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Connections Between Sub-cloud Coherent Updrafts and the Life Cycle of Maritime Shallow Cumulus Clouds in Large Eddy Simulation

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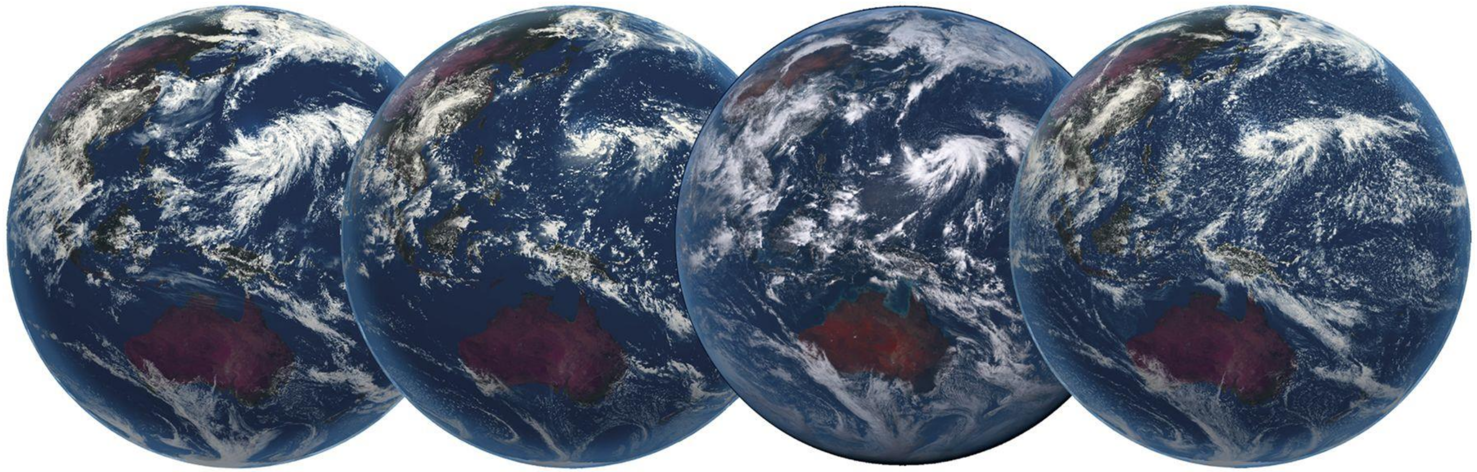
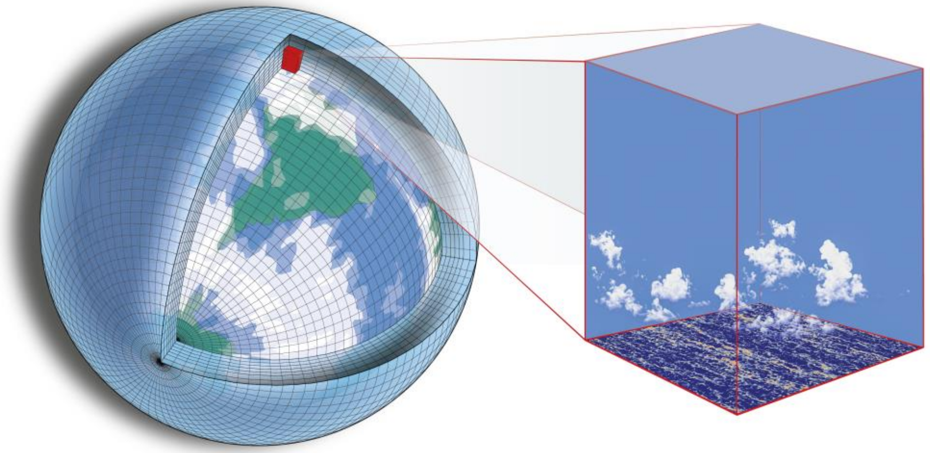
Motivation



Stevens et al. 2019

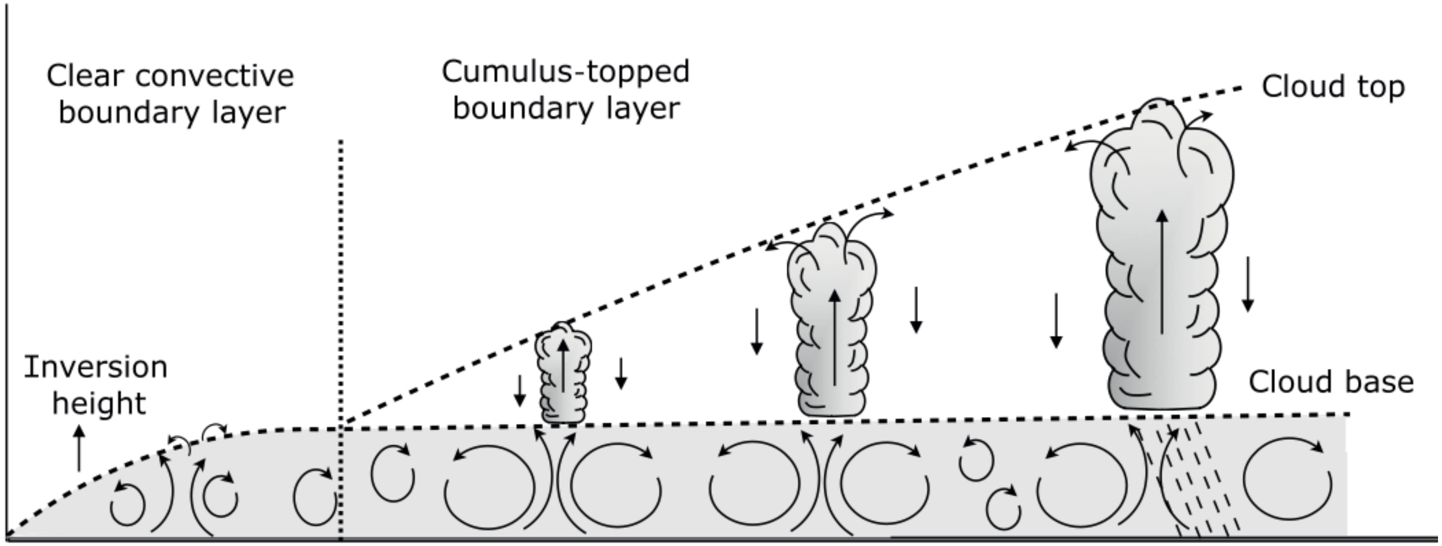


Schneider et al. 2017

Reasonable representation of various processes associated with clouds in weather and climate models is critical for accurate weather forecast and reliable climate projections (Sherwood et al. 2014; Bony et al. 2015; Schneider et al. 2017; Siebesma et al. 2020).

