Understanding moist convection-environment interactions from high-resolution modeling and observations

US CLIVAR summit
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National Center for Atmospheric Research
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Moist convection and its role in climate system

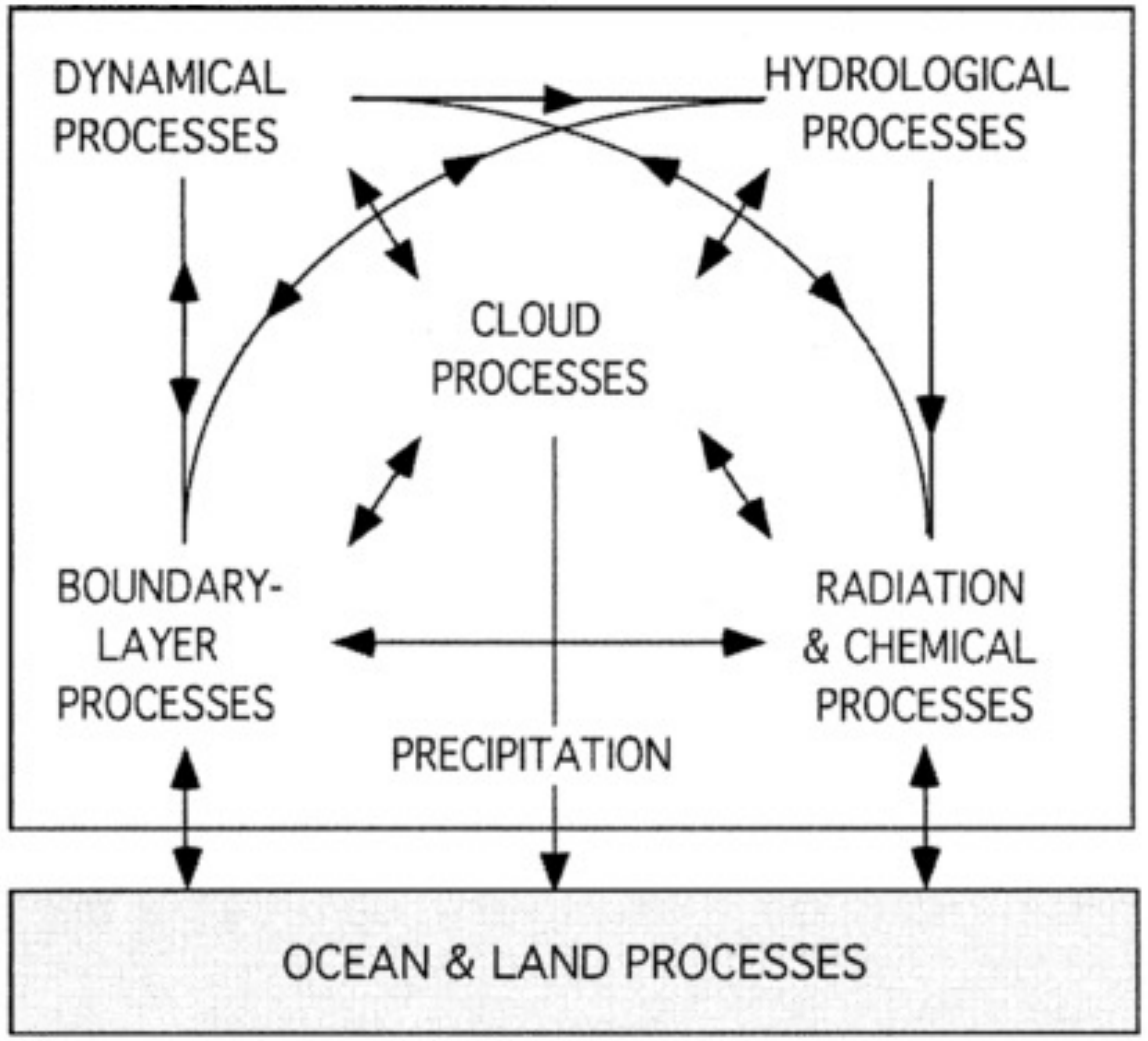
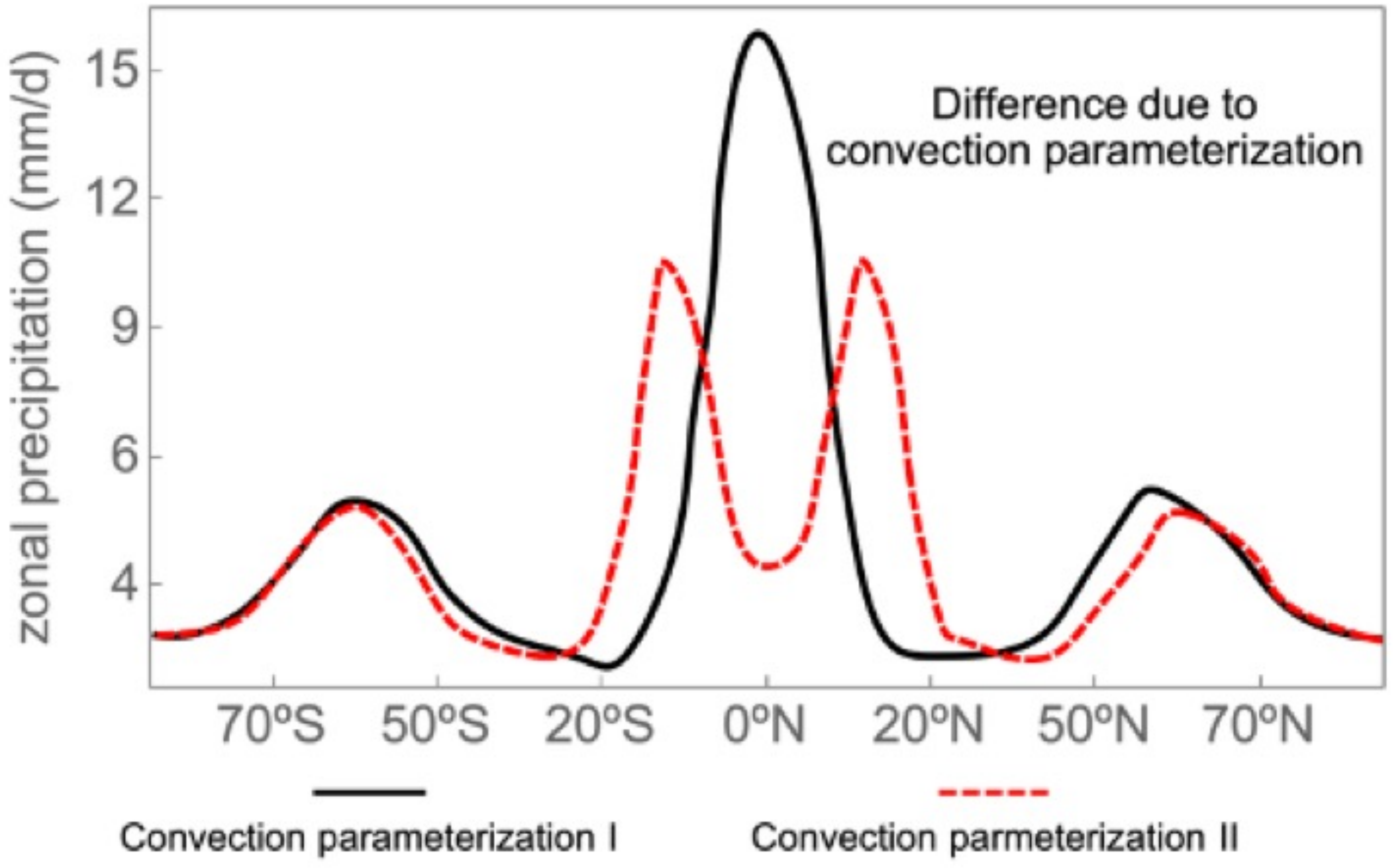


FIG. 1. Interactions between various processes in the climate system.

