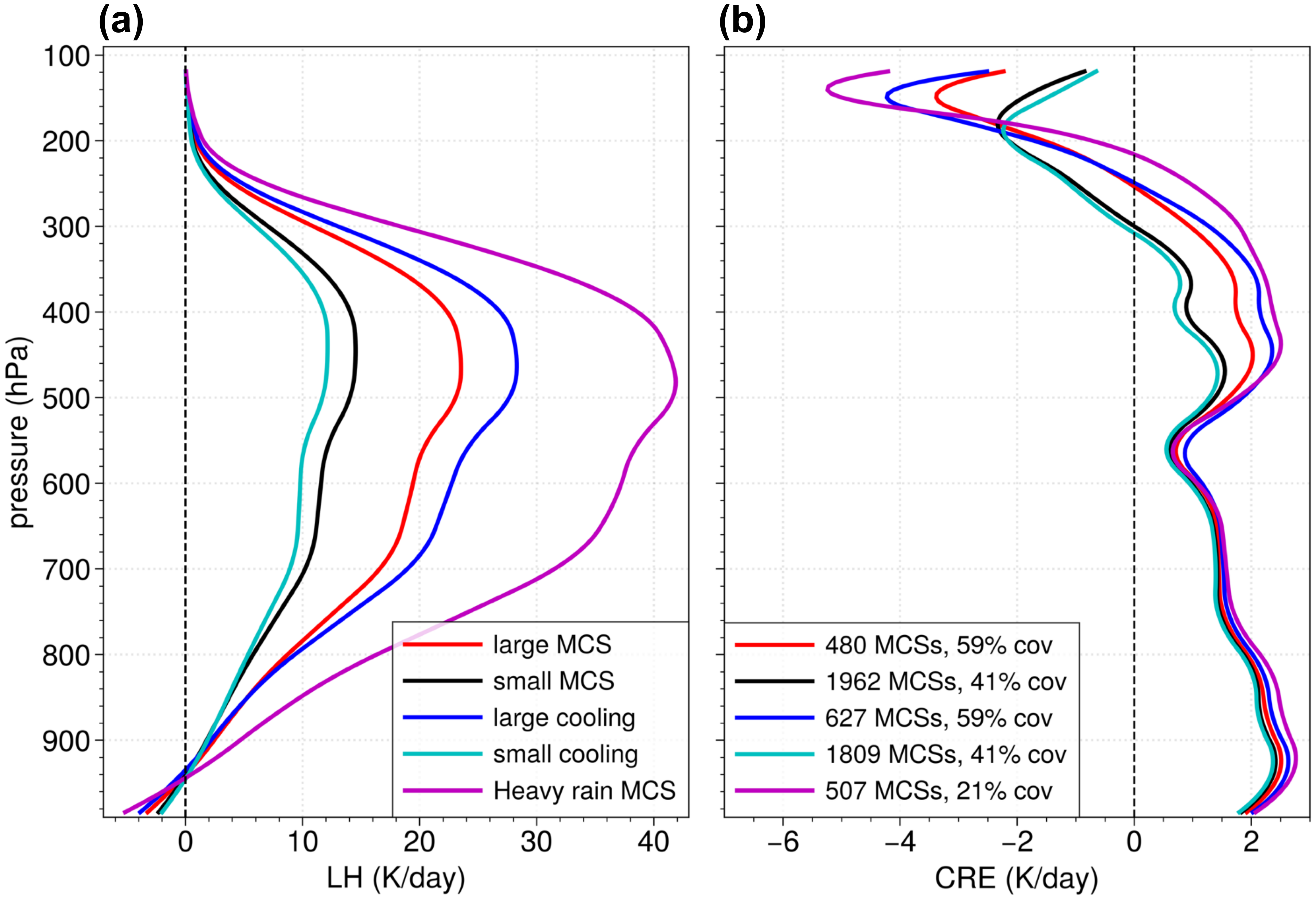
Identification of MCS horizontal structure:

Convective cores, Ci anvil & surrounding thin Ci from $\boldsymbol{\varepsilon_{cld}}$

Grid cell resolution 0.5°,

sub-grid Cb, Ci, thin Ci fraction

Diabatic heating of MCSs of different intensities



MCS reconstruction using CIRS P_{cld} and ε_{cld} (Stubenrauch et al. 2023)

Collocation with ML diabatic heating(only orbits)