Unified Parameterization

Unified parameterizations were proposed to minimize the inconsistency between different parameterizations of boundary layer turbulence, shallow convection and deep convection.

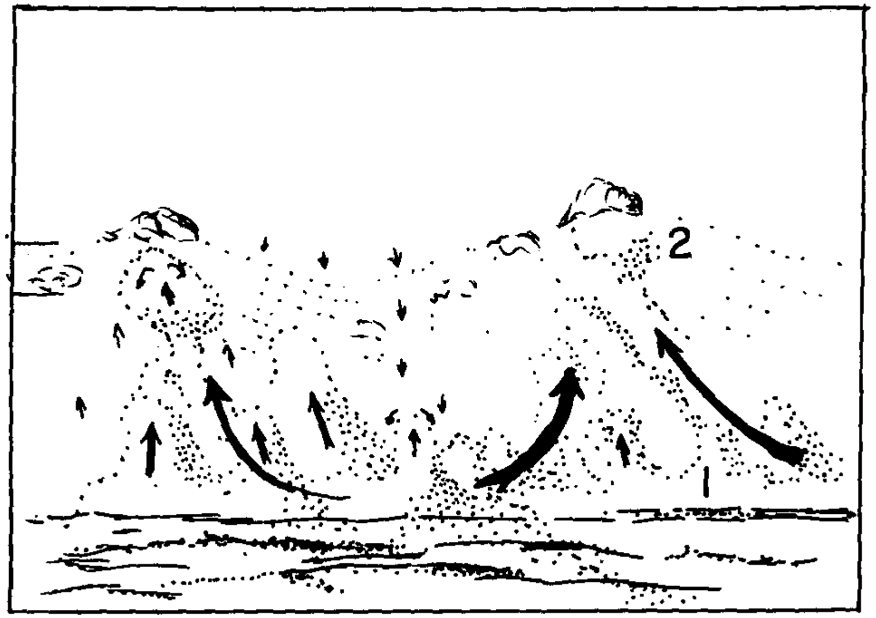


Siebesma et al. 2020

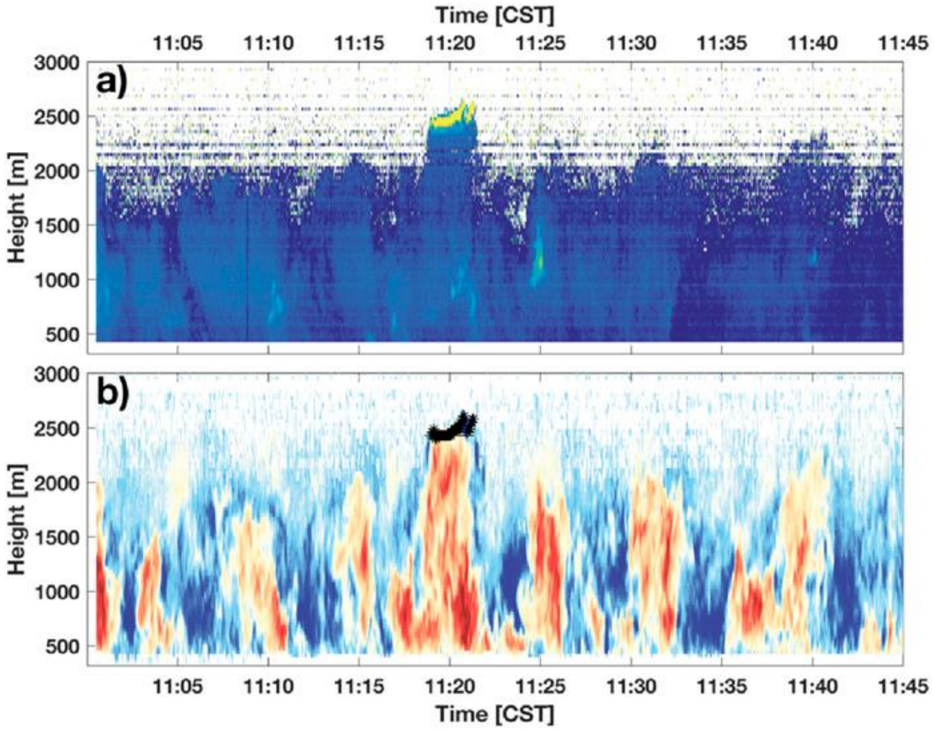
Mass Flux Framework (e.g. Eddy-Diffusivity Mass Flux/EDMF, Siebesma and Teixeira 2000; Siebesma et al. 2007; Suselj et al. 2019 **)**

Joint Probability Distribution (e.g. CLUBB, Larson et al. 2000; Golaz and Larson 2002a,b; Larson and Golaz 2005; Larson 2017)

Physical Foundation of EDMF



LeMone and Pennell 1976



Lareau et al. 2018

Cumulus clouds are rooted in the sub-cloud boundary layer

Assumptions in parameterization:

Steady state; Sub-cloud coherent updrafts terminated once cease ascending; constant area fraction

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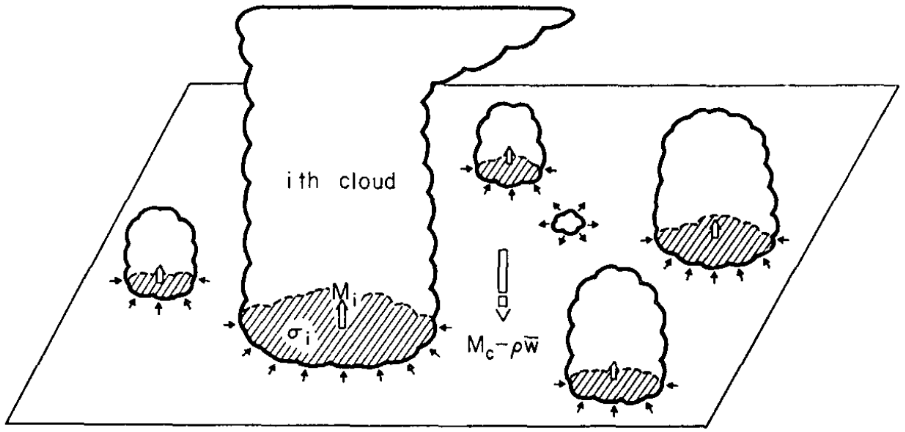
Challenges

