Physical origins of the properties of mesoscale convective systems and implications for high impact events

PhD Defense, Université Paris Science Lettre

Sophie Abramian

under the supervision of **Caroline Muller** (ISTA) & **Camille Risi** (LMD, Sorbonne Université)

Laboratoire de Météorologie Dynamique, Ecole Normale Supérieure de Paris, Ecole Doctorale 129

Jury's composition :

Présidente du jury: **Sabrina Speich** (LMD, ENS)

Rapporteurs: **J-P. Chaboureau** (Laboratoire d'Aérologie) & **P. Gentine** (Columbia University)

Examinateurs: **S. Bony** (LMD, Sorbonne Université), **R. Roca** (OMP-LEGOS), **J. Haerter** (Potsdam University)

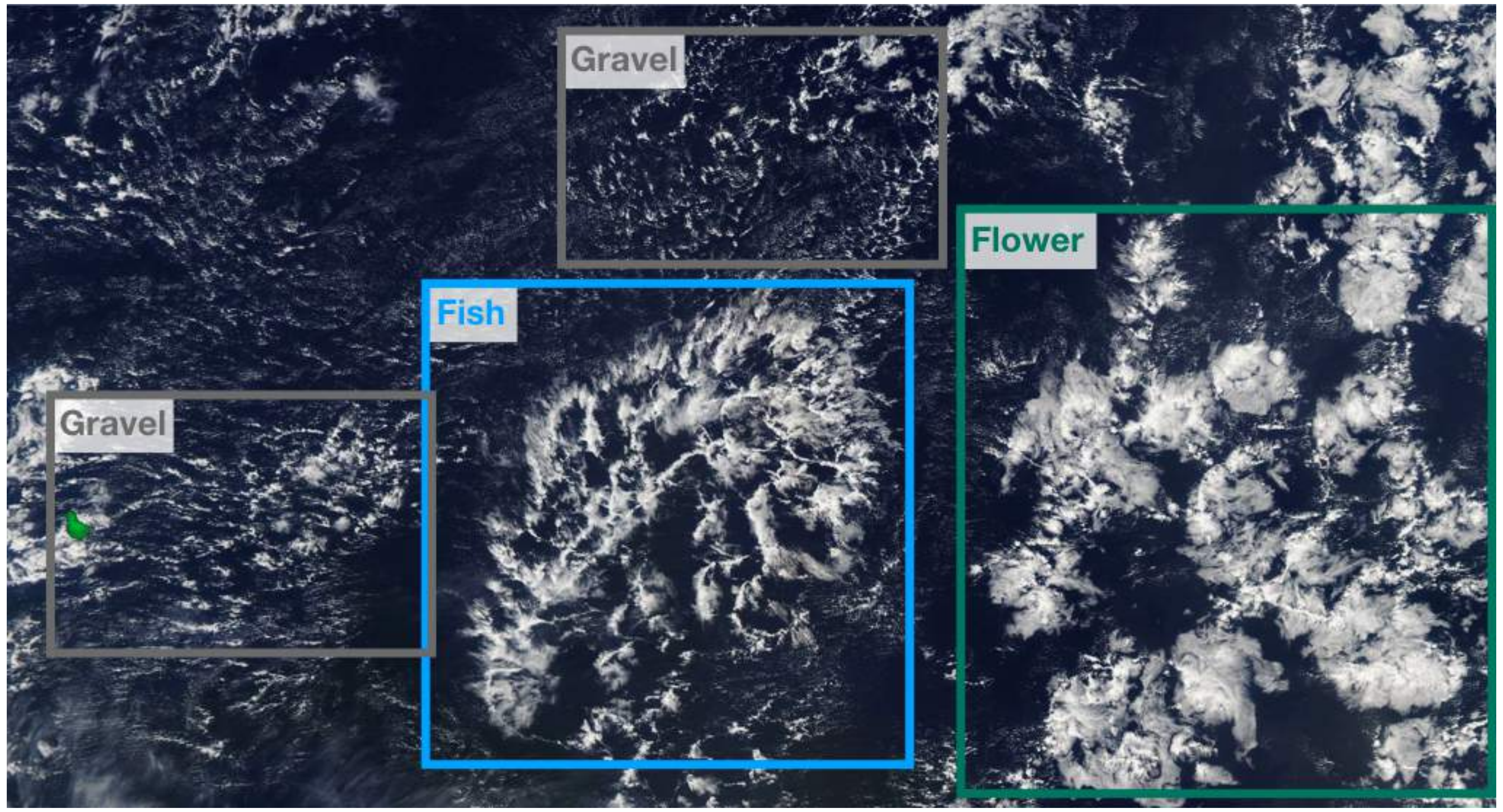
Tuesday, December 5th 2023


Gravity Waves
Mesoscale Convective Systems
Clouds Streets

Definition : What is Convective Organization ?

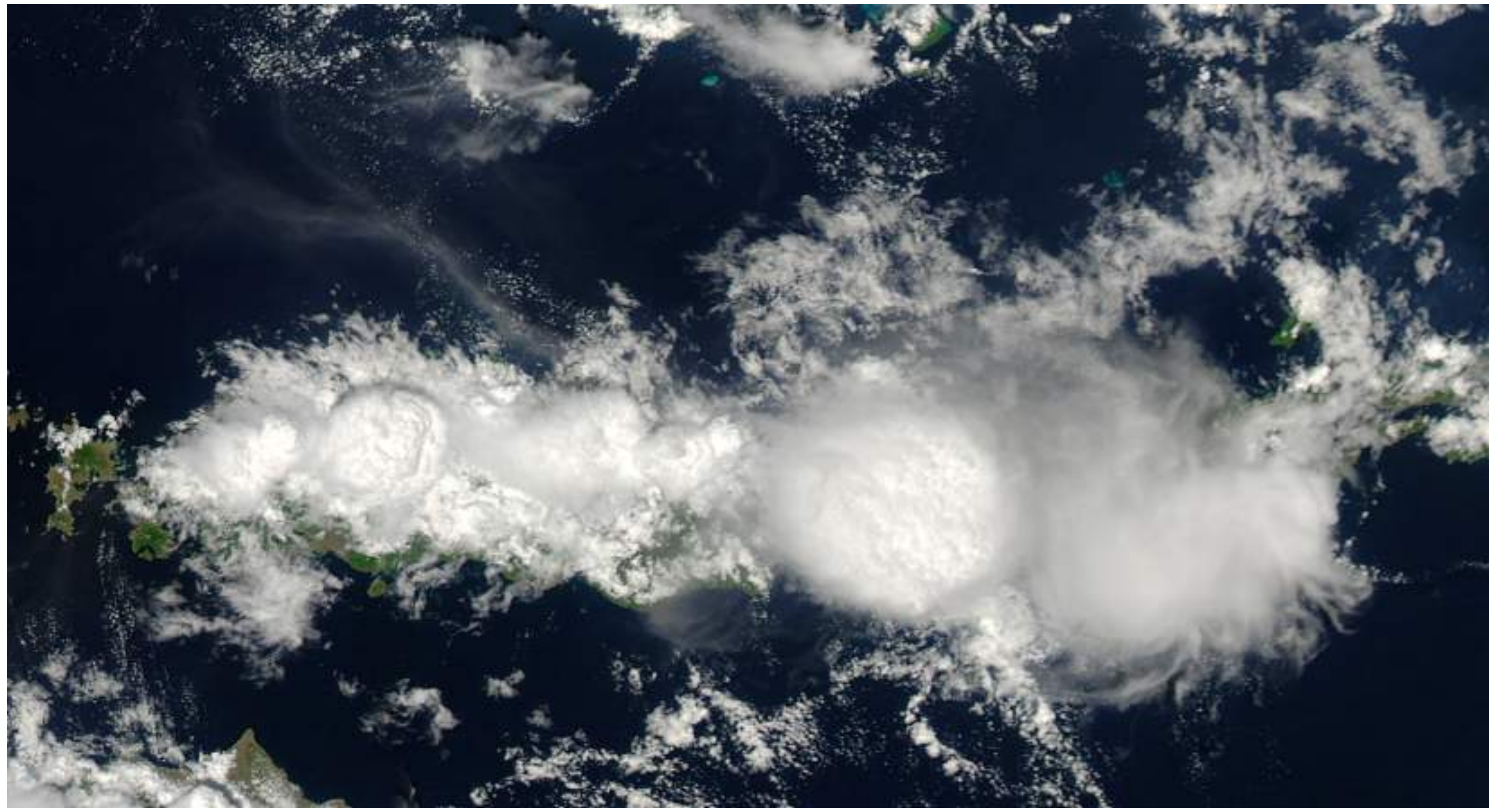
Convective Organization is **Order in Disorder**

Organized shallow convection



Bony et al. 2017, Stevens et al. 2021

Organized deep convection



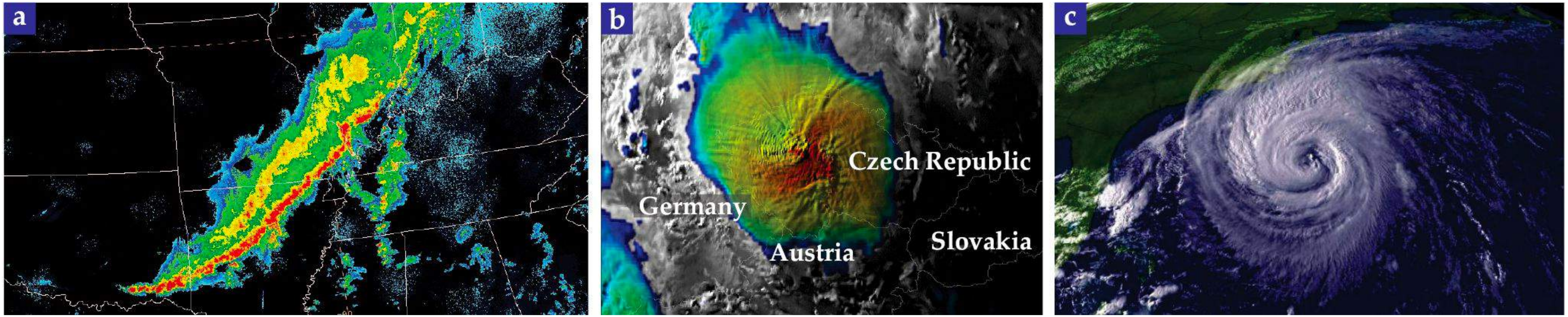
Wing 2015

Convective organization is when **convective cells** clump, show **patterns**, or **cluster together**, in space, and are surrounded by comparatively **dry regions** *(Pendergrass 2018)*

Definition : What is Convective Organization ?

Mesoscale Convective Systems (MCSs), example of deep convection organization

Squall Line *Mesoscale Convective Complex* *Tropical Cyclone*



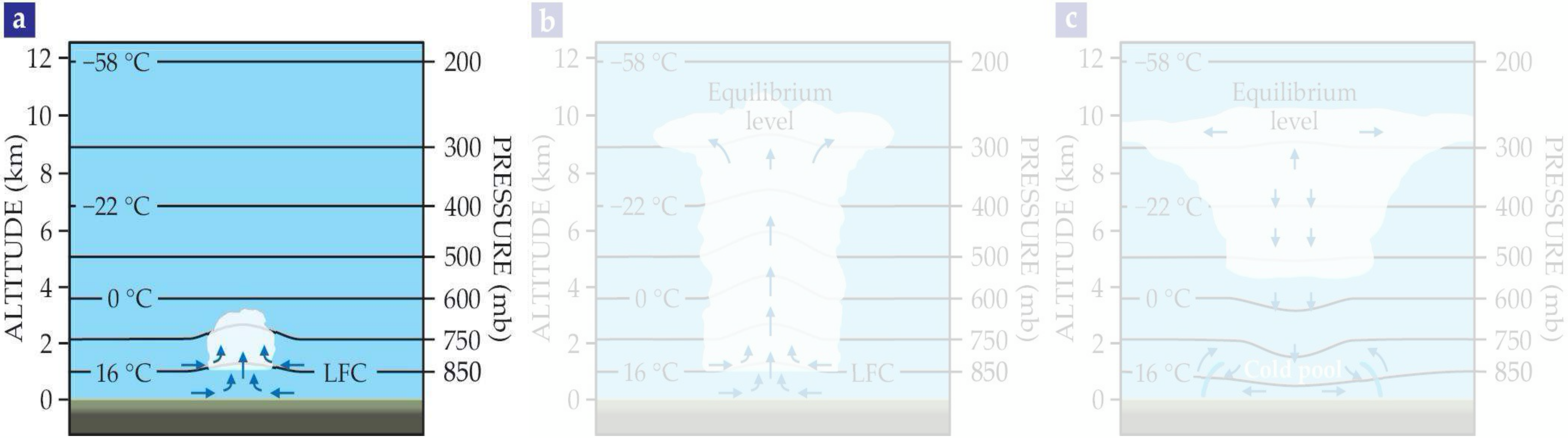
Typically last several hours and span a horizontal scale of 100km
associated with extreme precipitation

What are the physical processes behind their organization ?

How do clouds become clouds ?

Three physical concepts

1. Archimedes principle: heated air goes upward
2. Adiabatic expansion : as pressure drops, water vapor condensate
3. Latent heat from phase change: condensation release heat



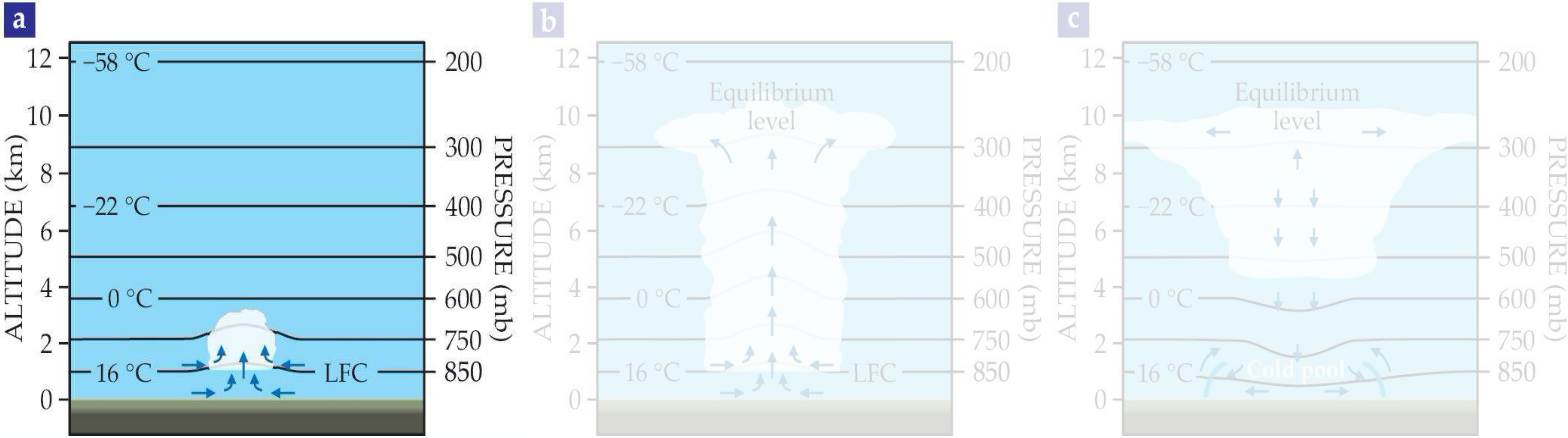
How do clouds cluster together ?

Muller C. & Abramian S., Physics Today 2023

How do clouds become clouds ?

Three physical concepts

1. Archimedes principle: heated air goes upward
2. Adiabatic expansion : as pressure drops, water vapor condensate
3. Latent heat from phase change: condensation release heat



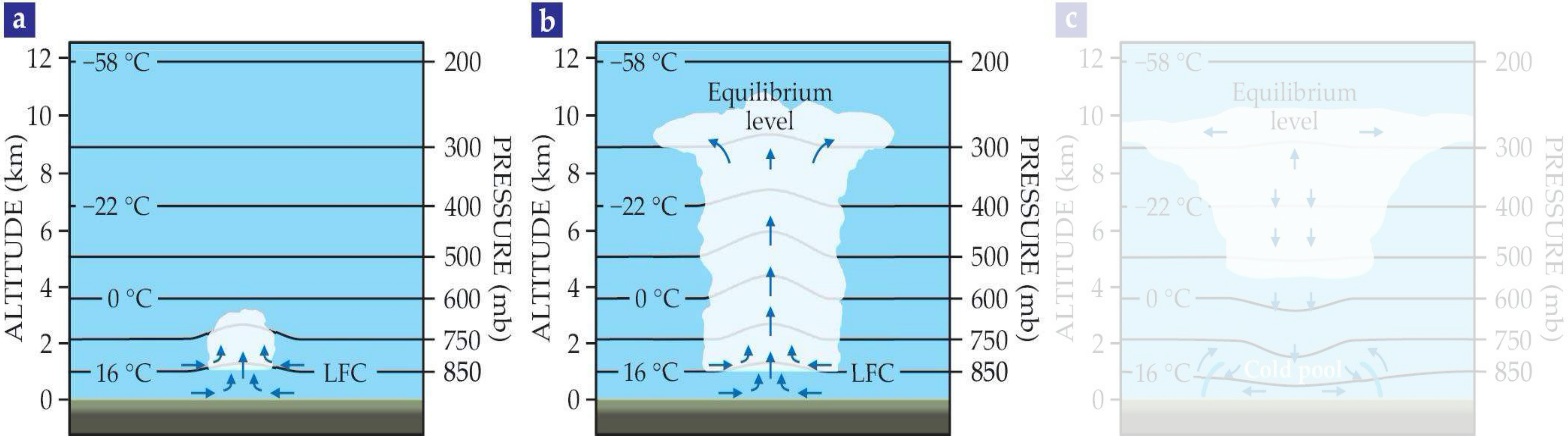
How do clouds cluster together ?

Muller C. & Abramian S., Physics Today 2023

How do clouds become clouds ?

Three physical concepts

1. Archimedes principle: heated air goes upward
2. Adiabatic expansion : as pressure drops, water vapor condensate
3. Latent heat from phase change: condensation release heat



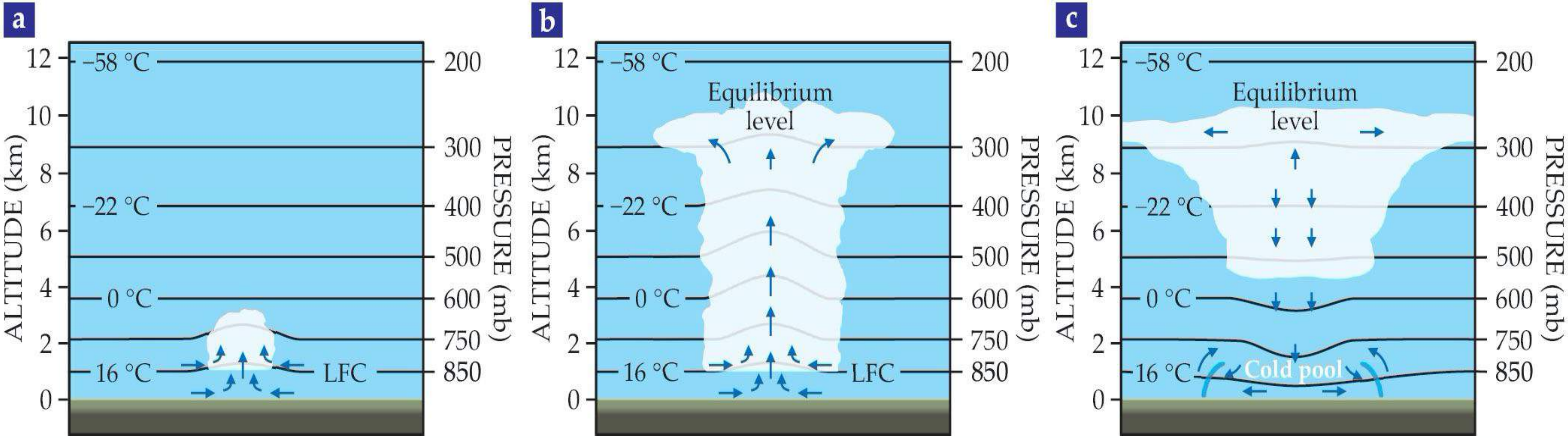
How do clouds cluster together ?

Muller C. & Abramian S., Physics Today 2023

How do clouds become clouds ?

Three physical concepts

1. Archimedes principle: heated air goes upward
2. Adiabatic expansion : as pressure drops, water vapor condensate
3. Latent heat from phase change: condensation release heat



How do clouds cluster together ?

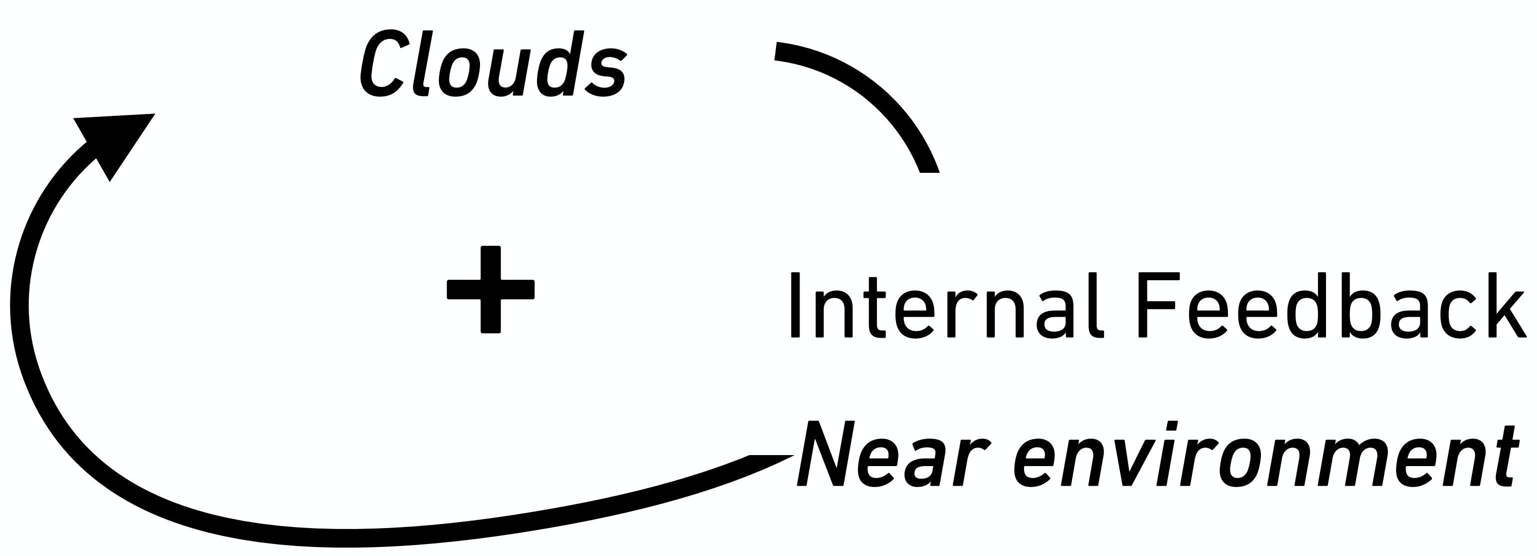
Muller C. & Abramian S., Physics Today 2023

How do clouds cluster together ?

Multicloud structures arise from positive feedback mechanisms that reinforce existing cloud distribution.

Near environment

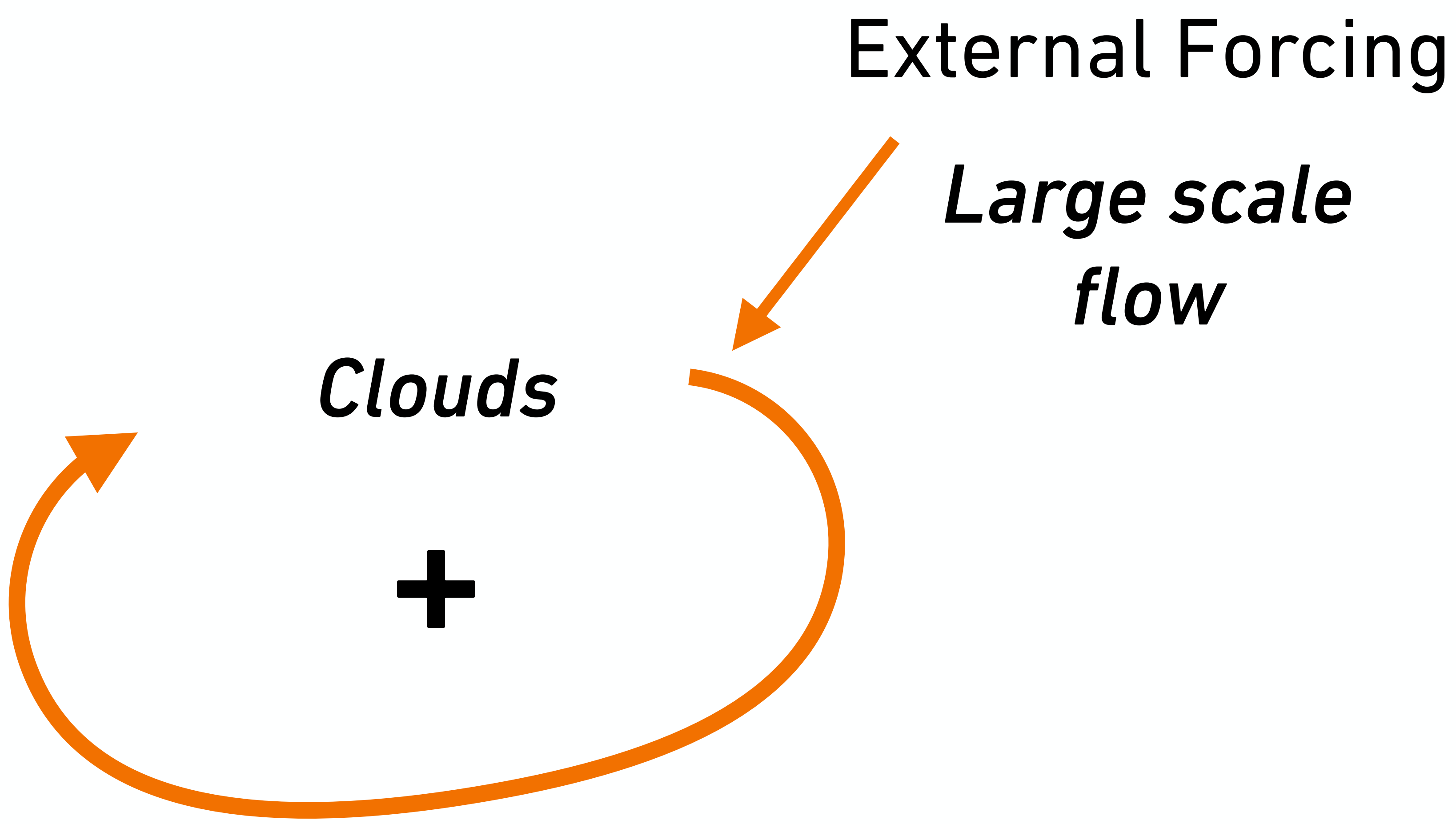
Internal Positive Feedback: the enhancing or amplification of an effect by its own influence.



Self-aggregation feedbacks

Atmosphere large-scale flow

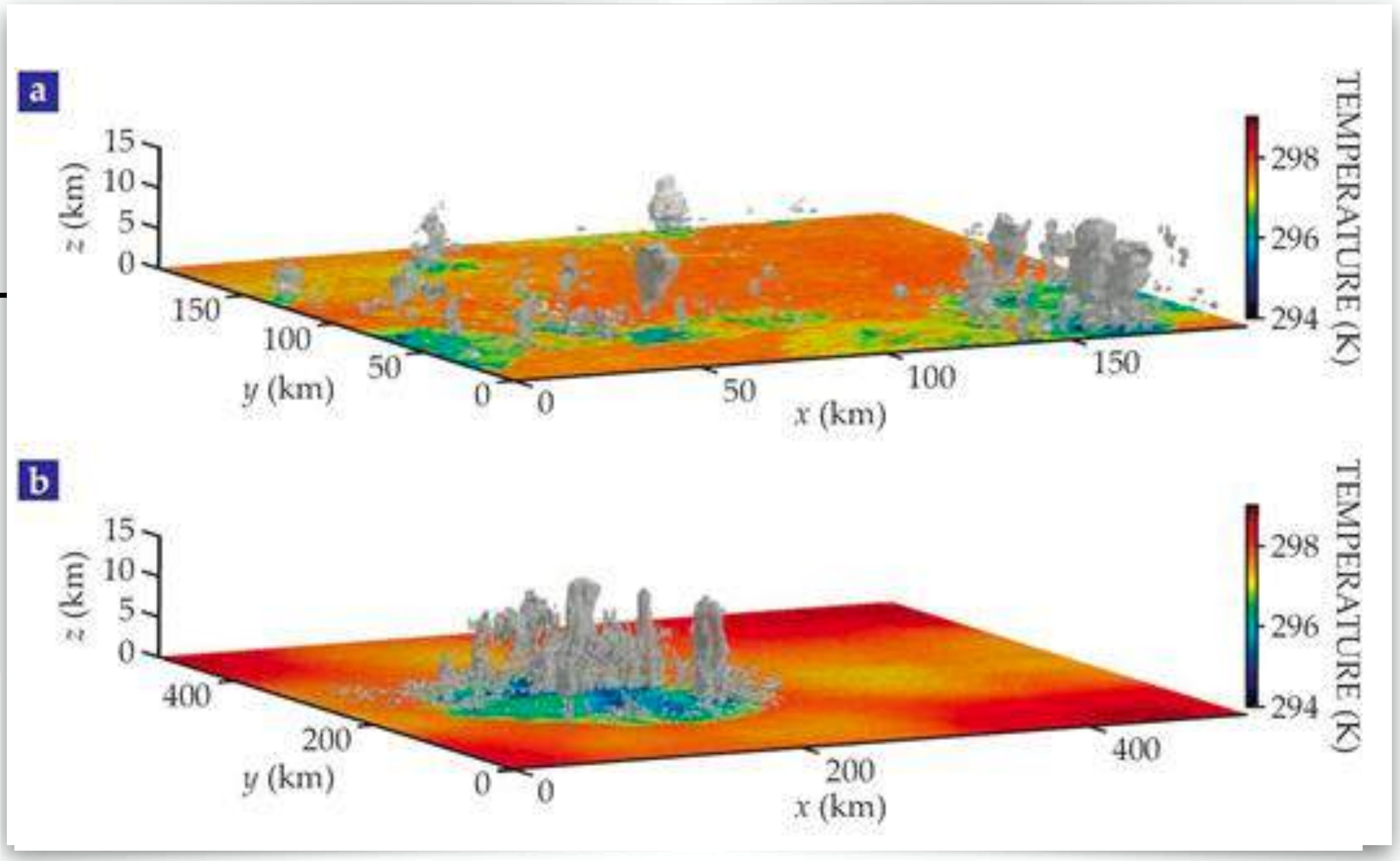
External Positive Forcing: the enhancing of an effect by an external process.

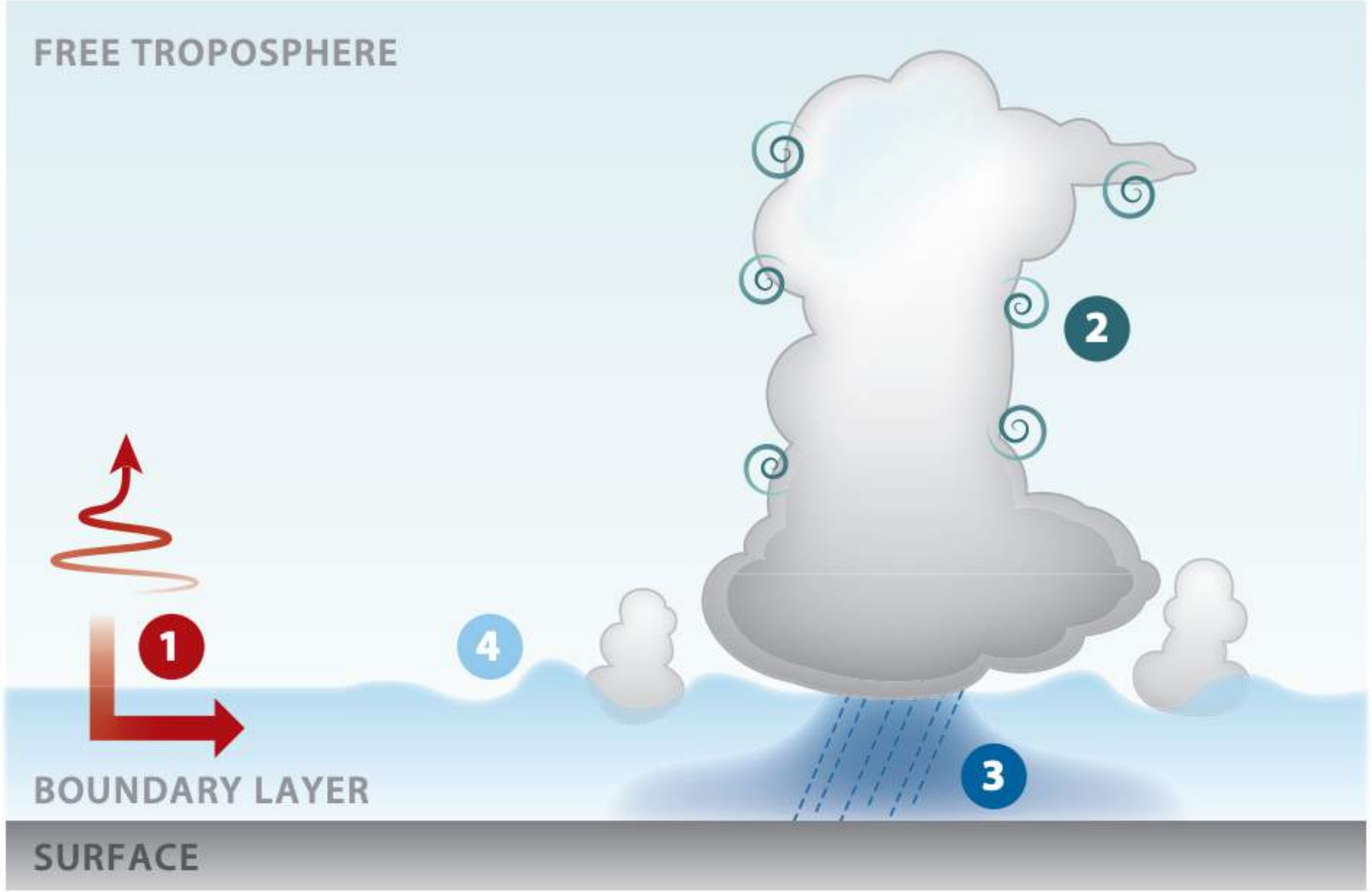


Example : Shear convection interaction

Internal-FeedBack : Self-aggregation

Definition of self-aggregation — Ability of deep clouds to spontaneously cluster in space, despite perfectly homogeneous boundary conditions in idealized numerical simulations.

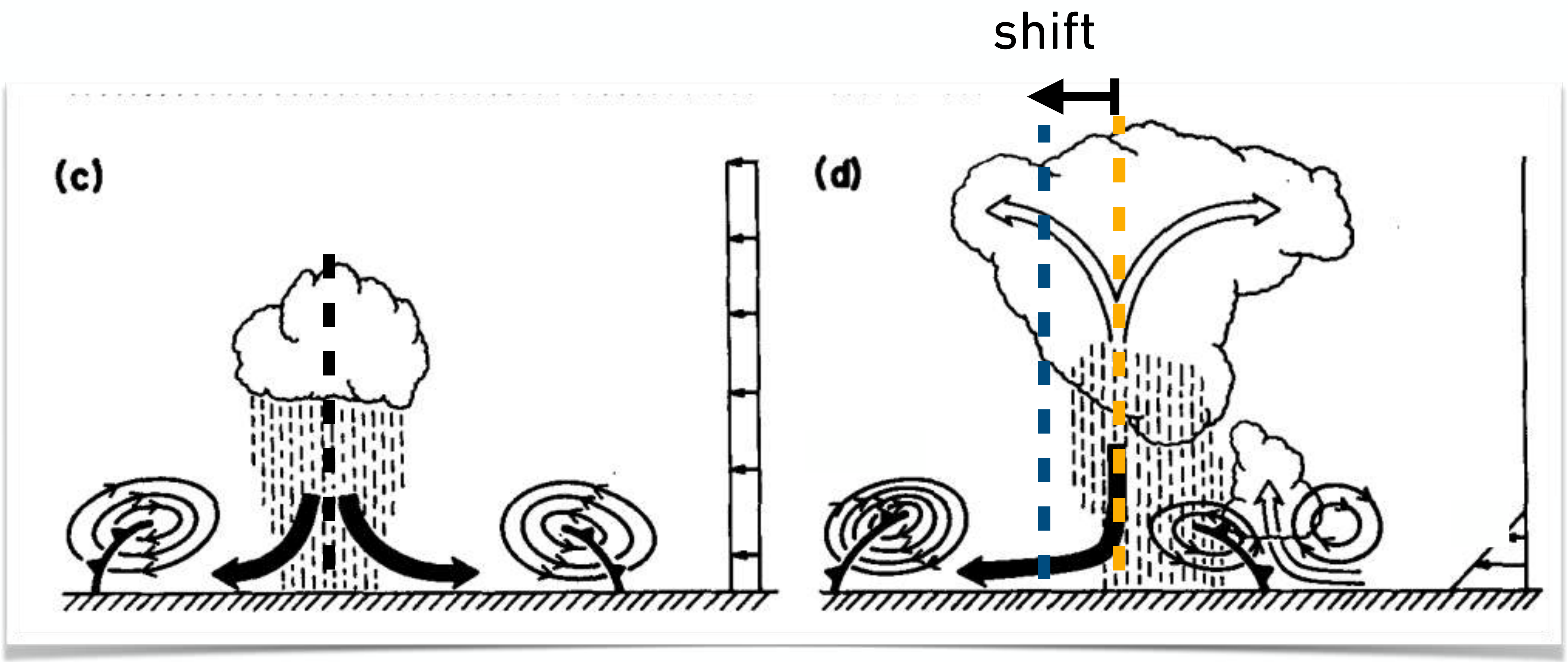


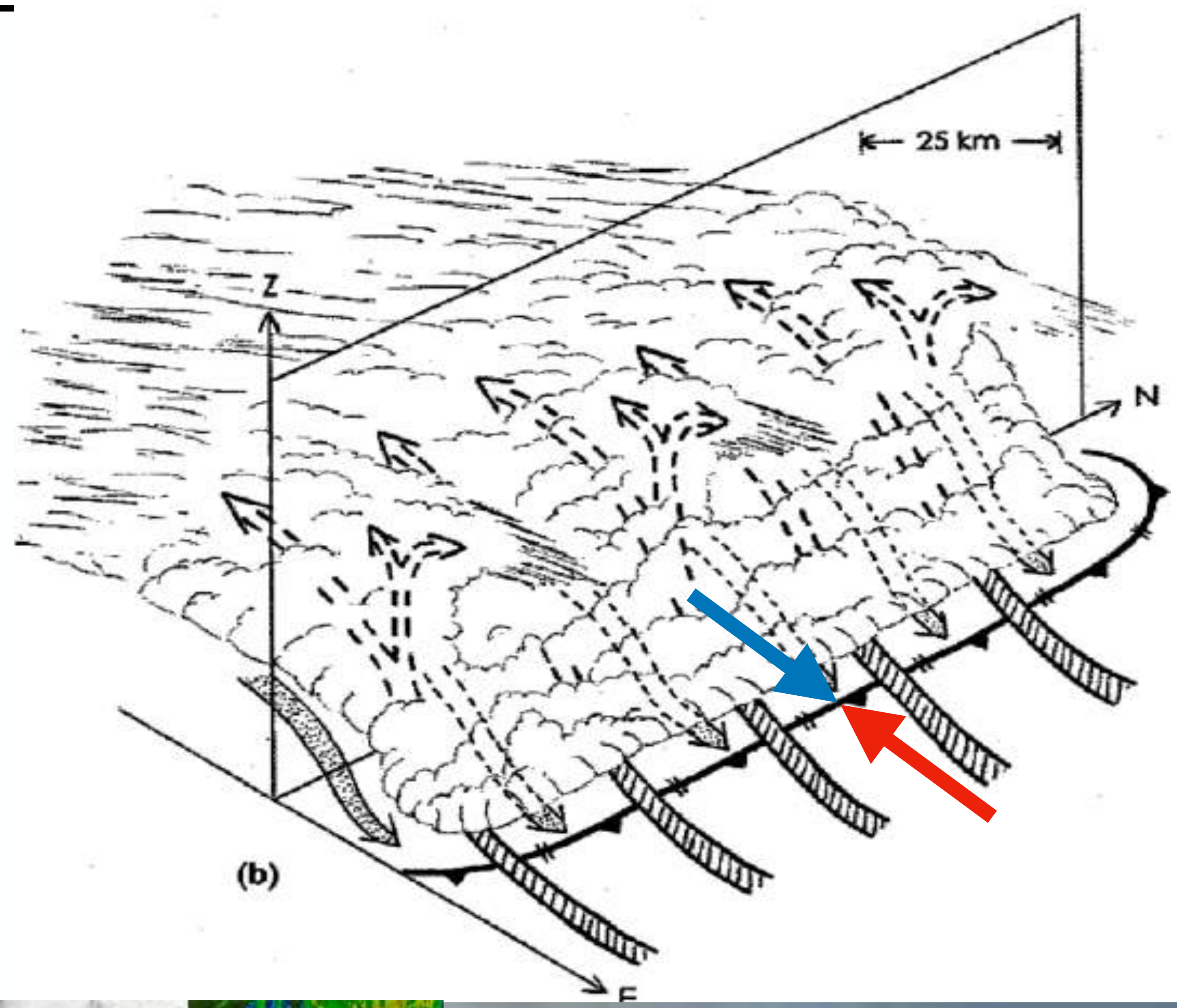


Key physical processes leading to self-aggregation (*Muller et al. 2022*) :

1. Enhanced radiative cooling in dry regions and associated circulation
2. Turbulent entrainment of environmental air at the edge of clouds
3. Evaporation-driven cold pools in the boundary layer
4. Boundary layer wave emission

External Forcing : Shear interaction





Key physical processes leading to squall line formation
(*Rotunno Klemp Weisman 1988*)

Wind Shear induces a symmetry breakage

Cold pool edge promotes updrafts

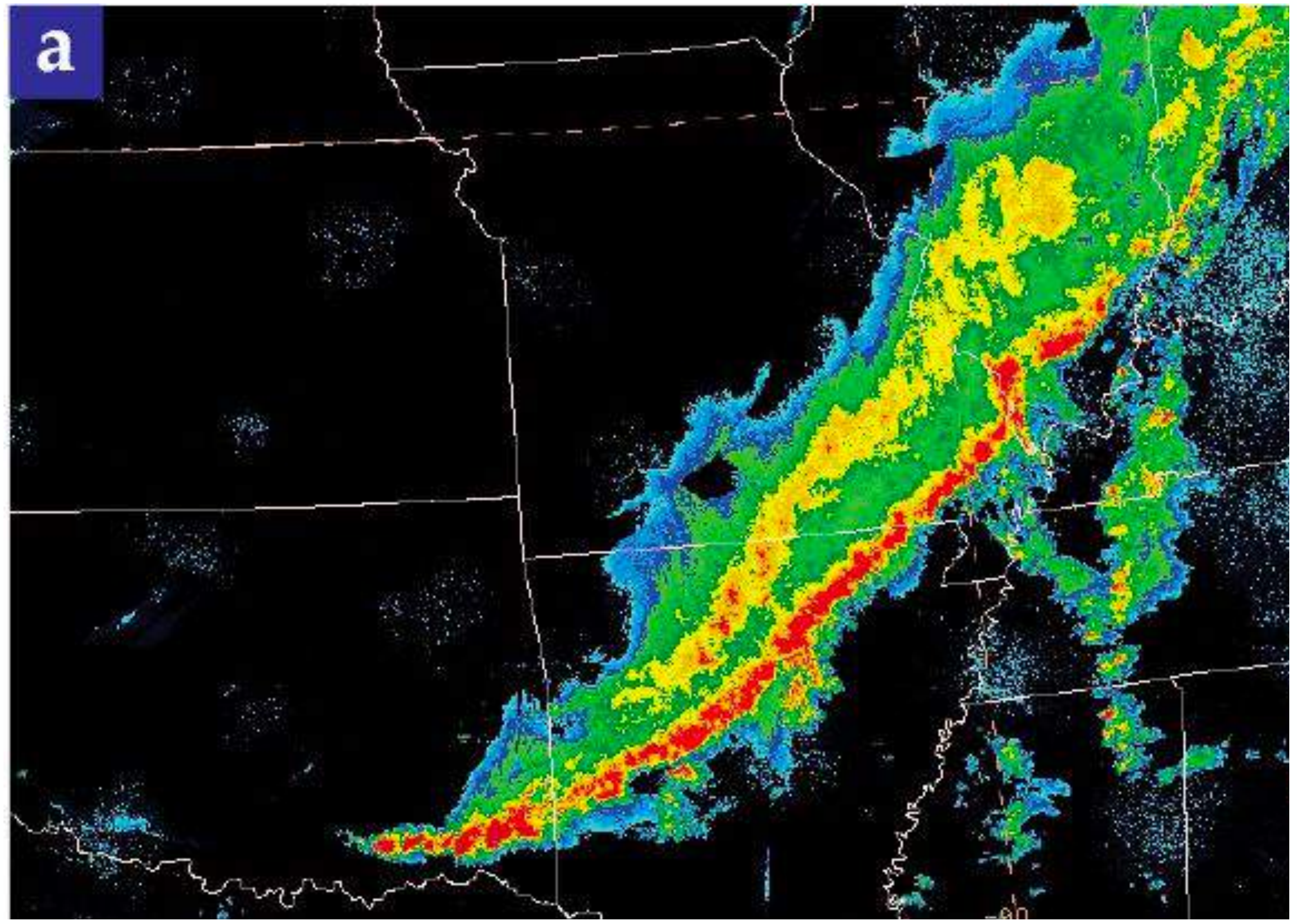
updrafts eventually feed the cold pool

self maintained process

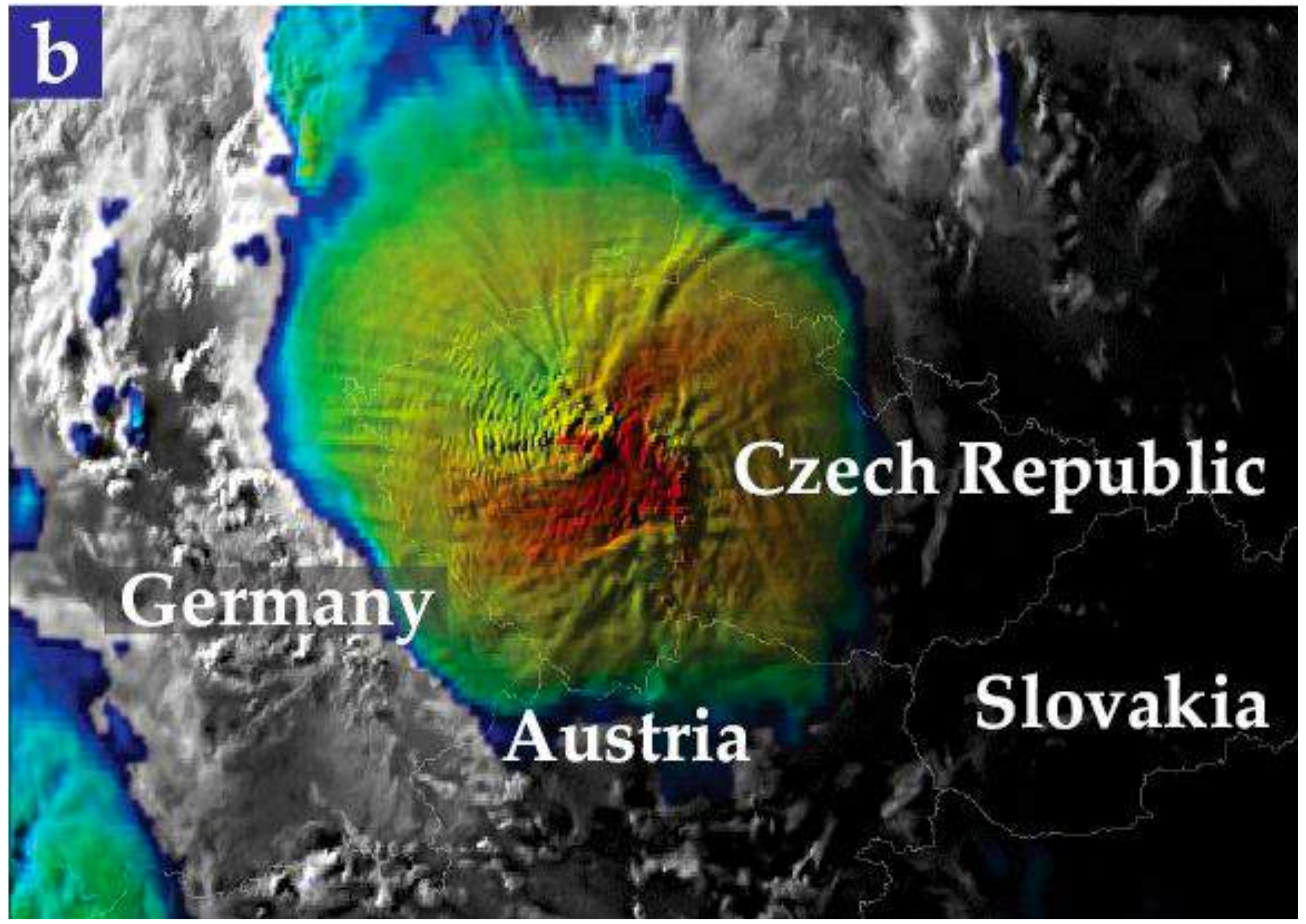
Wide range of Mesoscale Convective Systems

How do these feedbacks **modulate MCSs properties** ?

Squall Line



Mesoscale Convective Complex



Orientation ?

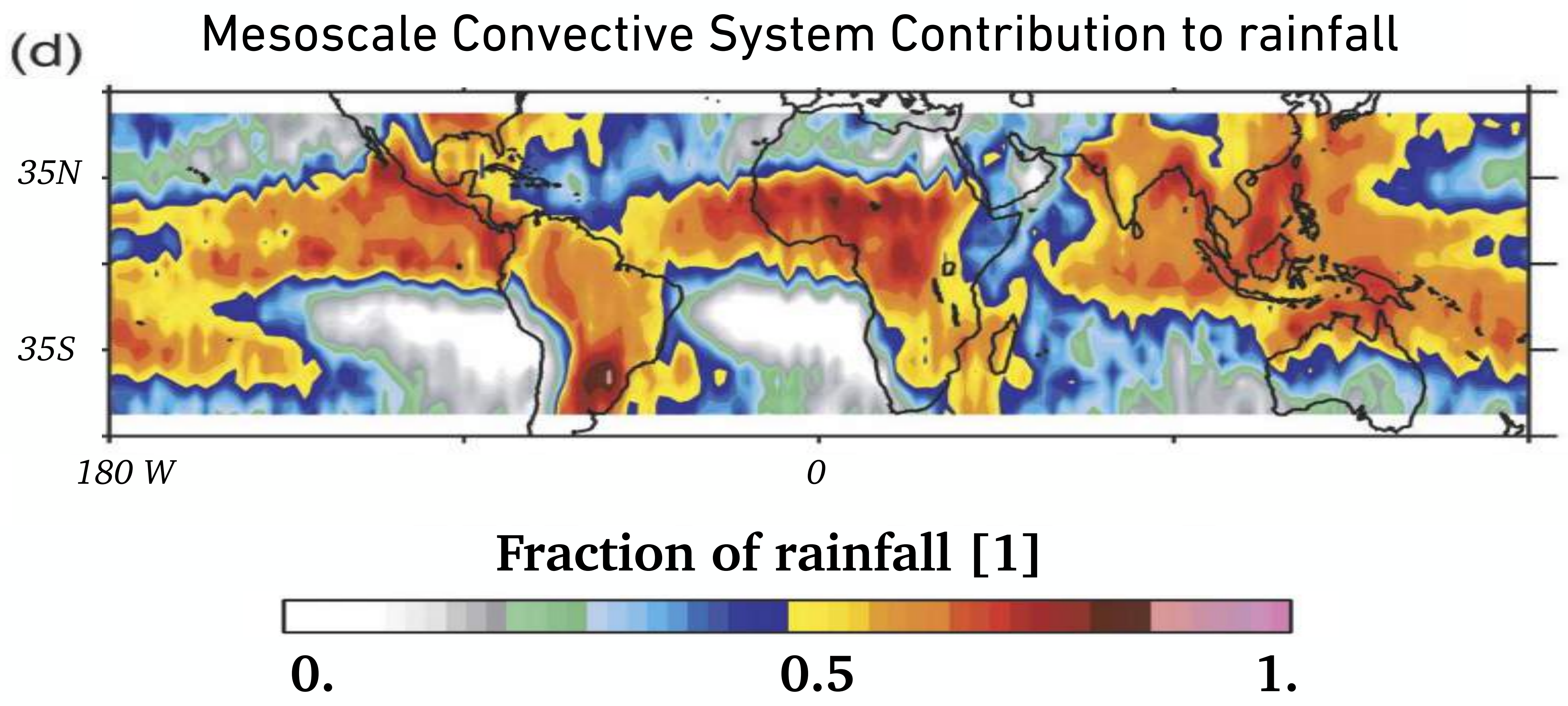
Maximal Area ?

How do these properties impact **precipitation extremes** ?

Organized deep convection is associated with precipitation extremes

The role of MCSs in Rainfall and Rainfall Extremes

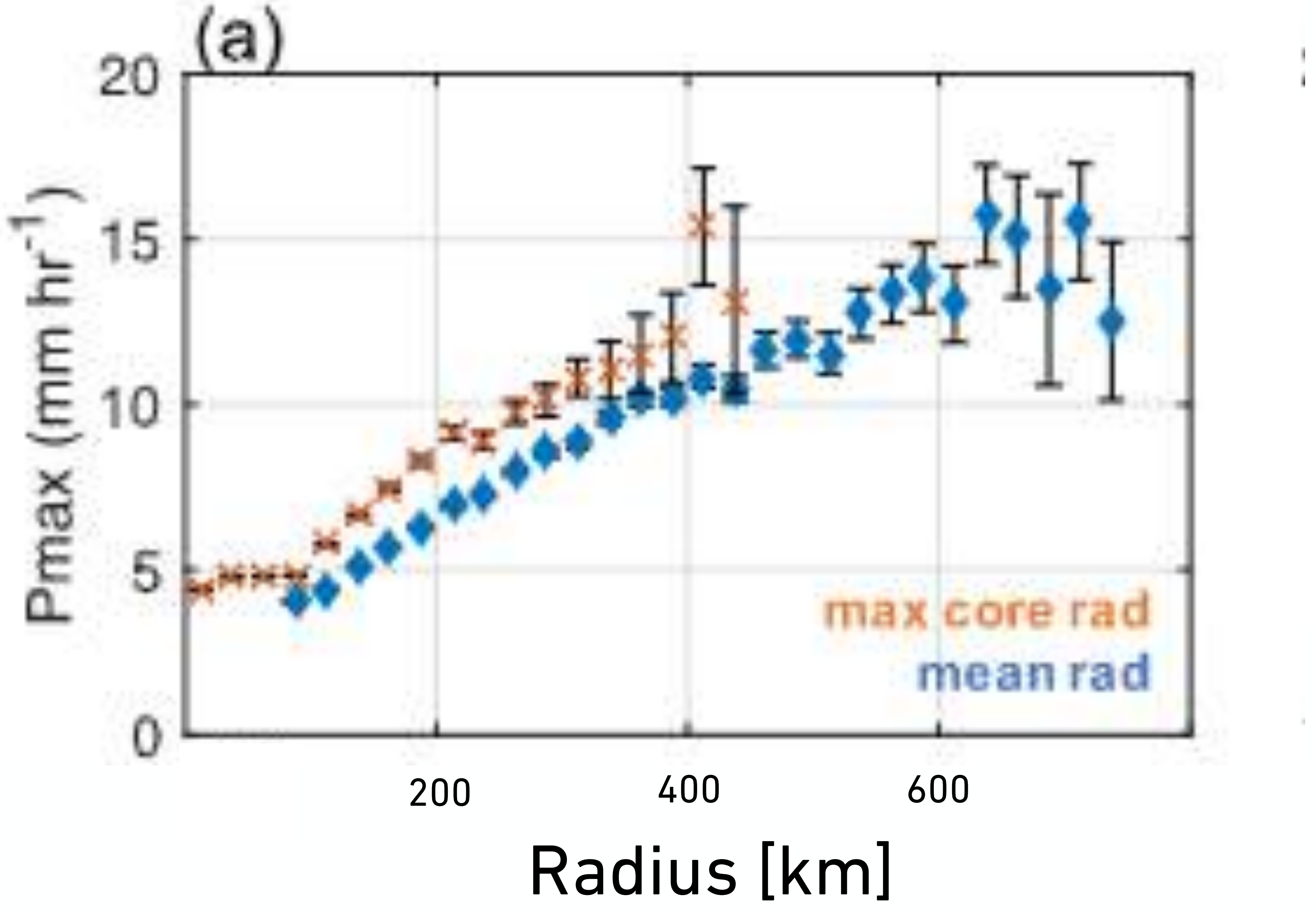
Nesbitt et al 2006, Schumacher and Rasmussen 2020



MCSs are responsible of more than 50% of tropical rain

Large and long lived MCSs and Rainfall Extremes

Schiro et al 2020, Roca & Fiolleau 2020



More extreme rainfall when convection is more aggregated *(Semie & Bony, 2020, Moseley et al 2016)*

What controls MCSs properties ?

General objective of the thesis

Better understand what is at the ***origin of mesoscale convective systems properties***

to better predict ***implications for high impact event***

Outline

Introduction

*Muller C. & **Abramian S.** 2023, Physics Today*

Part 1

Squall Lines

What sets tropical squall lines orientation and why ?

__Abramian S.__, Muller C., Risi C., 2022, GRL

How does the orientation of the line impact extreme precipitation ?

__Abramian S.__, Muller C., Risi C., 2023, JAMES

Part 2

MCSs Tracking

What sets the maximal extension of MCSs ?

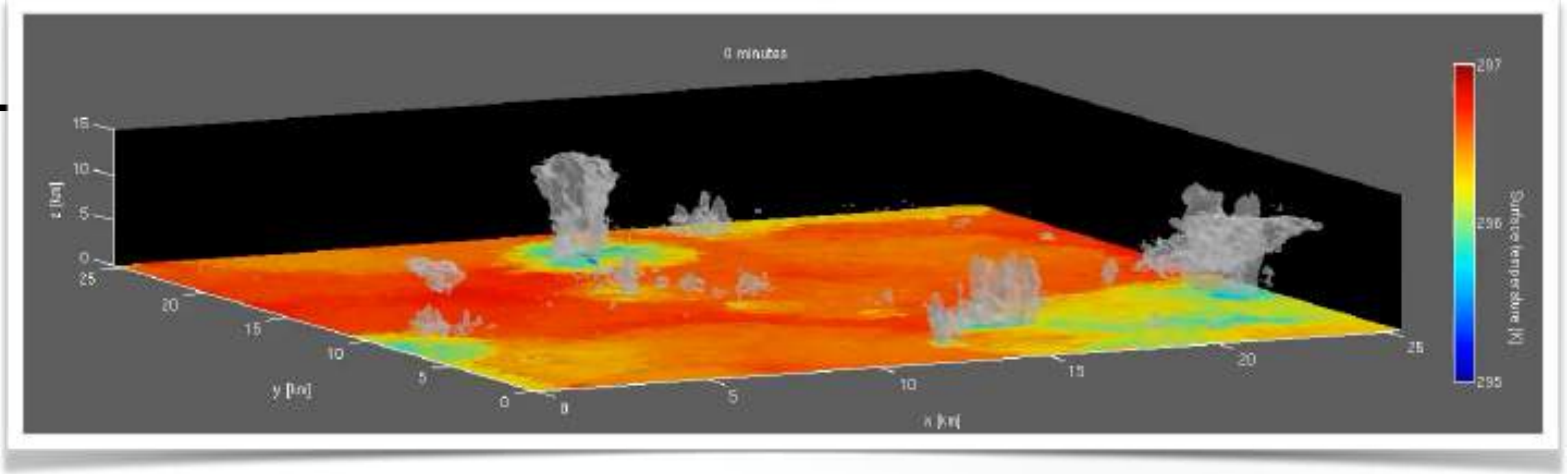
*In Prep. **Abramian S.**, Muller C., Risi C., Roca R., Fiolleau T.,*

How convective systems are recorded in past climate archive ?

*Risi C., Muller C., Vimeux F., Blossey P., Védeau G., Dufaux C., **Abramian S.**, 2023, JAMES*

Conclusion and Perspectives

Khairoutdinov & Randall 2003



Methodology

Introduction

Part 1

Idealized Simulations

What sets tropical squall lines orientation and why ?

Abramian S., *Muller C., Risi C., 2022, GRL*

How does the orientation of the line impact extreme precipitation ?

Abramian S., *Muller C., Risi C., 2023, JAMES*

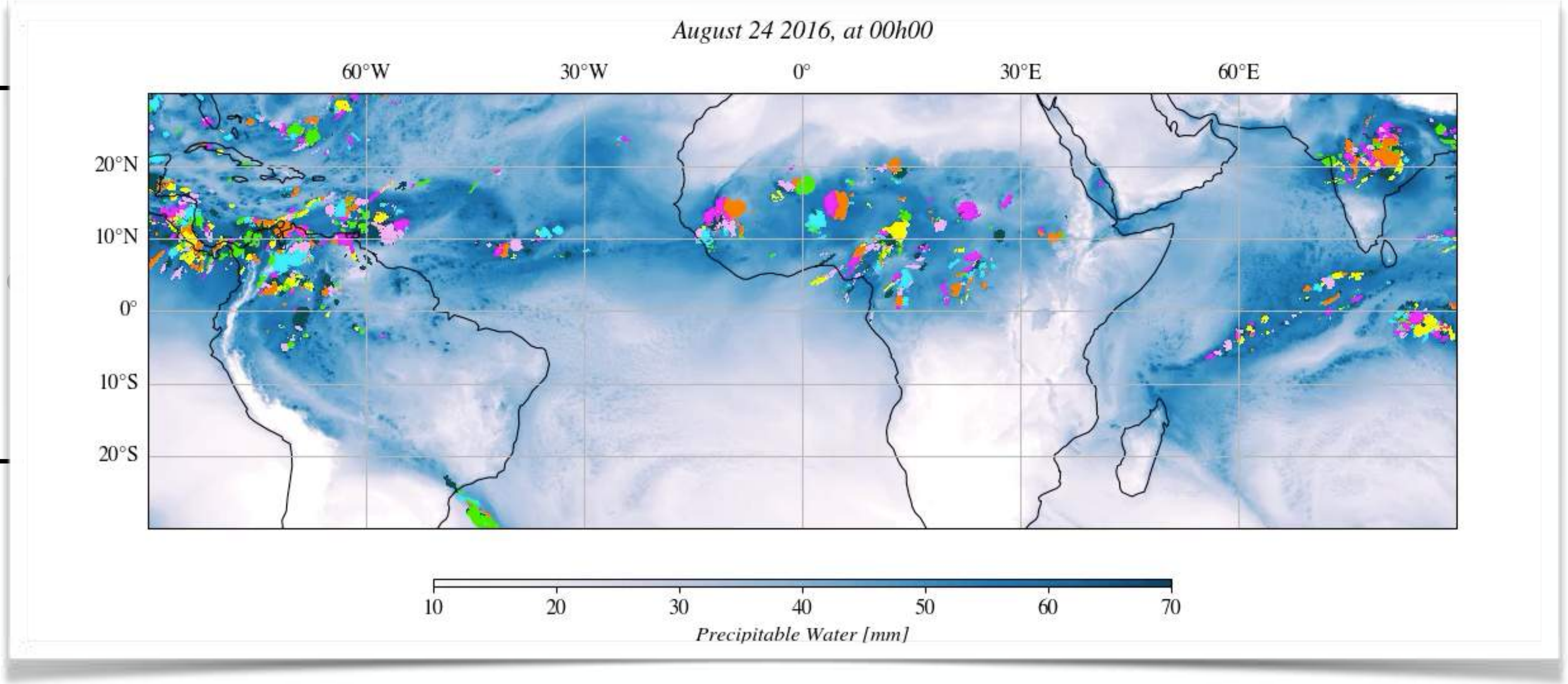
Part 2

Realistic Global Simulations

What sets the maximal extension of MCSs ?

In Prep. ***Abramian S.***, *Muller C., Risi C., Roca R., Fiolleau T.,*

How convective systems are recorded in past clim



Conclusion and Perspectives

Stevens et al. 2019

Oultine

Introduction

*Muller C. & **Abramian S.** 2023, Physics Today*

Part 1

Idealized Simulations

What sets tropical squall lines orientation and why ?

***Abramian S.**, Muller C., Risi C., 2022, GRL*

How does the orientation of the line impact extreme precipitation ?

***Abramian S.**, Muller C., Risi C., 2023, JAMES*

Part 2

Realistic Global Simulations

What sets the maximal extension of MCSs ?

*In Prep. **Abramian S.**, Muller C., Risi C., Roca R., Fiolleau T.,*

How convective systems are recorded in past climate archive ?

*Risi C., Muller C., Vimeux F., Blossey P., Védeau G., Dufaux C., **Abramian S.**, 2023, JAMES*

Conclusion and Perspectives

Oultine

Introduction

*Muller C. & **Abramian S.** 2023, Physics Today*

Part 1

Idealized Simulations

What sets tropical squall lines orientation and why ?

***Abramian S.**, Muller C., Risi C., 2022, GRL*

How does the orientation of the line impact extreme precipitation ?

***Abramian S.**, Muller C., Risi C., 2023, JAMES*

Part 2

Realistic Global Simulations

What sets the maximal extension of MCSs ?

