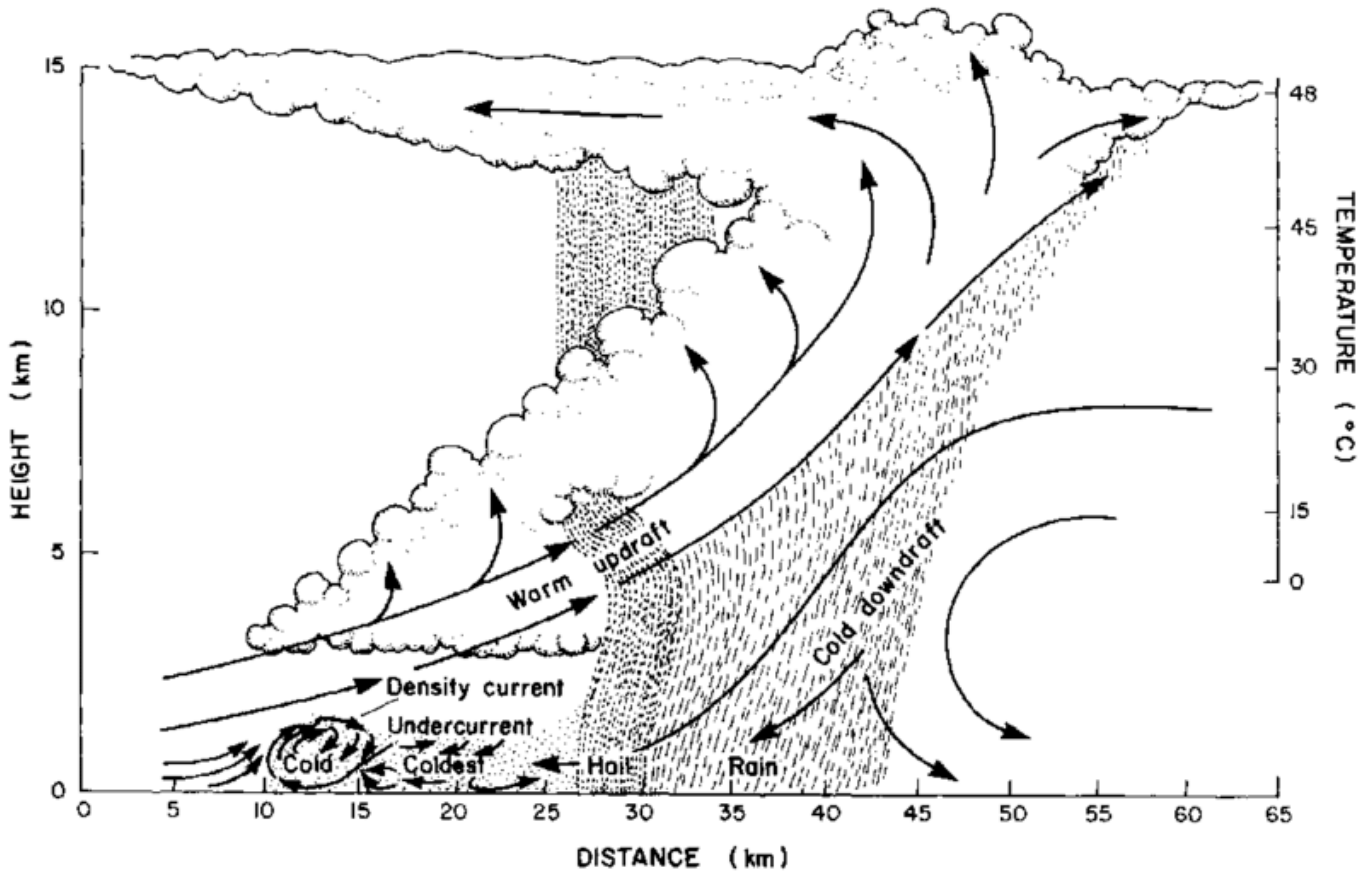
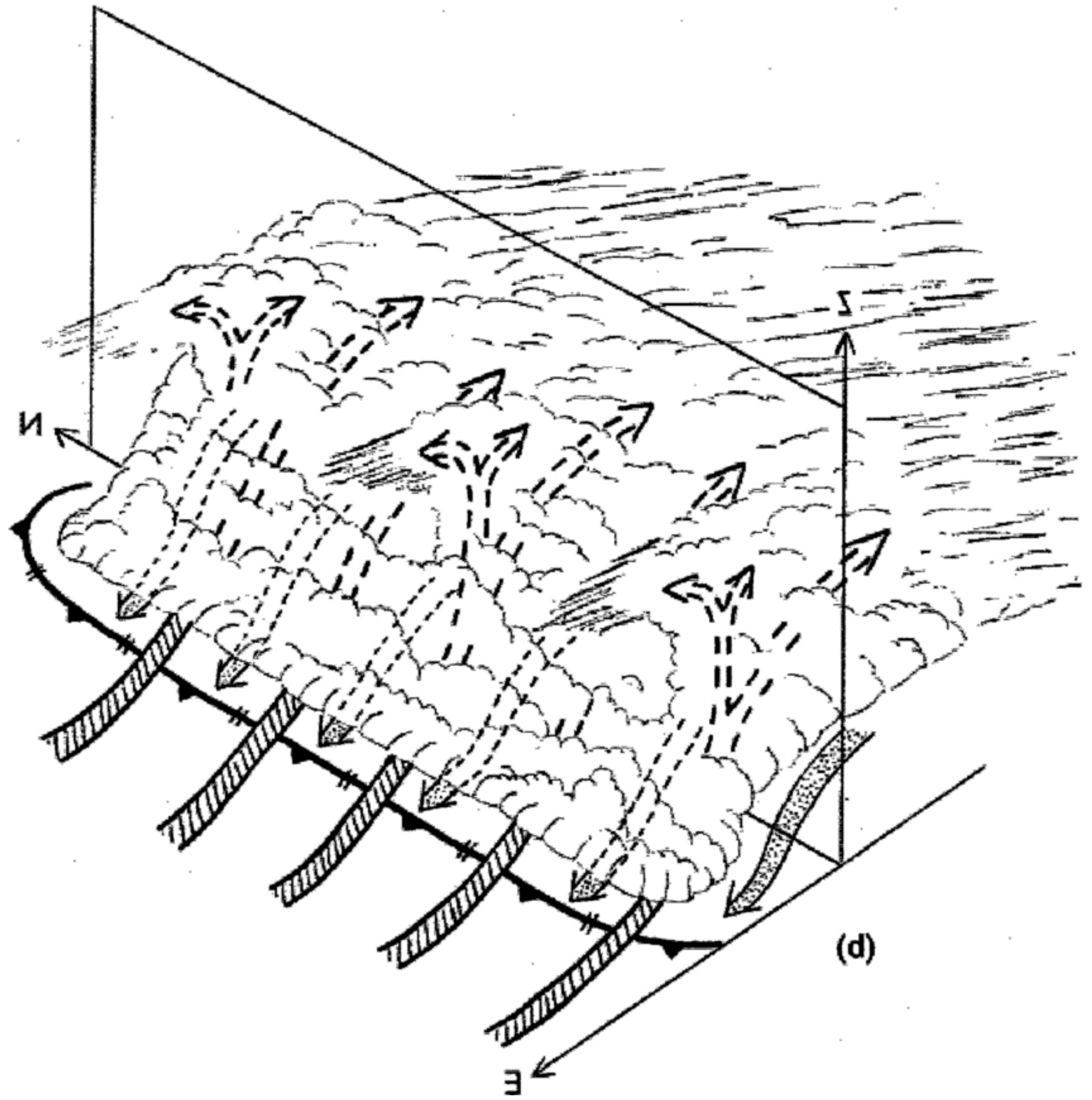
Squall Lines Orientation and its Impact on Precipitation Extremes

3RD PAN-GASS Meeting Understanding and Modeling Atmospheric Processes, Monterey, July 25-29 2022





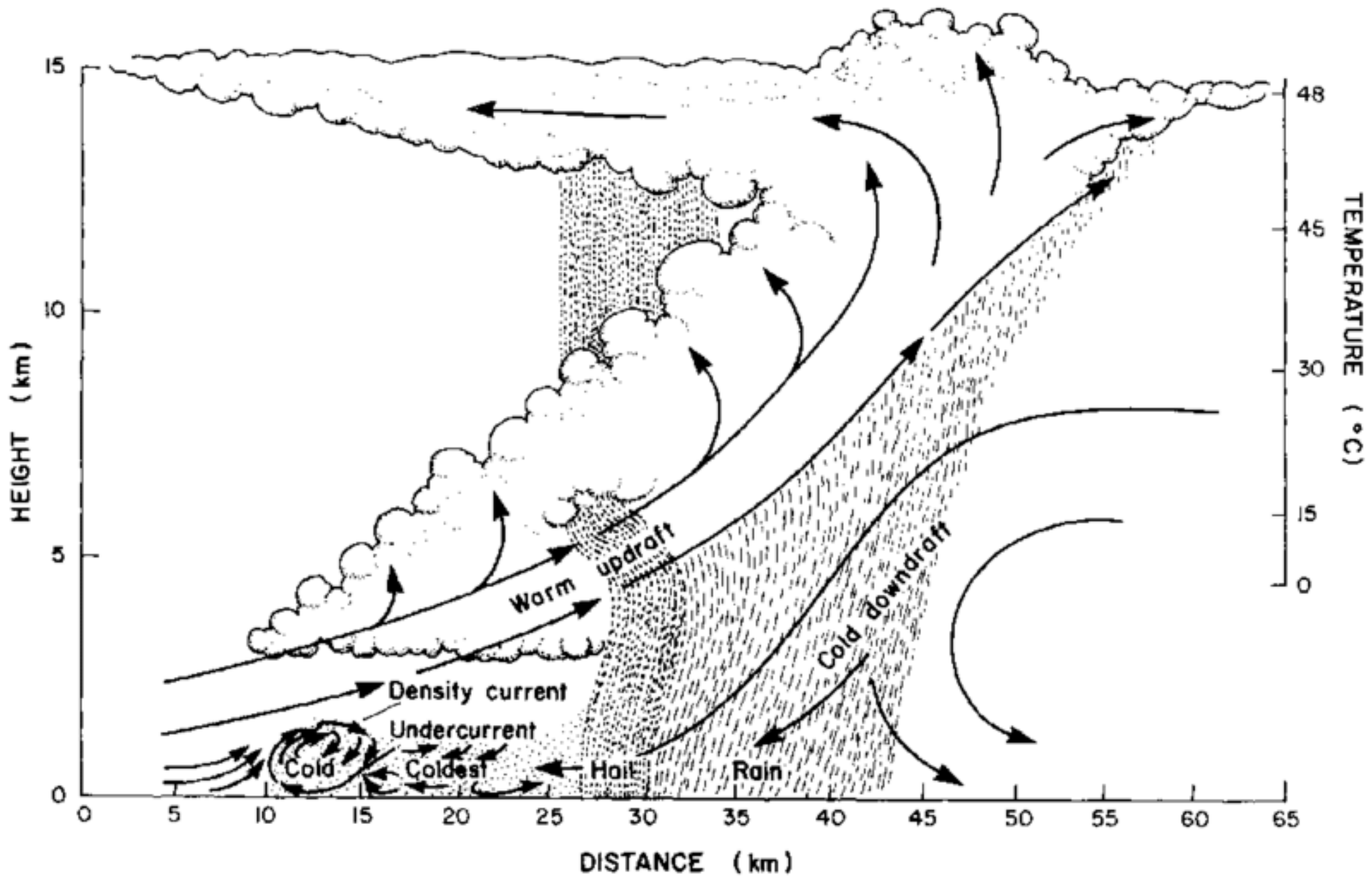
Sophie Abramian

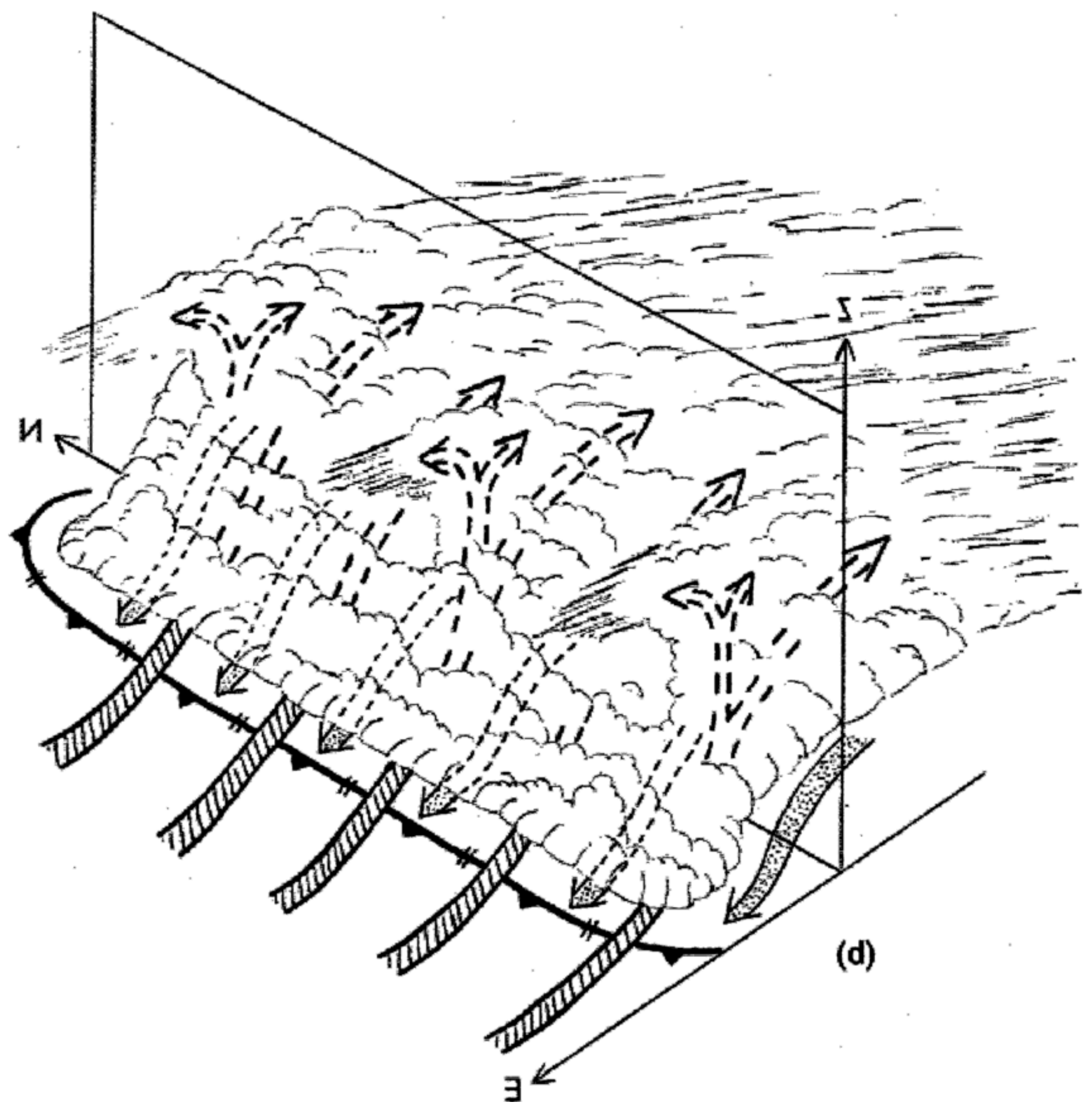
Under the supervision of :

Caroline Muller, Institute of Science and Technology, Vienna

Camille Risi, Laboratoire de Météorologie Dynamique, Paris

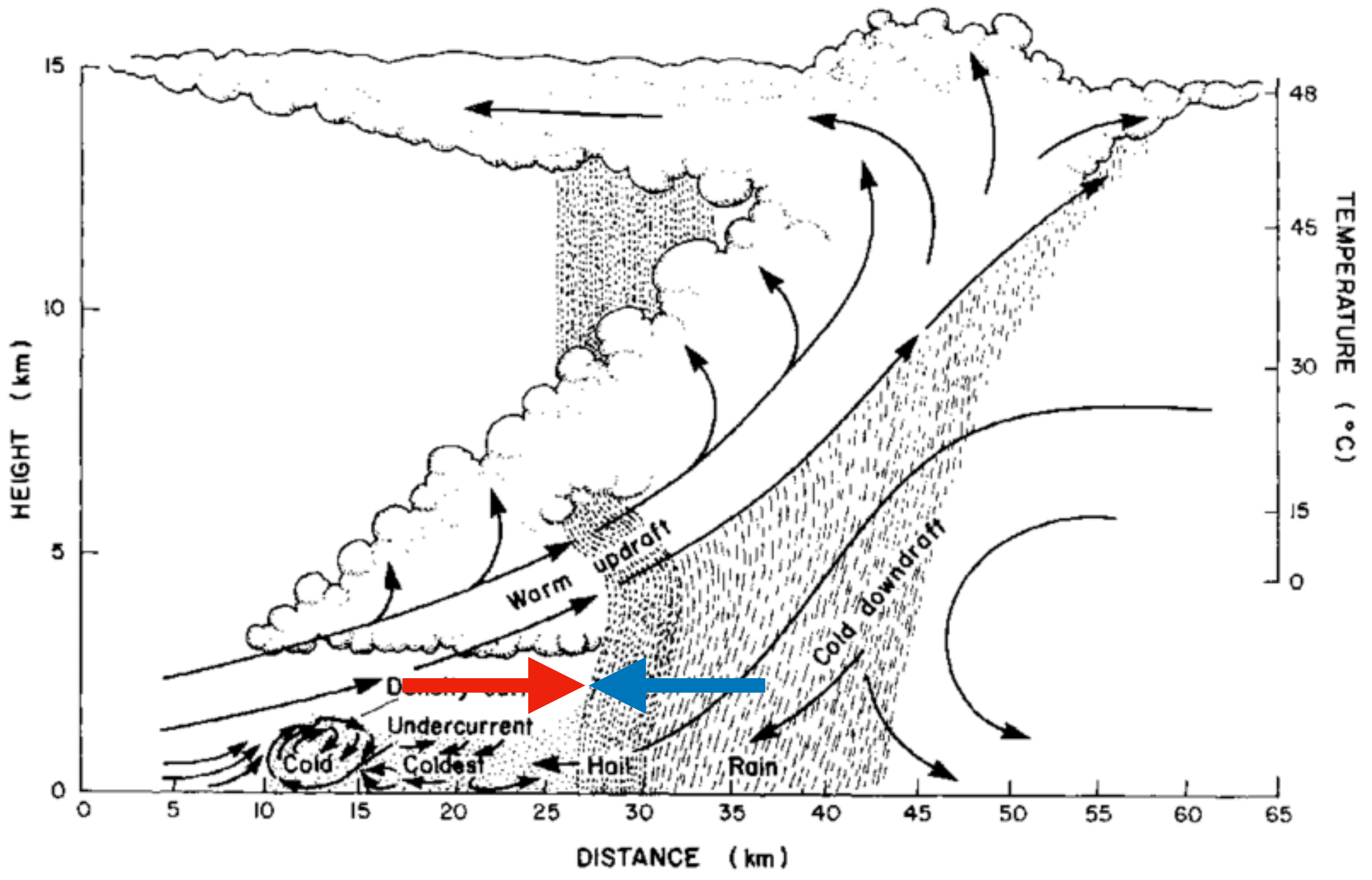
What are the physical processes responsible for squall line organization ?

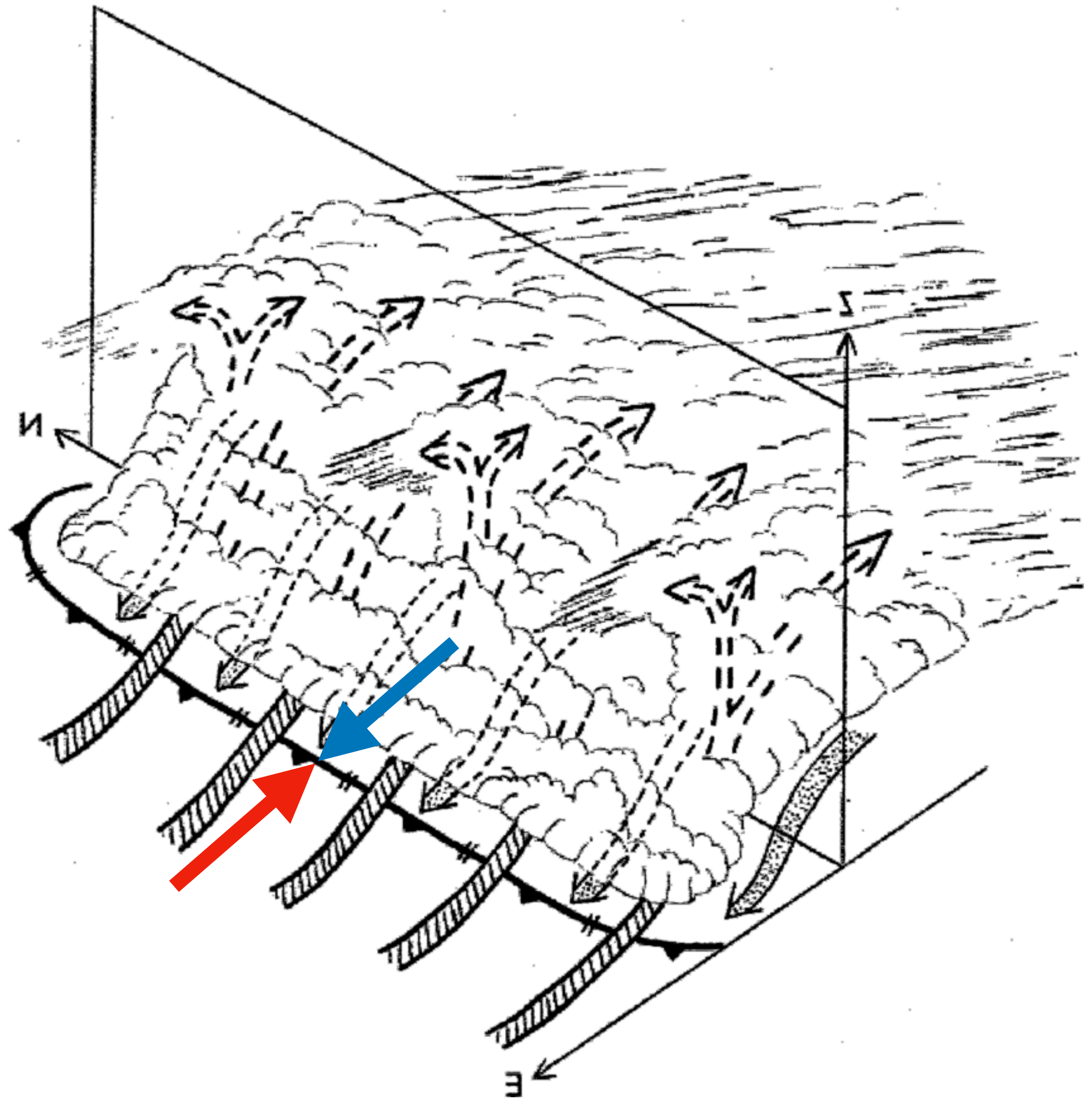




Interactions between wind shear and cold pool spreading

What are the physical processes responsible for squall line organization ?