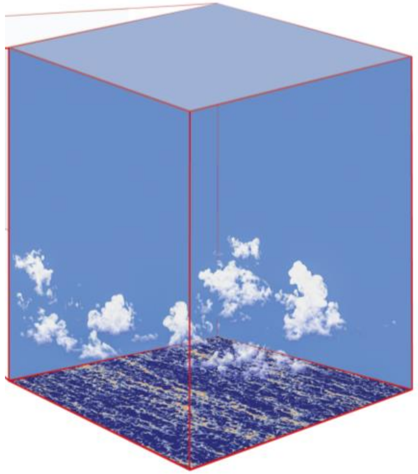
Macroscopic: Equilibrium ……

Microscopic: Evolutionary ……



Arakawa and Schubert 1974

Increased Resolution



Schneider et al. 2017

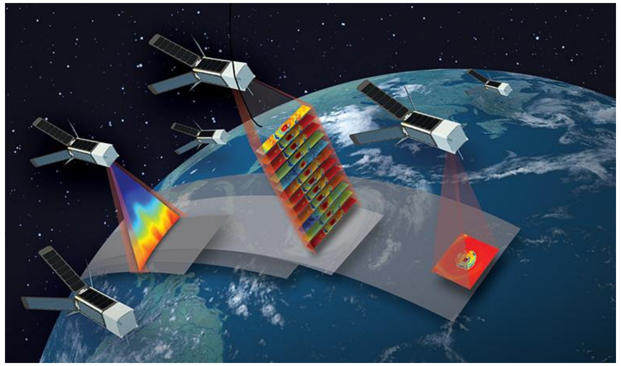
Considering cloud evolution can help improve convection schemes to more reasonably capture the transition between shallow and deep convection (Kairoutdinov and Randall 2002; Kuang and Bretherton 2006), the spatial organization of convection (Neggers and Griewank 2021, 2022).

How do sub-cloud coherent updrafts affect cloud evolution?

(trigger, evolution, dissipation)

Challenges

We lack appropriate methods to directly detect the subcloud-cloud coupling during the cloud life cycle.



Satellite

Contiunous monitoring

Lack information in the sub-cloud layer

Ground based observations

Sub-cloud structures detection

Lack of continuous cloud tracking

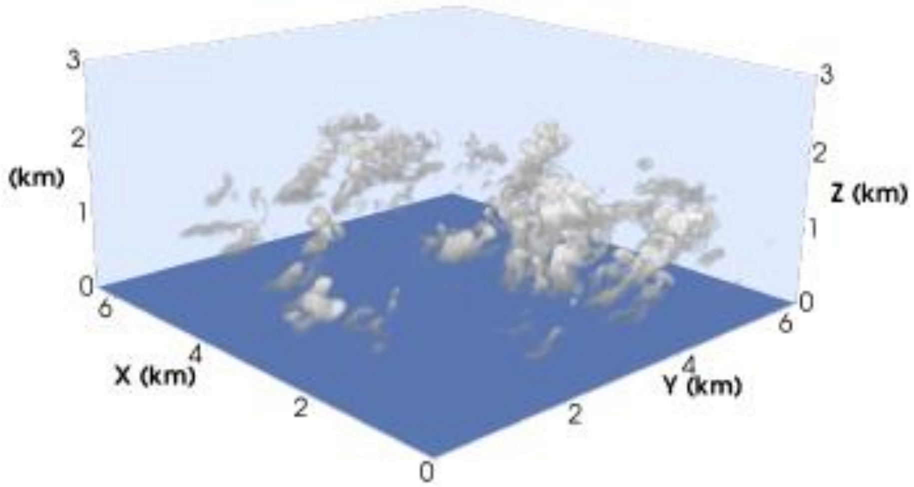
Methodology

- **Large eddy simulation**
- **BOMEX** (Met Office-NERC Cloud model)

  25 m resolution (both horizontal and vertical)

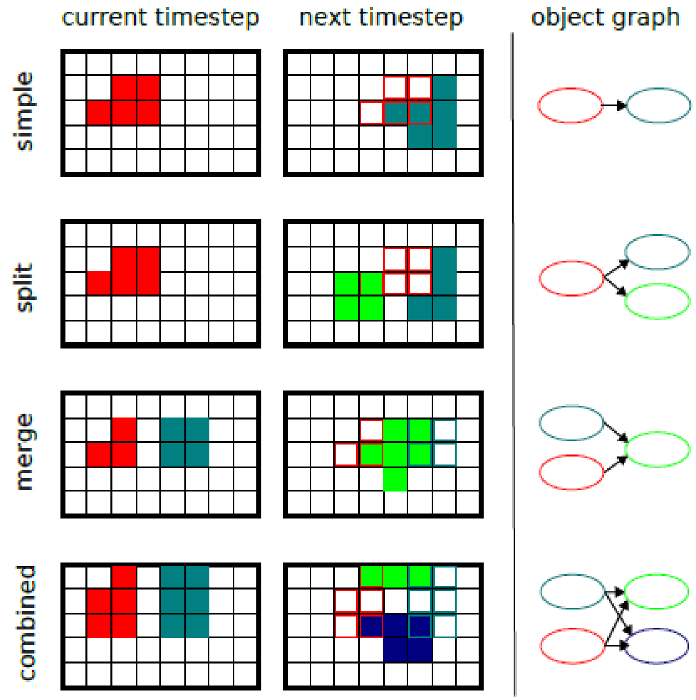
  3D Smagorinsky turbulence scheme

  1 min output frequency

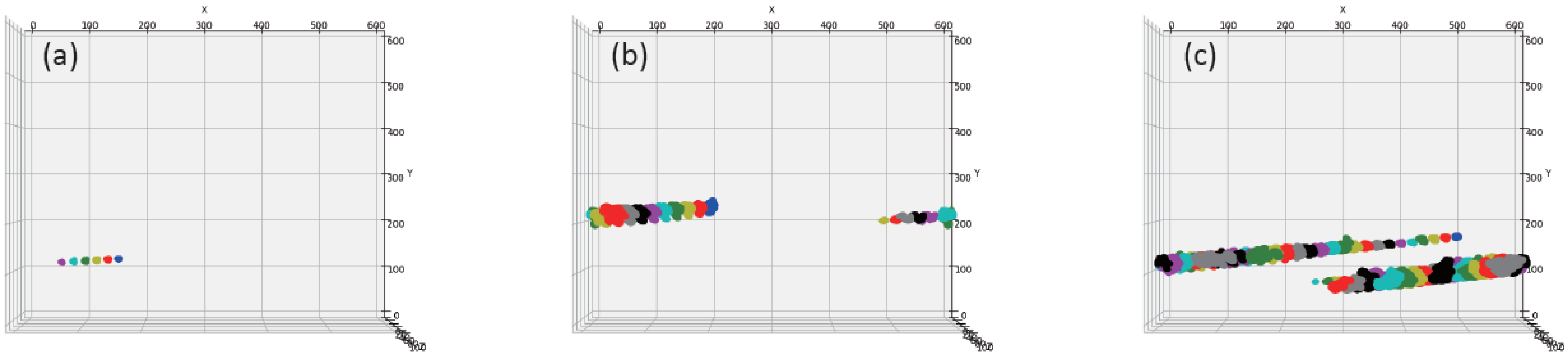


- **3D Cloud tracking**
- An extension of Muetzelfeldt's 2D cloud tracking algorithm
- For complicated life cycles, only the cloud object that has the closest cloud depth with previous time is kept.