Cooling above MCS core increases with opacity
A proxy of deep convection

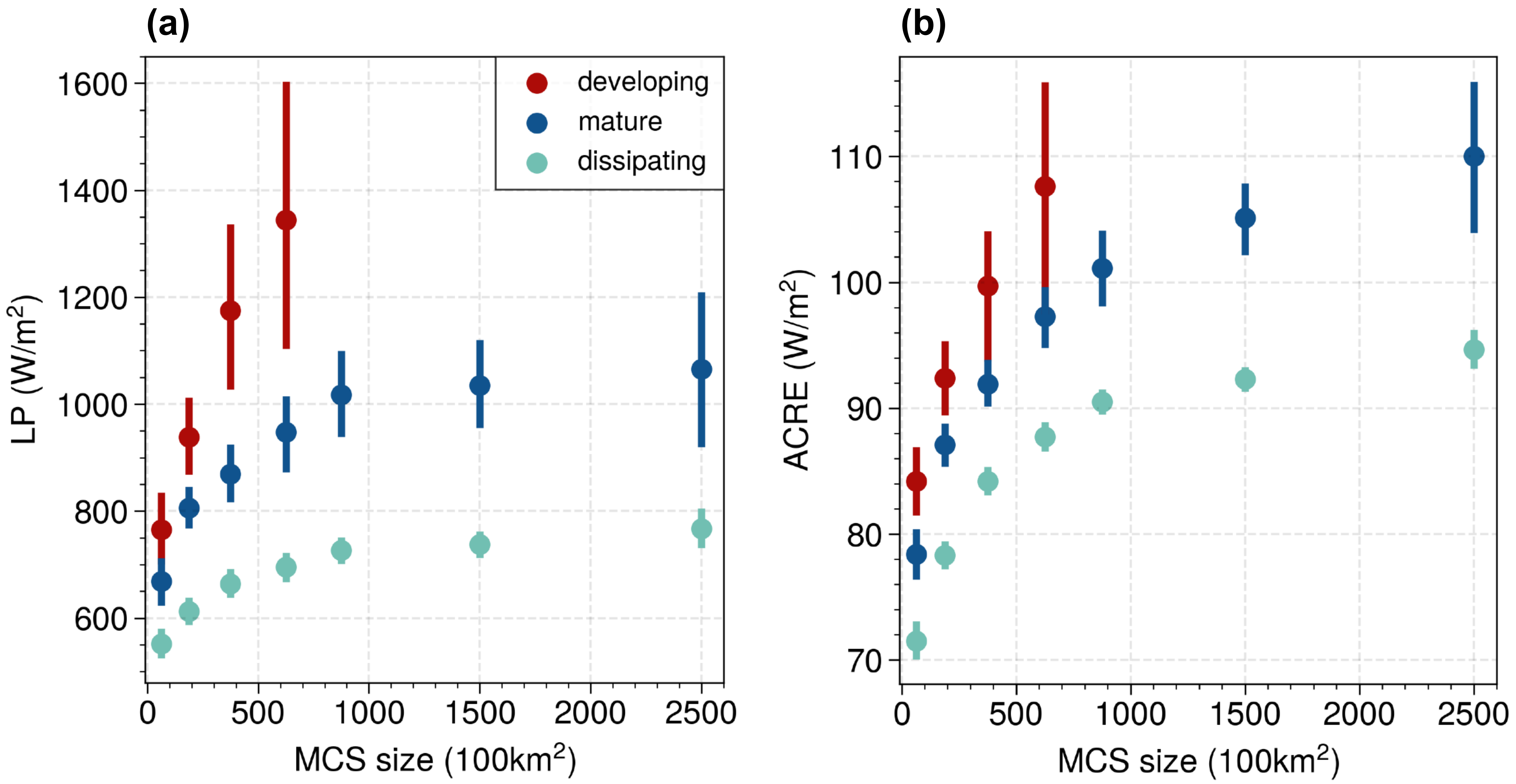
- Heavily raining MCS produce largest LH
- Deep convection can also be distinguished by large MCS size or large cooling above MCS cores

Result1: ACRE modulation by MCS size

Proxy for life stage:

Convective core fraction within the MCS:
given by the ratio of convective core size over MCS size

Developping CF 0.6-0.9
Mature: CF 0.4-0.6
Dissipating: CF 0.2-0.4



- Both LP and ACRE increase with MCS size, the increase flattens for larger MCS size.
- For a similar MCS size, LP and ACRE decrease from developing towards dissipating stage
- These behaviors are in line with those of the fraction of precipitation area within the MCS and the minimum temperature within the convective core, respectively.