Arakawa and Schubert 1974



Cloud processes contribute to one of the largest uncertainties in climate projection

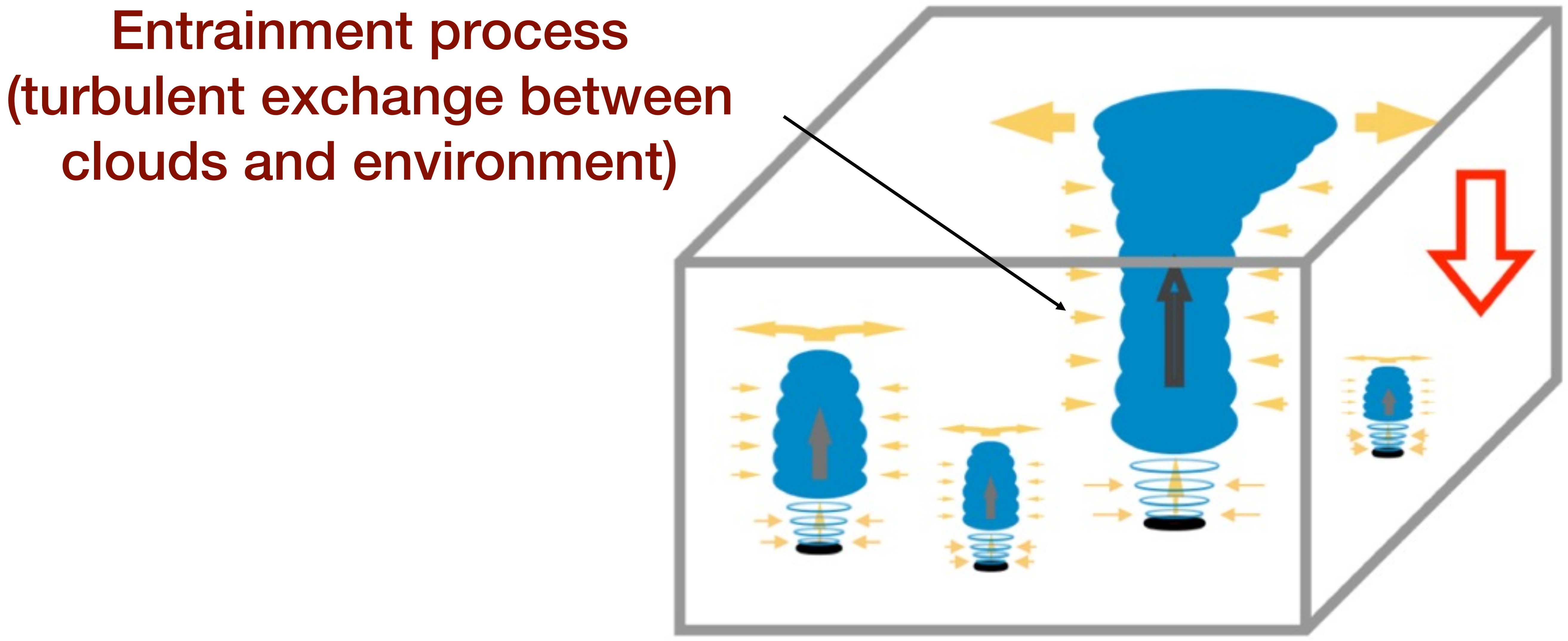
Gaps in convective process understanding and how to address them

- Controlling factors of entrainment mixing and how to represent it in convection scheme
  - ➢ An idealized high-res modeling framework + linear response function
- What determines the diurnal cycle of convection and precipitation and how to improve its representation in climate models
  - ➢ A theoretical plume model forced with observational data to investigate shallow to deep transition
  - ➢ A new tracking algorithm is developed to investigate mechanism of convective aggregation
- Potential usage of machine learning to automatically identify model bias in precipitation

Scientific question

What are the controlling factors of entrainment mixing? How to disentangle the relative role of each factor in contributing to the turbulent mixing between clouds and environment?

Entrainment representation—at the core of convection parameterization



$$\frac{\partial \varphi_c}{\partial z} = -\varepsilon(\varphi_c - \varphi_e) + S_c$$

$$\frac{1}{M}\frac{\partial M}{\partial z} = \varepsilon - \delta$$

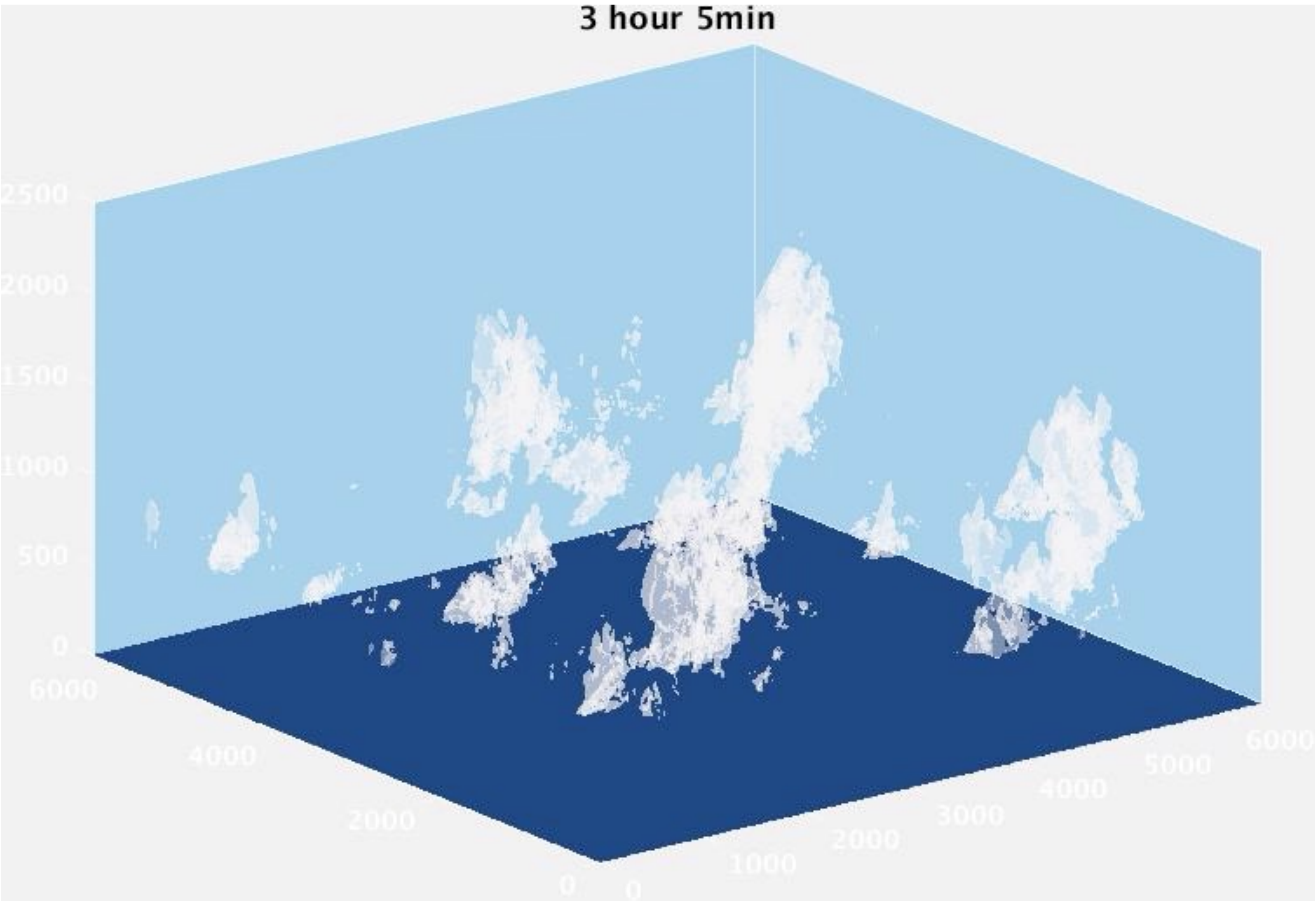
Cloud mass flux and its thermodynamical and dynamic properties are changed due to mixing with environmental air