Muetzelfeldt 2020; Gu et al. 2020



Cloud Object Tracking

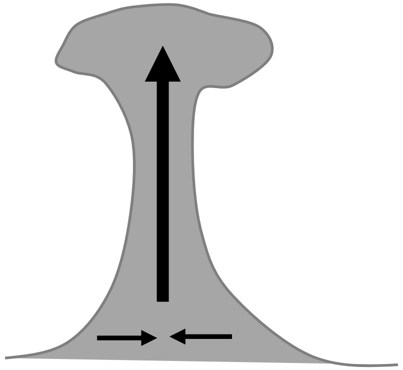


How can we detect the presence of sub-cloud coherent updrafts?

Subcloud Coherent Updrafts

Passive tracers: A passive tracer is emitted from the surface with a constant surface flux and undergoes a radioactive decay at a constant time scale τ_0

$$\frac{\partial C}{\partial t} = -\frac{C}{\tau_0}$$

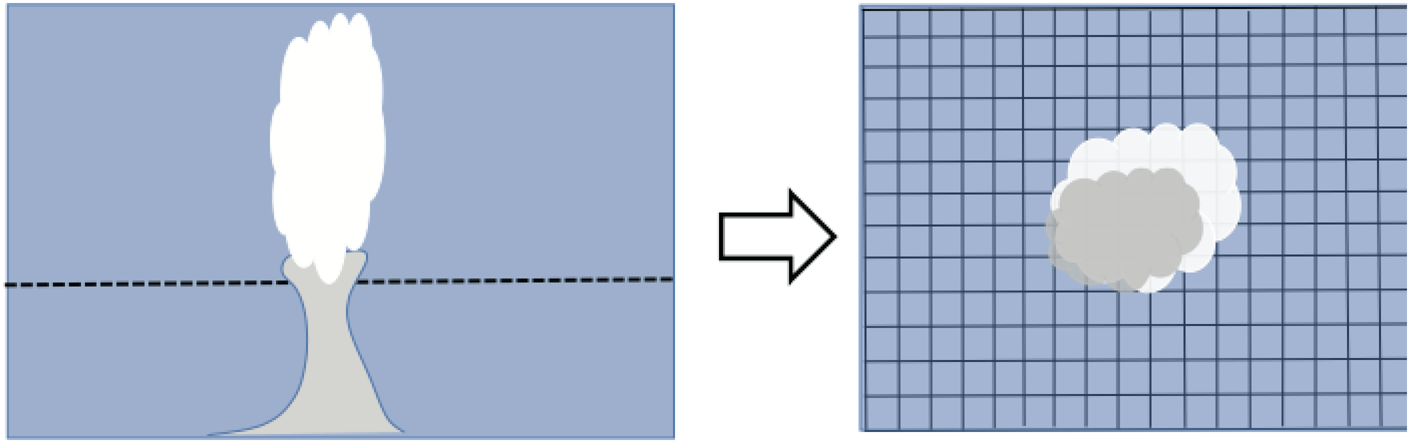


Subcloud coherent updrafts (Couvreux et al. 2010**):**

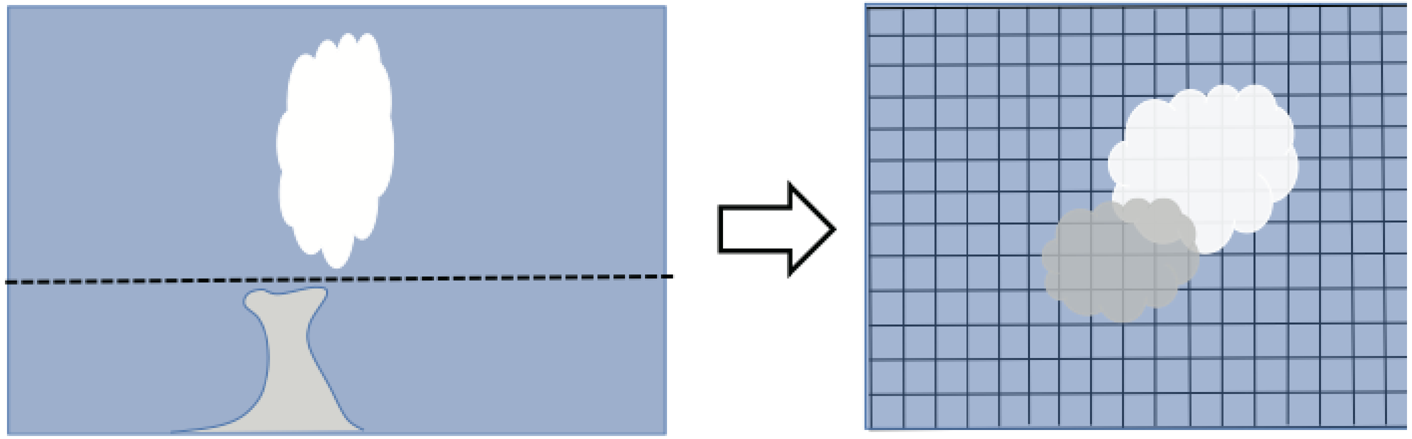
$$x \in SCU \text{ if } C' > m \times \max(\sigma_C, \sigma_{\min}) \;\&\; w > 0,$$

Find the grid points that satisfy the above criterion, and identify the sub-cloud coherent updrafts in a similar way to the cloud object identification.

