

## Introduction | Collective behavior of cumulus clouds & its numerical representation

### Cumulus ensemble and the large-scale environment

- Interaction of clouds and the large-scale field is one of the biggest issues in atmospheric science<sup>1,2</sup>.
- Traditionally, the spectral representation of clouds underlies a school of the cumulus parameterization<sup>1,3,4</sup>.
- Tropical deep convection simulated by cloud-resolving models(CRM) or global CRM depends on  $\Delta x$ .<sup>5,6,10,11,12</sup>

### Self-aggregation under an idealized radiative-convective equilibrium (RCE)

- A spontaneous organization of clouds under RCE might play important roles in the earth's climate<sup>2,7,8</sup>.
- The aggregation only occurs with  $\Delta x > 2\text{km}$  and  $L > 200\text{km}$  when initialized by homogeneous moisture fields<sup>9</sup>.

### Research questions

- What statistical properties does the cumulus ensemble simulated by CRM show under idealized RCE?
- And, do that properties converge to the exact "solution" as the resolution increases?
- Why is convective self-aggregation simulated only with the lower-resolution?
- And, what is the mathematical and physical implication of self-aggregation?

### References

- <sup>1</sup>Arakawa & Schubert, 1974; <sup>2</sup>Bony et al., 2015; <sup>3</sup>Chikira & Sugiyama, 2010; <sup>4</sup>Baba, 2019;  
<sup>5</sup>Miyamoto et al., 2013; <sup>6</sup>Satoh et al., 2019; <sup>7</sup>Bretherton et al., 2005; <sup>8</sup>Mauritsen & Stevens, 2015; <sup>9</sup>Muller & Held, 2012;  
<sup>10</sup>Khairoutdinov et al., 2009; <sup>11</sup>Scheufele, 2014; <sup>12</sup>Sueki et al., 2020. See also, **Yanase & Takemi, 2018.**

## Method | Numerical model, experimental setups & analytical method

**Model: WRF-ARW Ver.3.8.1** (Skamarock et al. 2008)

**Radiation: RRTMG (SW + LW)** (Iacono et al. 2008)

- diurnally variable shortwave
- interactive with cloud and water vapor

**Microphysics: WSM6** (Hong and Lim 2006)

- bulk single moment (qv, qc, qr, qi, qs, and qg)