Result1: ACRE modulation by MCS size

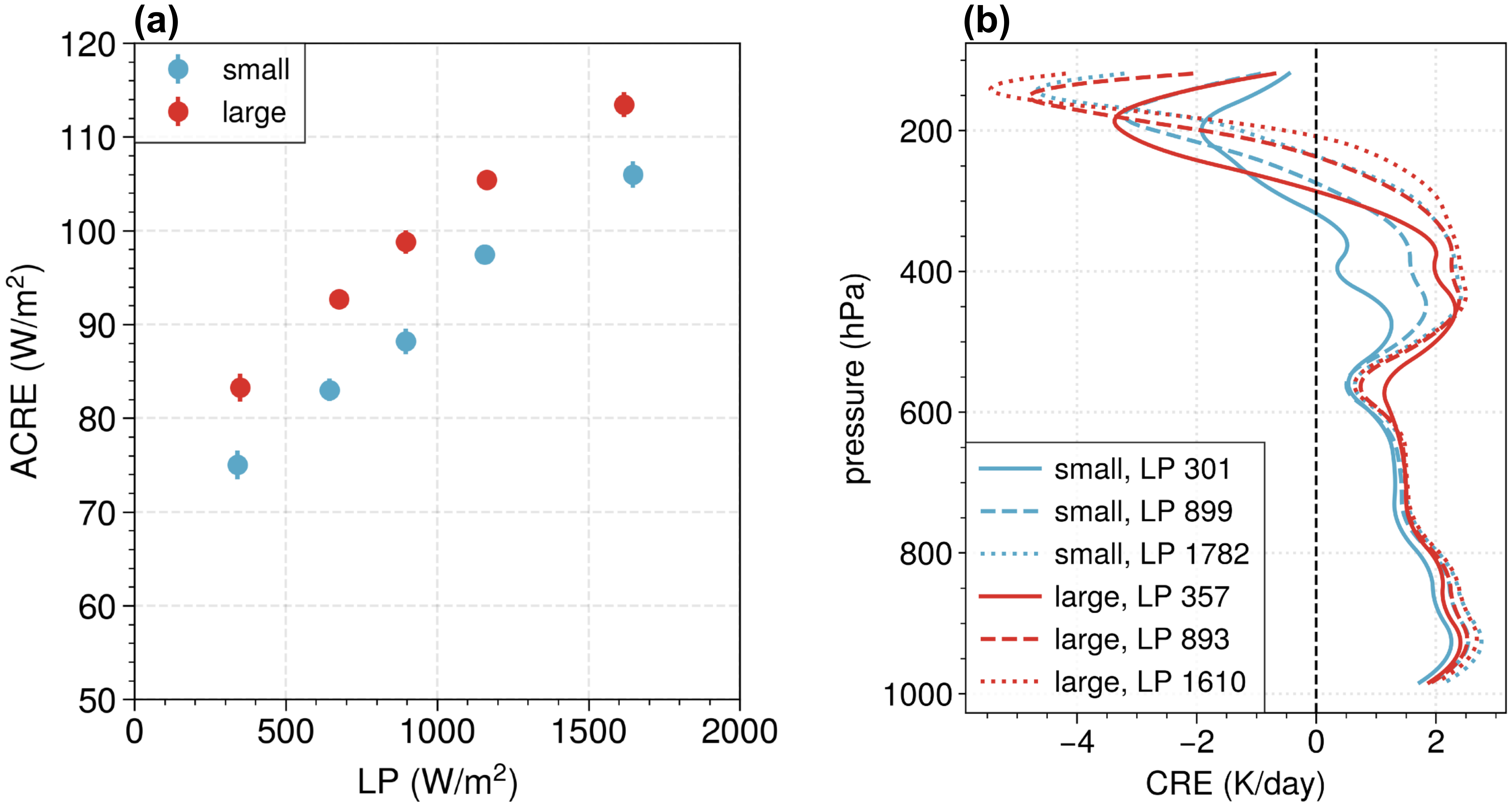
Proxy for convective organisation:

MCS size at the same rain intensity (LP)

Proxy for mature MCS:

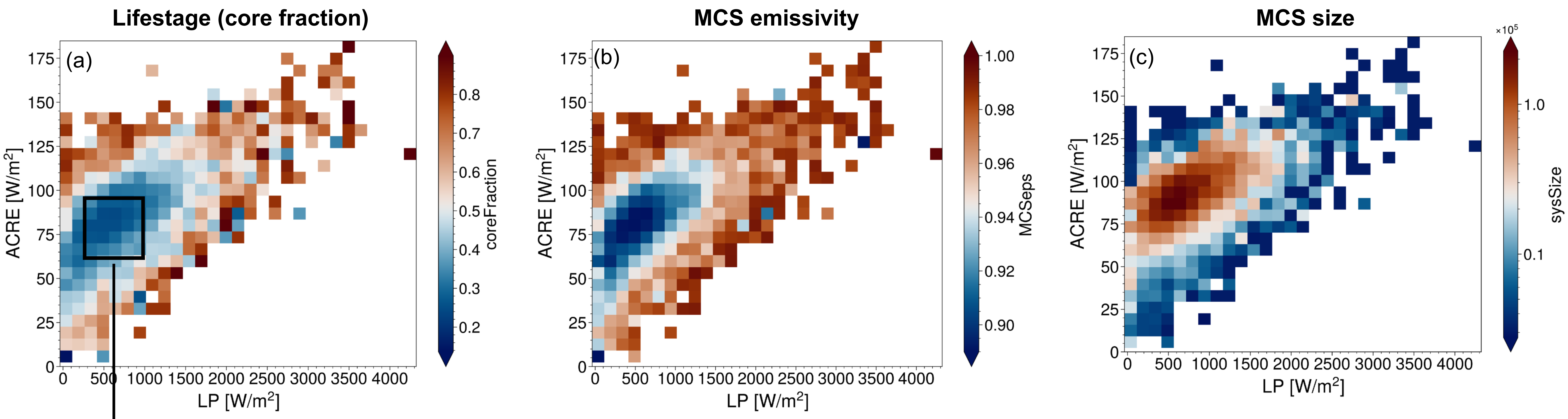
Core Fraction: 0.4-0.6

MCSs larger than 4 grid cells (**1°× 1°**)



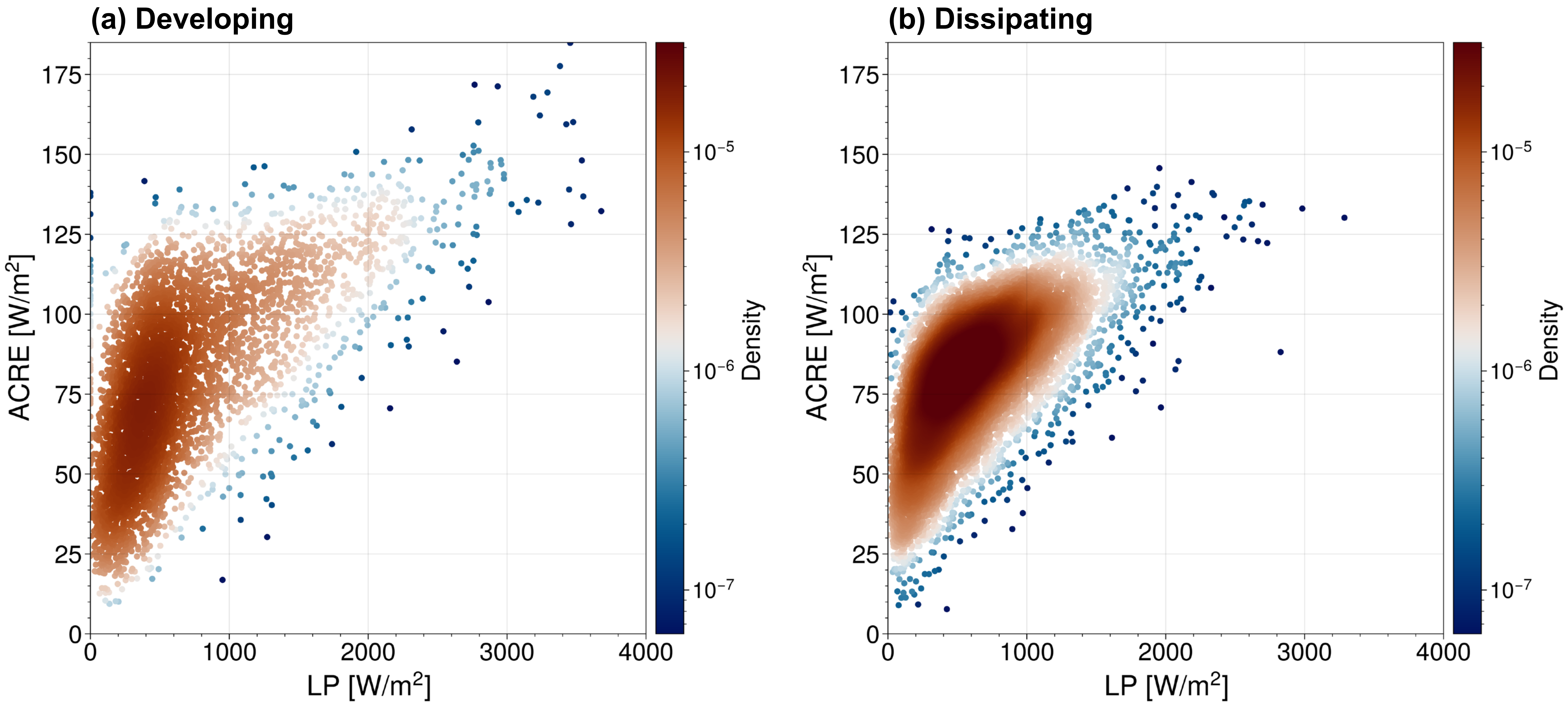
- ❖Convective organisation enhances ACRE by about 10 Wm^{-2} for larger, more organised MCSs than for smaller, less organized MCSs at similar average rain intensity.
- ❖More organized MCSs show larger vertical heating gradients at similar rain intensity.
- ❖This additional ACRE and vertical heating gradients support stronger, sustained convection and impact large-scale environments.