Cloud-subcloud Coupling Detection

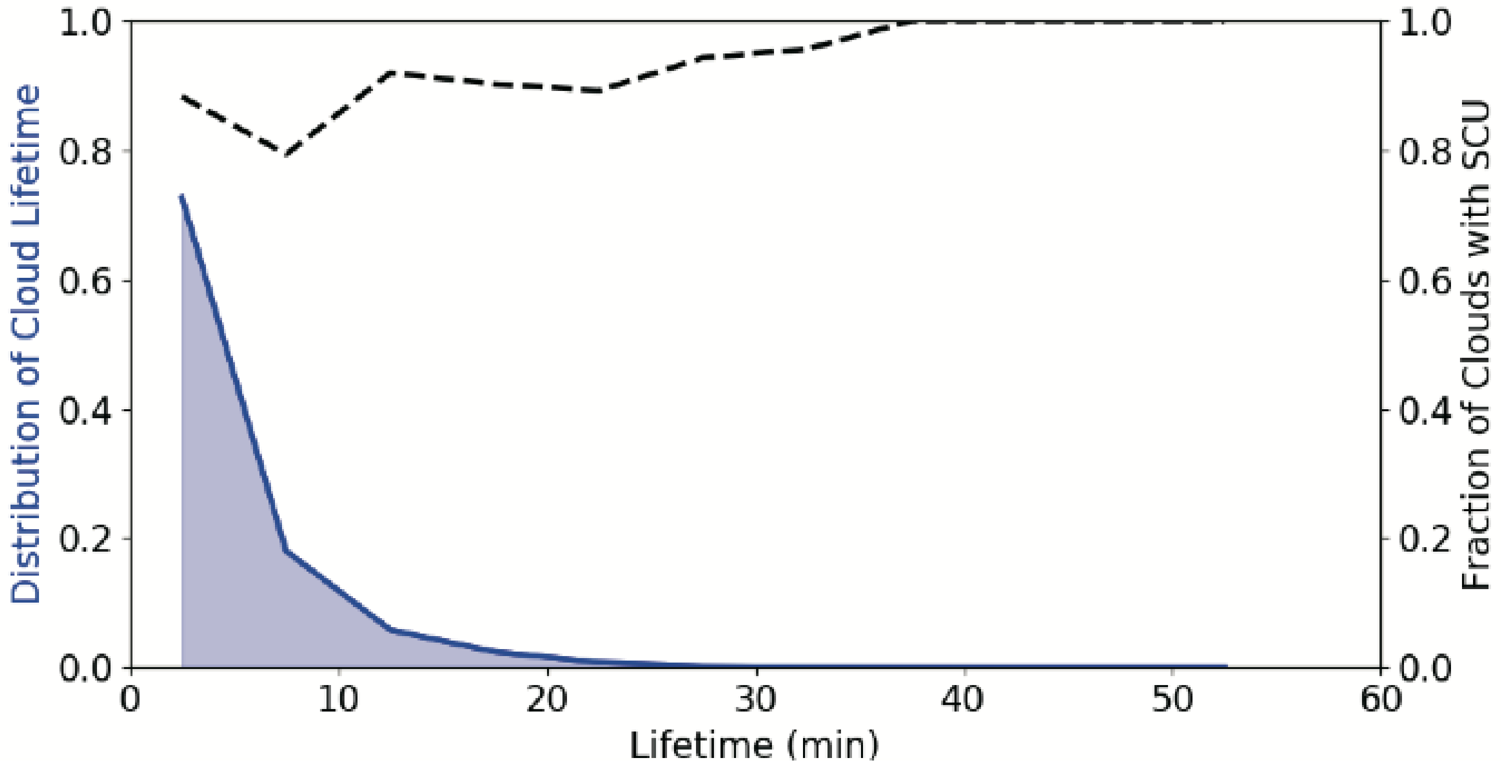


Direct Connection



Indirect Connection

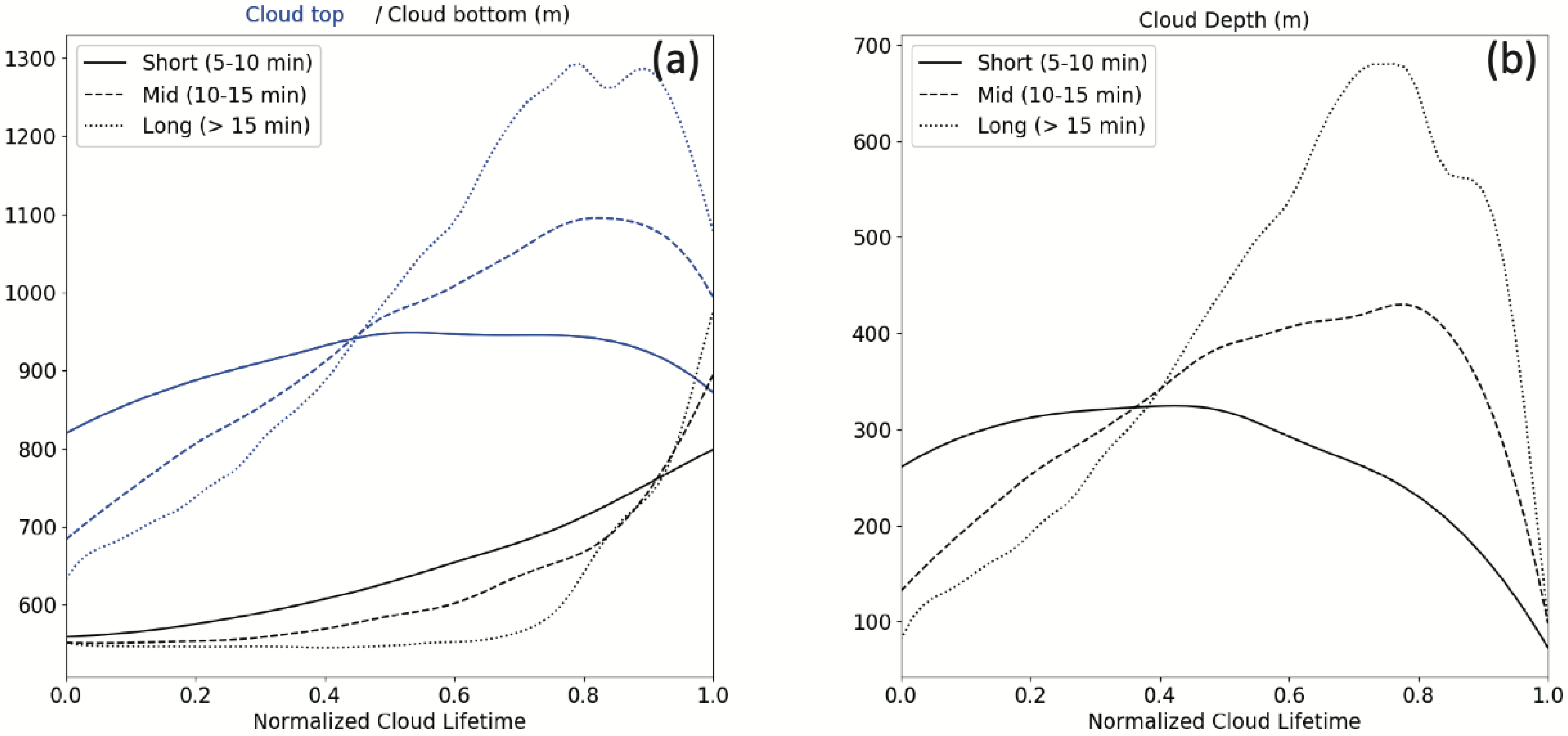
Cloud-subcloud Coupling



Most of the shallow cumulus clouds are connected with the sub-cloud coherent updrafts;