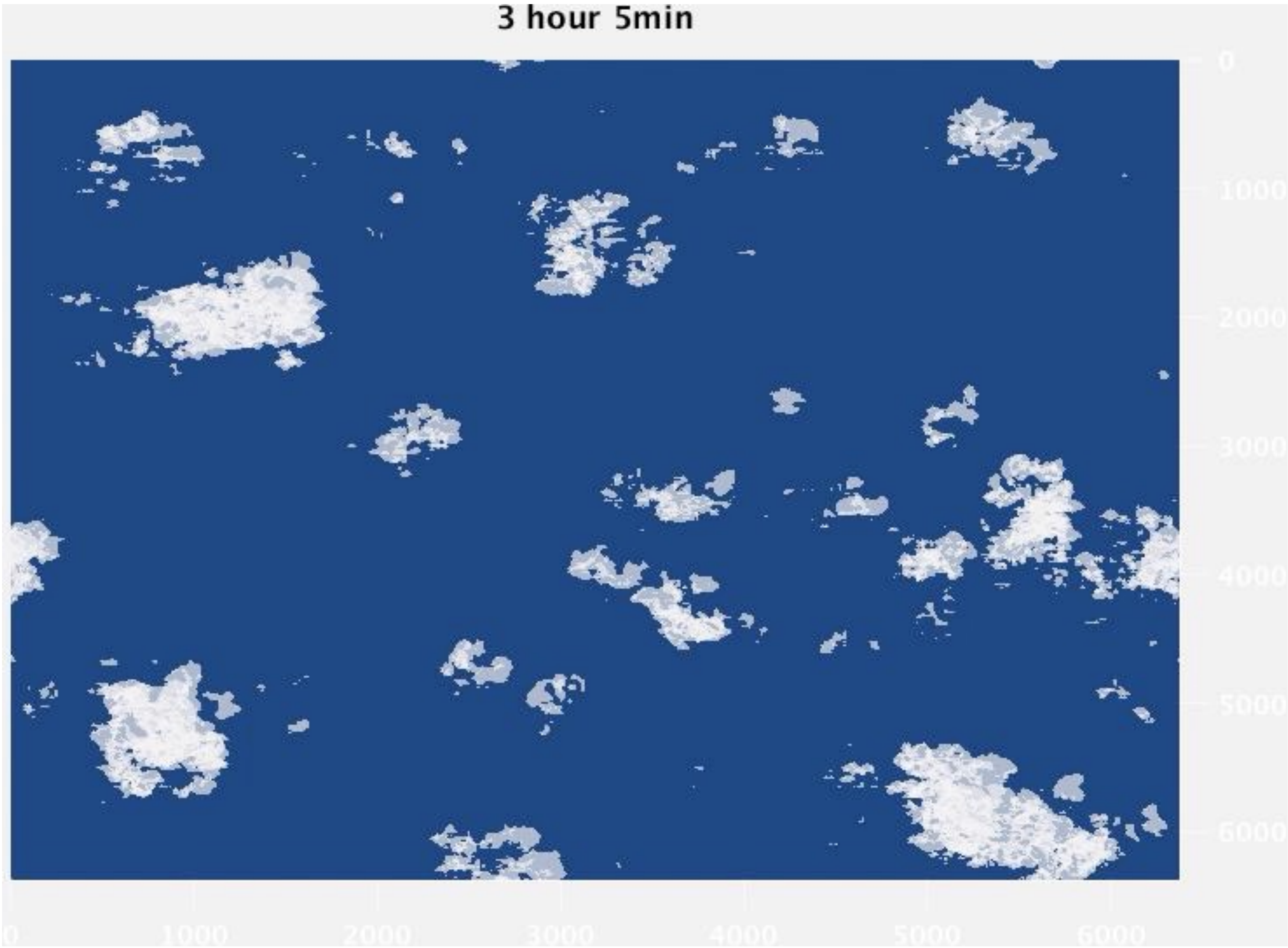
Entrainment representation is consequential to general circulation model’s (GCM) behavior, which is among the most uncertain processes in climate projections

Complicated due to statistical confounding

Entrainment representation—at the core of convection parameterization

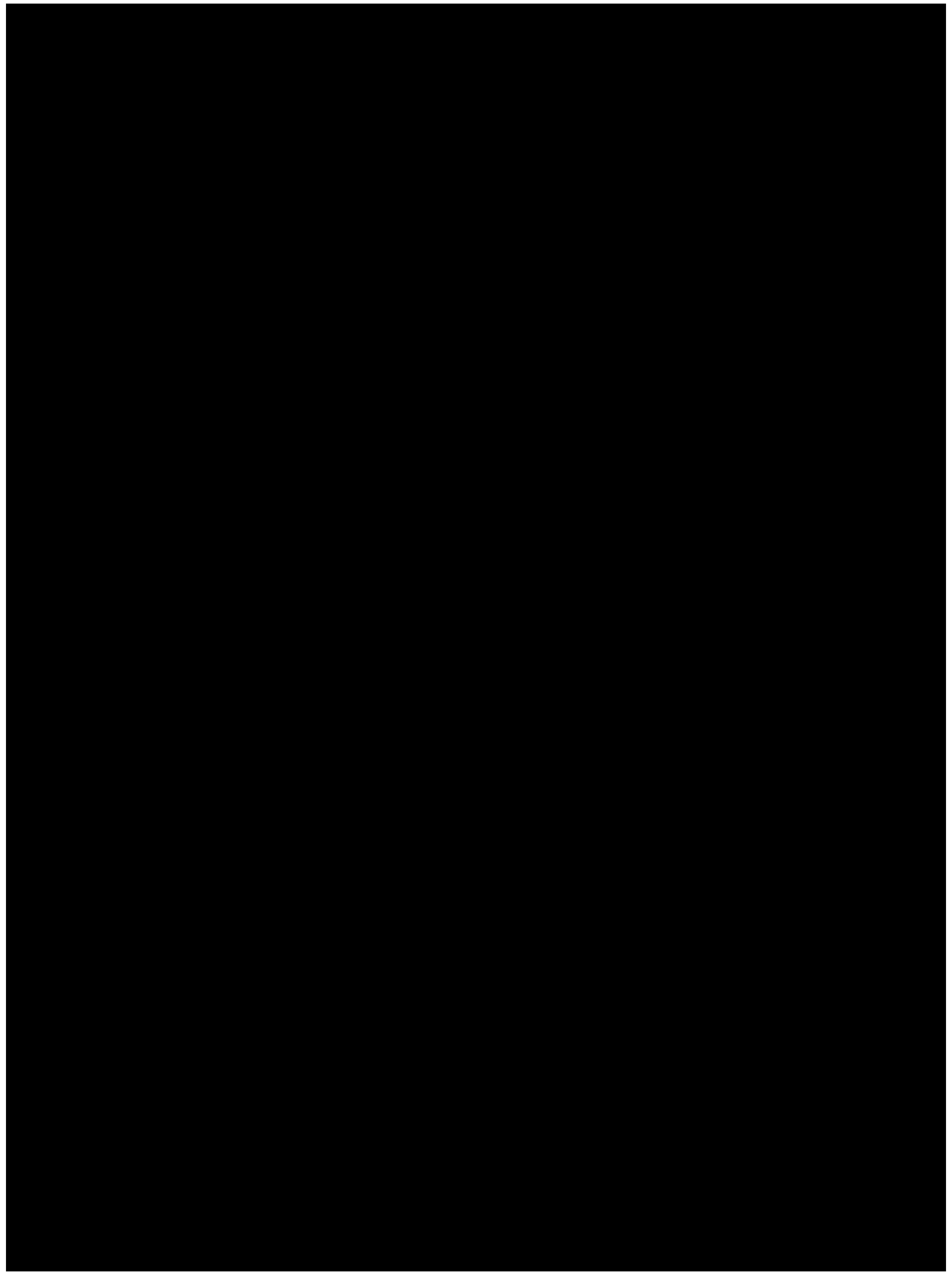
- Large Eddy Simulation: System for Atmospheric Modeling (Khairoutdinov and Randall 2001), resolves large eddies that carry most turbulent energy
- Initial conditions and large-scale forcing: BOMEX field campaign, quasi-steady state shallow convection
- 6.4 x 6.4 km, 50m horizontal resolution, 25m vertical resolution, 1s temporal resolution