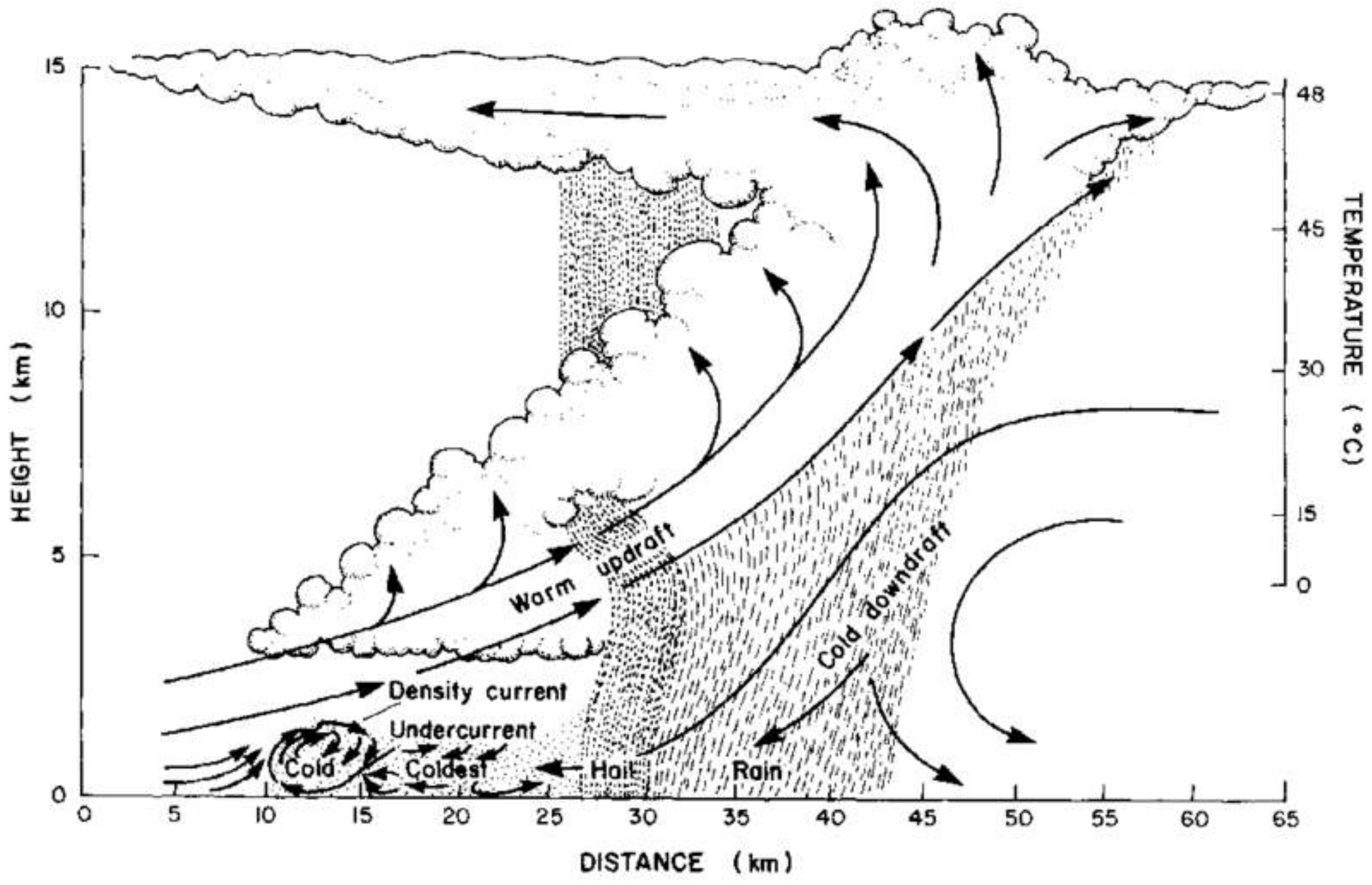
*In Prep. **Abramian S.**, Muller C., Risi C., Roca R., Fiolleau T.,*

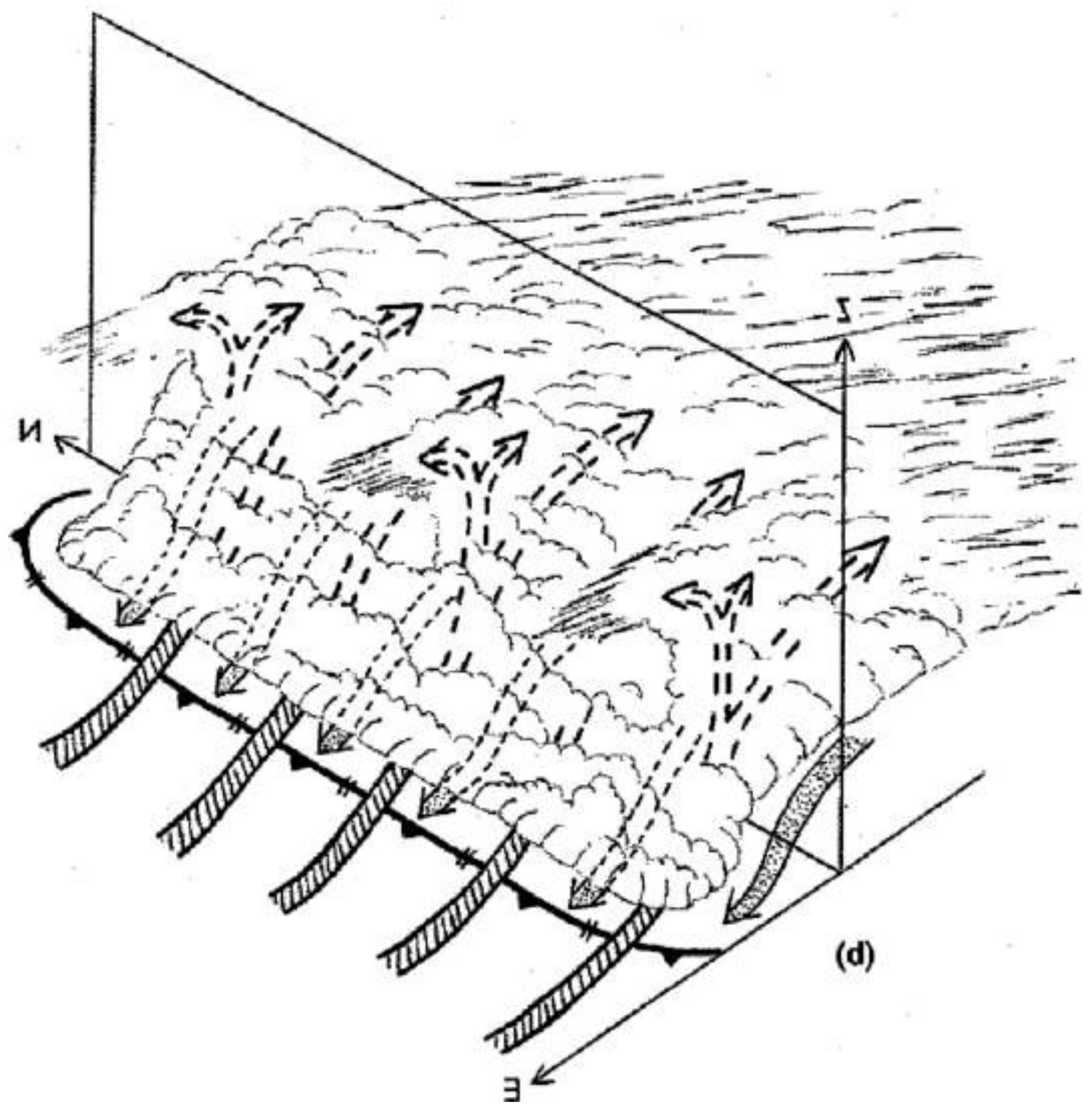
How convective systems are recorded in past climate archive ?

*Risi C., Muller C., Vimeux F., Blossey P., Védeau G., Dufaux C., **Abramian S.**, 2023, JAMES*

Conclusion and Perspectives

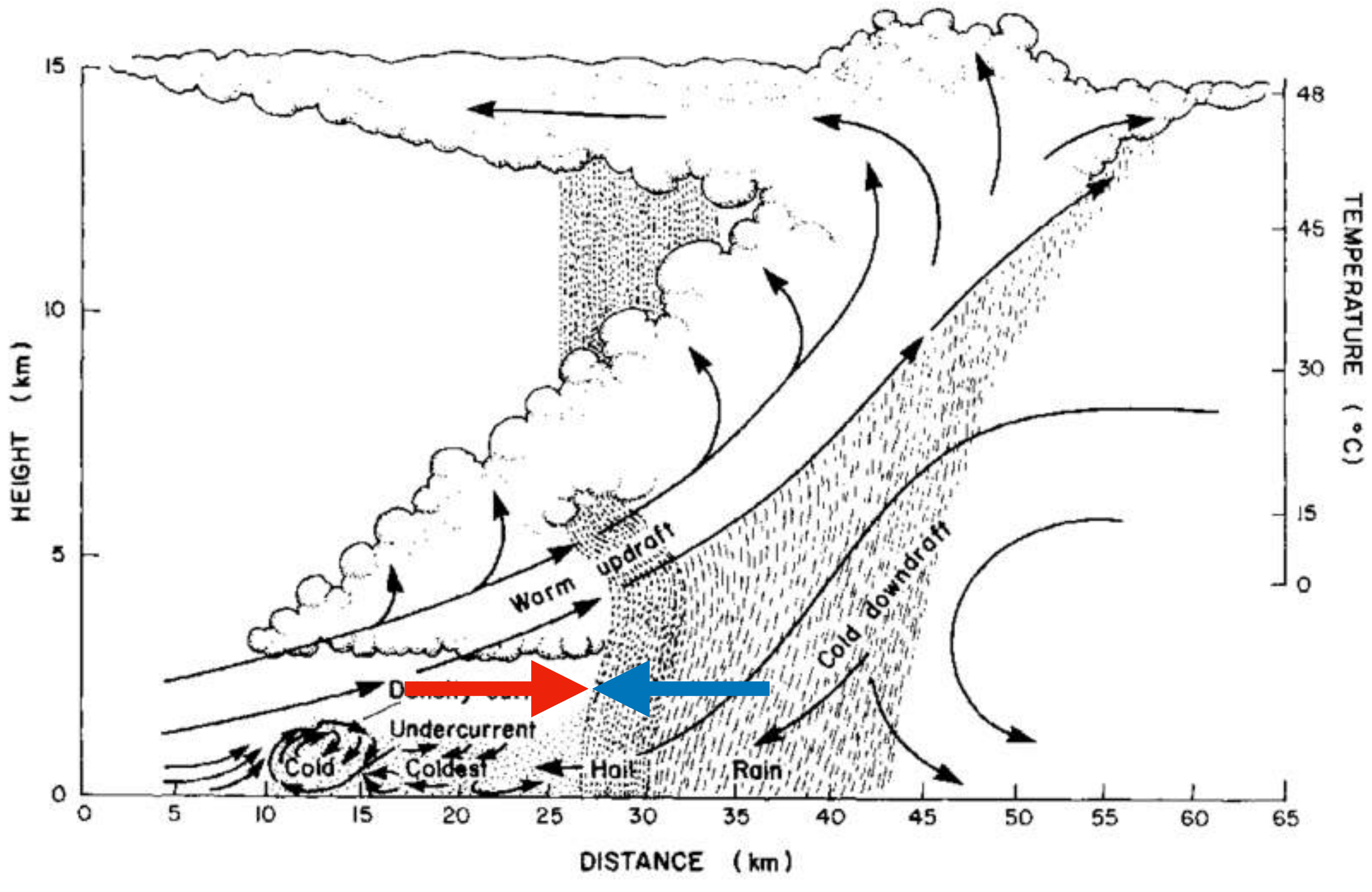
What are the physical processes responsible for squall line organization ?

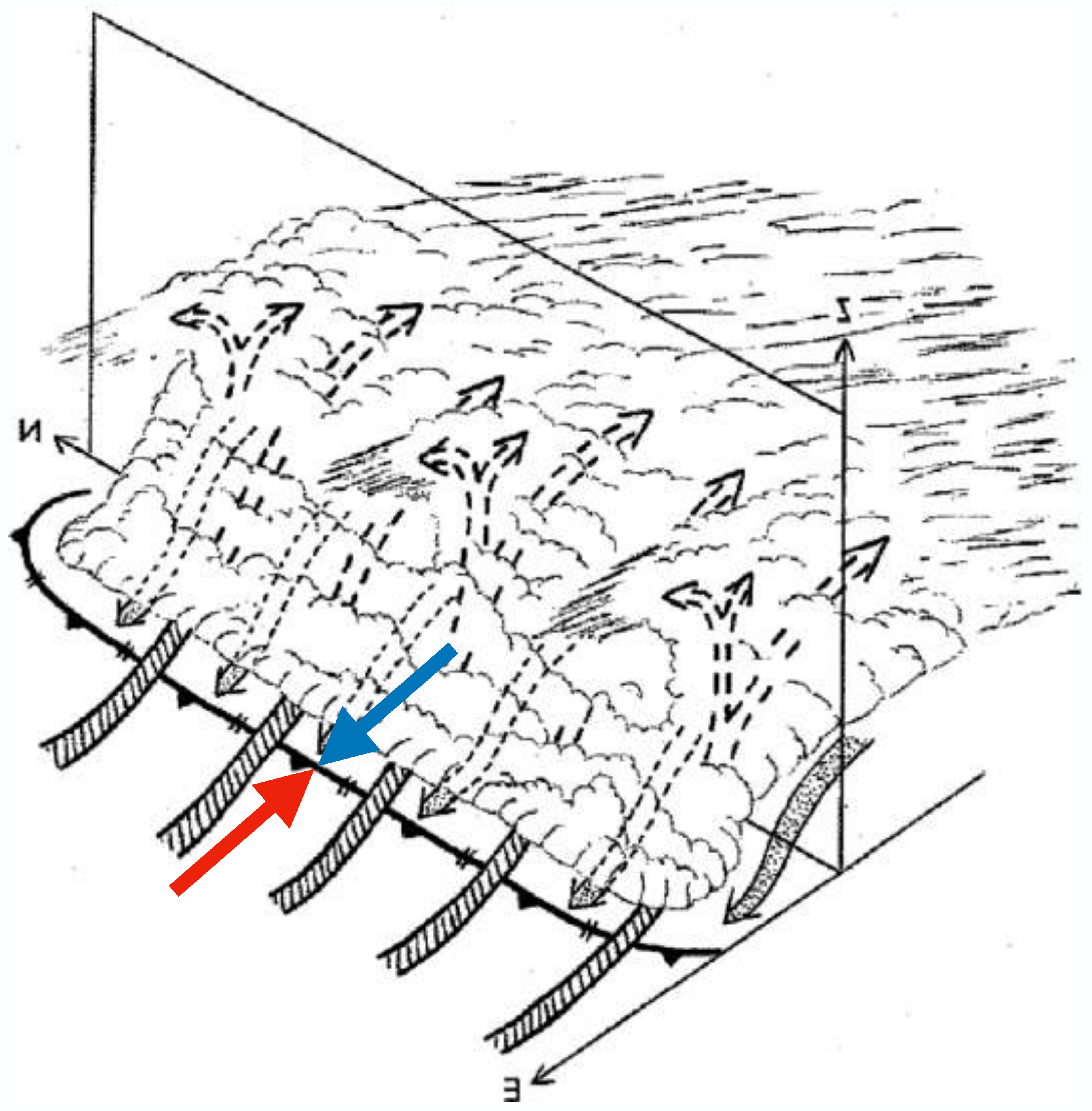




Interactions between wind shear and cold pool spreading

What are the physical processes responsible for squall line organization ?





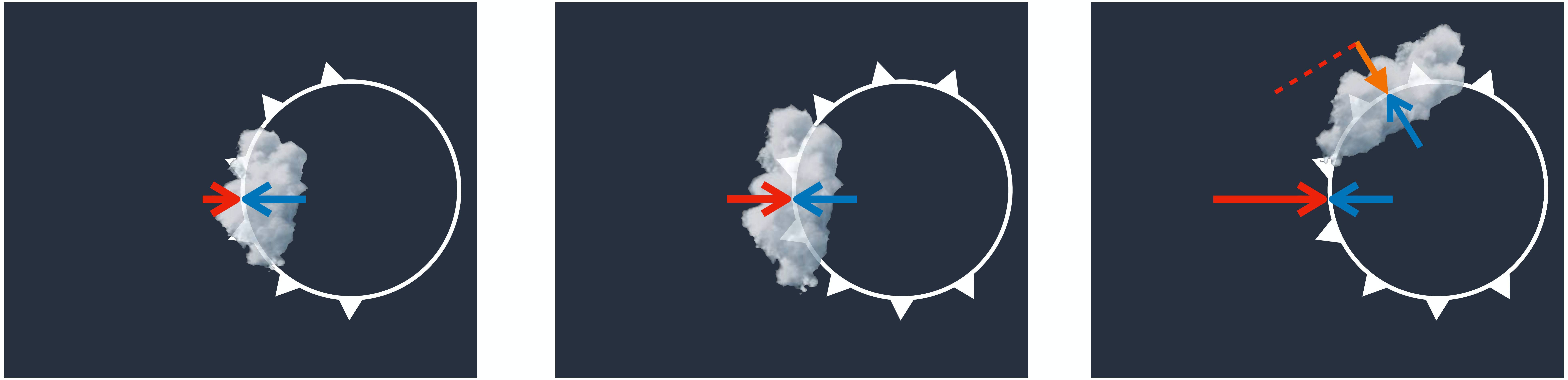
Wind Shear **Cold Pool Spreading**

Interactions between wind shear and cold pool spreading

Hypothesis for Squall Lines orientation

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

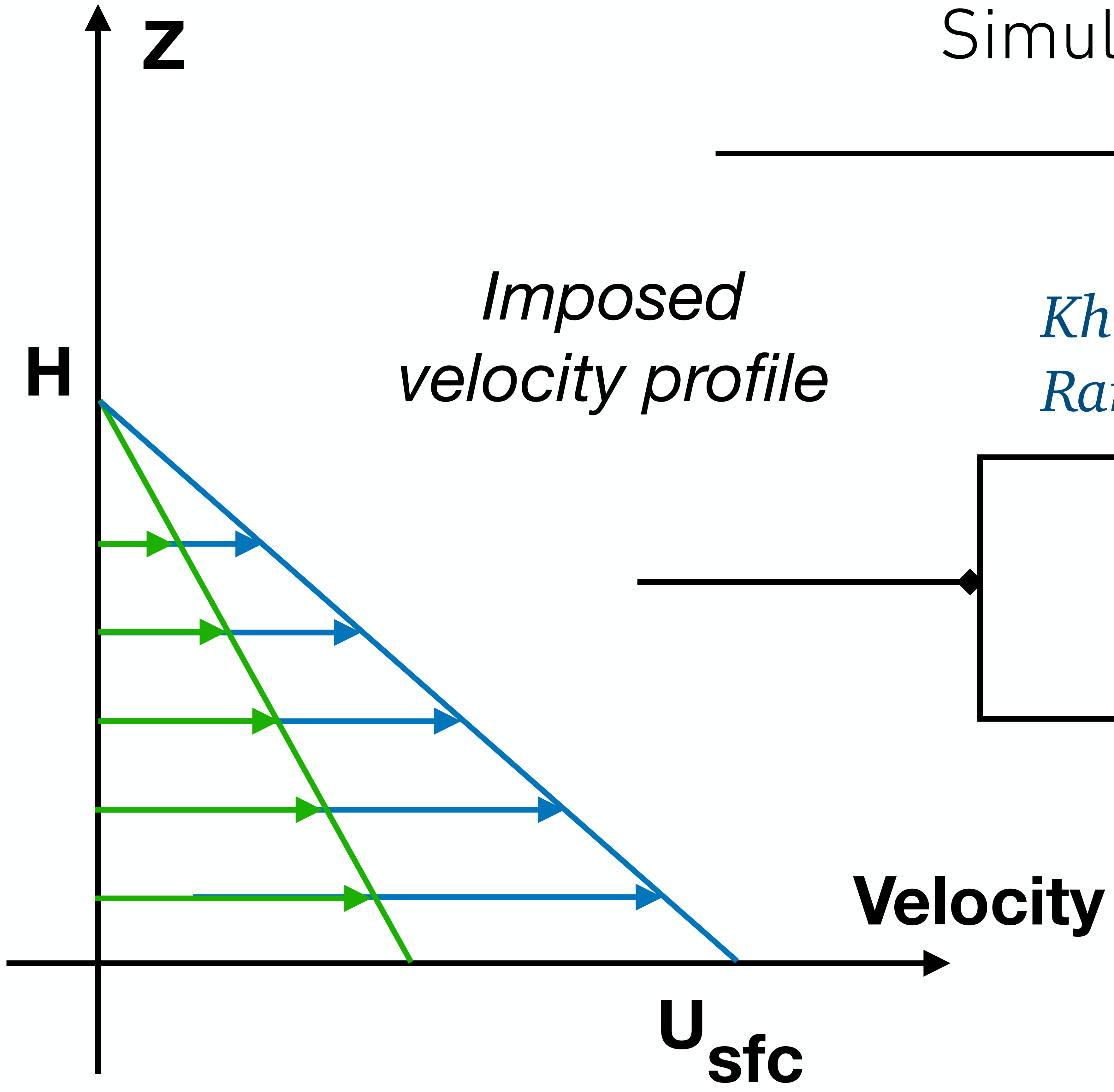
Suboptimal | **Optimal** | **Superoptimal**



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

Simulation set-up

Imposed velocity profile

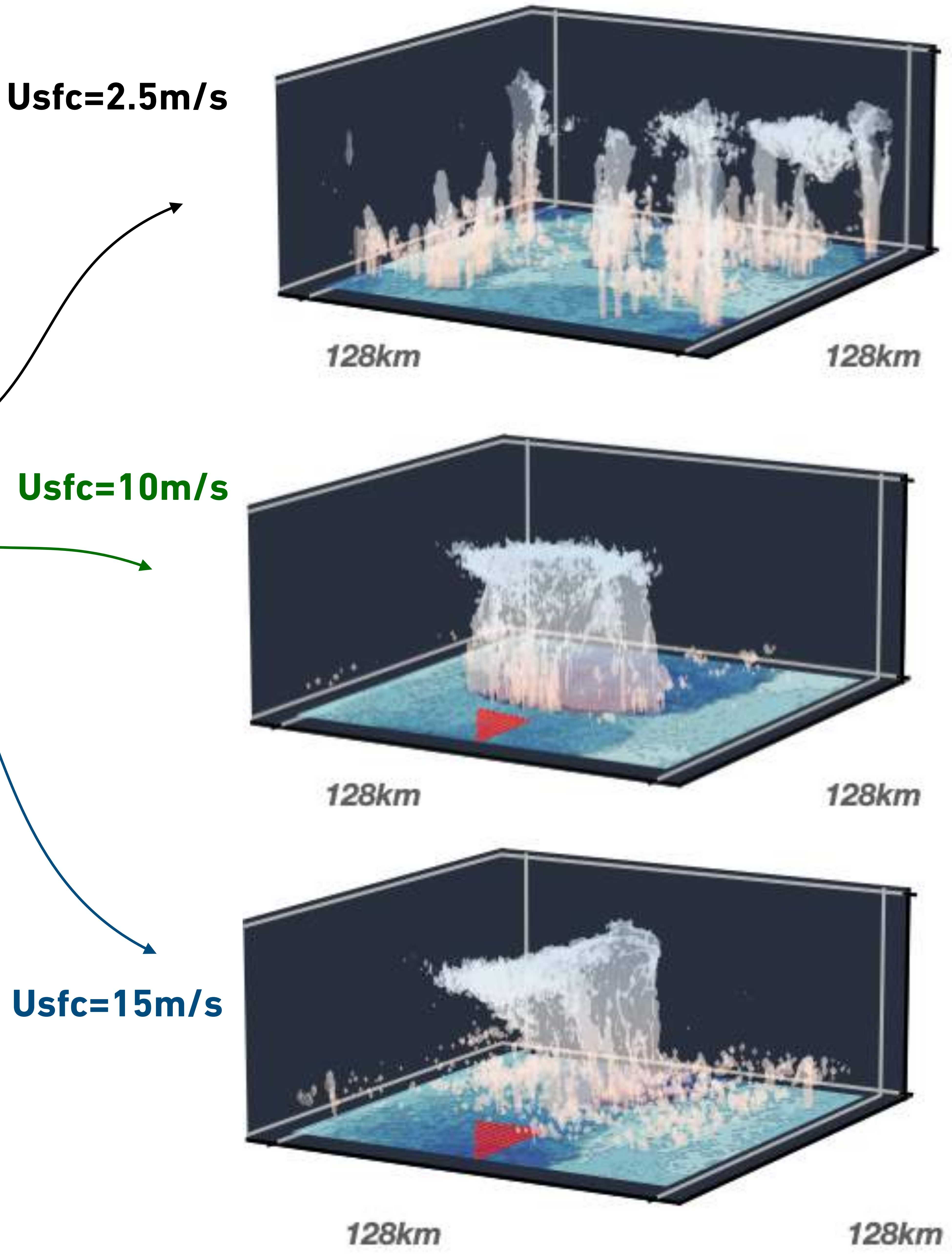


Khairoutdinov & Randall 2003

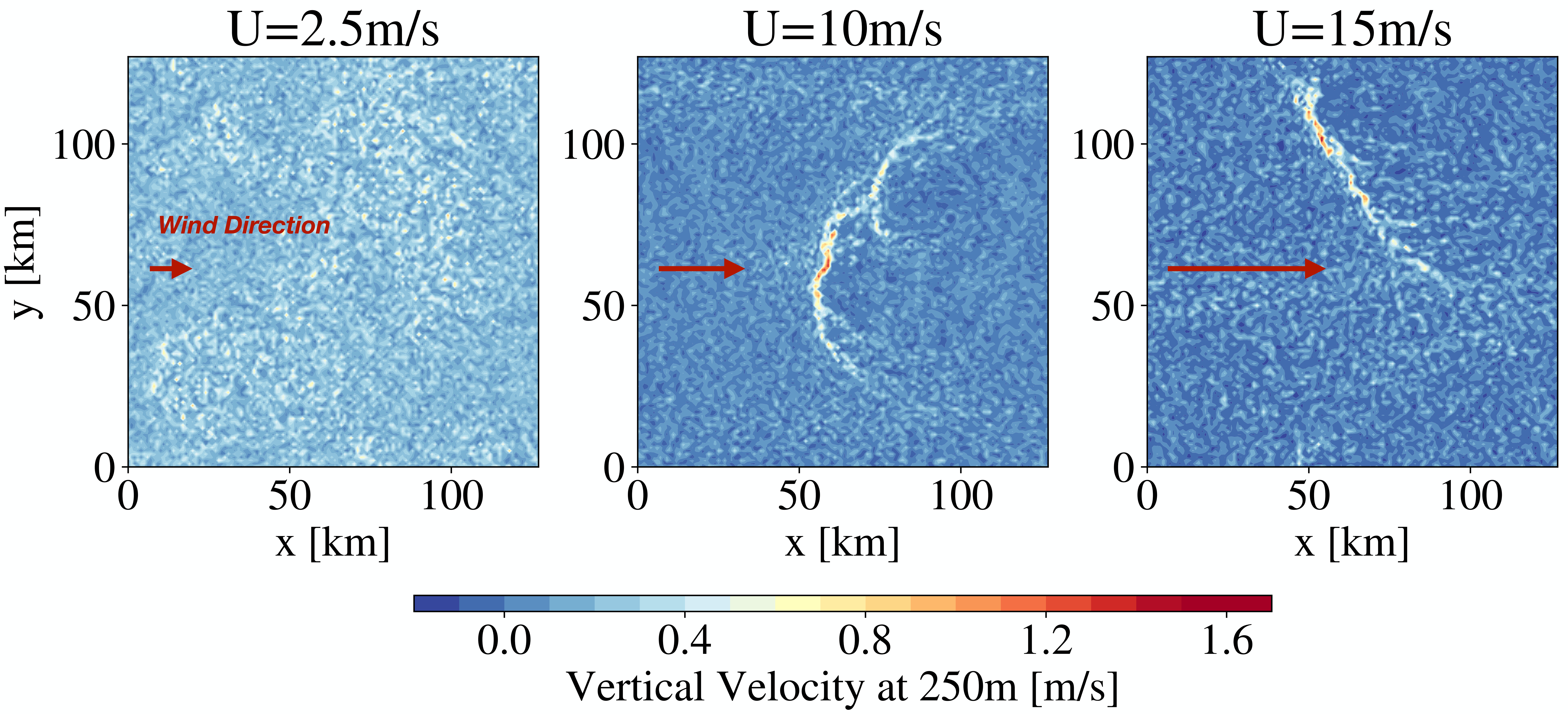
CRM
SAM

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

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

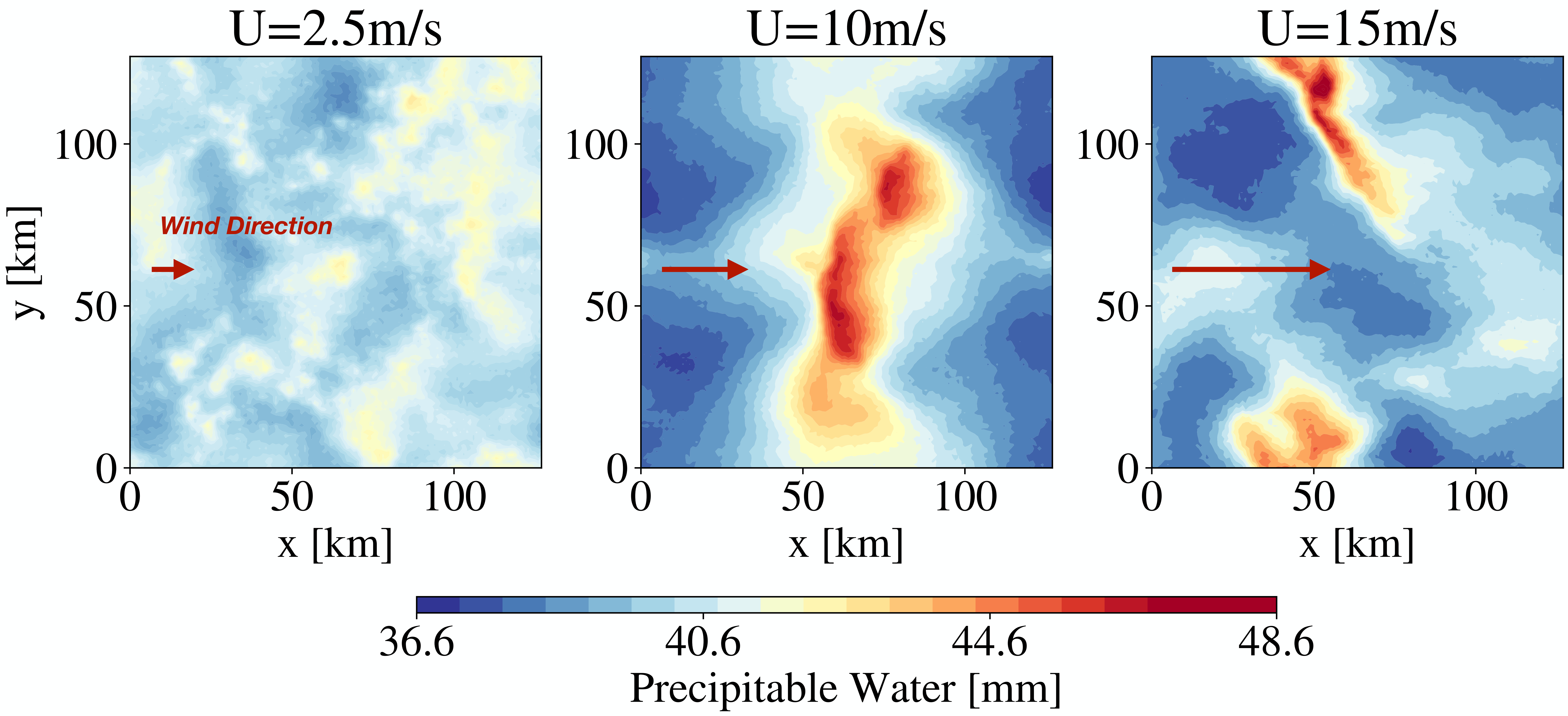


Cloud Resolving Overview



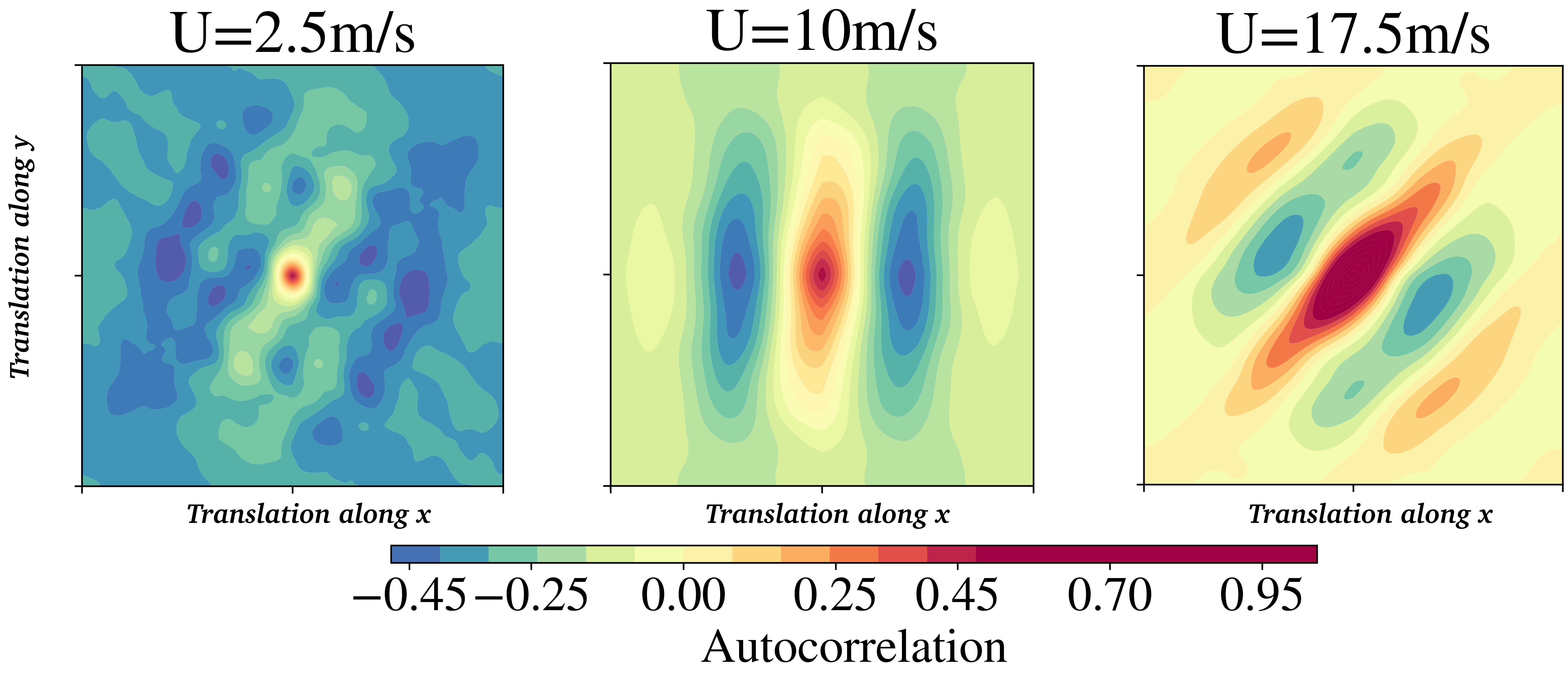
How to measure orientation of Squall Lines ?

Cloud Resolving Overview



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

Autocorrelation Images



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

Angle Measurement Procedure

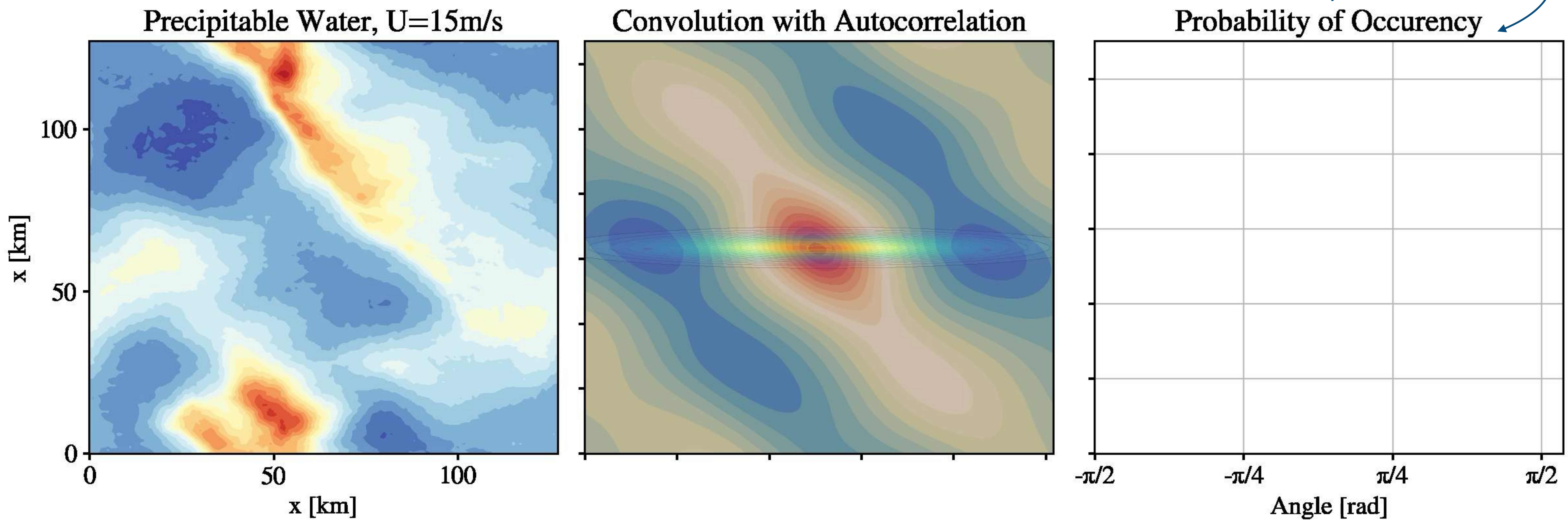
For each time step

1. Calculate the autocorrelation image

2. Compute the convolution between the gaussian and the autocorrelation

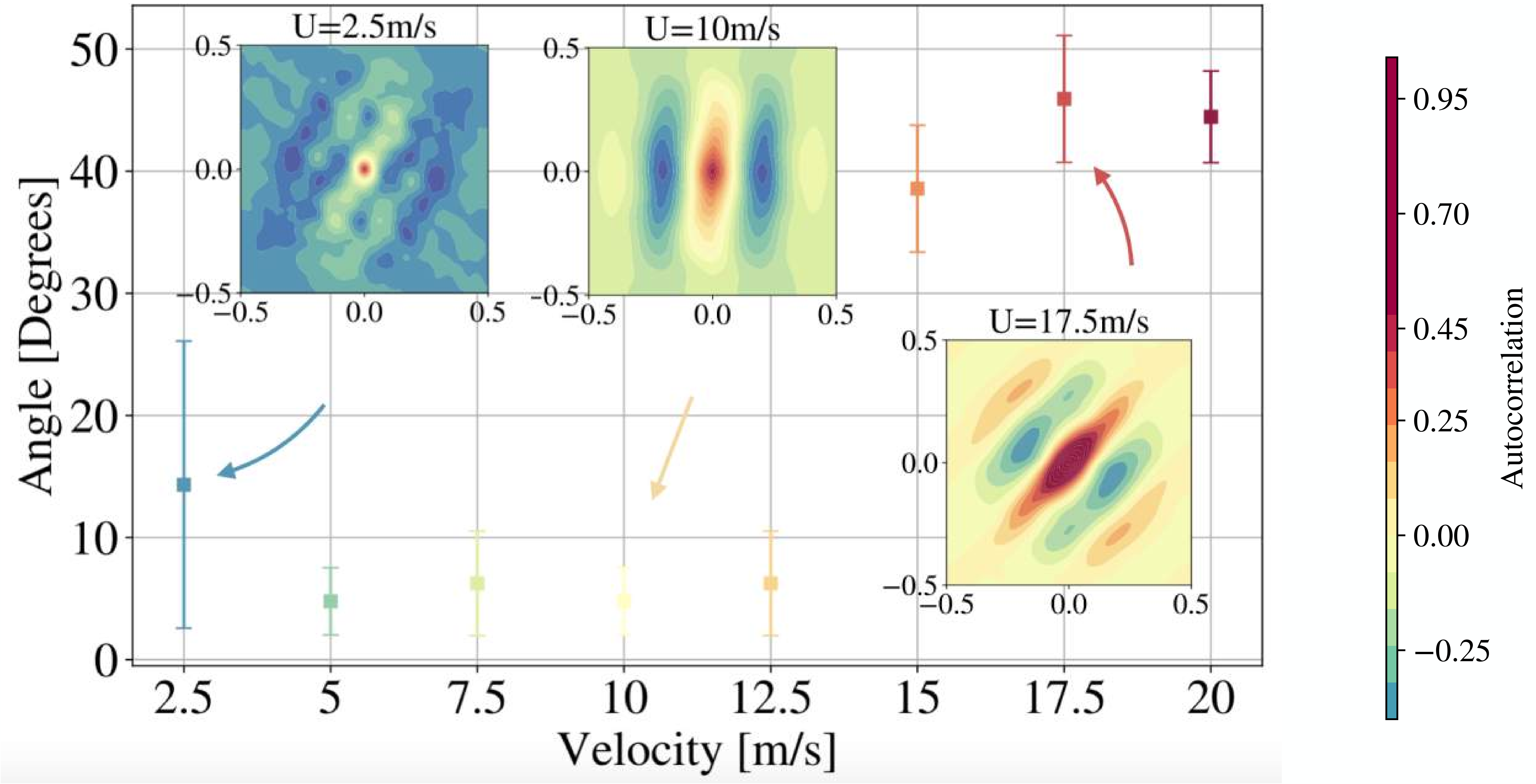
3. Obtain Angle Distribution

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



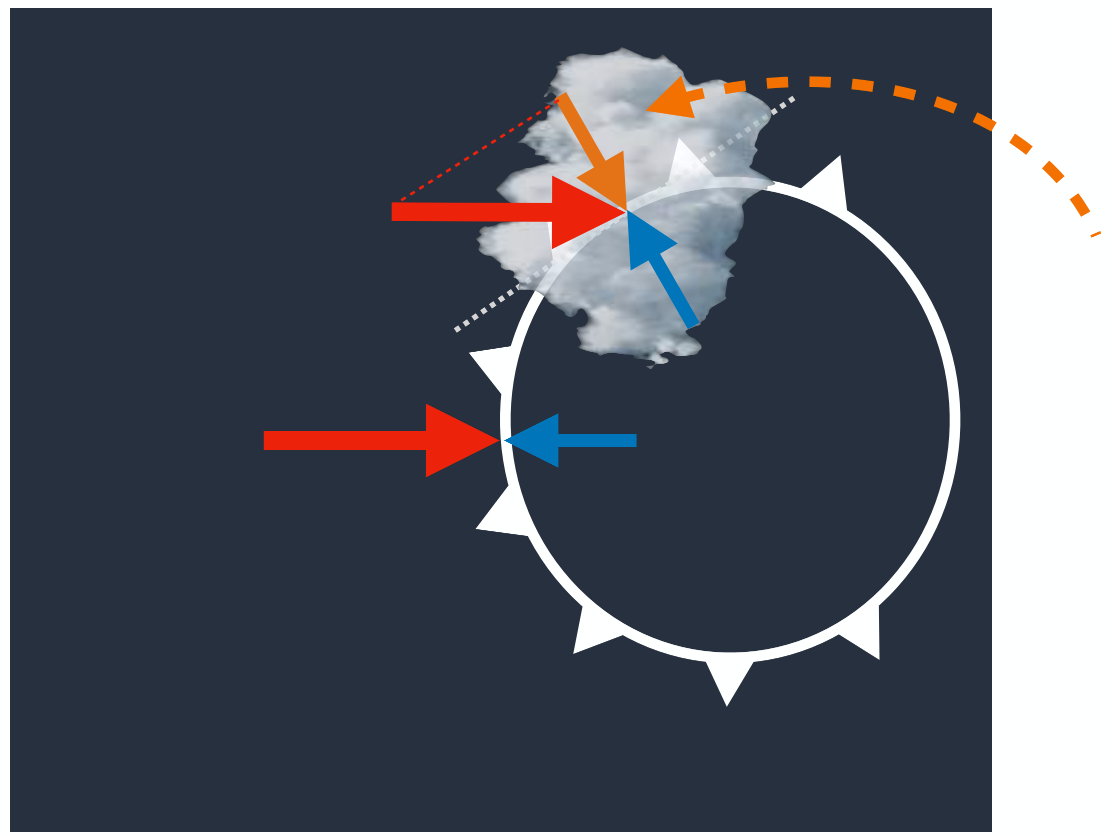
Angle results

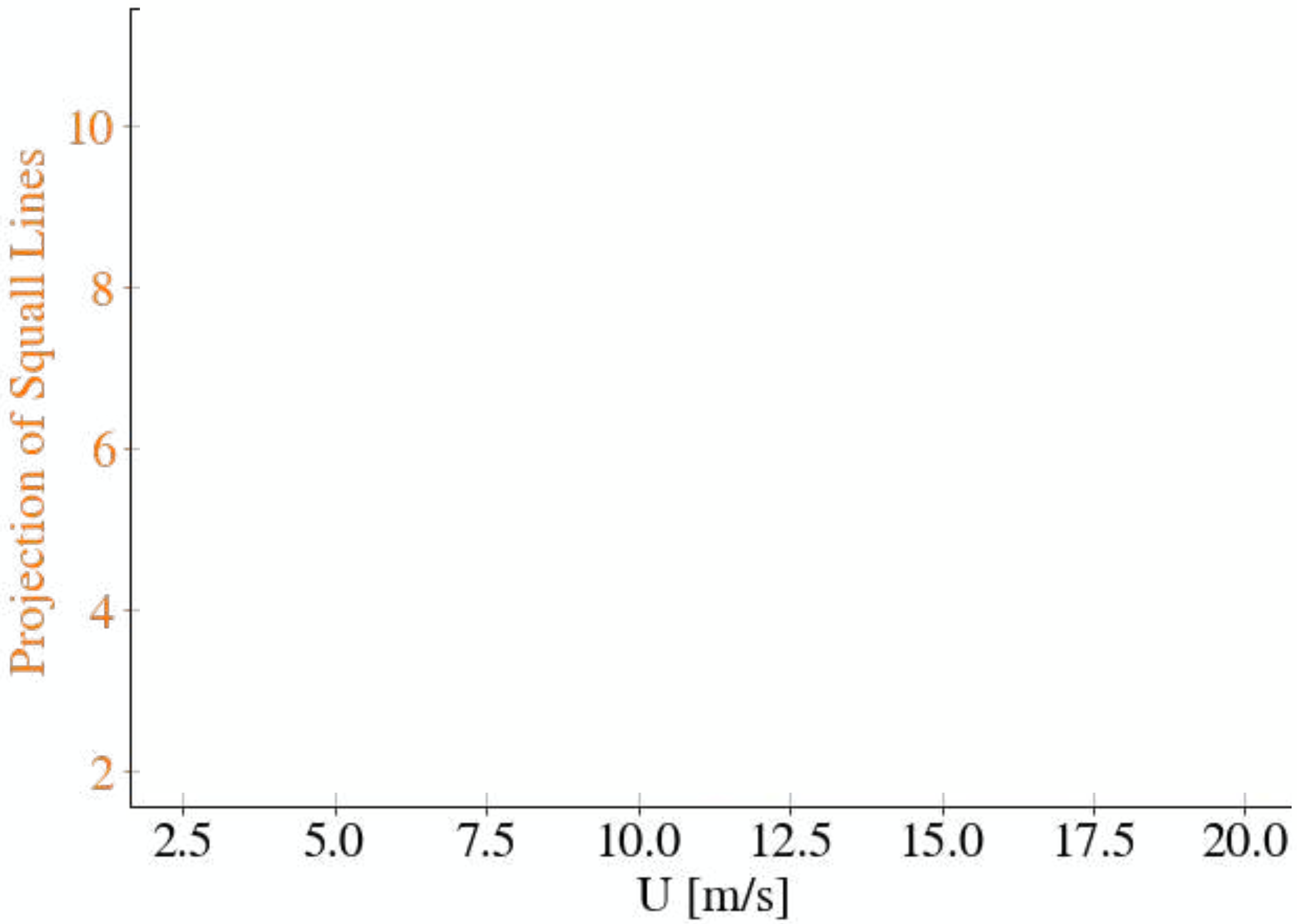
Sub-critical regime **Optimal case** *Super-critical regime*



Conservation of the shear ?

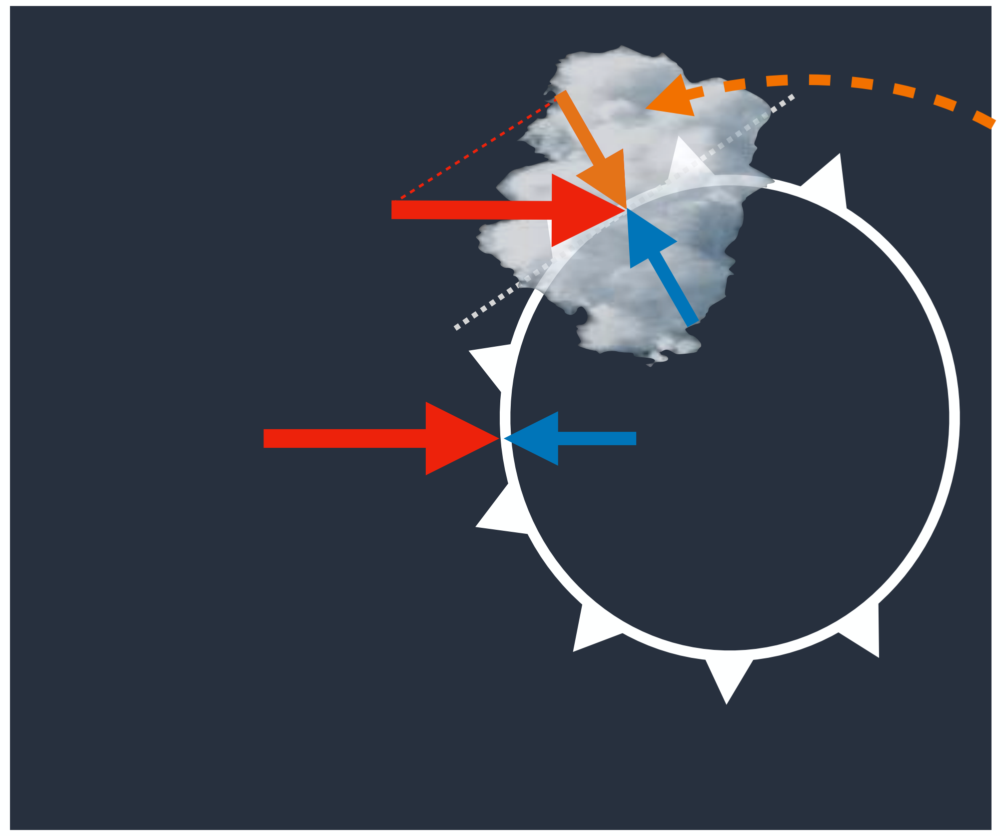
Hypothesis : Conservation of the projected shear near the optimal value

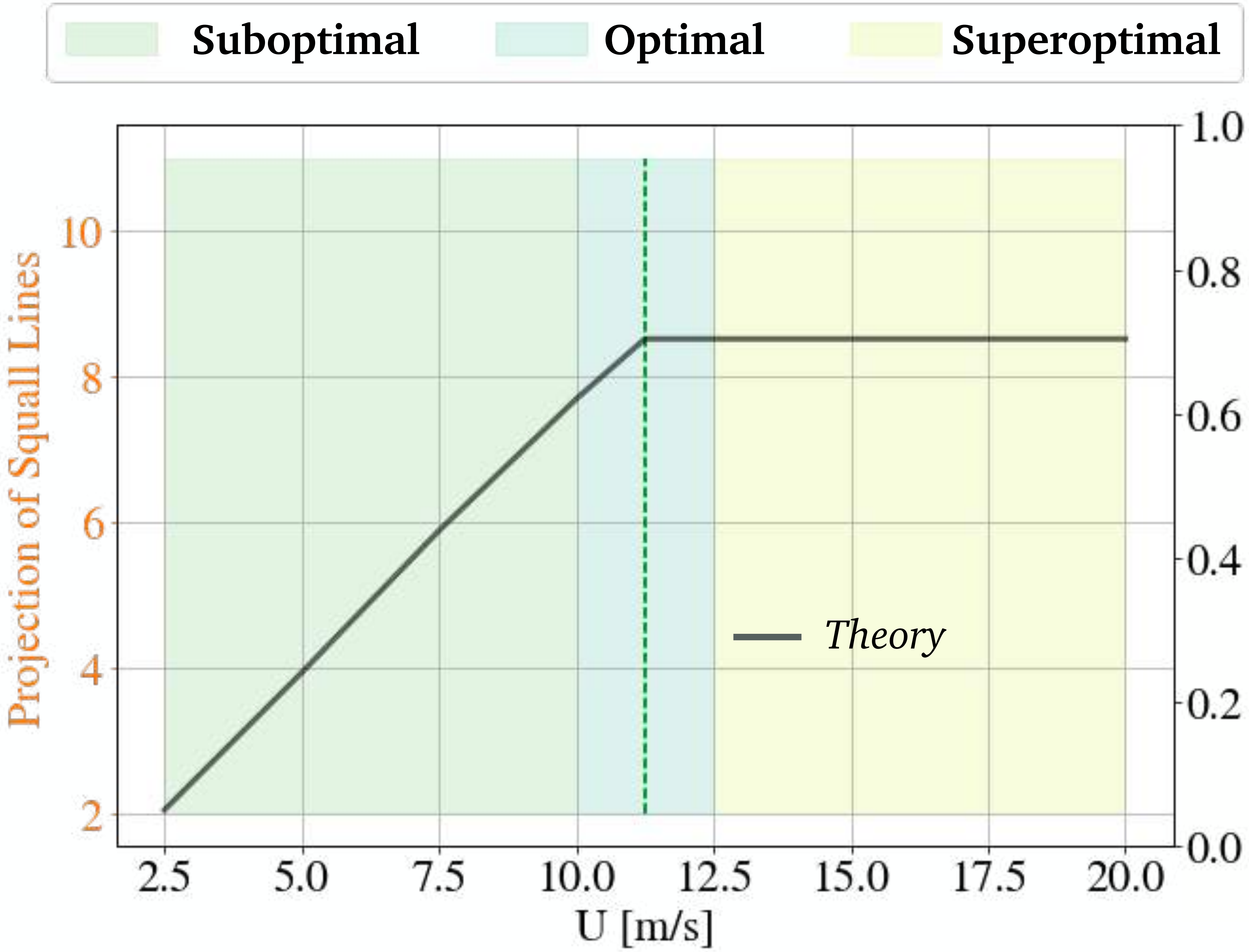




Conservation of the shear ?

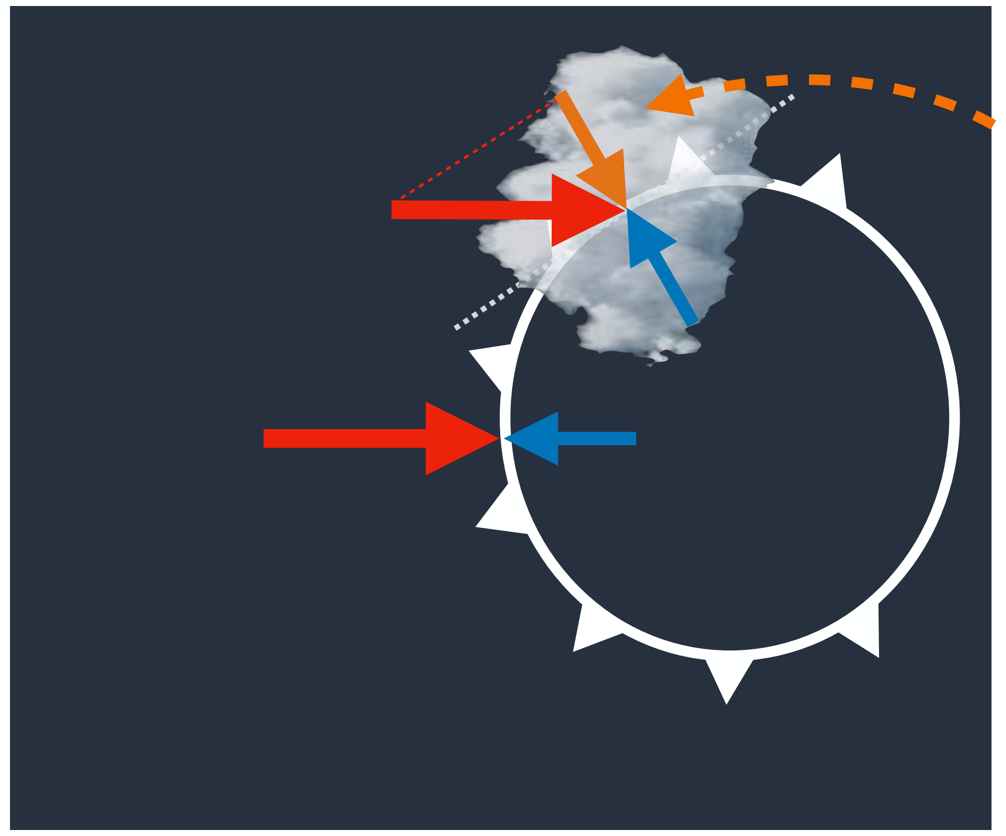
Hypothesis : Conservation of the projected shear near the optimal value

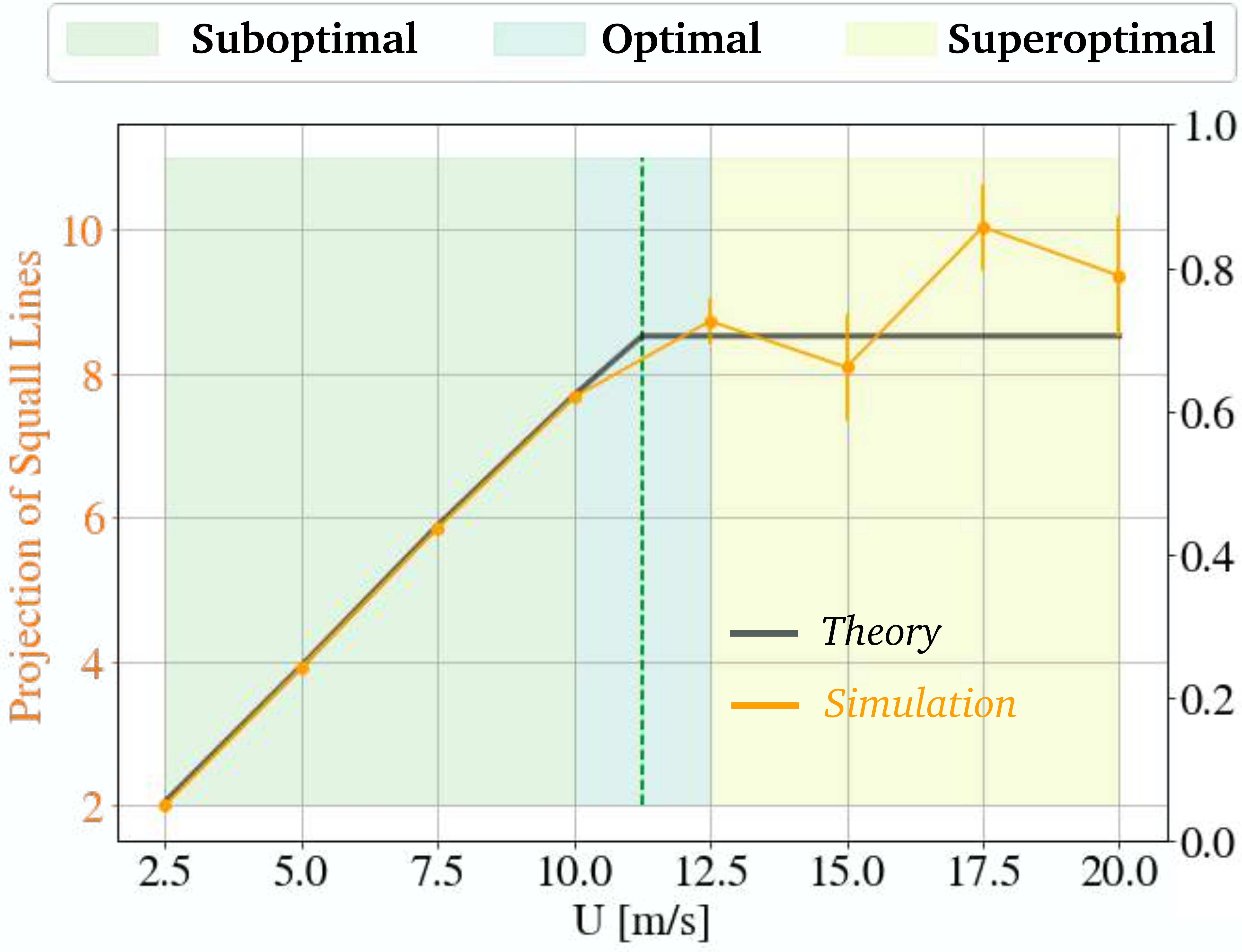




Conservation of the shear ?