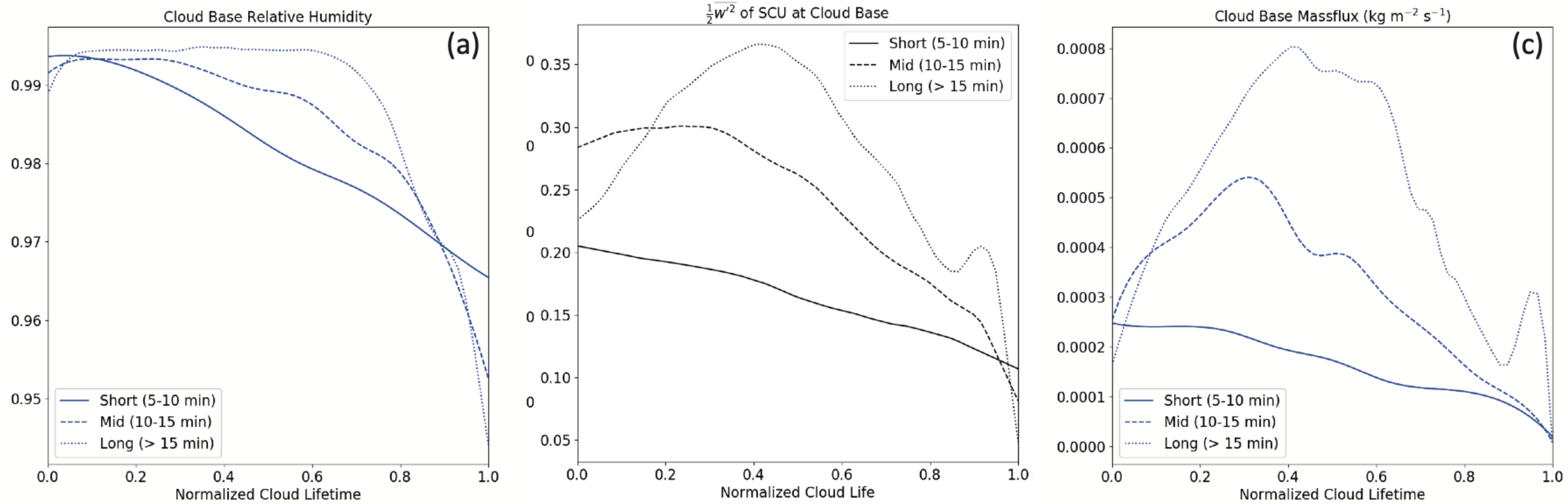
Longer lived clouds are 100% connected with sub-cloud coherent updrafts;

Cloud Life Cycle



- Cloud base starts to rise before cloud top stops ascending.
- Cloud base approaches cloud top during decaying stage.

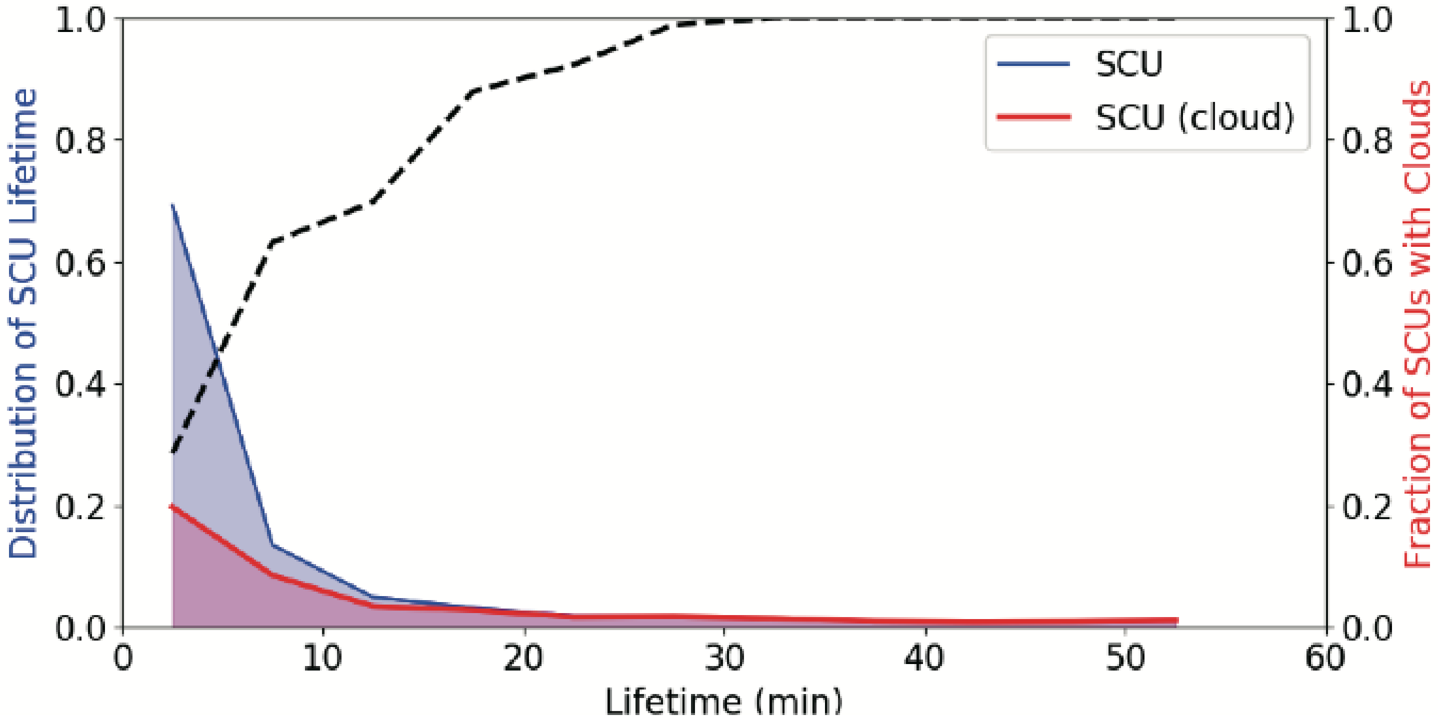
Cloud Life Cycle



云底相对湿度　　云底SCU垂直动能　　云底垂直质量通量

- Longer lived clouds have longer periods of higher relative humidity in normalized life time.
- Longer lived clouds have stronger cloud base massflux due to larger cloud base area coverage.
- The evolution vertical velocity variance of SCU at cloud base leads that of clouds.