Experiment design step 2 — Release particles

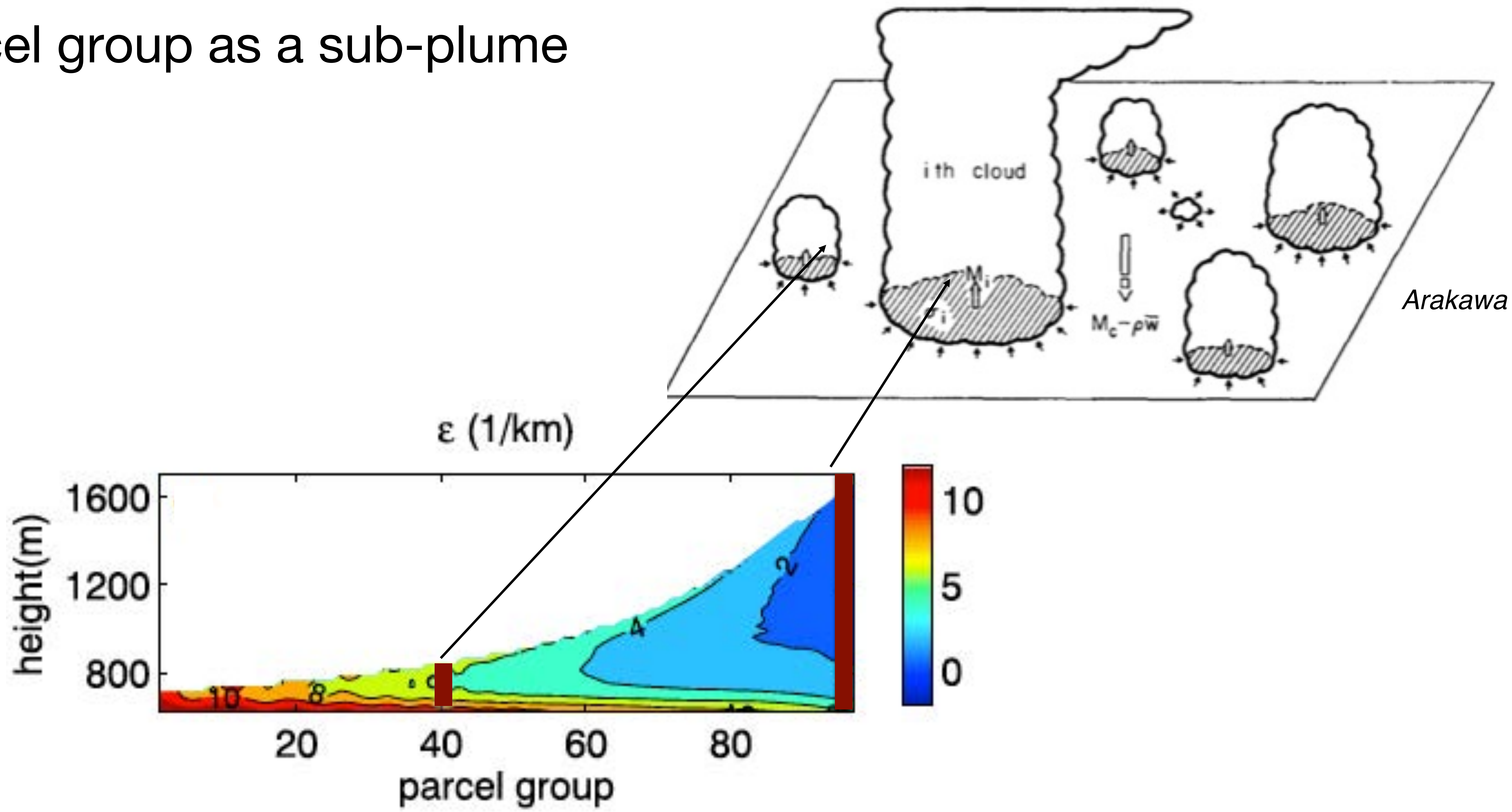
- Release Lagrangian particles into the simulated cloud field, 20 per grid box, totaling 32 million
- Combine particle trajectory with 3D output from cloud simulation



Langhans et al. 2015

Experiment design step 3 — Cast particles into spectral plumes

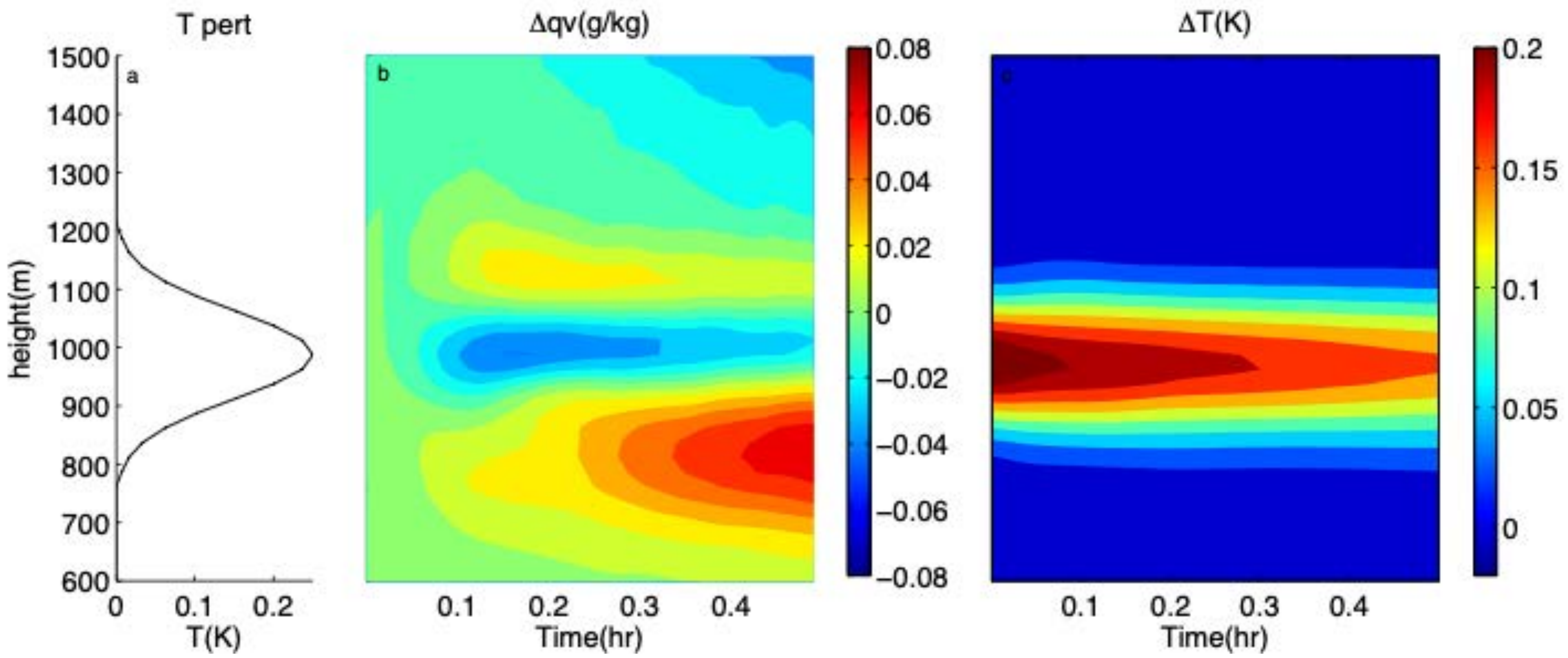
Think of each parcel group as a sub-plume