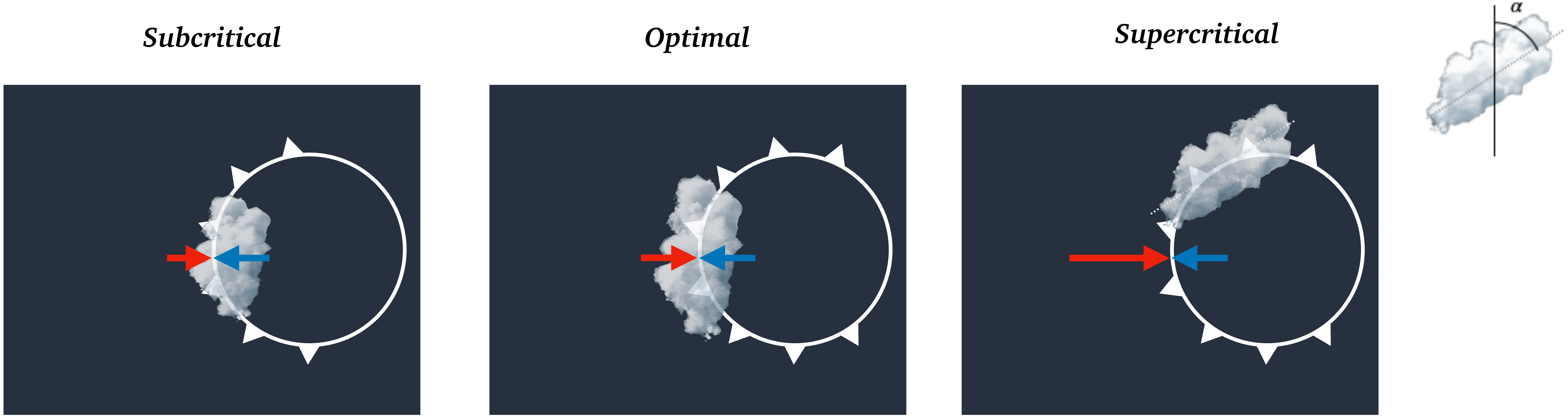
Wind Shear   *Cold Pool Spreading*

Interactions between wind shear and cold pool spreading

What are the regimes of development of Squall Lines ?

Cold Pool wins | *Equality* | *Shear wins*

Subcritical | *Optimal* | *Supercritical*



Questions

A. What sets tropical squall lines orientation, and why ?

(Abramian et al 2021, GRL)

B. What is the effect of the orientation on extreme precipitations ?

(In Prep Abramian et al 2022, JAMES)

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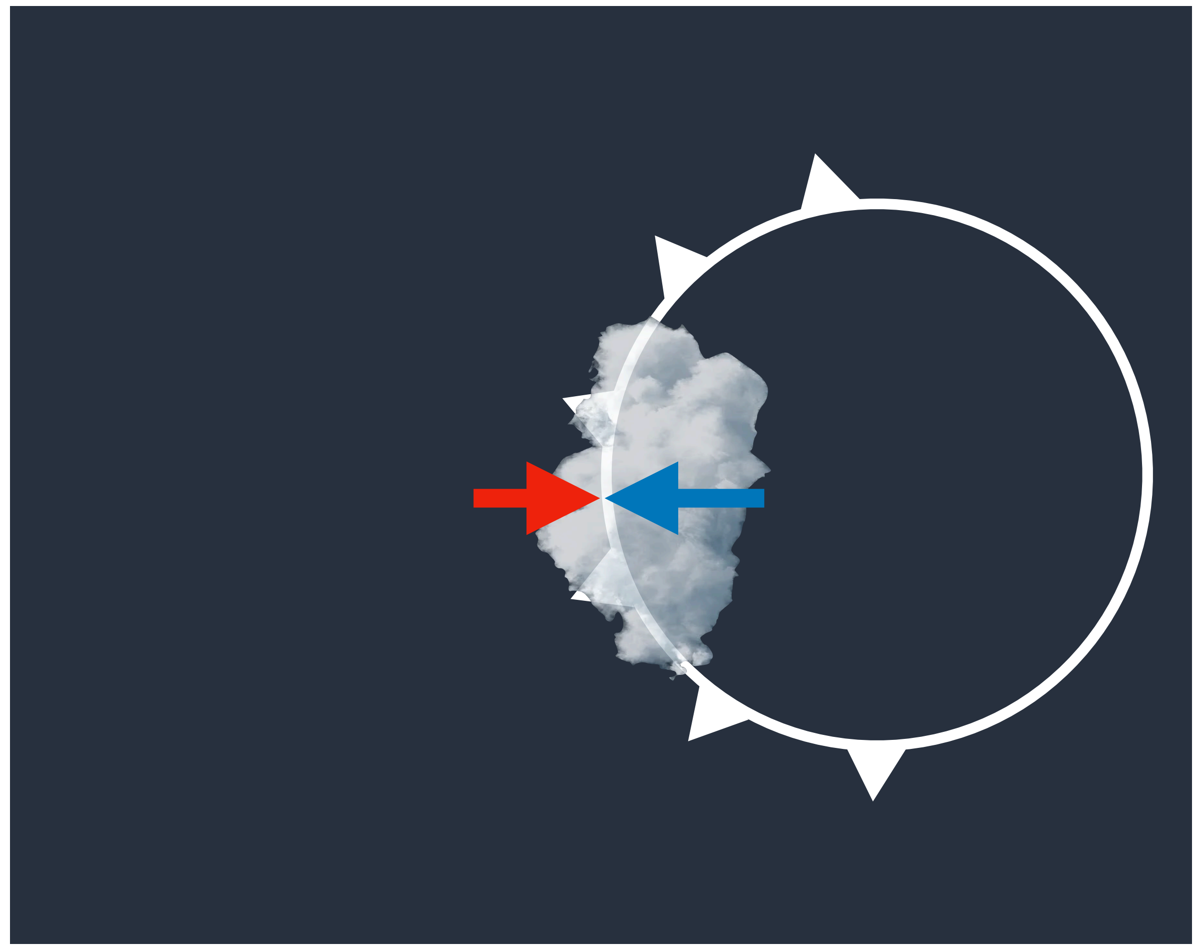
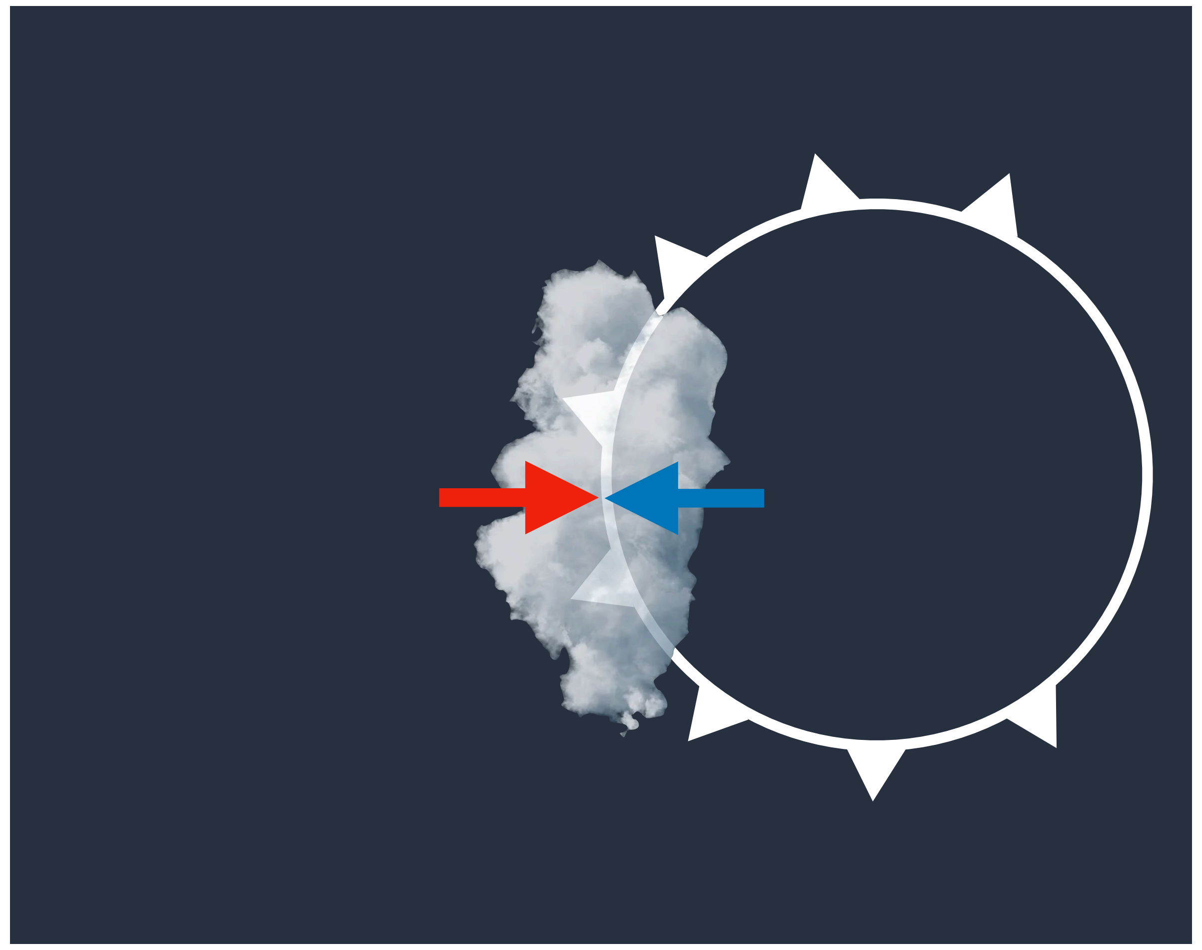
Hypothesis for Orientation of Squall Lines

Cold Pool wins ***Equality*** ***Shear wins***

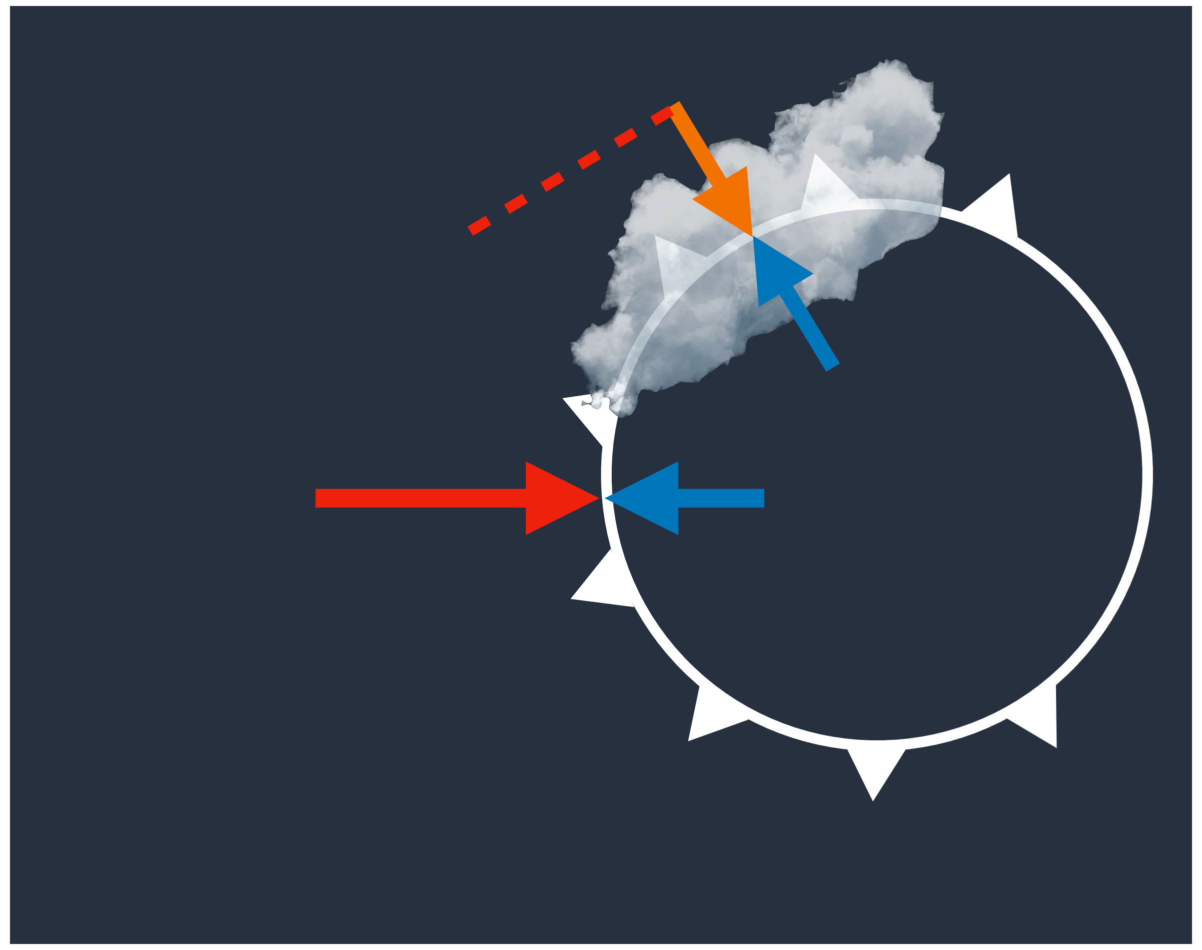
Subcritical



Optimal

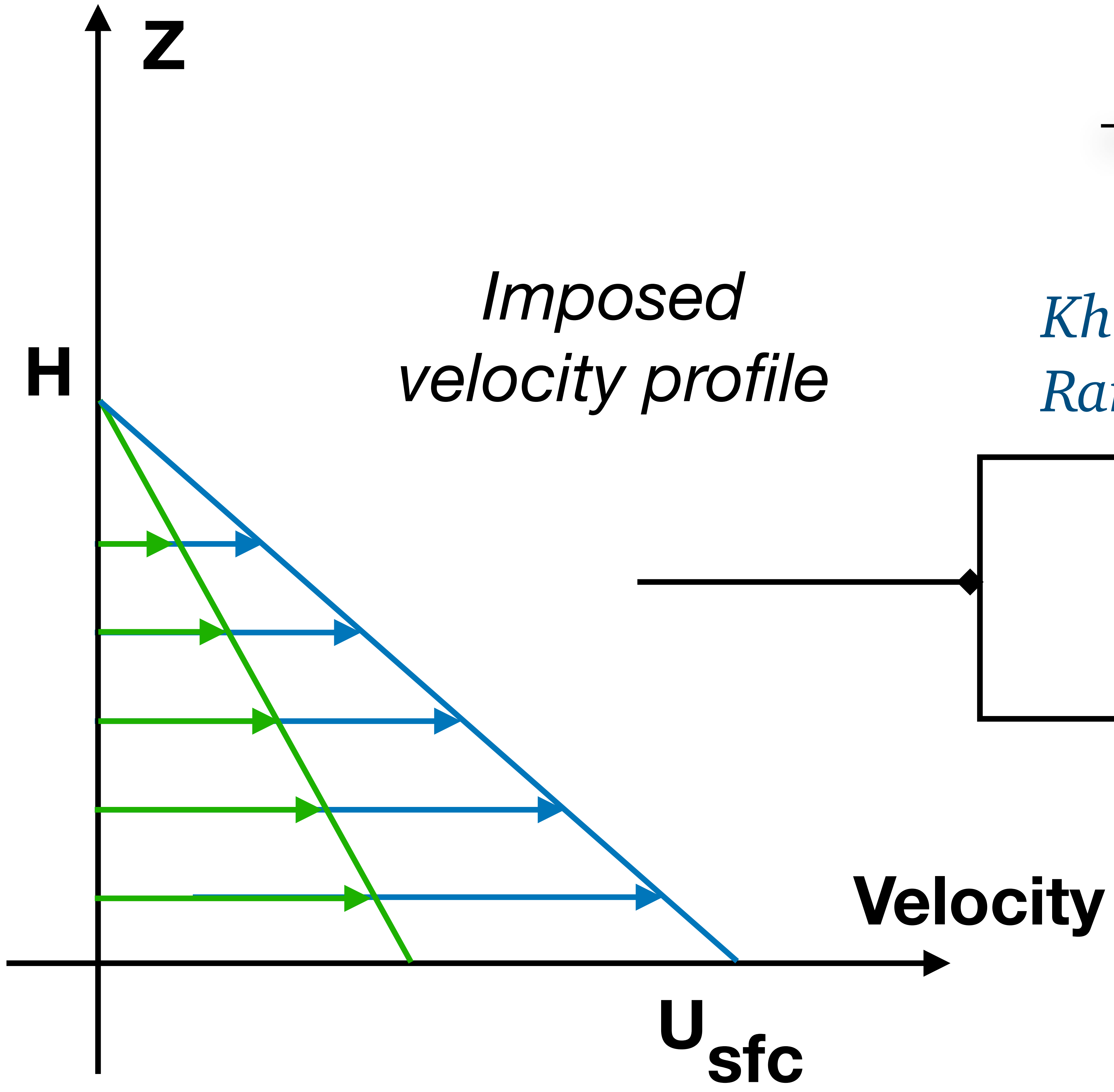


Supercritical



Rotunno, Klemp, Weisman (RKW) 1988,
Robe & Emmanuel, 2001

Methodology

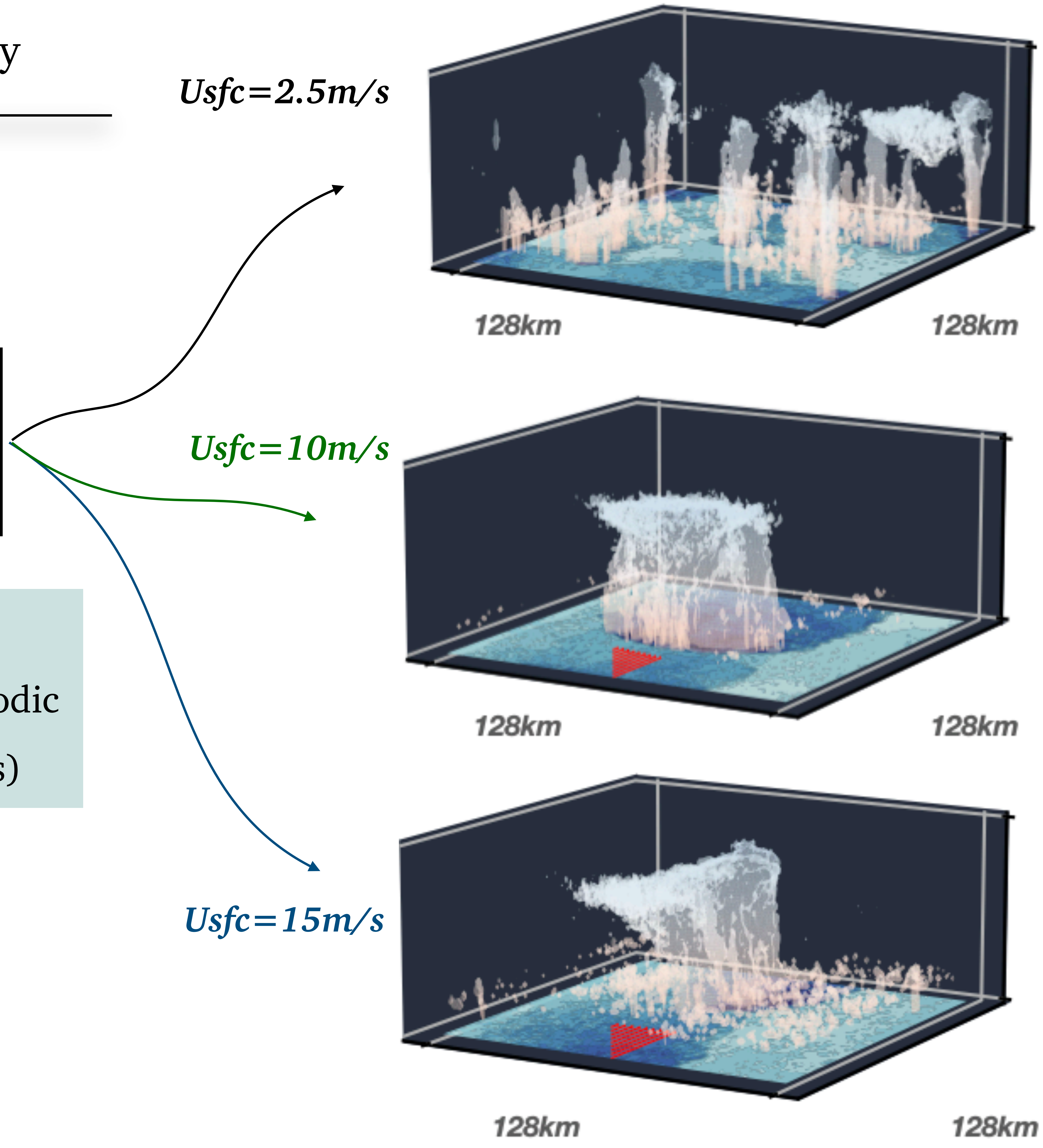


- Basal velocity $\mathbf{U_{sfc}}$: [0 , 20] m/s, by steps of 2.5 m/s
- Shear depth **H** : 1000m

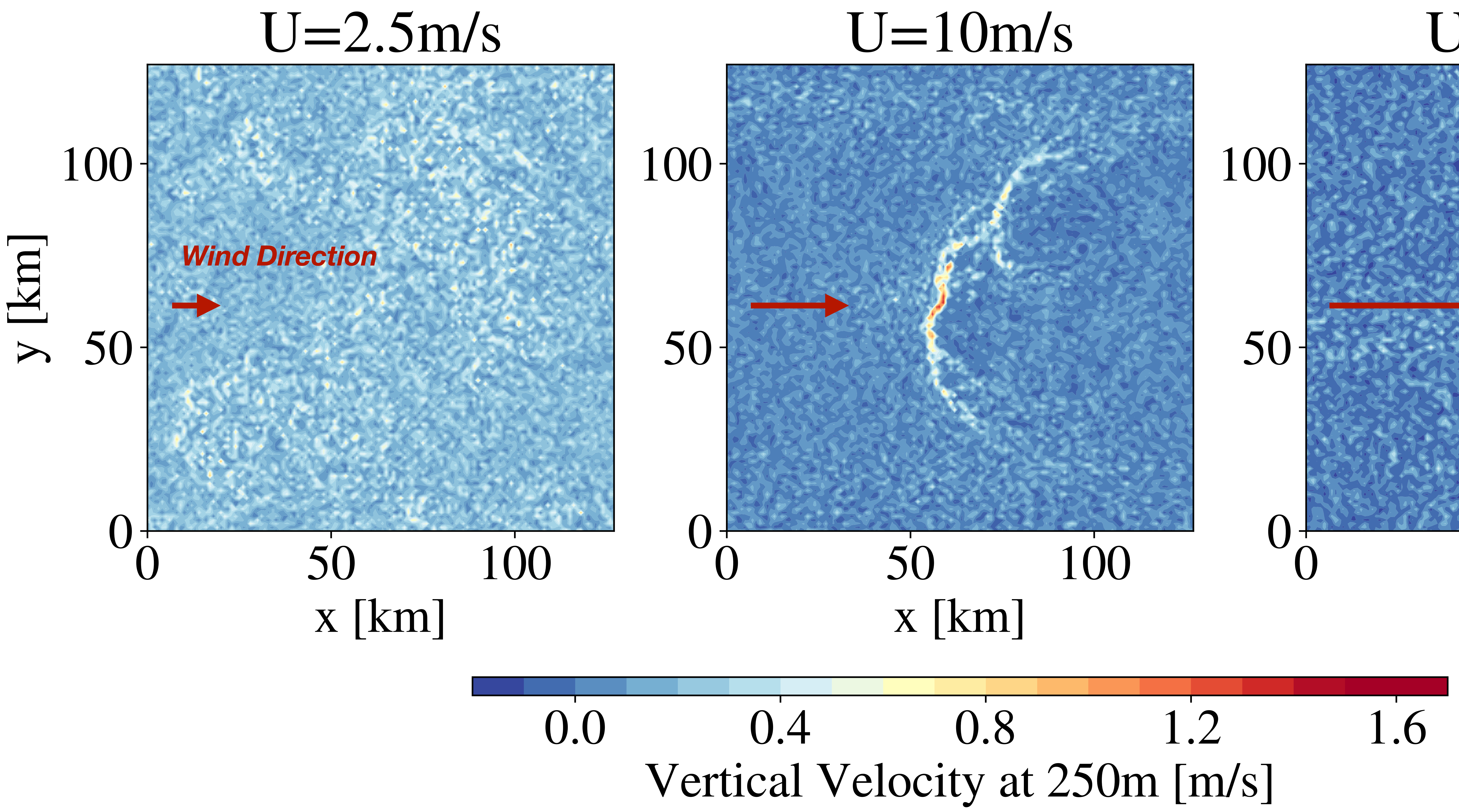
Khairoutdinov & Randall 2003

CRM SAM

- RCE
- Doubly periodic
- f=0 (Tropics)