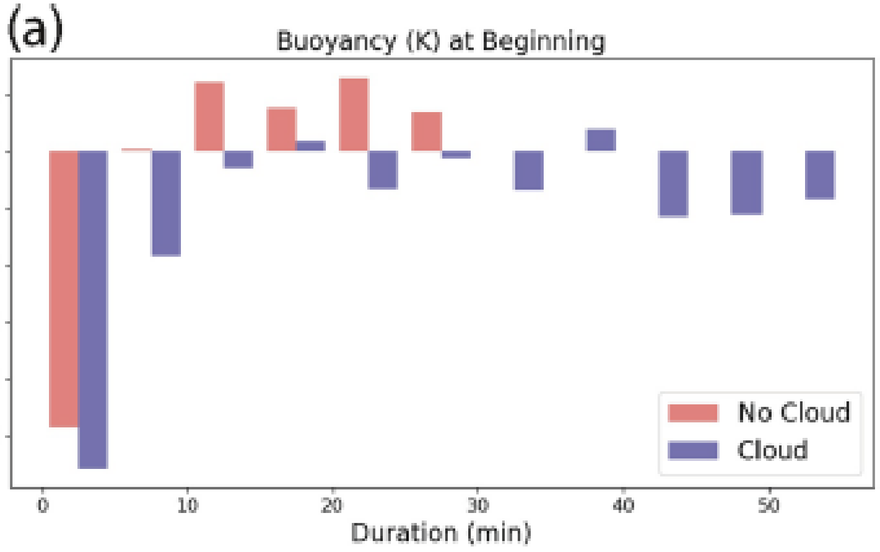
Cloud-subcloud Coupling

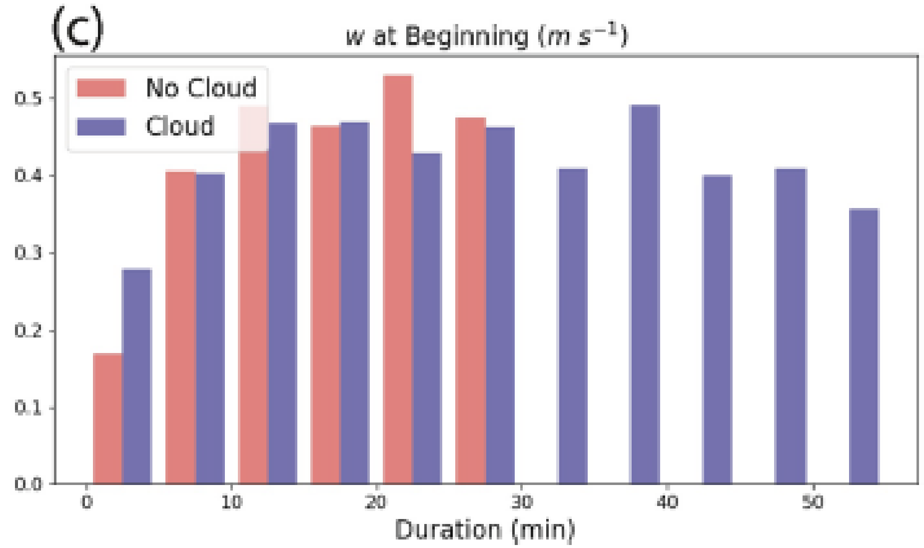


- Longer lived subcloud coherent updrafts are more likely to be associated with shallow cumulus clouds.

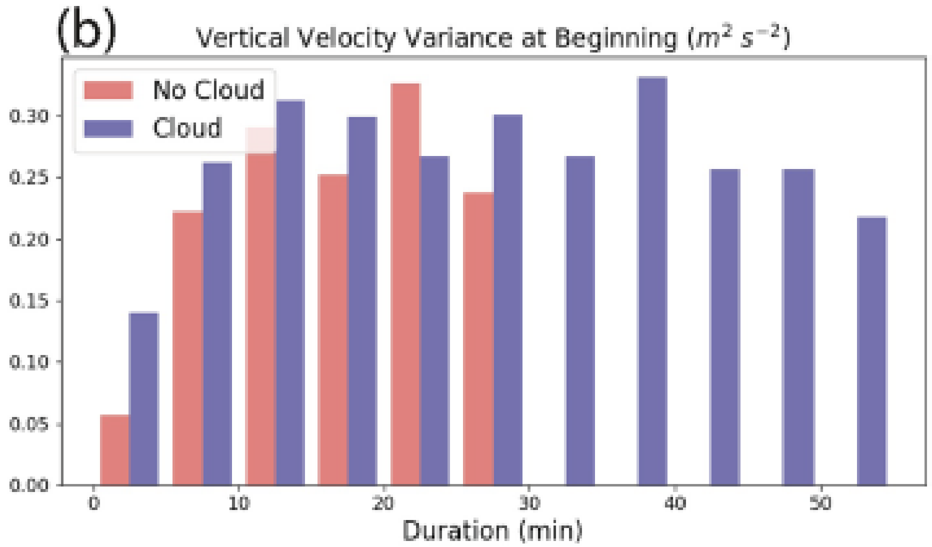
- Positive feedback are present between subcloud updrafts and shallow cumulus clouds.