**Turbulence: Smagorinsky model** (Lilly 1962)

- no PBL scheme

**Surface: Monin-Obukhov similarity**

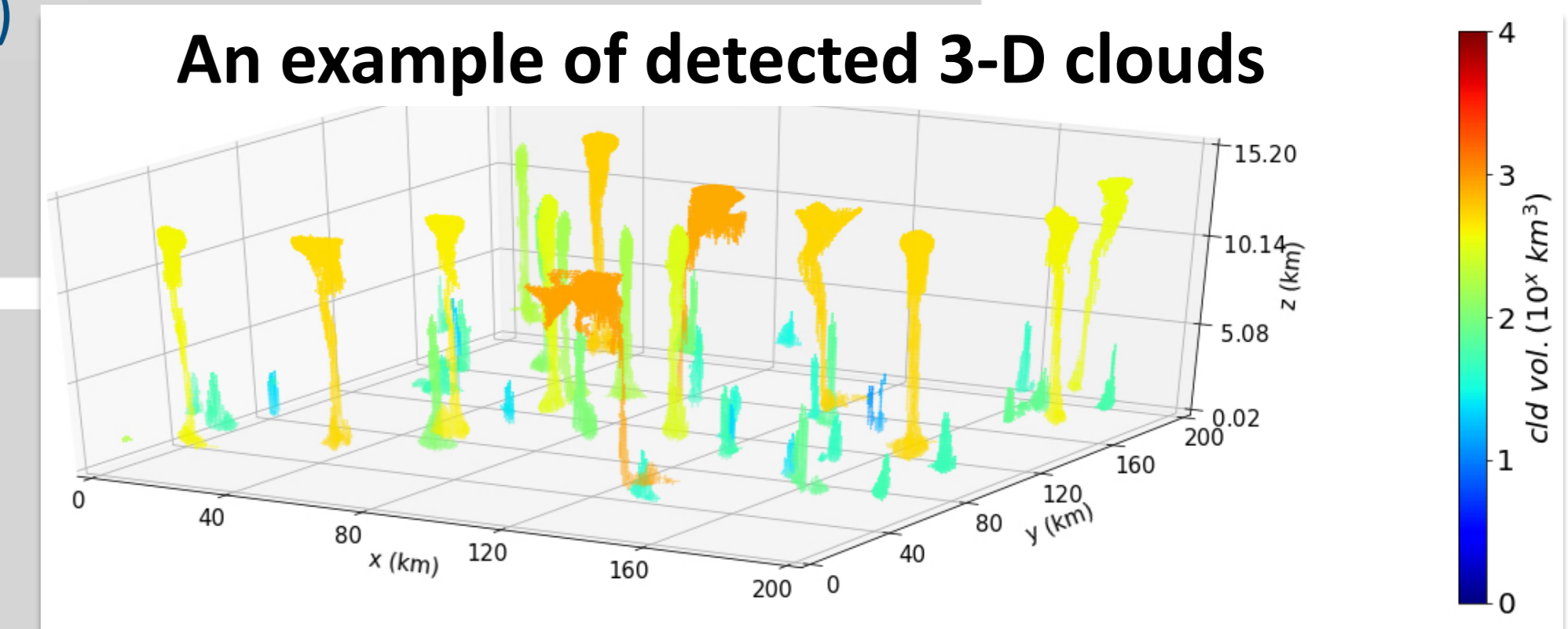
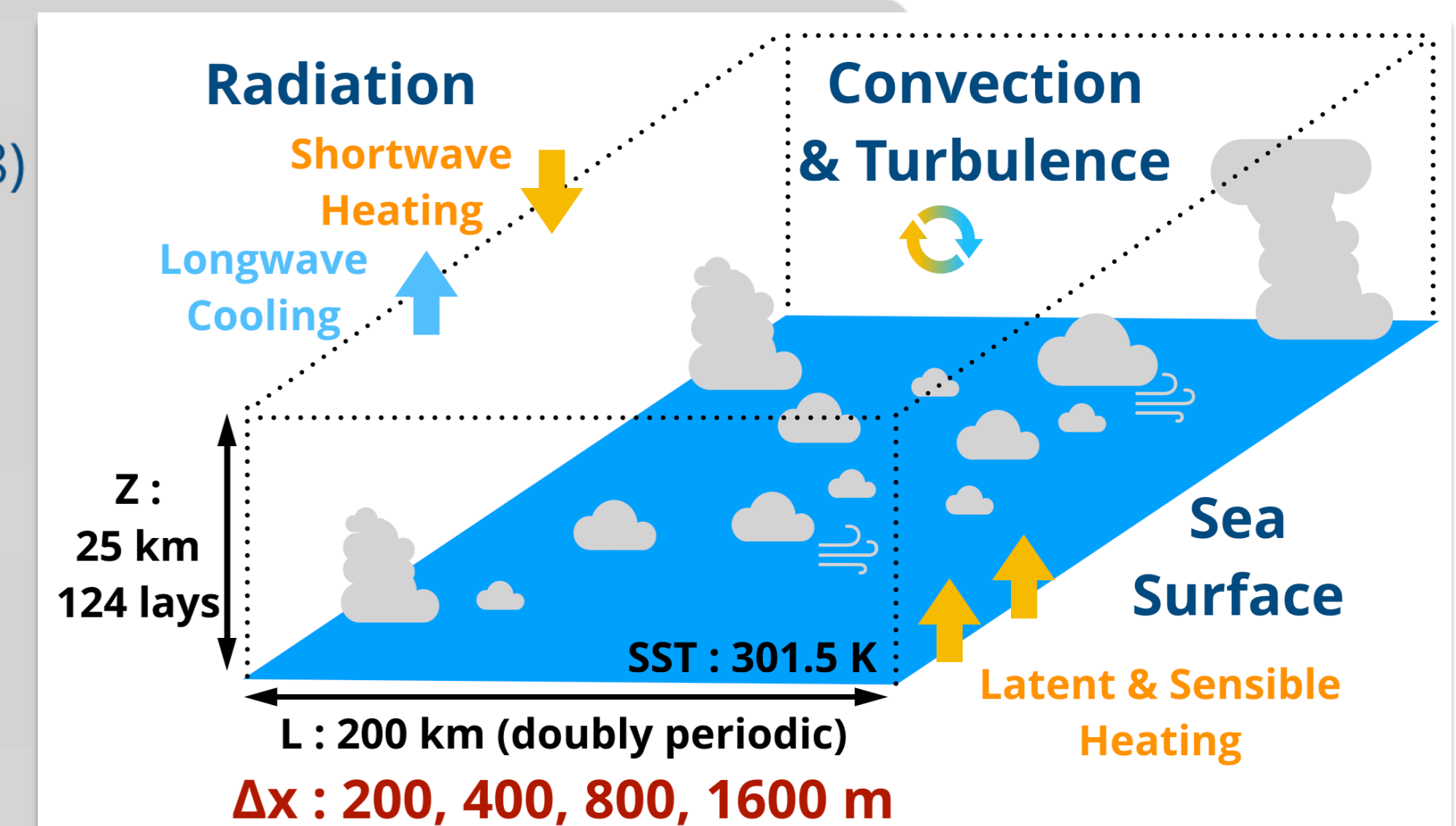
(Jimenez et al. 2012)