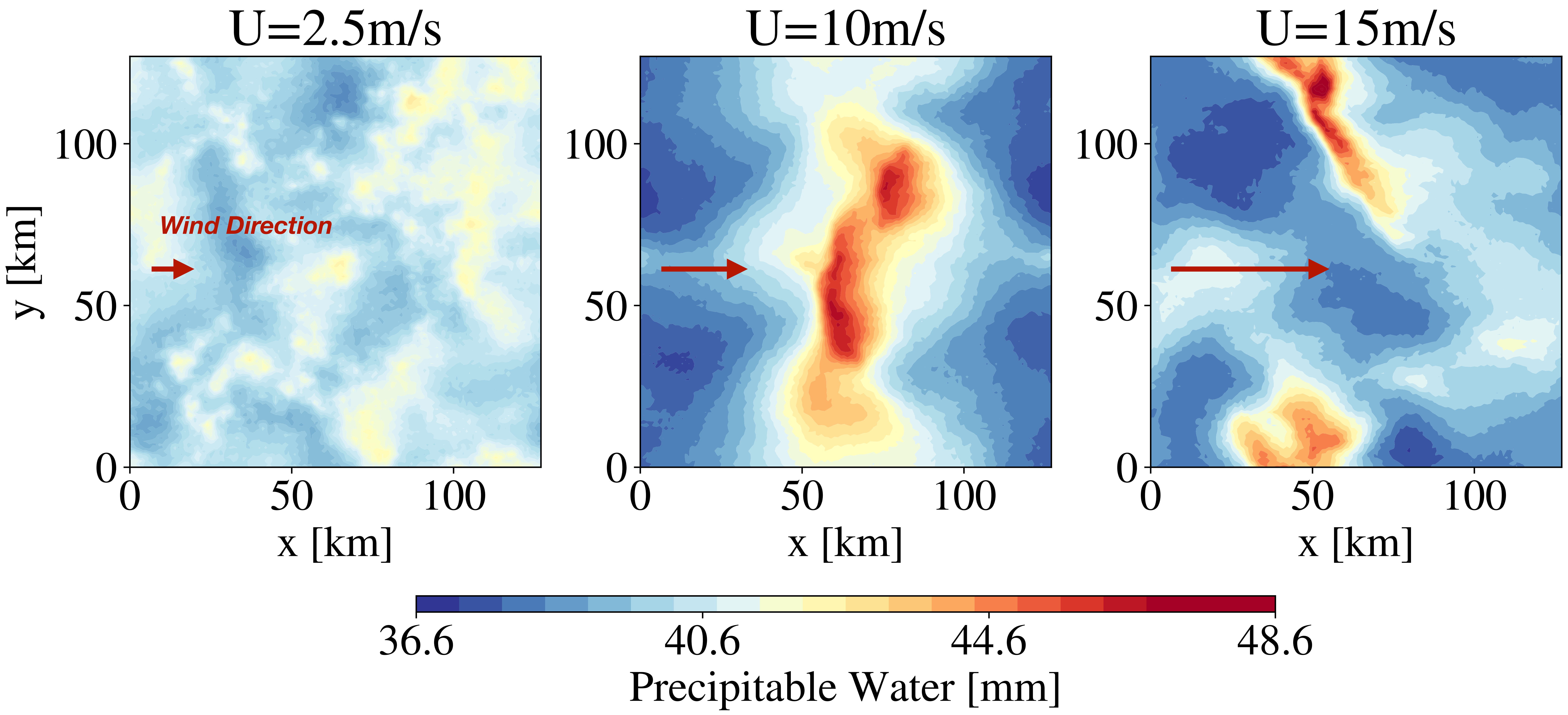


Cloud Resolving Model Overview



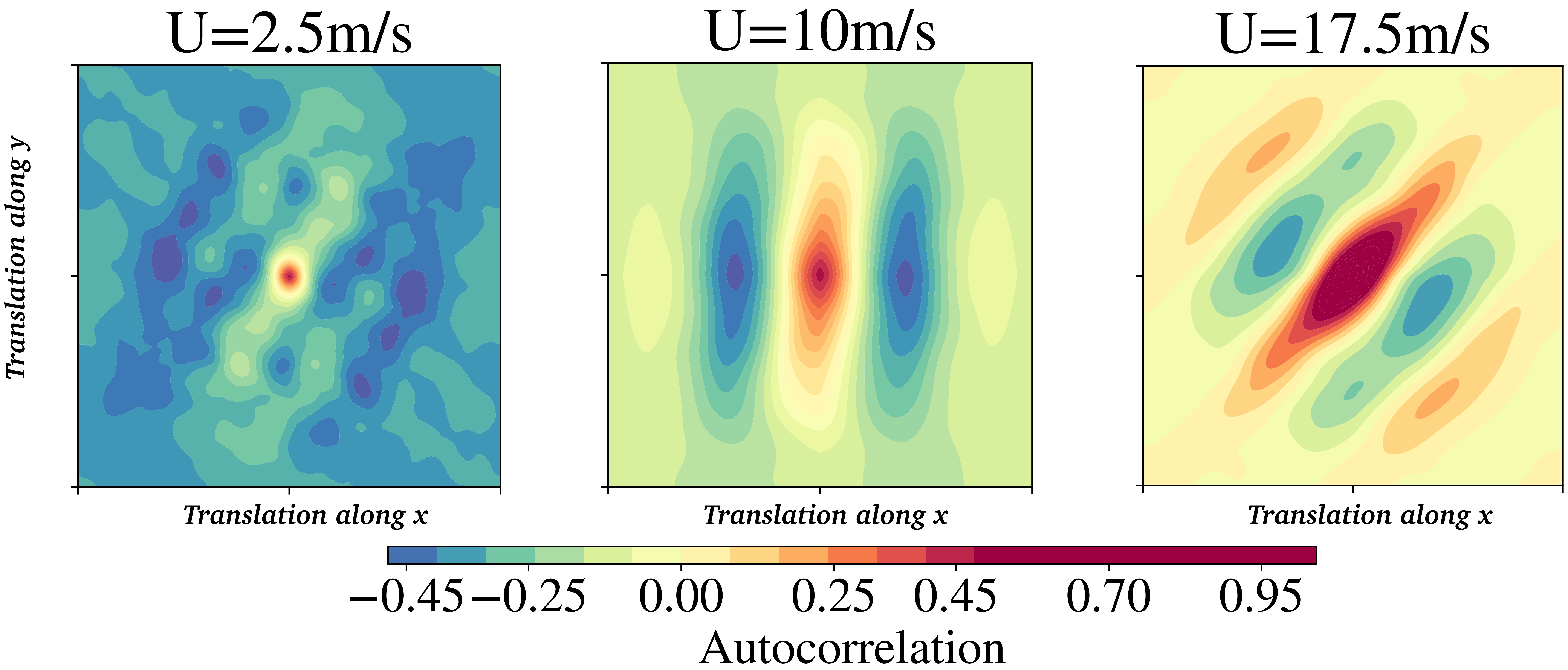
How to measure orientation of Squall Lines ?

Cloud Resolving Model Overview



Problem : Lines are moving, and often form arcs and bands

Autocorrelation Image



Autocorrelation : a useful mean to detect invariant and regularity of image

Angle Measurement Procedure

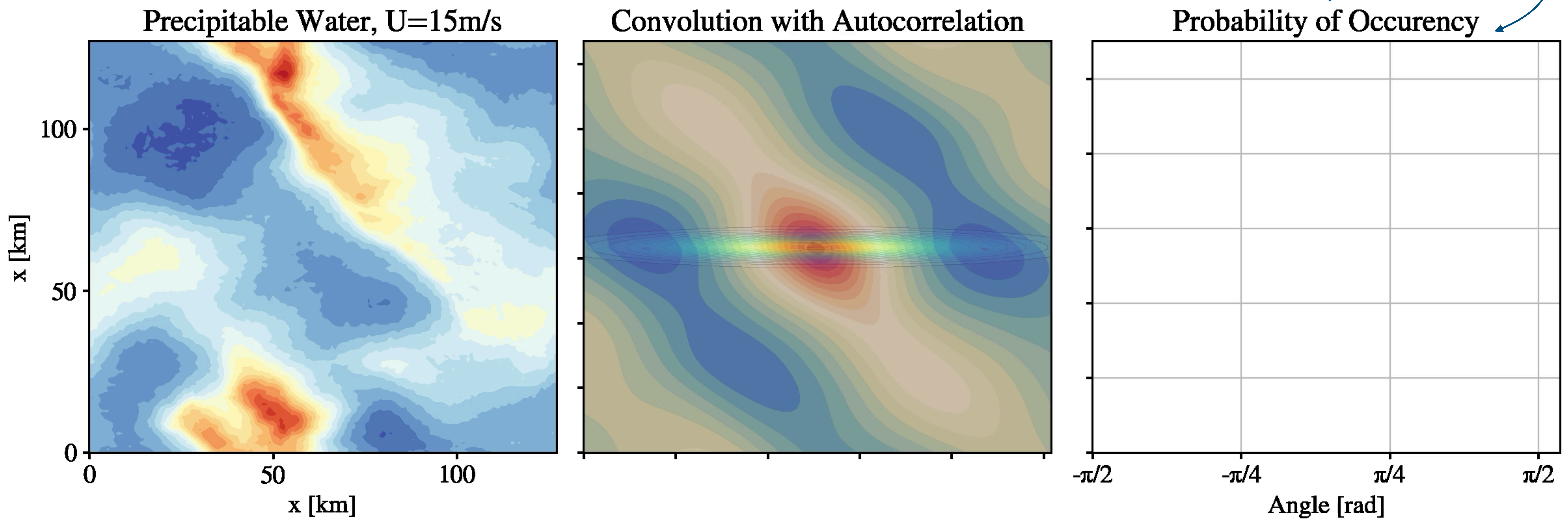
For each time step

1. Calculate the autocorrelation image

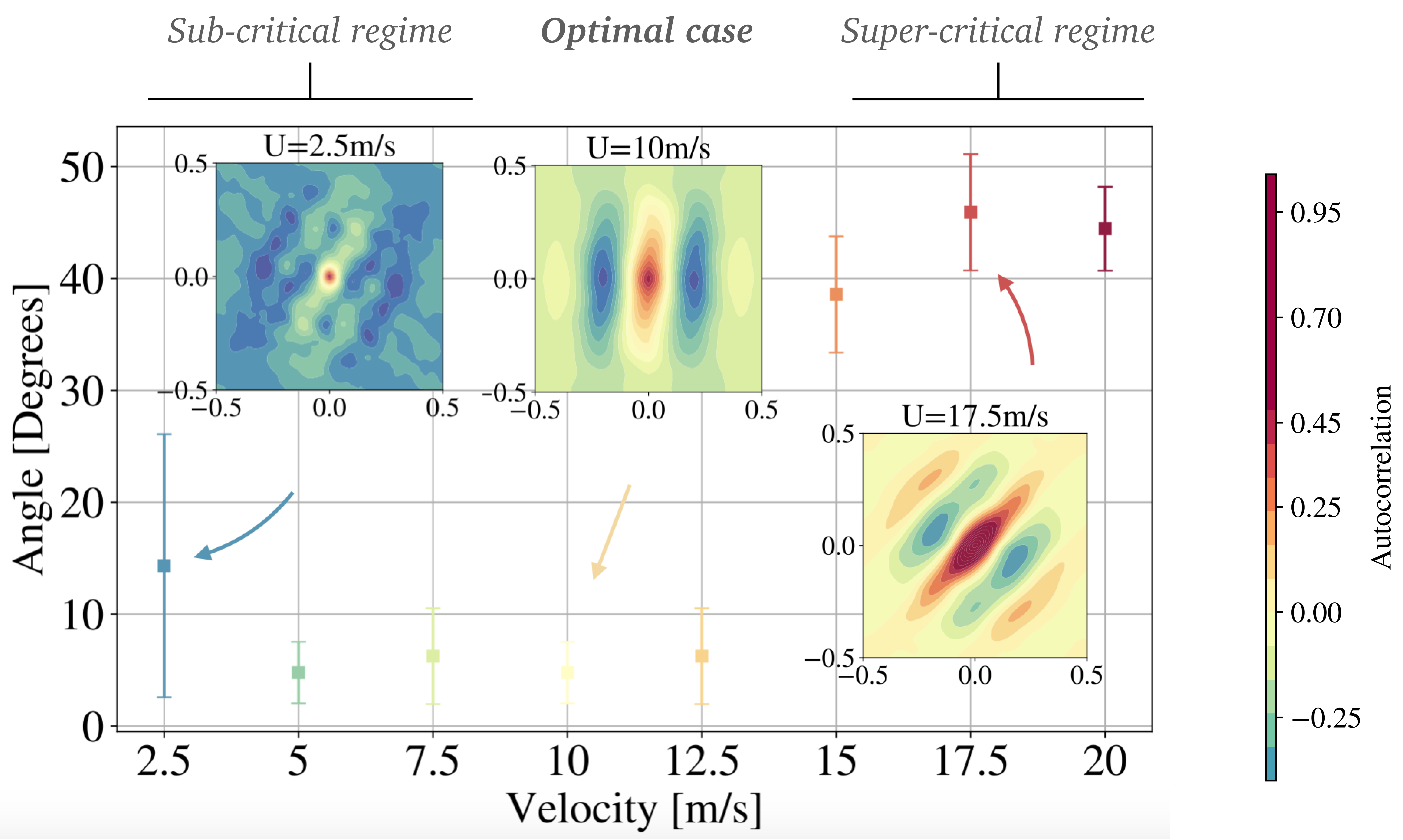
2. Compute the convolution between the gaussian and the autocorrelation

3. Obtain Angle Distribution

$$P(\theta) = \int_x \int_y G_\theta(x, y) * A(x, y) dxdy$$

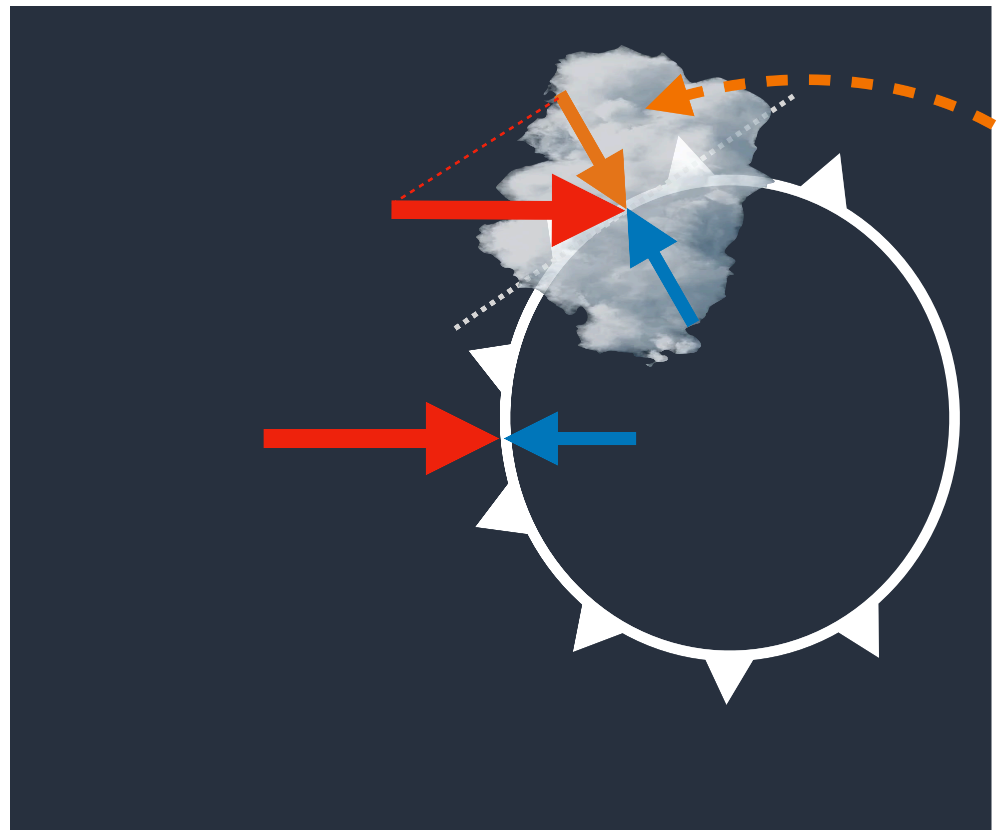


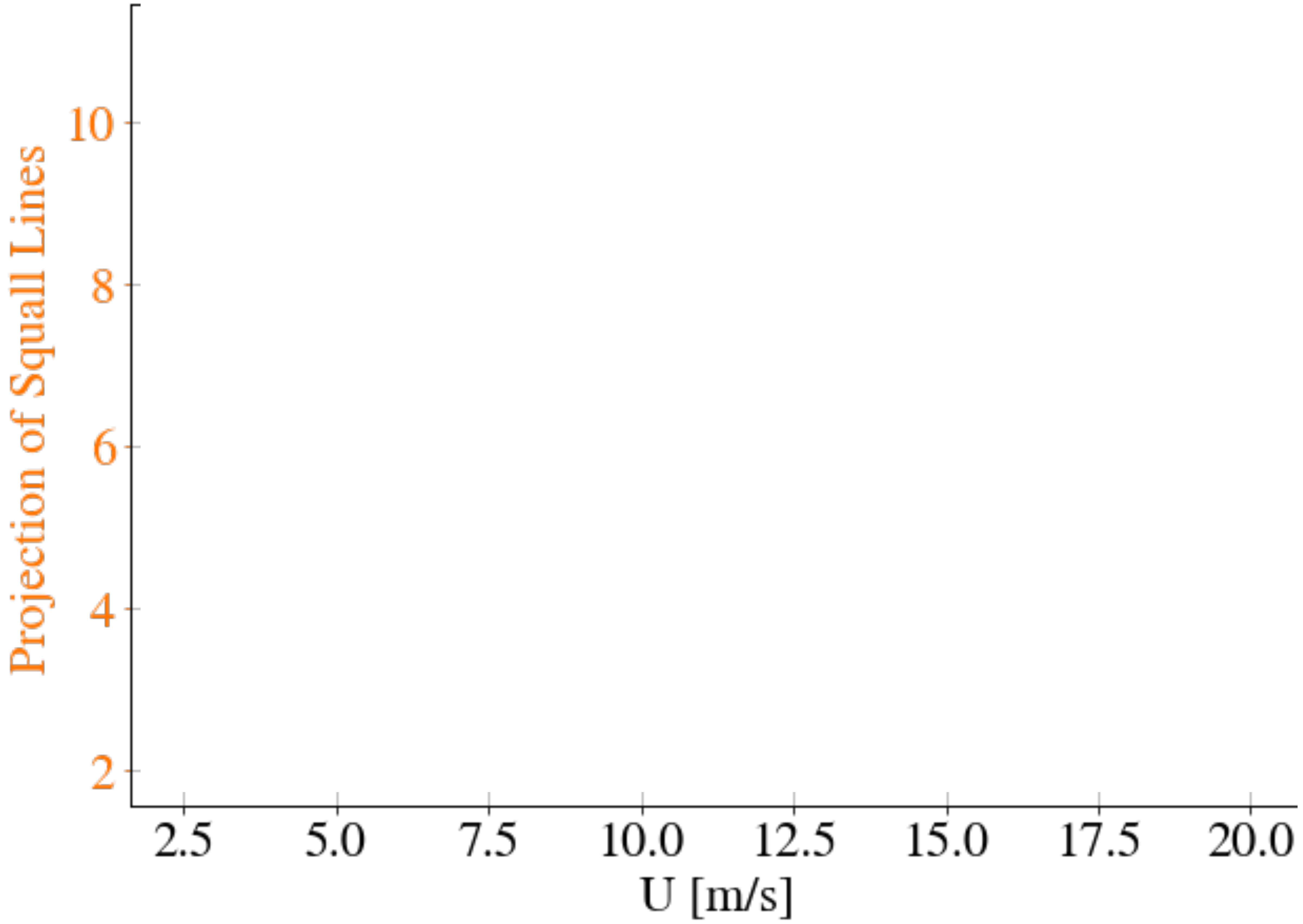
Angle Results



Conservation of the shear ?