Hypothesis : Conservation of the projected shear near the optimal value





Good agreement with RKW 1988 Theory

Abramian et al 2021, Geophysical Research Letter

Oultines

Introduction — *Muller C. & **Abramian S.** 2023, Physics Today*

Part 1

Idealized Simulations

What sets tropical squall lines orientation and why ? — ***Abramian S.**, Muller C., Risi C., 2022, GRL*

How does the orientation of the line impact extreme precipitation ? — ***Abramian S.**, Muller C., Risi C., 2023, JAMES*

Part 2

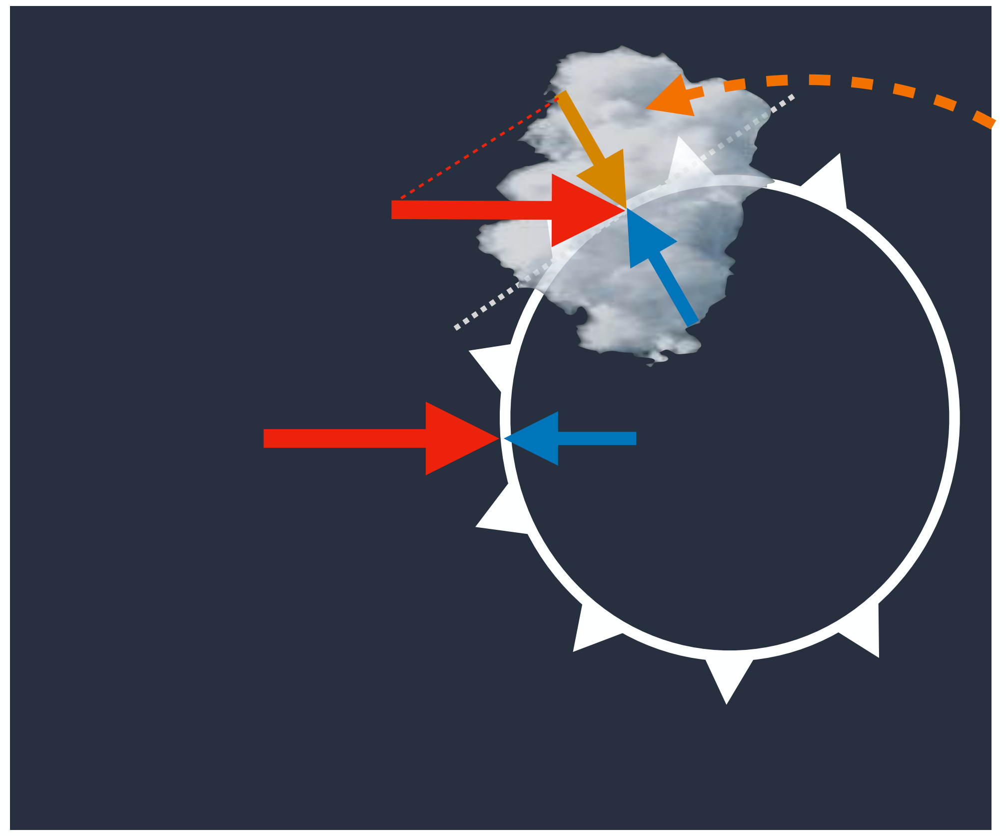
Realistic Global Simulations

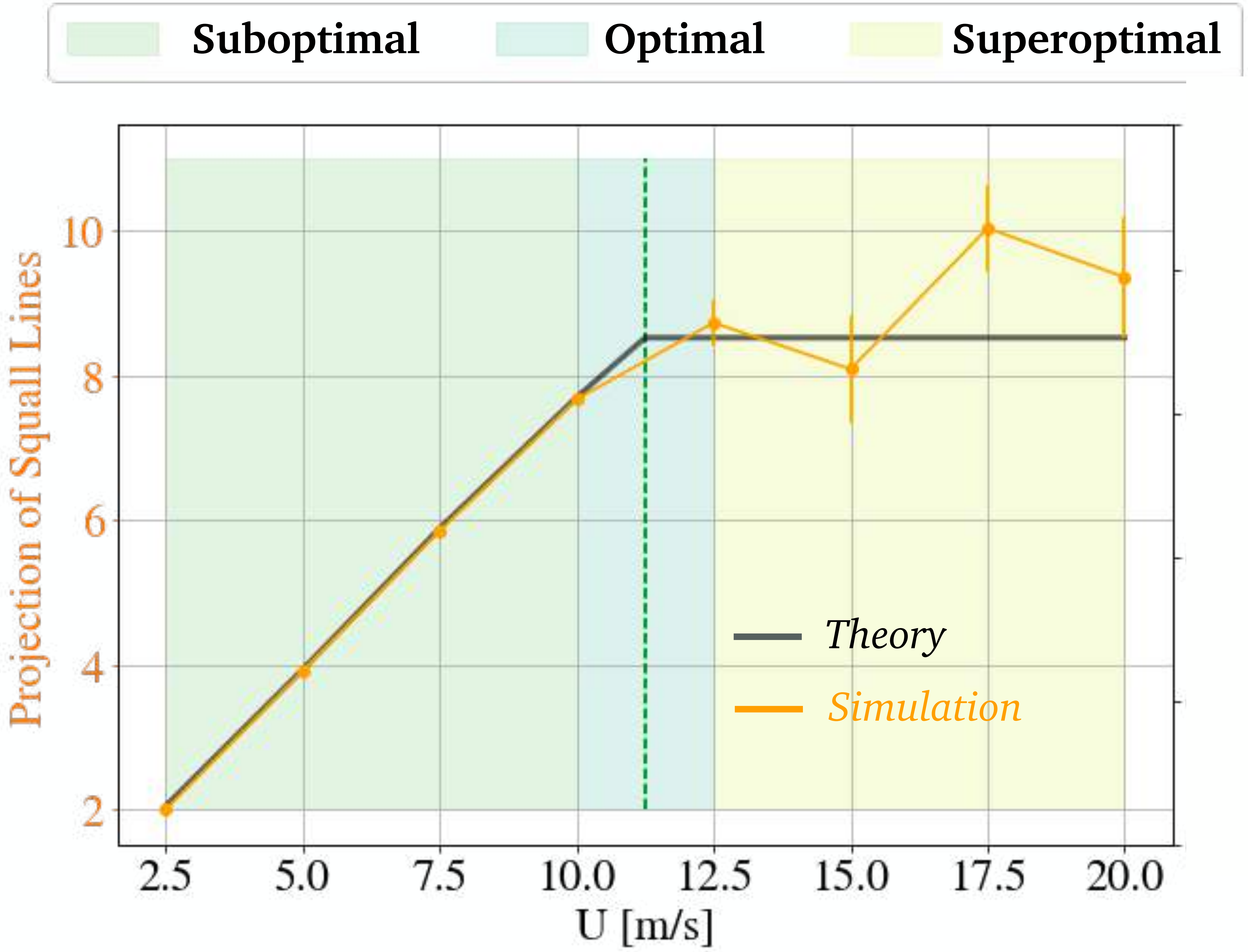
What sets the maximal extension of MCSs ? — *In Prep. **Abramian S.**, Muller C., Risi C., Roca R., Fiolleau T.,*

How convective systems are recorded in past climate archive ? — *Risi C., Muller C., Vimeux F., Blossey P., Védeau G., Dufaux C., **Abramian S.**, 2023, JAMES*

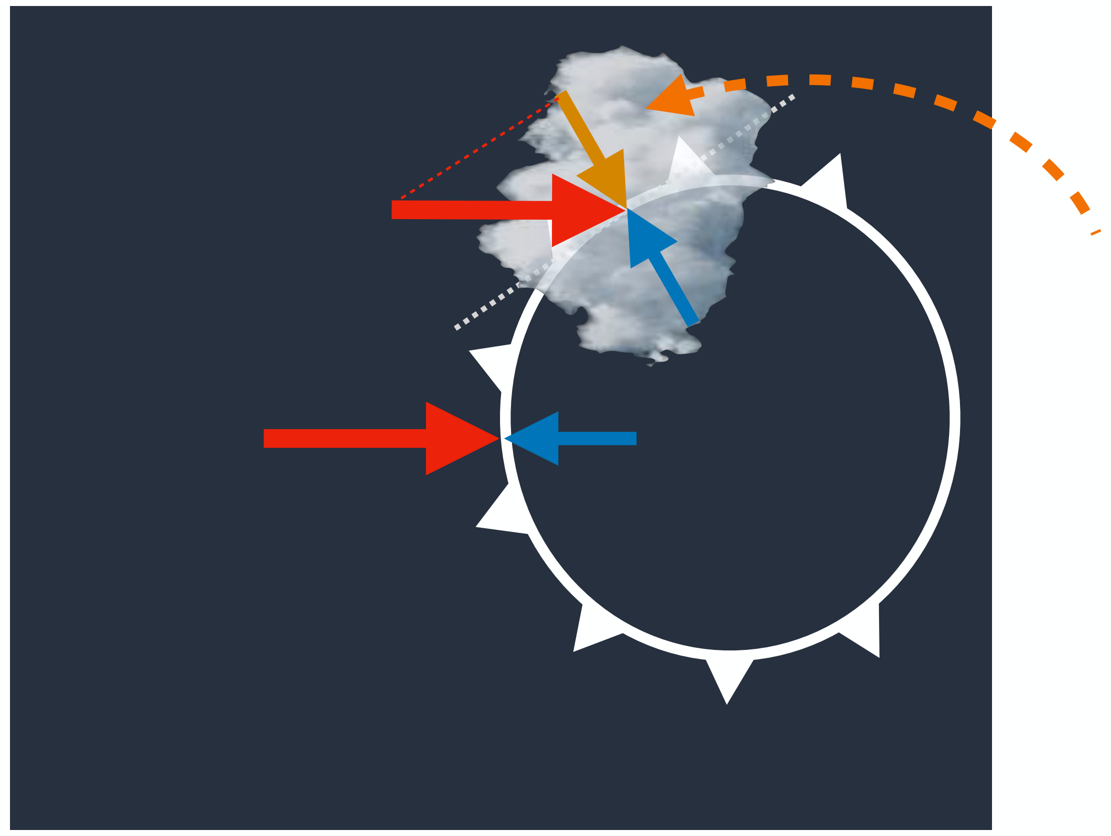
Conclusion and Perspectives

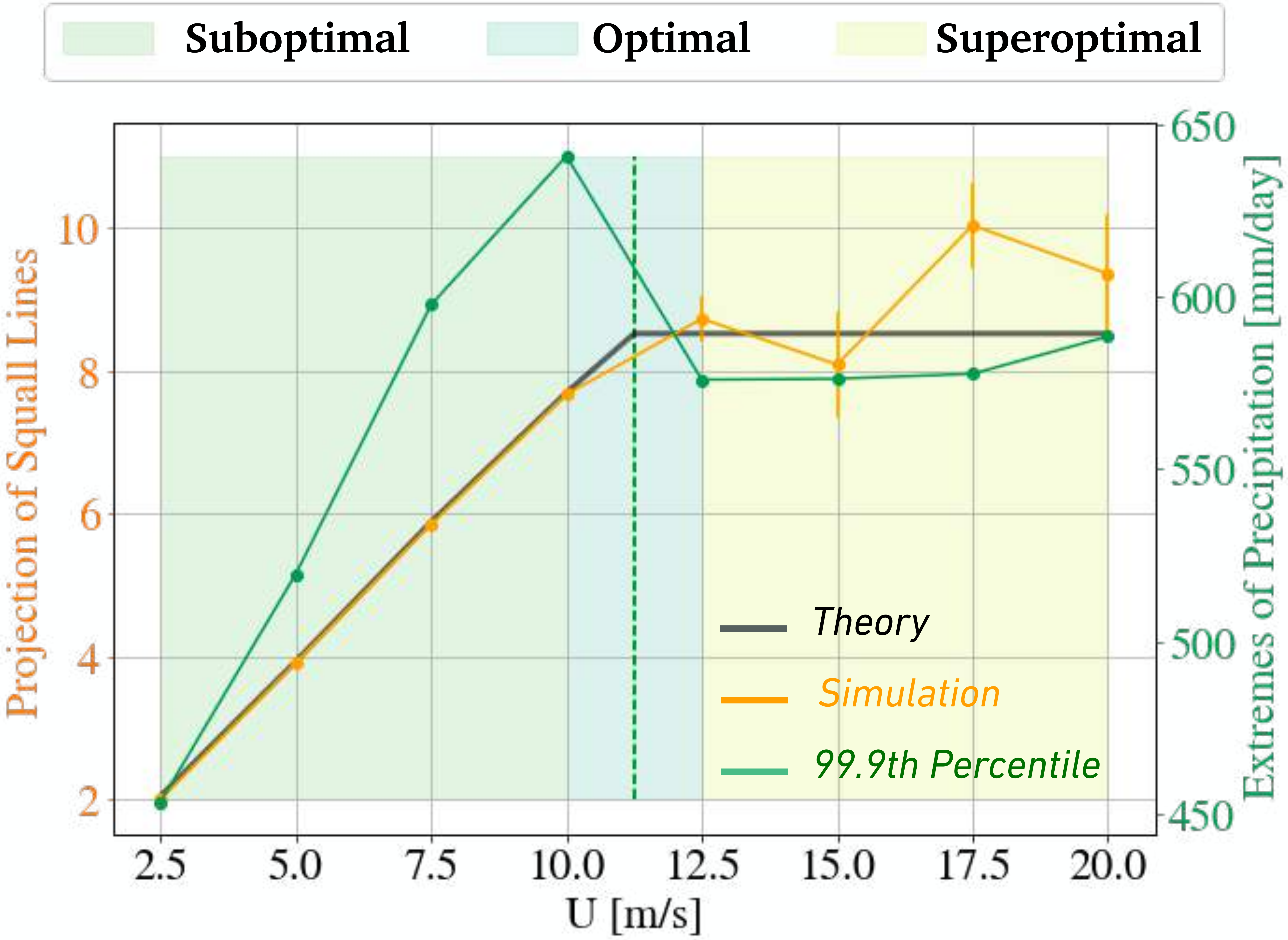
How do Extremes of Precipitation evolve with Squall Lines regime ?



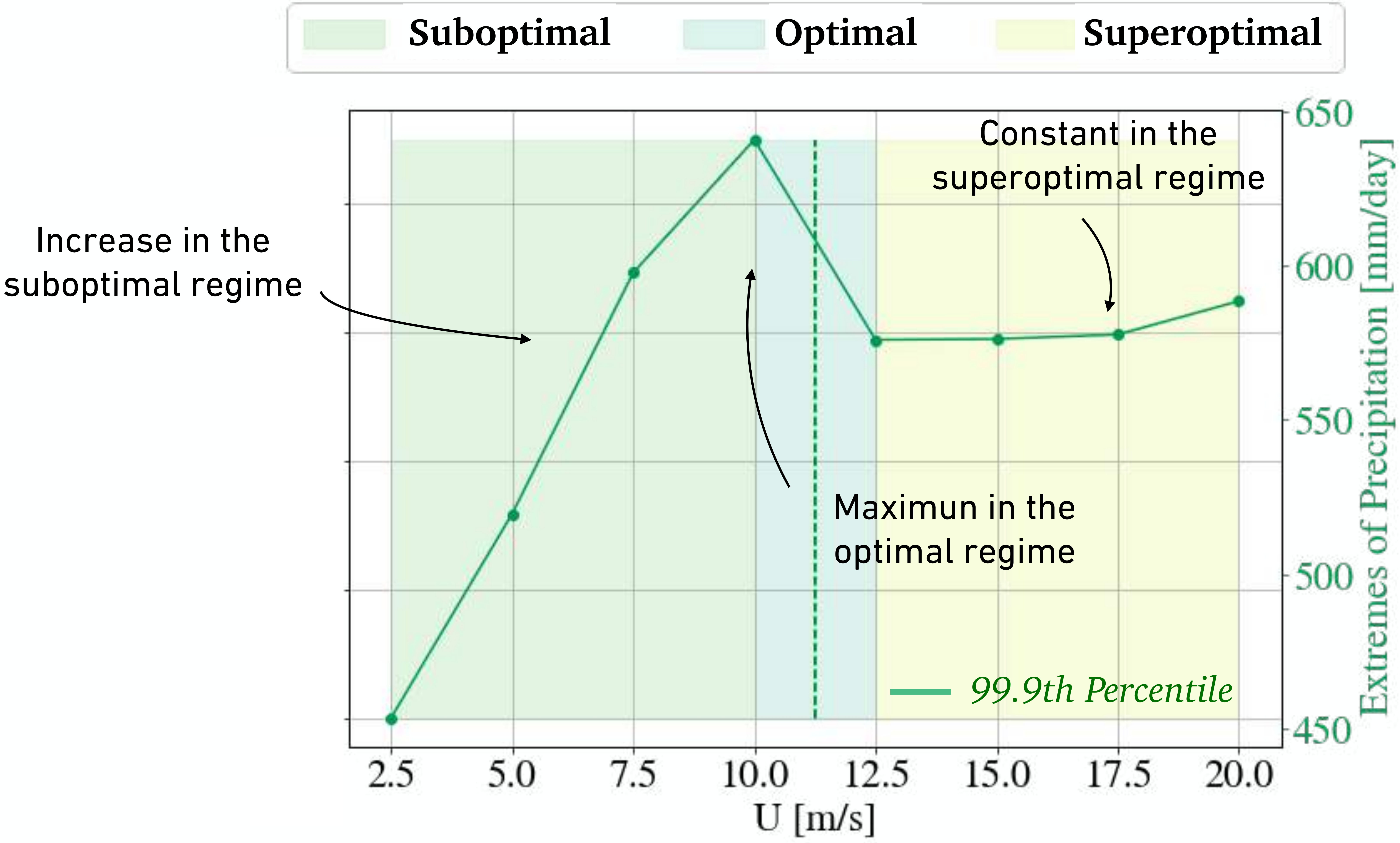


How do Extremes of Precipitation evolve with Squall Lines regime ?

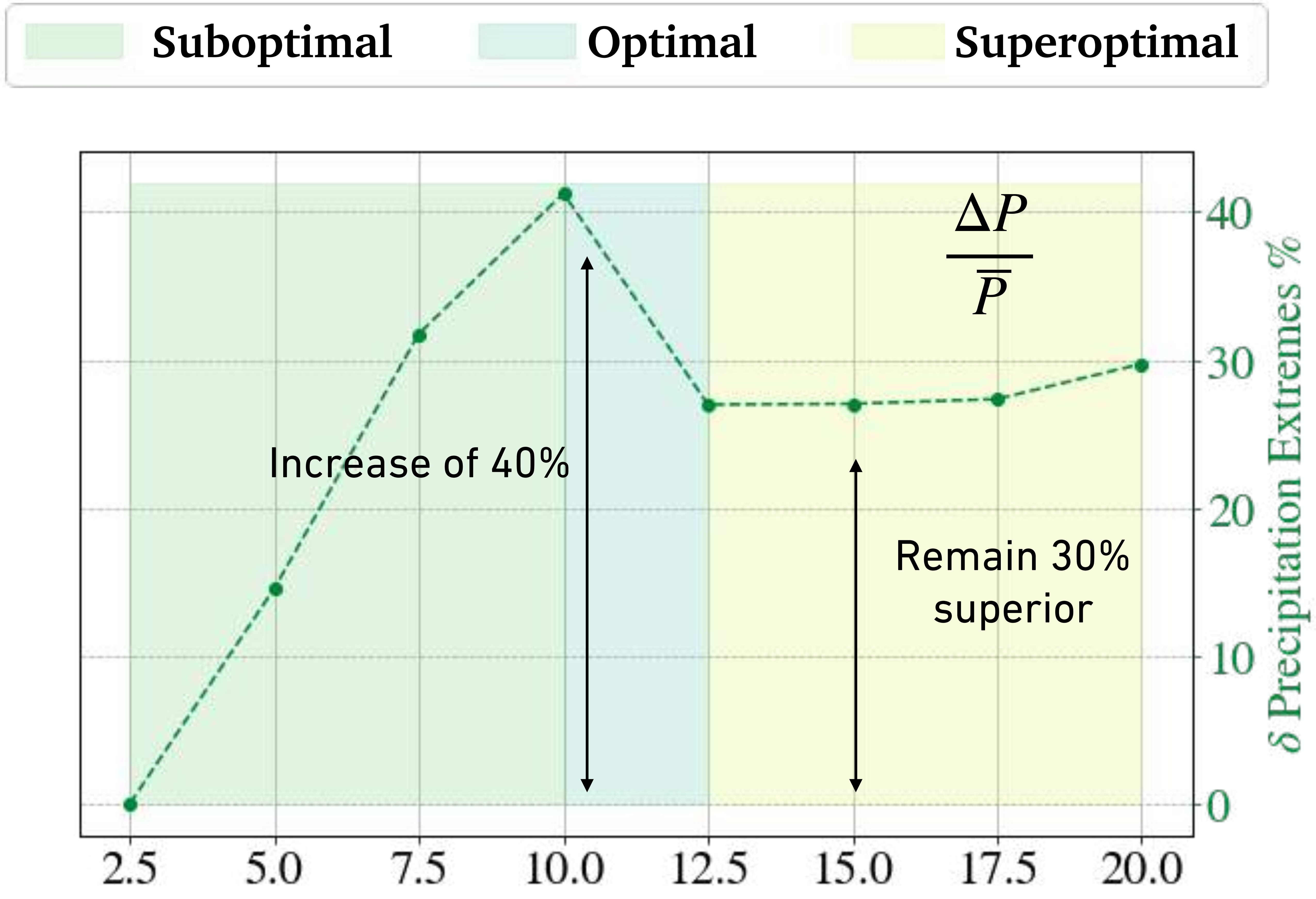




How do Extremes of Precipitation evolve with Squall Lines regime ?

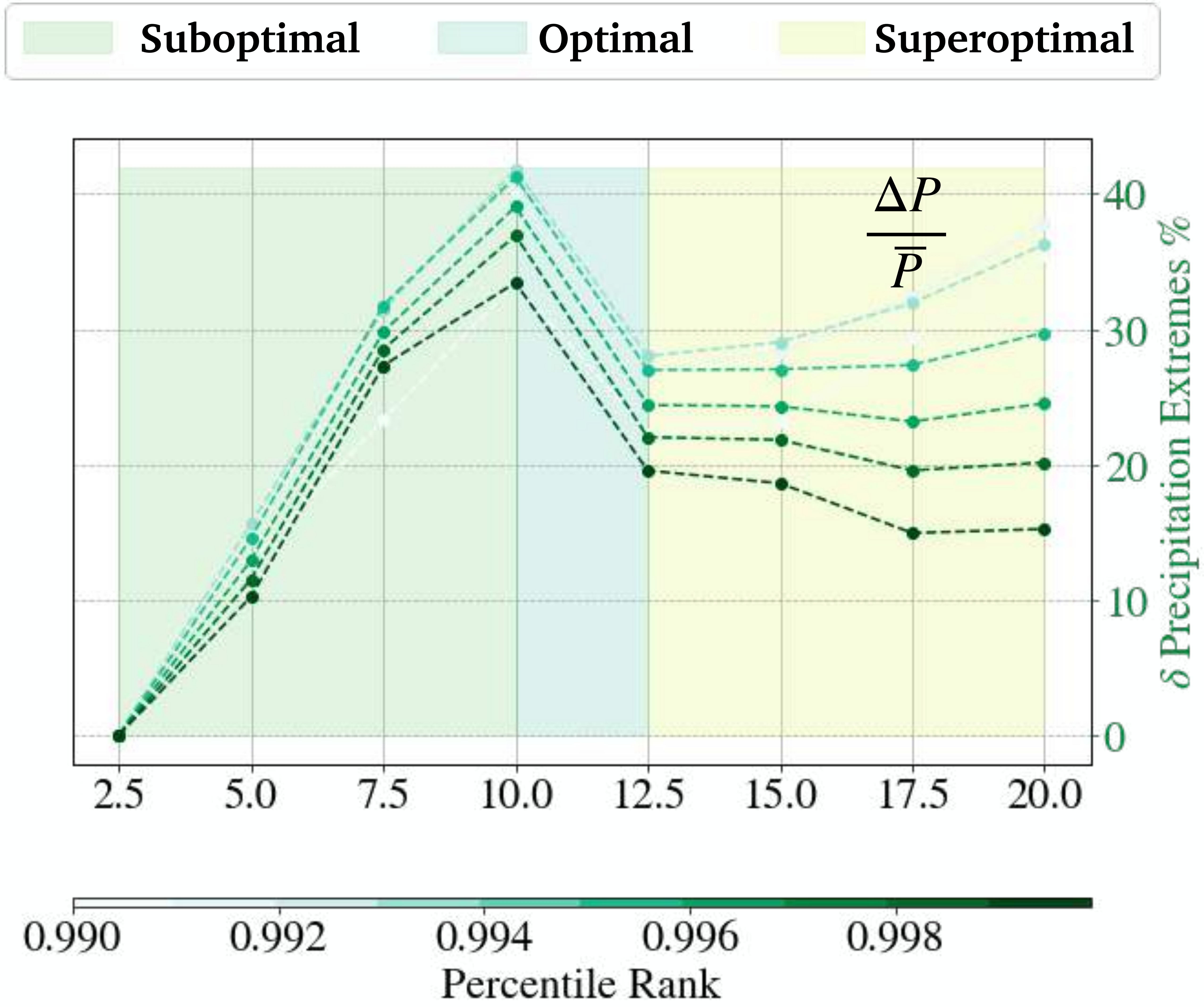


How do Extremes of Precipitation evolve with Squall Lines regime ?



How do Extremes of Precipitation evolve with Squall Lines regime ?

Robust at higher percentile



→ Why ?

Scaling for Extreme Precipitation (Singh & O'Gorman 2014, Muller & Takayabu 2020)

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

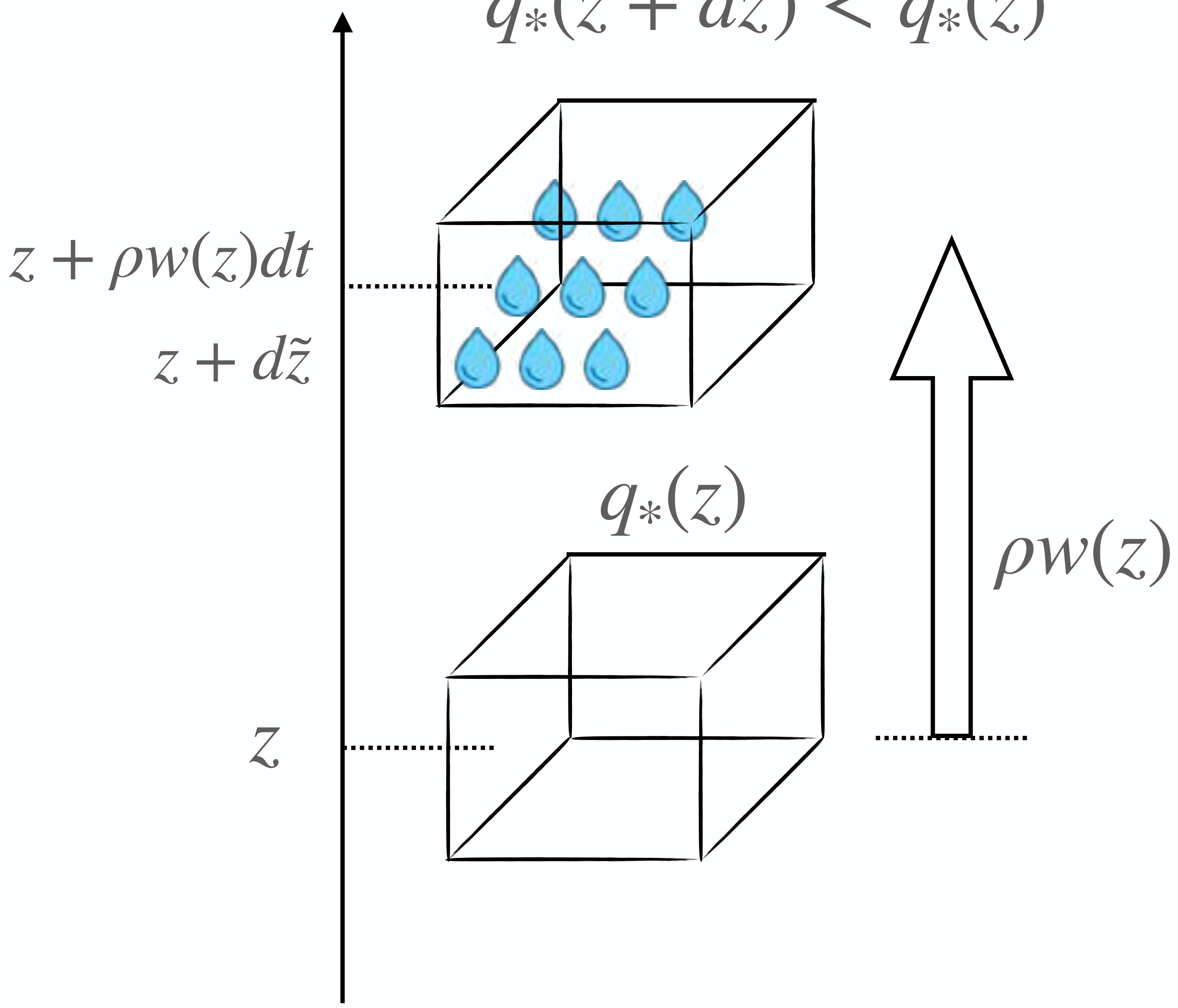
Precipitation efficiency (microphysic)

Condensation rate

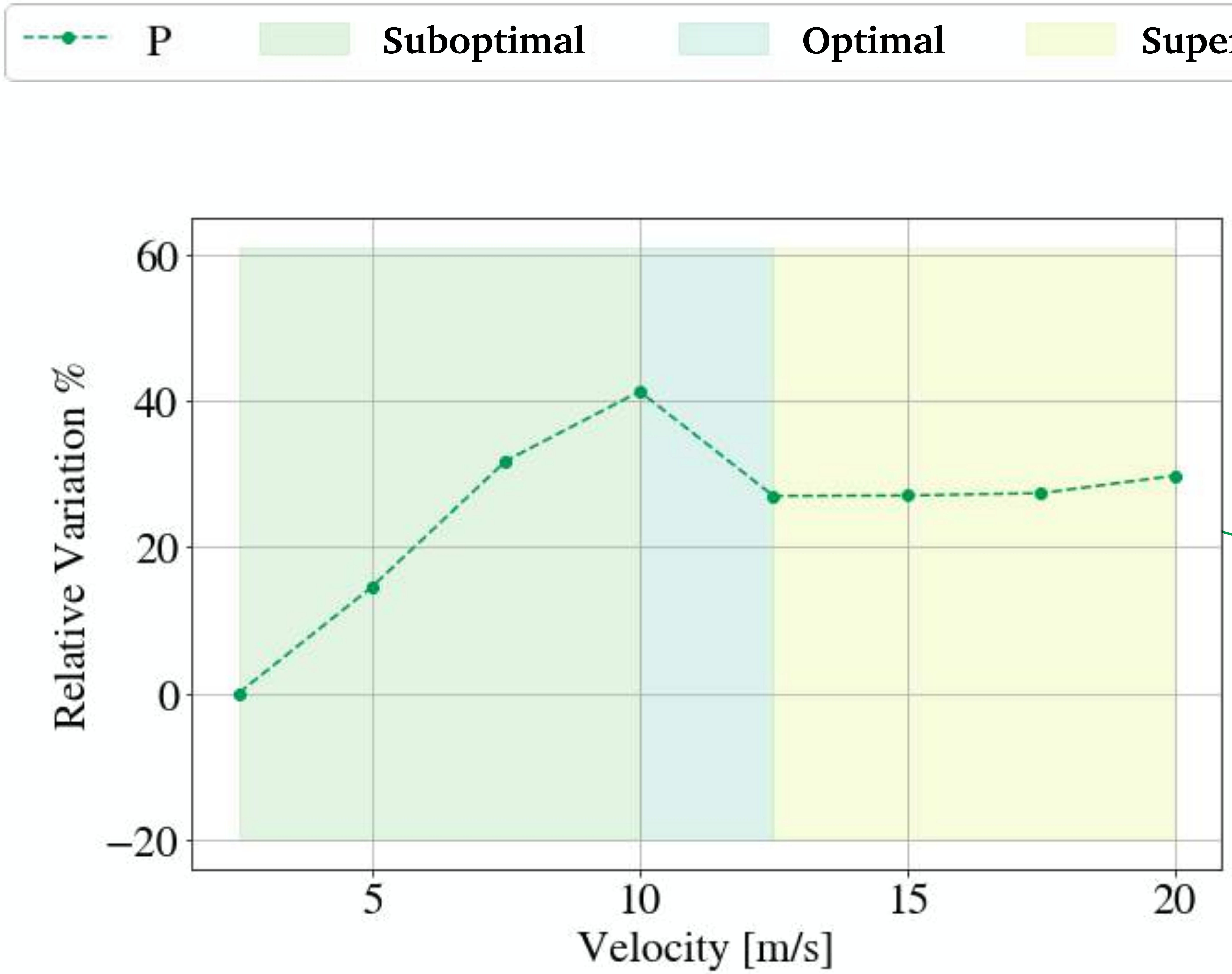
Not all the droplets make it to the ground

Stay in the cloud

Evaporate

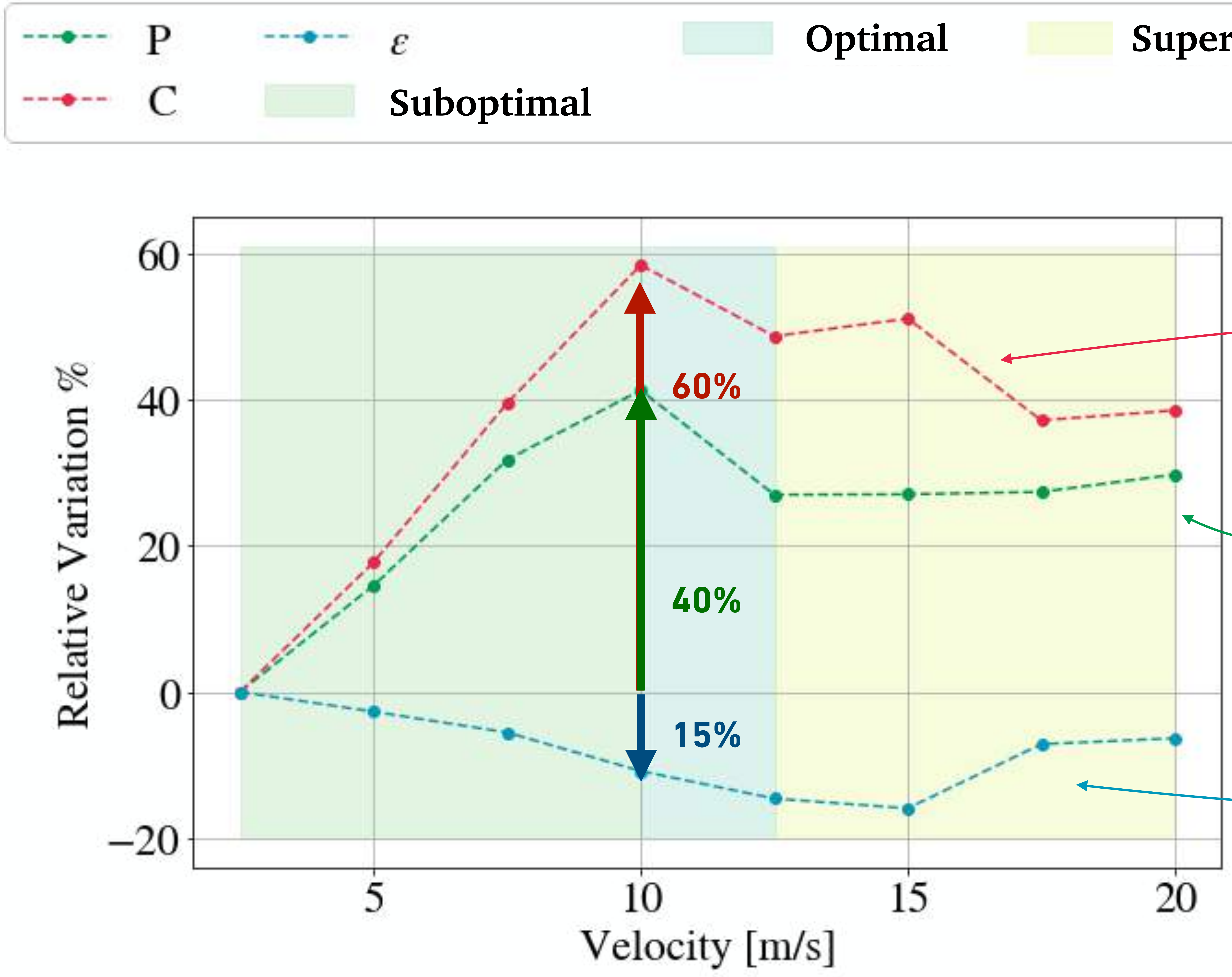


Scaling for Extreme Precipitation (Singh & O'Gorman 2014, Muller & Takayabu 2020)



$$\frac{\Delta P}{P} \sim \frac{\Delta \epsilon_p}{\epsilon_p} + \frac{\Delta C}{C}$$

Scaling for Extreme Precipitation (Singh & O'Gorman 2014, Muller & Takayabu 2020)



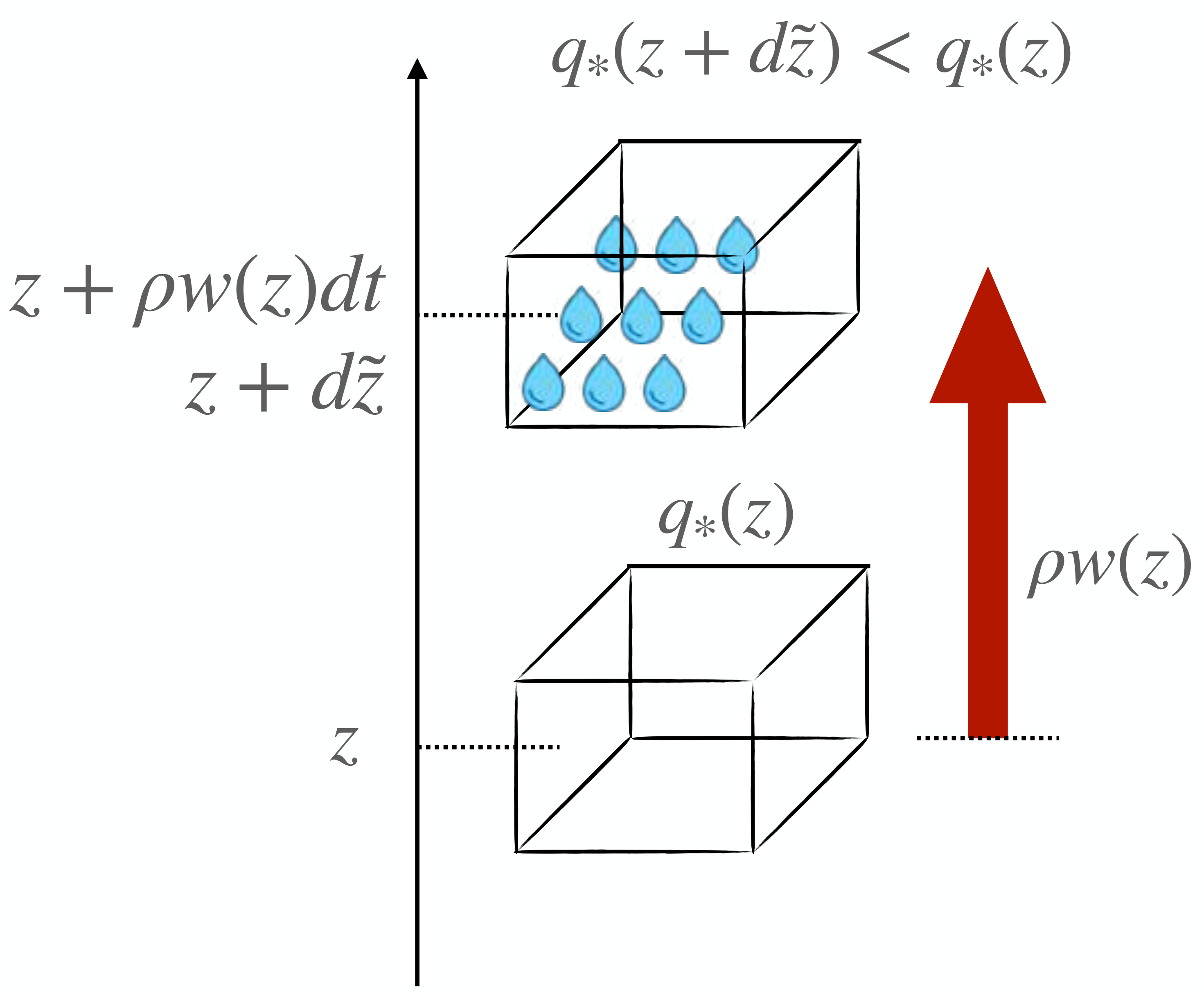
$$\frac{\Delta P}{P} \sim \frac{\Delta \epsilon_p}{\epsilon_p} + \frac{\Delta C}{C}$$

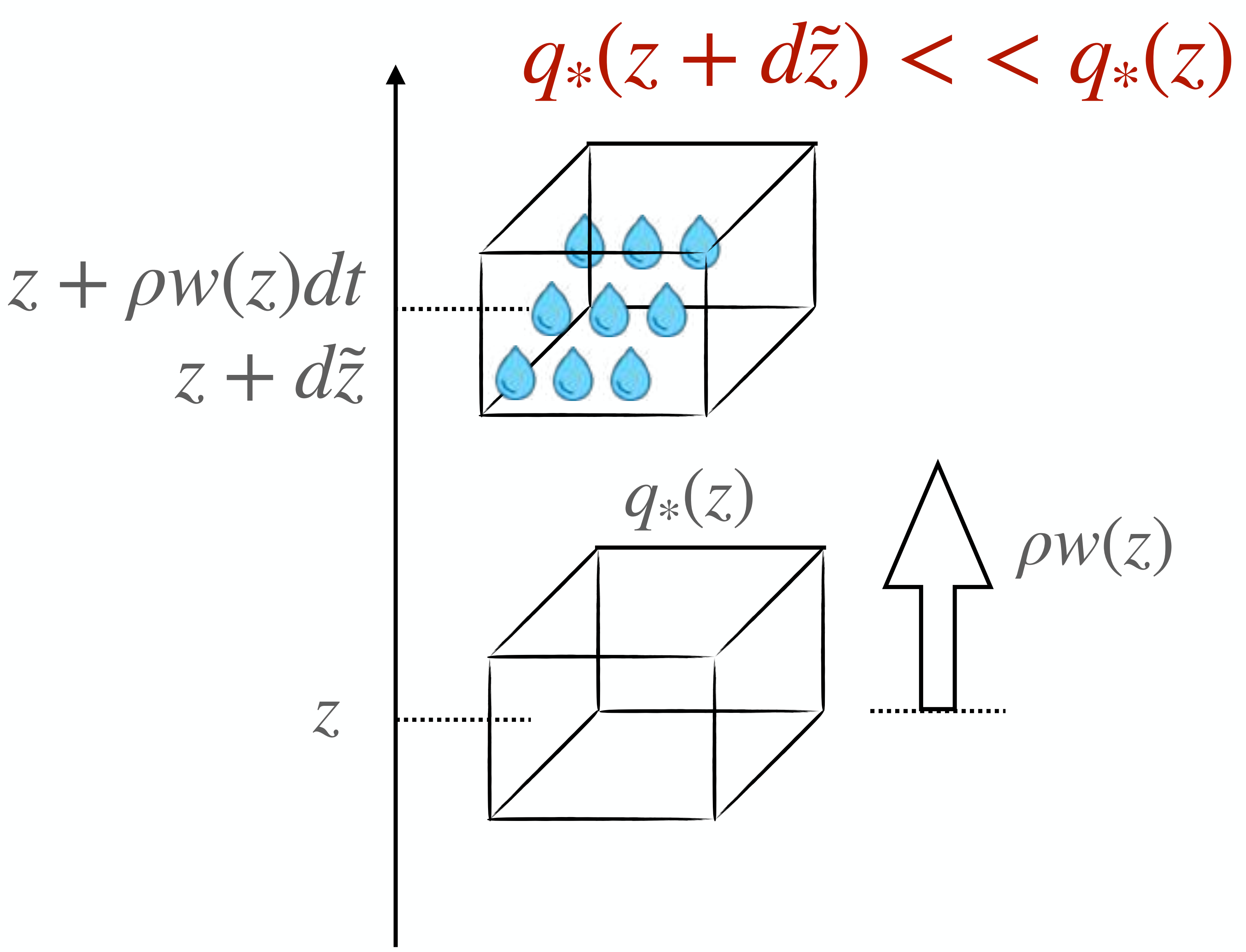
Condensation is sensitive to squall line regime

Scaling for Extreme Precipitation (Singh & O'Gorman 2014, Muller & Takayabu 2020)

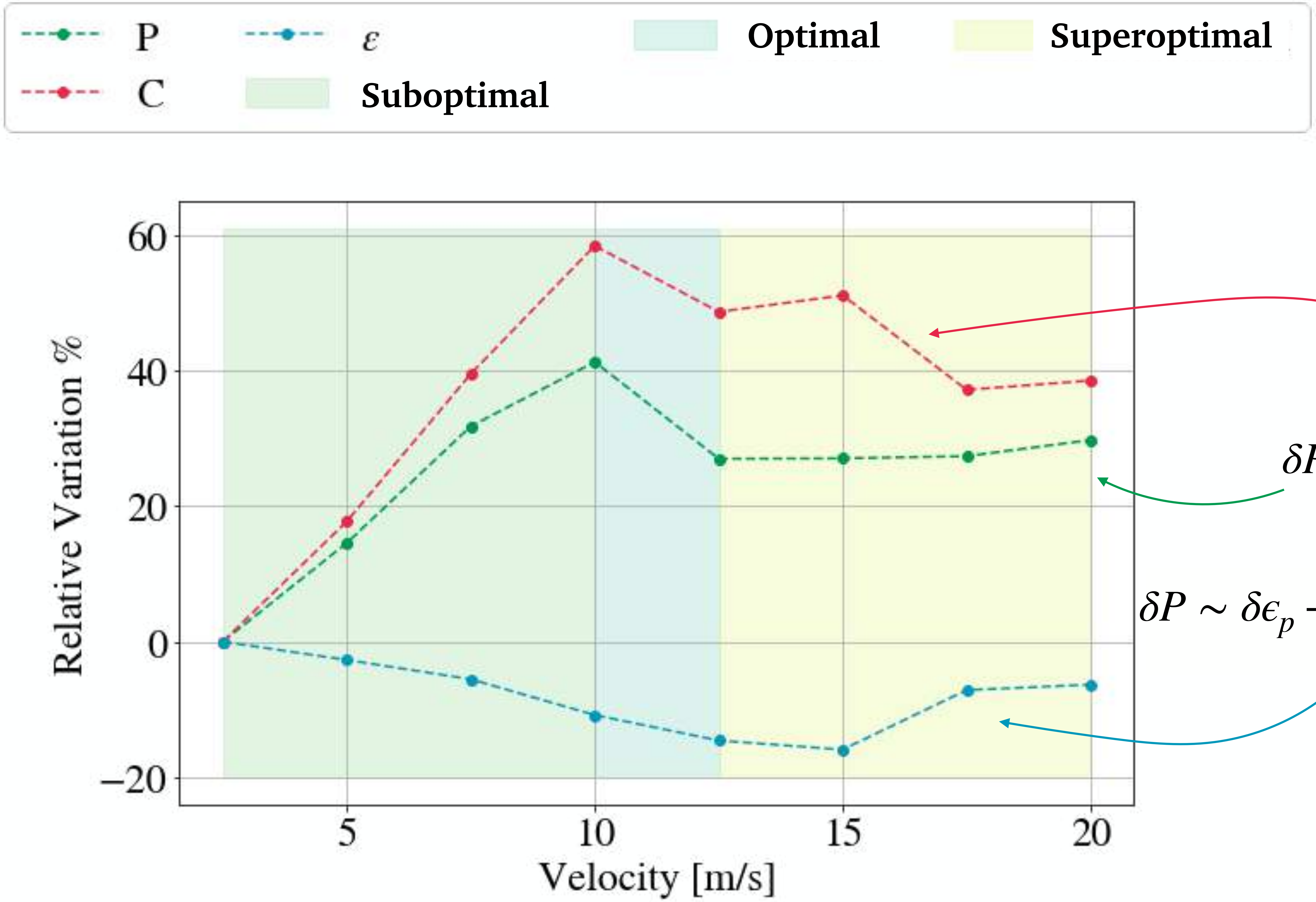
$$\delta P \sim \delta\{\epsilon_p \int \rho w \frac{-\partial q_*}{\partial z} dz\}$$

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





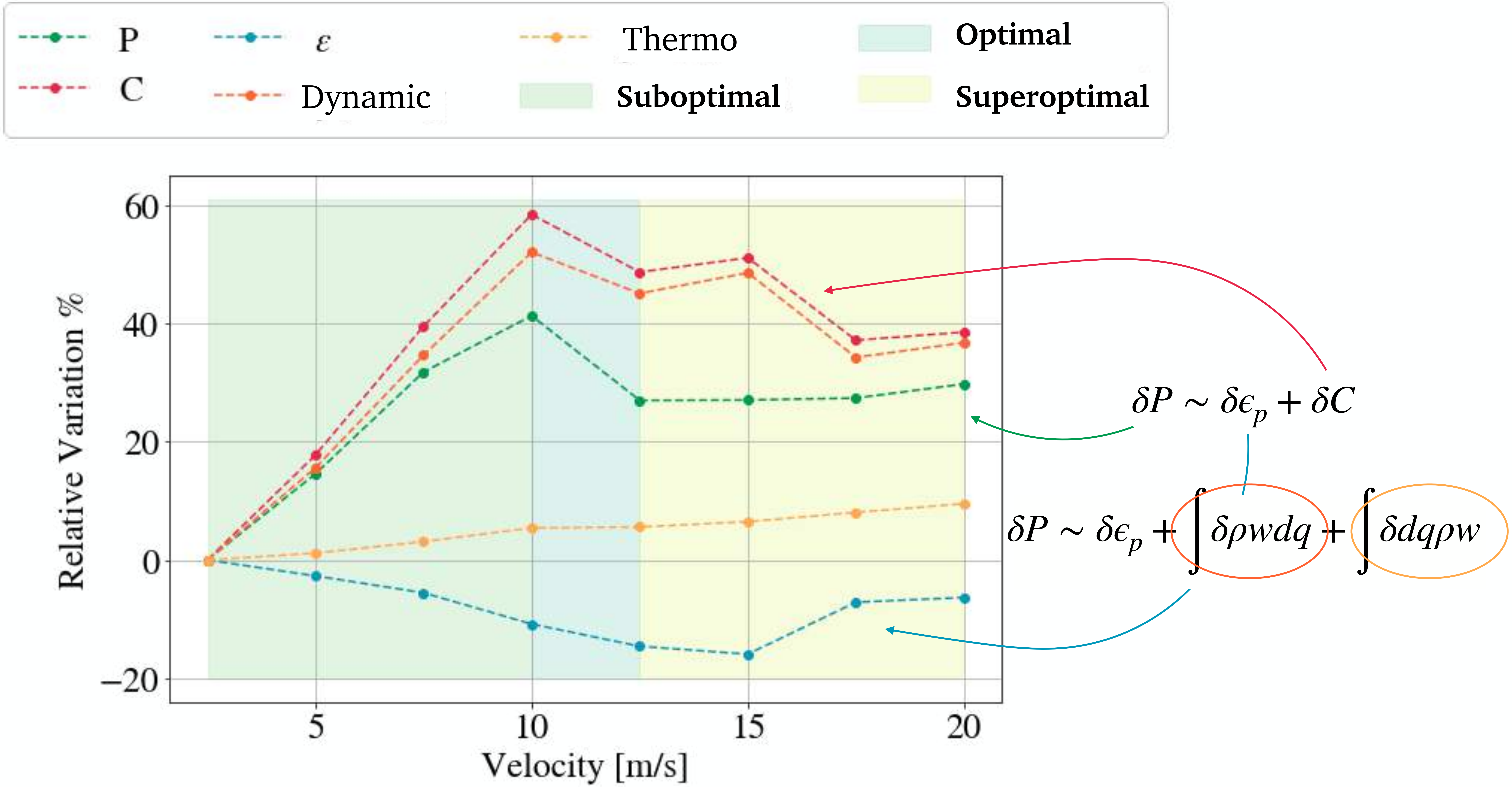
Scaling for Extreme Precipitation (Singh & O'Gorman 2014, Muller & Takayabu 2020)



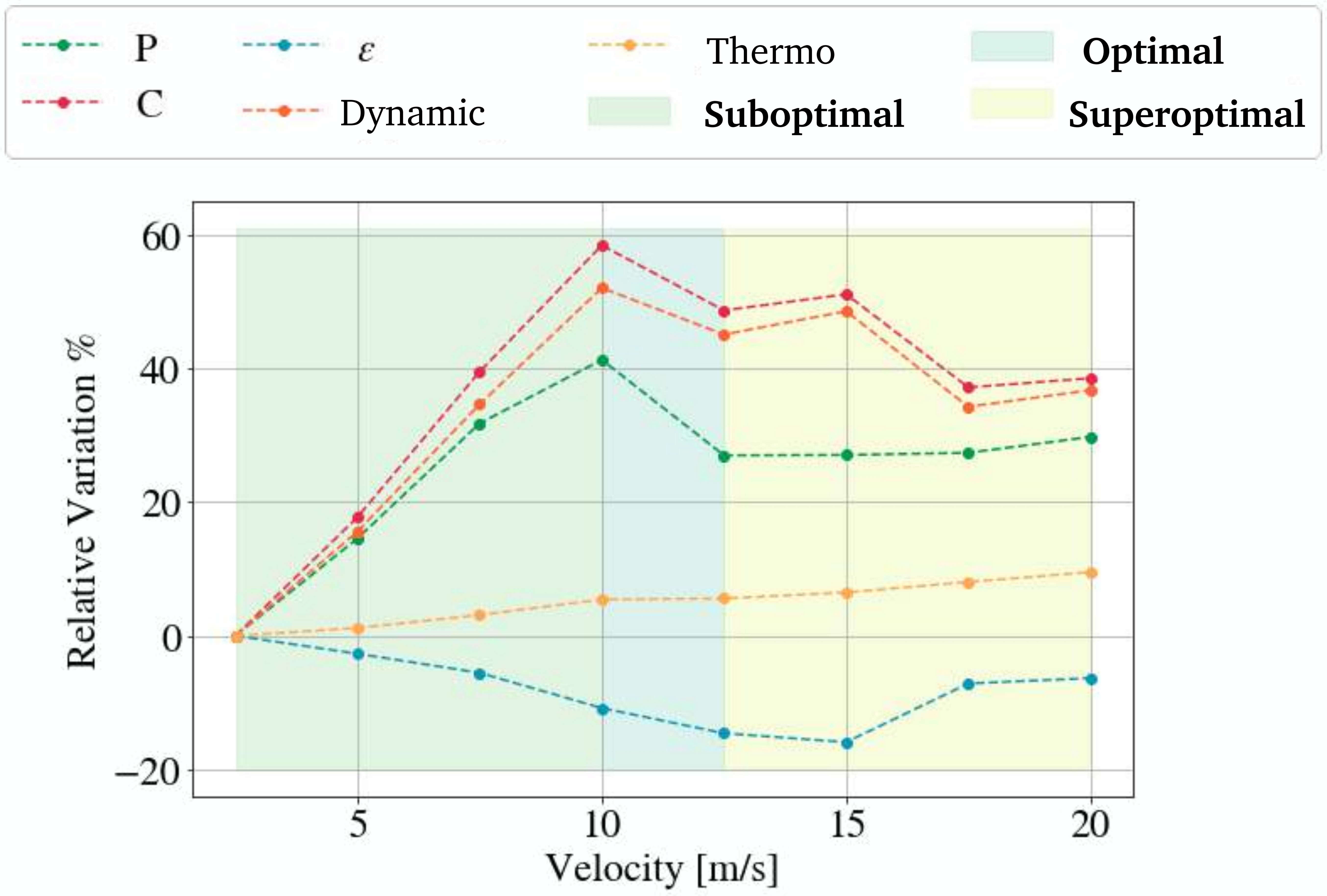
$$\delta P \sim \delta \epsilon_p + \delta C$$

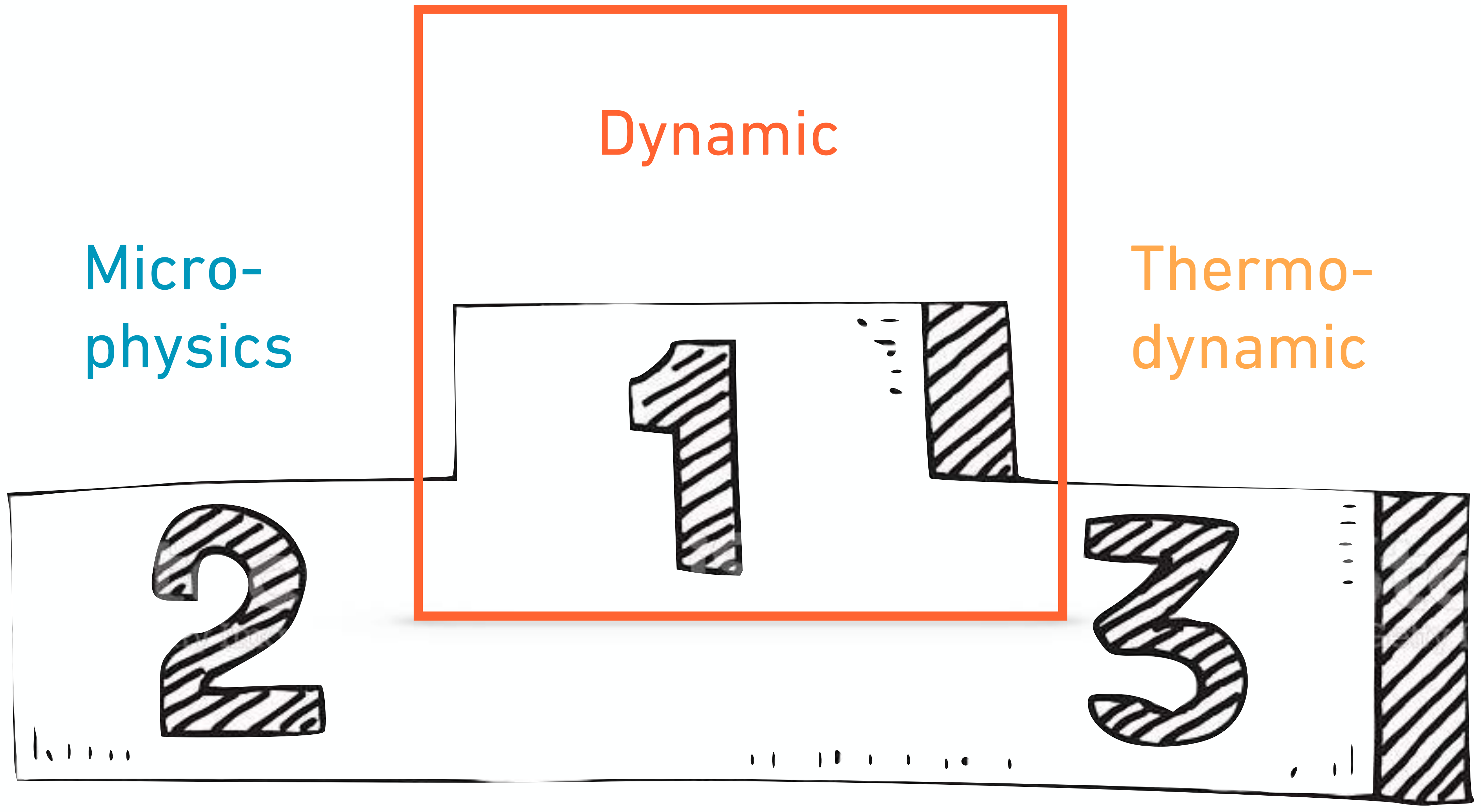
$$\delta P \sim \delta \epsilon_p + \int \delta \rho w dq + \int \delta dq \rho w$$

Scaling for Extreme Precipitation (Singh & O'Gorman 2014, Muller & Takayabu 2020)



Contribution that mainly explains change in extreme precipitation





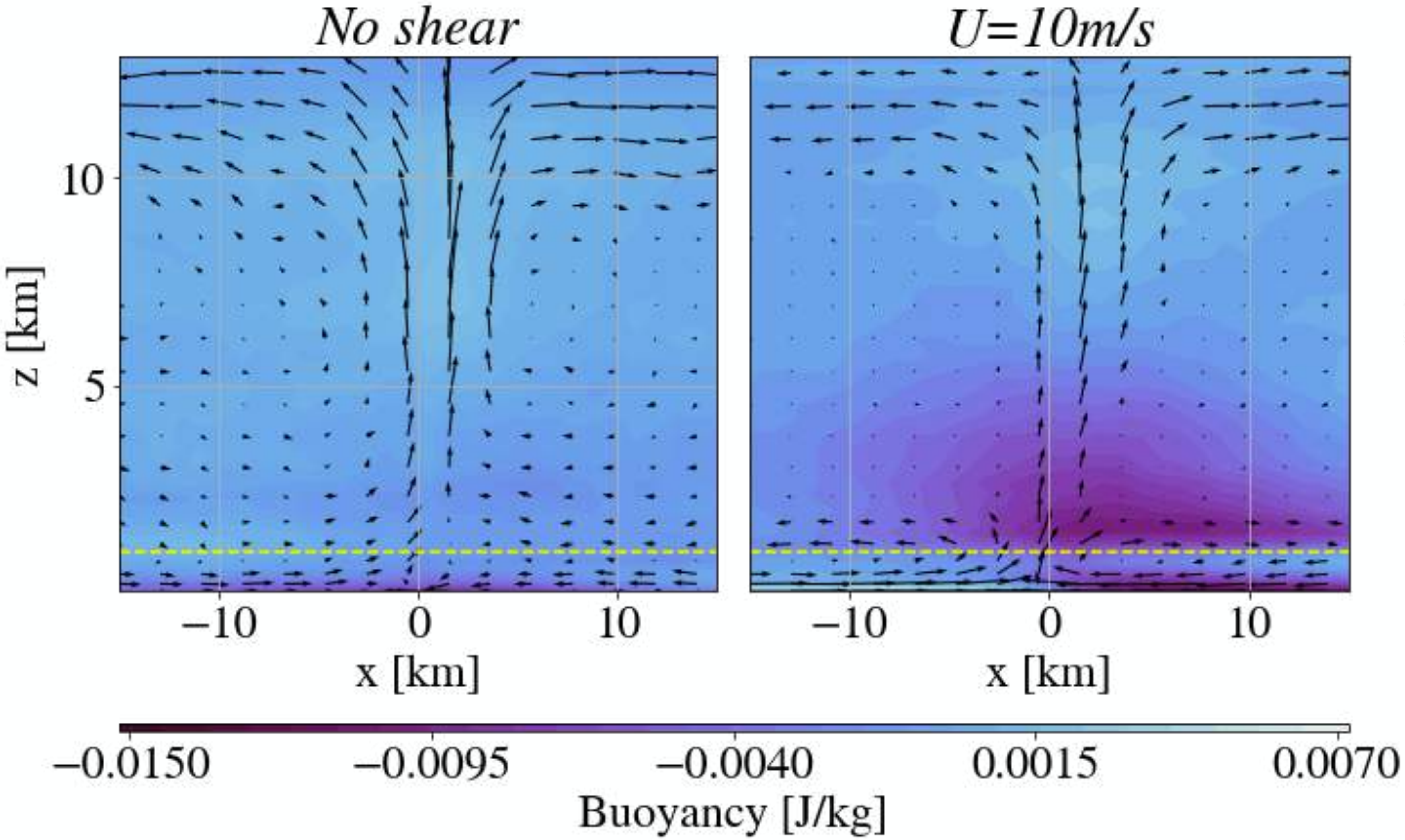
→ What physical mechanisms control the behavior of these contributions ?