**Others:**

- no Coriolis force, initial U, V
- no large-scale advective forcing, nudging

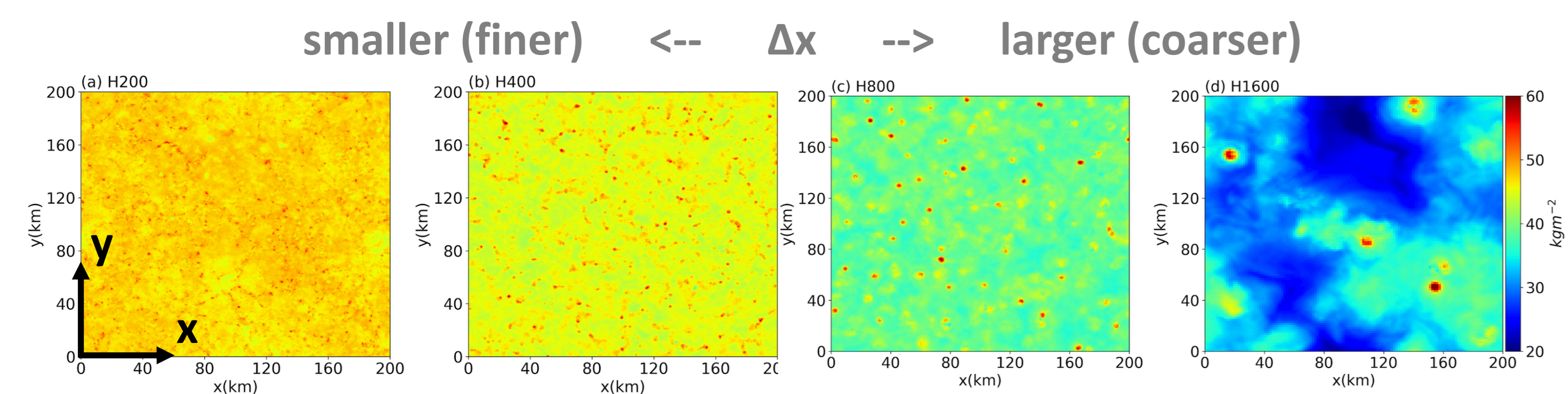
**3-D cloud detection method** (Tsai and Wu 2017)

- define cloud grids as  $(q_c + q_i > 1e-5 \text{ kg kg}^{-1})$
- identify a cloud as 6-connected volume
- define convective clouds as (cloud base height < 1 km) & (cloud depth > 1 km)