Hypothesis : Conservation of the projected shear near the optimal value





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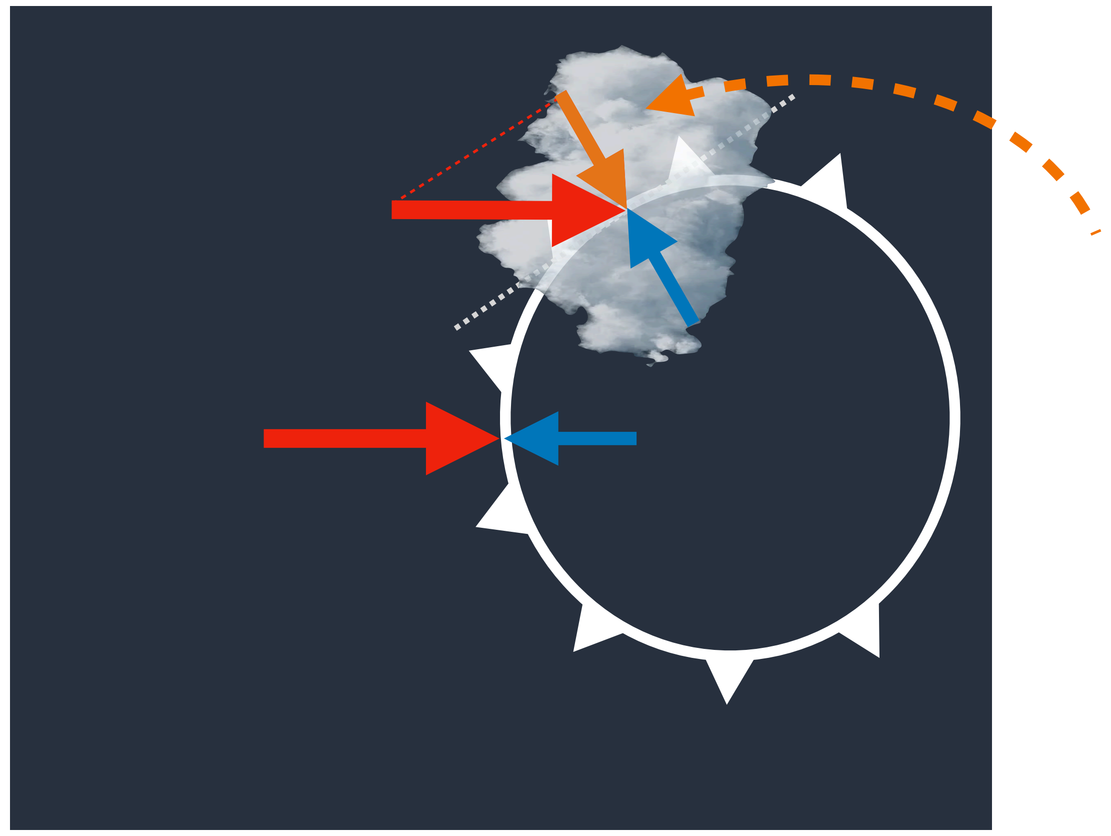

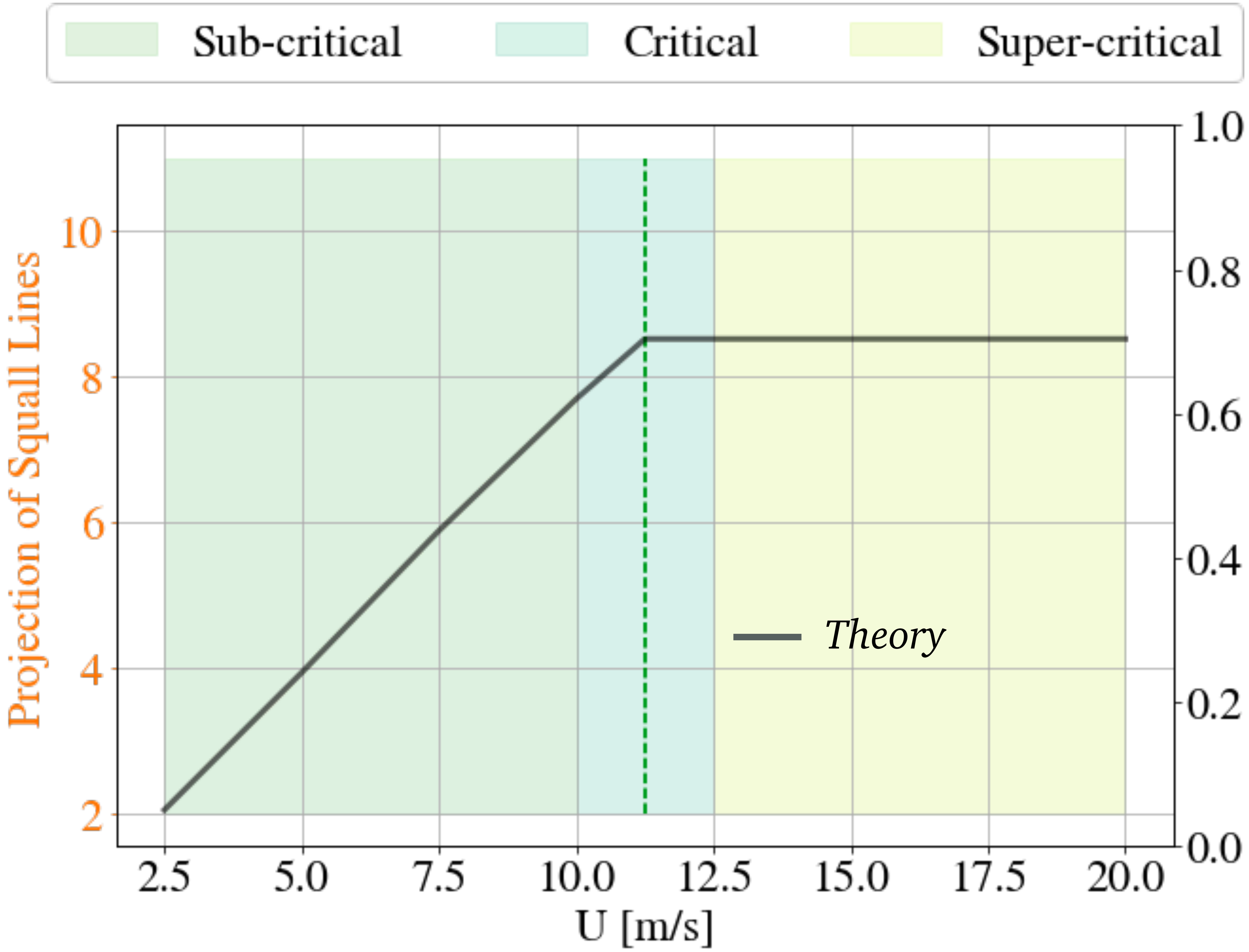

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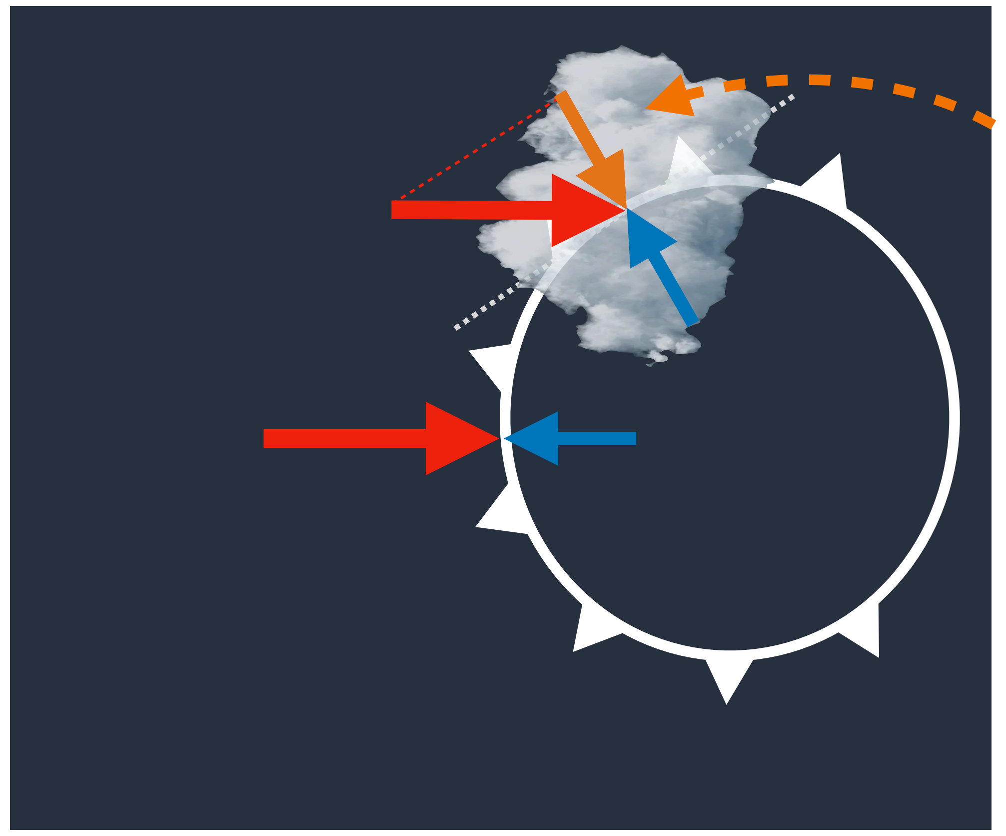

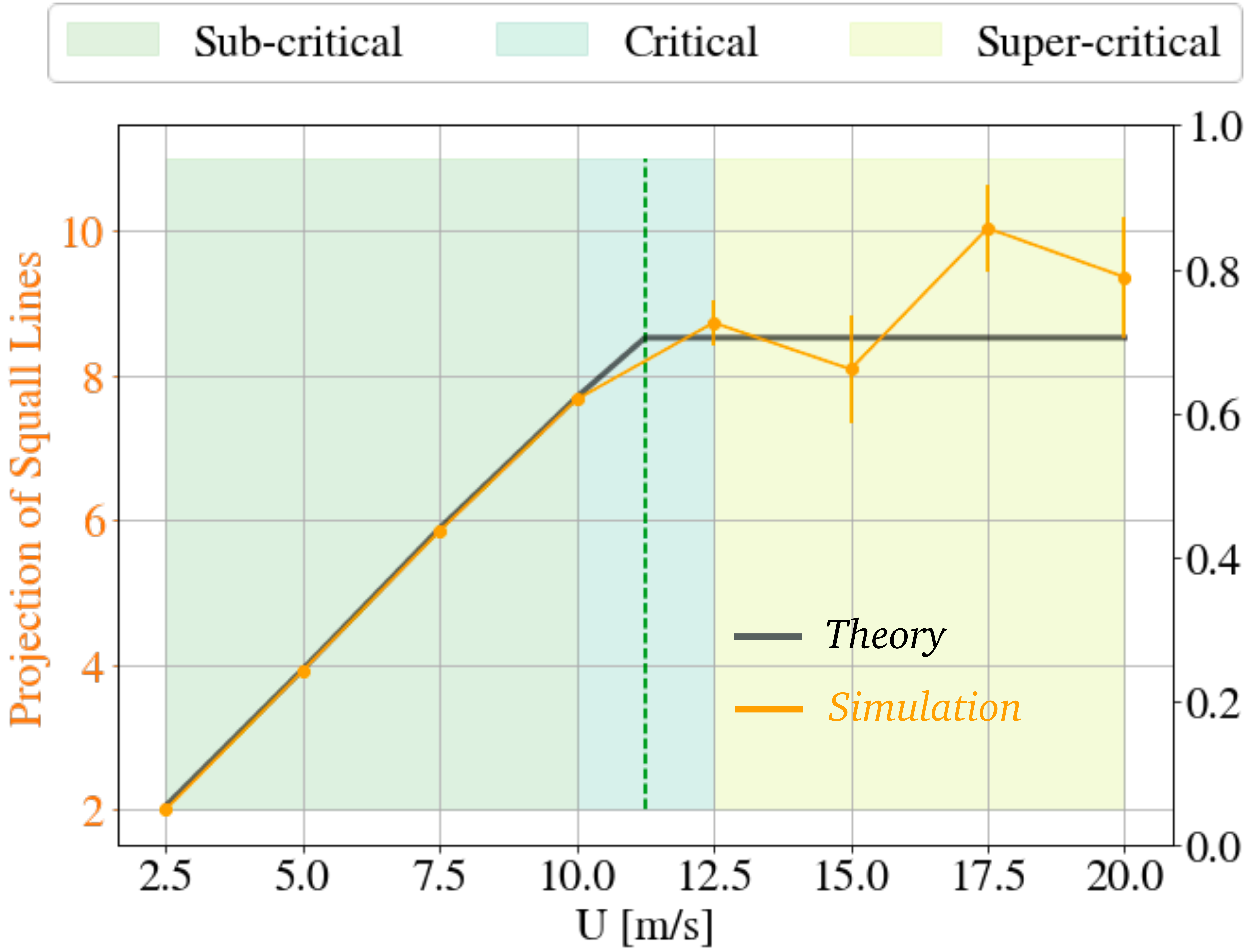

Good agreement with RKW 1988 Theory

Abramian et al 2021, Geophysical Research Letter

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A. What sets tropical squall lines orientation, and why ?

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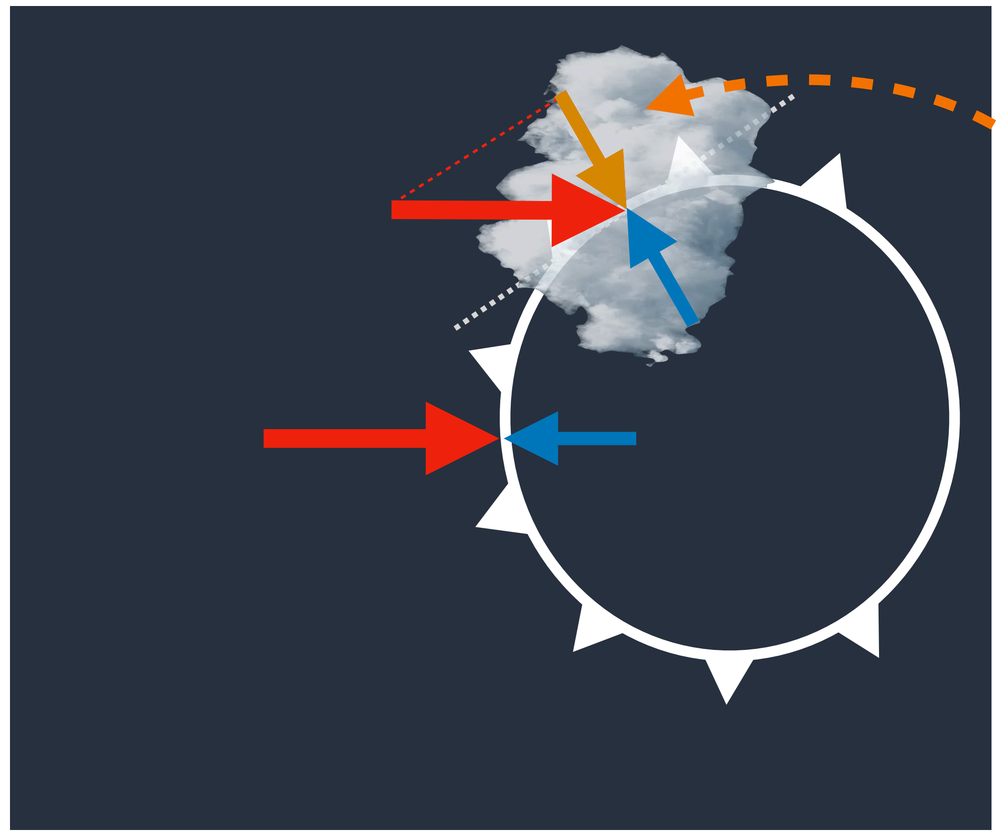
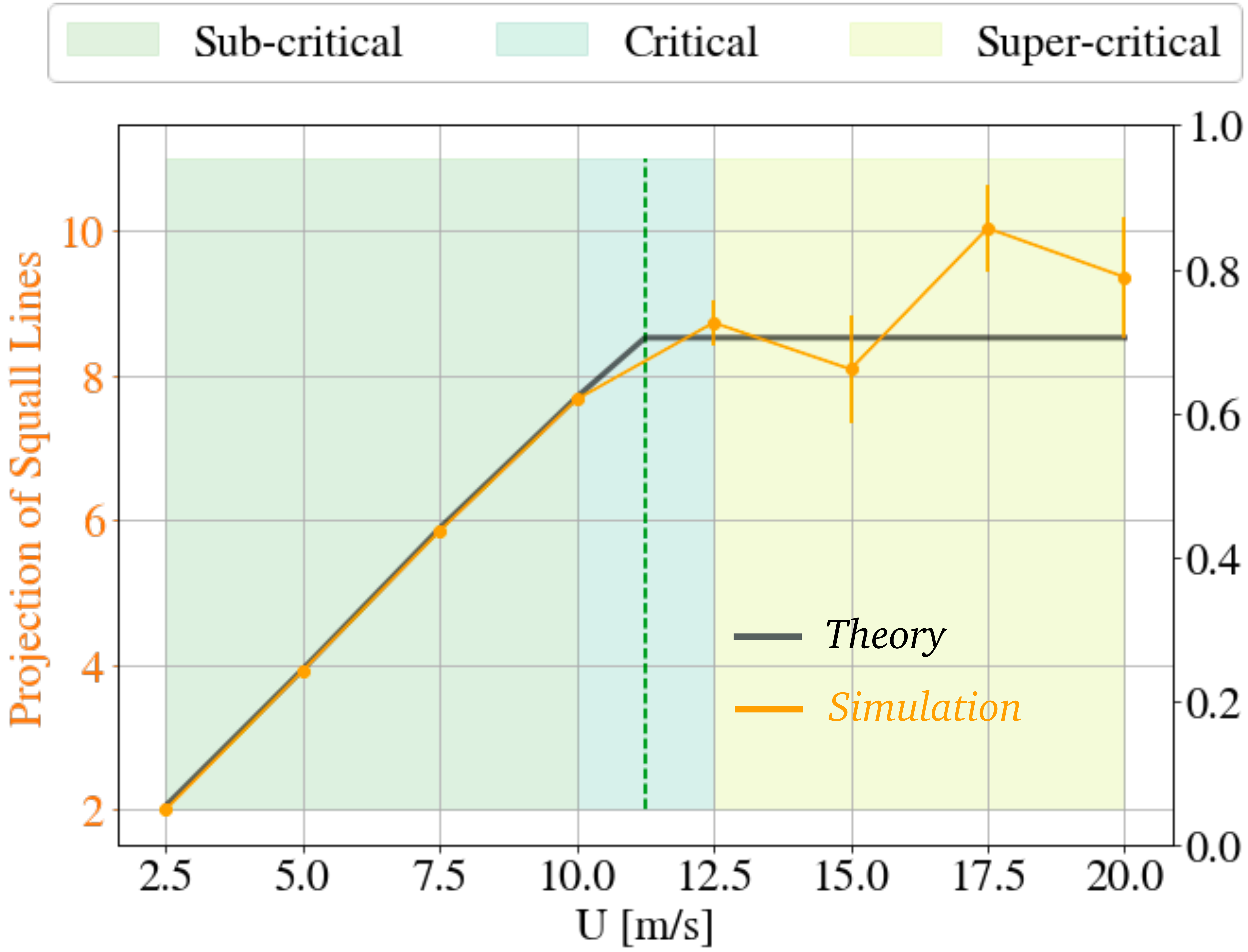
How do Extremes of Precipitation evolve with Squall Lines regime ?





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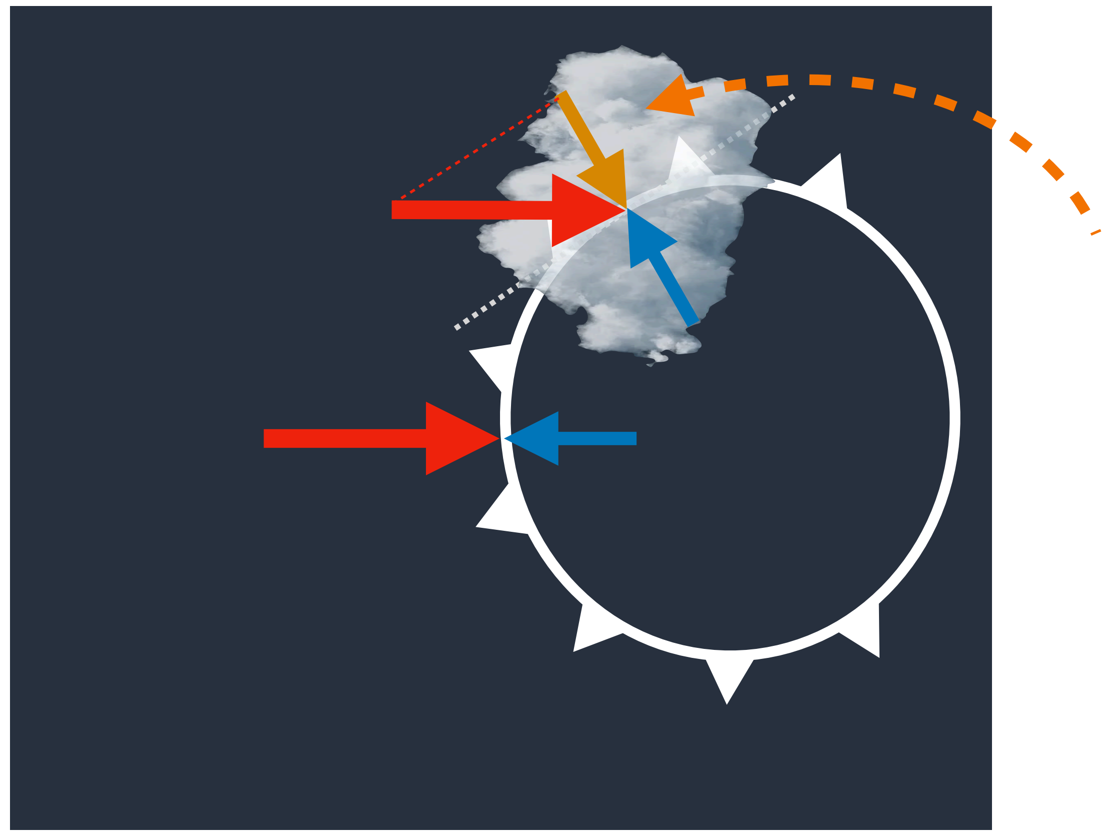