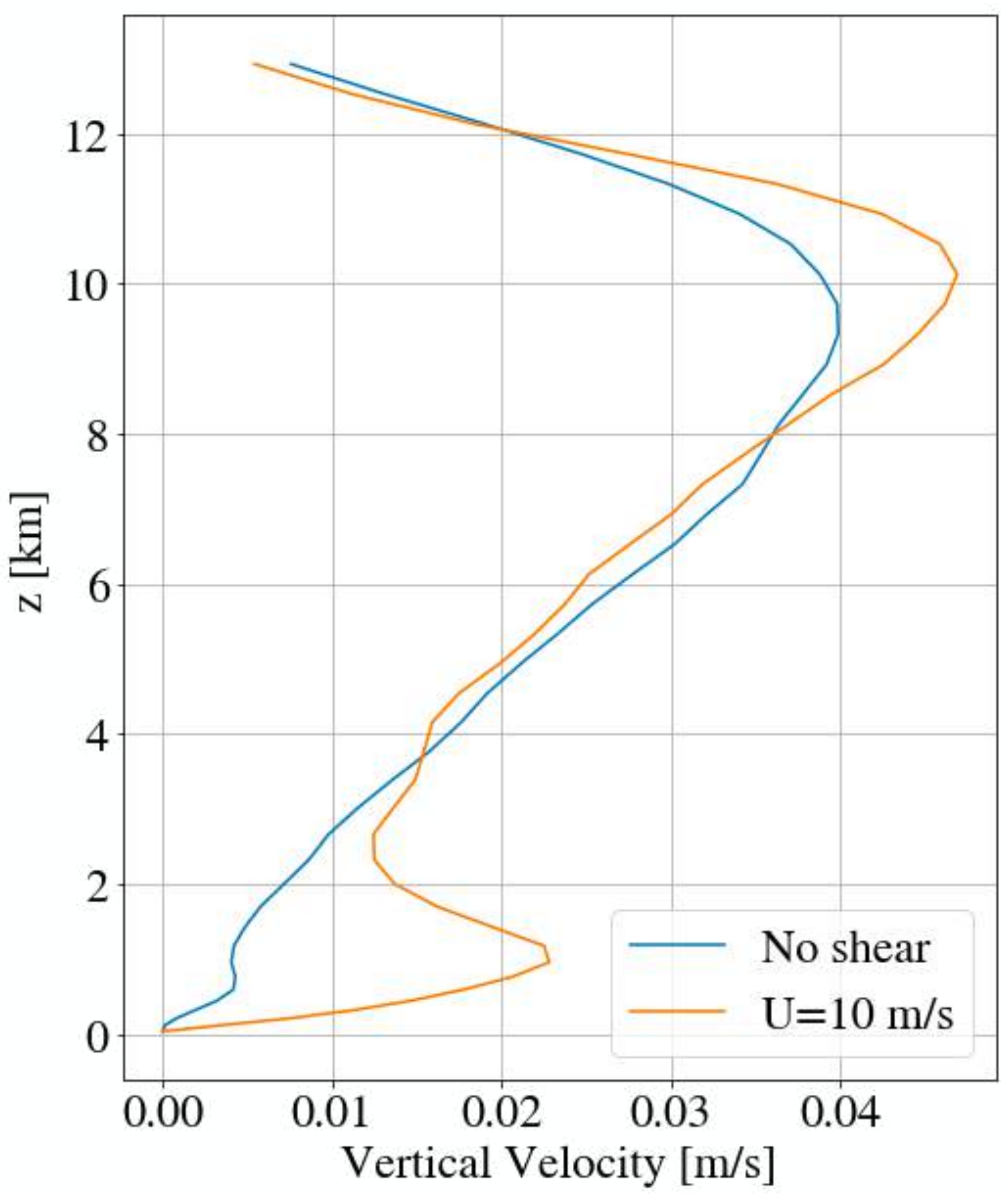
Physical Processes

Dynamic Contribution

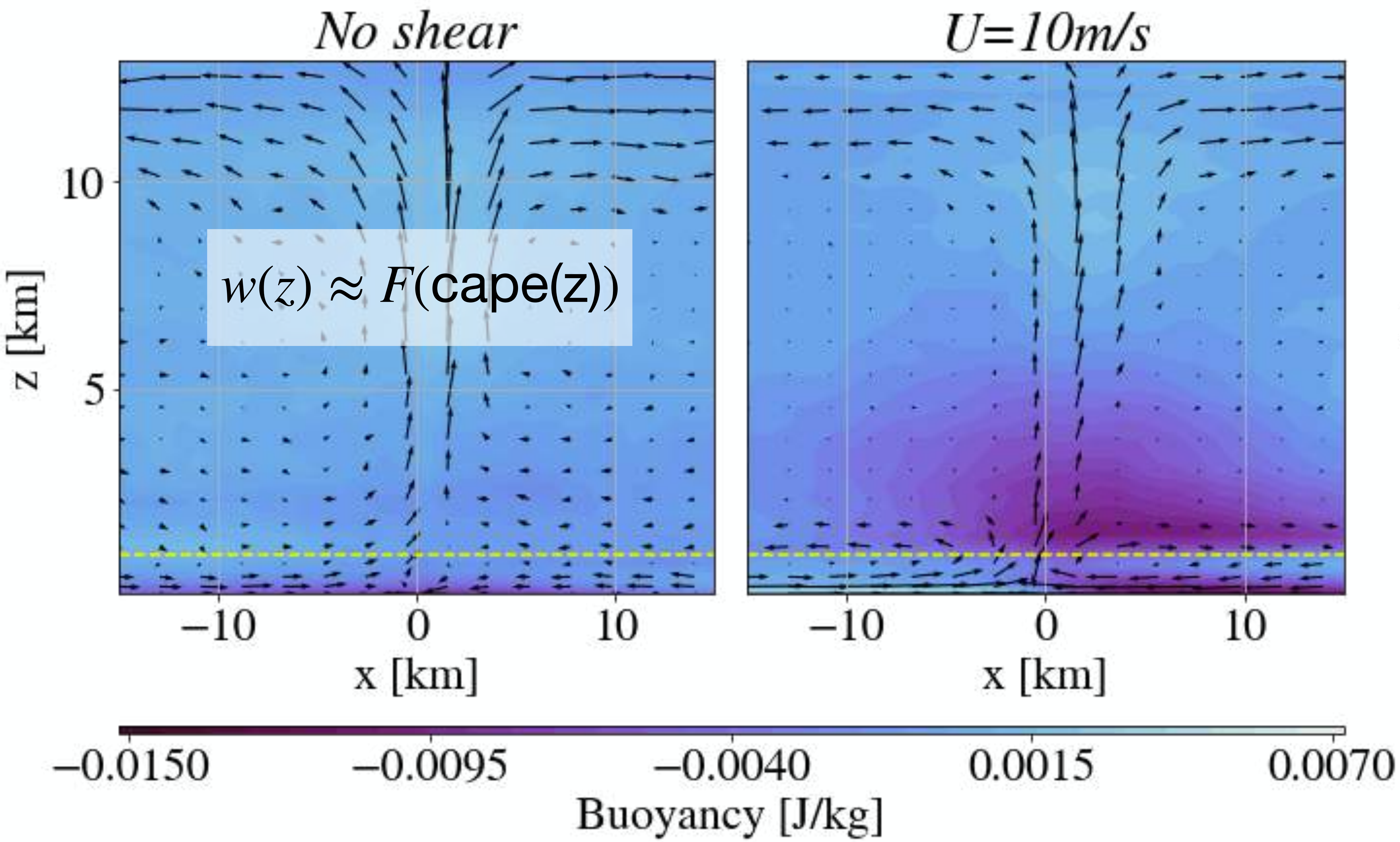
Microphysic & Thermodynamic Contributions

Dynamic Contributions



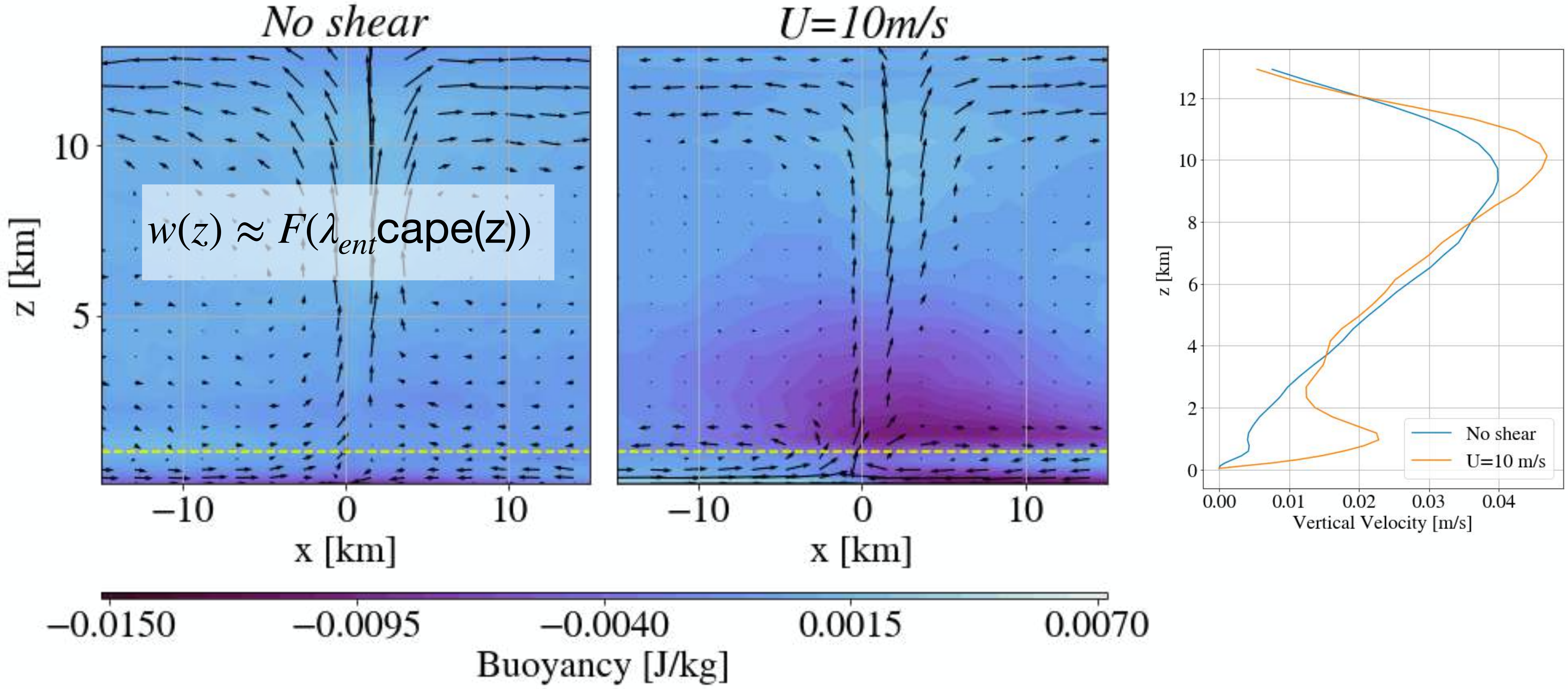


Dynamic Contributions

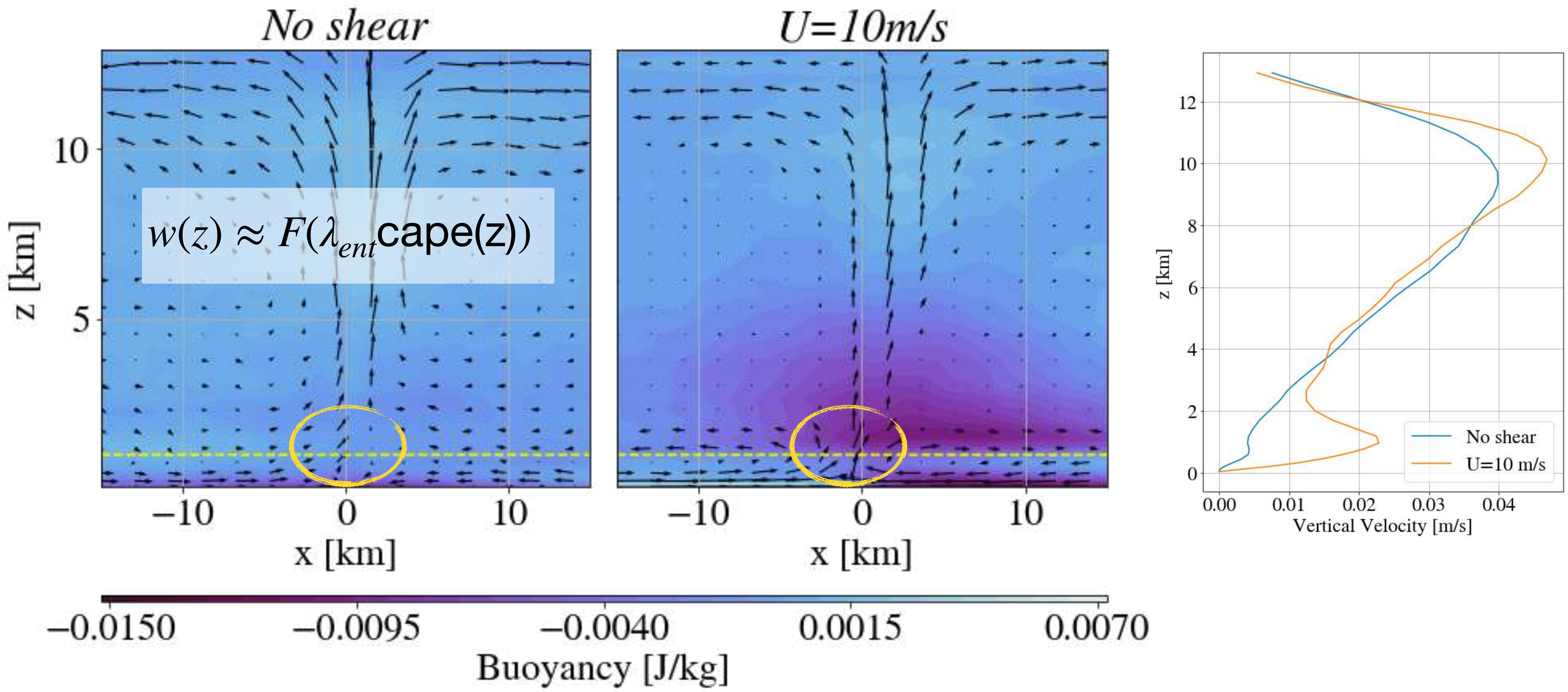


Dynamic Contributions

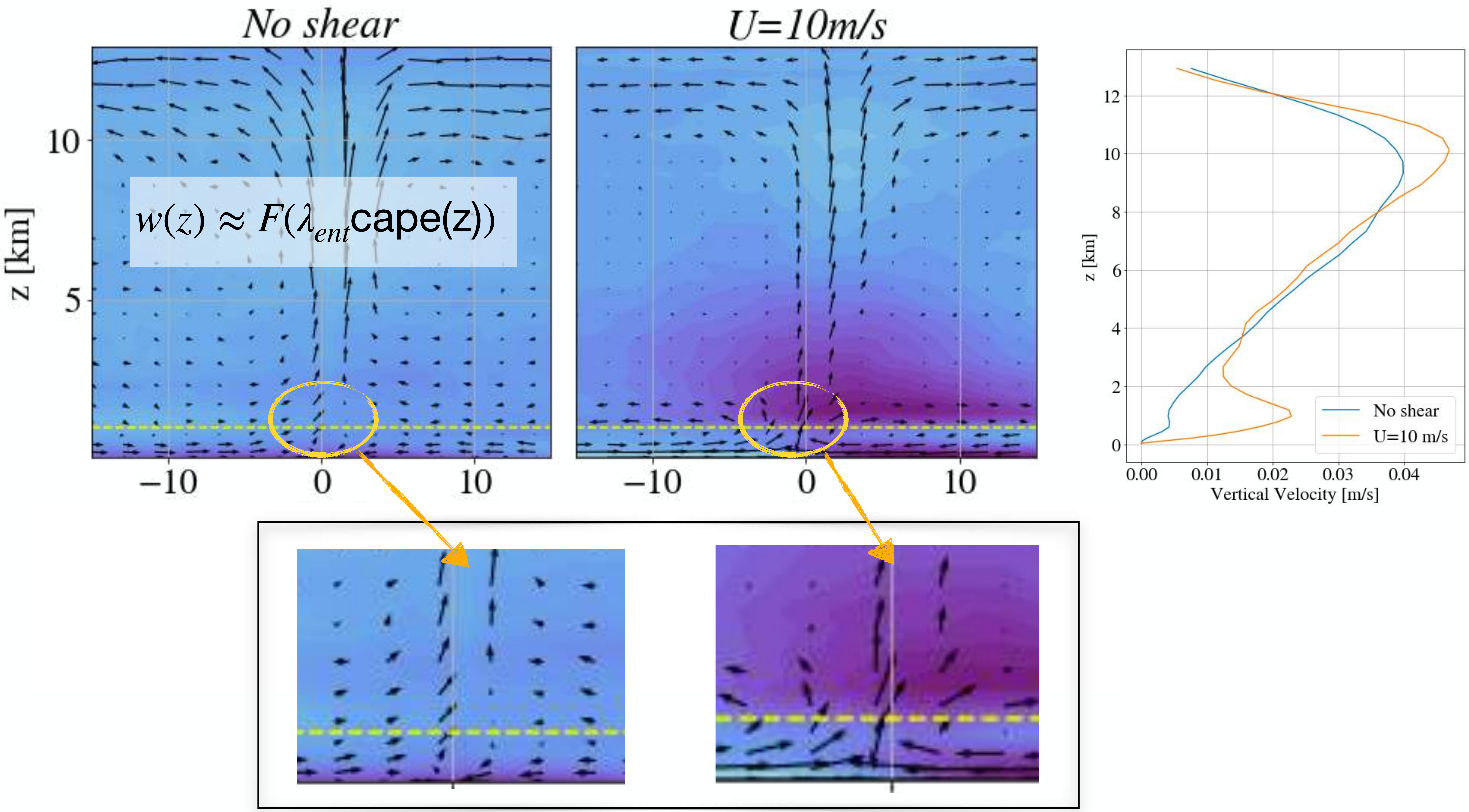
$$w(z) \approx F(\lambda_{ent}\text{cape(z)})$$



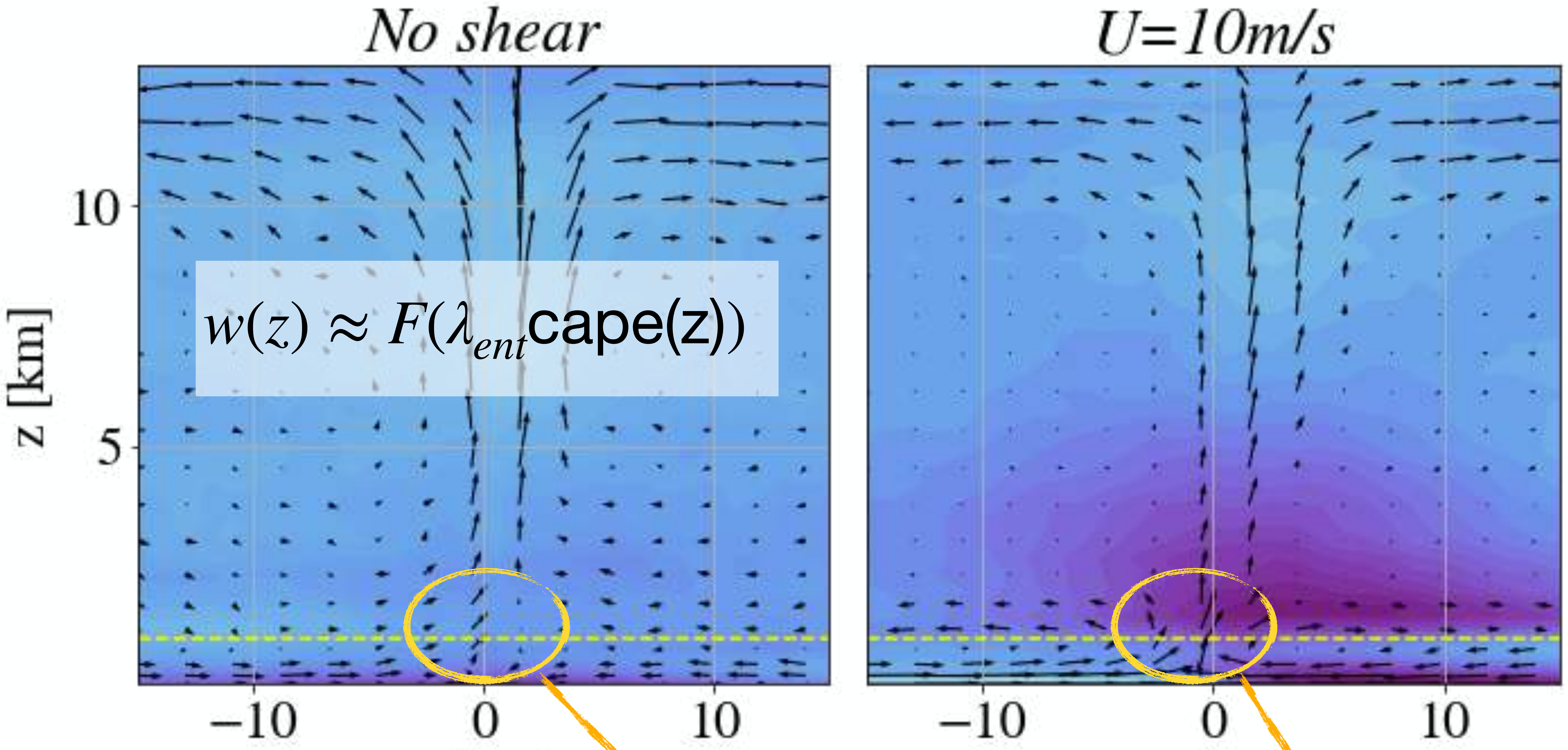
Dynamic Contributions

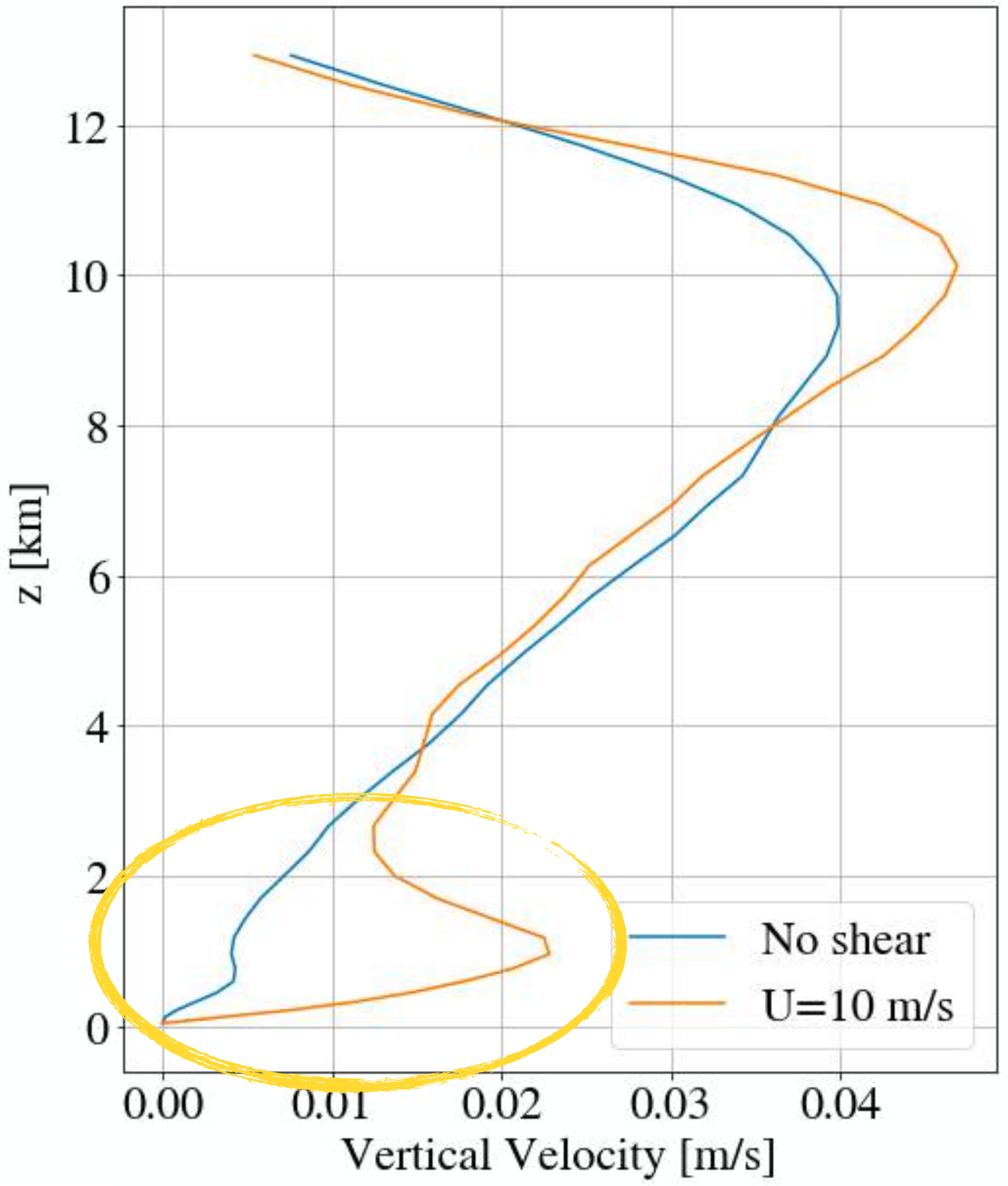


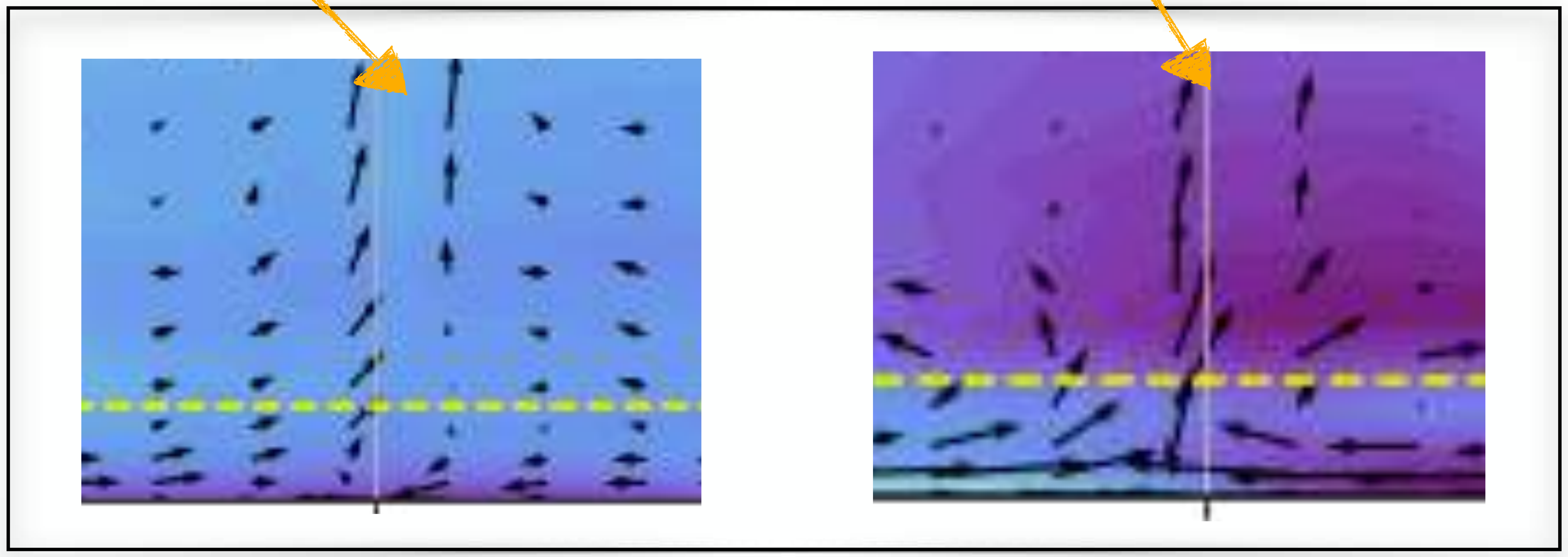
Dynamic Contributions



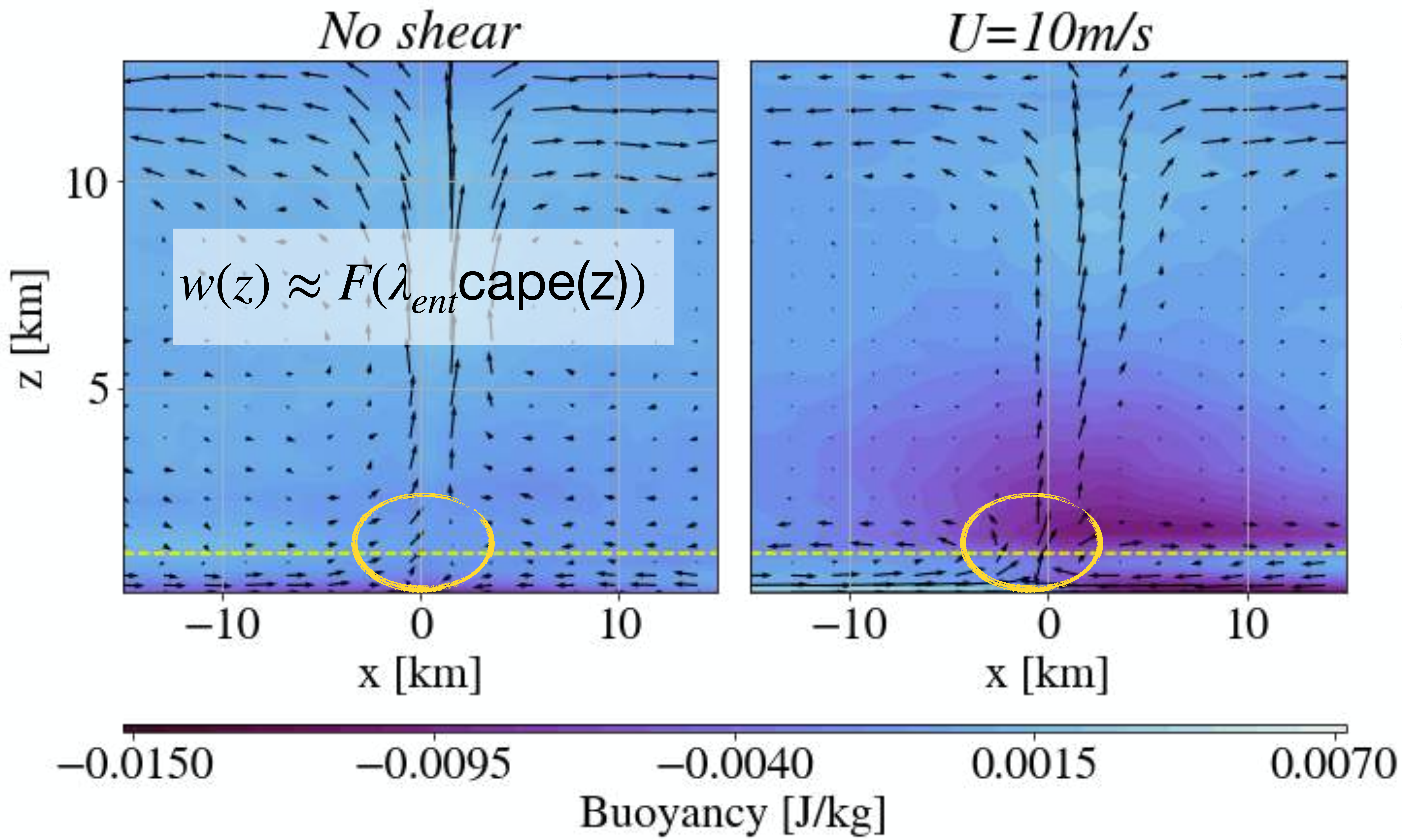
Dynamic Contributions

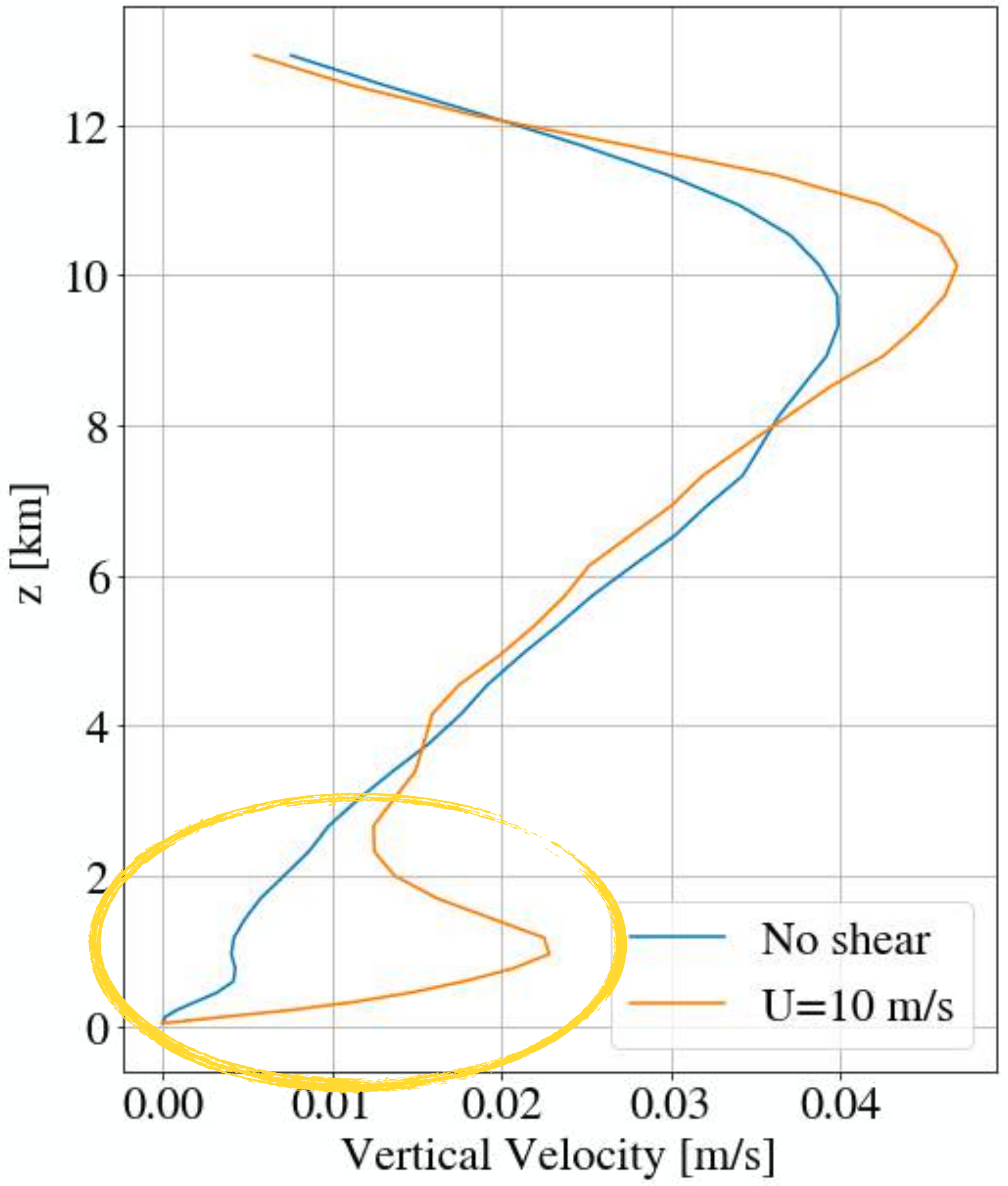




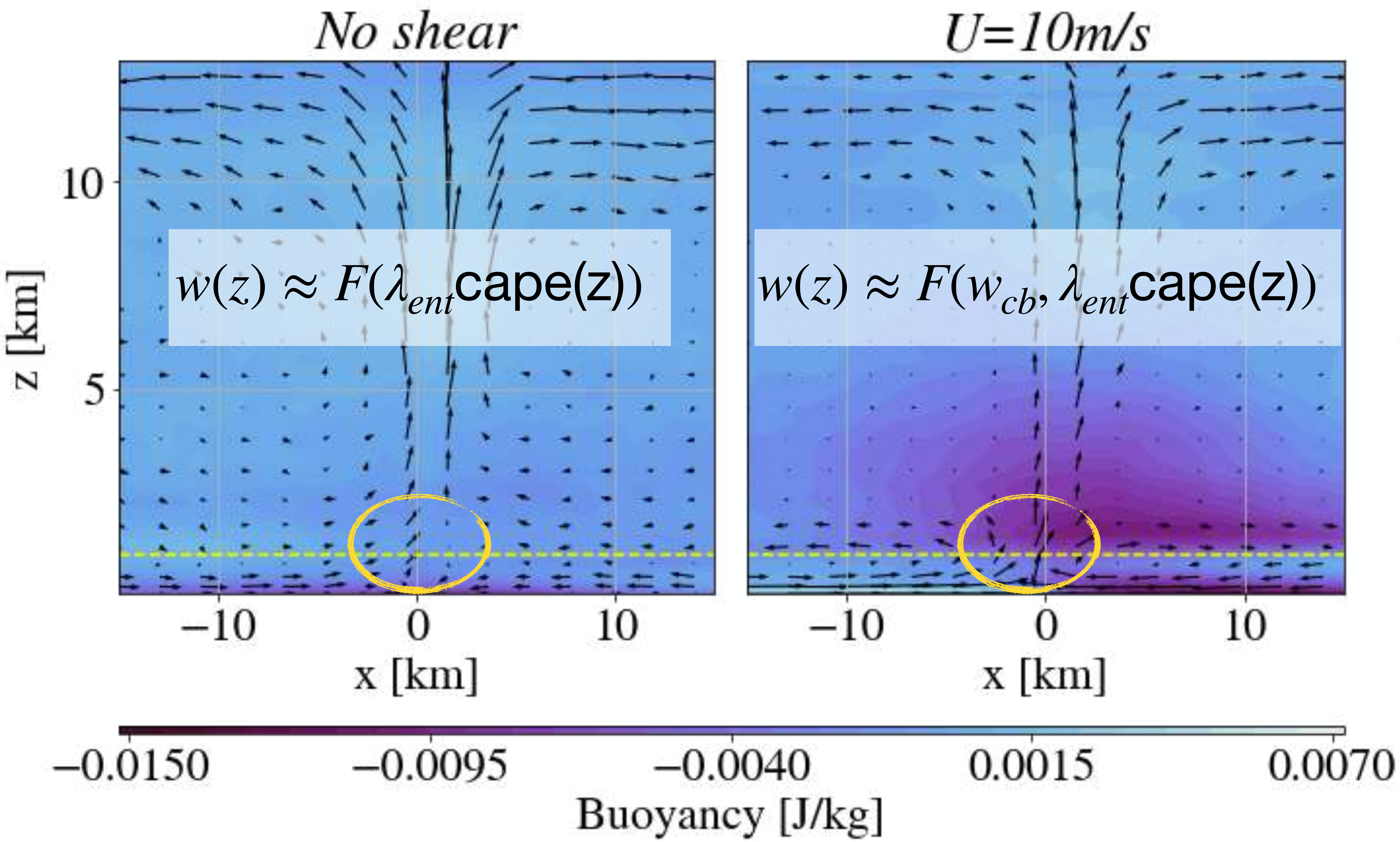


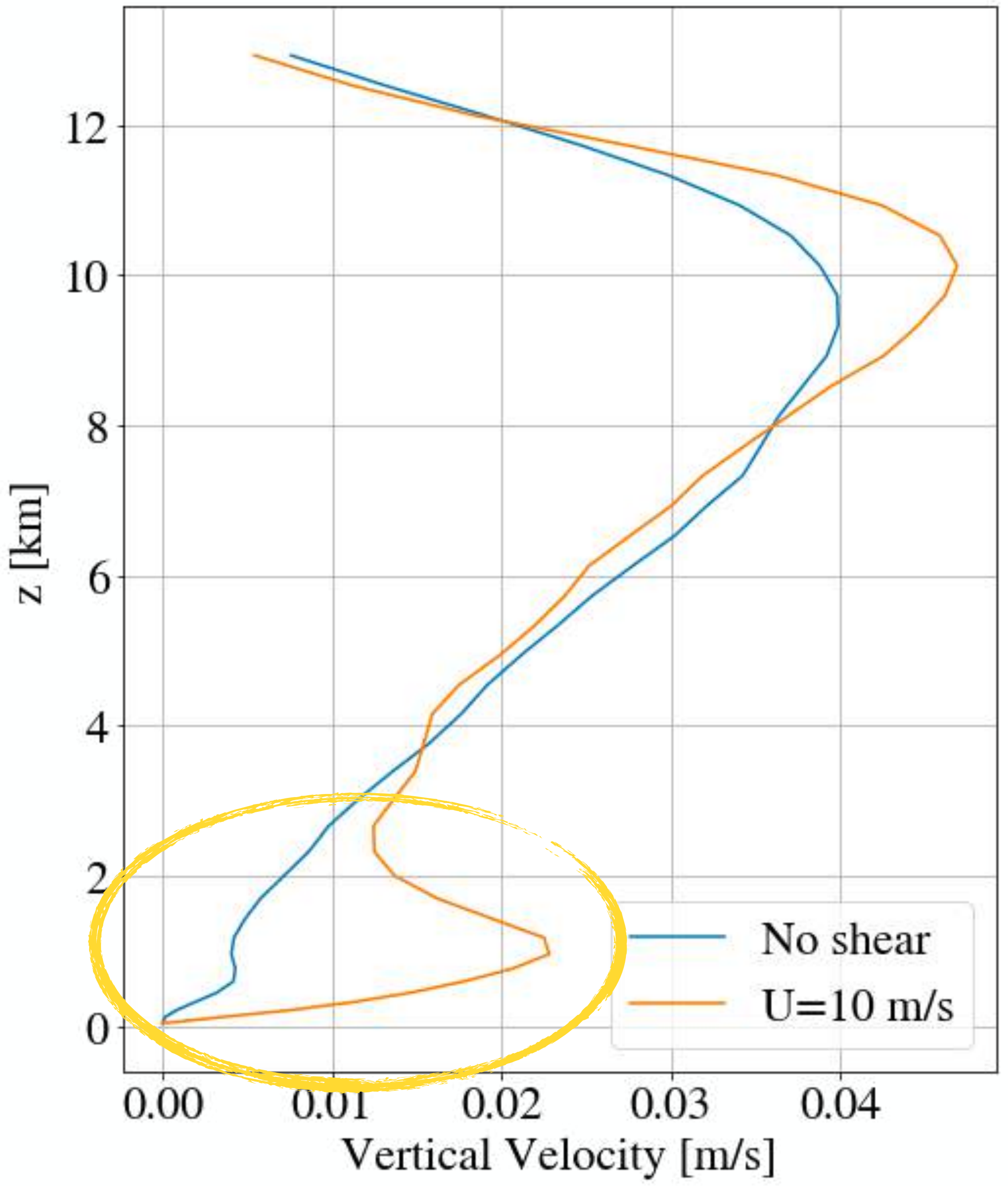
Dynamic Contributions



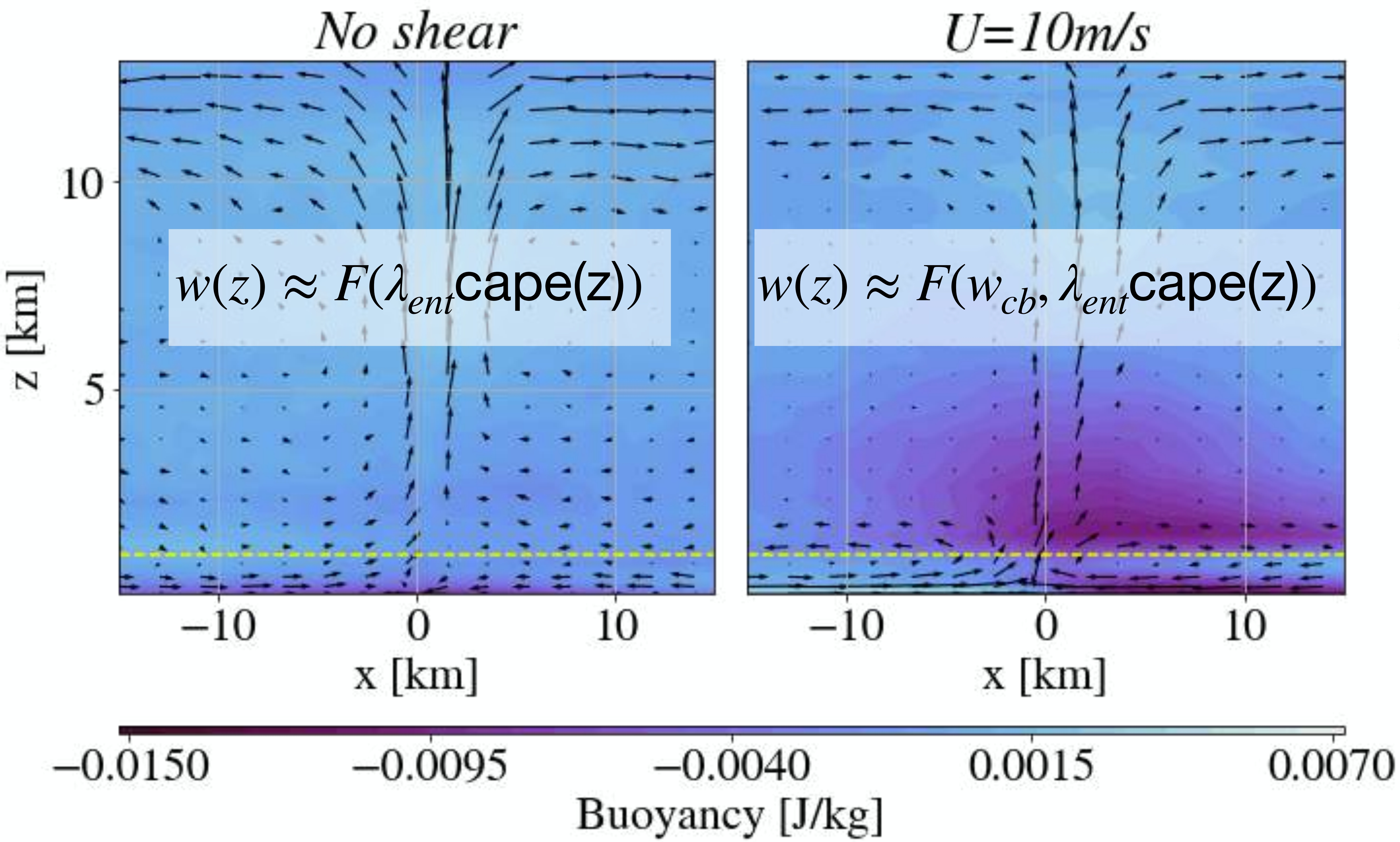


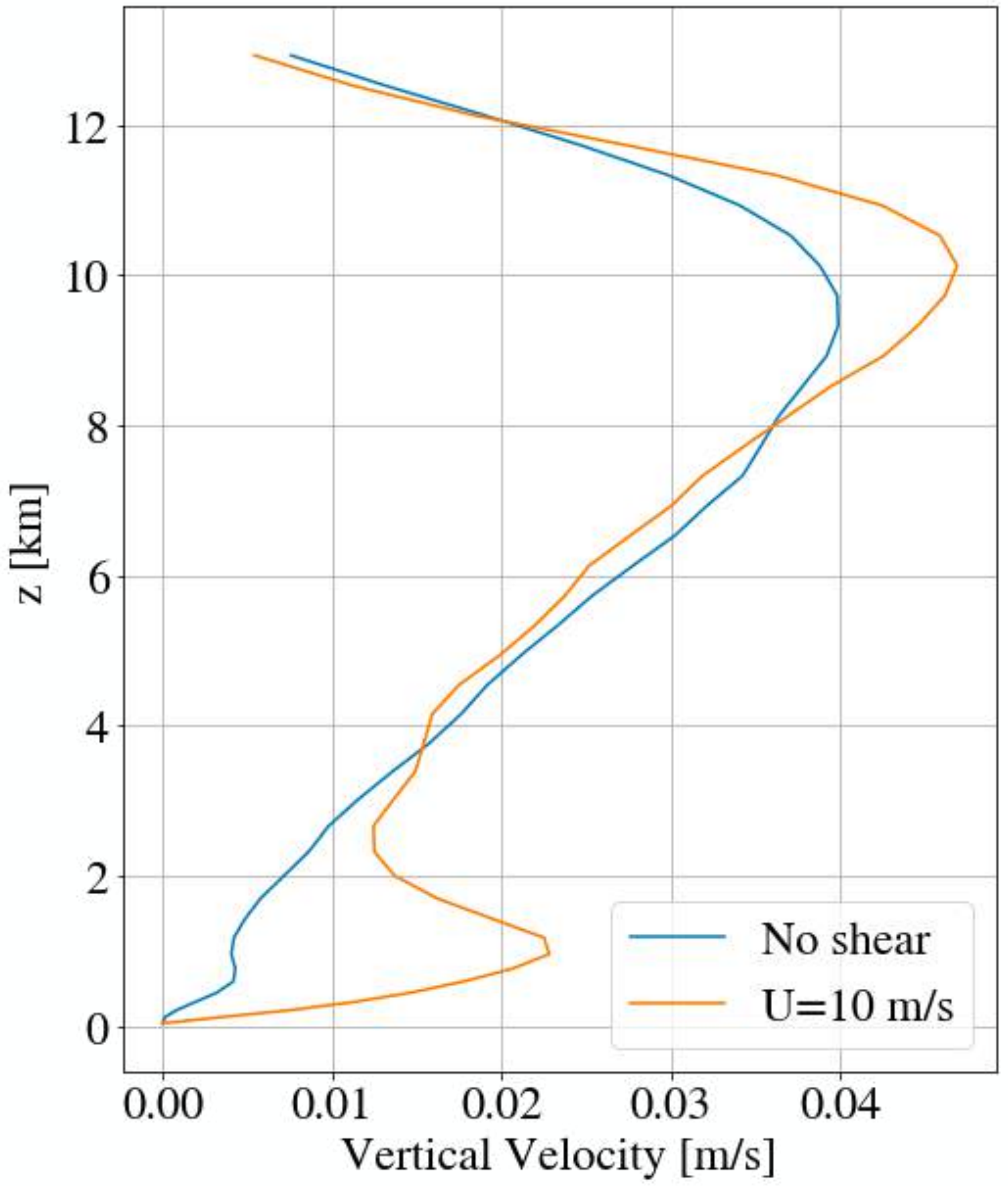
Dynamic Contributions





Dynamic Contributions

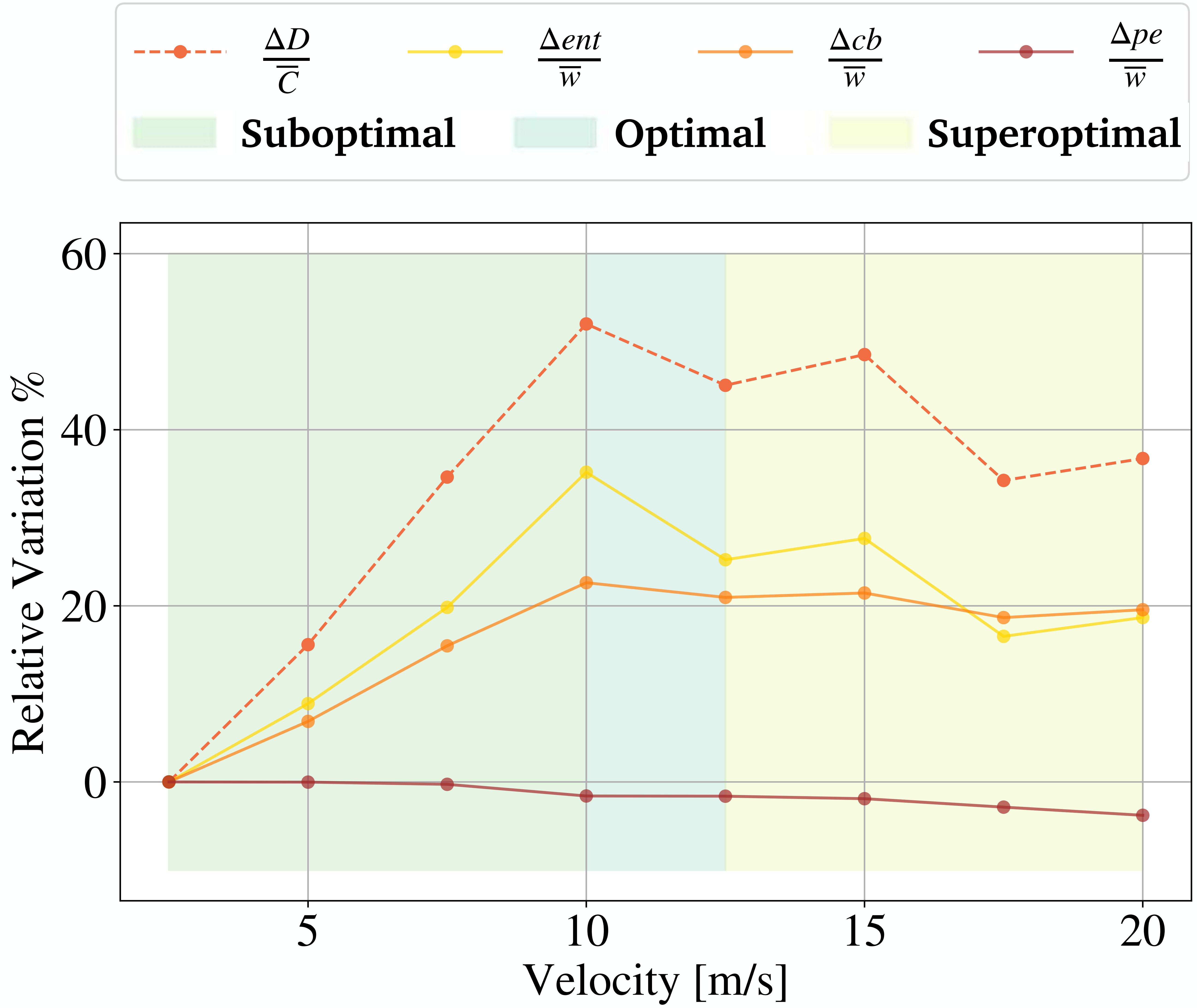




$$\text{Dynamic} \approx \tilde{F}(w_{cb}, \lambda_{ent}, cape)$$

Dynamic Contributions

$$D \approx \tilde{F}(w_{cb}, \lambda_{ent}, cape)$$



Suboptimal regime

Reduced entrainment
Increased cloud-base velocity

→ Enhanced dynamics

Optimal and Superoptimal

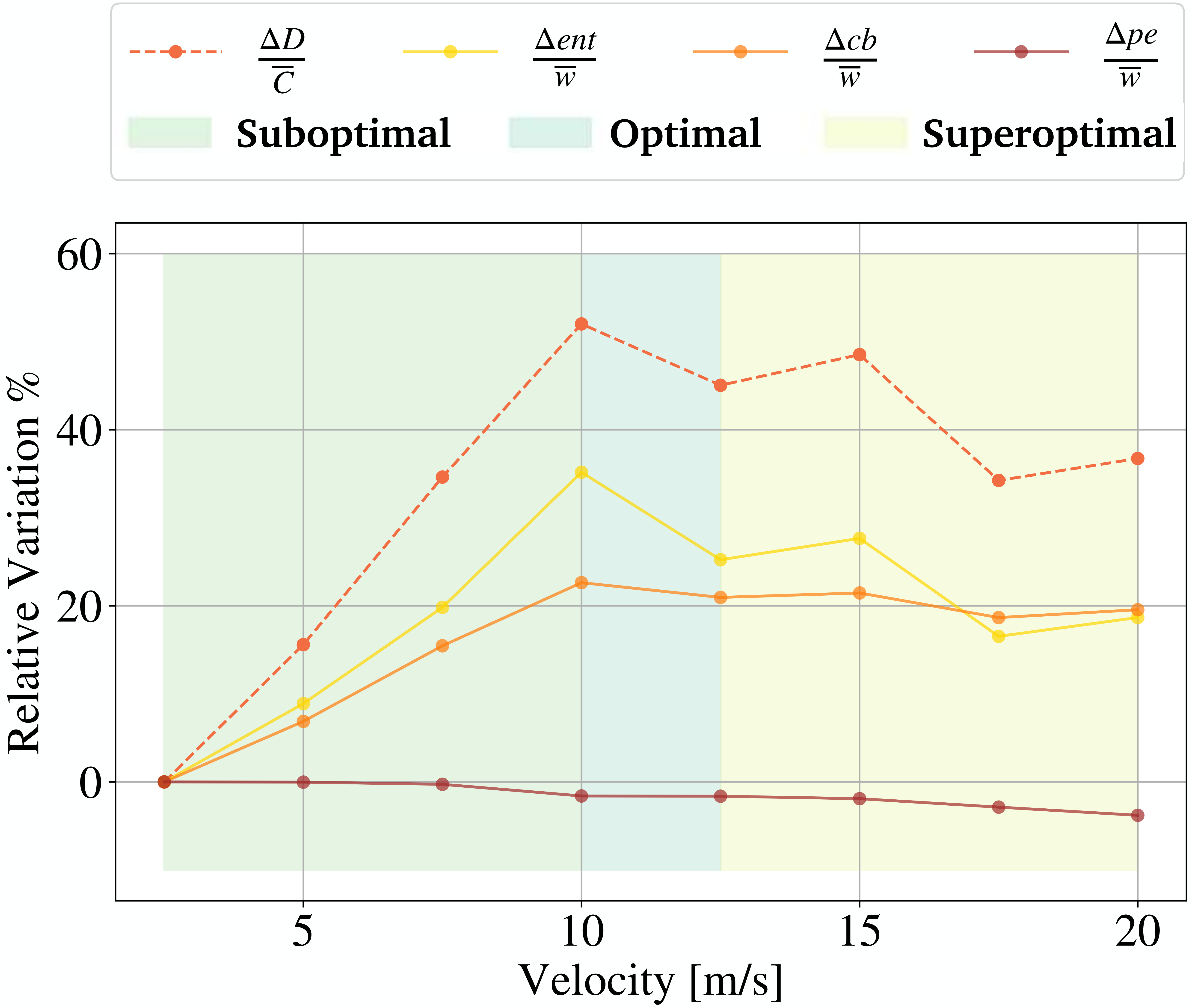
Both saturate

→ Near constant dynamics

→ Atmospheric instability doesn't play a key role

Dynamic Contributions

$$D \approx \tilde{F}(w_{cb}, \lambda_{ent}, cape)$$



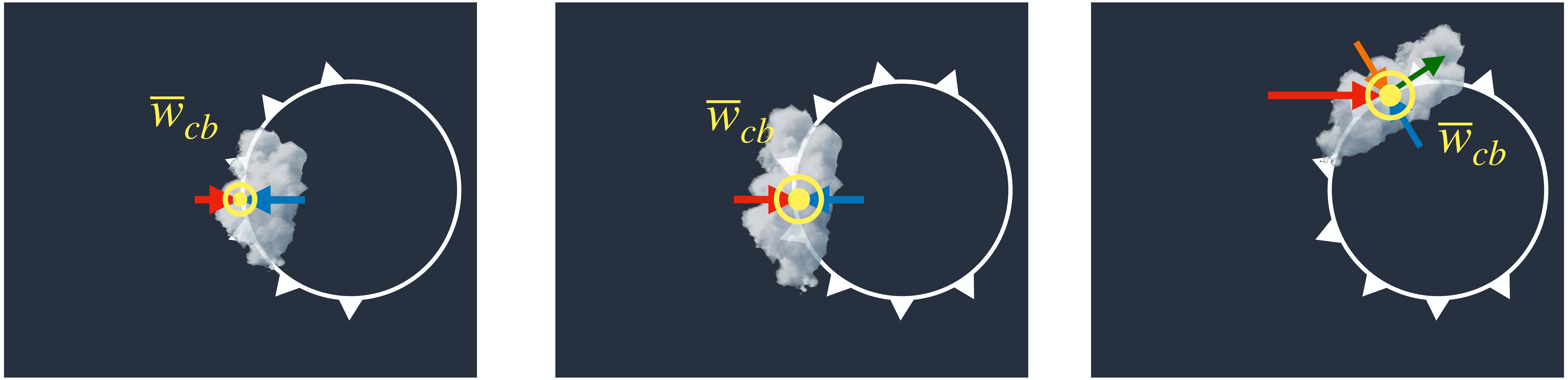
→ Entrainment

How Does Vertical Wind Shear Influence Entrainment in Squall Lines? Mulholland et al 2021, JAS

→ Cloud Base Initial Velocity ?

Dynamic Contributions

Suboptimal **Optimal** **Superoptimal**



Cloud Base initial velocity mainly depends on the convergence at the edge of the cold pool

Exceeding momentum is transferred to tangential component

→ Preserved by the squall line orientation

Physical Processes

Dynamic Contribution

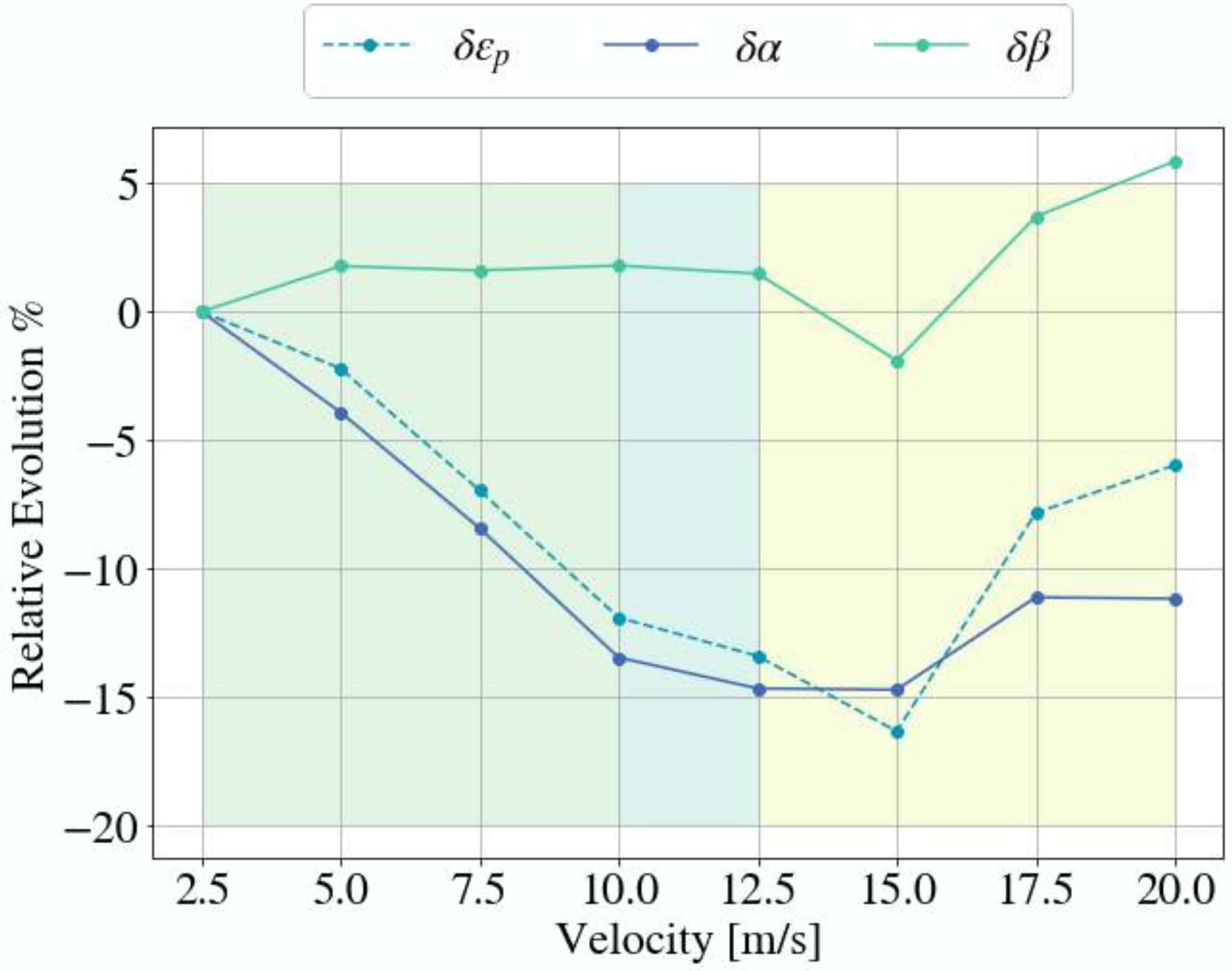
Microphysic & Thermodynamic Contributions

Microphysic and Thermodynamic contributions

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

Conversion from cloud to precipitating condensates

Precipitating condensates reaching the ground



→ Conversion dominates

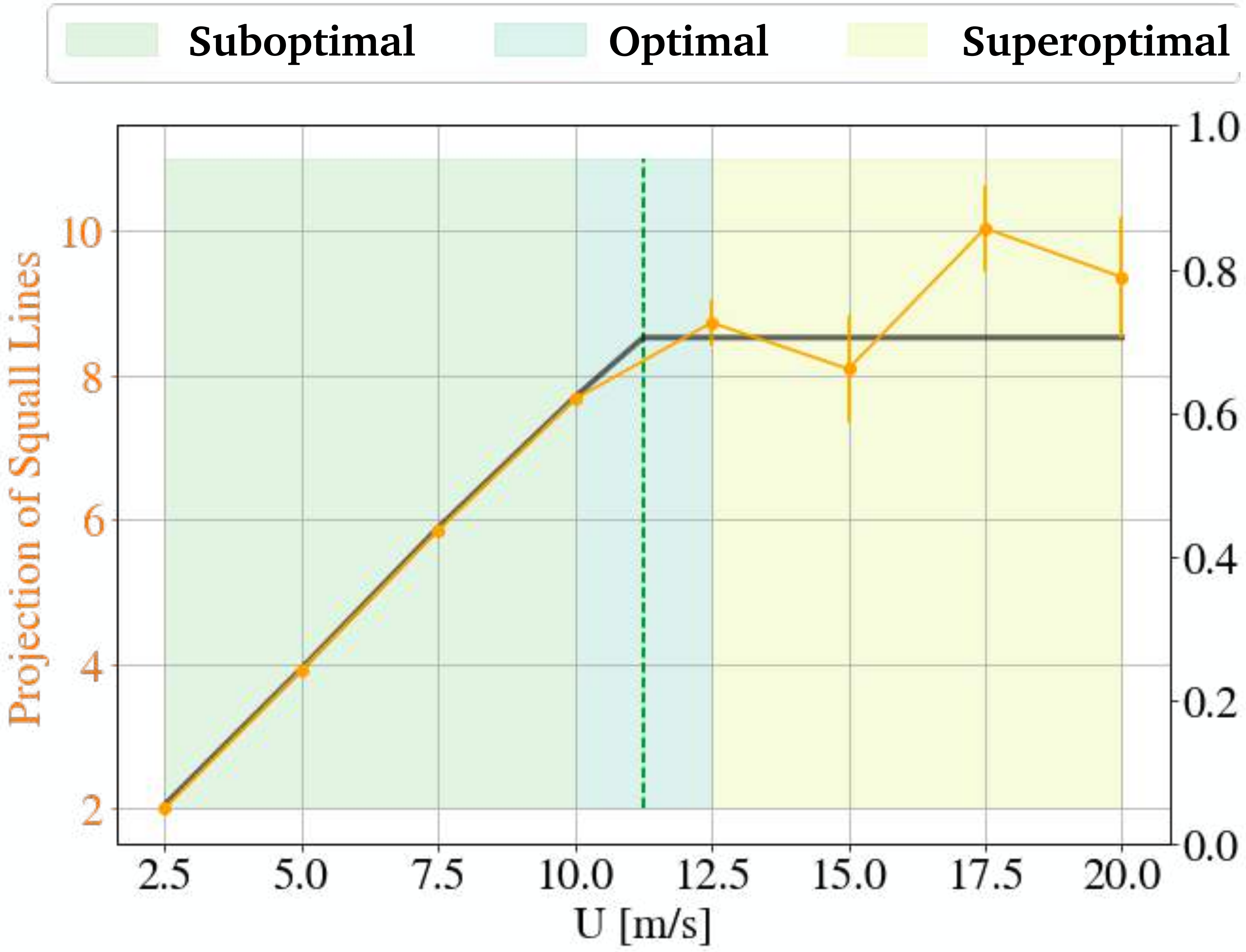
- Thermodynamic is weak (below 10%)