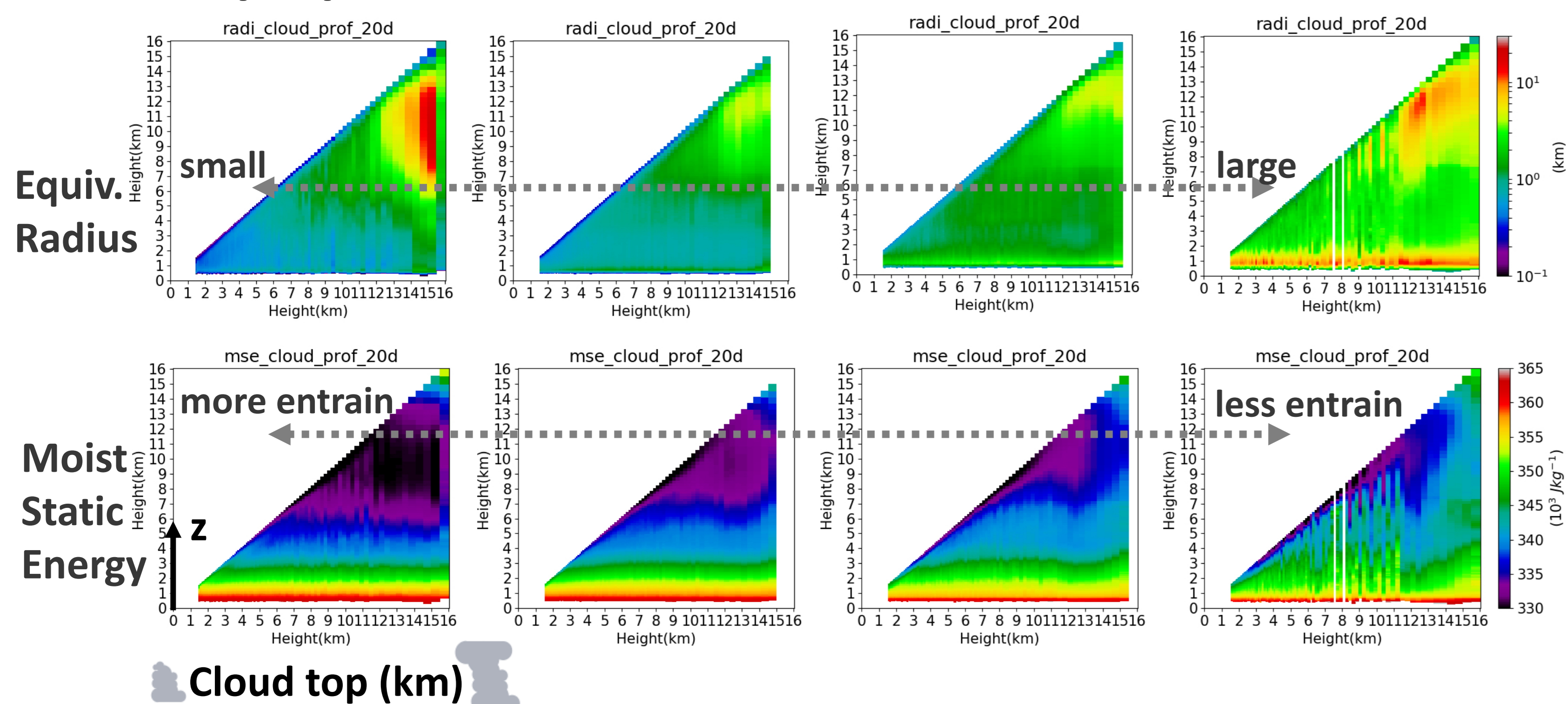


## Results & Discussion | In-cloud properties & vertical distribution of cumulus ensemble

### Moisture horizontal distribution (column-integrated)

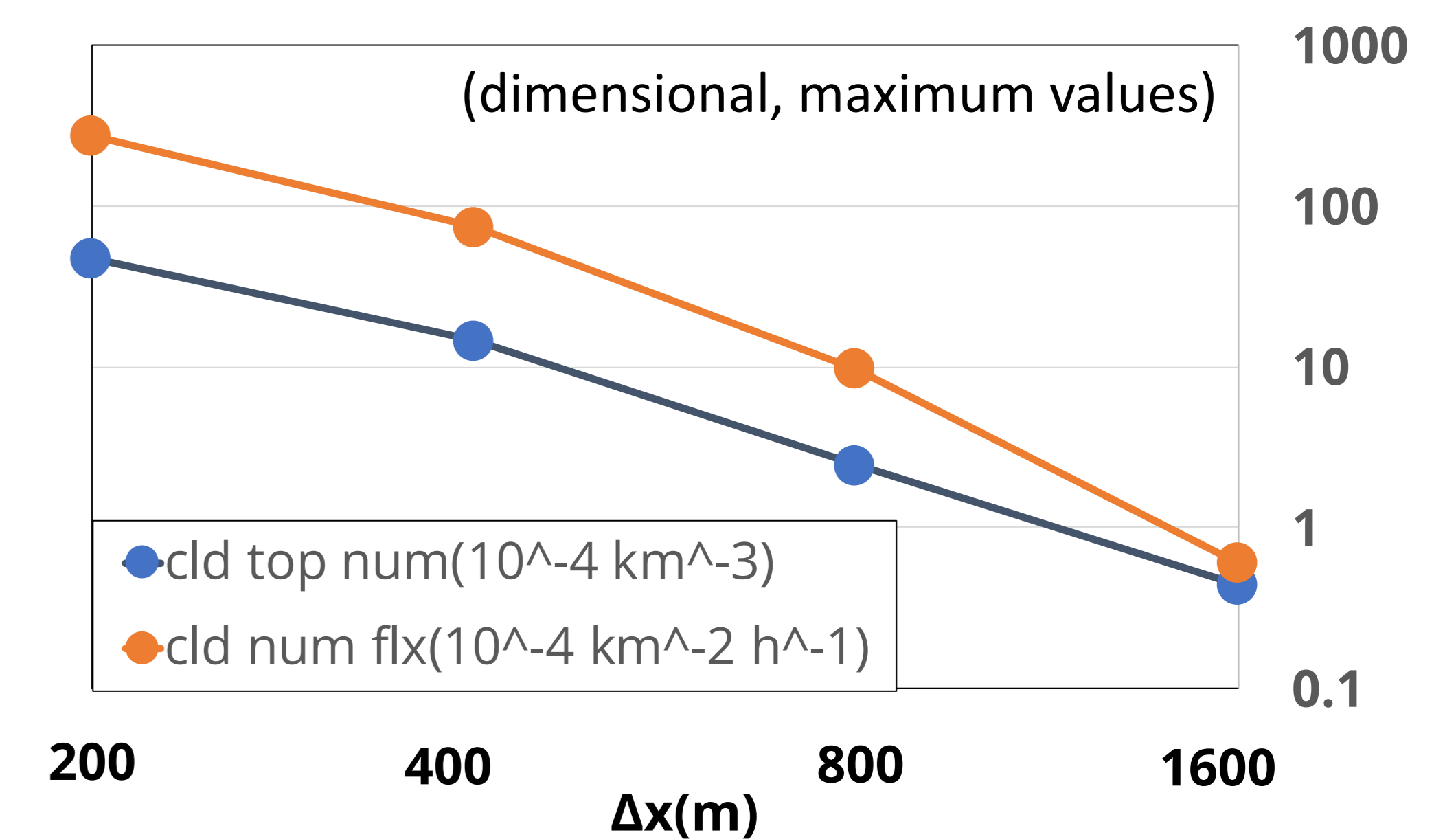
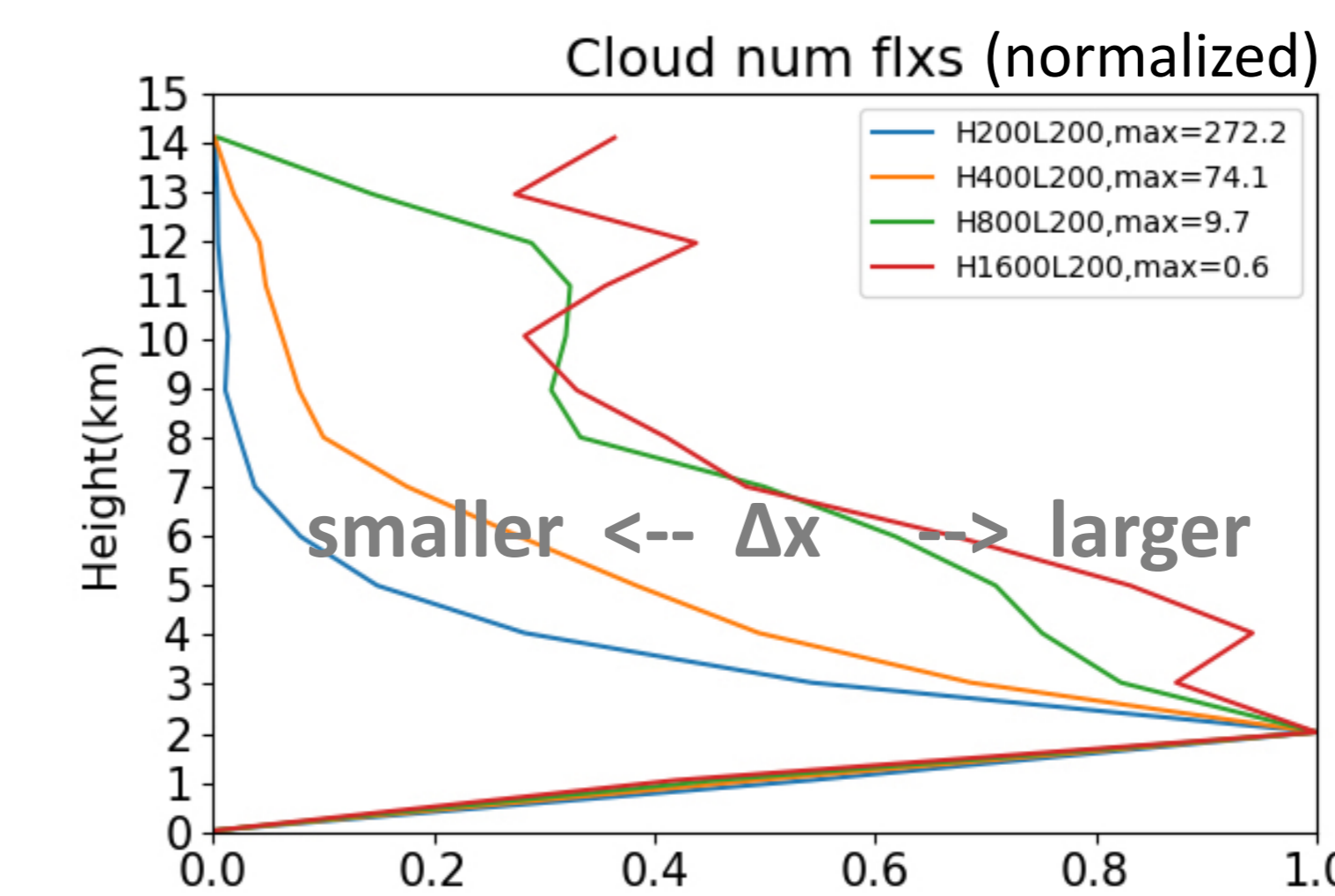
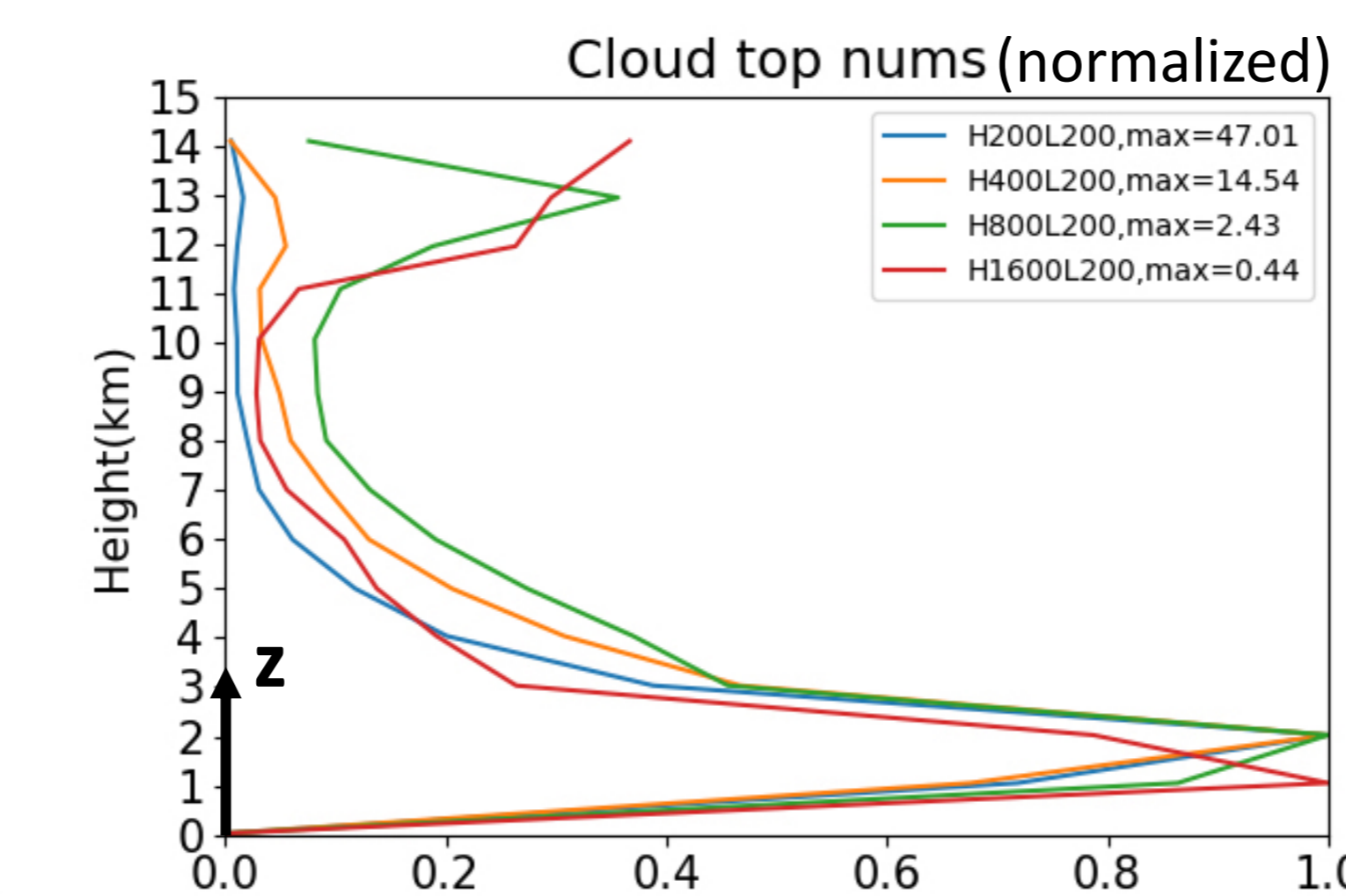


### In-cloud properties of cumulus ensemble



### Number and "number flux" of cumulus ensemble

- The number of clouds whose top height are in a unit volume. [ $10^{-4} \text{ km}^{-3}$ ]
- The number of clouds passing upward per unit horizontal plane per unit time [ $(100 \text{ km})^{-2} \text{ h}^{-1}$ ]



### Research answers

- The vertical reduction of in-cloud MSE reflects entrainment of environmental air. [microscopic view]  
The vertical reduction of the cloud number flux reflects a selective process of cumulus ensemble. [macroscopic view]
- The number of clouds increases and the clouds proportion reaching the upper troposphere decreases, as the resolution increases. The properties show the convergence characteristics, but it needs further higher-resolution.  
The atmosphere becomes wetter as the resolution increase (probably due to enhanced near surface gustiness).
- Only the lowest-resolution simulation ( $\Delta x 1600$ ) shows a large-scale inhomogeneity in moisture, a sign of self-aggregation. In  $\Delta x 1600$ , few number, large size, and strongly buoyant deep clouds dominate in the ensemble, between which a dry patch appears.
- Self-aggregation simulated with low-resolution is considered artificially exaggerated. However, the aggregation might occur even with higher-resolution if the number of clouds is suppressed locally in a larger domain.