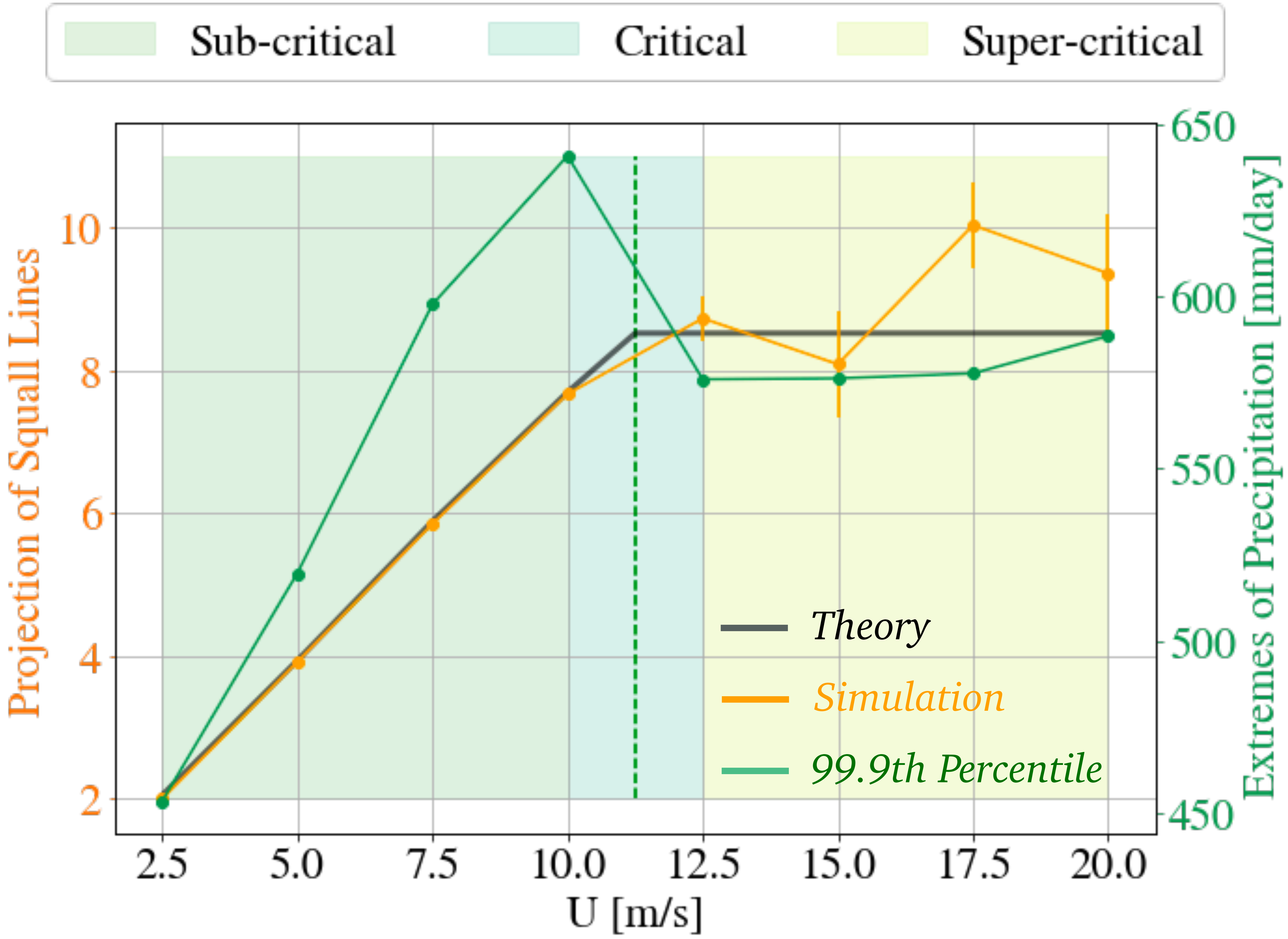

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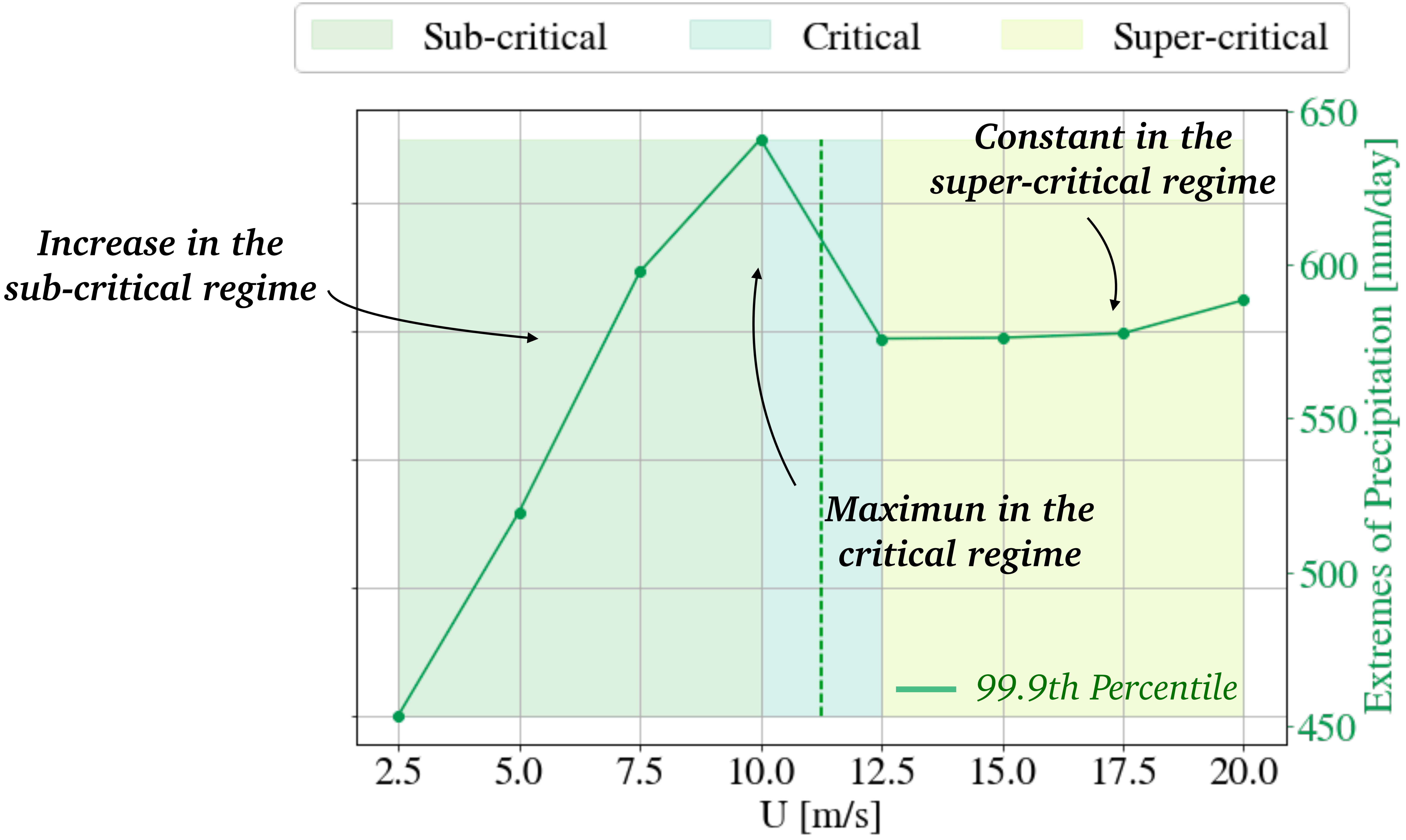

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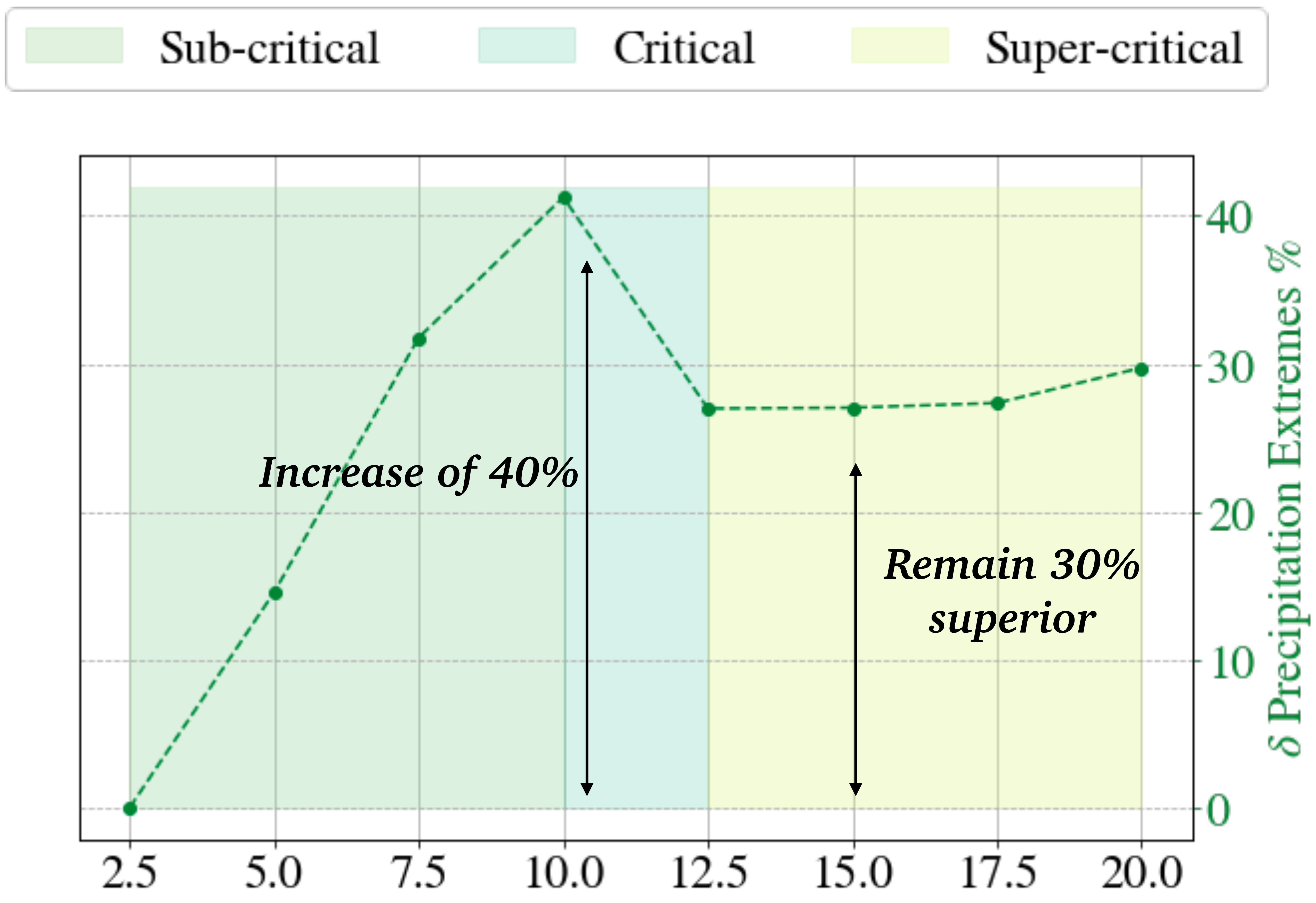

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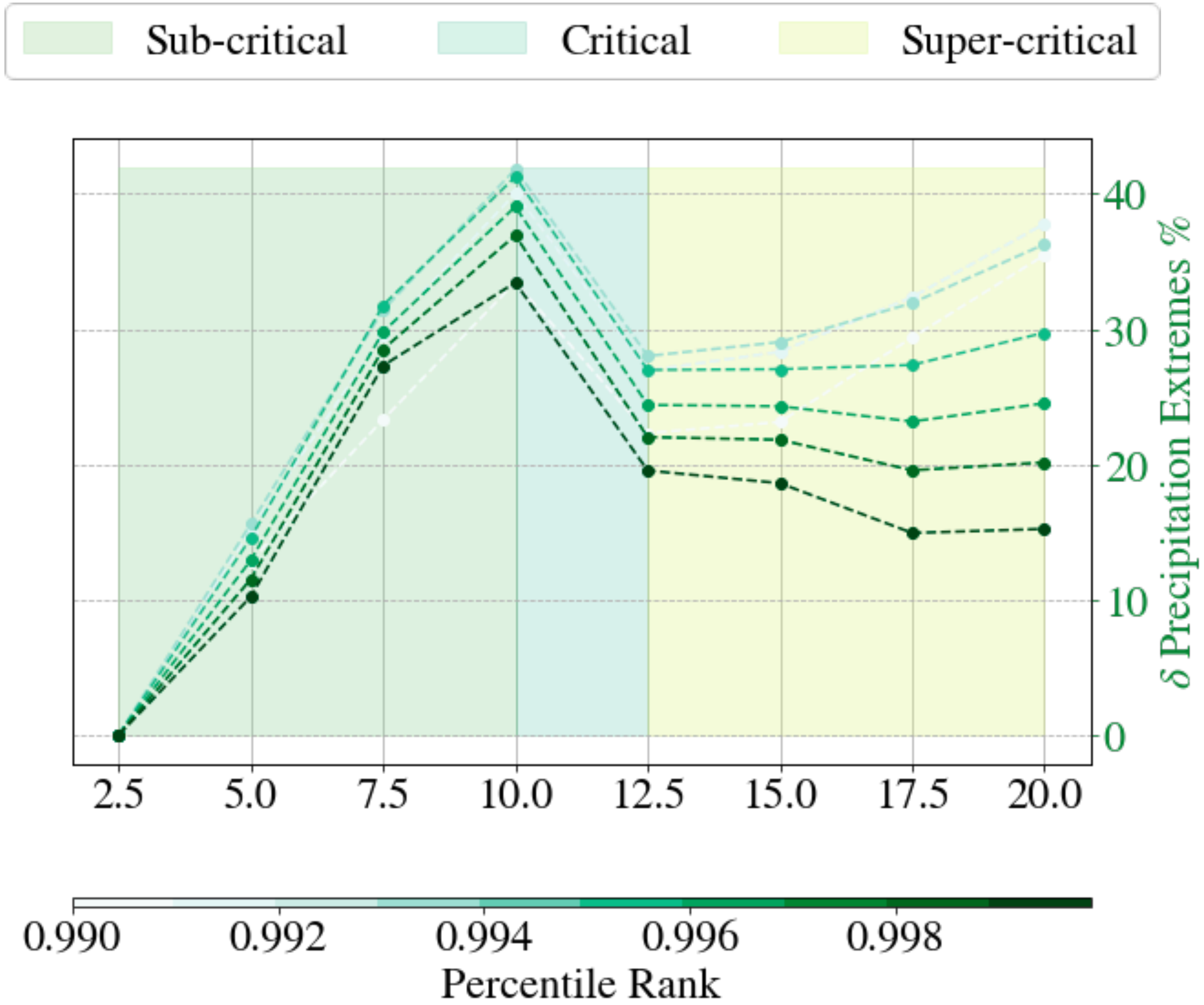


Robust at higher percentile

→ Why ?

Scaling for Extreme Precipitations (Muller & Takayabu 2020)

$$P \sim \epsilon_p \int \rho w \frac{-\partial q_*}{\partial z} dz \sim \epsilon_p C$$

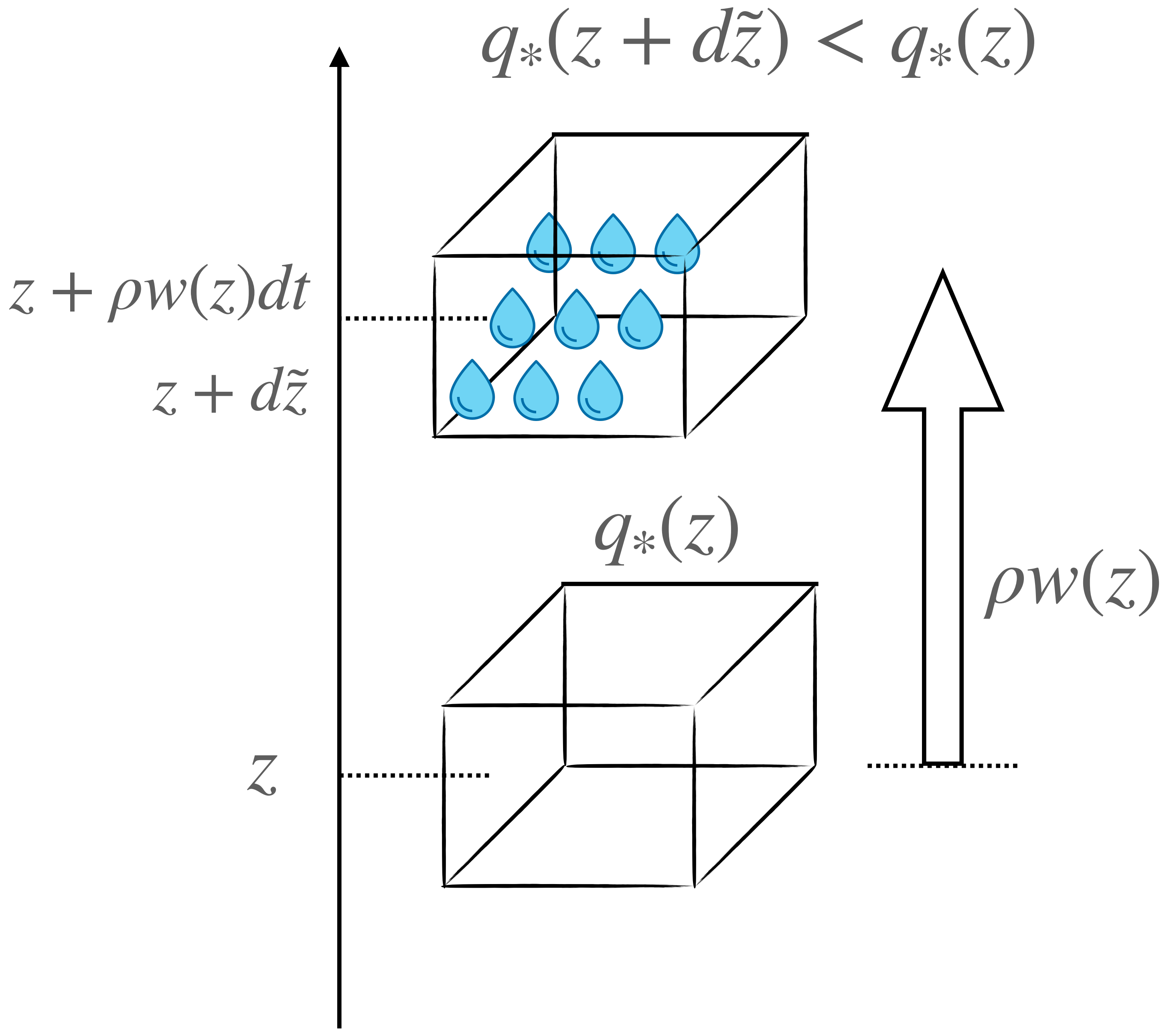
Precipitation efficiency (microphysic)

Condensation rate

Not all the droplets make it to the ground

Stay in the cloud

Evaporate



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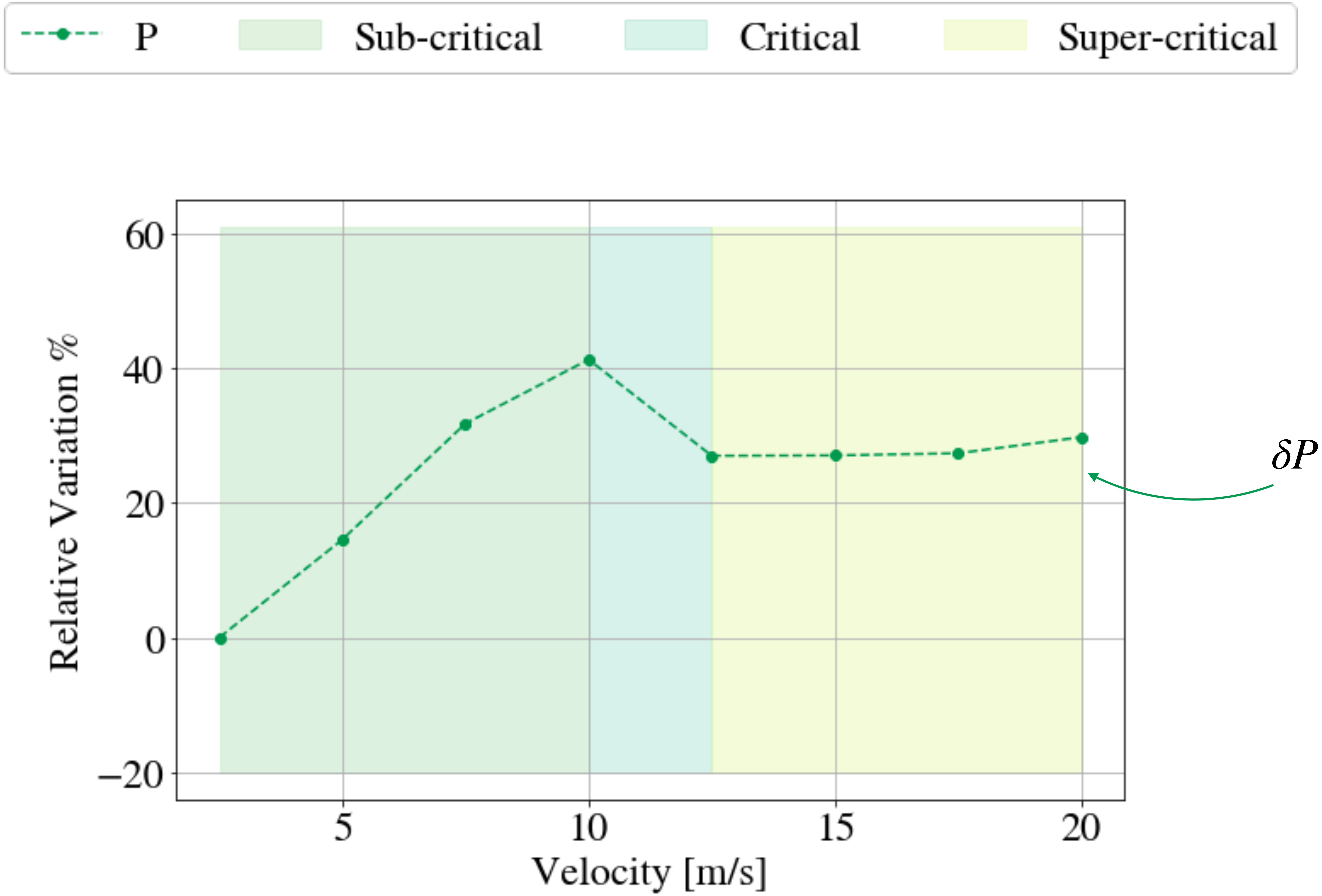
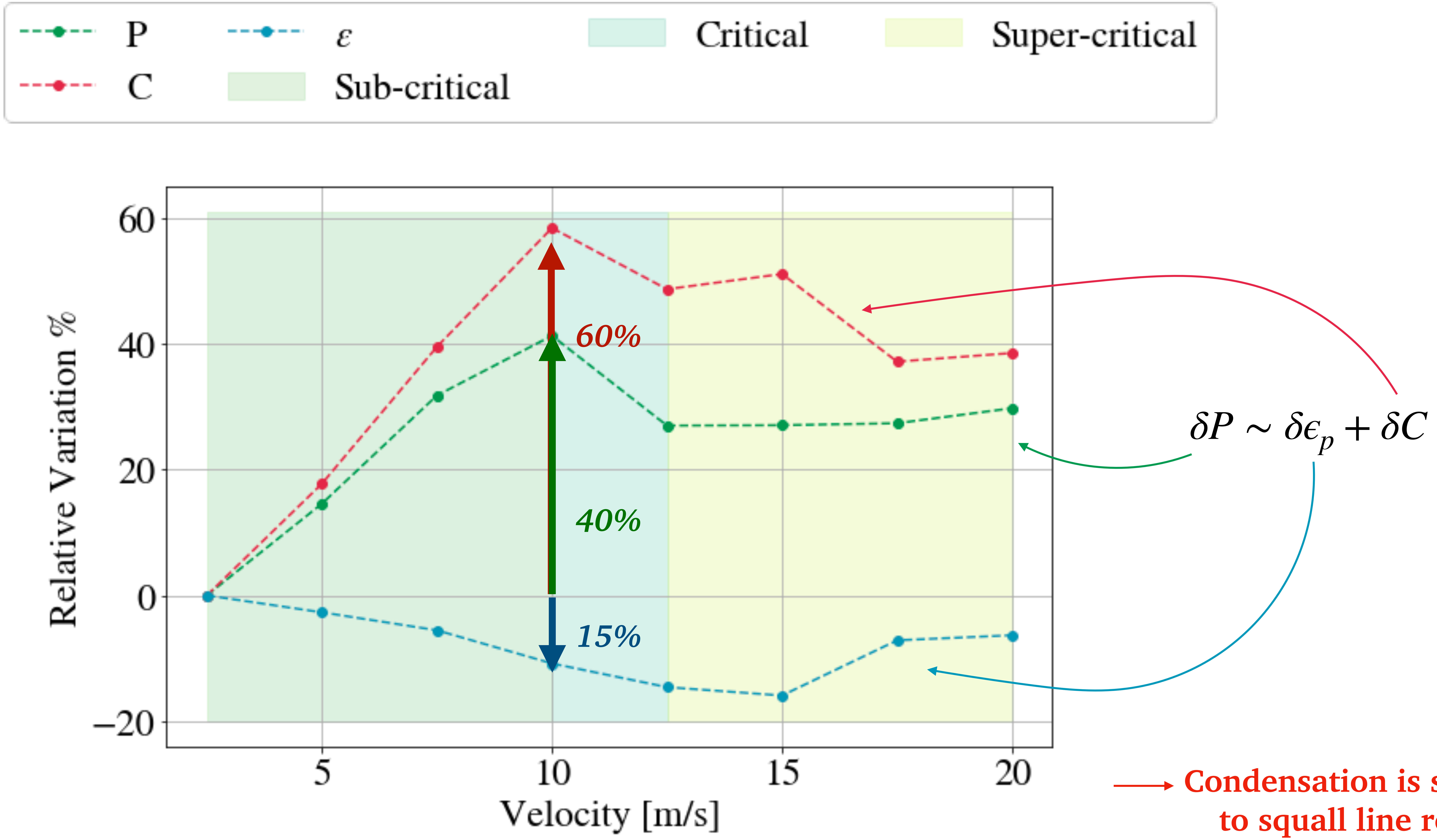


$$\delta P \sim \delta \epsilon_p + \delta C$$

Scaling for Extreme Precipitations (Muller & Takayabu 2019)