Result2: MCS properties as function of LP and ACRE



- Masunaga and Takahashi (2024, GRL, under review): the MCSs converge during their evolution to a **settling point** with LP of about **700 Wm^{-2}** and ACRE of about **75 Wm^{-2}**.
- Our MCS and life stage identifications are different, but a similar converging area can still be clearly observed:
  - MCSs with a larger core fraction and emissivity, smaller size occupy the LP-ACRE space at the border.
  - MCS in the later life stage (smaller core fraction and emissivity, larger size) occupy the LP-ACRE space closer to the settling point.

Result2: MCS properties as function of LP and ACRE



A broad scattering is in the LP-ACRE space of MCSs in the developing stage and a narrower distribution of MCSs is in the dissipating stage.

Summary and Outlook

- ❖ We reconstructed longterm datasets of 3D radiative and latent heating at 4 observation times using ANN (2004-2018).
- ❖ While the mean and variability of radiative heating rates are well predicted,

  the mean of predicted latent heating rates agree well with observations but show smaller variability.
- ❖ Nevertheless, this expansion allows us to study horizontal fields of diabatic heating, in particular within MCSs.
- ❖ Convective organisation enhances ACRE by about 10 Wm^{-2}; more organized MCSs show larger vertical heating gradients, supporting stronger and sustained convection.
- ❖ MCSs converge toward a mean LP-ACRE over their life cycle.

Future Plans:

- ❖ Future studies should incorporate the time dimension (convection tracking).
- ❖ The distribution of MCS properties in the LP–ACRE plane could be used to investigate GCRM and GCM simulations.

References

❖ Chen, X., Stubenrauch, C. J., & Mandorli, G. (2024). Relationship between latent and radiative heating fields of tropical cloud systems using synergistic satellite observations. EGUsphere, 2024, 1–35. 10.5194/egusphere-2024-3434.

❖ Chen, X., Stubenrauch, C. J., & Mandorli, G. (2024). Diabatic heating of mesoscale convective cloud systems from synergistic satellite data, 2024 (Submitted to IOP Conference Series: Earth and Environmental Science (EES))

❖ Stubenrauch, C. J., Mandorli, G., & Lemaitre, E. (2023). Convective organization and 3D structure of tropical cloud systems deduced from synergistic A-Train observations and machine learning. Atmospheric Chemistry and Physics. 23. 5867-5884. 10.5194/acp-23-5867-2023.

❖ Stubenrauch, C. J., Caria, G., Protopapadaki S.E., and Hemmer F. (2021). 3d radiative heating of tropical upper tropospheric cloud systems derived from synergistic a-train observations and machine learning. Atmospheric Chemistry and Physics, 21(2), 1015-1034.

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Radiative heating rates are now available:

https://gewex-utcc-proes.aeris-data/fr