→ Consistent with near surface humidity increase

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

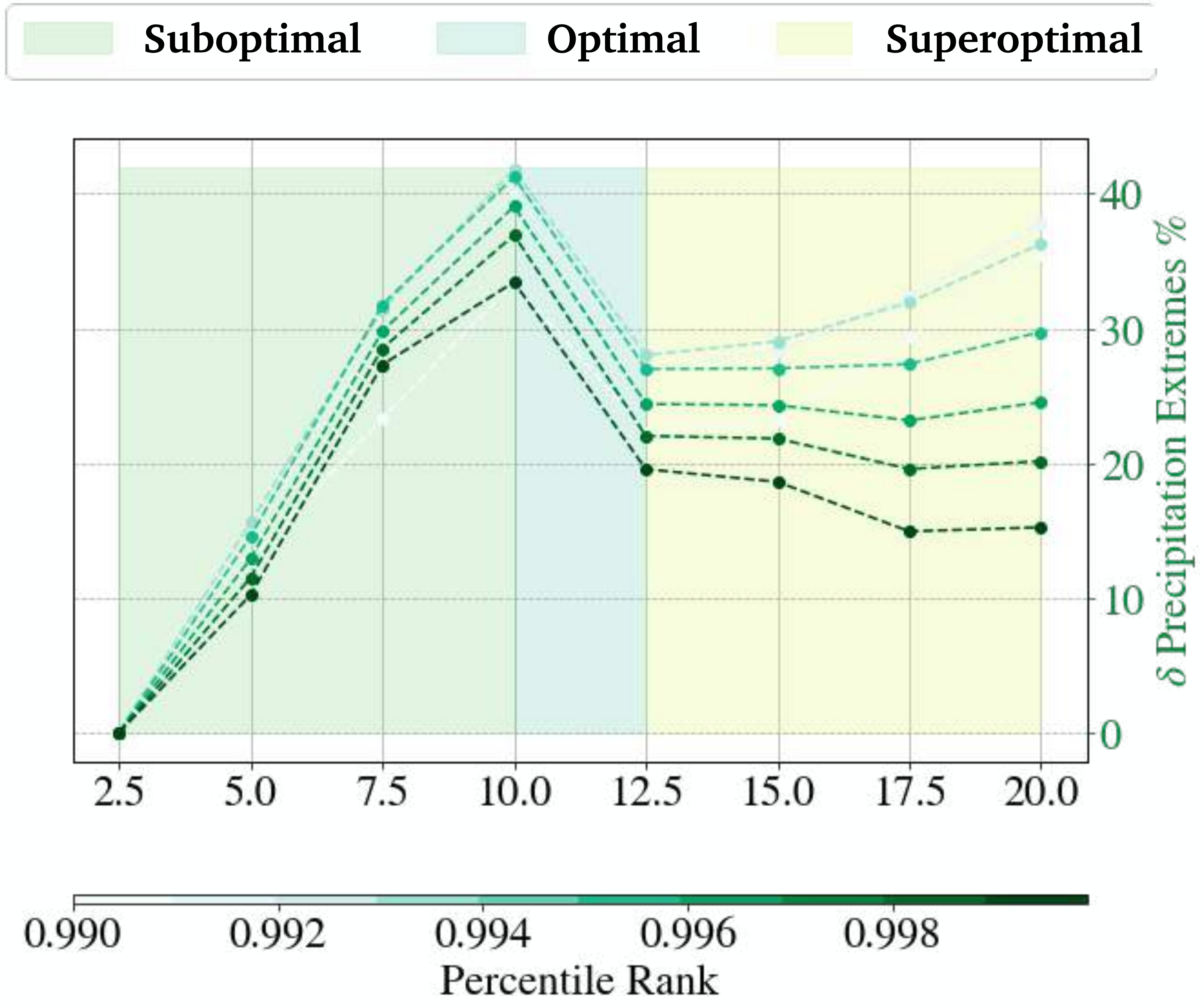
Conclusions

1. Theory of Squall Line Orientation is verified



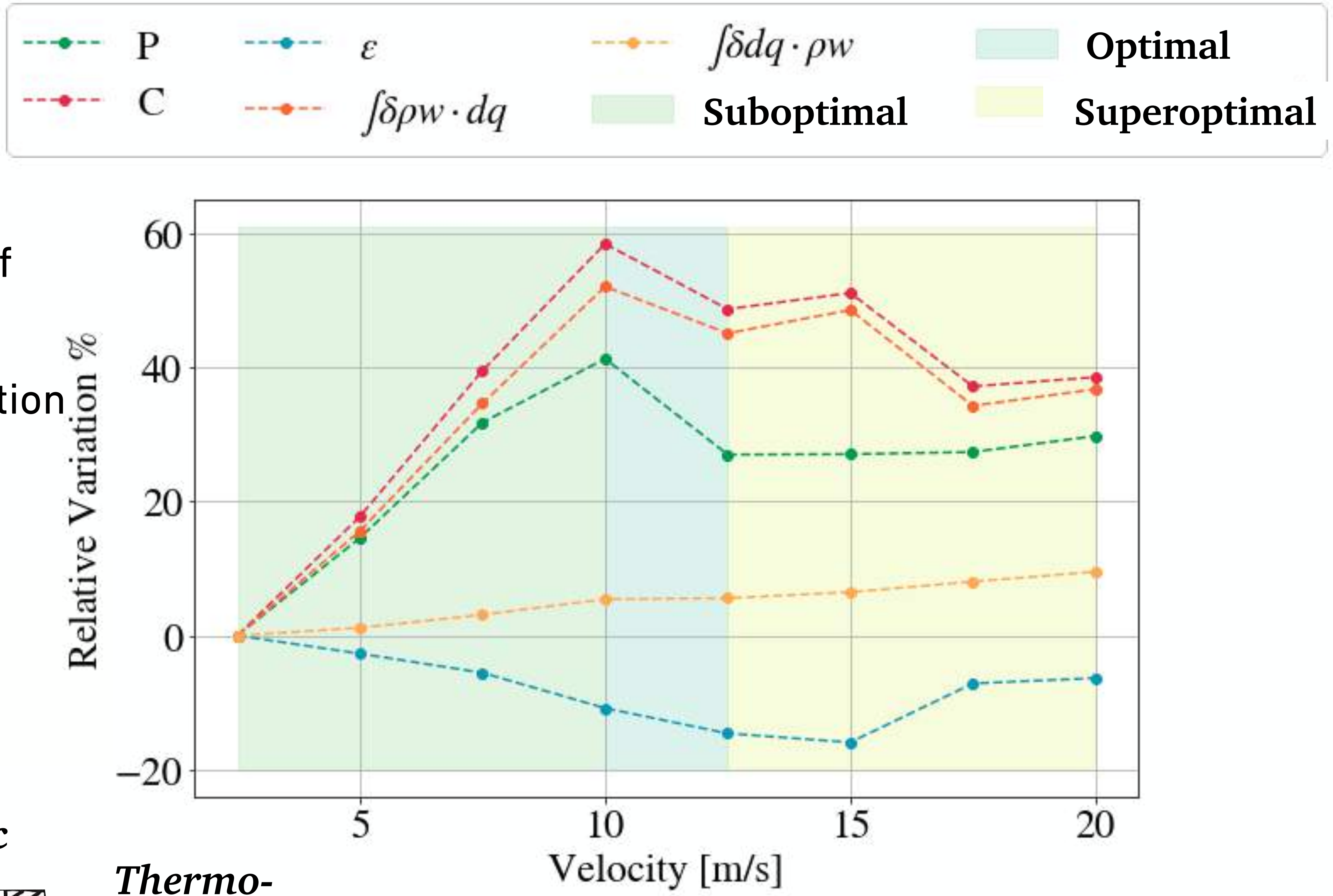
Conclusions

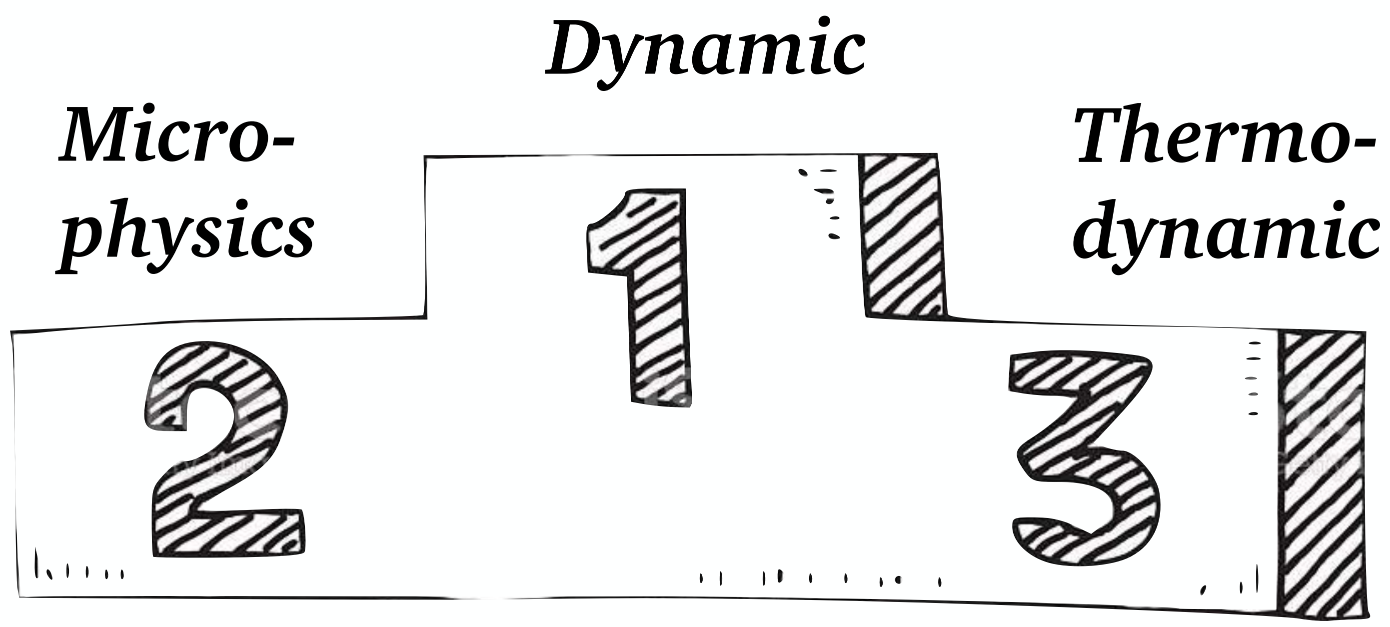
1. Theory of Squall Line Orientation is verified
2. Extremes of Precipitations are sensitive to the regime of development of Squall Lines



Conclusions

1. Theory of Squall Line Orientation is verified
2. Extremes of Precipitations are sensitive to the regime of development of Squall Lines
3. Contributions that mainly explain variations in precipitation extremes are (1) Dynamic, (2) Microphysic and (3) Thermodynamic





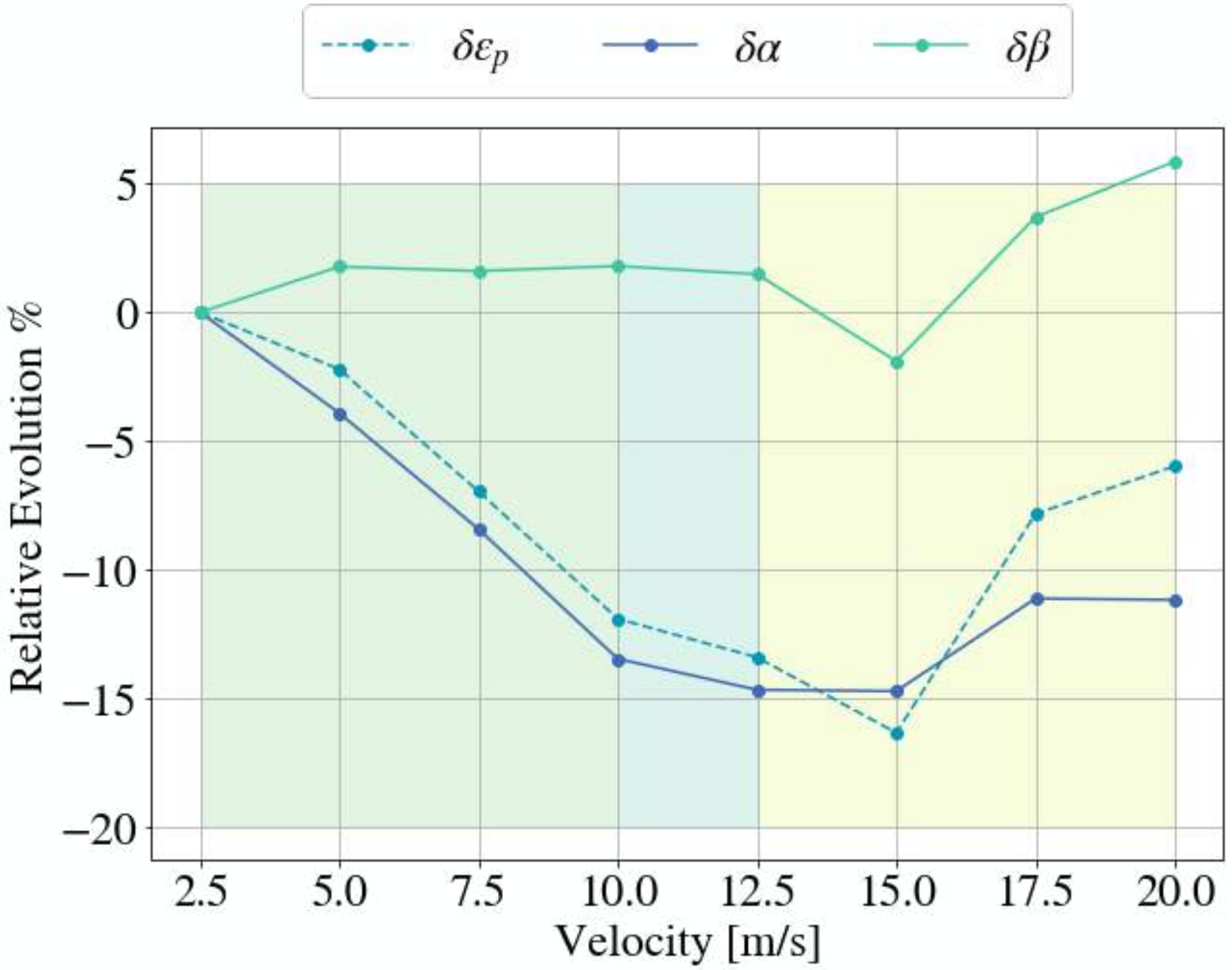
Conclusions

1. Theory of Squall Line Orientation is verified
2. Extremes of Precipitations are sensitive to the regime of development of Squall Lines
3. Contributions that mainly explain variations in precipitation extremes are (1) Dynamic, (2) Microphysic and (3) Thermodynamic
4. Change cloud base velocity (1)

Conclusions

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

1. Theory of Squall Line Orientation is verified
2. Extremes of Precipitations are sensitive to the regime of development of Squall Lines
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)



Oultines

Introduction

*Muller C. & **Abramian S.** 2023, Physics Today*

Part 1

Idealized Simulations

What sets tropical squall lines orientation and why ?

***Abramian S.**, Muller C., Risi C., 2022, GRL*

How does the orientation of the line impact extreme precipitation ?

***Abramian S.**, Muller C., Risi C., 2023, JAMES*

Part 2

Realistic Global Simulations

What sets the maximal extension of MCSs ?

*In Prep. **Abramian S.**, Muller C., Risi C., Roca R., Fiolleau T.,*

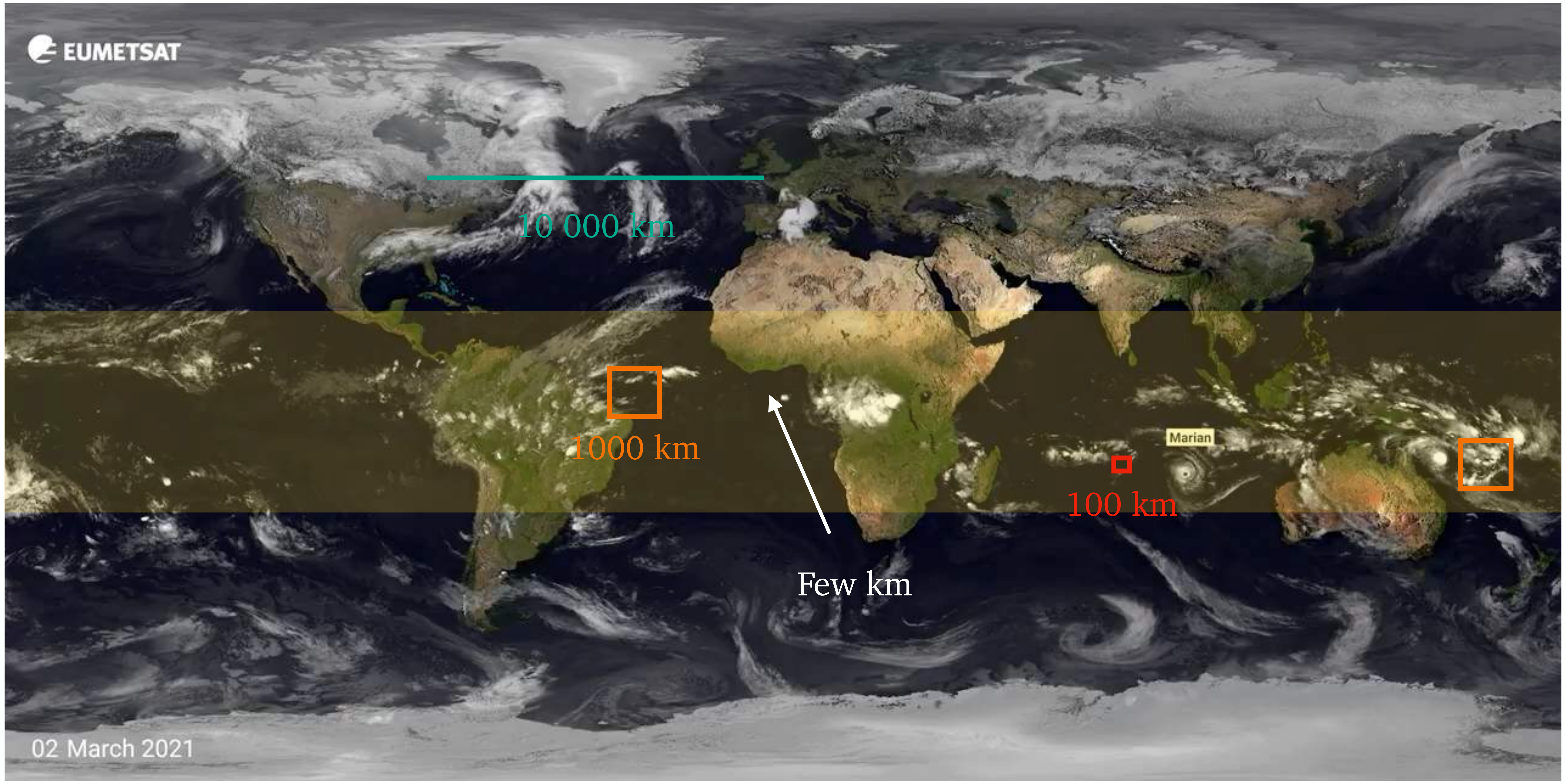
How convective systems are recorded in past climate archive ?

*Risi C., Muller C., Vimeux F., Blossey P., Védeau G., Dufaux C., **Abramian S.**, 2023, JAMES*

Conclusion and Perspectives

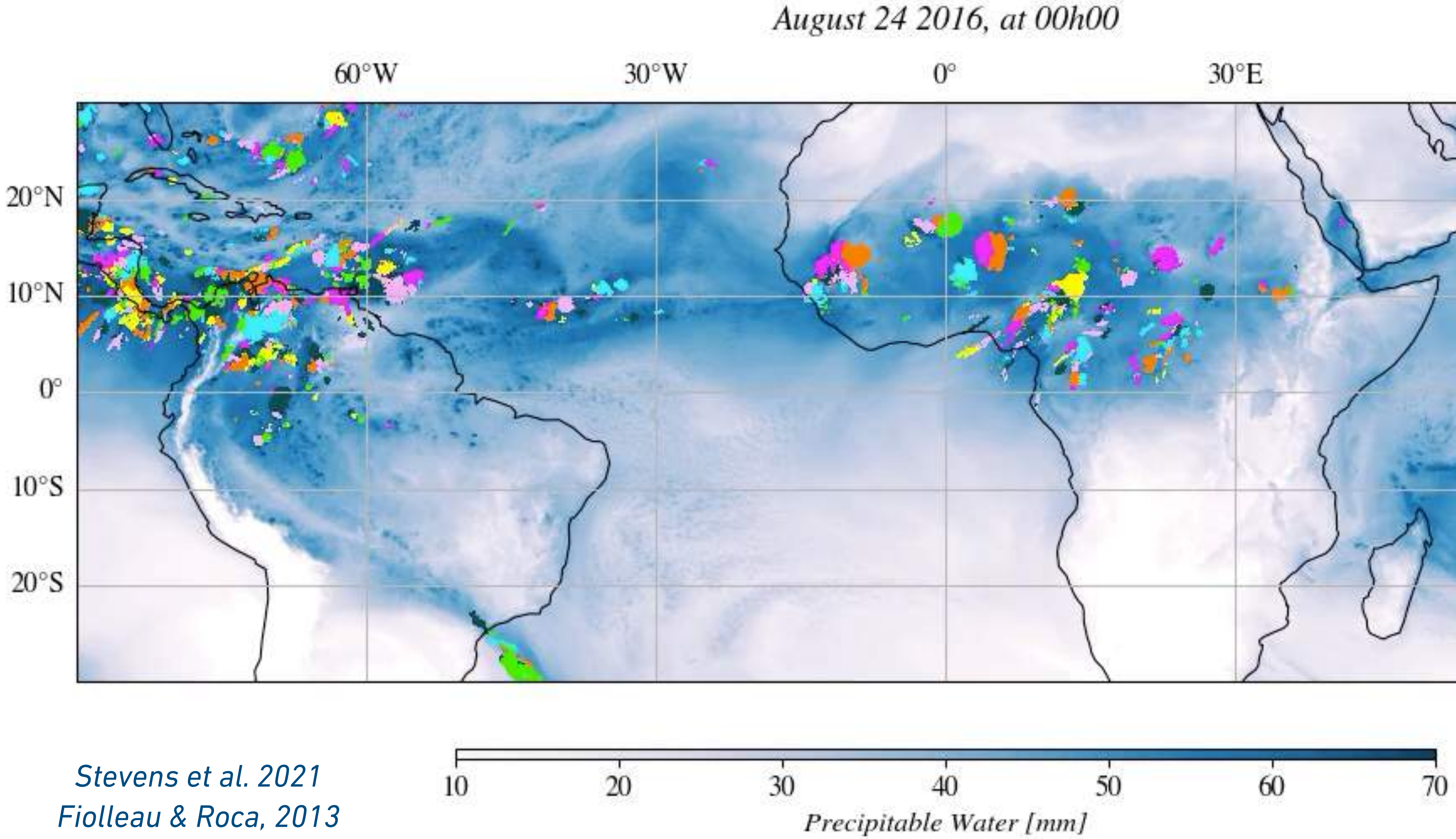
Different scales for Deep Convection Organization

Tropics



Interation between large scale circulation and mesoscale convective organization

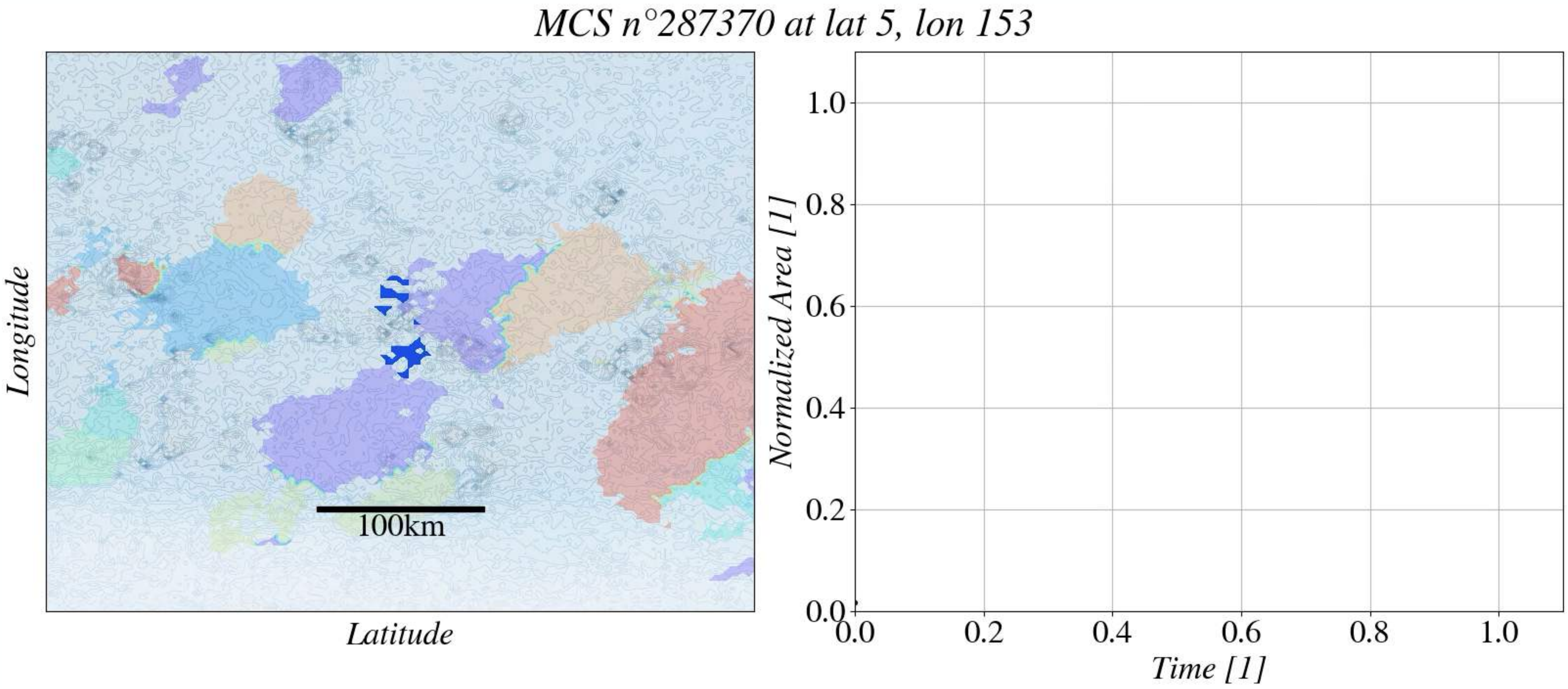
Mesoscale Convective Systems in Global High resolution Simulation DYamond-NextGems



Stevens et al. 2021
Fiolleau & Roca, 2013

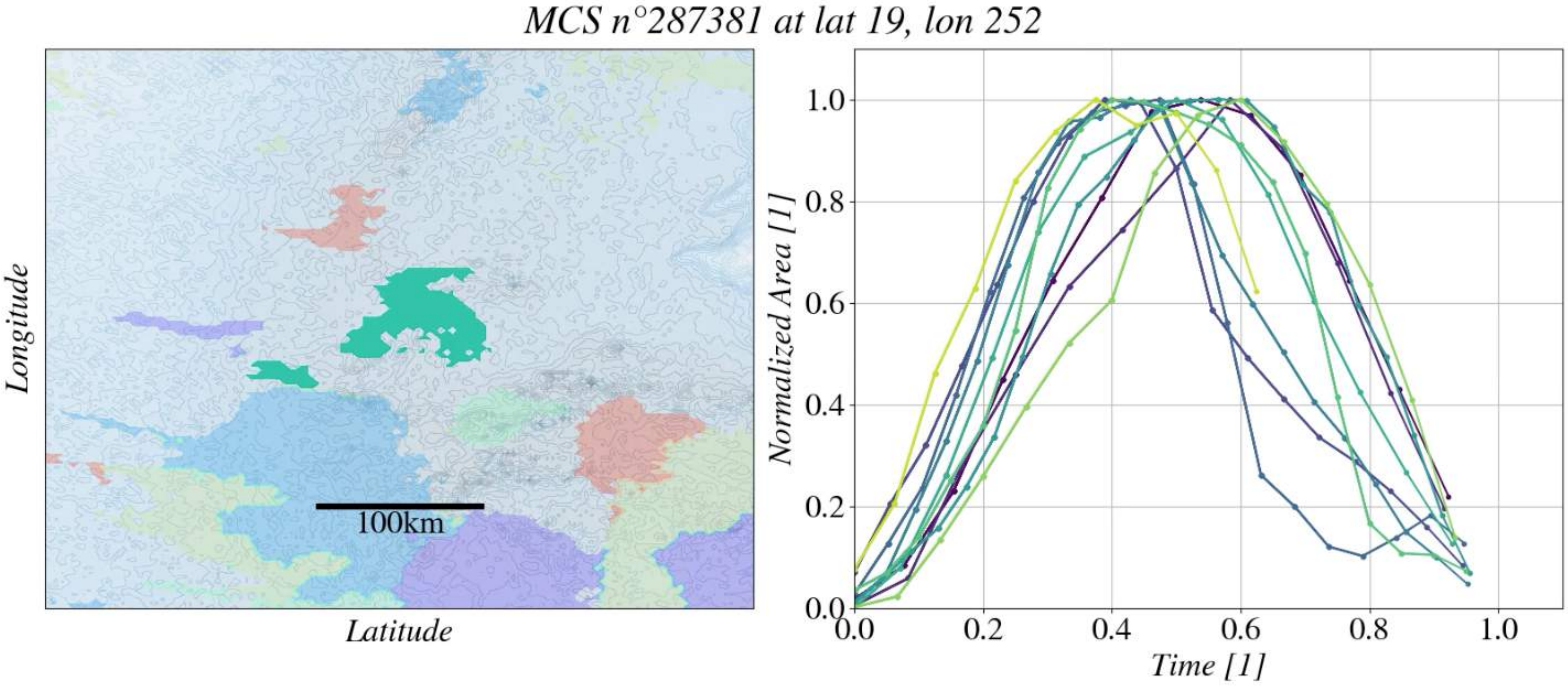
Credit to Ben Fildier!

Life Cycle



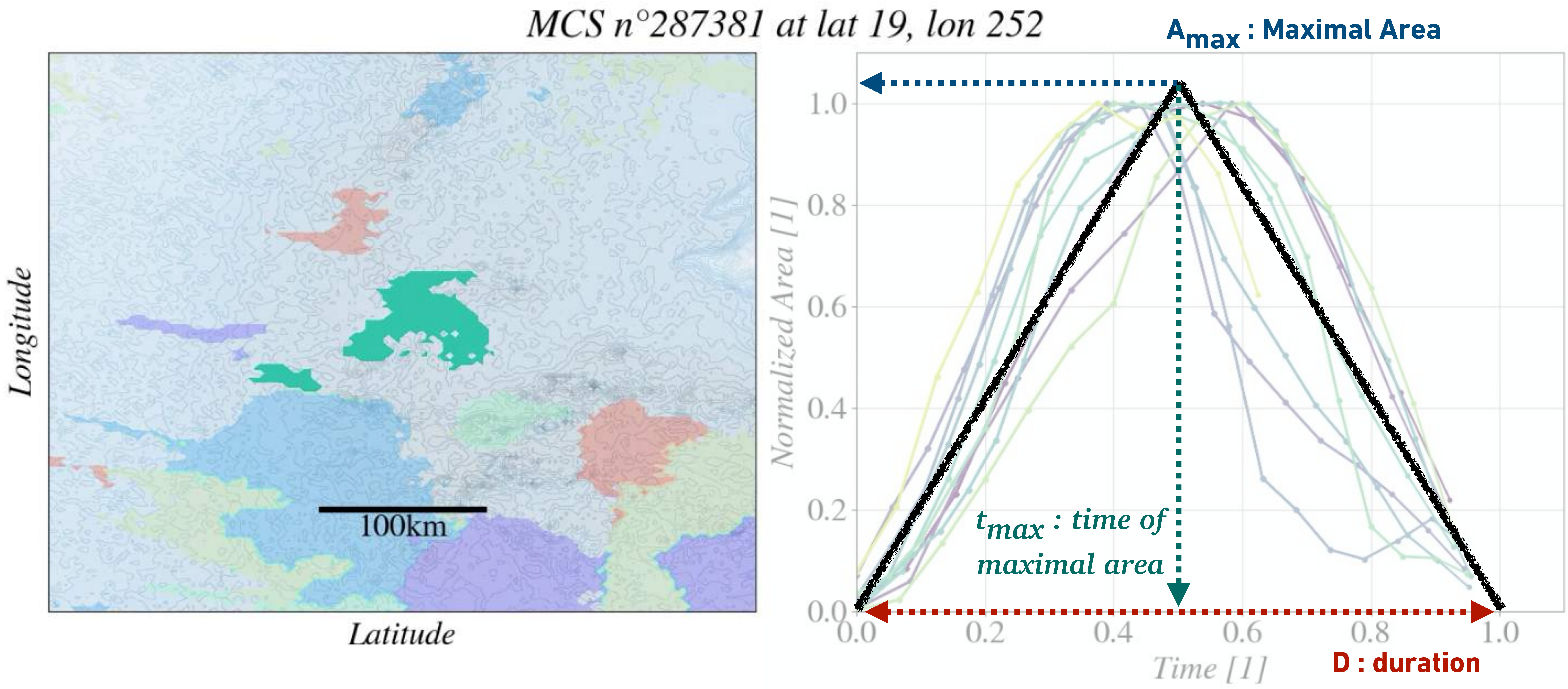
MCS n°287370 at lat 5, lon 153
Longitude
Latitude
100km
Normalized Area [1]
Time [1]
0.0
0.2
0.4
0.6
0.8
1.0

Life Cycle



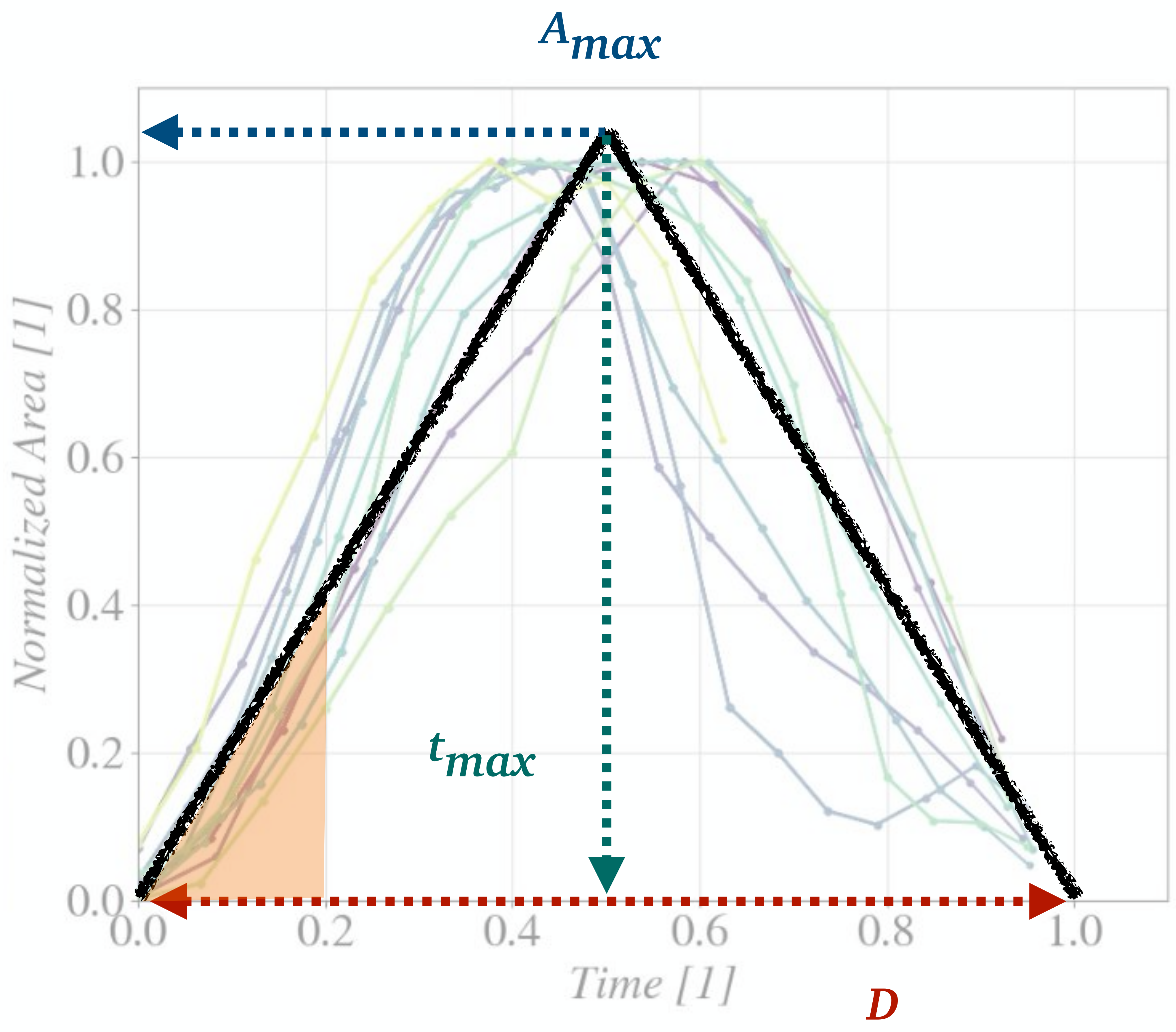
⟶ Similar pattern for all Mesoscale Convective System !

Life Cycle



Roca, Fiolleau, Bouniol 2017, A Simple Model of the Life Cycle of Mesoscale Convective Systems Cloud Shield in the Tropics, Journal of Climate

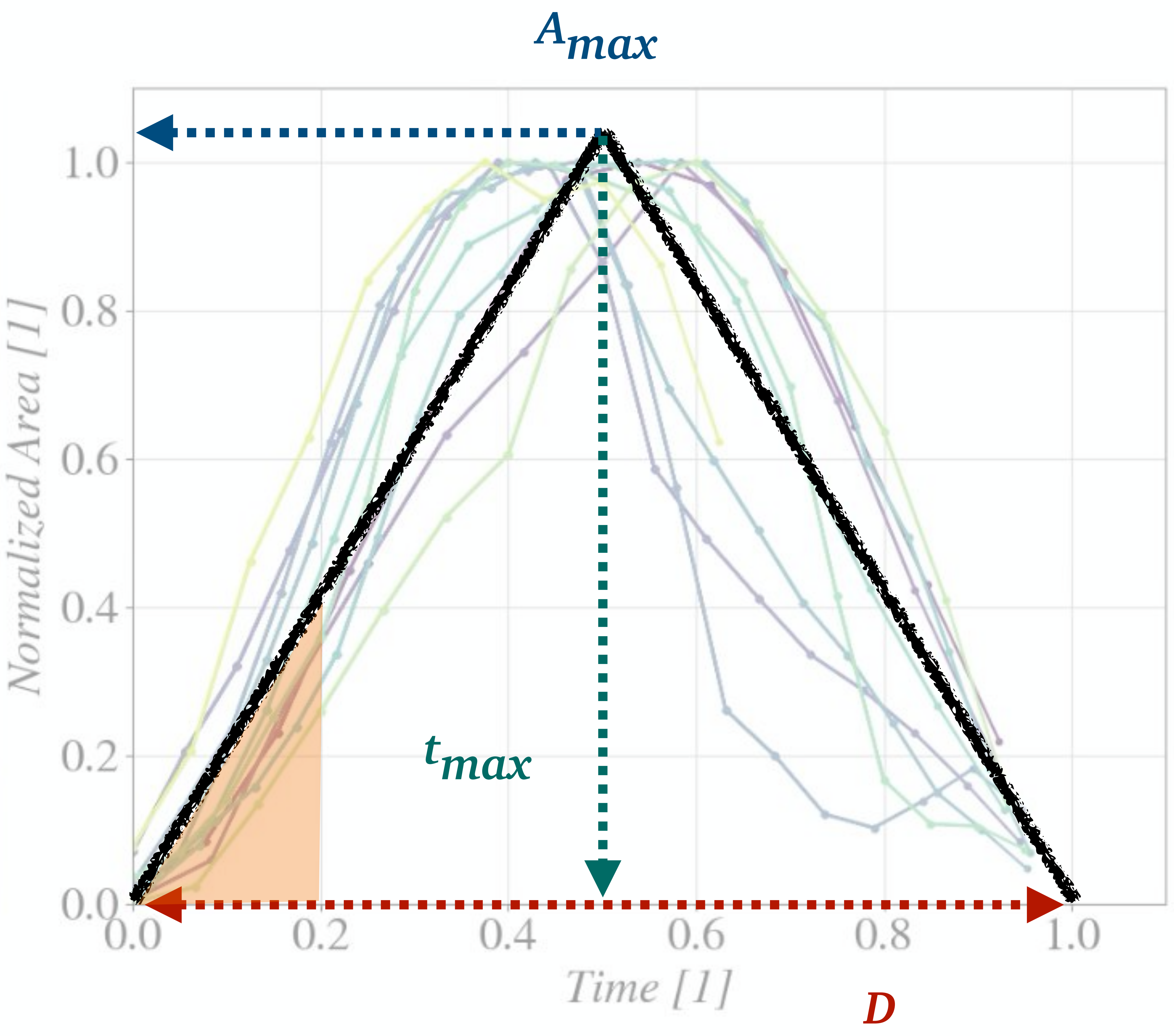
Life Cycle



A_{max}	Maximal Area
t_{max}	Duration of Growth
D	Total Duration

What controls these three parameters ?

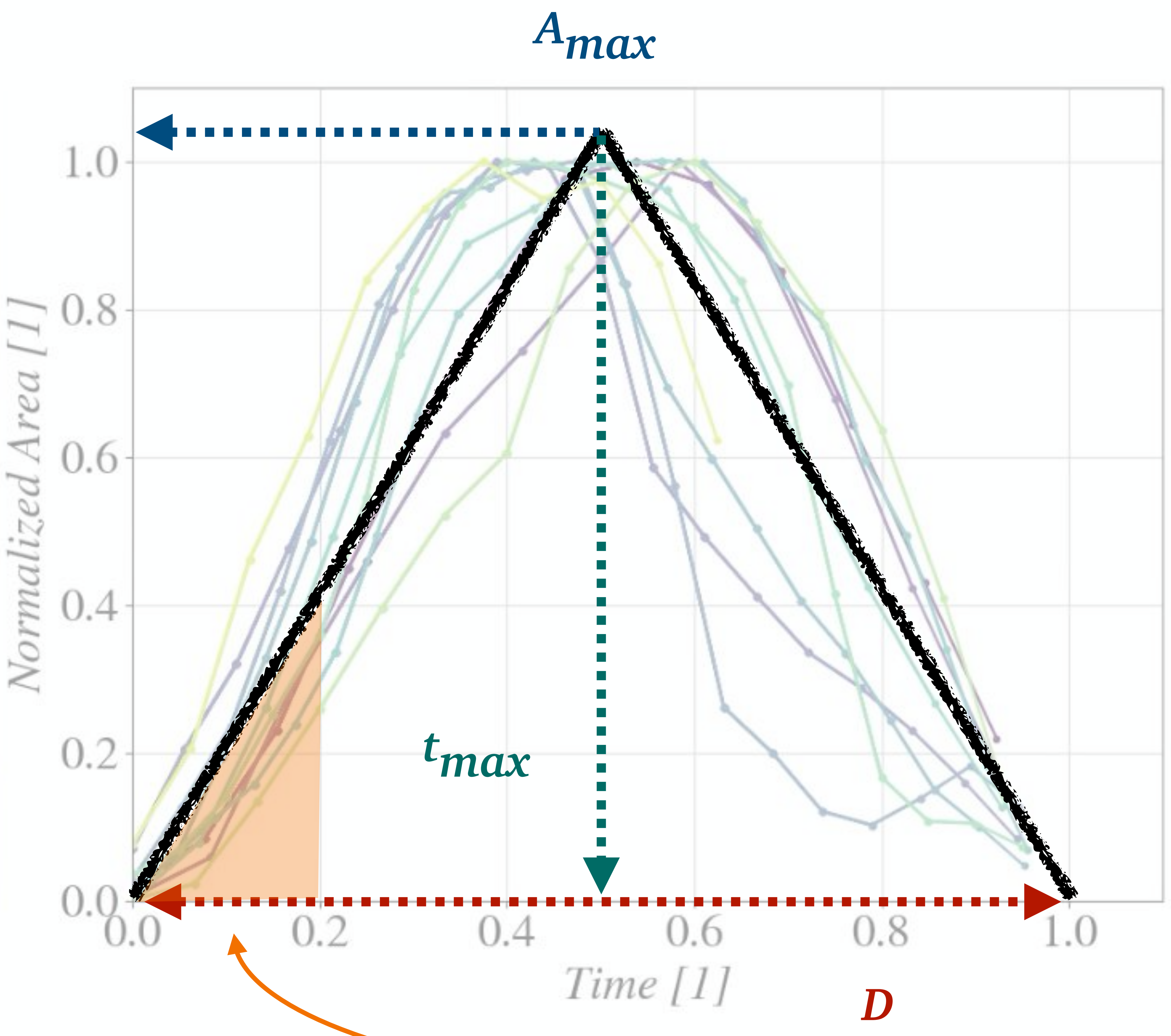
Life Cycle



A_{max}	Maximal Area
t_{max}	Duration of Growth
D	Total Duration

What controls these three parameters ?

Questions

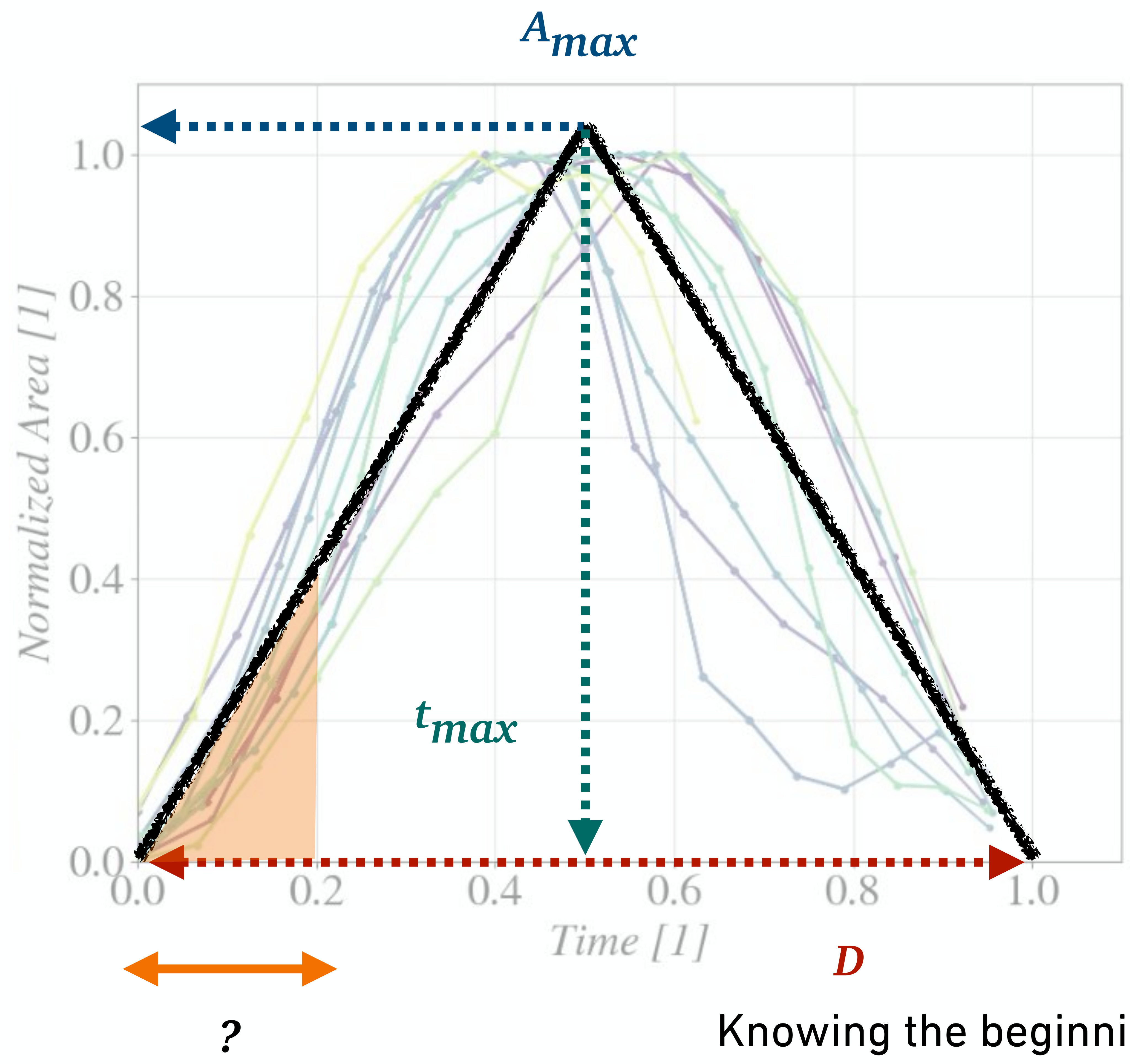


Knowing the beginning of its life cycle can we predict its maximal area?

A_{max}	Maximal Area
t_{max}	Duration of Growth
D	Total Duration

What controls these three parameters ?

Questions



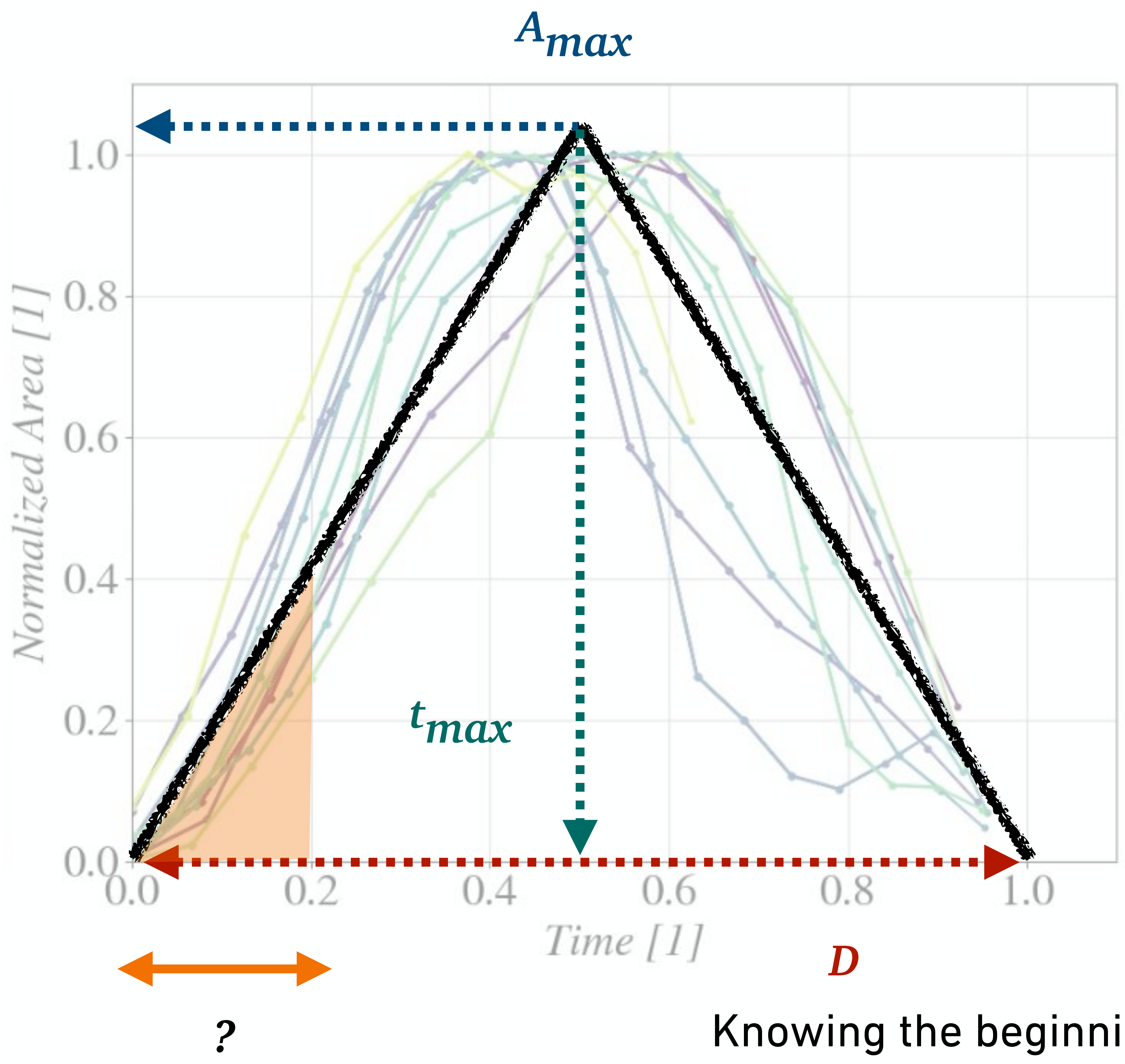
A_{max}	Maximal Area
t_{max}	Duration of Growth
D	Total Duration

What controls these three parameters ?

Knowing the beginning of its life cycle can we predict its maximal area?

How sensitive to the observed period the prediction is ?

Questions



A_{max}	Maximal Area
t_{max}	Duration of Growth
D	Total Duration

What controls these three parameters ?

Knowing the beginning of its life cycle can we predict its maximal area?

How sensitive to the observed period the prediction is ?

Is it the system or the environment that accounts for the prediction ? Why ?

Questions

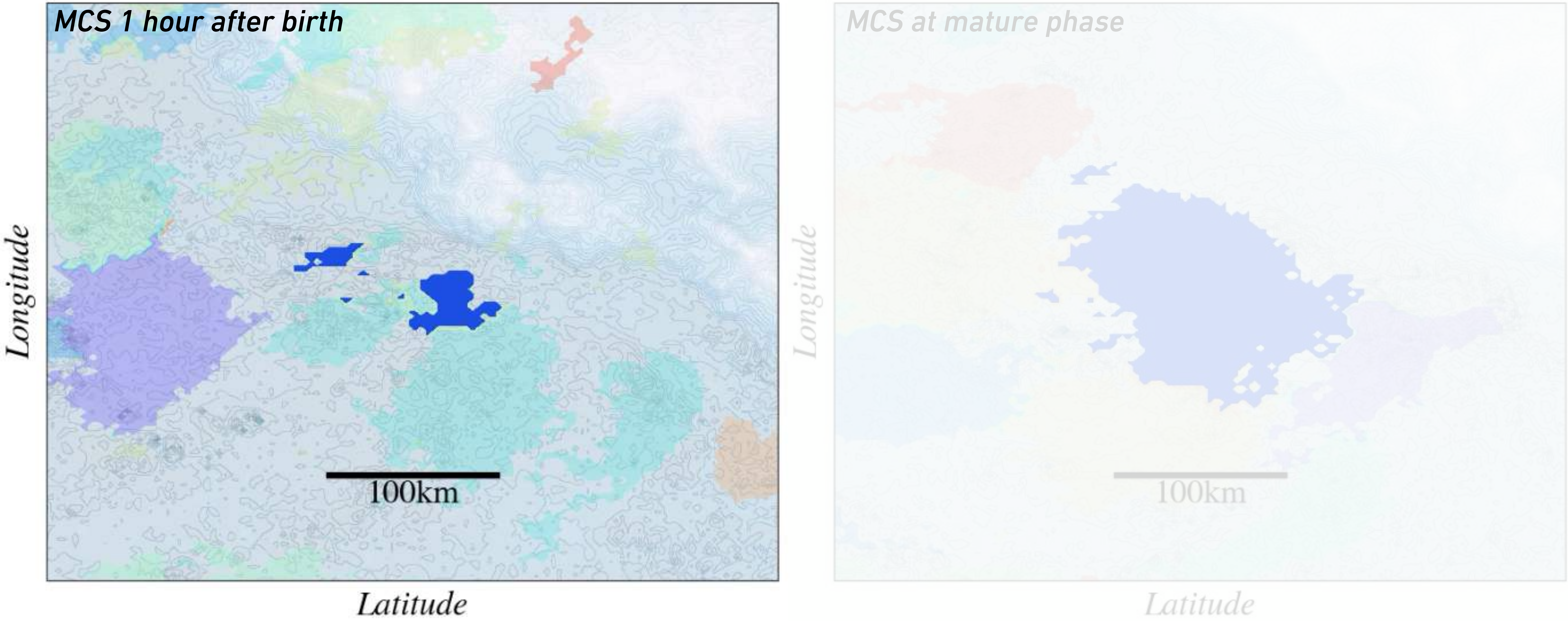
Has the life of the MCS been written from the start? if so, when exactly?

Are there individual, innate characteristics that will shape it, or does it depend on its environment?

Questions

Has the life of the MCS been written from the start? if so, when exactly?

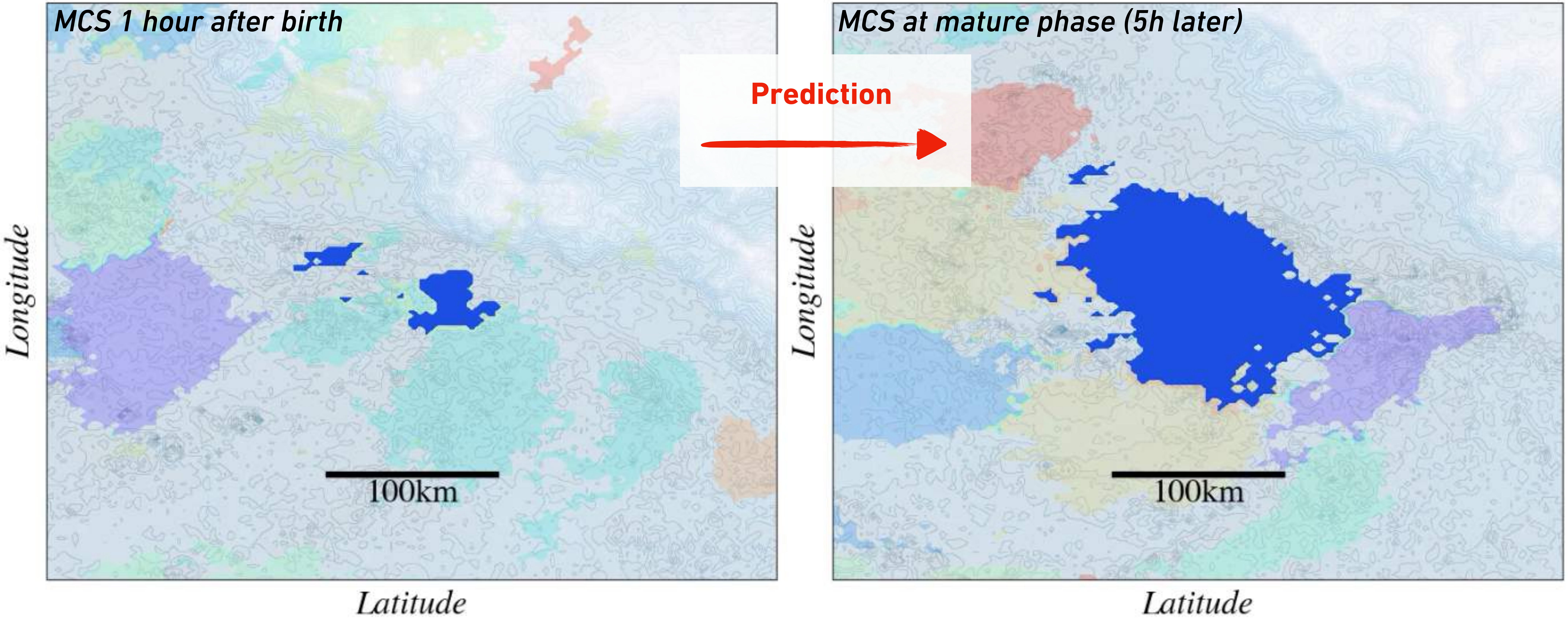
Are there individual, innate characteristics that will shape it, or does it depend on its environment?



Questions

Has the life of the MCS been written from the start? if so, when exactly?

Are there individual, innate characteristics that will shape it, or does it depend on its environment?



Questions

Has the life of the MCS been written from the start? if so, when exactly?

Are there individual, innate characteristics that will shape it, or does it depend on its environment?

Method

Using Machine Learning

Early growth features →

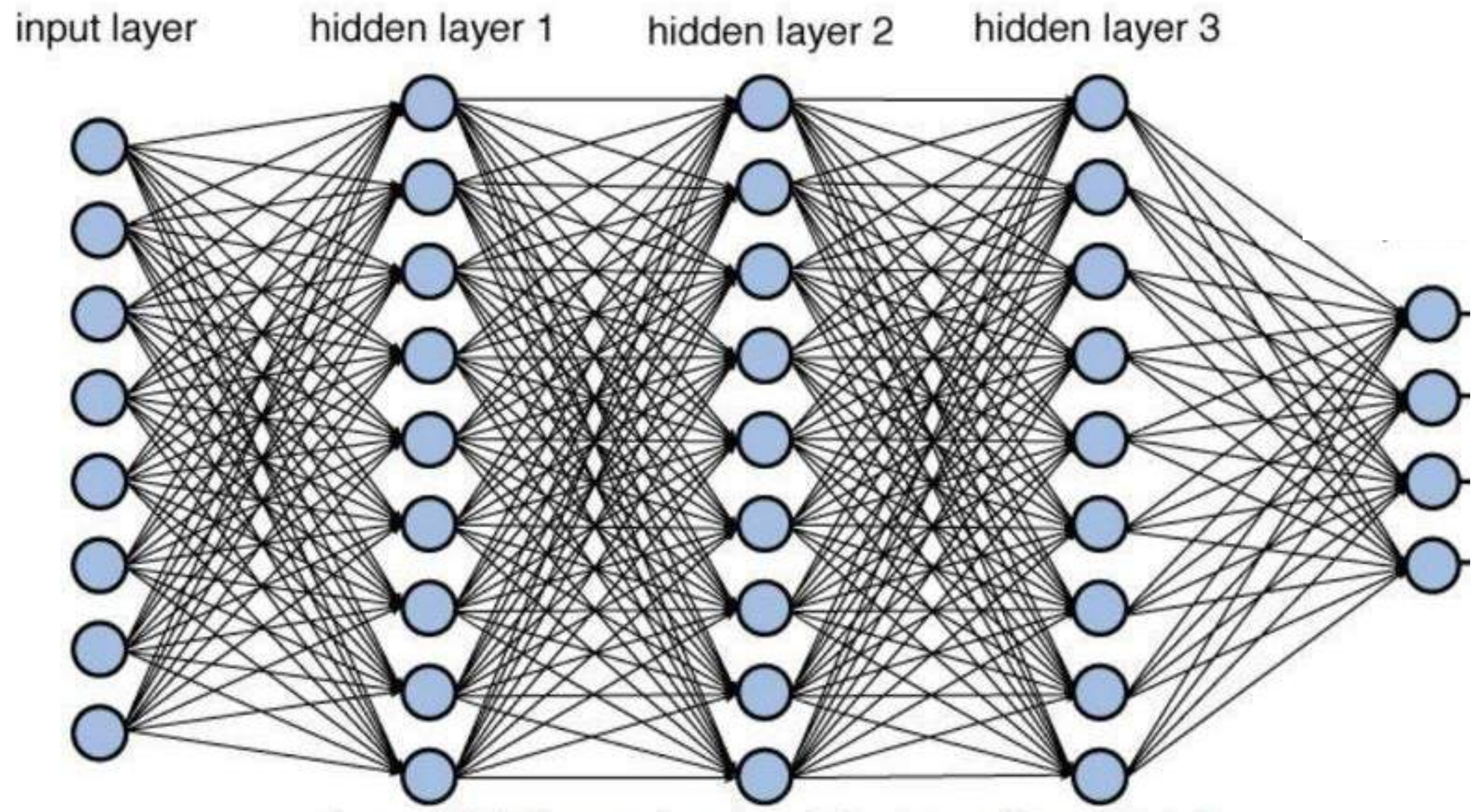


Figure 12.2 Deep network architecture with multiple layers.

→ Maximal Extension

$$\sqrt{A_{max}}$$

Questions

Has the life of the MCS been written from the start? if so, when exactly?

Are there individual, innate characteristics that will shape it, or does it depend on its environment?

Method Using Machine Learning

$$\sqrt{A_{max}}$$

Early growth features →

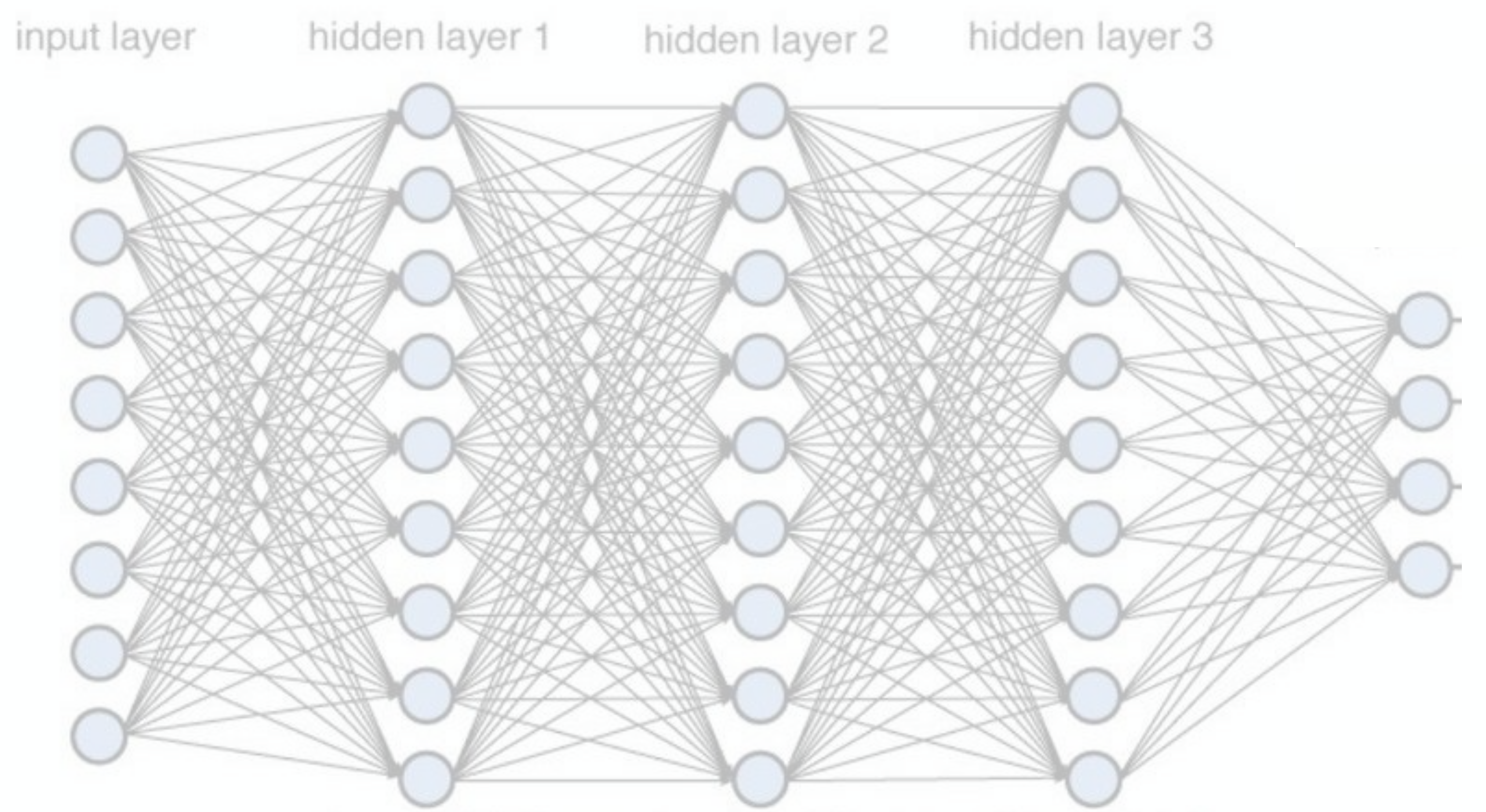
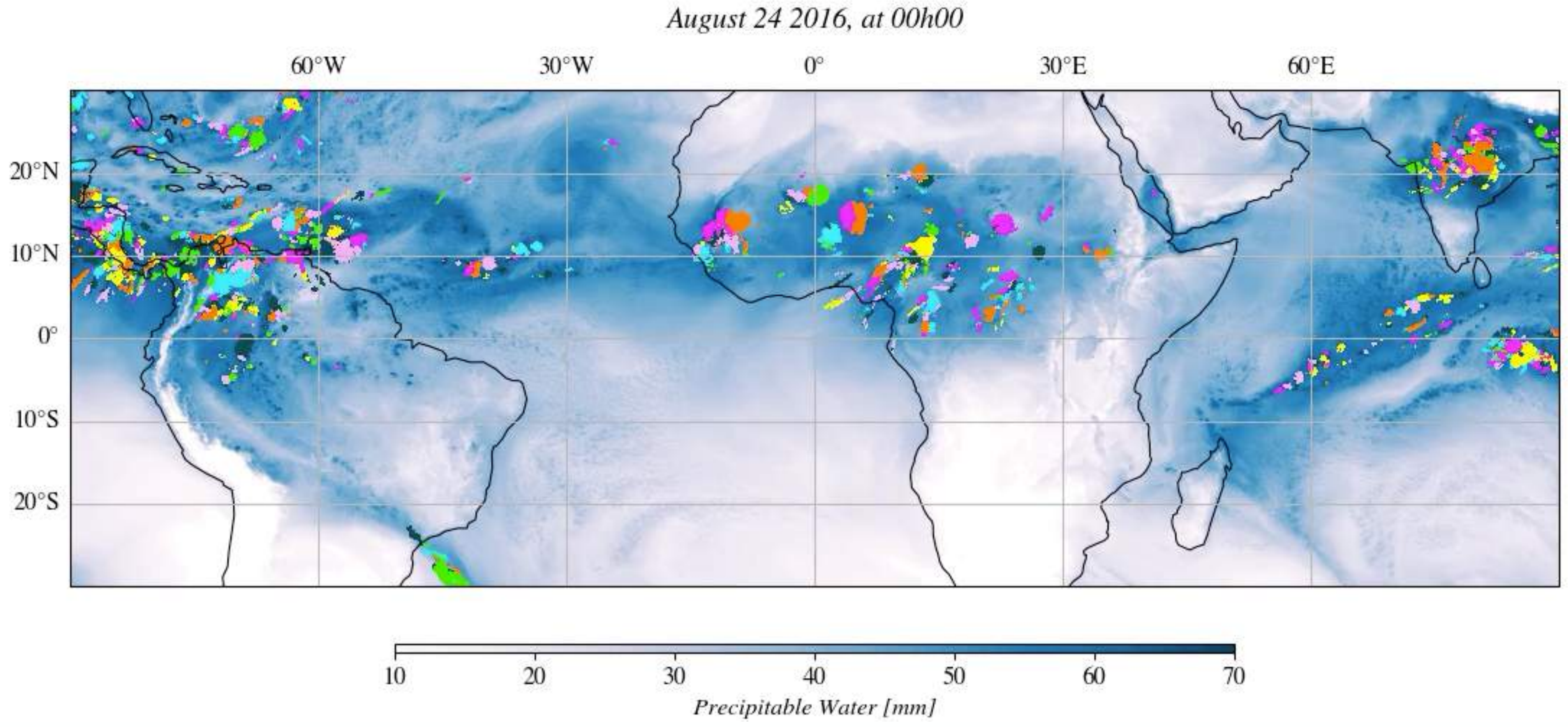


Figure 12.2 Deep network architecture with multiple layers.