→ Condensation is sensitive to squall line regime

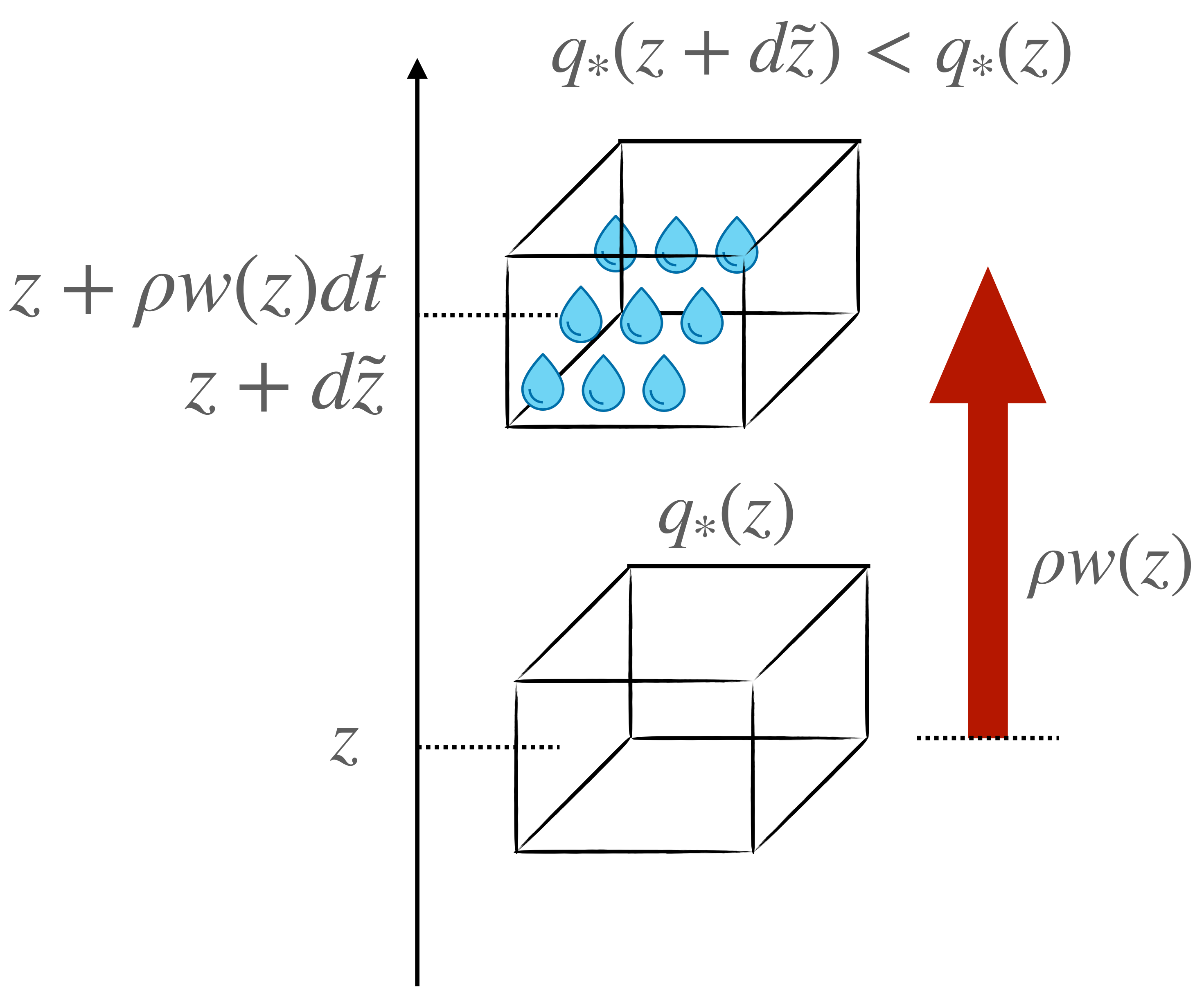
Scaling for Extreme Precipitations (Muller & Takayabu 2019)

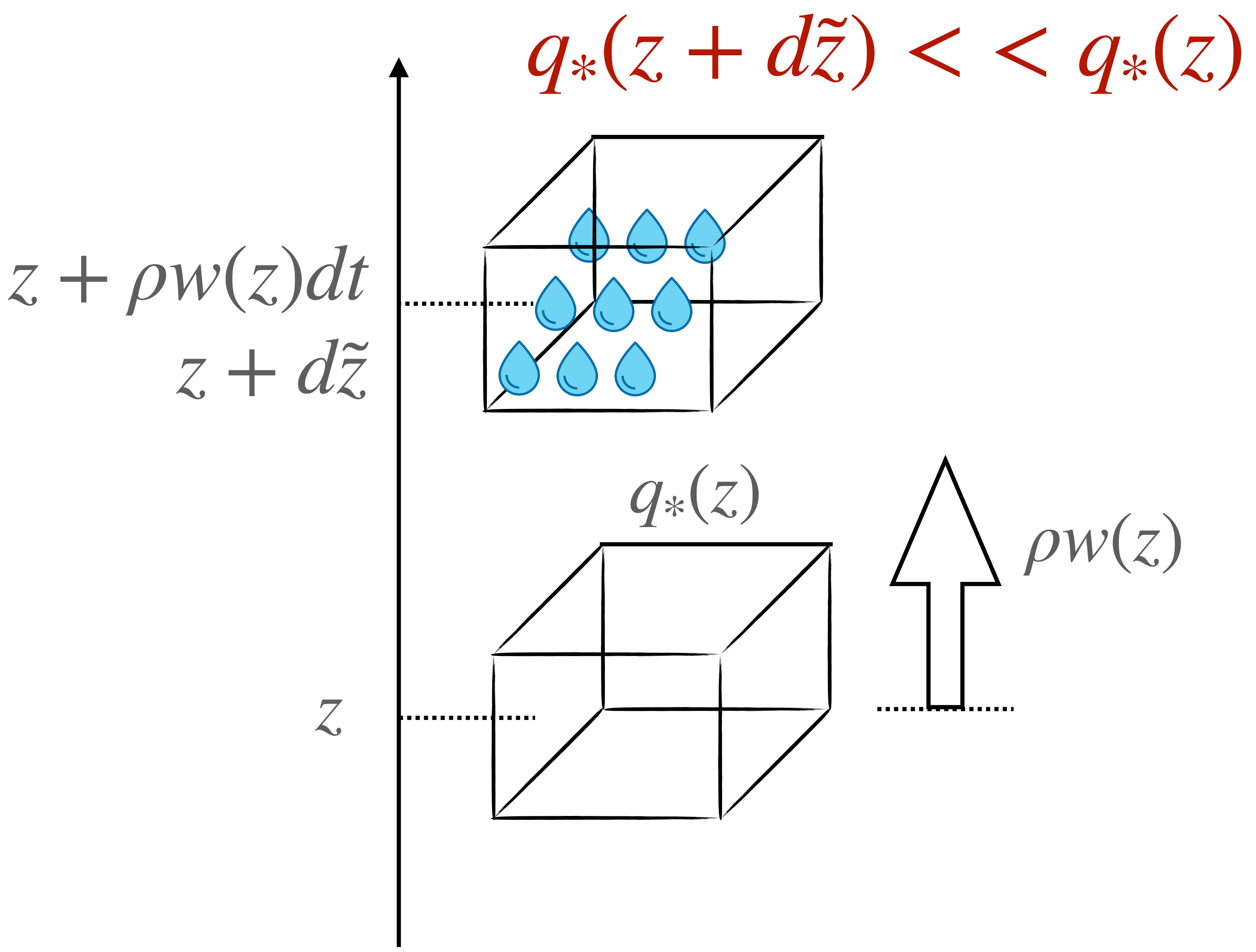
$$\delta P \sim \delta\{\epsilon_p \int \rho w \frac{-\partial q_*}{\partial z} dz\}$$

$$\delta C \sim \delta \int \rho w \frac{-\partial q_*}{\partial z} dz \sim \int \{\delta(\rho w) \frac{-\partial q_*}{\partial z} + (\rho w) \delta \frac{-\partial q_*}{\partial z}\} dz$$

Dynamics Contribution

Thermodynamics Contribution





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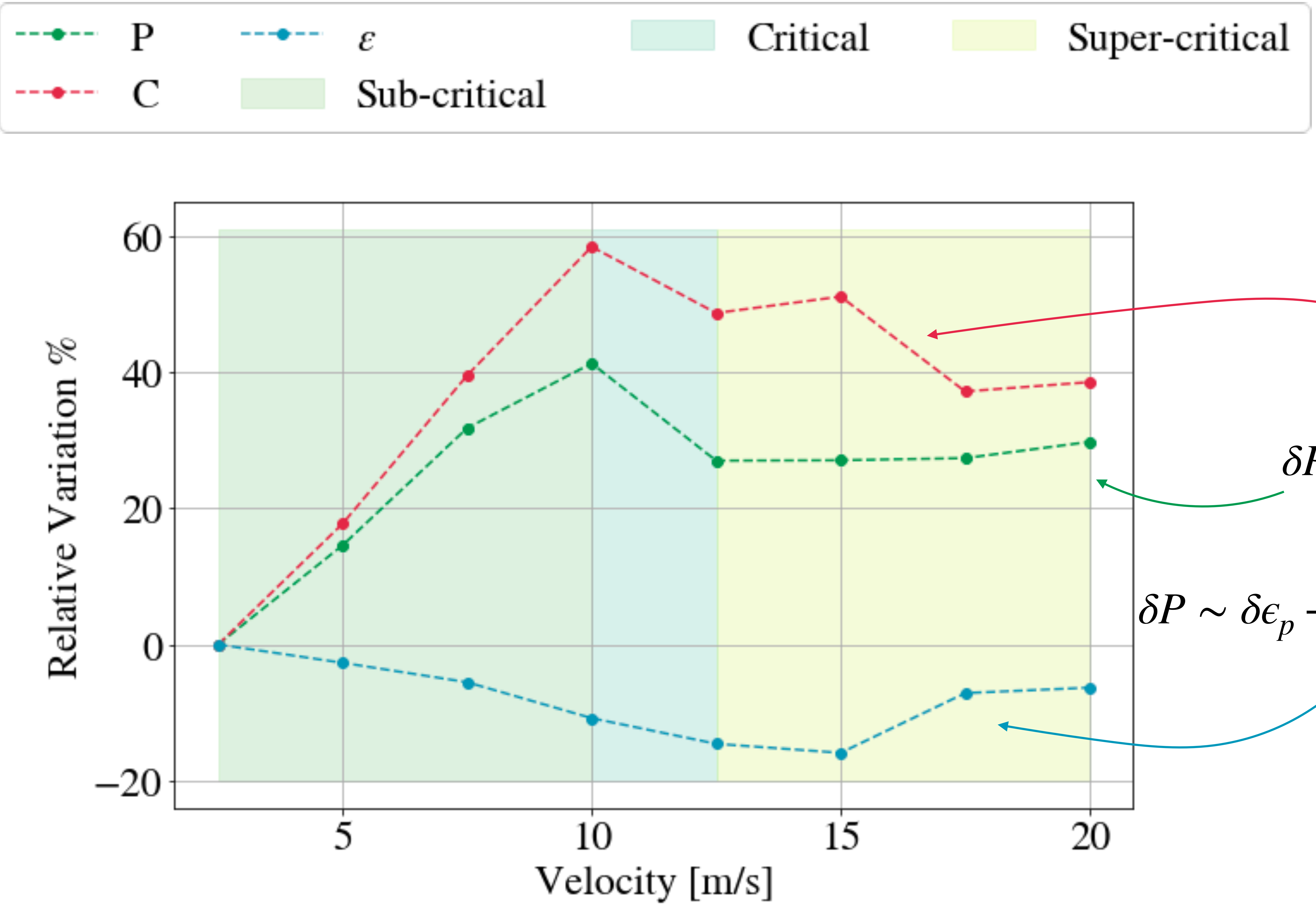
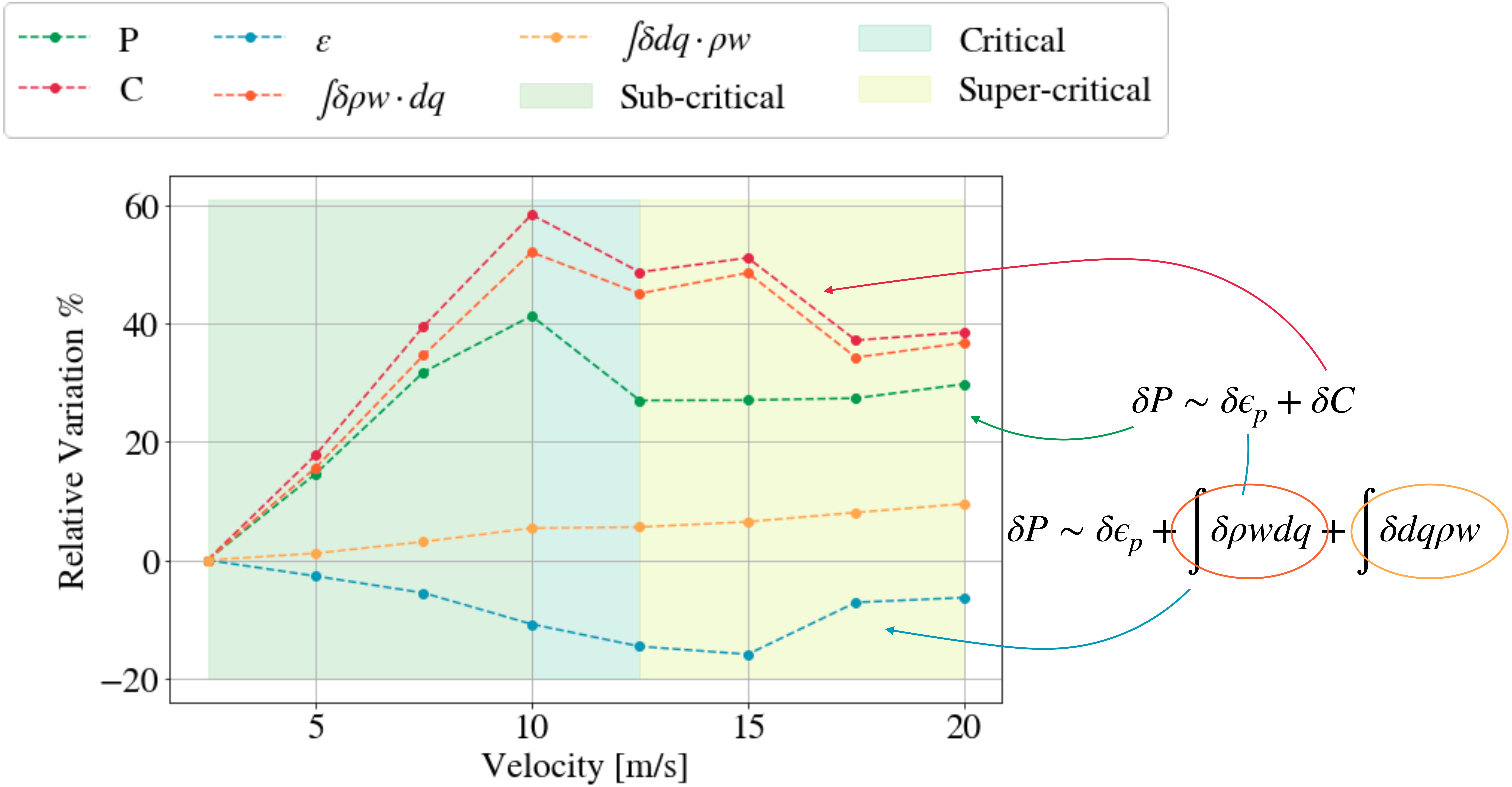


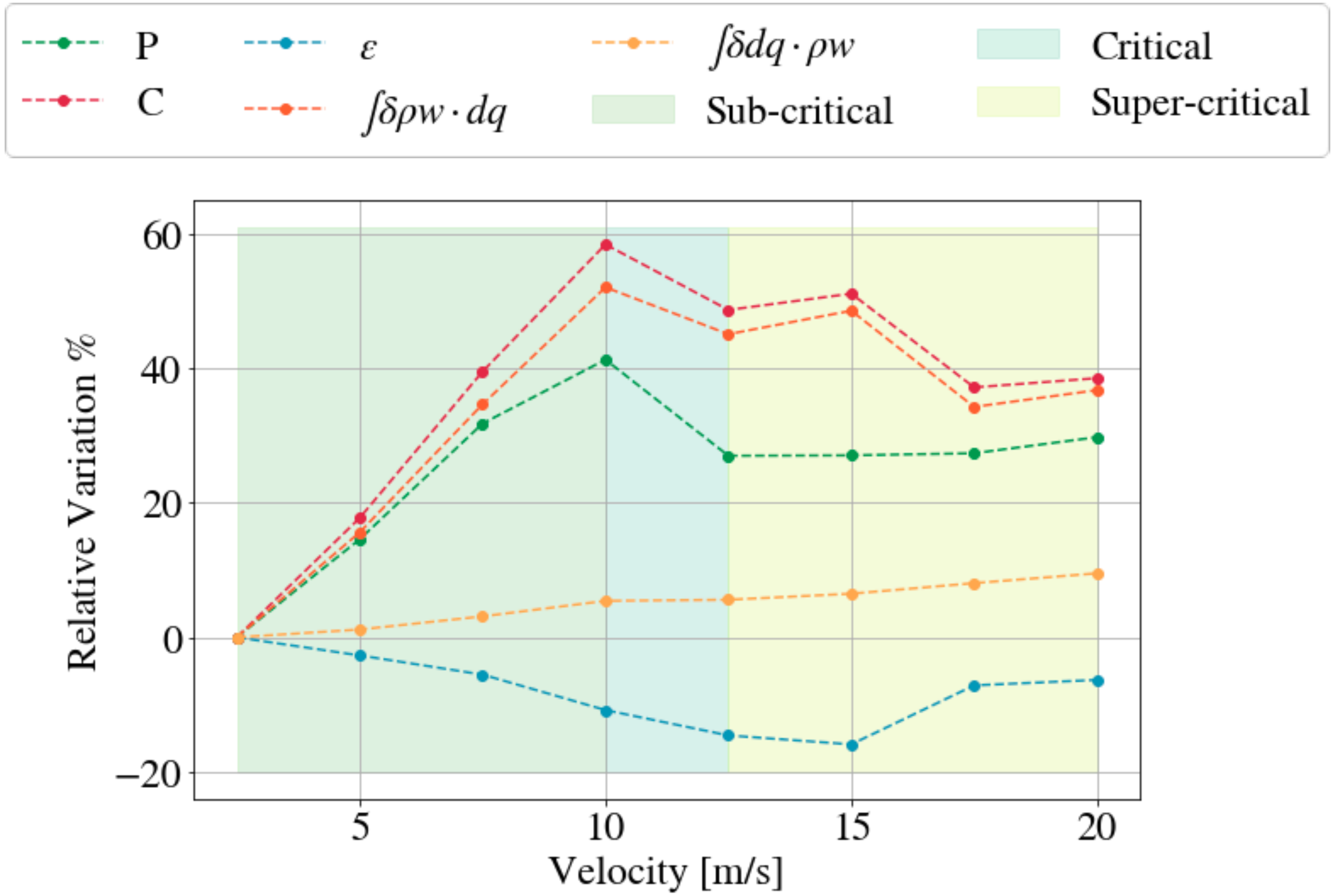
$$\delta P \sim \delta \epsilon_p + \delta C$$

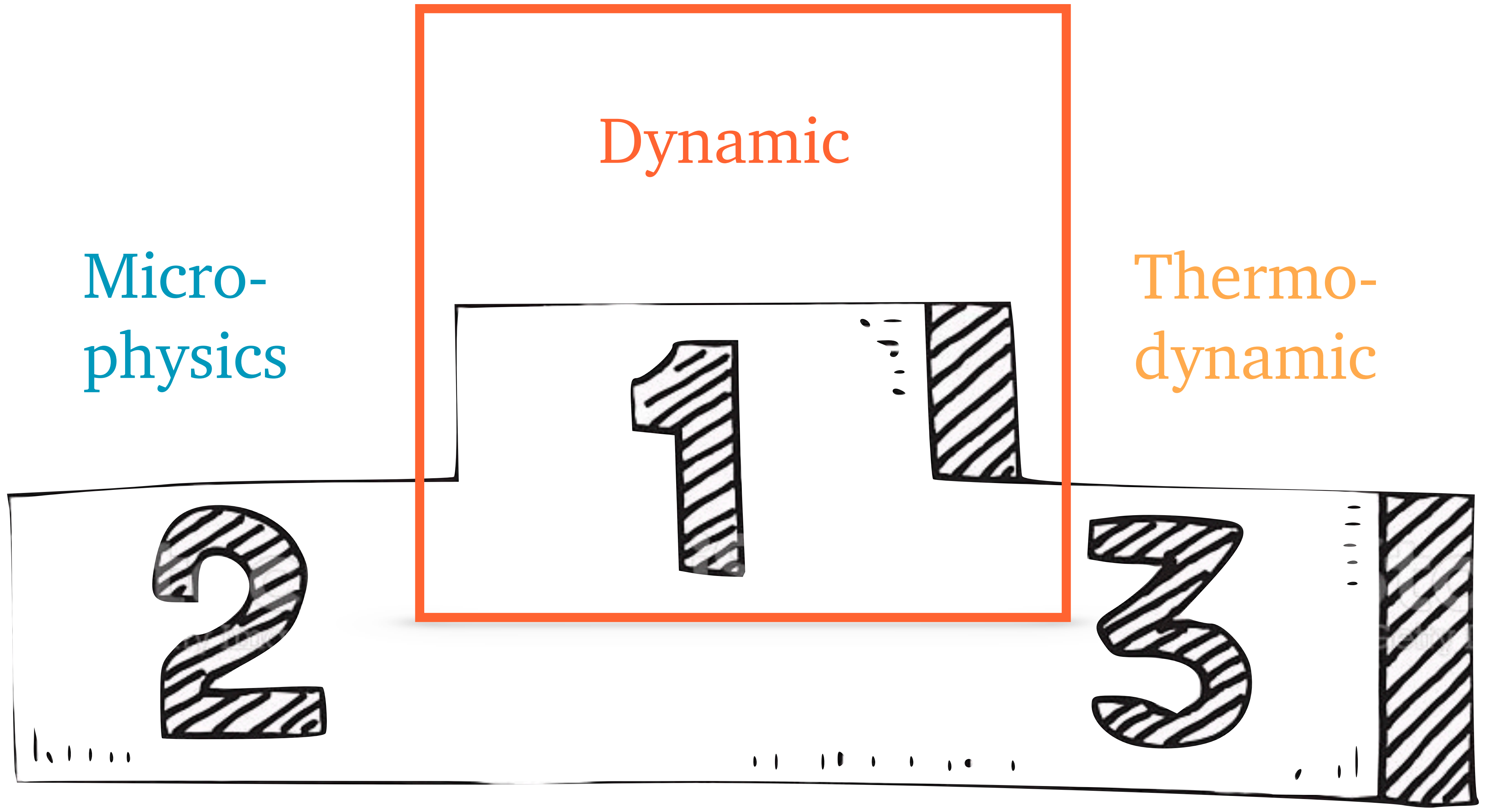
$$\delta P \sim \delta \epsilon_p + \int \delta \rho w dq + \int \delta dq \rho w$$