Arakawa and Schubert (1974)

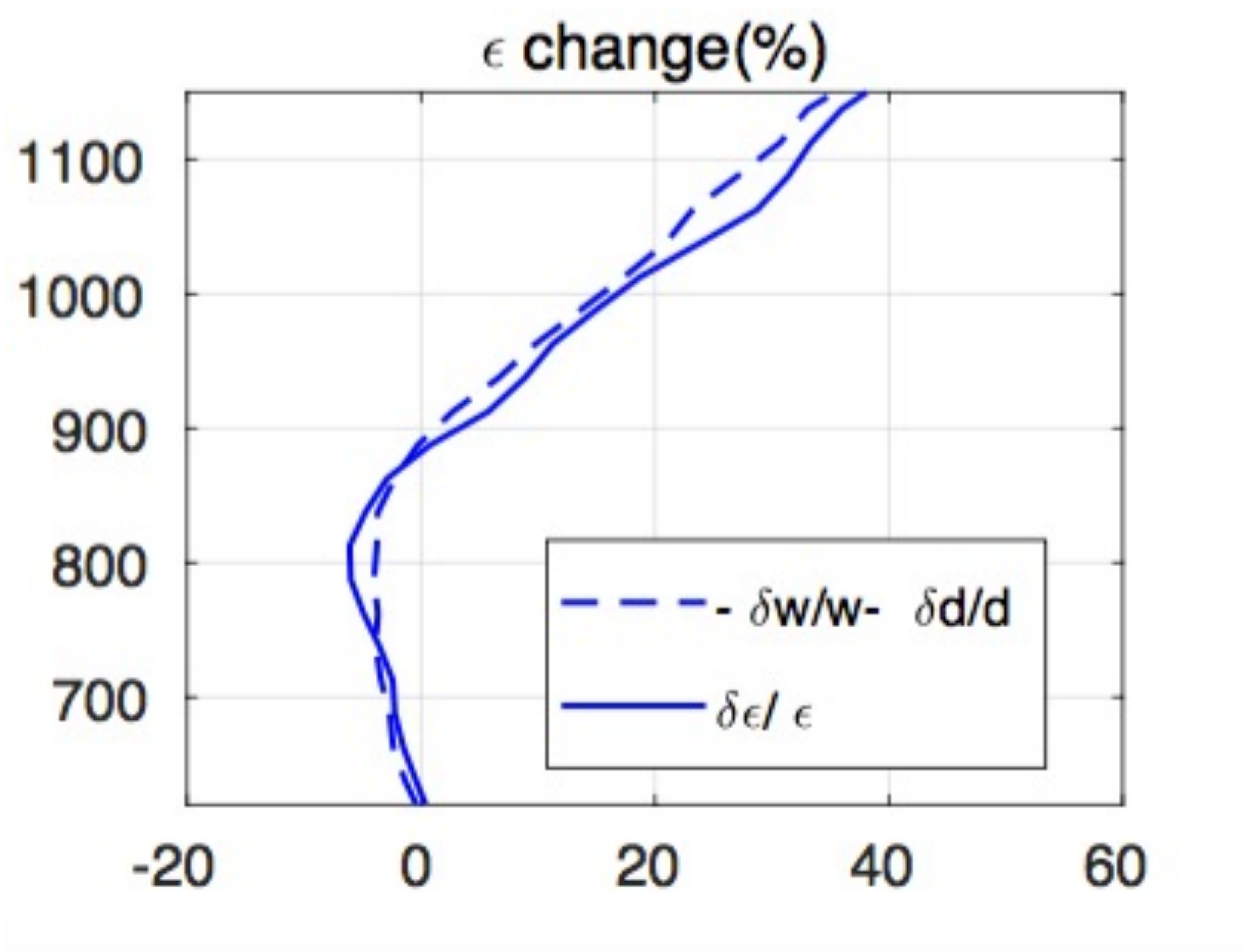
Experiment design step 4 — Create perturbed runs

- Gaussian-shape temperature perturbation: centered at 975m with +0.25K peak value.
- Repeat step 1-3 to obtain cloud statistics