→ Maximal Extension

Dataset



<u>*Initial dataset :*</u>

- *nb of systems : 50 000*
- *4km of resolution*
- *1 months with time resolution = 30 min*
- *2D variables from DYamond data*

DKRZ DEUTSCHES KLIMARECHENZENTRUM

<u>*Only in the tropics, minimal duration and size*</u>

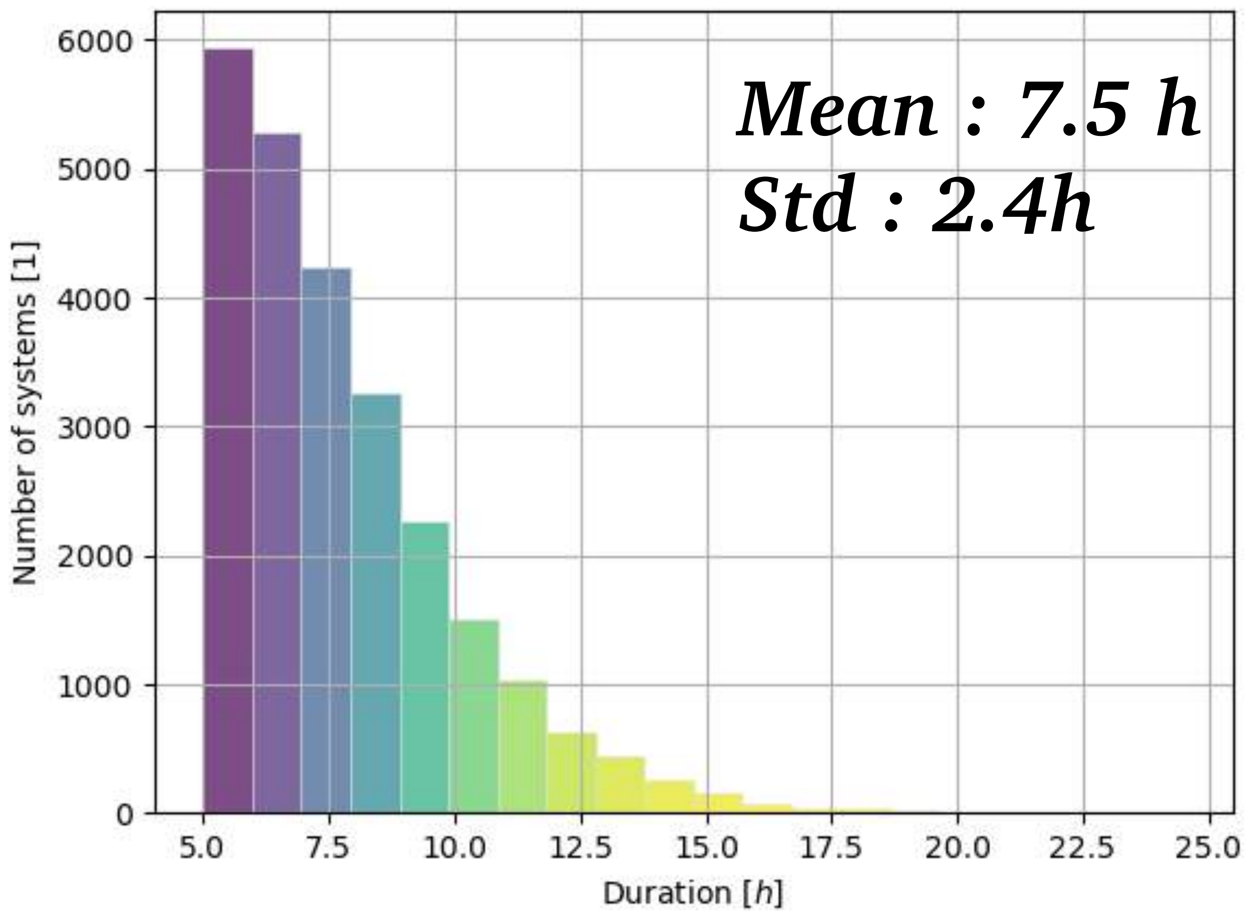
+/- 30° in latitude

Minimal duration of 5h

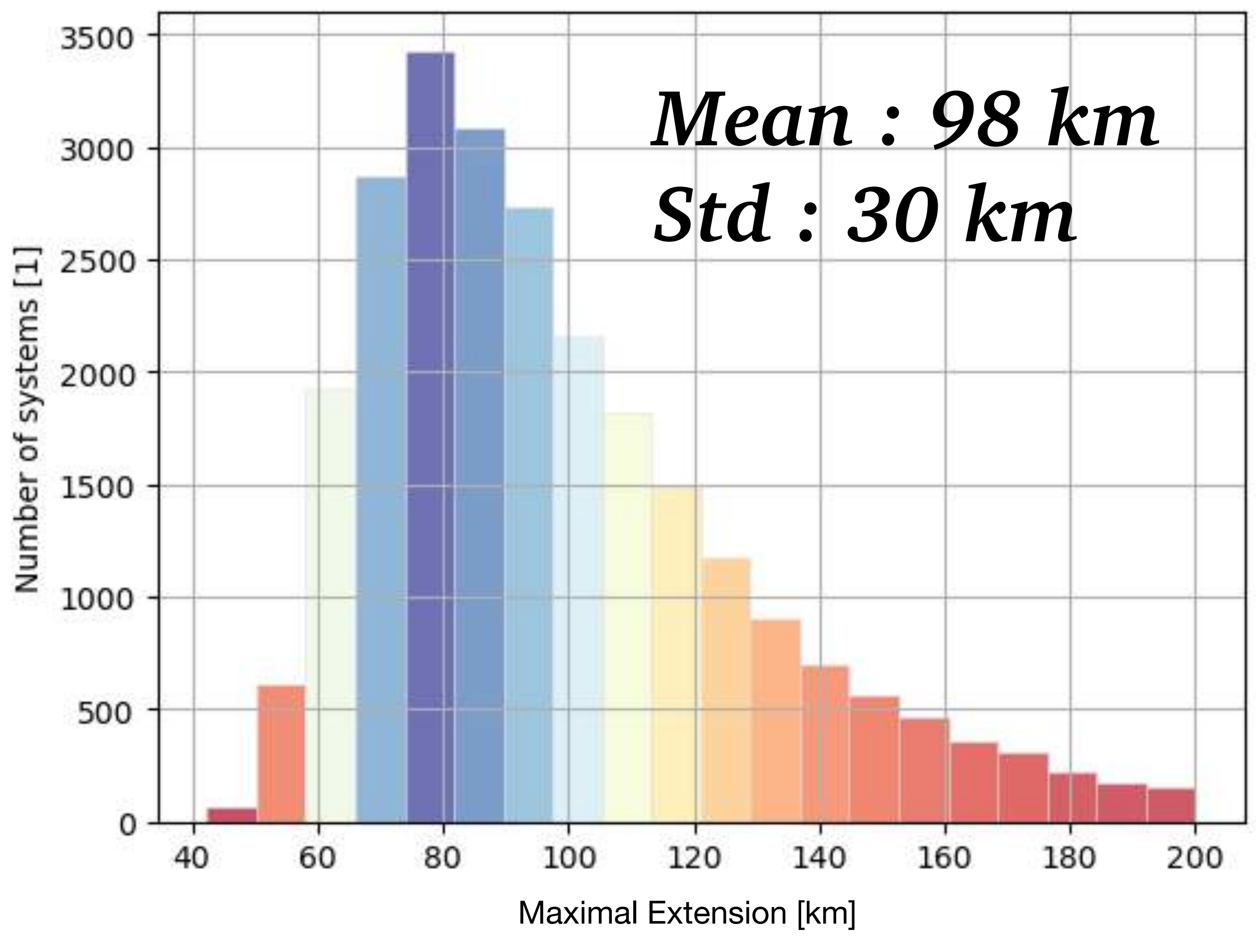
Minimal size of 40 km

Active life cycle

Distribution of MCS duration



Distribution of MCS maximal extension



Preprocessed dataset : nb of systems = 30 000

Dataset

All the systems ~ 30 000 MCS

Train Dataset | Validation Dataset | Test Dataset

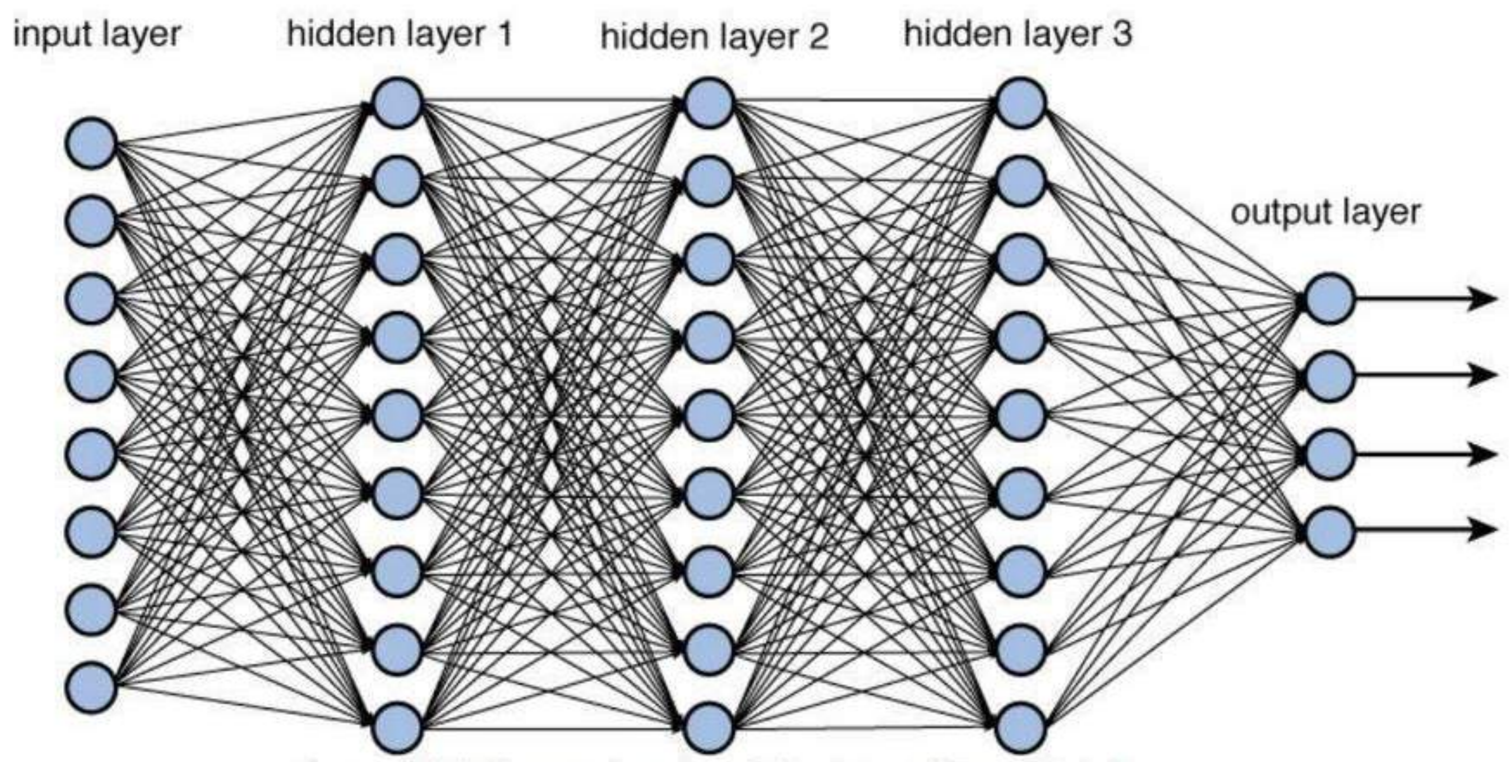


Figure 12.2 Deep network architecture with multiple layers.

Iterative process to optimize the weight of the model for a specific task

Infer the model on unknown data to evaluate the model

Questions

Has the life of the MCS been written from the start? if so, when exactly?

Are there individual, innate characteristics that will shape it, or does it depend on its environment?

Method

Using Machine Learning

$\sqrt{A_{max}}$

Early growth features →

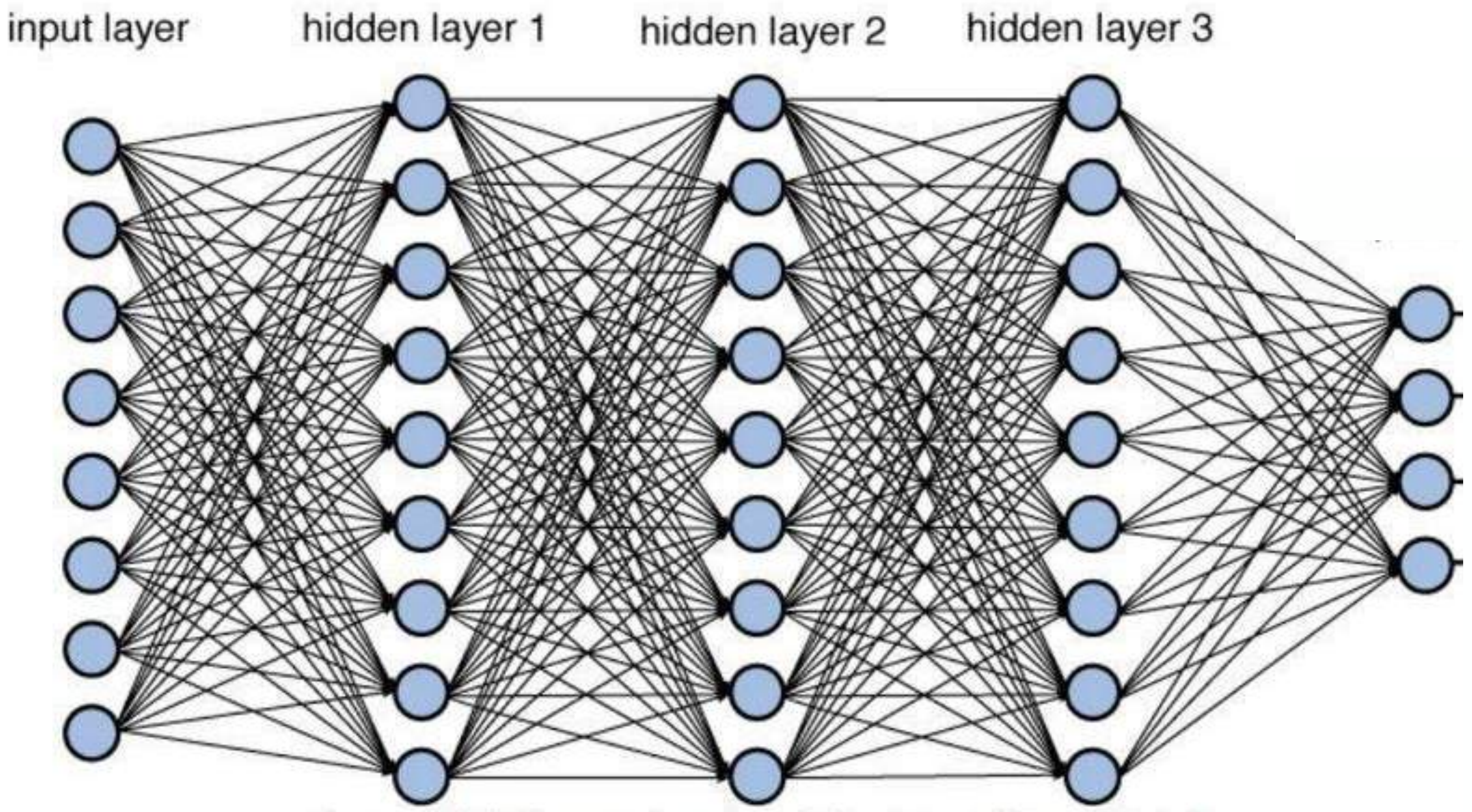
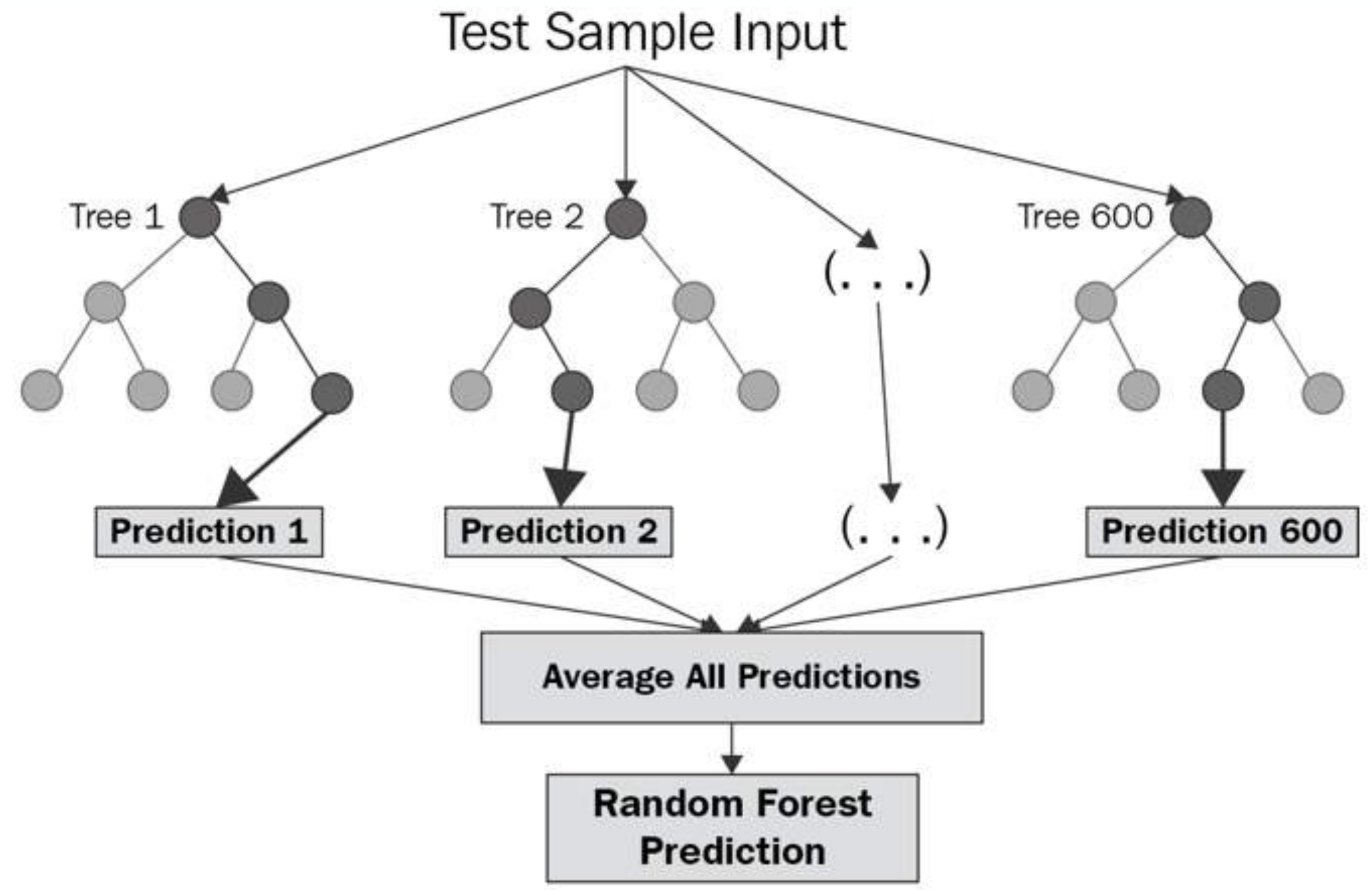


Figure 12.2 Deep network architecture with multiple layers.

→ Maximal Extension

Machine Learning Models

Random Forest Regressor



$$\sqrt{\mathscr{A}_{max}} = RF(x_1, x_2, \ldots, x_n)$$

Multi-linear model (Lasso)

$$Y = M \cdot X$$

Regularization of weight

$$\sqrt{\mathscr{A}_{max}} = \mathscr{L}(x_1, x_2, \ldots, x_n)$$
$$= c_1x_1 + c_2x_2 + .. + c_nx_n$$

Neural Network

$$Y = M(X) \cdot X$$

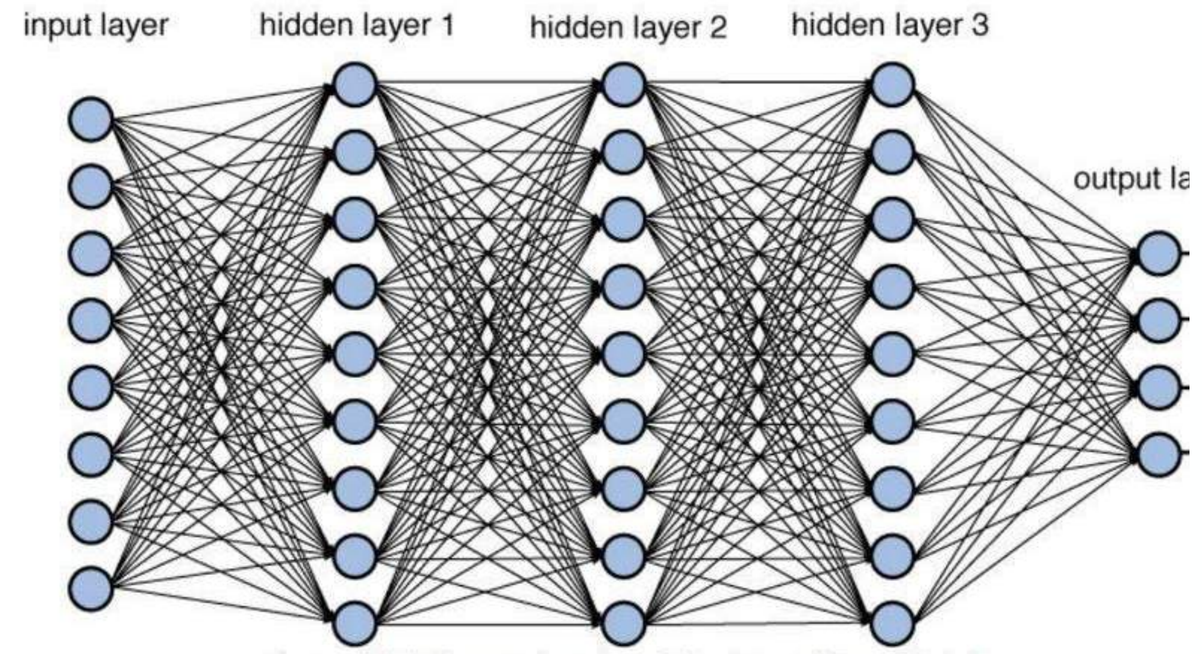
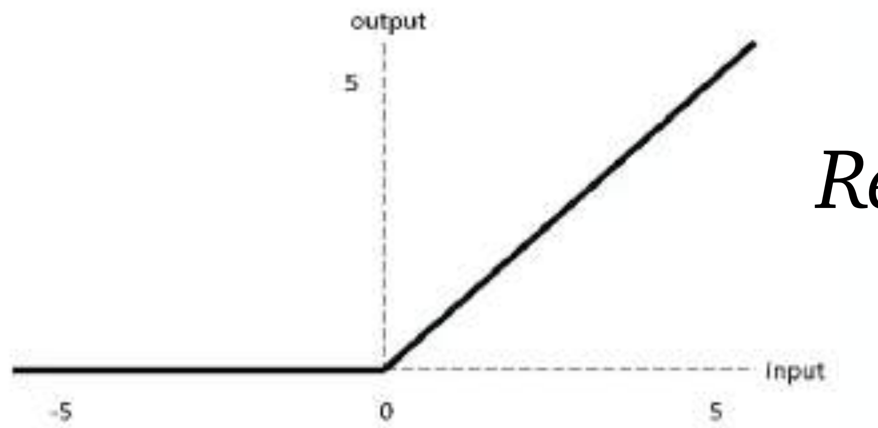


Figure 12.2 Deep network architecture with multiple layers.



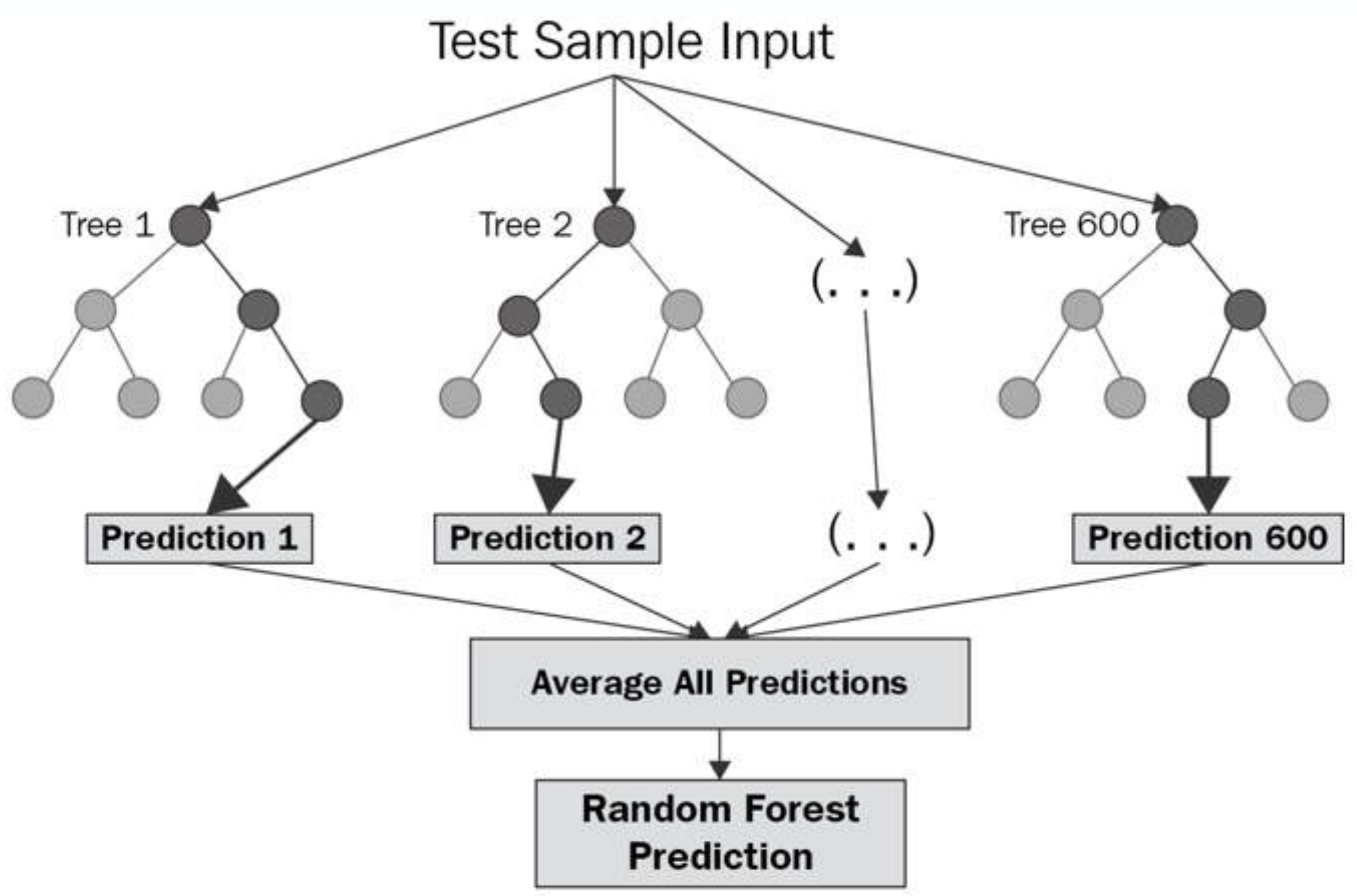
ReLu function

$$\sqrt{\mathscr{A}_{max}} = NN(x_1, x_2, \ldots, x_n)$$
$$= \sigma_1(x_1)w_1x_1 + \sigma_2(x_2)w_2x_2 + .. + \sigma_n(x_n)w_nx_n$$

Machine Learning Models

Random Forest Regressor	*Multi-linear model (Lasso)*	*Neural Network*

Easy to interpret



$$\sqrt{\mathscr{A}_{max}} = RF(x_1, x_2, \ldots, x_n)$$

$$Y = M \cdot X$$

Regularization of weight

$$\sqrt{\mathscr{A}_{max}} = \mathscr{L}(x_1, x_2, \ldots, x_n)$$
$$= c_1x_1 + c_2x_2 + .. + c_nx_n$$

$$Y = M(X) \cdot X$$

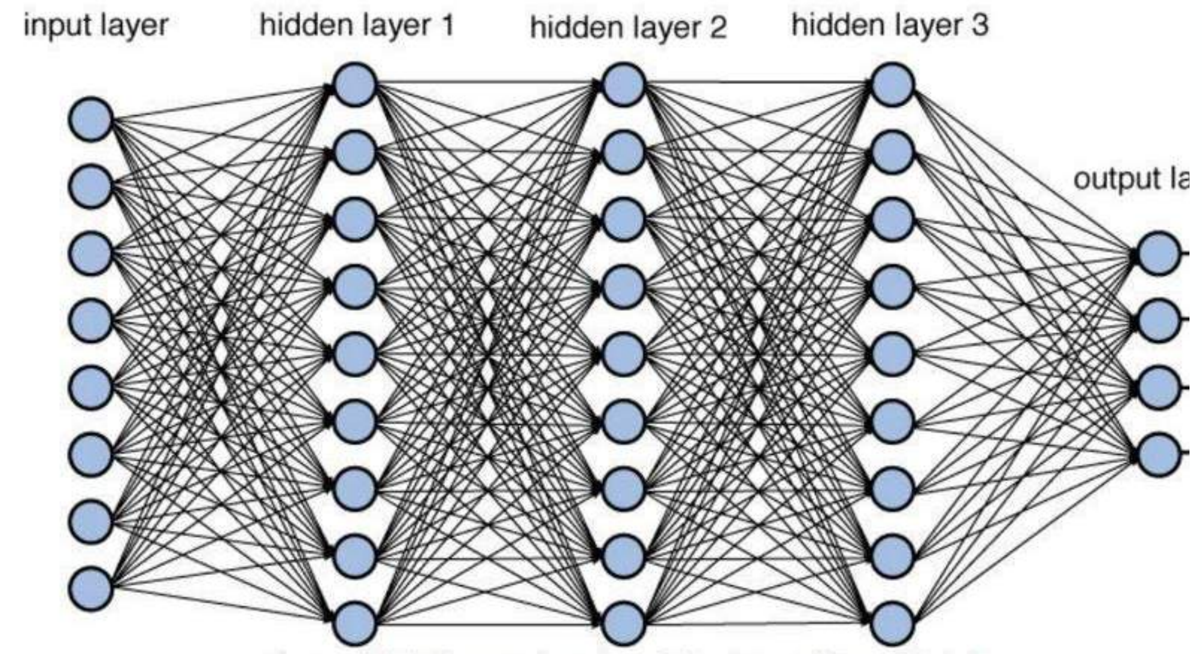
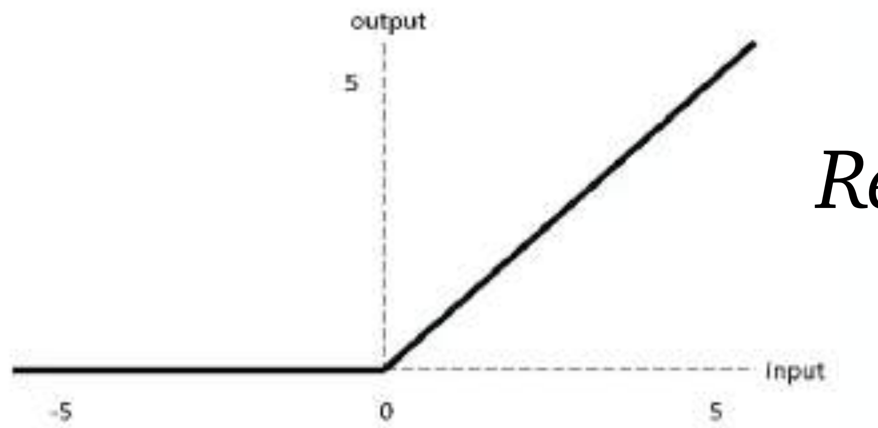


Figure 12.2 Deep network architecture with multiple layers.



ReLu function

$$\sqrt{\mathscr{A}_{max}} = NN(x_1, x_2, \ldots, x_n)$$
$$= \sigma_1(x_1)w_1x_1 + \sigma_2(x_2)w_2x_2 + .. + \sigma_n(x_n)w_nx_n$$

Questions

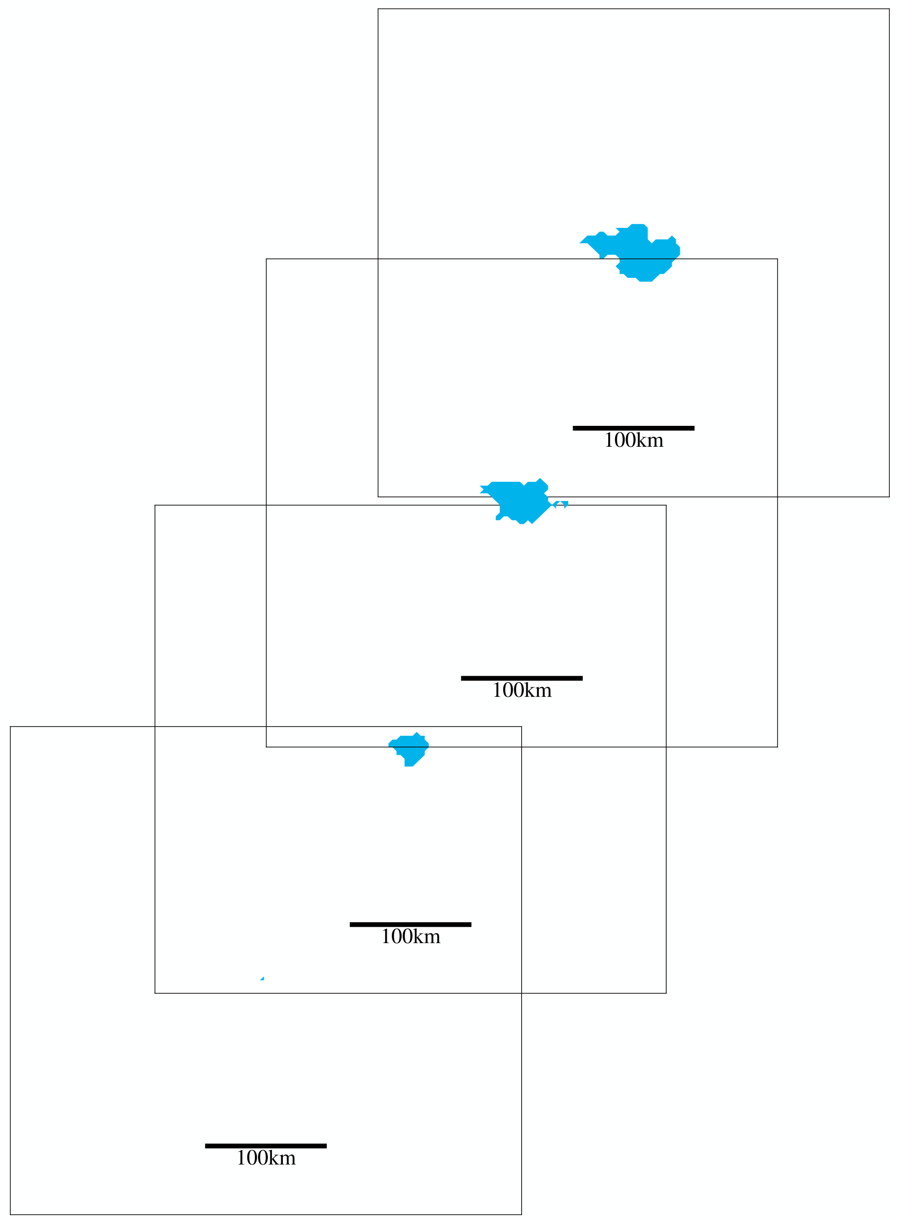
Has the life of the MCS been written from the start?

if so, when exactly?

Are there individual, innate characteristics that will shape it,
or does it depend on its environment?

First Experiment: Baseline

Growth rate : $$r(t) = \frac{A(t) - A(t - \Delta t)}{\Delta t}$$



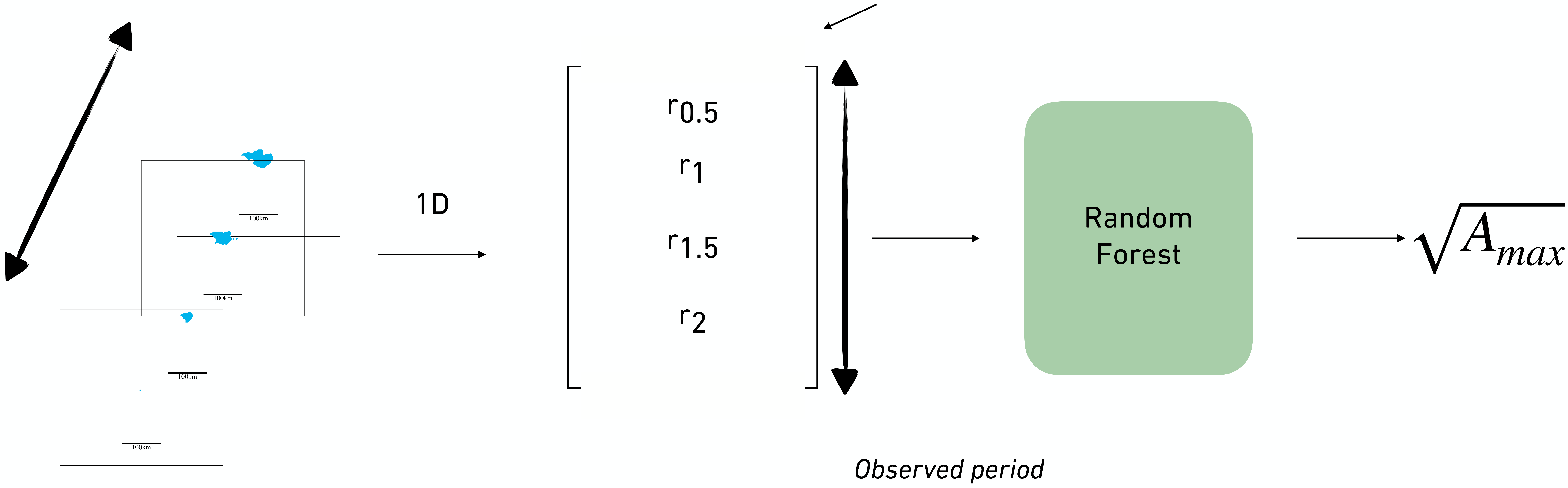
1D →

$$\begin{bmatrix} r_{0.5} \\ r_{1} \\ r_{1.5} \\ r_{2} \end{bmatrix}$$

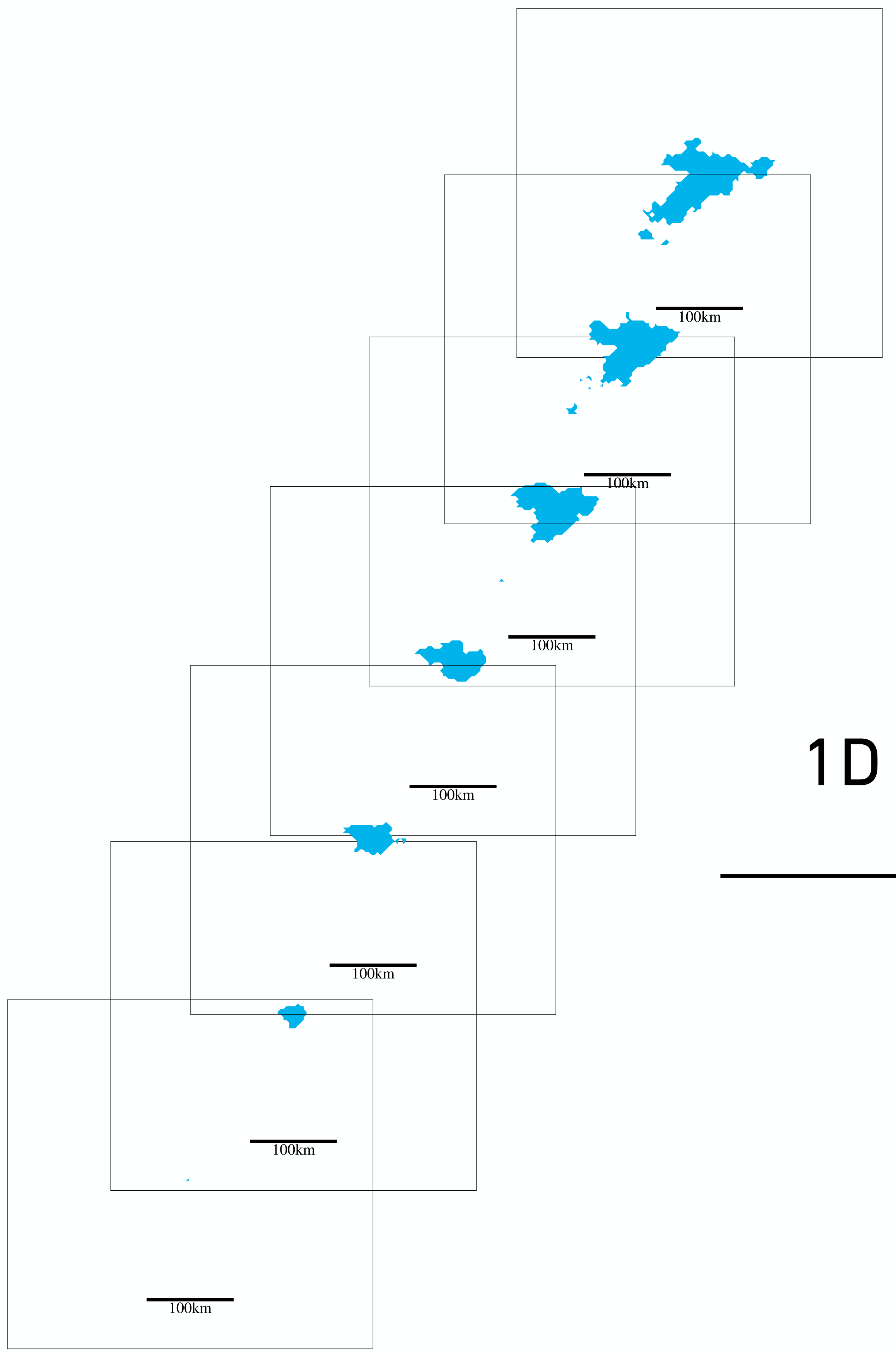
→ Random Forest → $\sqrt{A_{max}}$

First Experiment: Baseline

Growth rate : $$r(t) = \frac{A(t) - A(t - \Delta t)}{\Delta t}$$



First Experiment: Baseline



1D →

Growth rate : $$r(t) = \frac{A(t) - A(t - \Delta t)}{\Delta t}$$

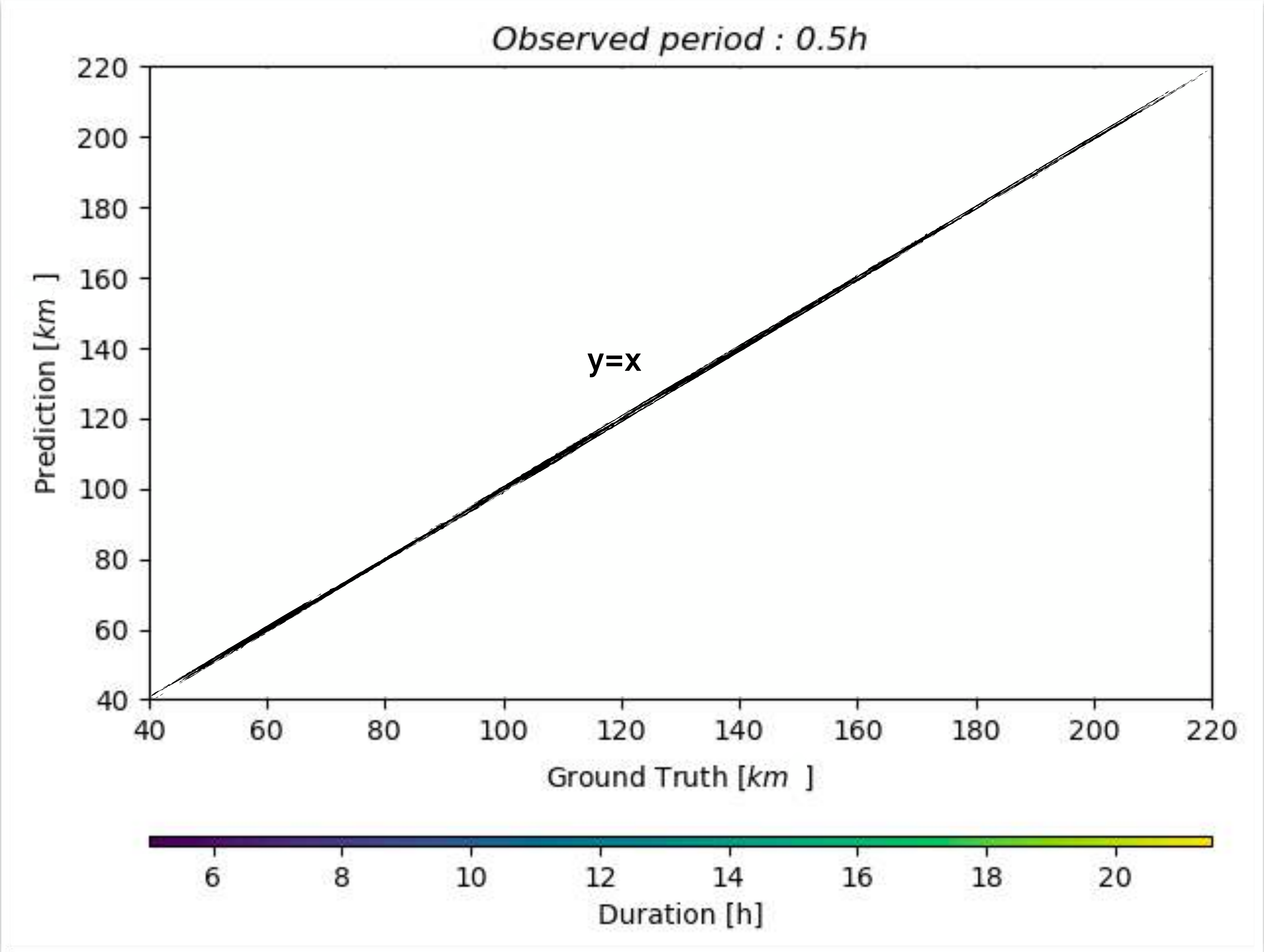
$$\begin{bmatrix} r_{0.5} \\ r_{1} \\ r_{1.5} \\ r_{2} \\ r_{2.5} \\ \ldots \\ r_{4.5h} \end{bmatrix}$$