Scaling for Extreme Precipitations (Muller & Takayabu 2019)



Contribution that mainly explains change in extreme precipitation



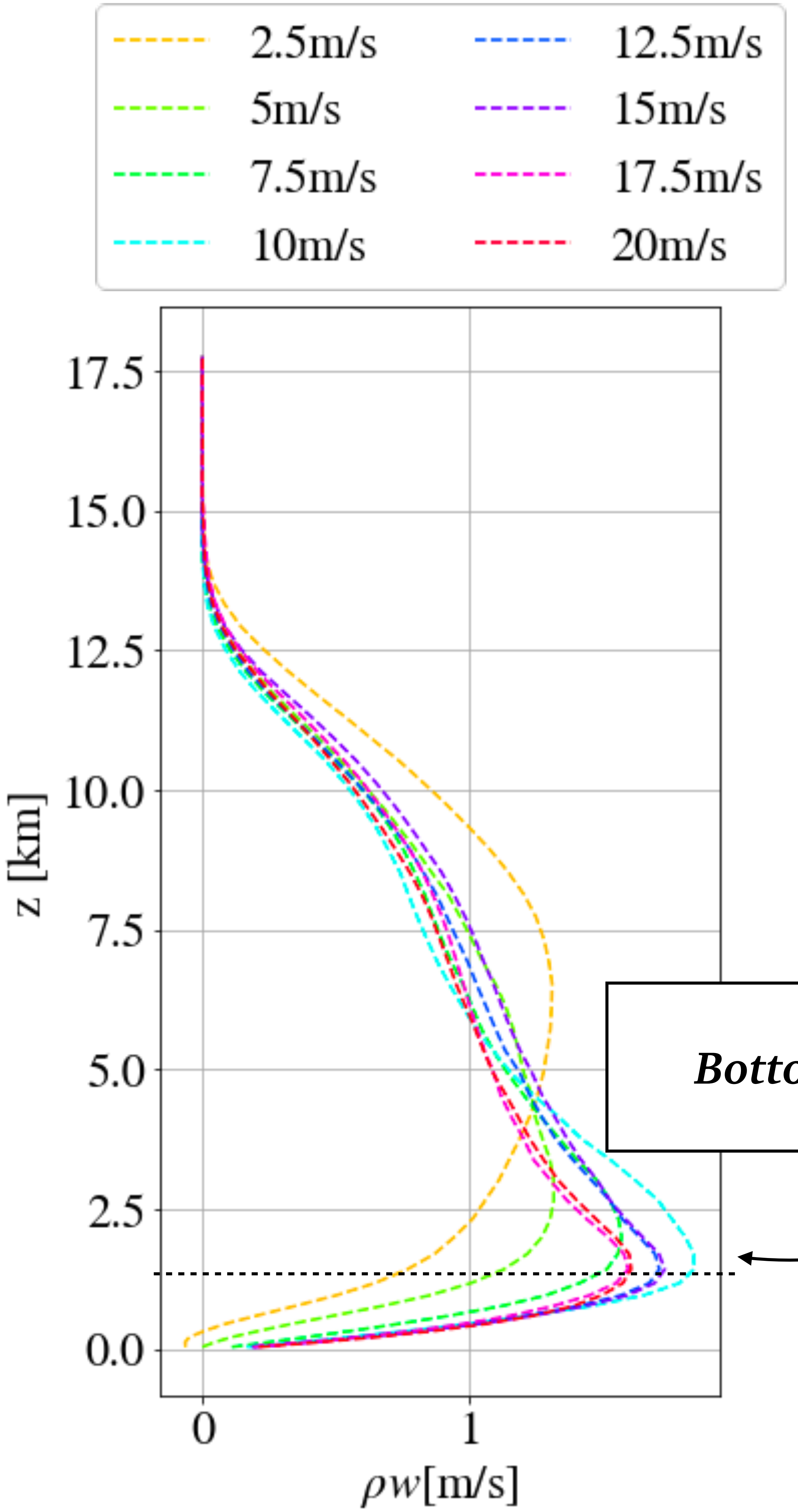


→ What physical mechanisms control the behavior of these contributions ?

Physical Processes

Dynamic Contribution

Microphysic & Thermodynamic Contributions



Bottom heavy profiles

Dynamic Contribution

Conversion of Potential Energy to Kinetic Energy

$$\frac{1}{2}w^2(z) = \int dCAPE(z)$$

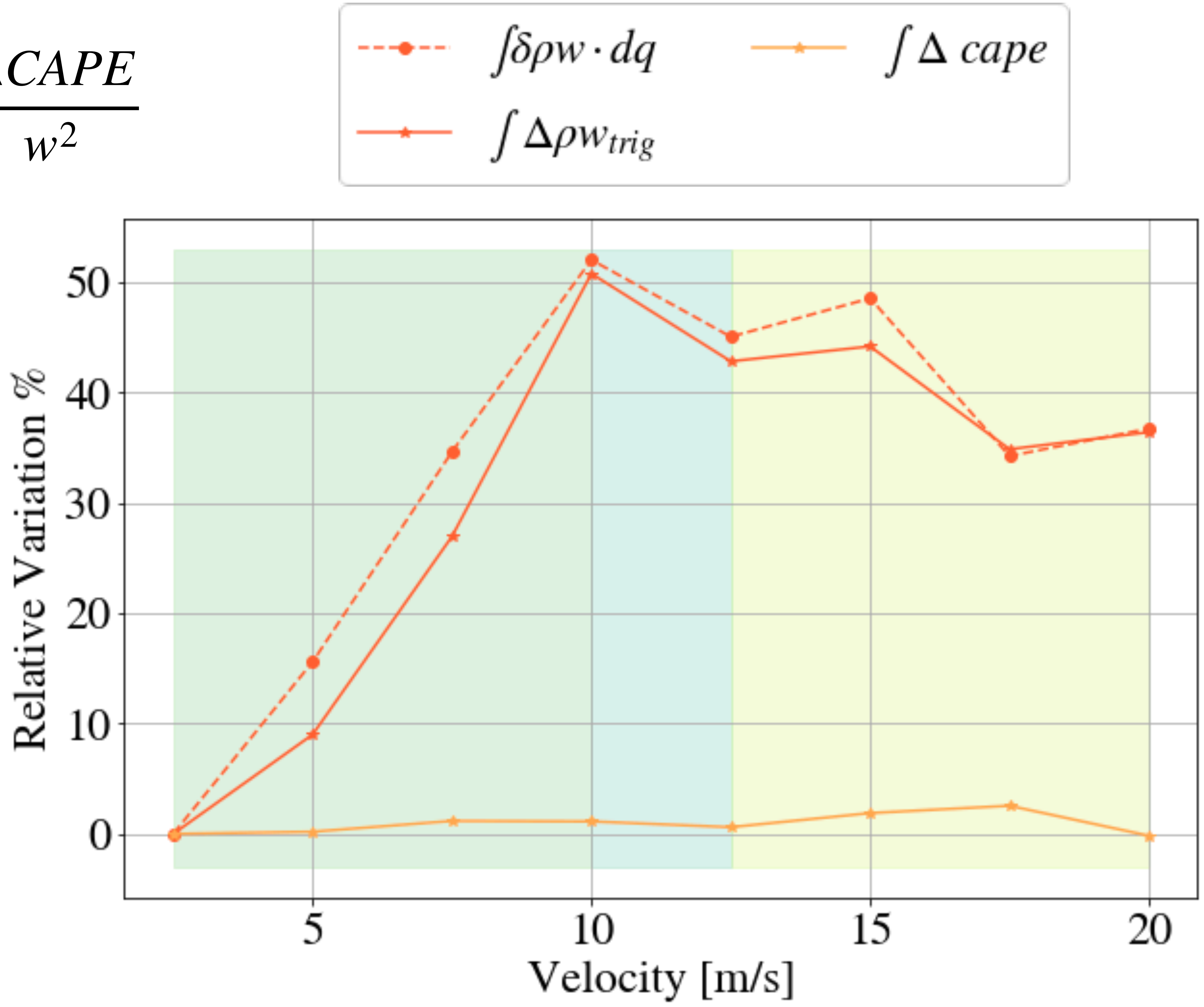
$$w^2(z) \sim w_{trig}^2 + 2CAPE(z)$$

Derived differential

$$\delta w \sim \int w_{trig}\frac{\Delta w_{trig}}{w^2} + \int \frac{\Delta CAPE}{w^2}$$

Dynamic Contribution

$$\delta w \sim \int w_{trig} \frac{\Delta w_{trig}}{w^2} + \int \frac{\Delta CAPE}{w^2}$$

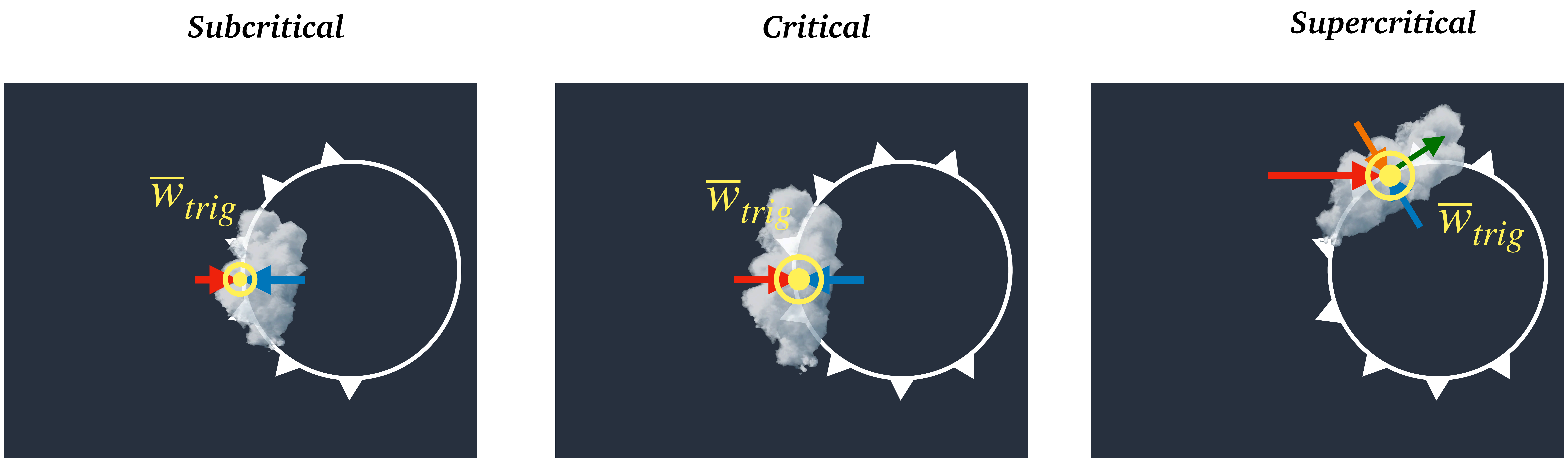


→ **The Convective triggering intensity of the vertical velocity is driving the dynamic**

→ **Triggering velocity is saturated**

→ **CAPE constant**

Dynamic Contribution



Triggering velocity mainly depends on the convergence perpendicular to the line

Exceeding momentum is transferred to tangential component

→ Increase and saturation beyond critical due to triggering by convergence

Physical Processes

Dynamic Contribution

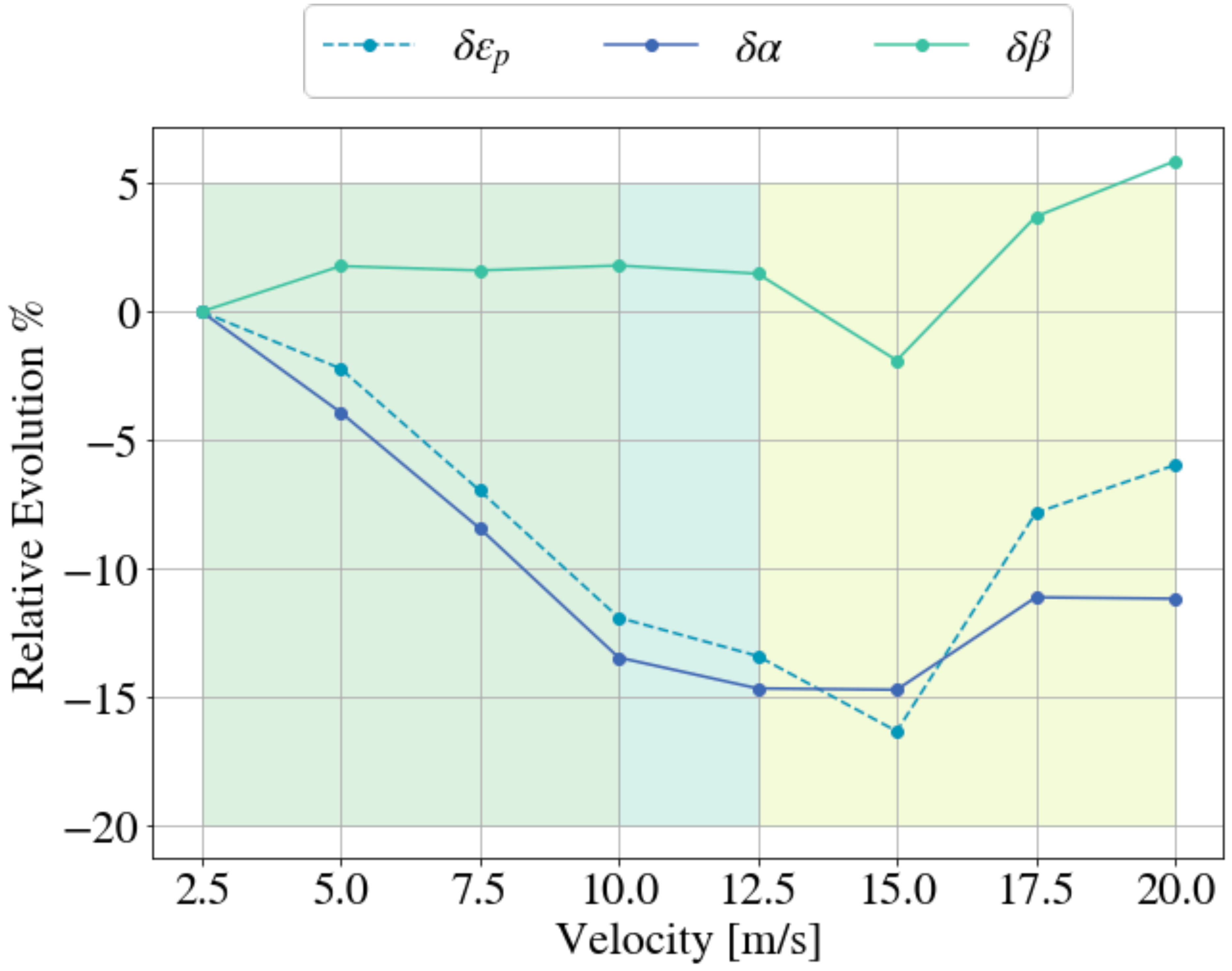
Microphysic & Thermodynamic Contributions

$$\epsilon \sim \frac{P}{C} \sim \frac{Q_p}{C} \times \frac{P}{Q_p}$$

Microphysic & Thermodynamic Contributions

Conversion from cloud to precipitating condensates

Precipitating condensates reaching the ground



→ *Conversion* dominates

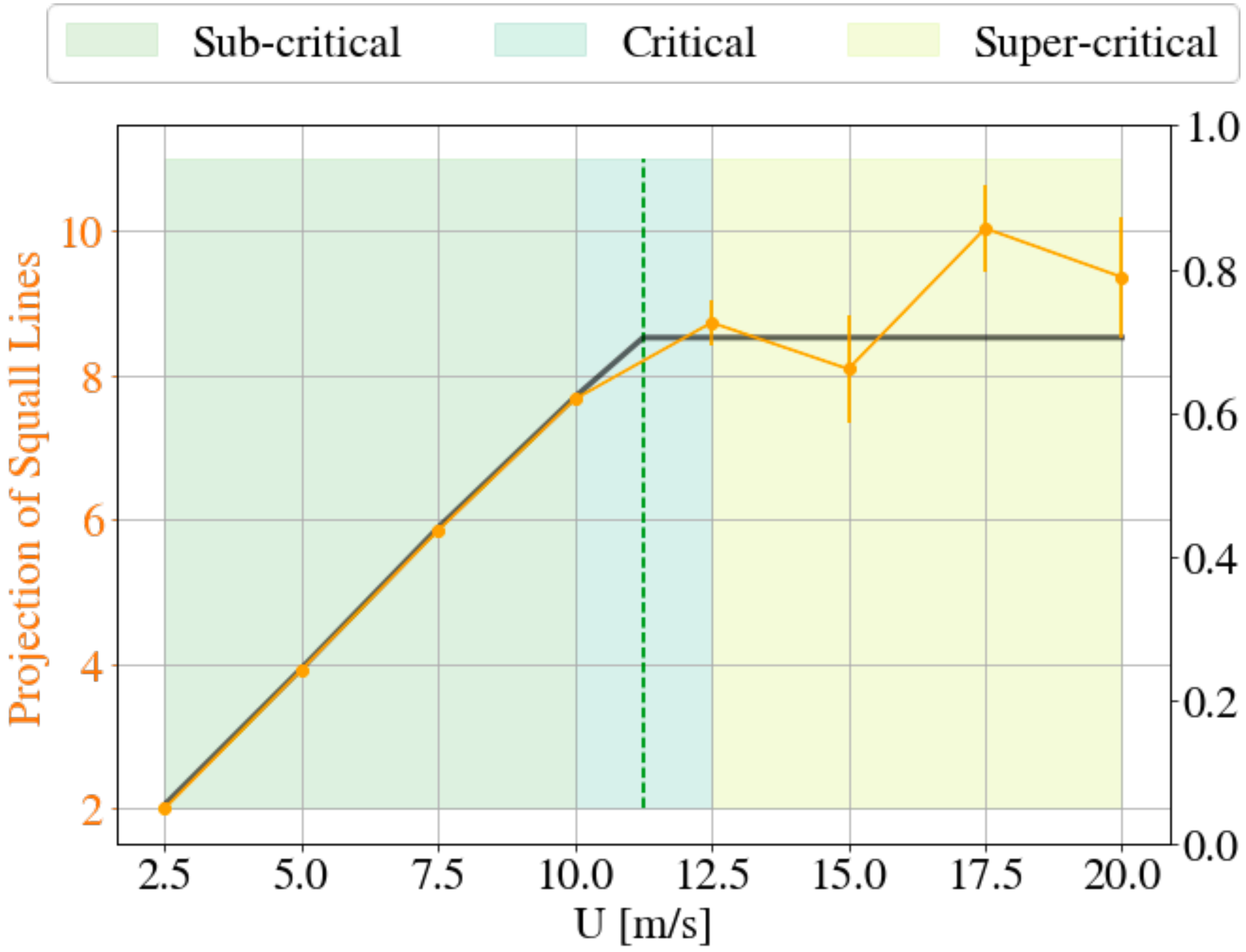
- Thermodynamic is weak (below 10%)

→ Consistent with near surface humidity increase

$$\int \overline{\rho w} \Delta \frac{-dq_*}{dz} dz \sim \overline{\rho w}_{500} \Delta q_*^{sfc}$$

Conclusion

1. Theory fo Squall Line Orientation is verified



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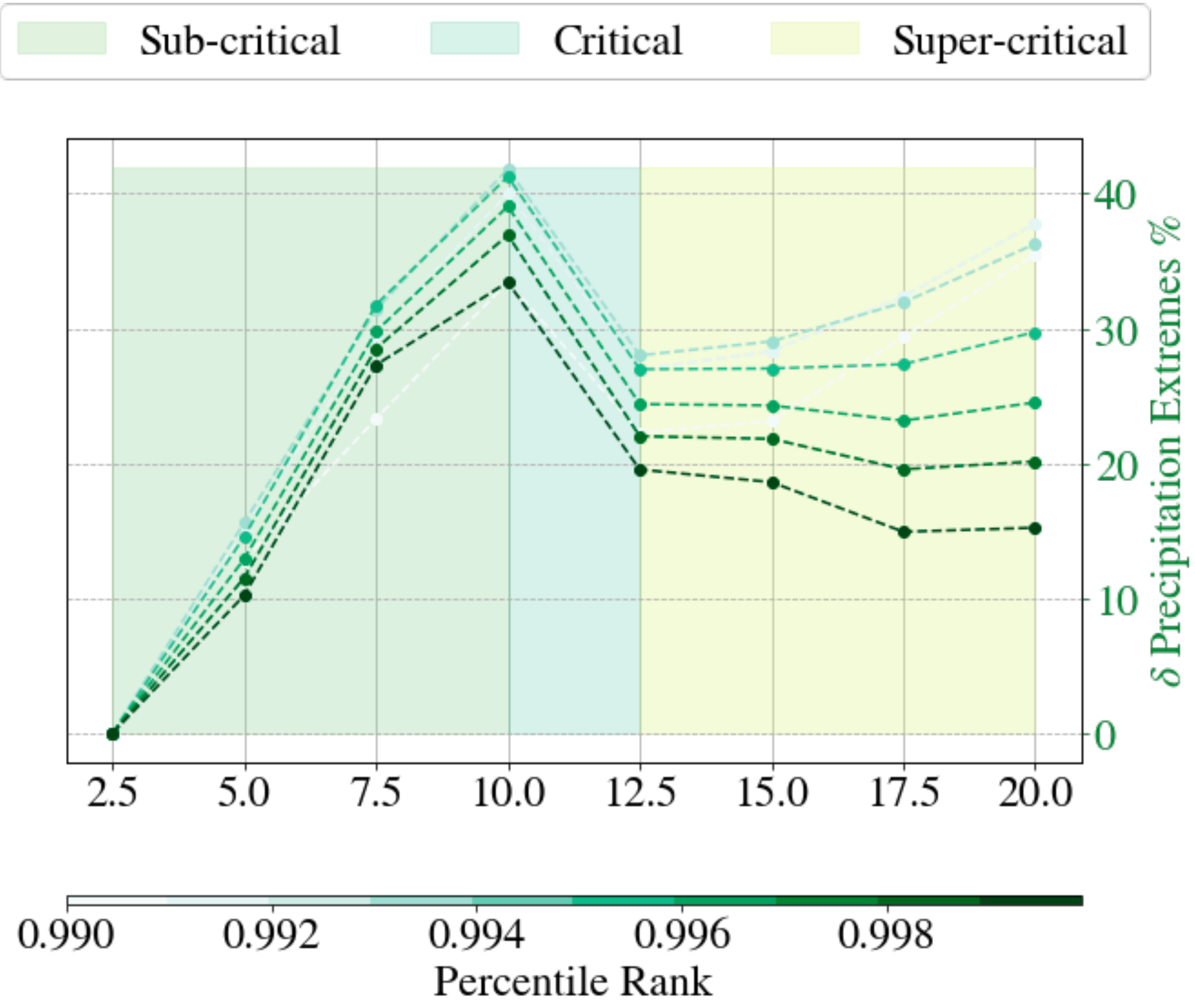