Linear response function to identify controlling factors of entrainment process

One single parcel group

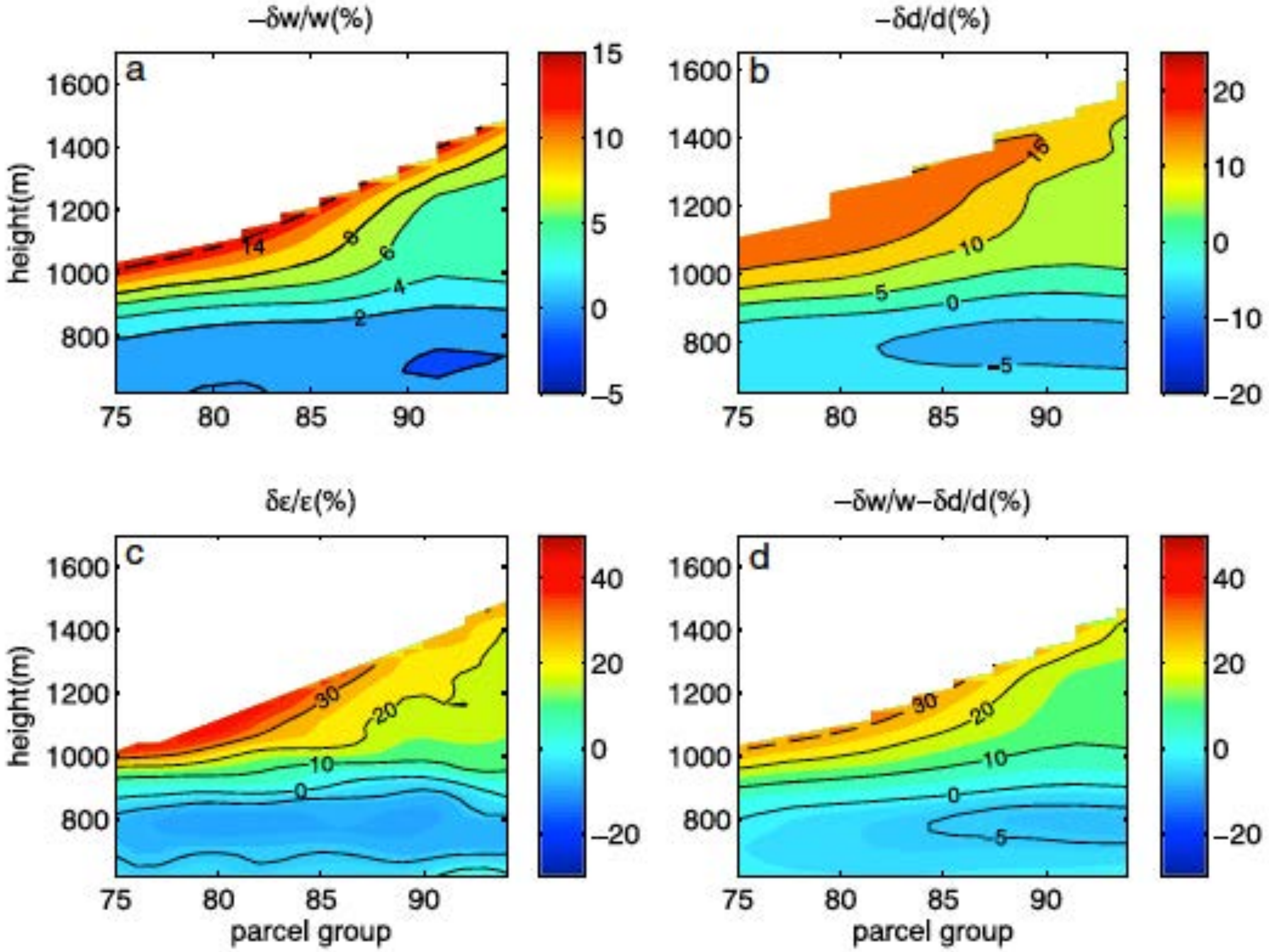


$$\delta\epsilon/\epsilon = -\delta w/w - \delta d/d$$

Proposed a new entrainment formula that is used in the latest EDMF-MYNN convection scheme in WRF to improve shallow cloud representation

Also proposed a new updraft model for velocity, both can be incorporated into a unified scheme in climate models.

All parcel groups



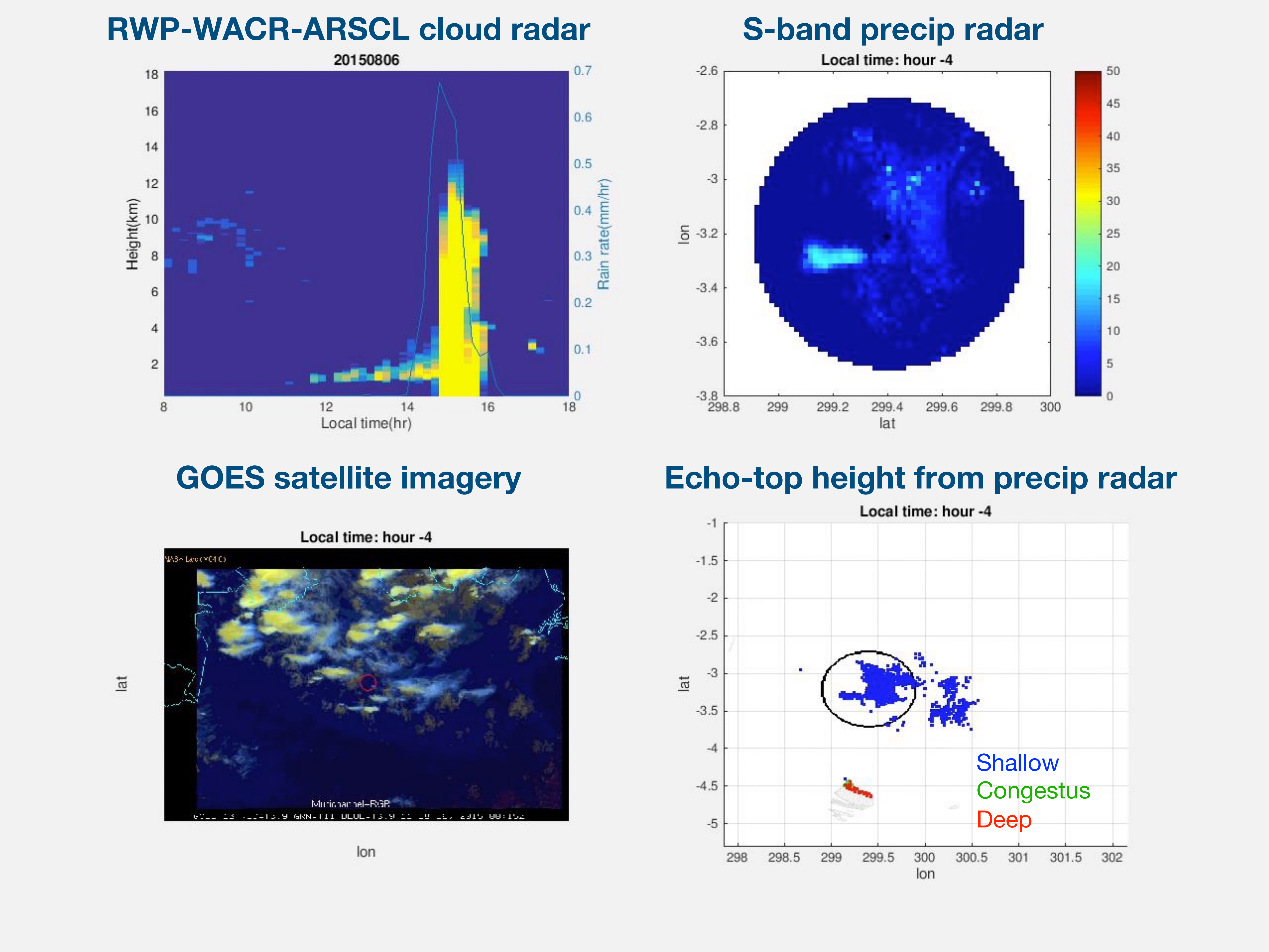
$$\delta\epsilon/\epsilon = -\delta w/w - \delta d/d$$

$$\epsilon_i = \frac{\alpha_i}{w_i d_i}$$

Scientific question

What are the controlling factors of convection upscaling? E.g. Shallow to deep transition, convective aggregation. How to disentangle the relative role of each parameter in contributing to the convective development?