Observed period

→ Random Forest → $\sqrt{A_{max}}$

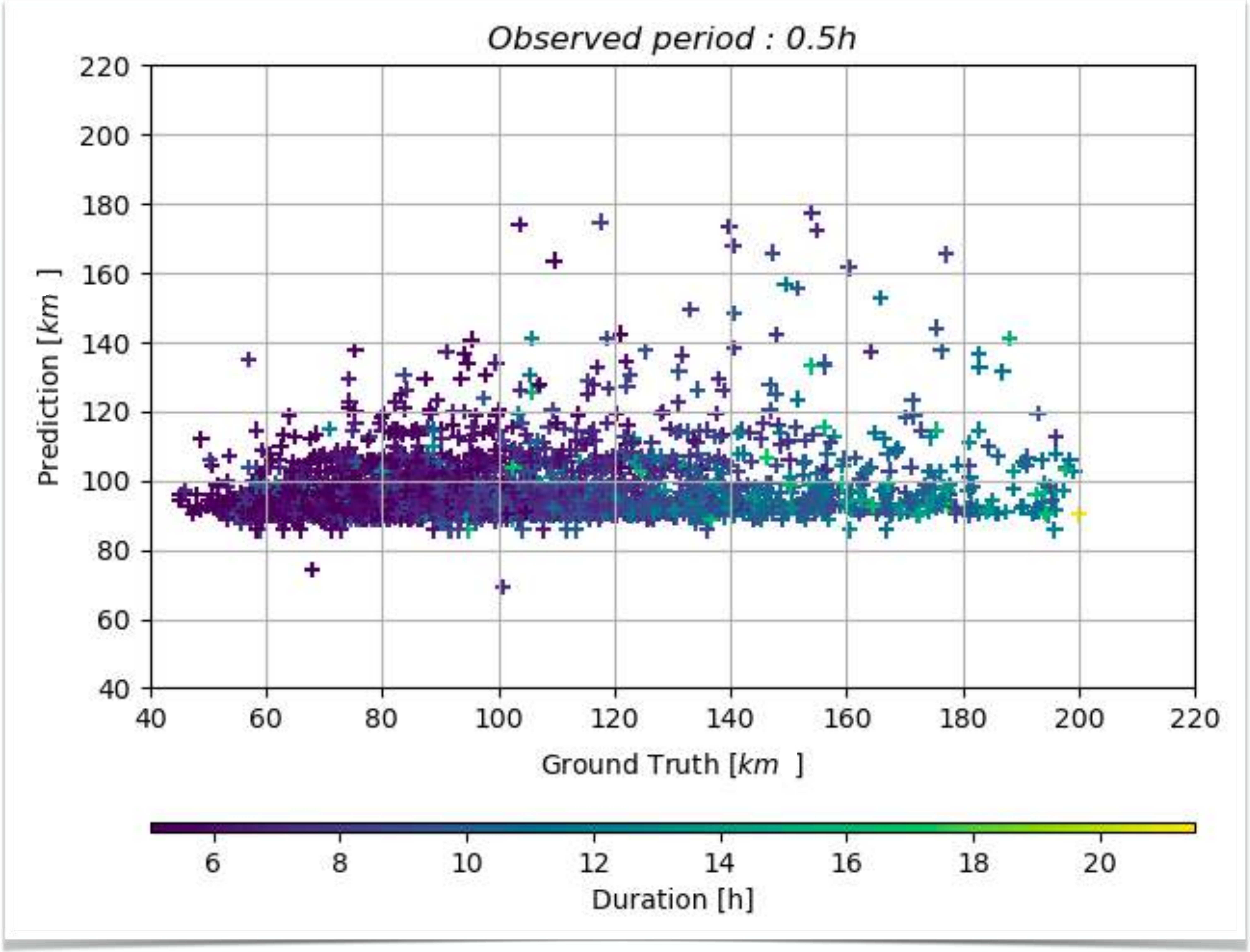
First Experiment: Baseline

Random Forest Results - Baseline



First Experiments: Baseline

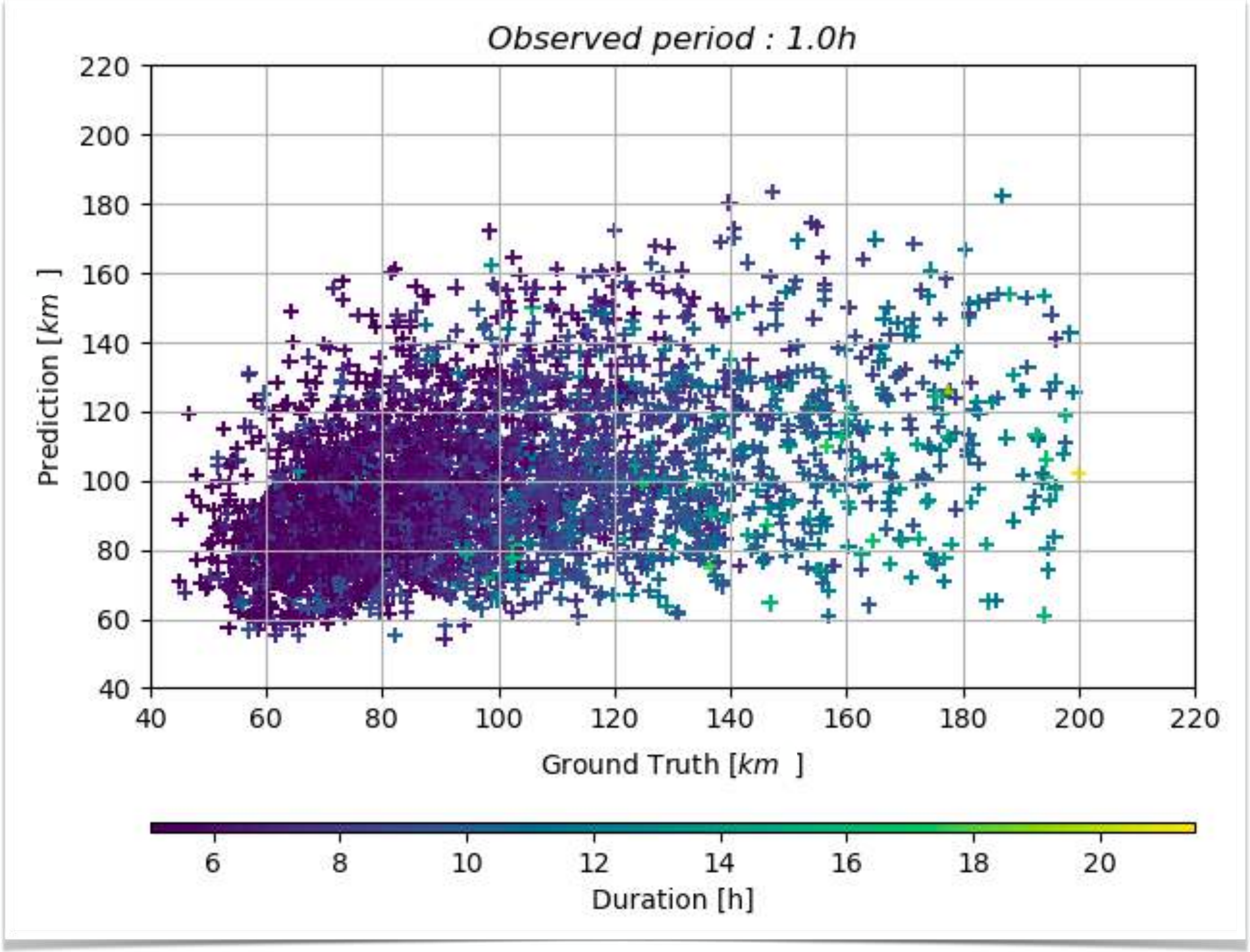
Random Forest Results - Baseline



R^2 = 0.2
RMSE ~ 30km

First Experiments: Baseline

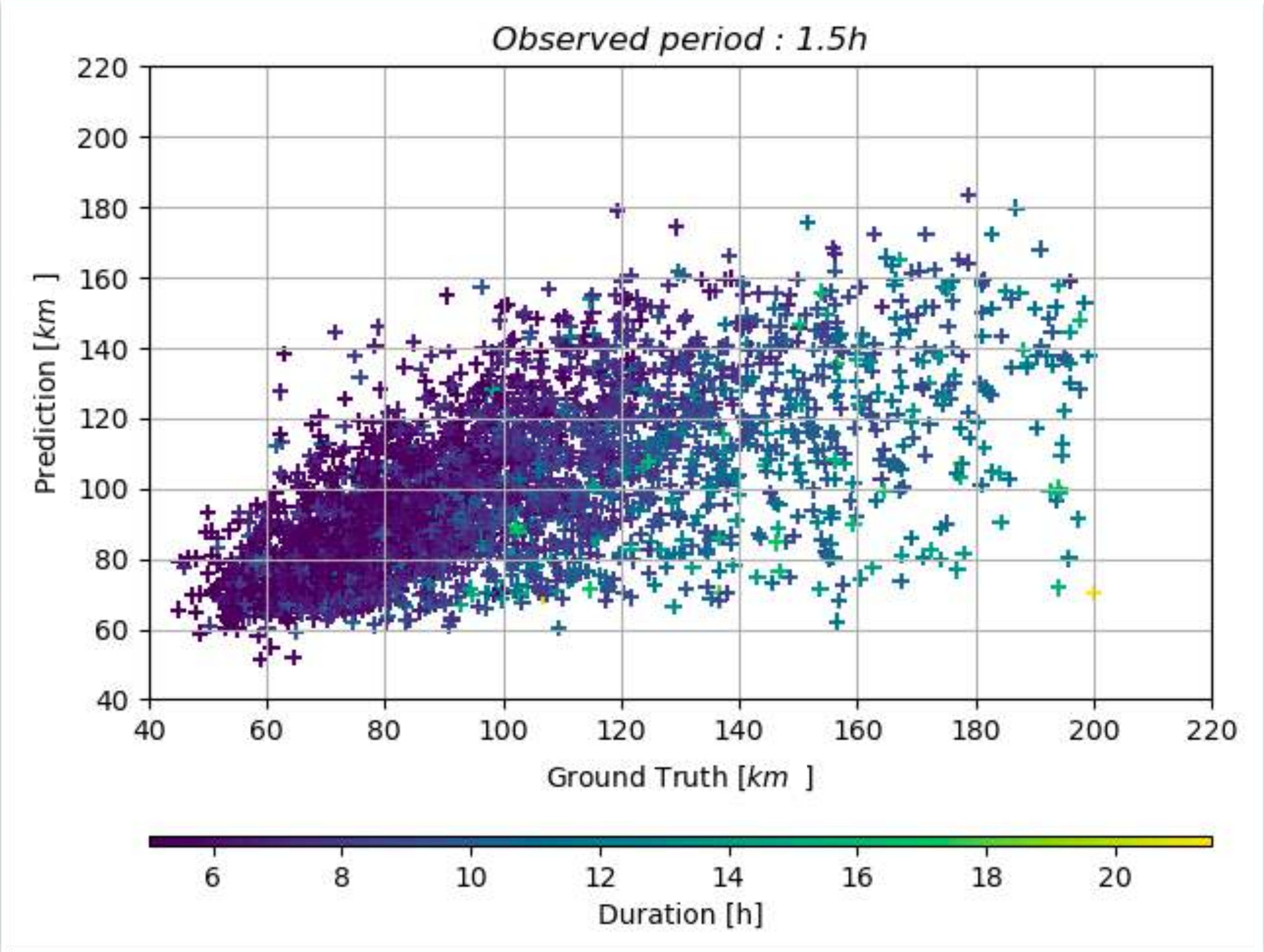
Random Forest Results - Baseline



R^2 = 0.4
RMSE ~ 30km

First Experiments: Baseline

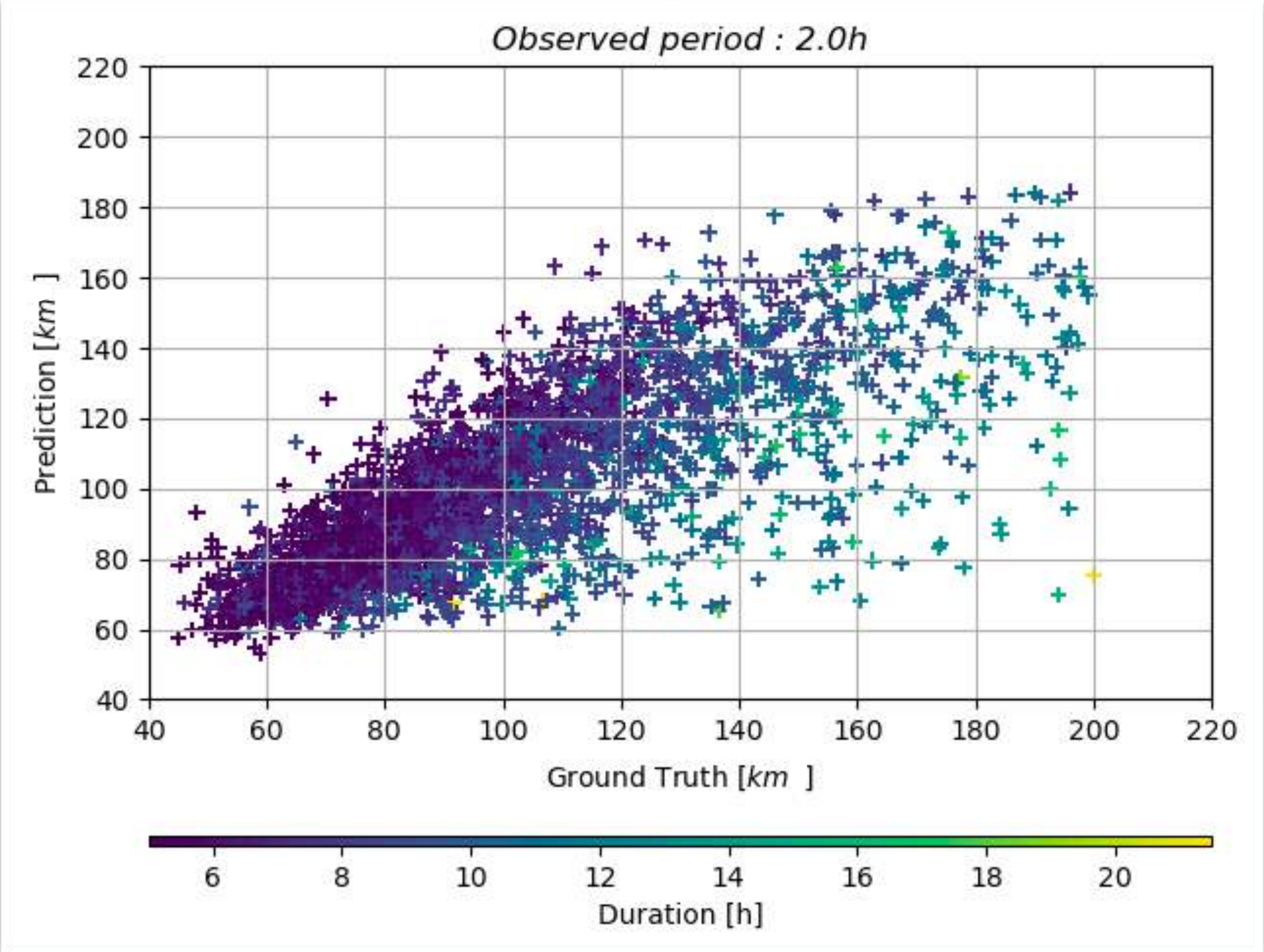
Random Forest Results - Baseline



R^2 = 0.63
RMSE ~ 25km

First Experiments: Baseline

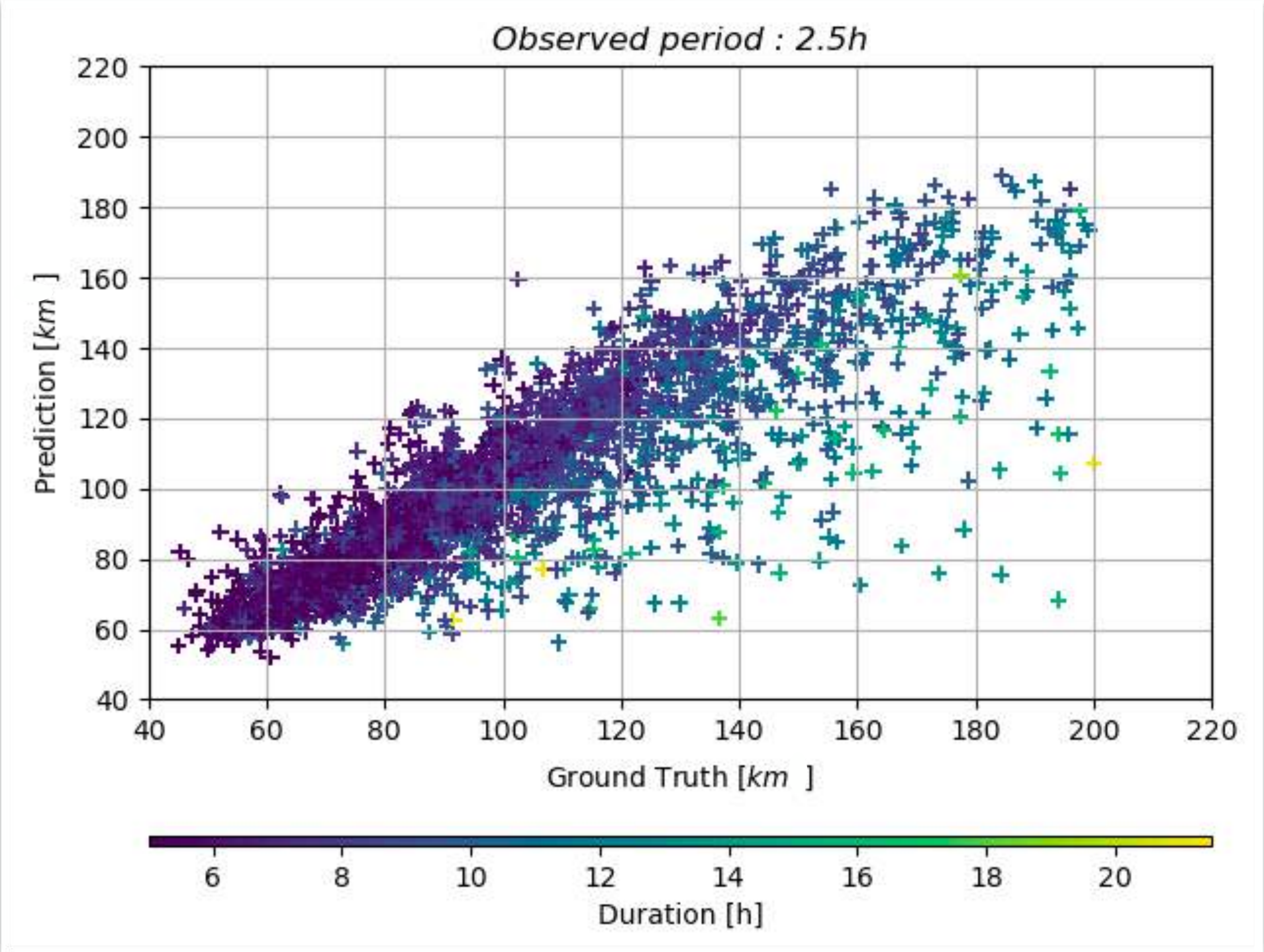
Random Forest Results - Baseline



R^2 = 0.8
RMSE ~ 18km

First Experiments: Baseline

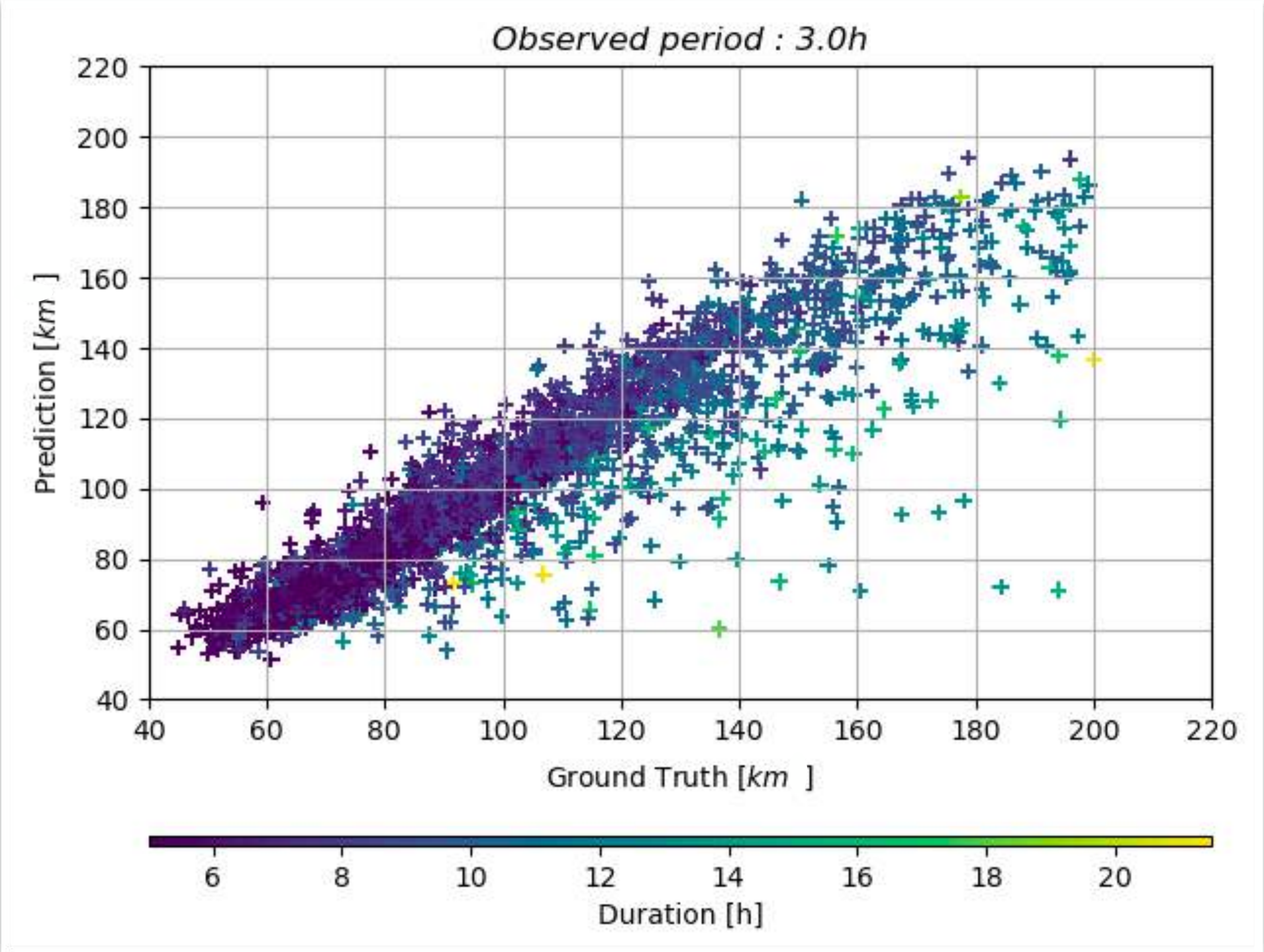
Random Forest Results - Baseline



R^2 = 0.9
RMSE ~ 15km

First Experiments: Baseline

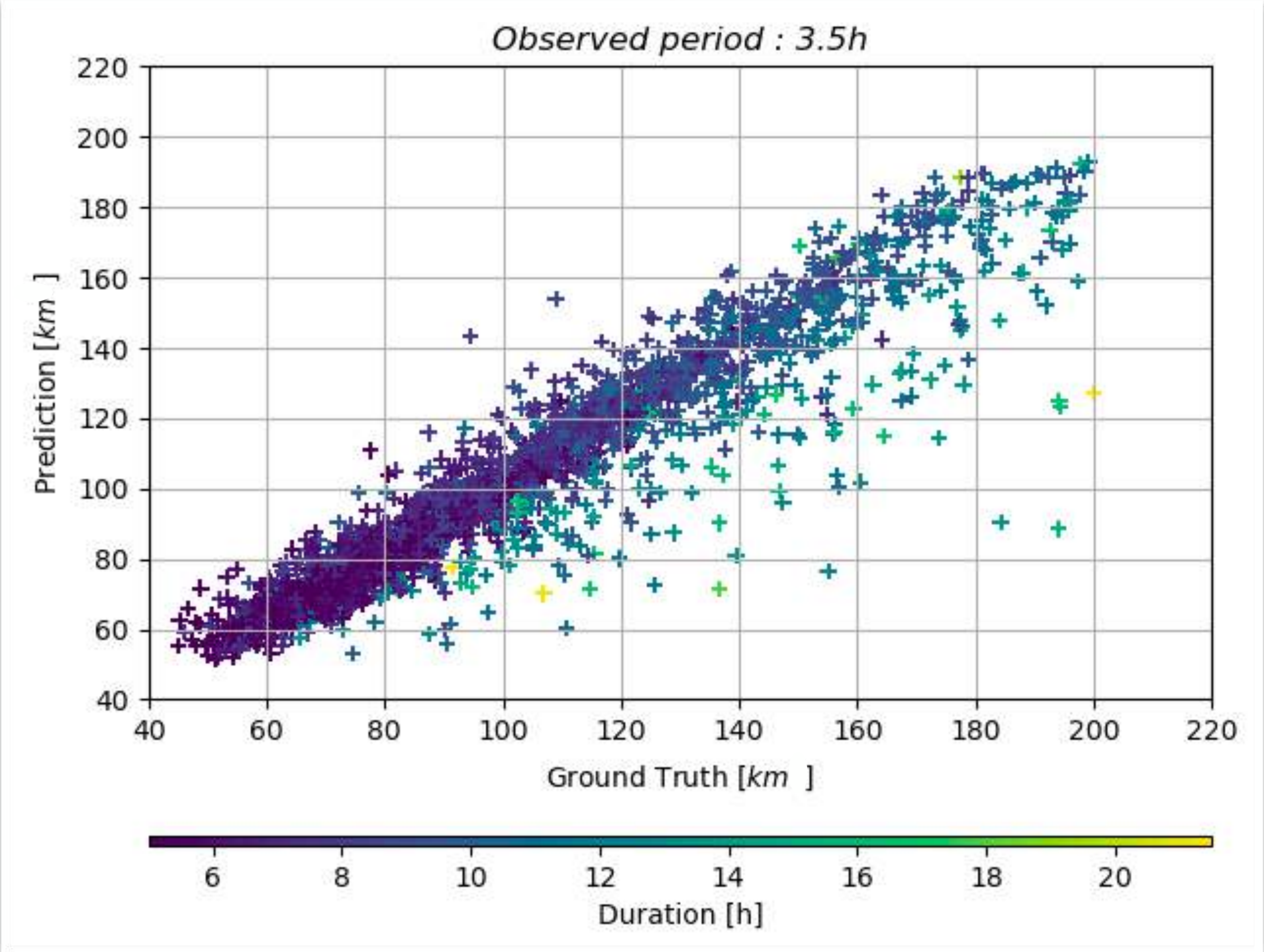
Random Forest Results - Baseline



R^2 = 0.93
RMSE ~ 12km

First Experiments: Baseline

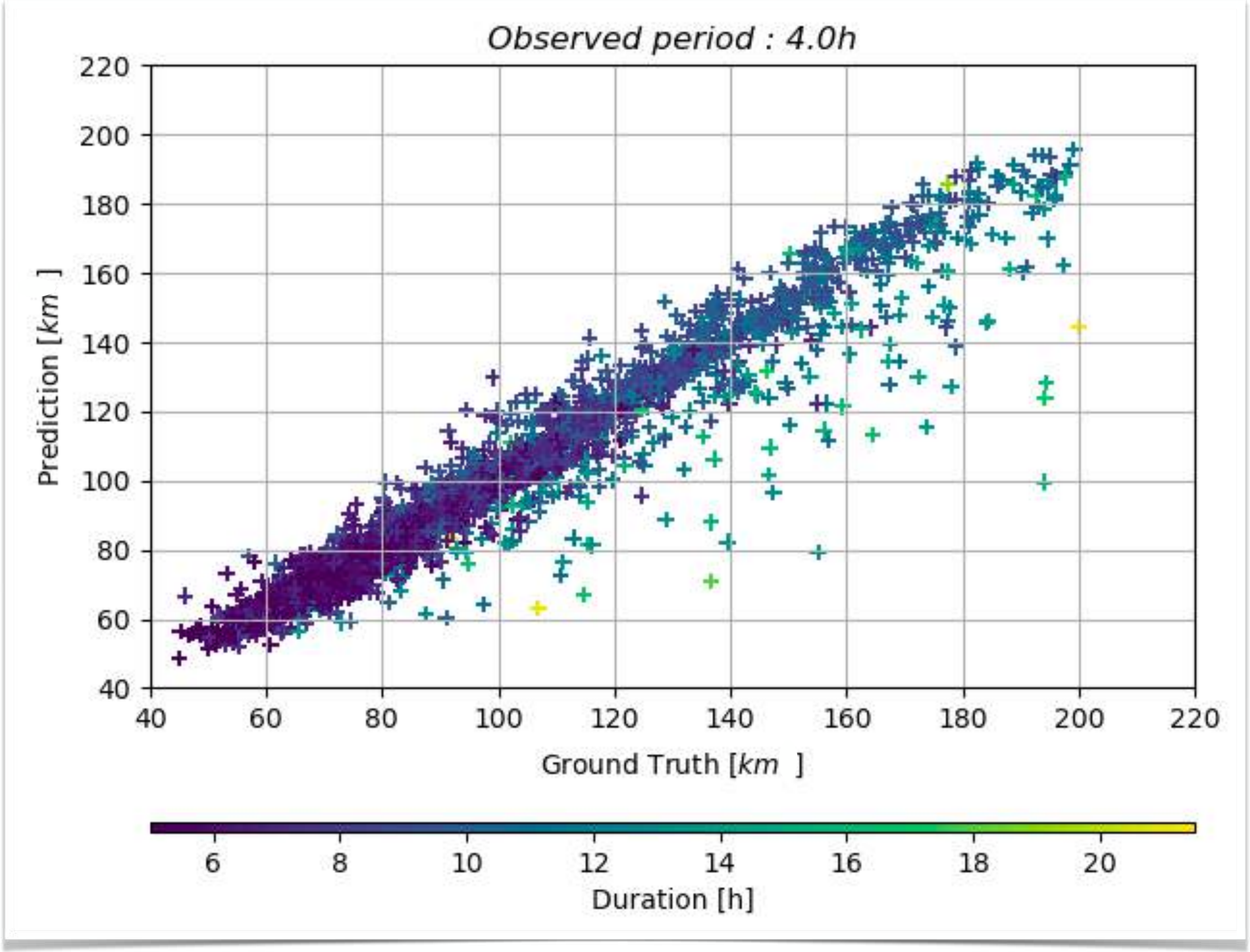
Random Forest Results - Baseline



R^2 = 0.95
RMSE ~ 10km

First Experiments: Baseline

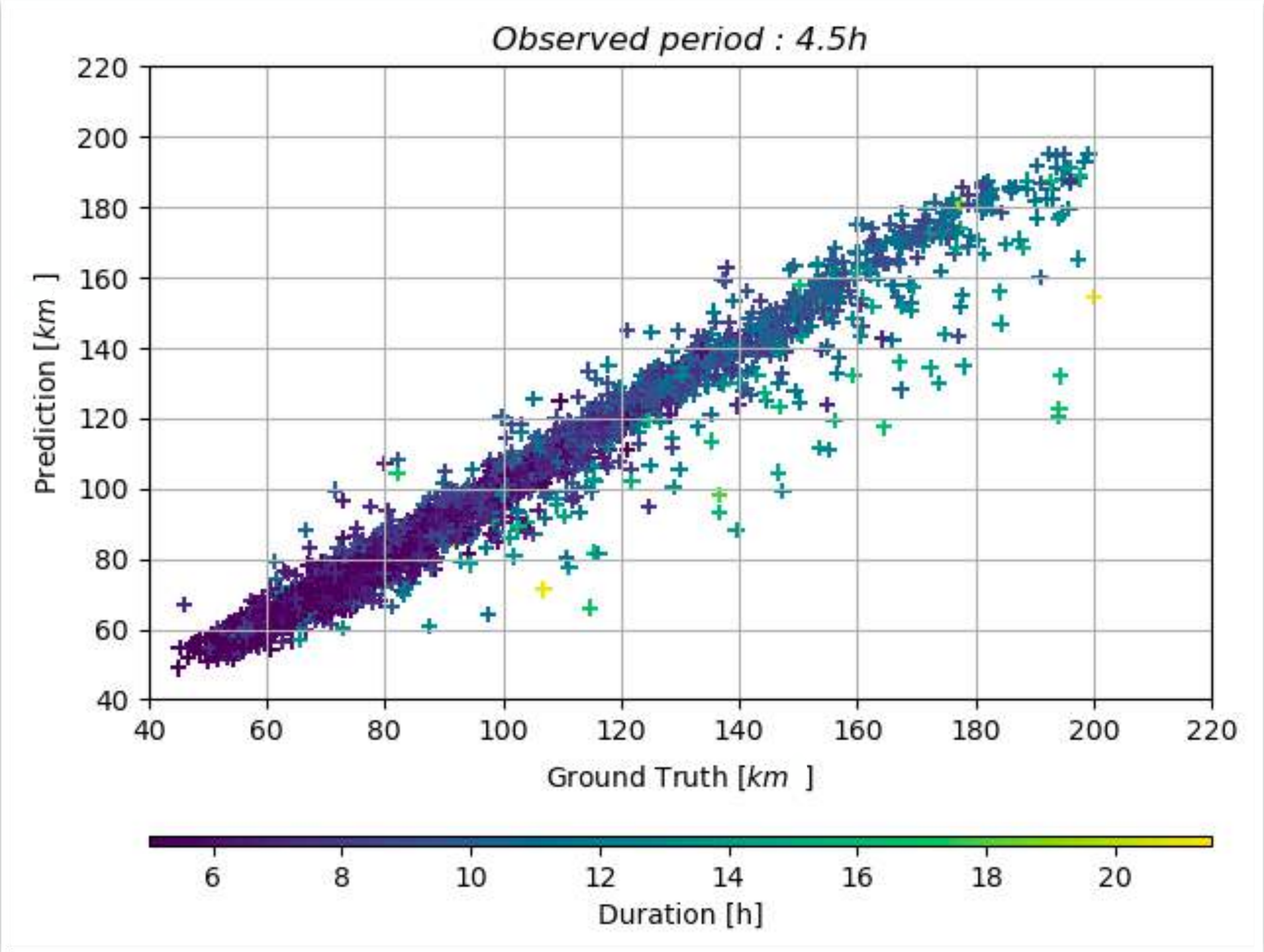
Random Forest Results - Baseline



R^2 = 0.97
RMSE ~ 7km

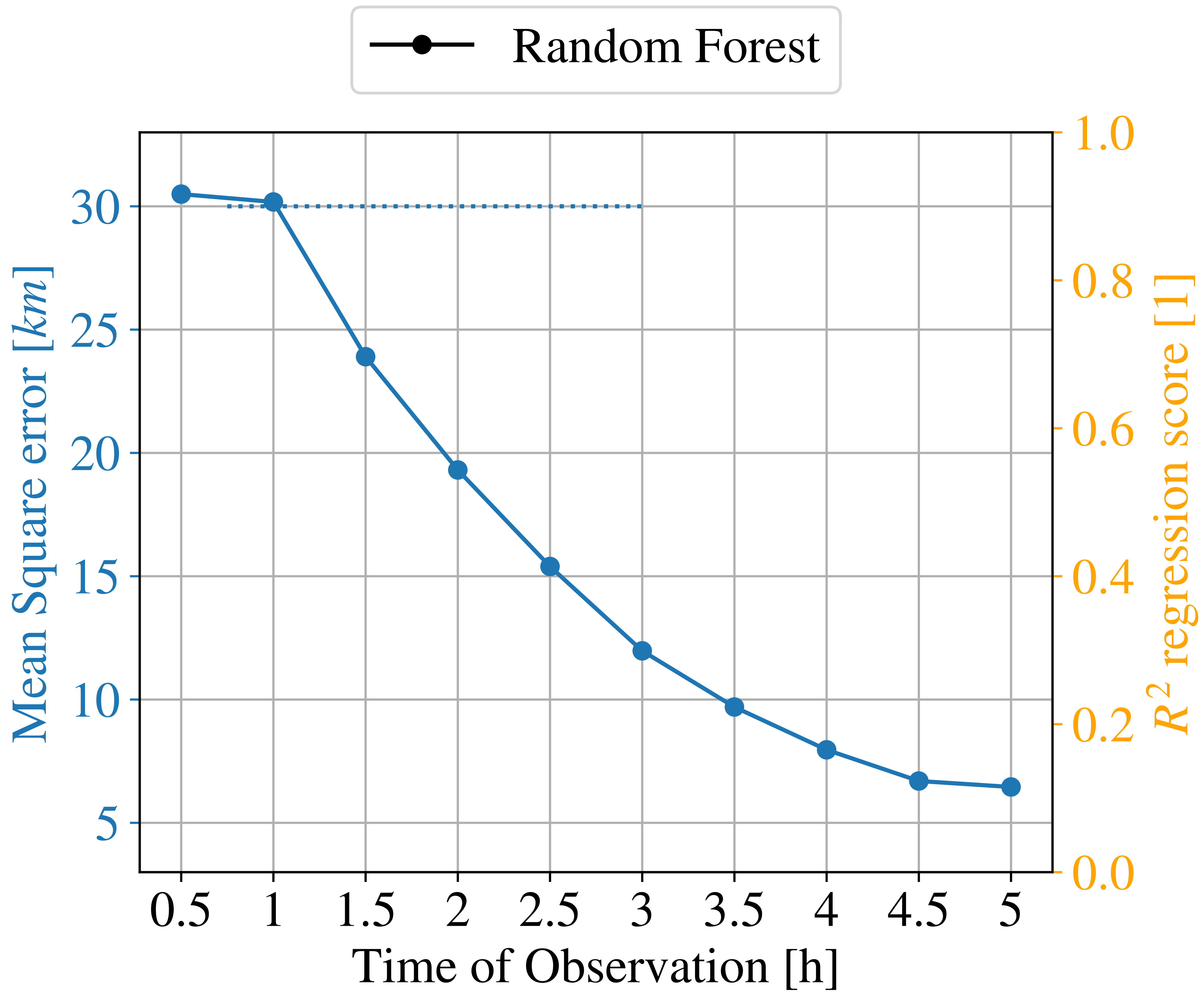
First Experiments: Baseline

Random Forest Results - Baseline

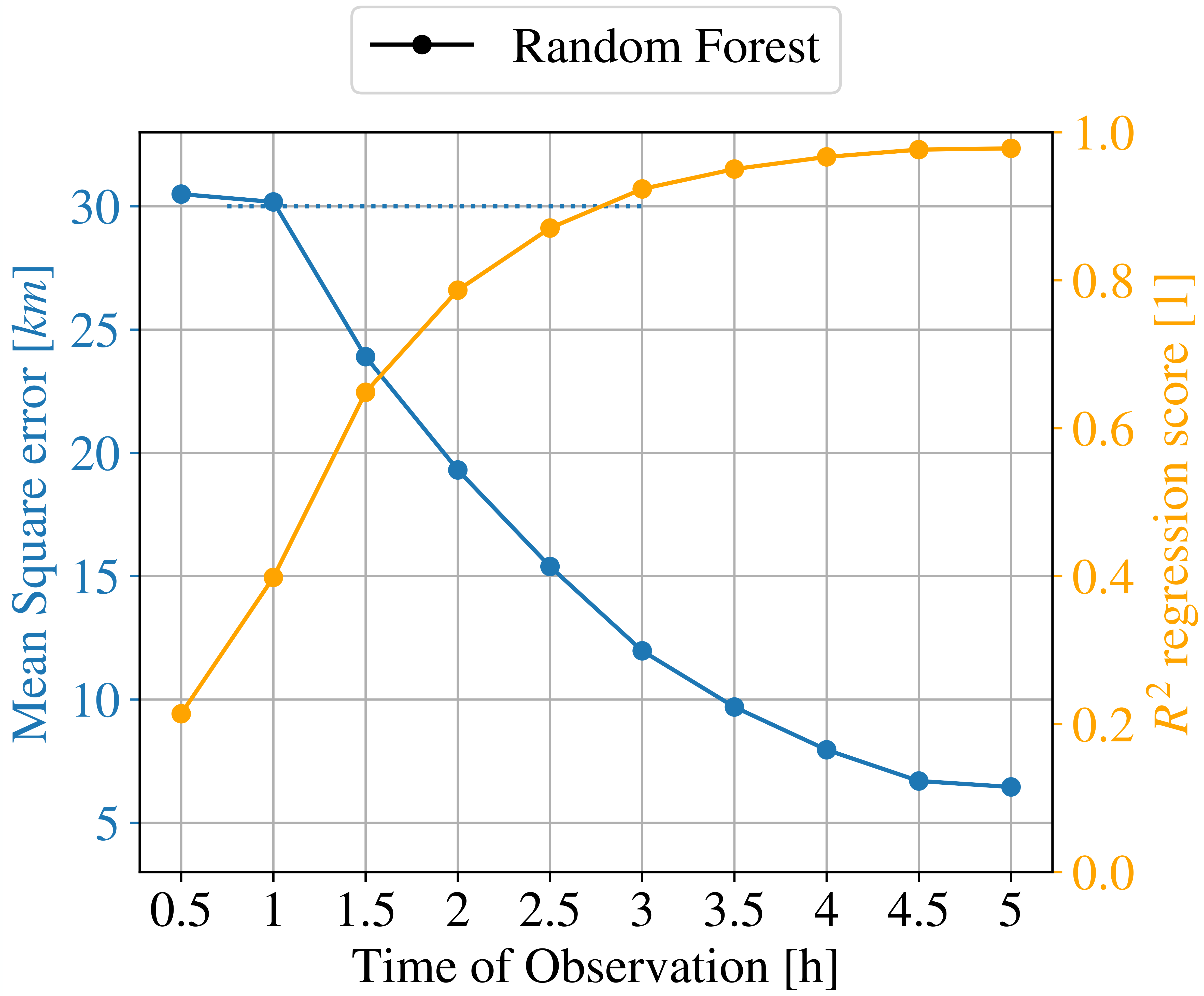


R^2 = 0.97
RMSE ~ 4km

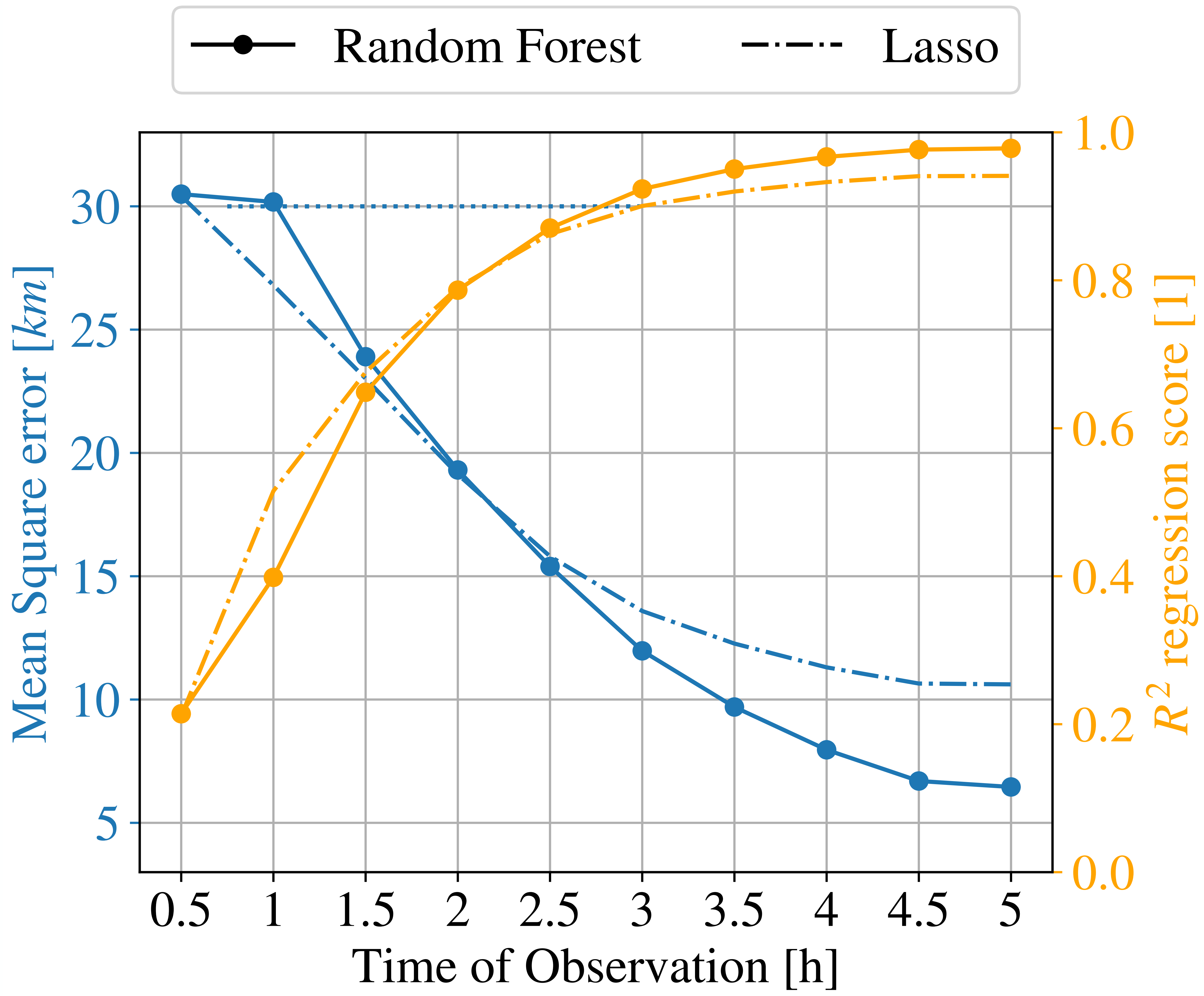
First Experiments: Baseline



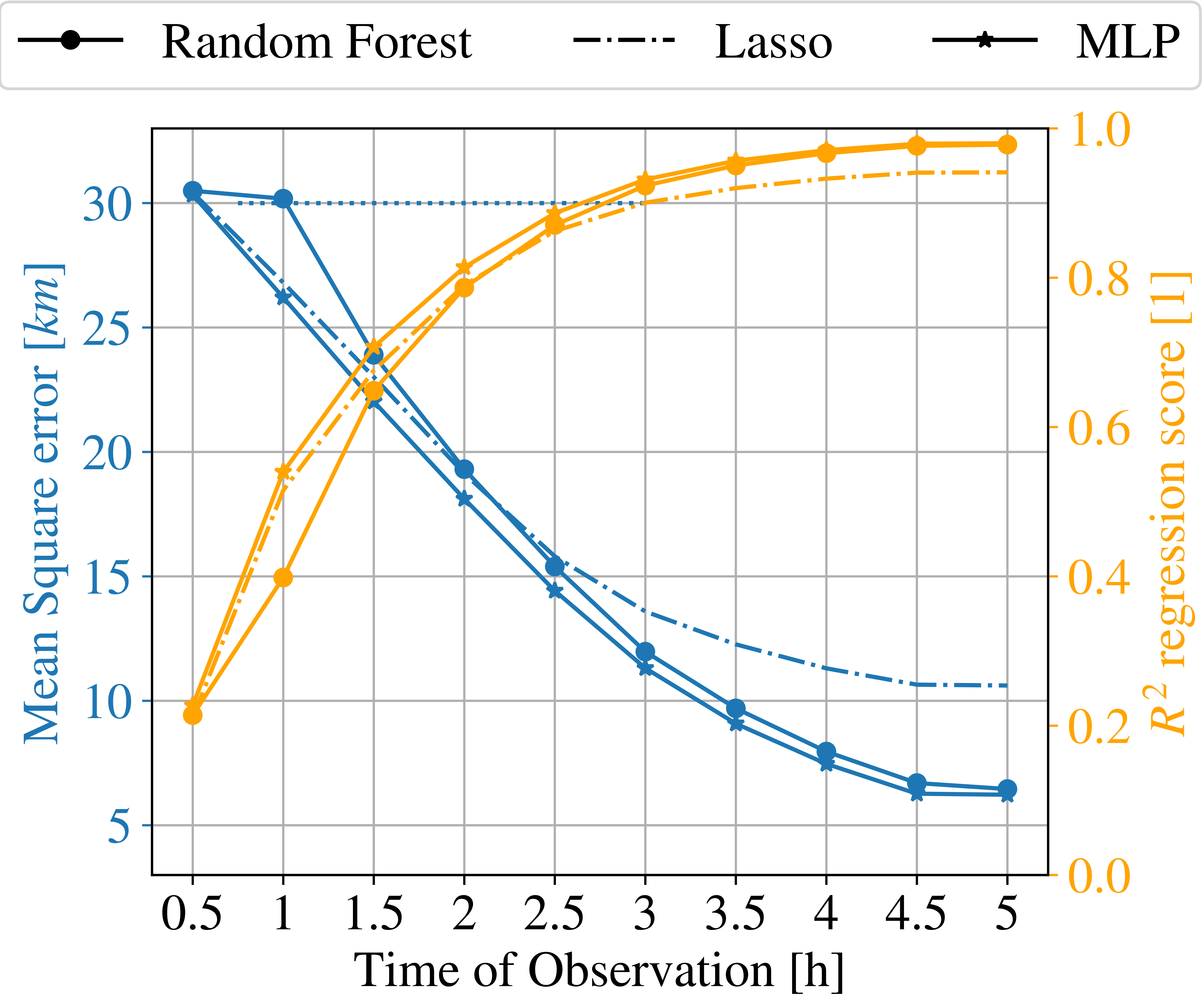
First Experiments: Baseline



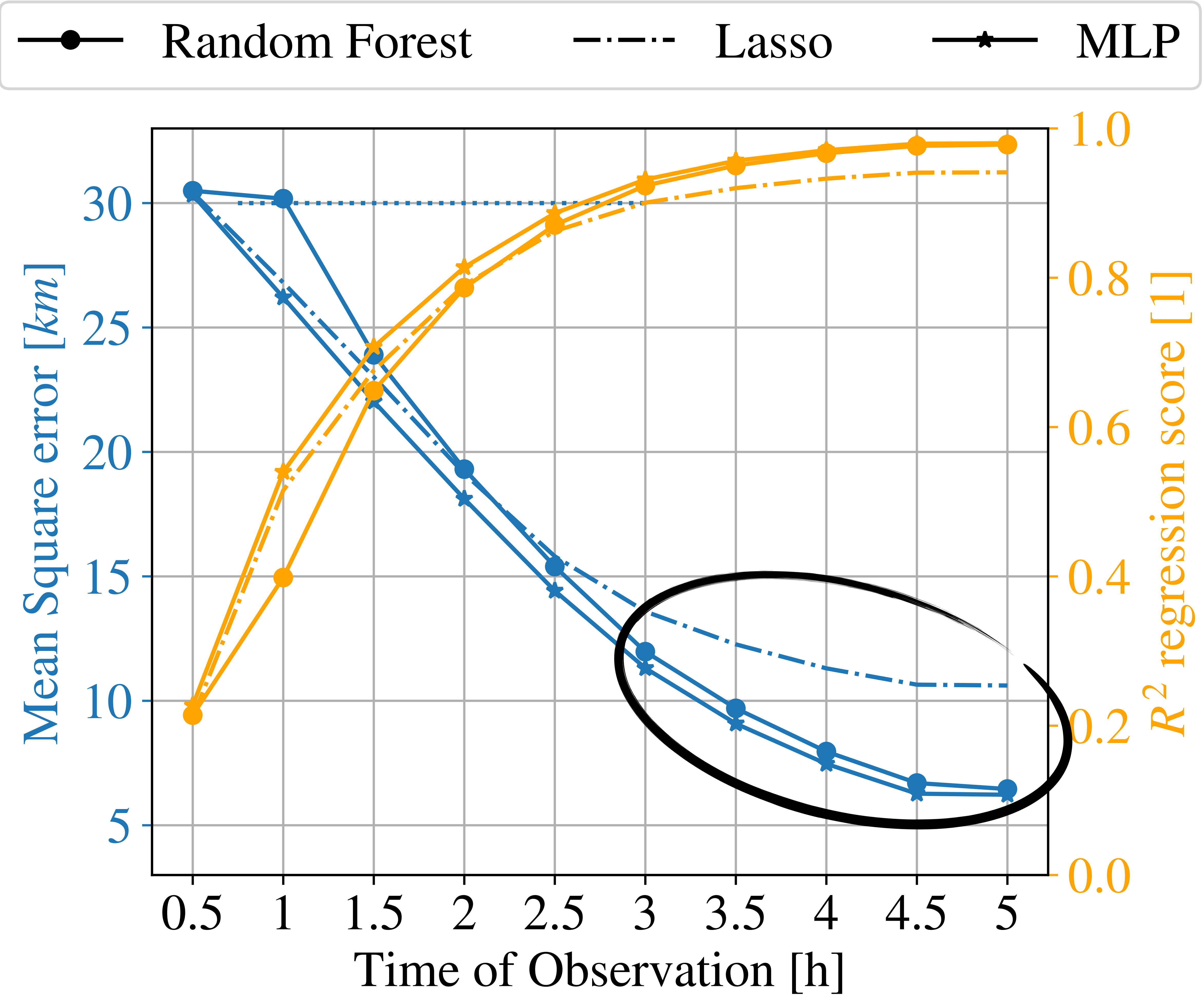
First Experiments: Baseline



First Experiments: Baseline

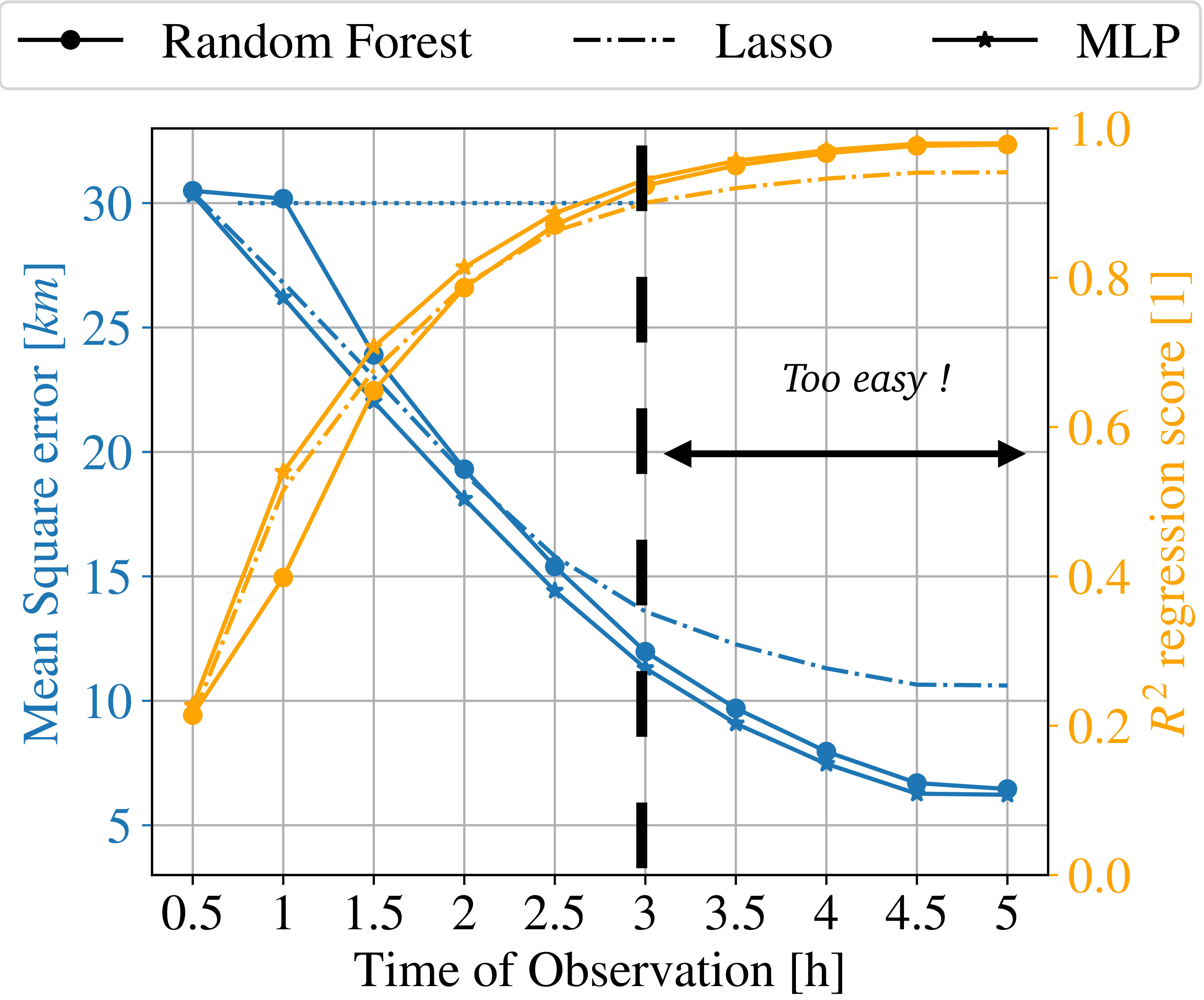


First Experiments: Baseline



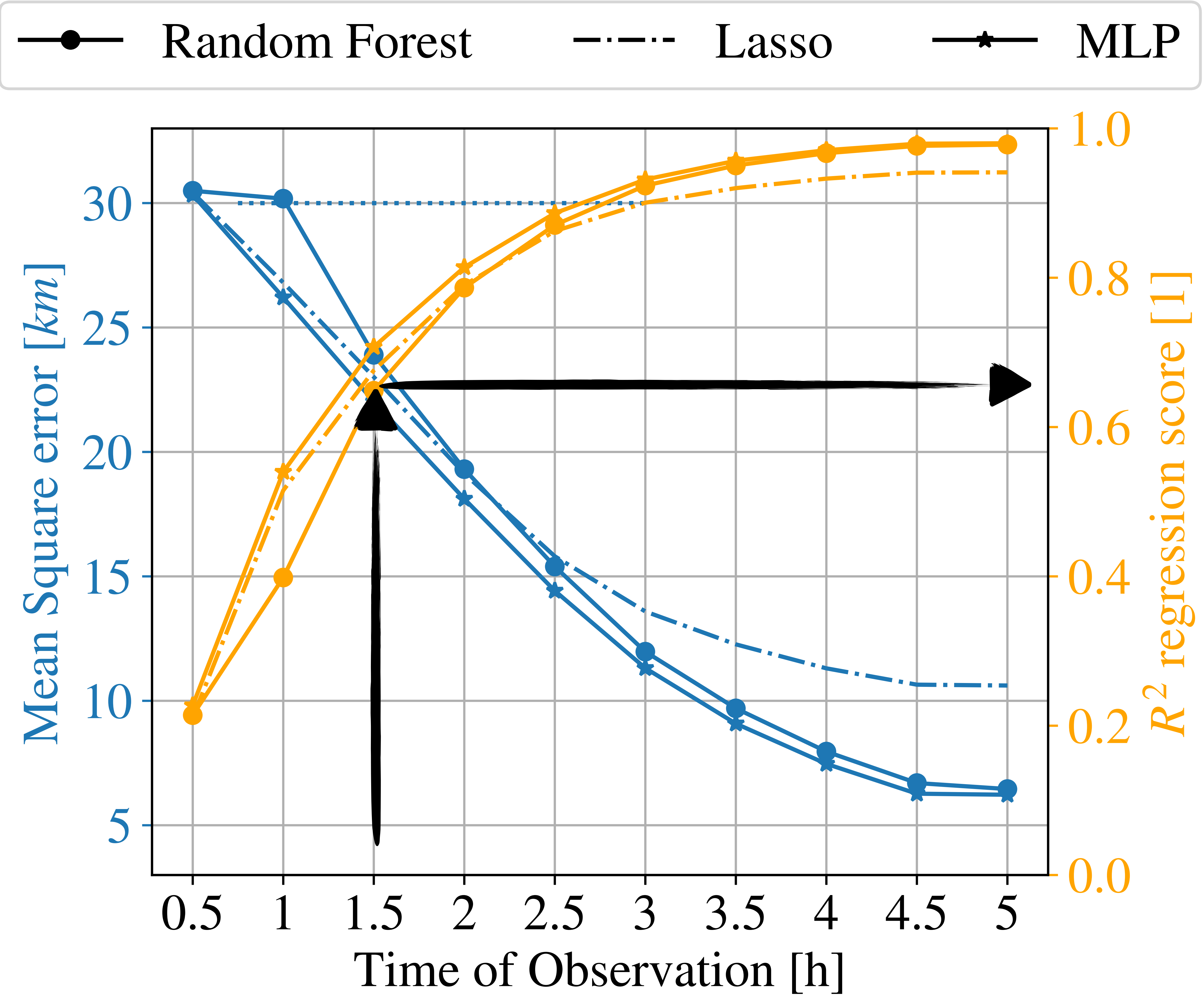
Equivalent performance for all models until 3h, then lineal model unable to correct the bias

First Experiments: Baseline



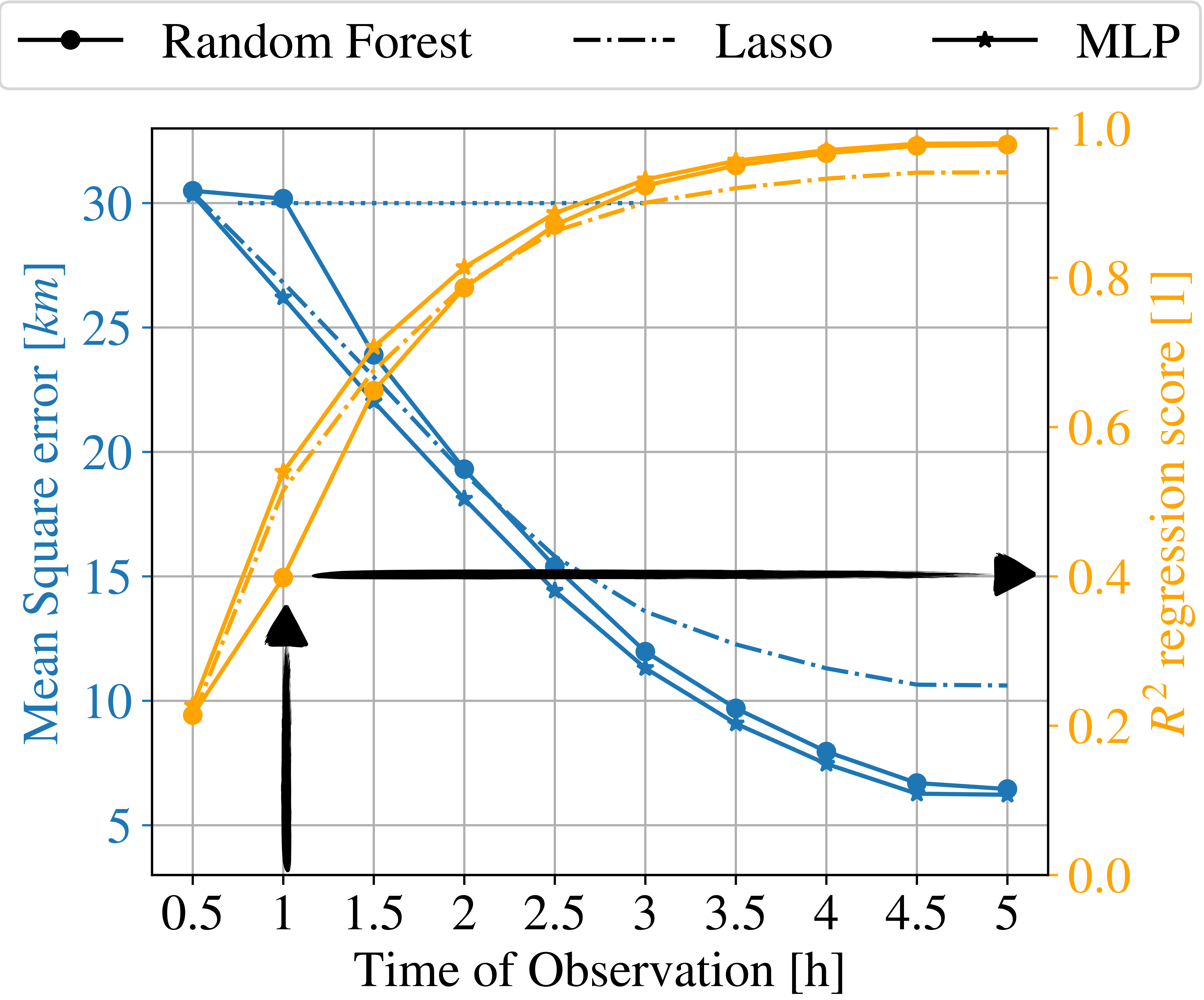
Systems lasts at least 5 hours and 7.5 hours in mean so most of them have reached their maximal area around 3h

First Experiments: Baseline



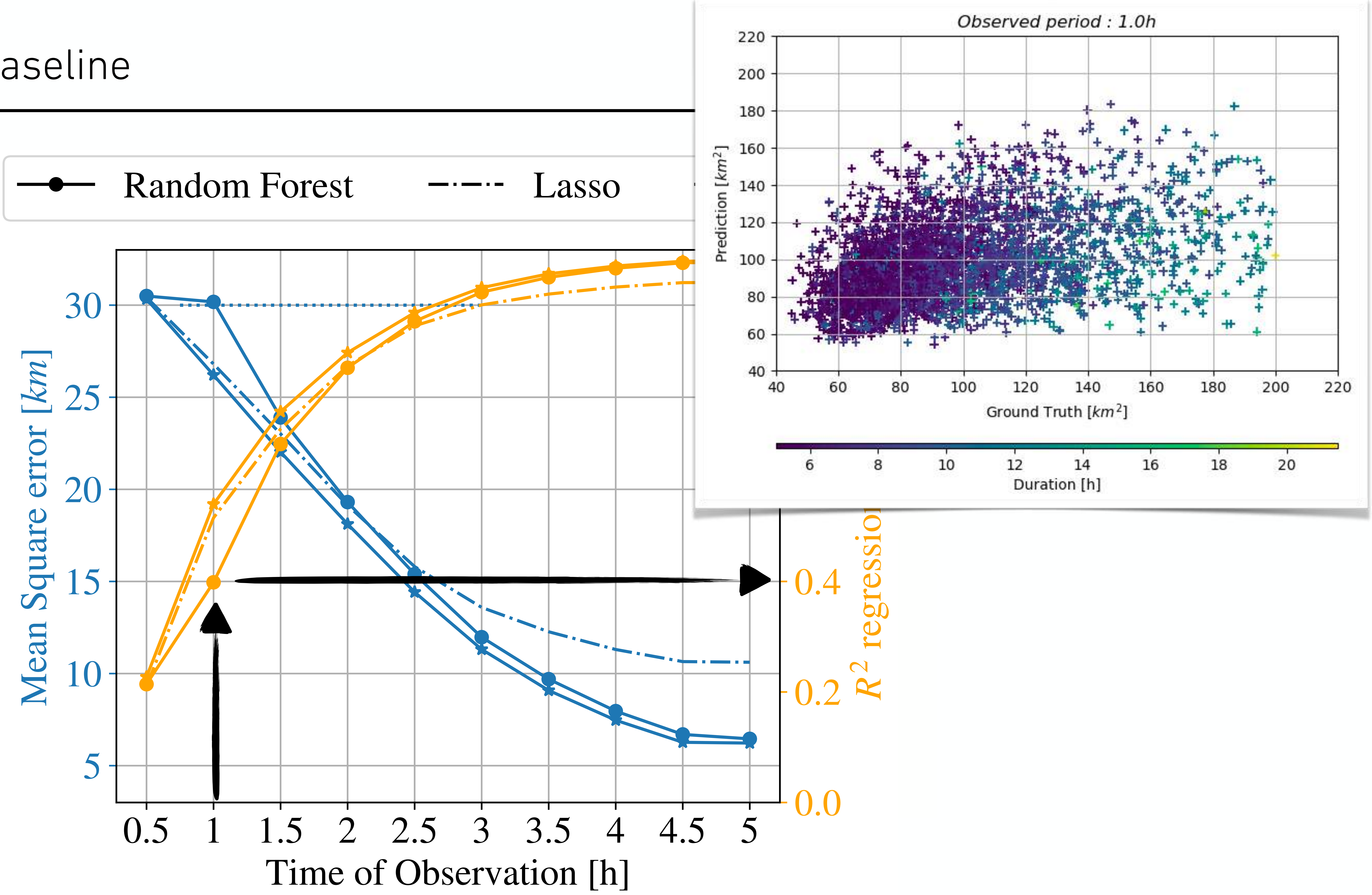
Systems lasts at least 5 hours and 7.5 hours in mean so most of them have reached their maximal area around 3h

First Experiments: Baseline



Systems lasts at least 5 hours and 7.5 hours in mean so most of them have reached their maximal area around 3h

First Experiments: Baseline

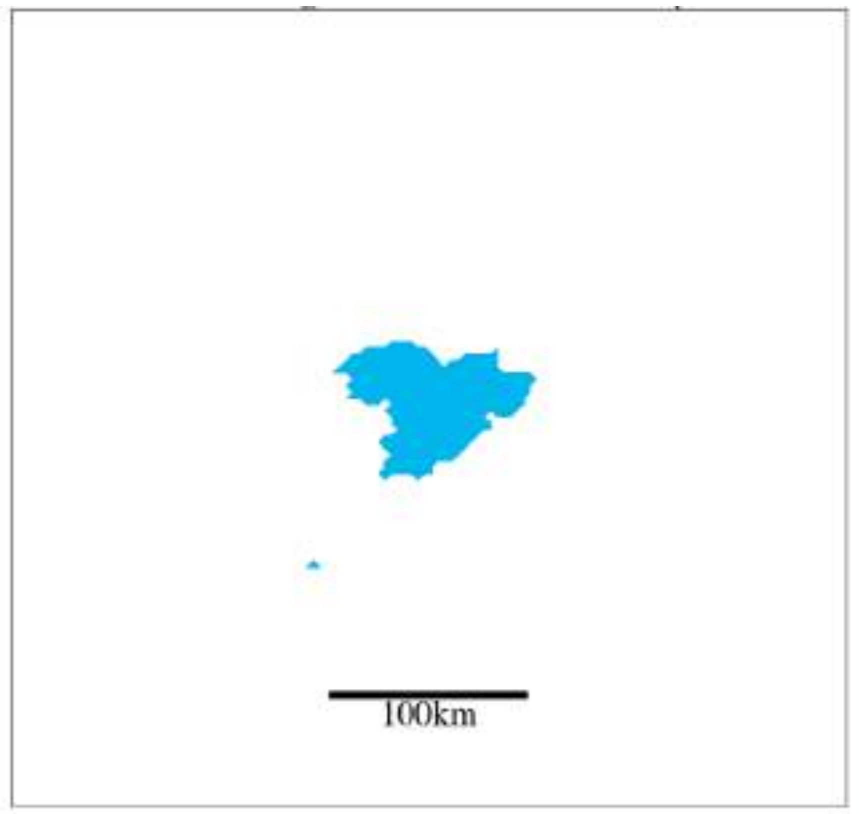


Systems lasts at least 5 hours and 7.5 hours in mean so most of them have reached their maximal area around 3h

→ *Can we improve the prediction at 1h ?*

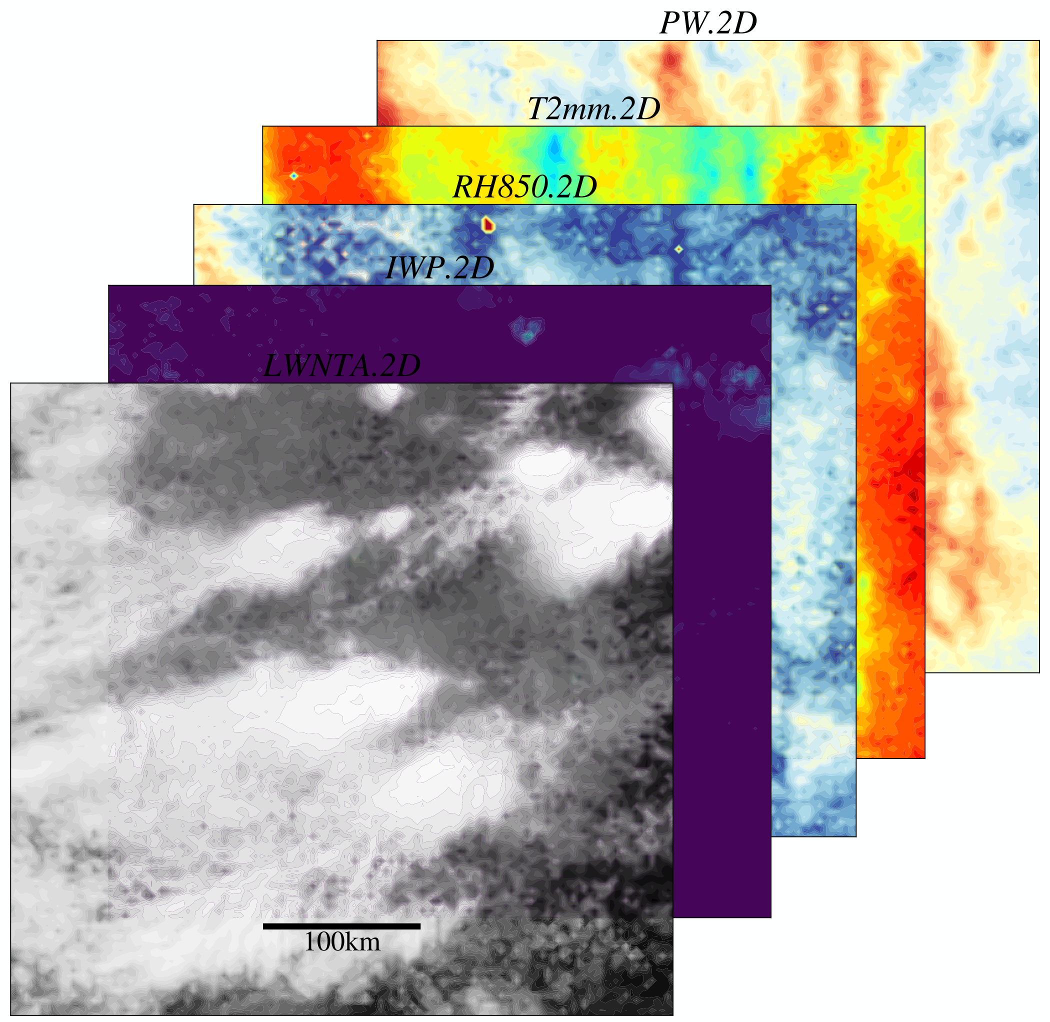
Second Experiment : Augmented Model

Shape of the cloud



Circularity of the system
Excentricity
Evolution in time

Physical field, in and out of the system



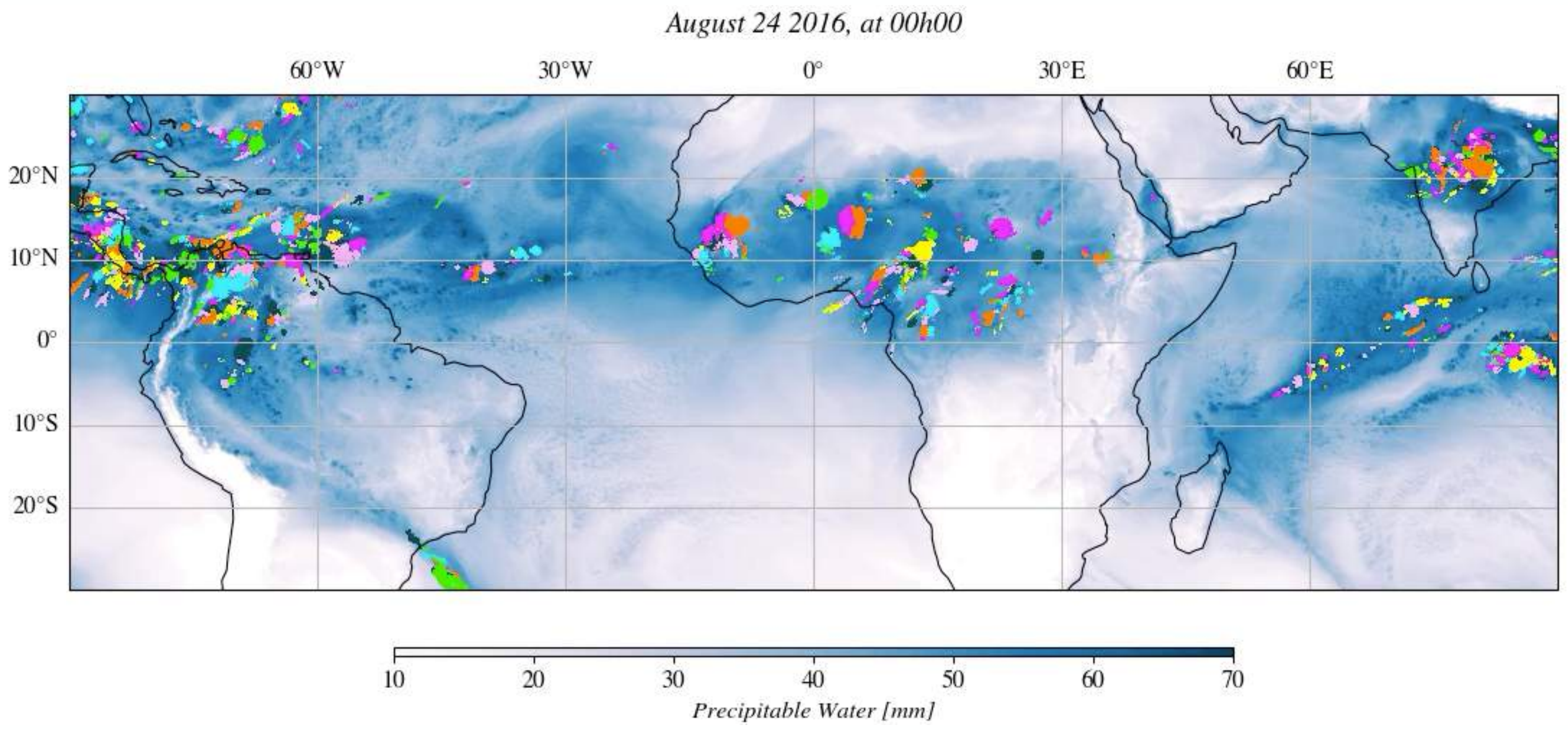
mean, std

System and environment

Only in the system

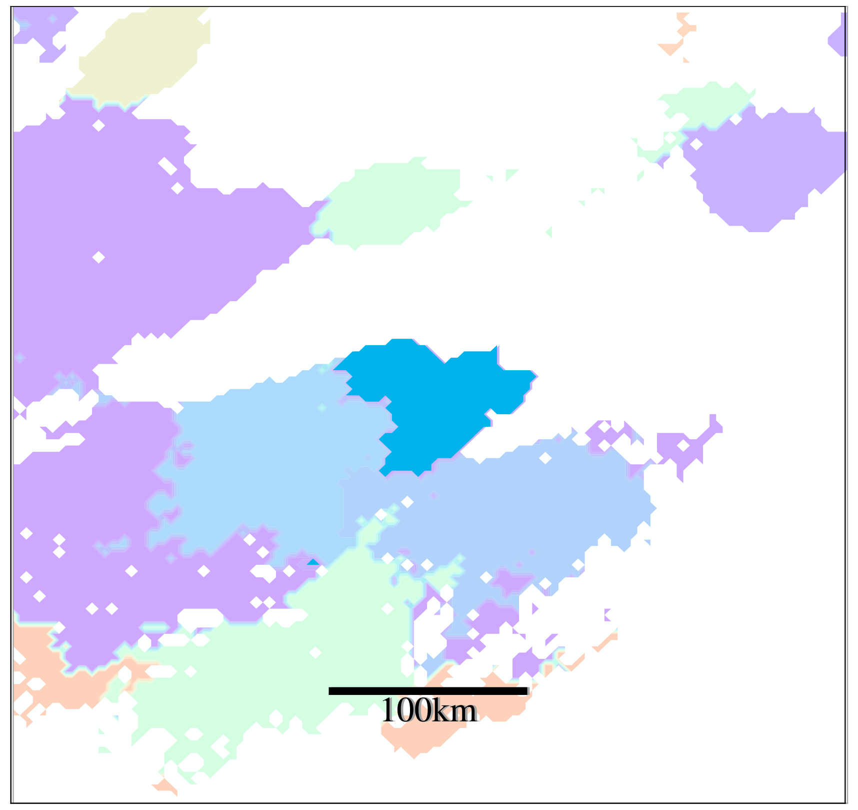
Only in the environnement

Trajectory and propagation velocity



Migration distance
Propagation velocity

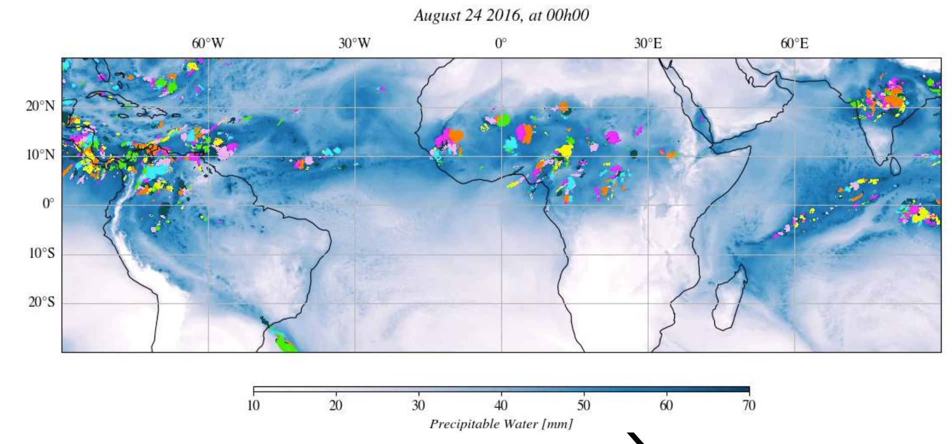
Surrounding systems influence

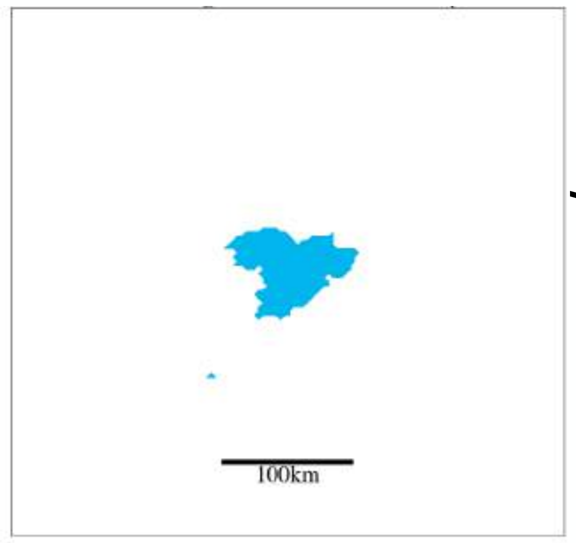


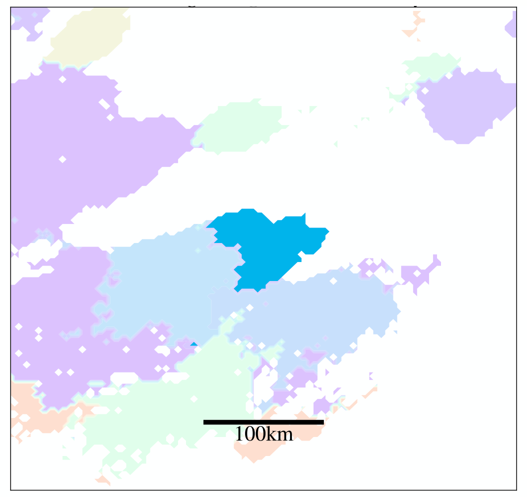
How many neighbors ?
Are they far from the system ?
How big are they ?
How old ?
Is there a very large one in the area ?