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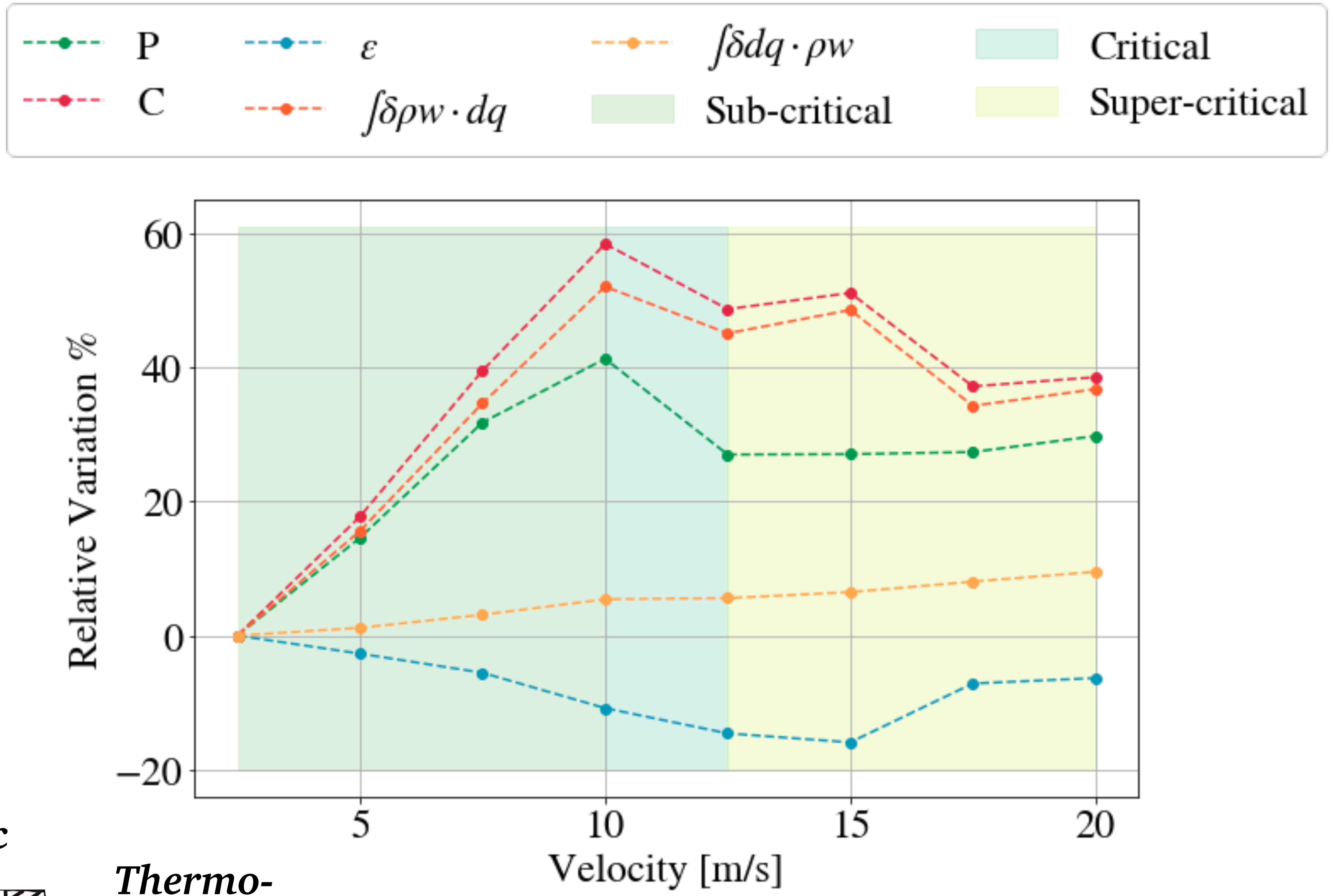
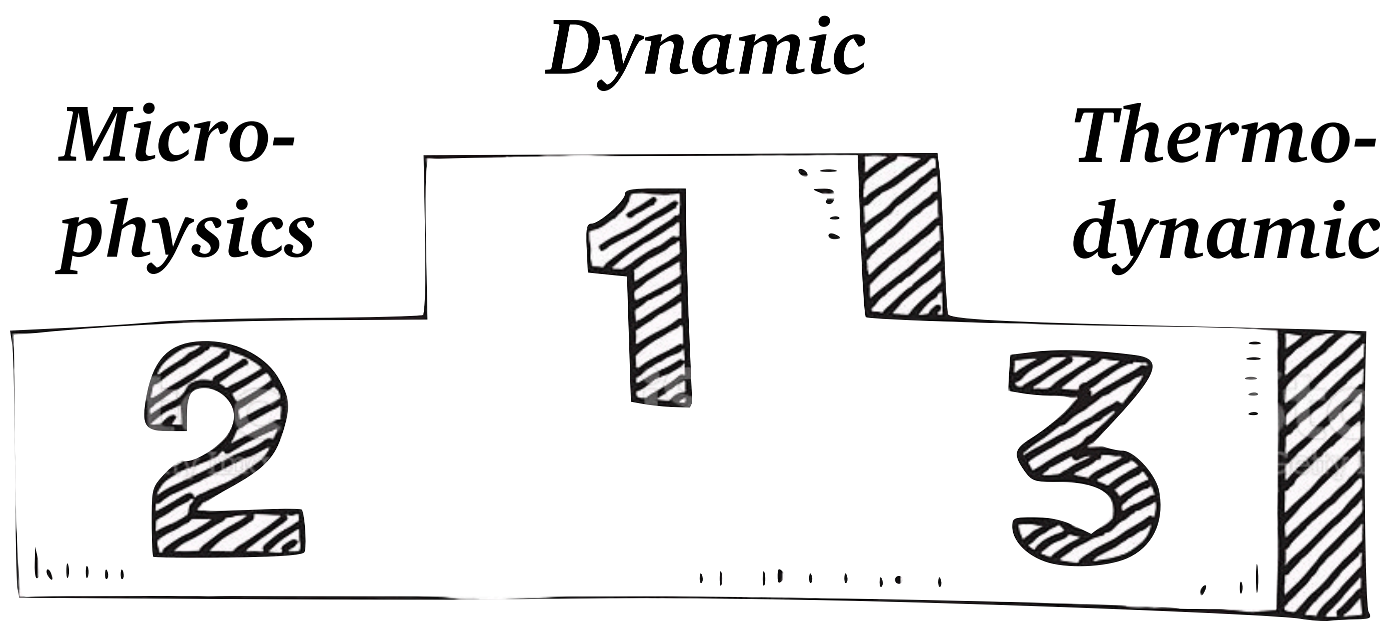
3. Contributions that mainly explain variations in precipitation extremes are (1) Dynamic, (2) Microphysic and (3) Thermodynamic





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4. Change Triggering velocity (1)

Conclusion

$$\epsilon \sim \frac{P}{C} \sim \frac{Q_p}{C} \times \frac{P}{Q_p}$$

1. Theory fo Squall Line Orientation is verified
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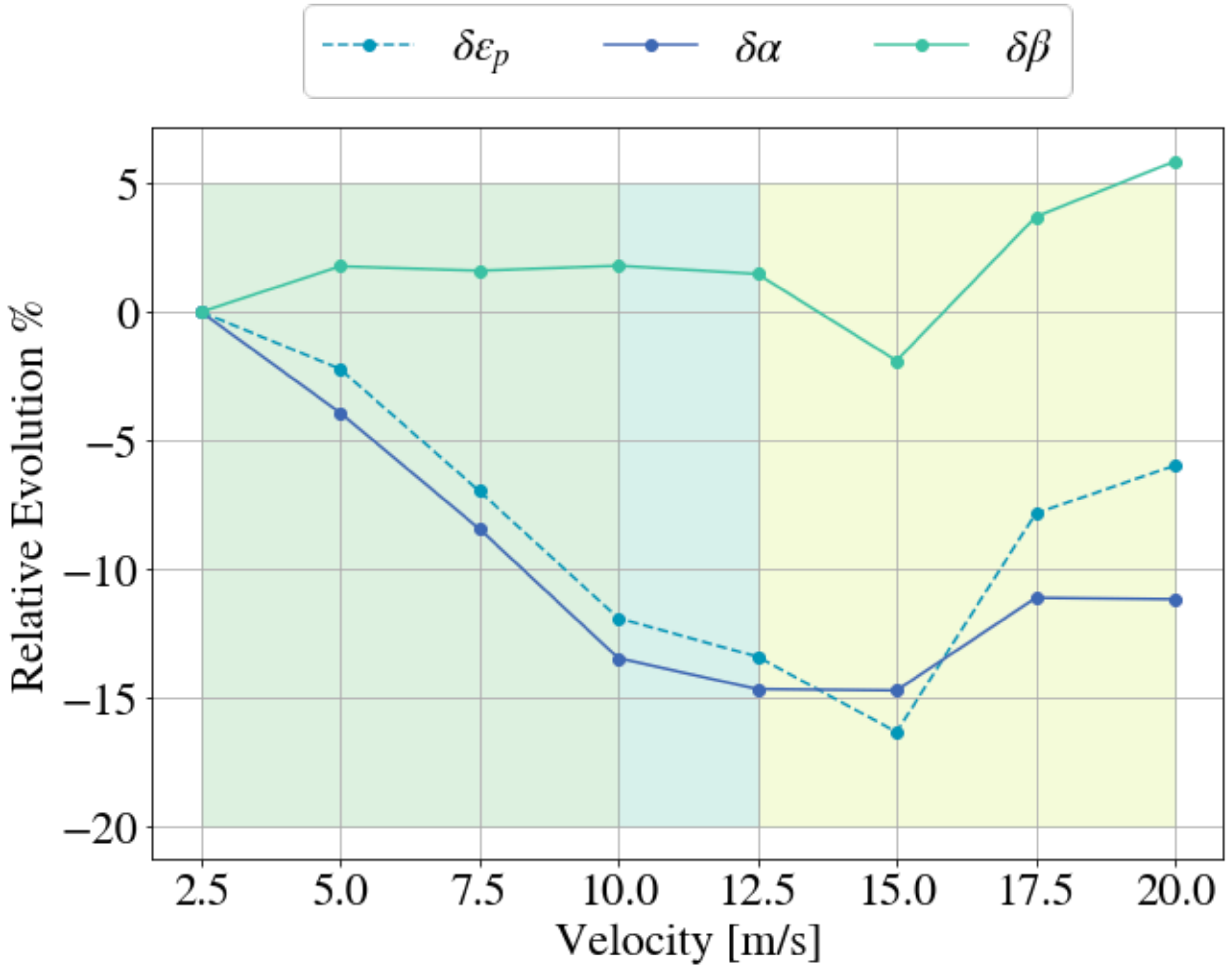
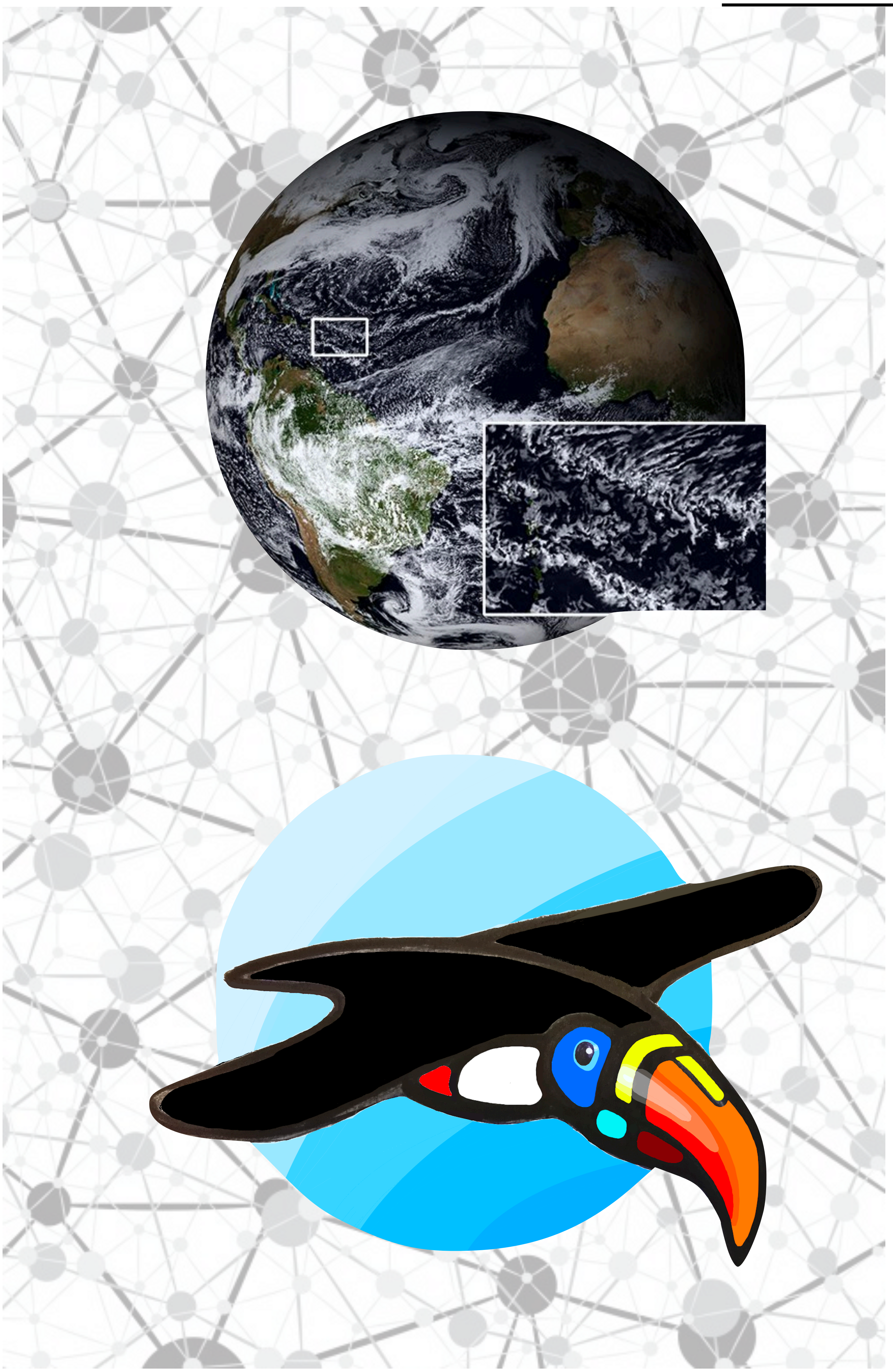
3. Contributions that mainly explain variations in precipitation extremes are (1) Dynamic, (2) Microphysic and (3) Thermodynamic
4. Change Triggering velocity (1)
5. Change in conversion rates (2) and near surface humidity (3)



To be submitted, Abramian, Muller, Risi 2022, JAMES

Perspective



Explore Squall Lines and MCSs in Dyamond-NextGEMS (SAM) using the tracking algorithm TOOCAN

How these new generation climate models can help us understand the life cycle of MCSs ?

Theoretical framework

Deep Learning

Deep Convolutionnal Neural Network (Pytorch)

Stevens, B., et al (2019). DYAMOND: the DYnamics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains. Progress in Earth and Planetary Science,

Fiolleau, T., & Roca, R. (2013). An algorithm for the detection and tracking of tropical mesoscale convective systems using infrared images from geostationary satellite. IEEE transactions on Geoscience and Remote Sensing

DeepMind, (2021), Skilful precipitation nowcasting using deep generative models of radar, Nature

Thank you !

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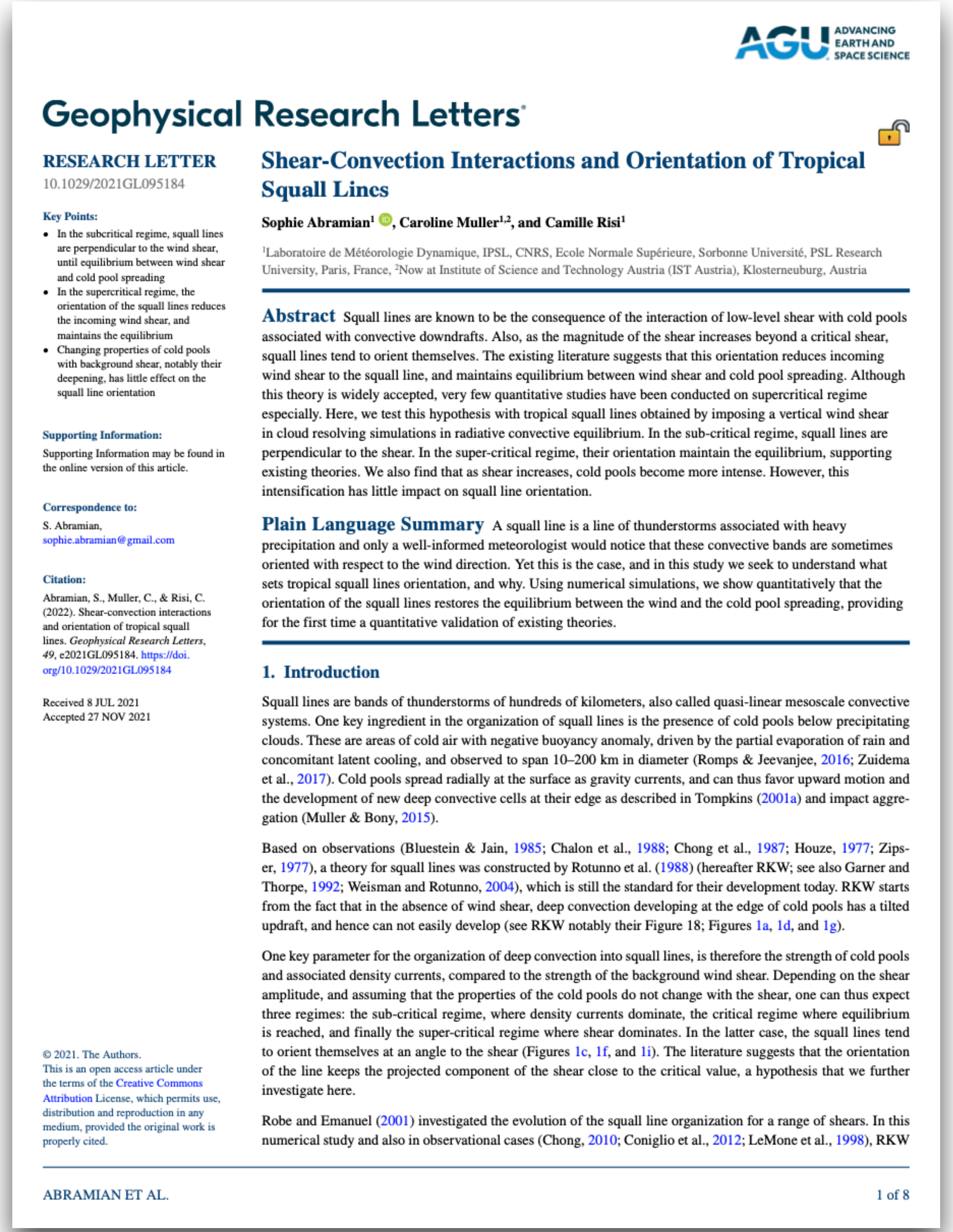

Geophysical Research Letters

RESEARCH LETTER
10.1029/2021GL095184

Key Points:
- In the subcritical regime, squall lines are perpendicular to the wind shear, until equilibrium between wind shear and cold pool spreading
- In the supercritical regime, the orientation of the squall lines reduces the incoming wind shear, and maintains the equilibrium
- Changing properties of cold pools with background shear, notably their deepening, has little effect on the squall line orientation

Supporting Information:
Supporting Information may be found in the online version of this article.

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Shear-Convection Interactions and Orientation of Tropical Squall Lines

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Abstract Squall lines are known to be the consequence of the interaction of low-level shear with cold pools associated with convective downdrafts. Also, as the magnitude of the shear increases beyond a critical shear, squall lines tend to orient themselves. The existing literature suggests that this orientation reduces incoming wind shear to the squall line, and maintains equilibrium between wind shear and cold pool spreading. Although this theory is widely accepted, very few quantitative studies have been conducted on supercritical regime especially. Here, we test this hypothesis with tropical squall lines obtained by imposing a vertical wind shear in cloud resolving simulations in radiative convective equilibrium. In the sub-critical regime, squall lines are perpendicular to the shear. In the super-critical regime, their orientation maintain the equilibrium, supporting existing theories. We also find that as shear increases, cold pools become more intense. However, this intensification has little impact on squall line orientation.

Plain Language Summary A squall line is a line of thunderstorms associated with heavy precipitation and only a well-informed meteorologist would notice that these convective bands are sometimes oriented with respect to the wind direction. Yet this is the case, and in this study we seek to understand what sets tropical squall lines orientation, and why. Using numerical simulations, we show quantitatively that the orientation of the squall lines restores the equilibrium between the wind and the cold pool spreading, providing for the first time a quantitative validation of existing theories.

1. Introduction

Squall lines are bands of thunderstorms of hundreds of kilometers, also called quasi-linear mesoscale convective systems. One key ingredient in the organization of squall lines is the presence of cold pools below precipitating clouds. These are areas of cold air with negative buoyancy anomaly, driven by the partial evaporation of rain and concomitant latent cooling, and observed to span 10–200 km in diameter (Romps & Jeevanjee, 2016; Zuidema et al., 2017). Cold pools spread radially at the surface as gravity currents, and can thus favor upward motion and the development of new deep convective cells at their edge as described in Tompkins (2001a) and impact aggregation (Muller & Bony, 2015).

Based on observations (Bluestein & Jain, 1985; Chalon et al., 1988; Chong et al., 1987; Houze, 1977; Zipser, 1977), a theory for squall lines was constructed by Rotunno et al. (1988) (hereafter RKW; see also Garner and Thorpe, 1992; Weisman and Rotunno, 2004), which is still the standard for their development today. RKW starts from the fact that in the absence of wind shear, deep convection developing at the edge of cold pools has a tilted updraft, and hence can not easily develop (see RKW notably their Figure 18; Figures 1a, 1d, and 1g).

One key parameter for the organization of deep convection into squall lines, is therefore the strength of cold pools and associated density currents, compared to the strength of the background wind shear. Depending on the shear amplitude, and assuming that the properties of the cold pools do not change with the shear, one can thus expect three regimes: the sub-critical regime, where density currents dominate, the critical regime where equilibrium is reached, and finally the super-critical regime where shear dominates. In the latter case, the squall lines tend to orient themselves at an angle to the shear (Figures 1c, 1f, and 1i). The literature suggests that the orientation of the line keeps the projected component of the shear close to the critical value, a hypothesis that we further investigate here.

Robe and Emanuel (2001) investigated the evolution of the squall line organization for a range of shears. In this numerical study and also in observational cases (Chong, 2010; Coniglio et al., 2012; LeMone et al., 1998), RKW

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