Integrate observations and theories to understand shallow-to-deep convection transition in Amazon rainforest



Dataset used:

- RWP-WACR-ARSCL
- SIPAM precip radar
- Radiosonde
- GOES-13 4km
- MET
- QCECOR
- GNDRAD
- SKYRAD
- VARANAL
- Doppler Lidar

Analysis is done over 150km domain centered at ARM site, classification is based on the diurnal cycle of precipitation radar/cloud radar cloud top heights over daytime (0800-1800LST)

Employ theoretical plume model to disentangle contributing factors

Conservation of energy

entrainment rate

$$\frac{\partial(h_c - L_i q_i)}{\partial z} = -\varepsilon\left(h_c - L_i q_i - h_a\right),$$

Simple microphysics scheme

$$f_i = \frac{1 - \tanh[(T_c - T_{0,i})/dT_i]}{2}$$

$$\dot{q}_{\text{cond}} = -w_c\left[\frac{\partial q_{v,c}}{\partial z} + \epsilon(q_{v,c} - q_{v,a})\right]$$

$$\dot{q}_{\text{auto}} = \frac{1}{\tau_{\text{auto}}}(q_w - q_{w,\text{crit}})H(q_w - q_{w,\text{crit}})$$

Conservation of moisture

$$\frac{\partial q_w}{\partial z} = -\varepsilon q_w + \frac{1}{w_c}\left(\dot{q}_{\text{cond}} - \dot{q}_{\text{auto}}\right),$$

Conservation of momentum

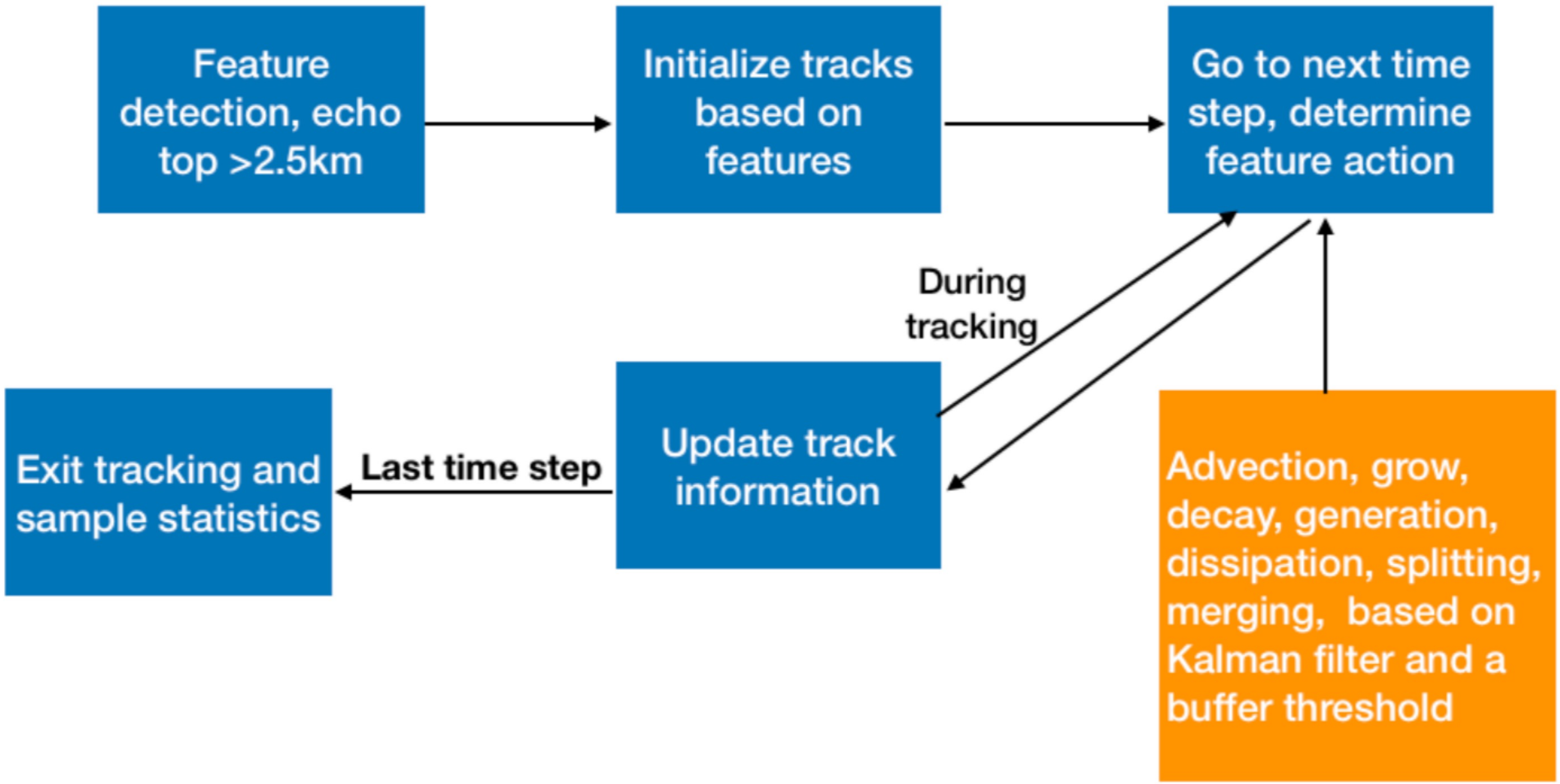
$$\frac{1}{2}\frac{\partial w_c^2}{\partial z} = a_B B - \varepsilon w_c^2 - c_D w_c^2,$$

First time using Doppler-lidar measured cloud base initial velocity to constrain the dynamical evolution of a plume model

Proposed a new control of convection depth through vertical wind shear in addition to the entrainment rate and lower troposphere relative humidity

This observational analysis framework can be directly consulted to evaluate Single Column Models (SCM)

A tracking algorithm based on S-band radar reflectivity is developed to explicitly track the behavior of convective aggregation

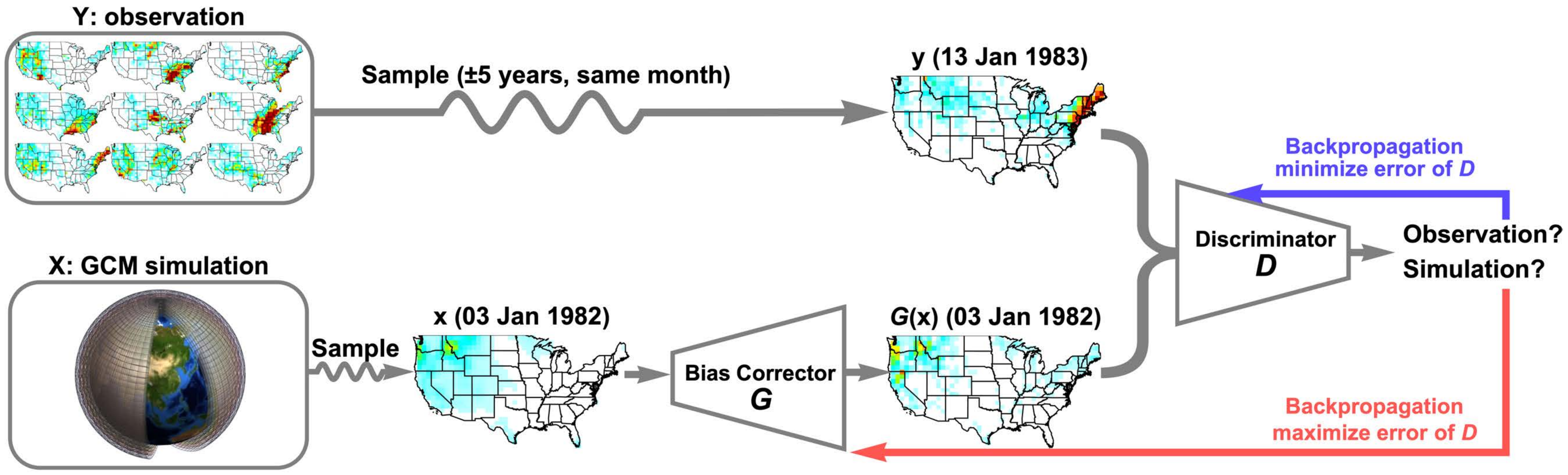


Results demonstrate that cluster-cluster interaction can be important for the diurnal cycle of precipitation