From Sub-cloud updraft to Clouds

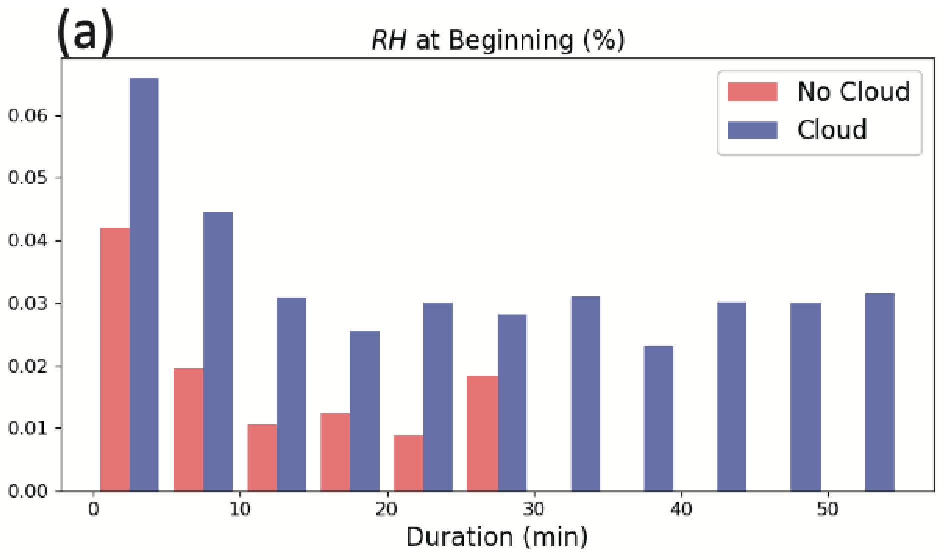


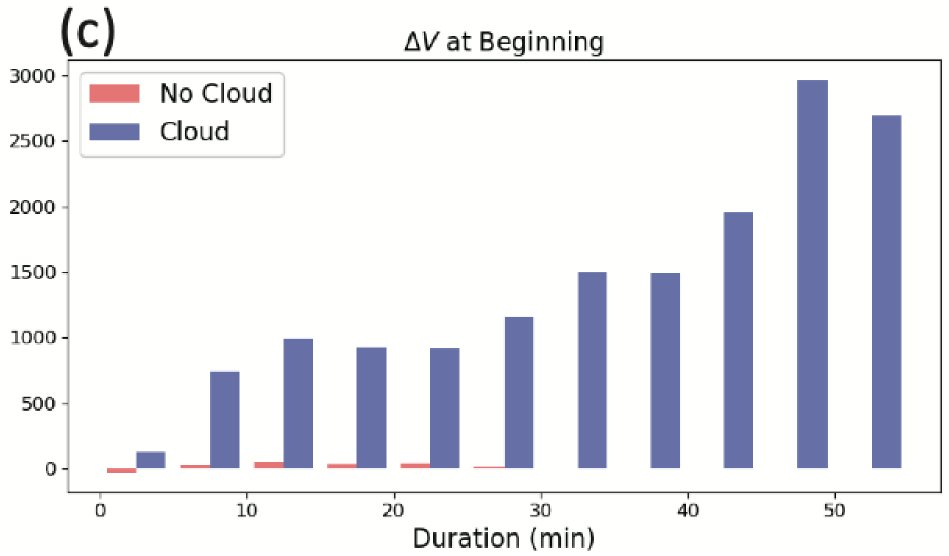


Buoyancy and vertical velocity are not good indicators of cloud triggering.

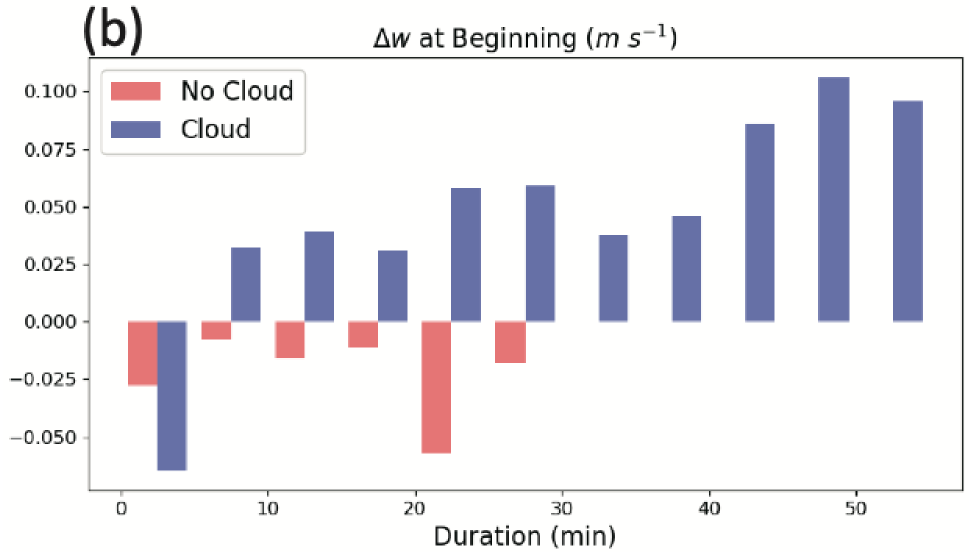


From Sub-cloud updraft to Clouds

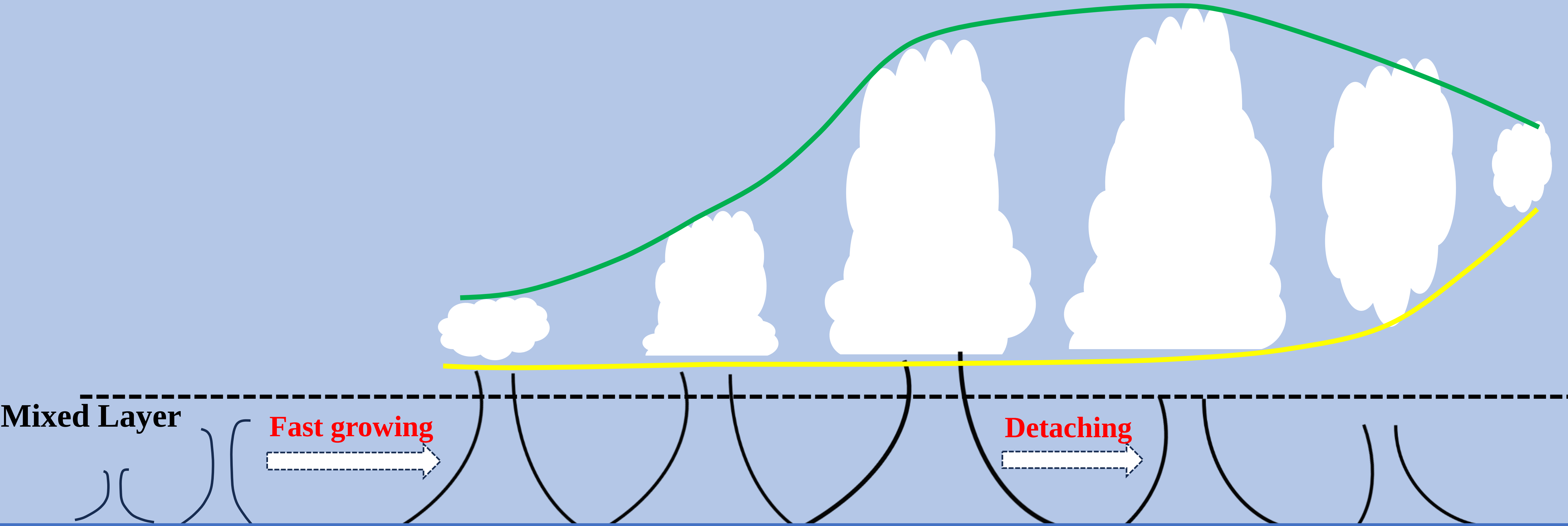




Fast growing and accelerating sub-cloud updrafts in humid regions are more likely to form clouds.



Conceptual Model



- Clouds are likely to be triggered by the humid faster growing sub-cloud coherent structures and start to dissipate without their ongoing support

- The evolution of cloud base mass-flux depends on cloud lifetime and is asymmetric around the middle of life for short and mid-lived clouds

What can we learn?

Cloud dynamics:

1. Sub-cloud coherent structures are essential for cloud life cycle. But what controls the activity of sub-cloud coherent structures?

2. The vertical acceleration and volume of sub-cloud coherent updrafts are important for cloud triggering. The dynamics of dry updrafts in the sub-cloud layer need further exploration.

Convection Parameterization:

1. Massflux based spectral cloud model and extended EDMF model

2. Not every sub-cloud updrafts that penetrate the cloud base can trigger shallow clouds

3. Cloud does not dissipate immediately when support from sub-cloud coherent updrafts terminate.

What can we learn?

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Observations:

We need new observational techniques to verify the results in large eddy simulations and improve the large eddy models.

Gu, J.-F.*, R. S. Plant, and C. E. Holloway, 2024: Connections between sub-cloud coherent updrafts with the life cycle of maritime shallow cumulus clouds in large eddy simulations. *Journal of Advances in Modeling Earth Systems*, **16**, e2023MS003986.