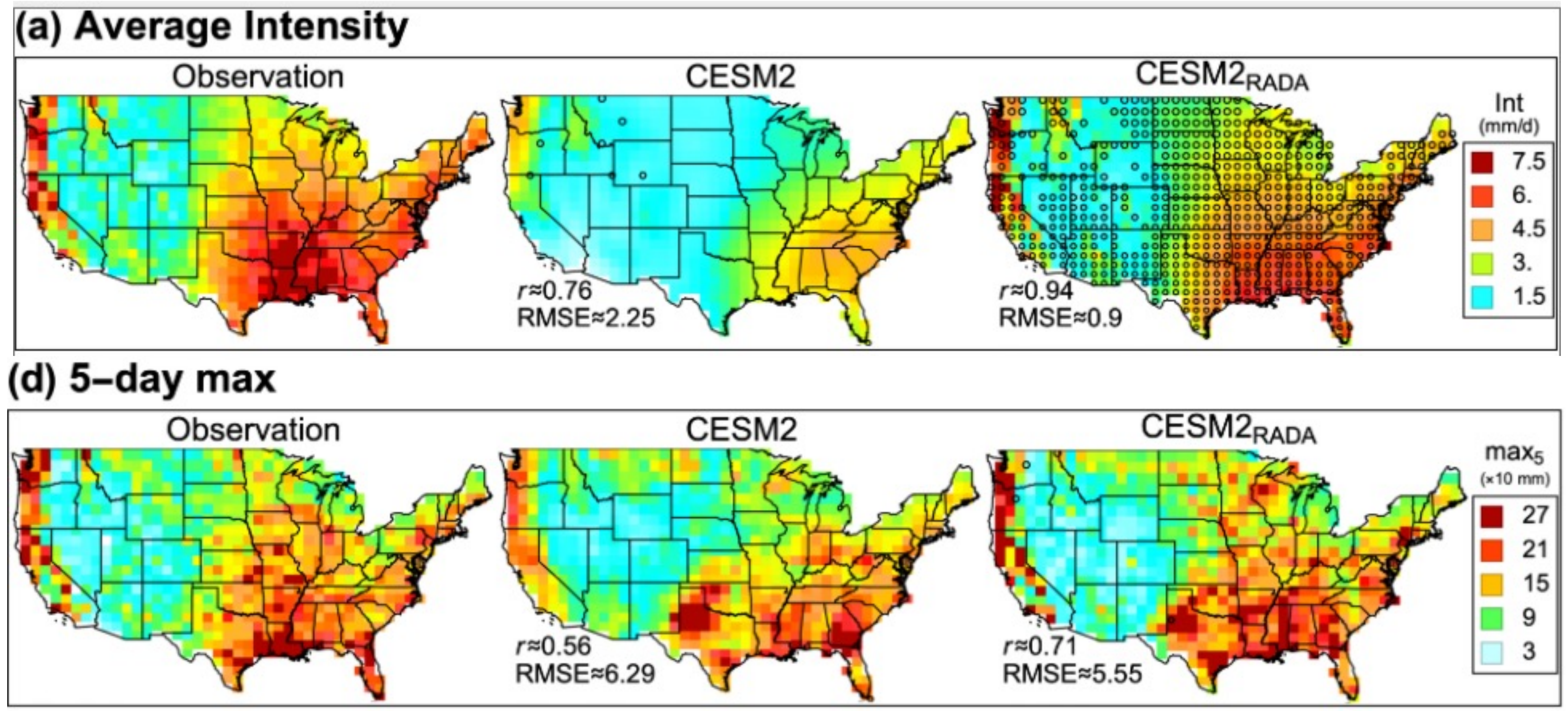
Scientific question

How to properly use machine learning techniques to help with convective process understanding?

Apply machine learning techniques to identify precipitation simulation bias

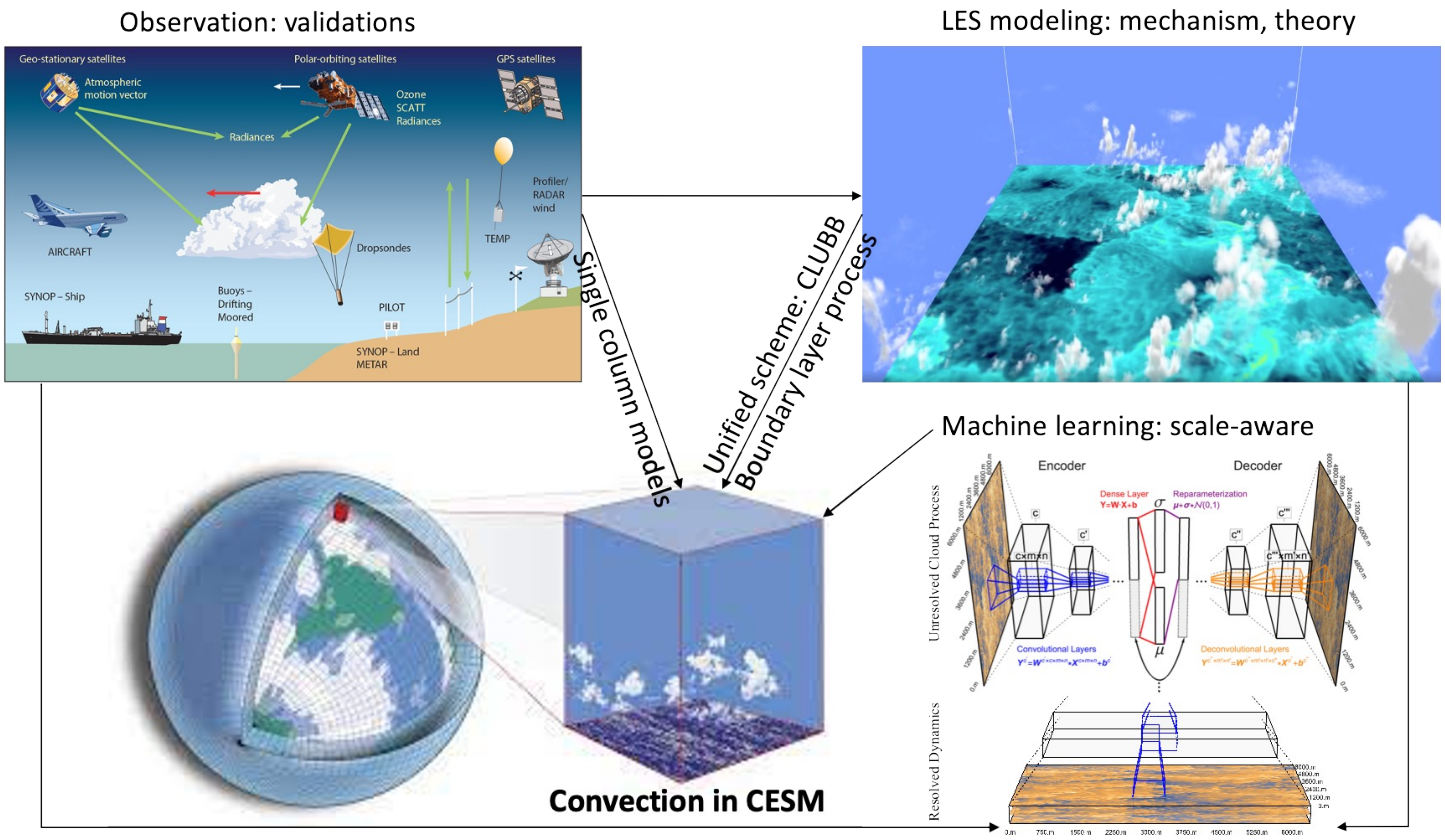


Generative adversarial network (GAN)



Our newly developed GAN-style machine learning technique (RADA) can automatically identify bias and correct simulation bias diagnostically

Future perspective — An integrative framework to improve the convective process understanding and its representation in GCMs



Other issues to address:

Convective organization and memory;

Land-convection coupling;

Unified cloud representation across multiple temporal and spatial scales

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