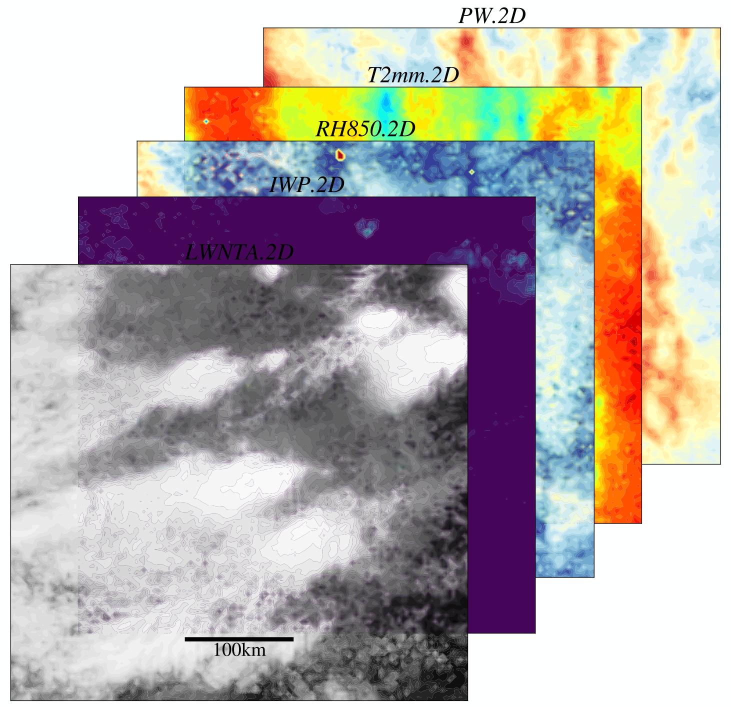
→ **95 scalar features computed for all MCS at each timestep**

Second Experiment : Augmented Model









feature_1

feature_2

feature_3

feature_4

feature_5

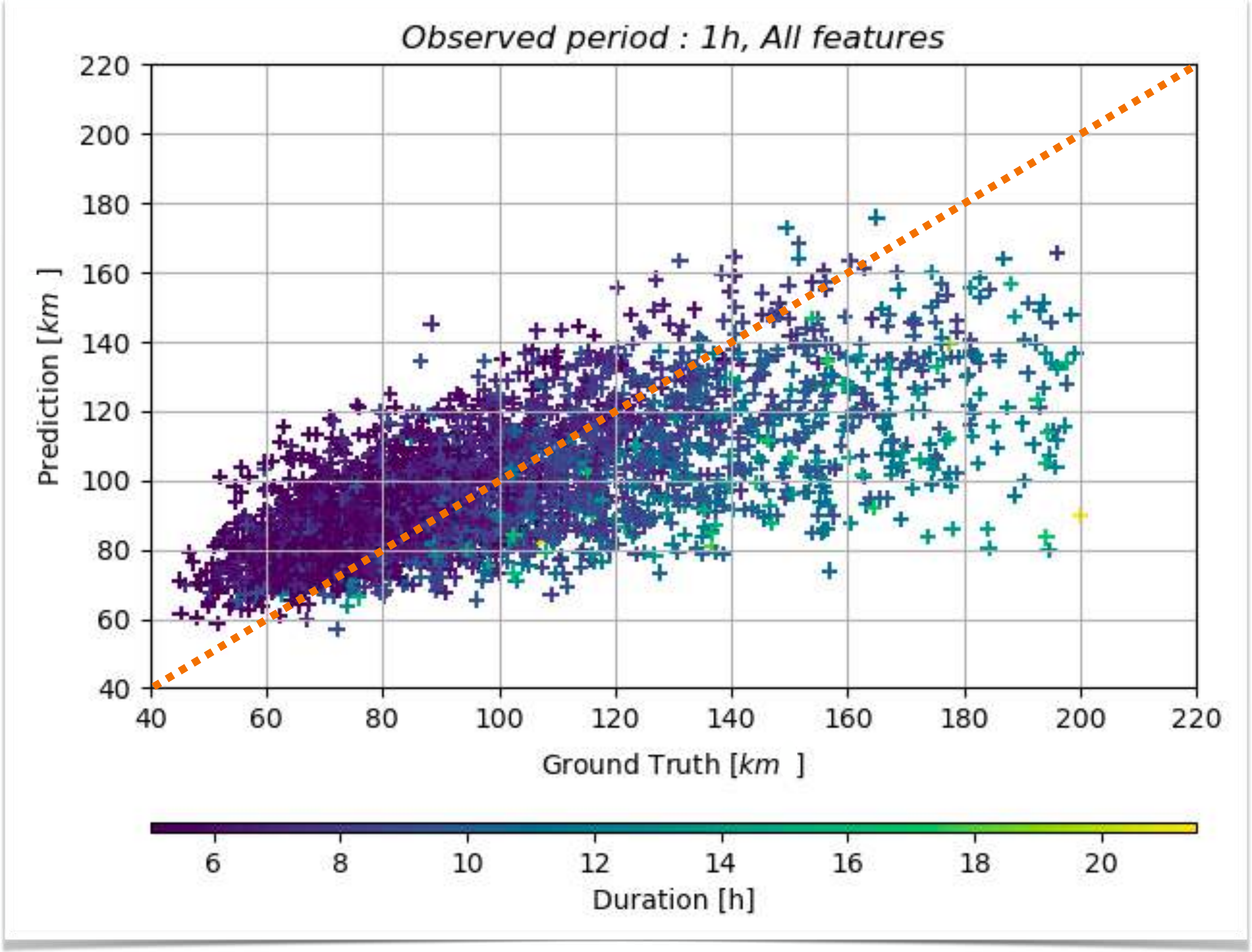
...

feature_190

→ Random Forest → $\sqrt{A_{max}}$

Only during the first hour

Second Experiment : Augmented Model

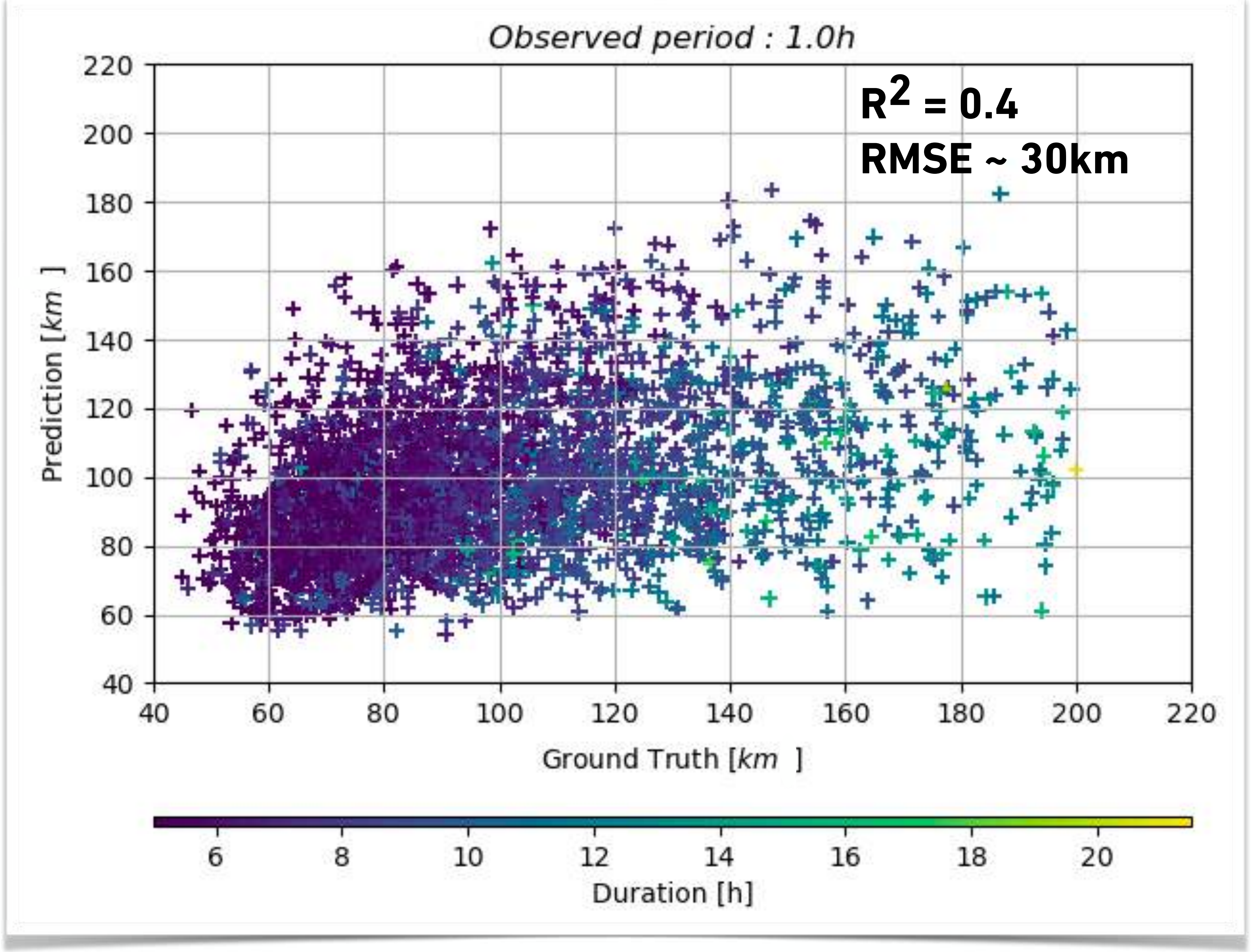


$R^2 = 0.7$

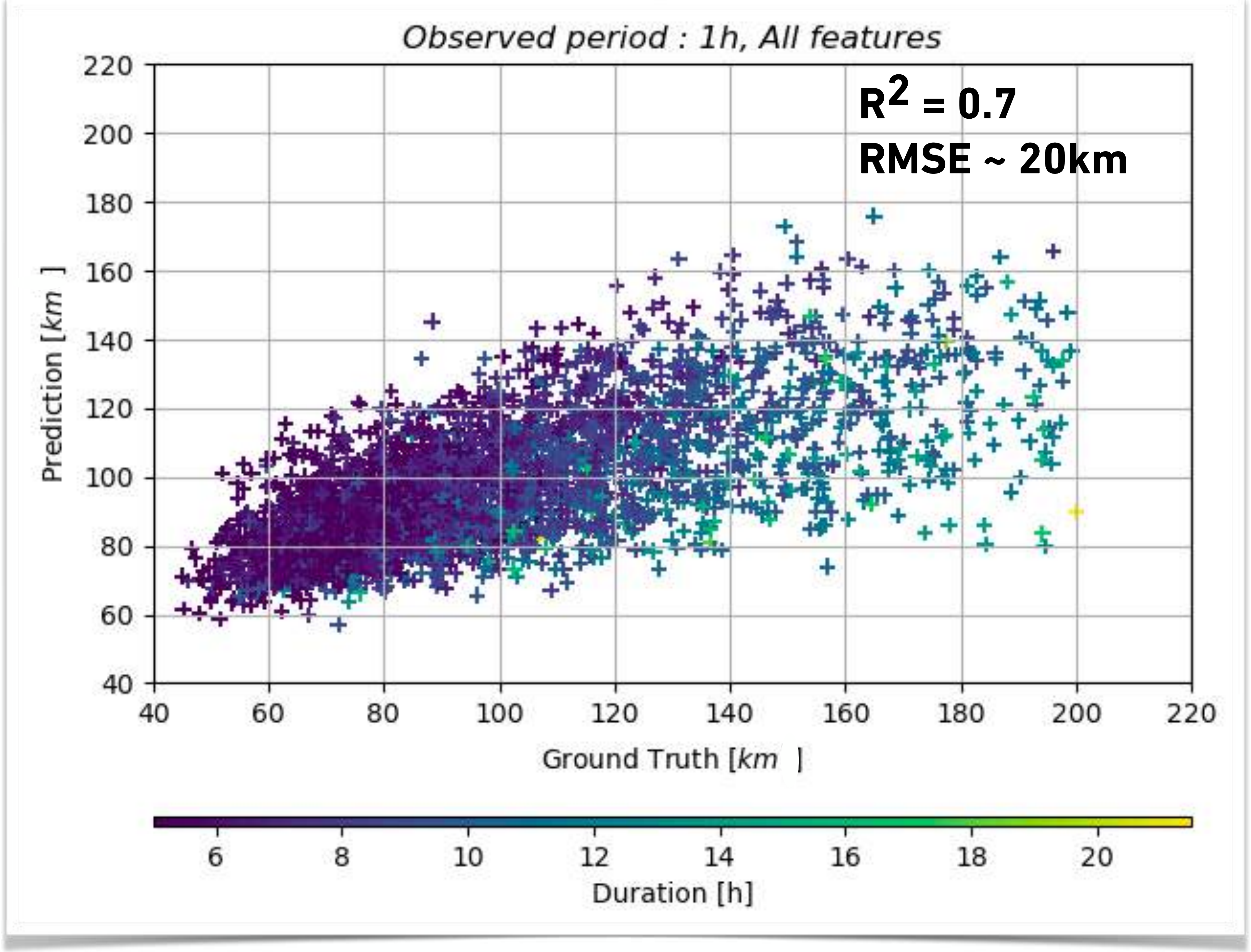
RMSE ~ 20km

Second Experiment : Augmented Model

Baseline

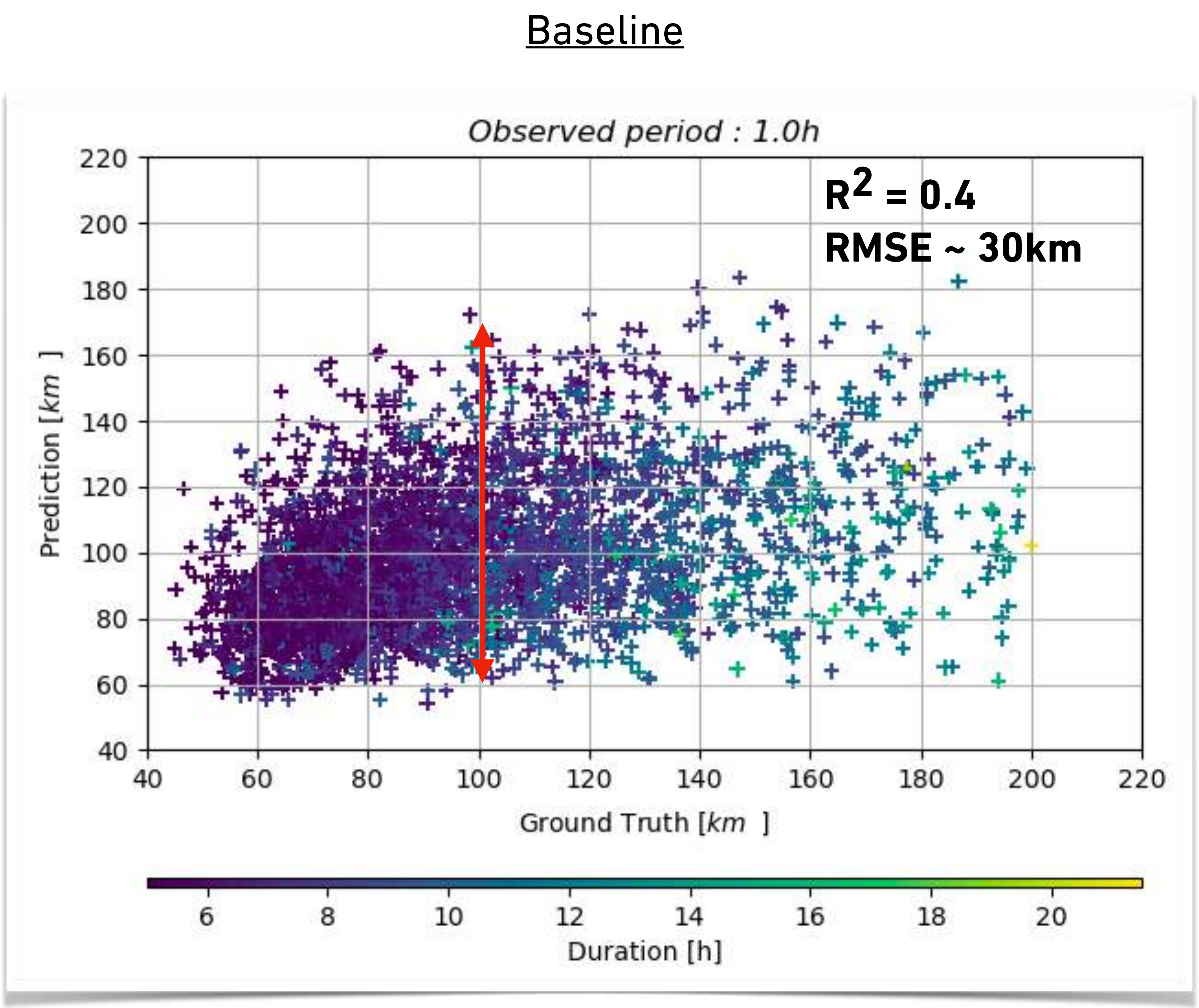


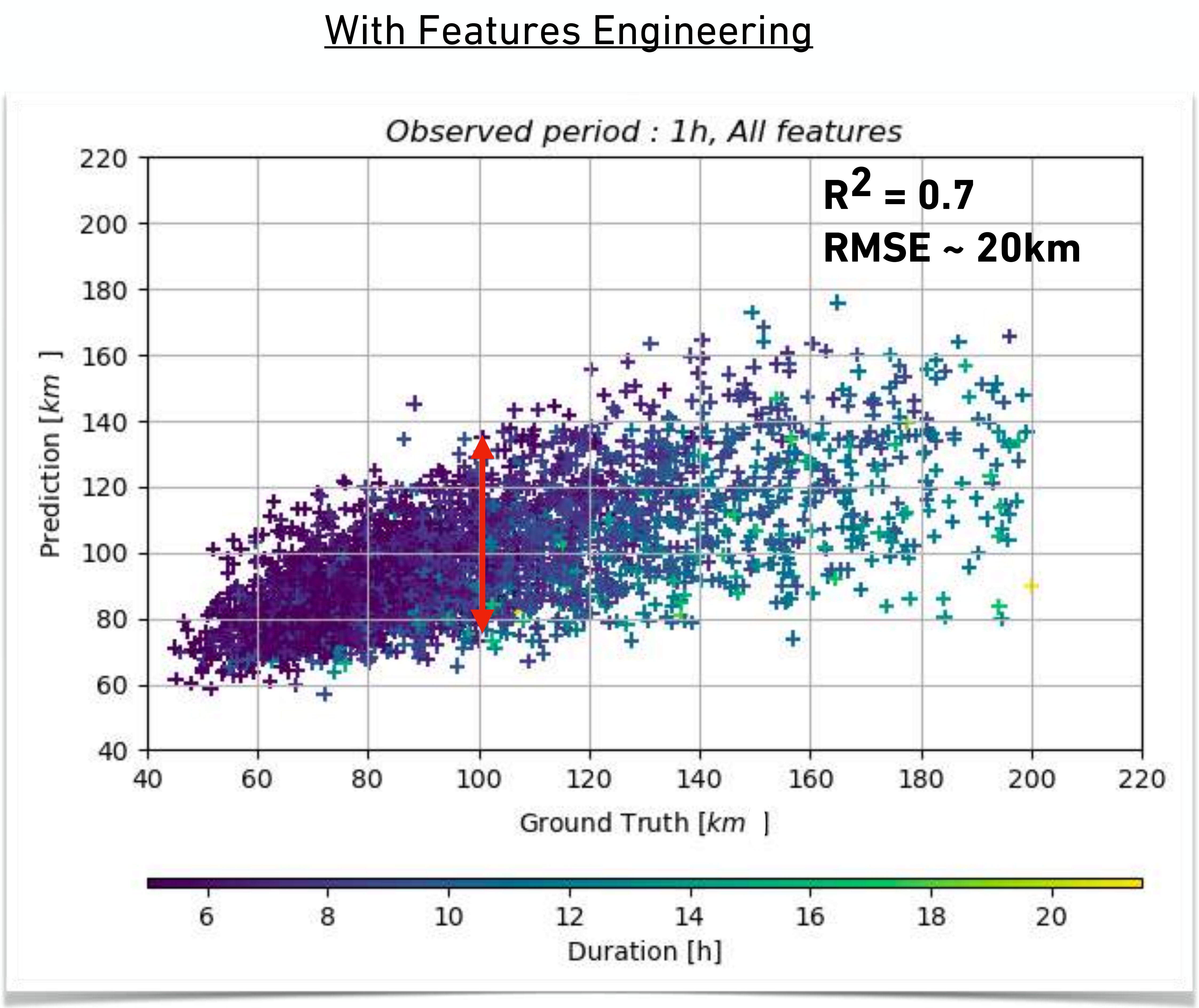
With Features Engineering



→ *More precise and add correction to the large systems*

Second Experiment : Augmented Model

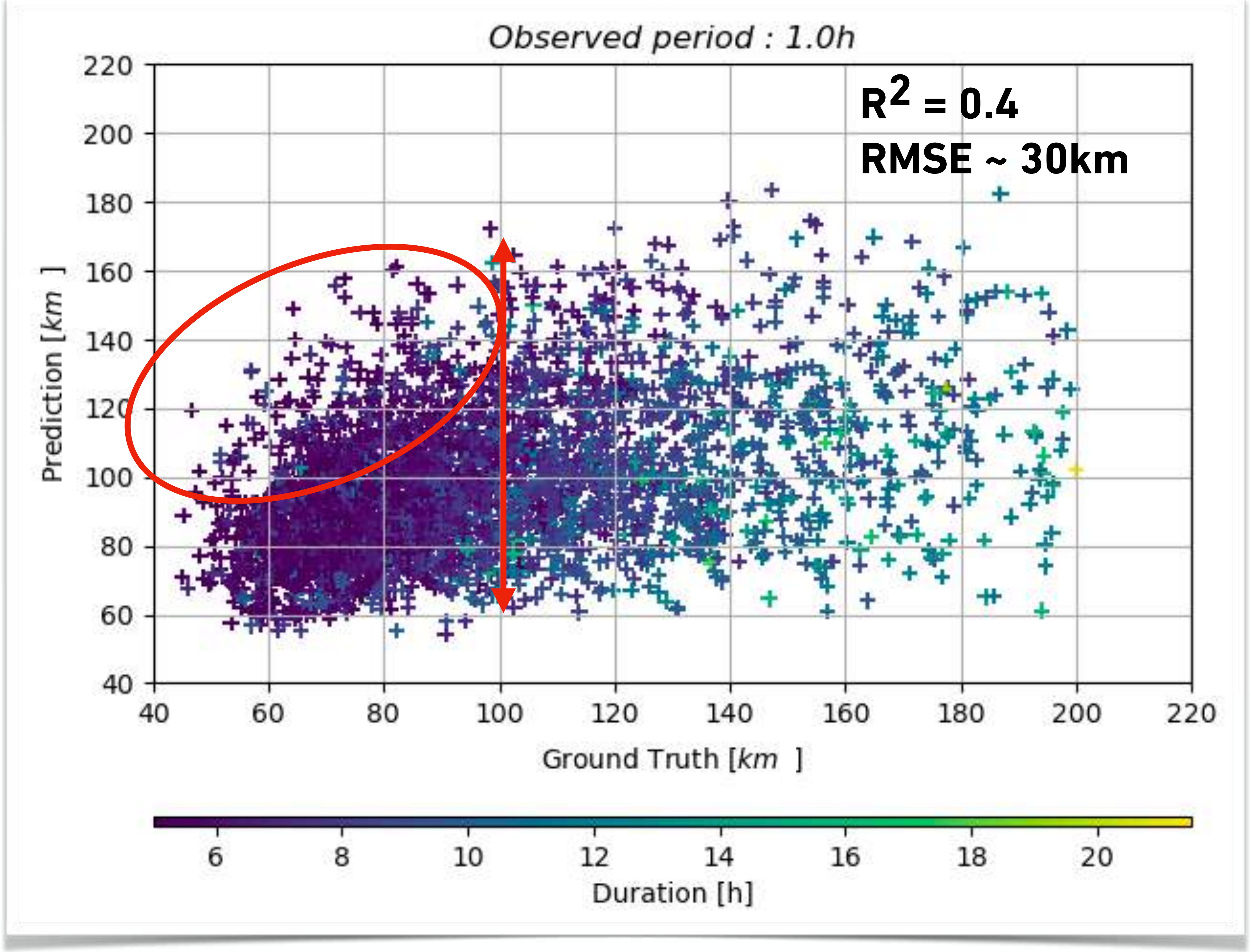




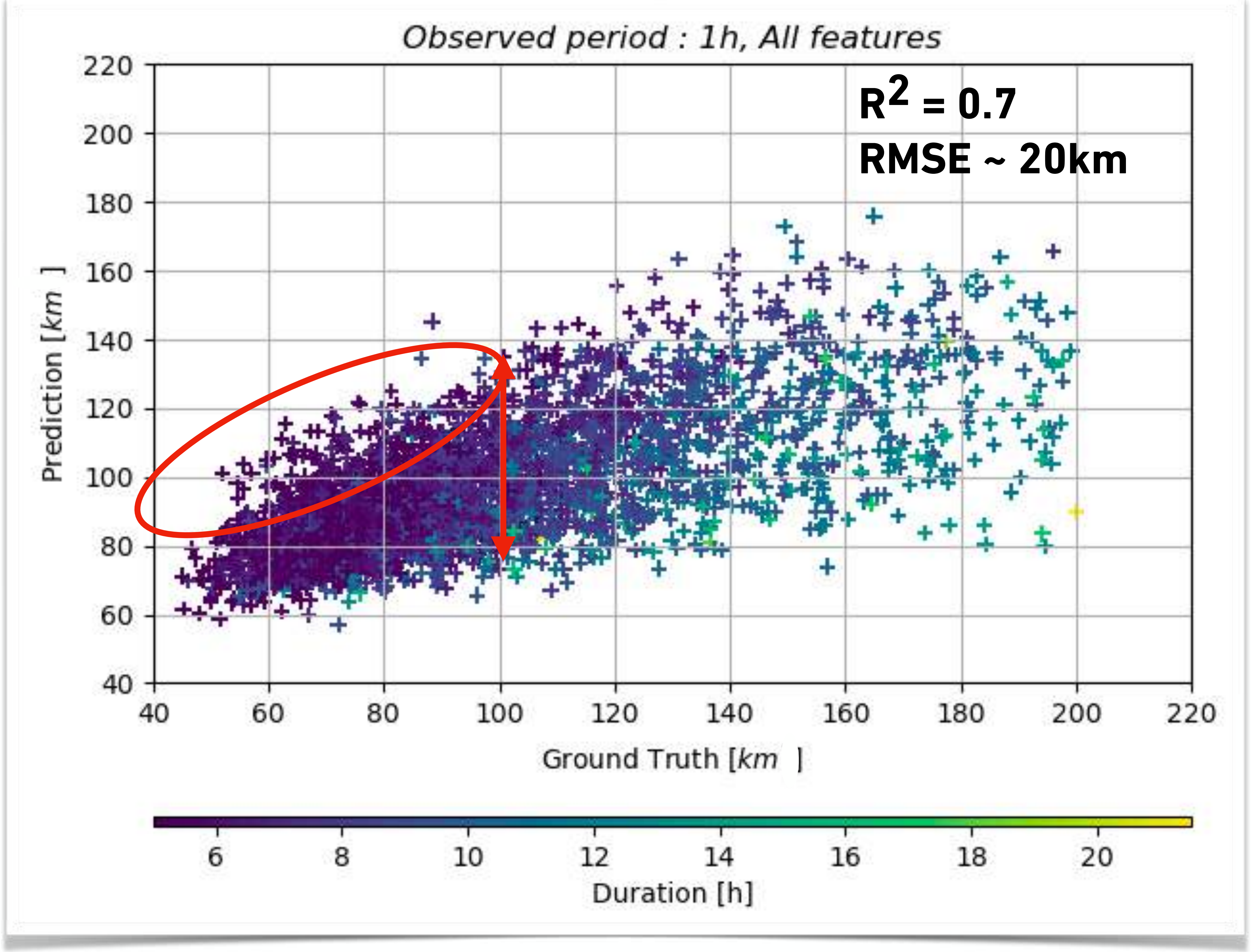
→ *More precise and add correction to the large systems*

Second Experiment : Augmented Model

<u>Baseline</u>



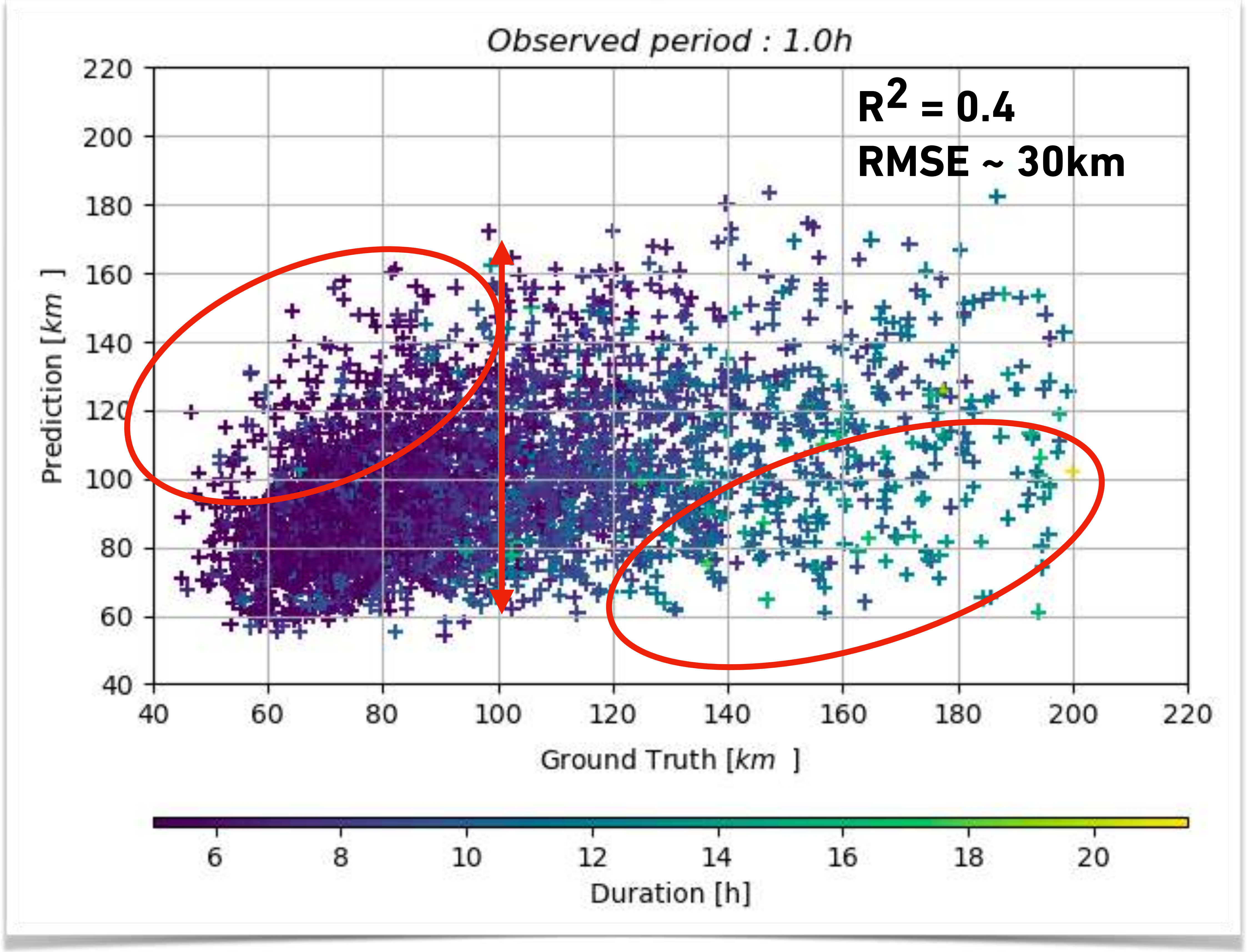
<u>With Features Engineering</u>



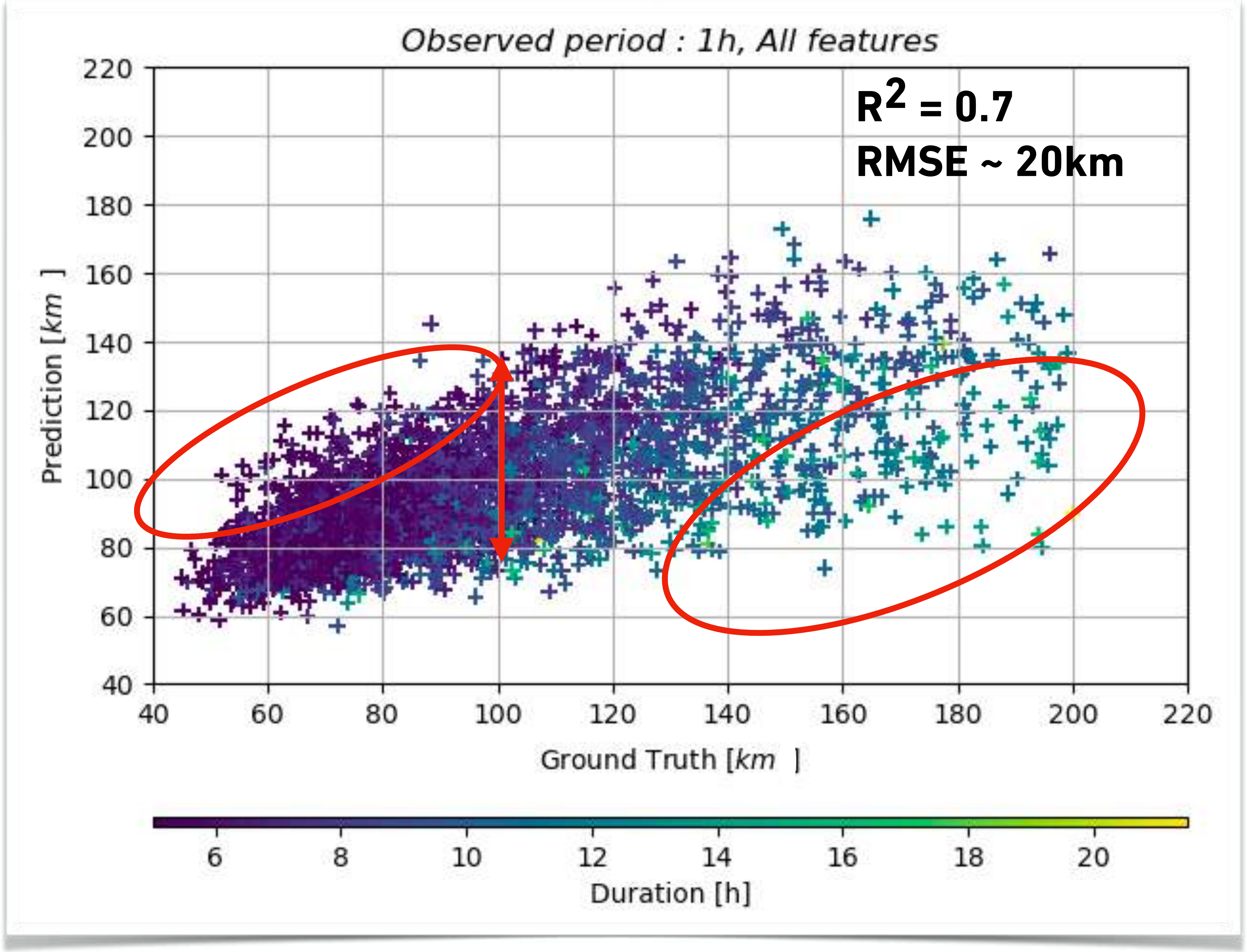
→ *More precise and add correction to the large systems*

Second Experiment : Augmented Model

Baseline

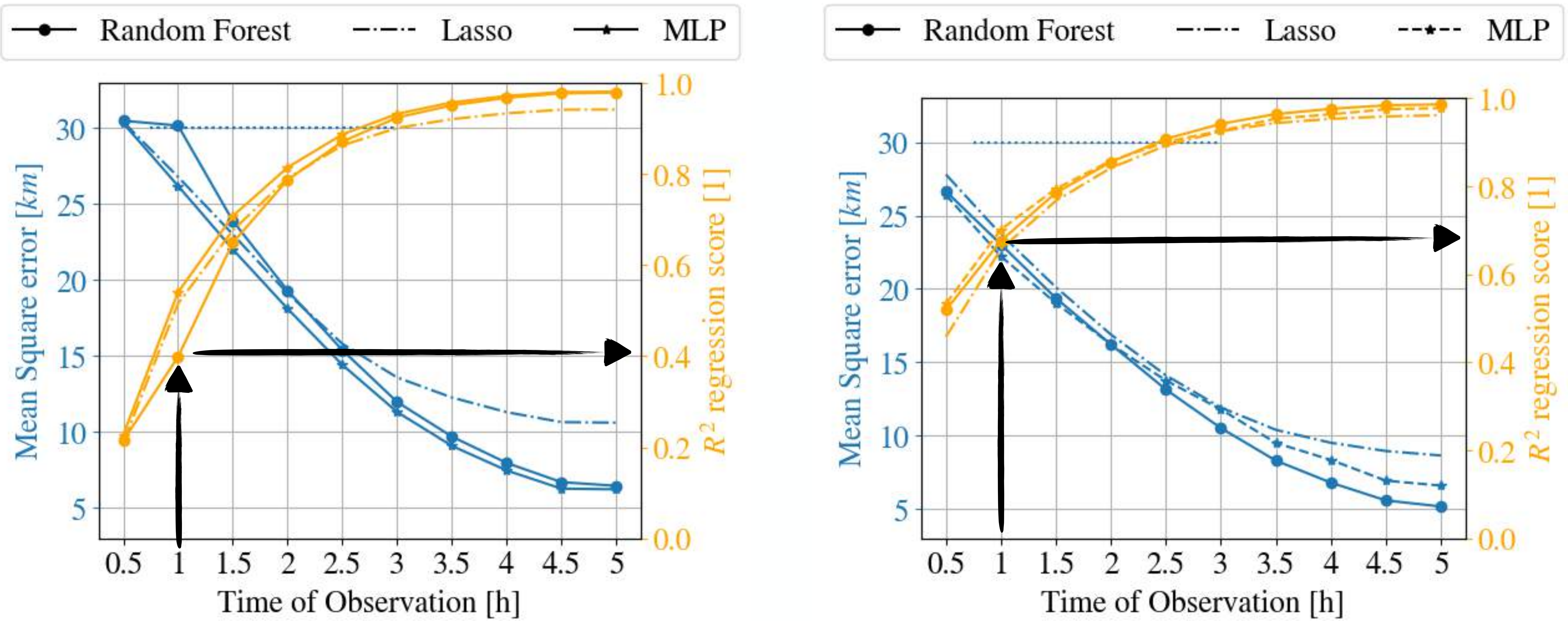


With Features Engineering



→ *More precise and add correction to the large systems*

Second Experiment : Augmented Model



Added features have strongly improve the prediction for all models

→ *Focus on the simplest : Multilinear one*

Questions

Has the life of the MCS been written from the start?

if so, when exactly?

Are there individual, innate characteristics that will shape it,
or does it depend on its environment?

Which features have the strongest impact on the prediction ?

→ Variables

Shape of the cloud	Physical field, in and out of the system
1. Instantaneous area growth rate	2. Std of IWP
4. Equivalent Diameter	3. Mean of LW only within the system
10. Excentricity (core)	6. Std of IWP only within the system
12. Excentricity (envelop)	8. Mean of vertical velocity at 500hPa
	9. Mean of LW

Trajectory and propagation velocity	Surrounding systems influence
11. Migration distance	5. Mean interaction with neighbors
13. Landmask	7. Max interaction with neighbors

Which features have the strongest impact on the prediction ?

→ Variables

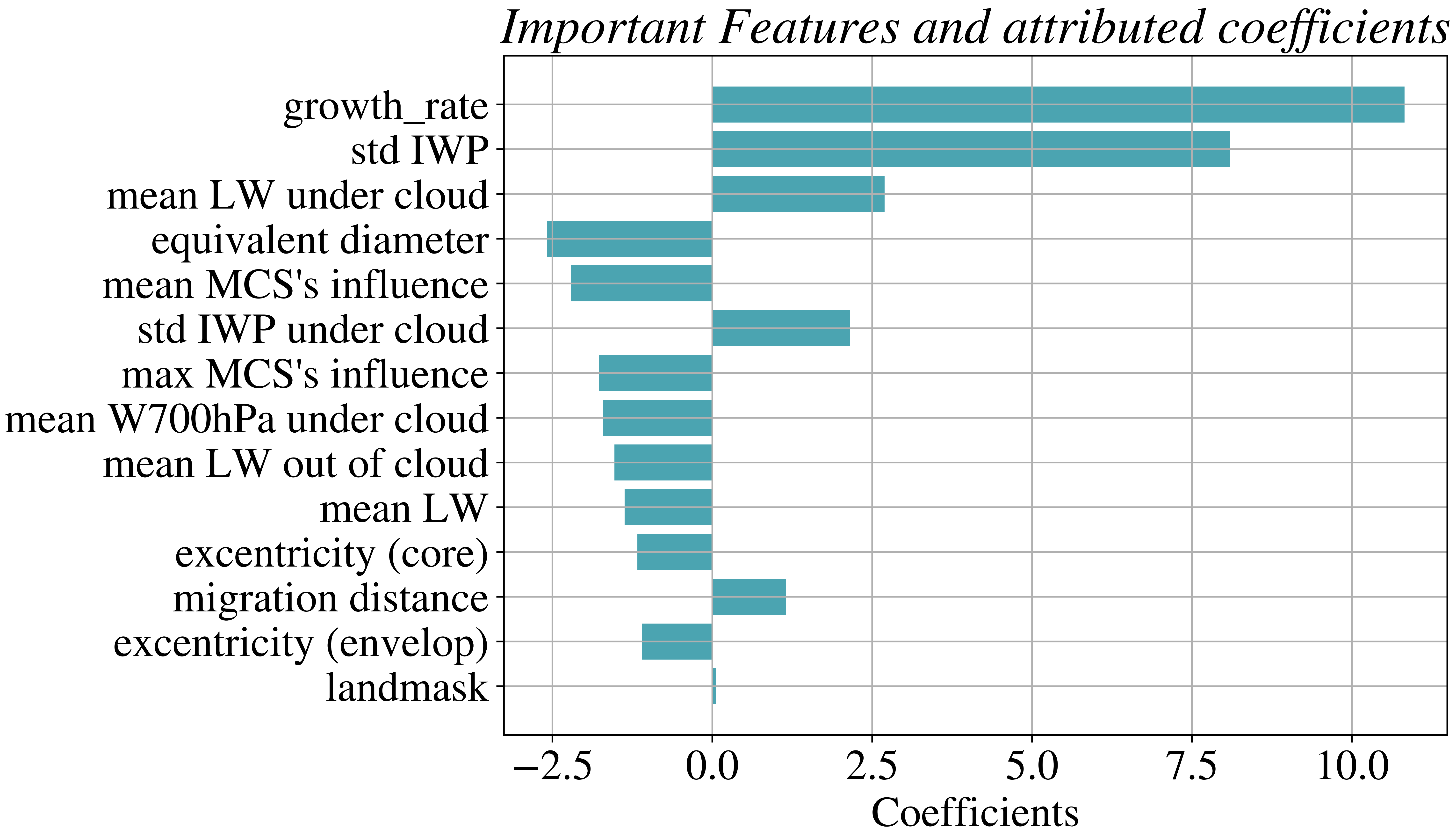
Systems vs Environment

Shape of the cloud	Physical field, in and out of the system
1. Instantaneous area growth rate	2. Std of IWP
4. Equivalent Diameter	3. Mean of LW only within the system
10. Excentricity (core)	6. Std of IWP only within the system
12. Excentricity (envelop)	8. Mean of vertical velocity at 500hPa
	9. Mean of LW
Trajectory and propagation velocity	**Surrounding systems influence**
11. Migration distance	5. Mean interaction with neighbors
13. Landmask	7. Max interaction with neighbors

→ Qualitatively both have strong impact on the prediction

Which features have the strongest impact on the prediction ?

$$\sqrt{\mathcal{A}_{max}} = \ell(f_1, f_2, \ldots f_n) \sim \ell(f_1, f_2, \ldots f_{13}) = c_1 f_1 + c_2 f_2 + \ldots + c_{13} f_{13}$$



→ Can features from environnement and the system itself be interpreted as principal component of the area variability ?

Principal Component Analysis

$$\sqrt{\mathscr{A}_{max}} = \ell(f_1, f_2, \ldots f_n) \sim \ell(f_1, f_2, \ldots f_{14}) = c_1 f_1 + c_2 f_2 + \ldots + c_{14} f_{14}$$

Features relative to the environment or to the system can be gathered

1. Instantaneous area growth rate
4. Equivalent Diameter
10. Excentricity (core)
12. Excentricity (envelop)
...

$$\sqrt{\mathscr{A}_{max}} \sim \underbrace{\sum_{i \in sys} c_i fi}_{X} + \underbrace{\sum_{j \in env} c_j f_j}_{Y}$$

2. Std of IWP
8. Mean of vertical velocity at 500hPa
9. Mean of LW
5. Mean interaction with neighbors
...

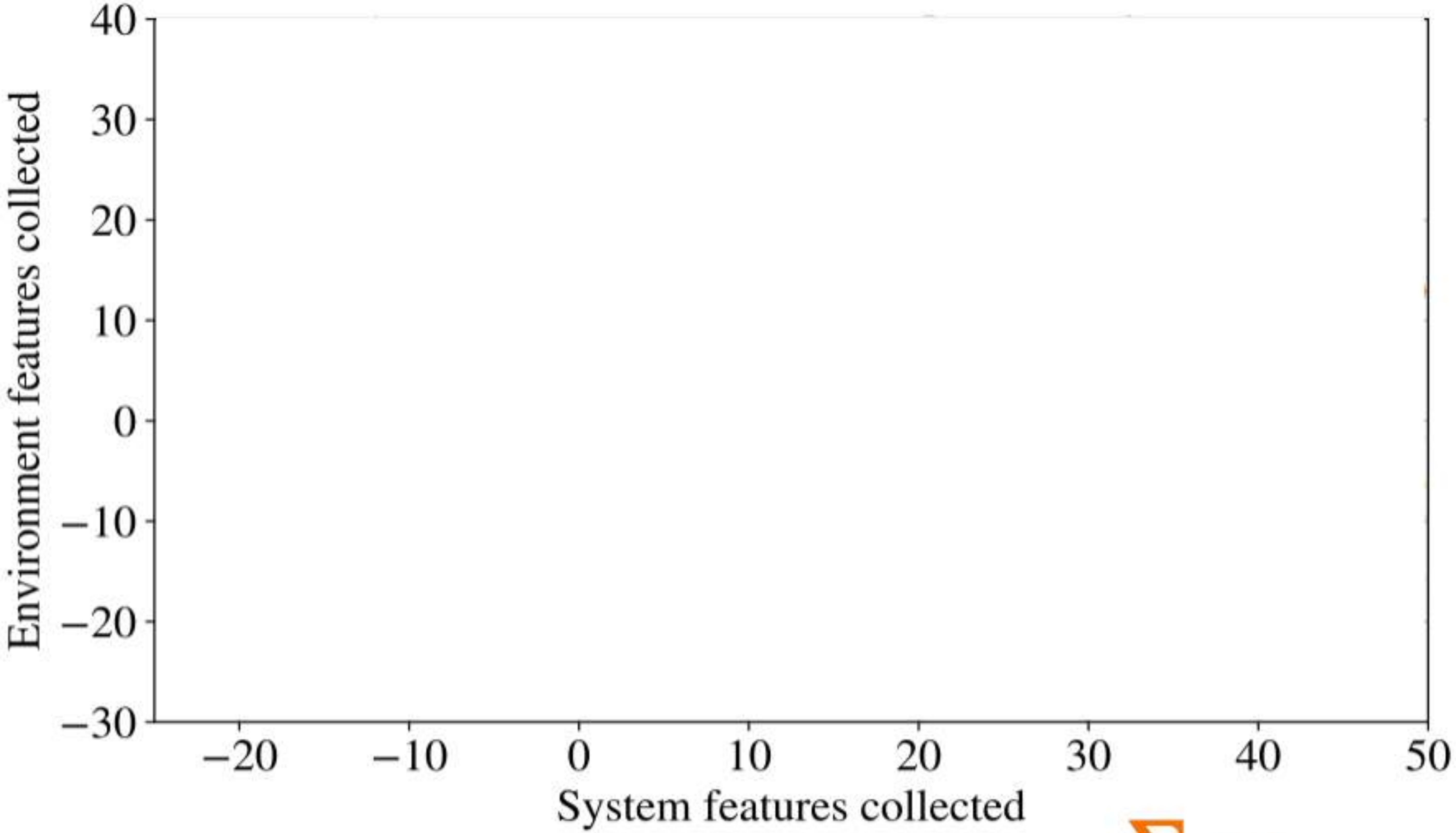
Does this decomposition explains the variability in maximal extension ?

$$\nabla \sqrt{\mathscr{A}_{max}} = \left\{ \frac{\partial \sqrt{\mathscr{A}_{max}}}{\partial X}, \frac{\partial \sqrt{\mathscr{A}_{max}}}{\partial Y} \right\}$$

Principal Component Analysis

$$\mathscr{A}_{max} = \sum_{i \in sys} c_i fi + \sum_{j \in env} c_j f_j$$

$$\sum_{j \in env} c_j f_j$$

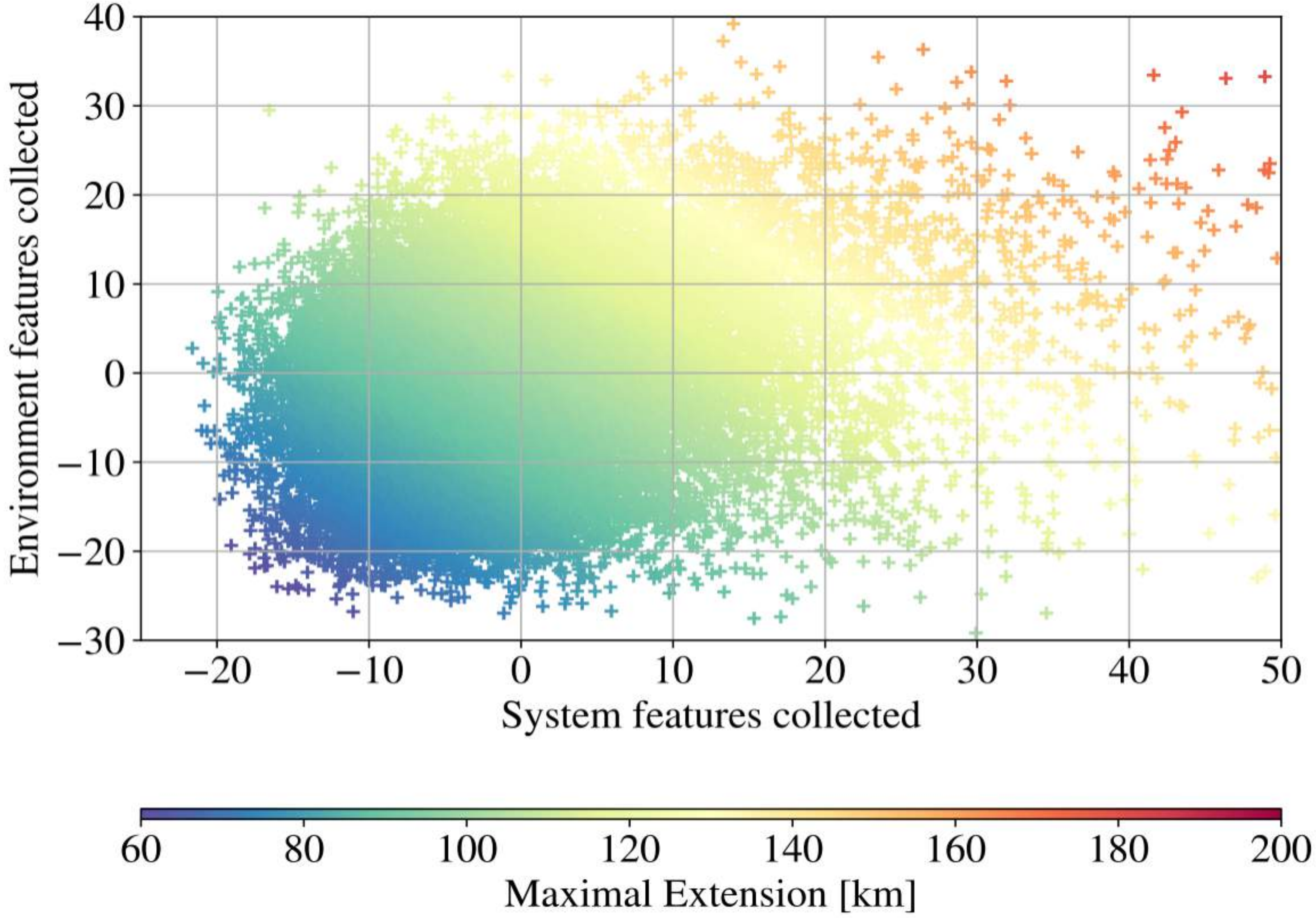


$$\sum_{i \in sys} c_i fi$$

Principal Component Analysis

$$\mathscr{A}_{max} = \sum_{i \in sys} c_i fi + \sum_{j \in env} c_j f_j$$

$$\sum_{j \in env} c_j f_j$$



$$\sum_{i \in sys} c_i fi$$

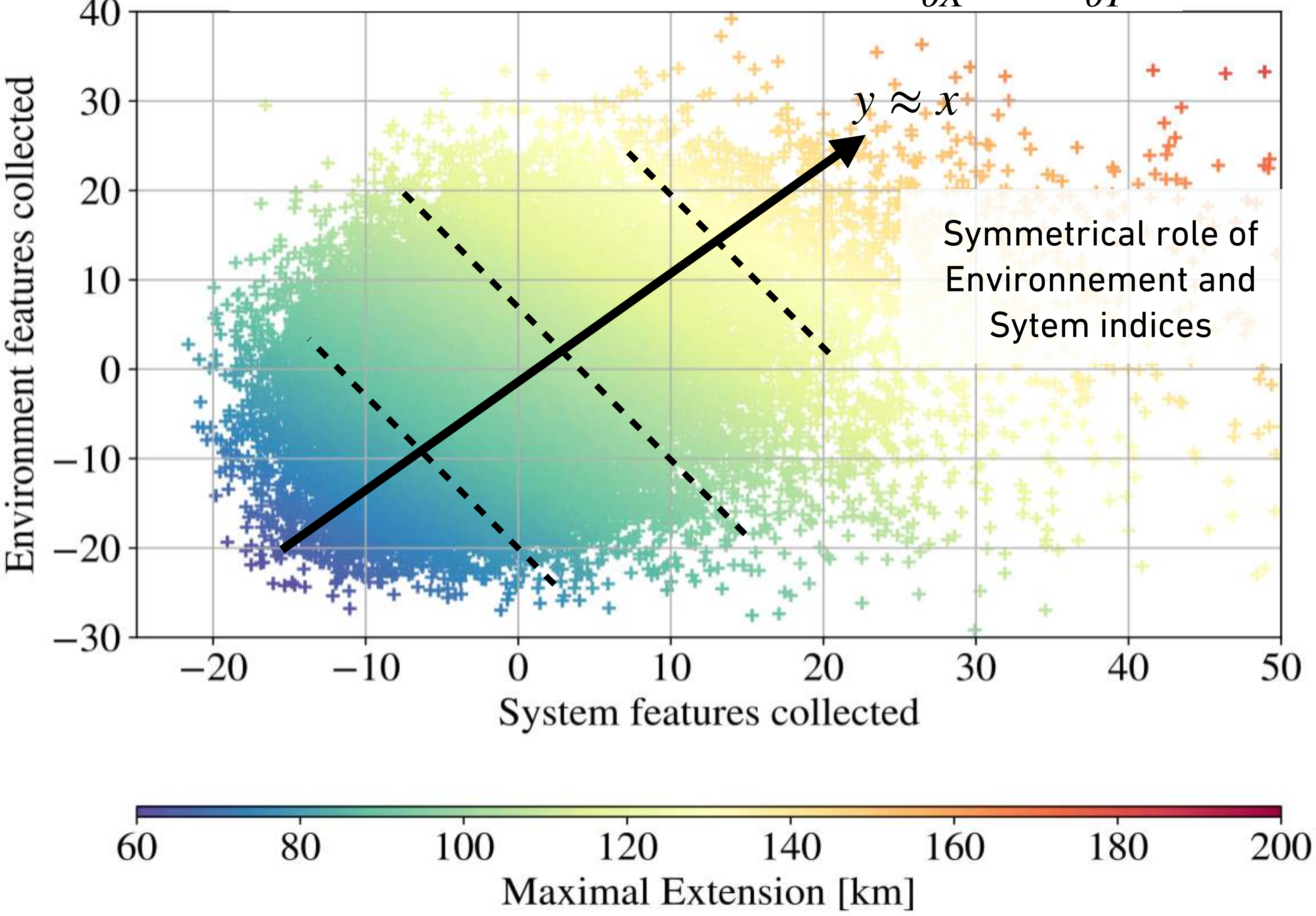
Linear increase of the maximal extension

Principal Component Analysis

$$\mathscr{A}_{max} = \sum_{i \in sys} c_i fi + \sum_{j \in env} c_j f_j$$

$$\nabla \sqrt{\mathscr{A}_{max}} = \{ \frac{\partial \sqrt{\mathscr{A}_{max}}}{\partial X}, \frac{\partial \sqrt{\mathscr{A}_{max}}}{\partial Y} \}$$

$\sum_{j \in env} c_j f_j$



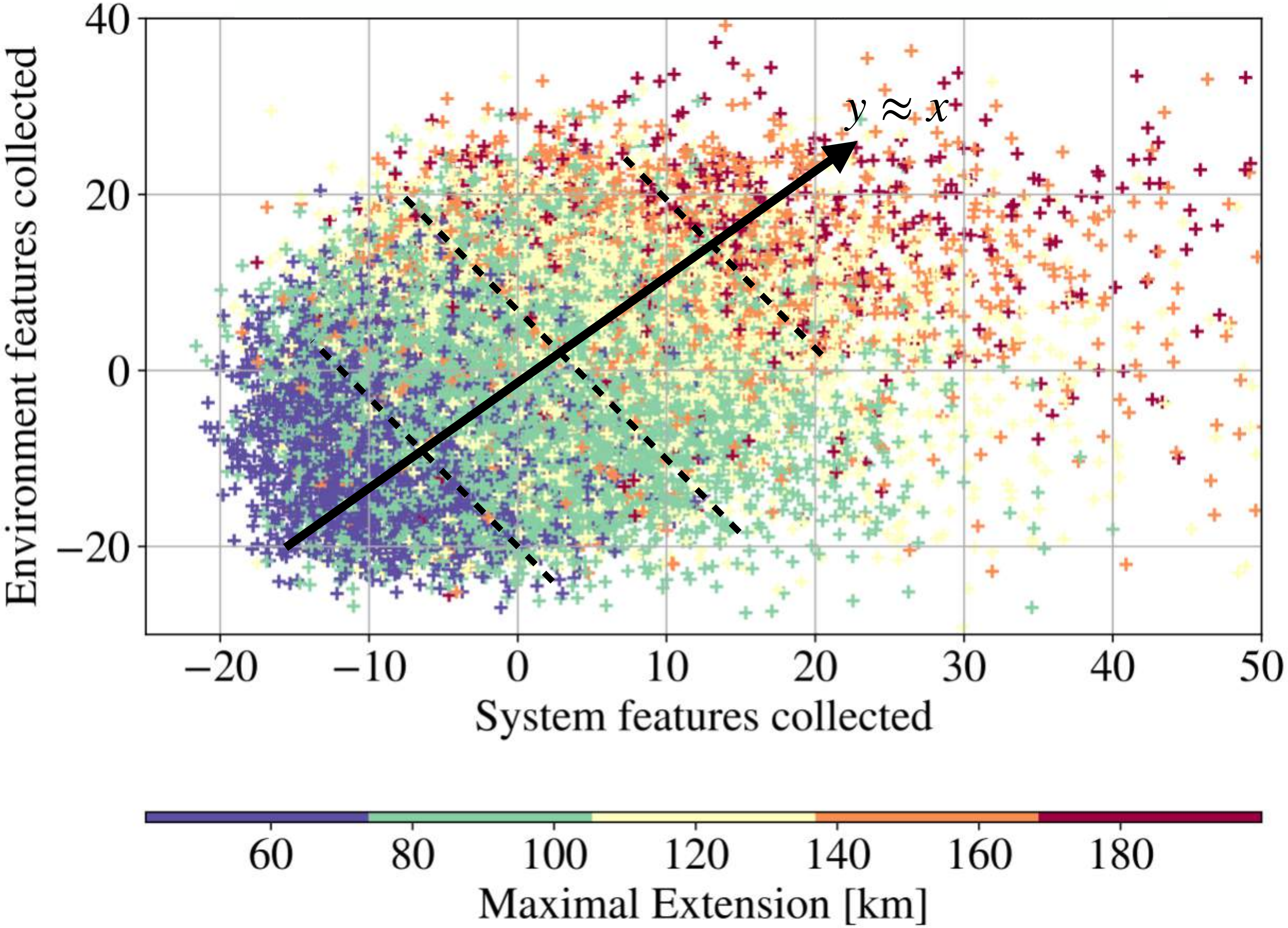
$\sum_{i \in sys} c_i fi$

→ *Similar impact of the weighted factors from the environnement and those from the system in the model*

Principal Component Analysis

$$\mathscr{A}_{max} = \sum_{i \in sys} c_i fi + \sum_{j \in env} c_j f_j$$

$\sum_{j \in env} c_j f_j$

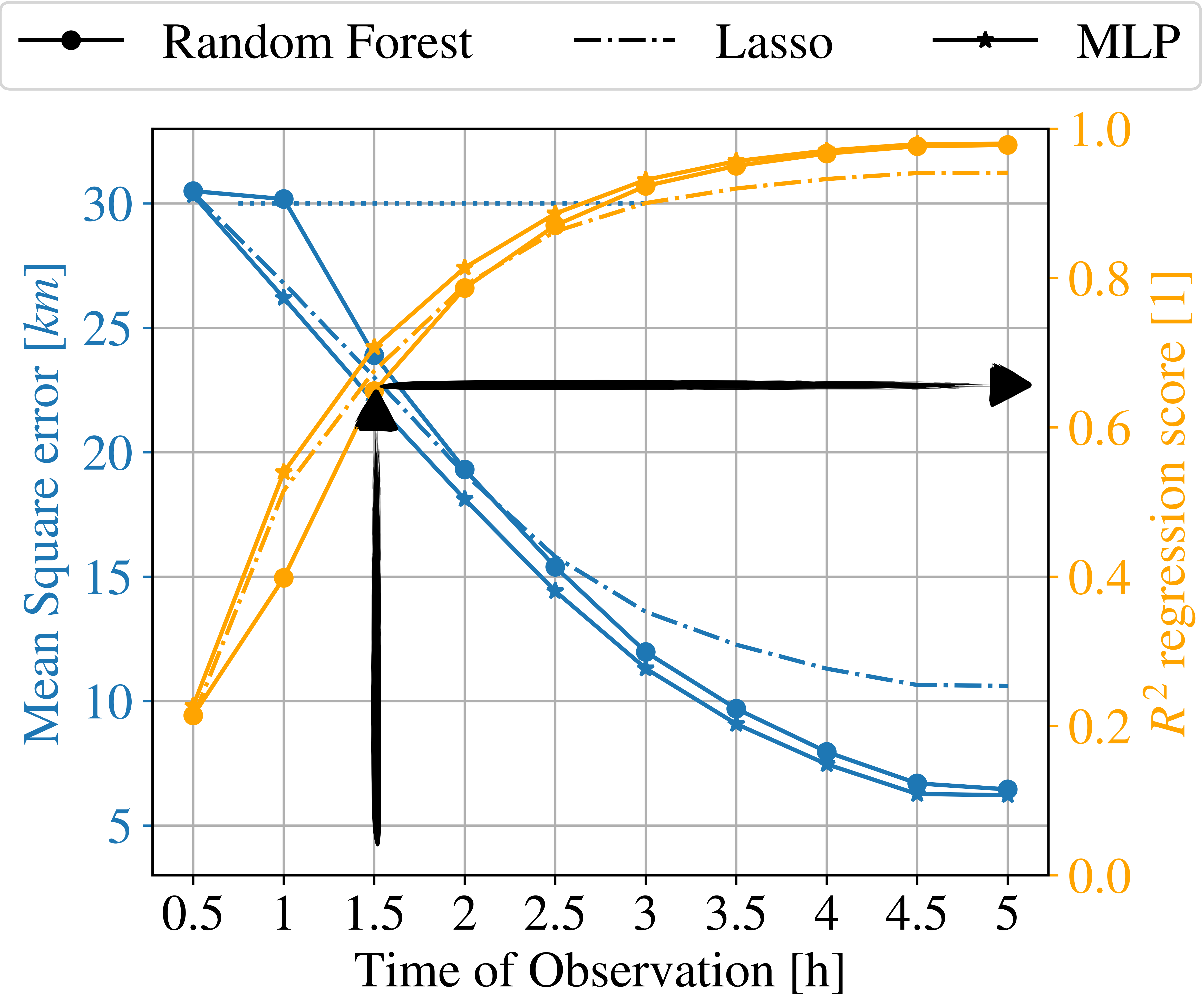


$\sum_{i \in sys} c_i fi$

→ Features from environnement and the system itself can be interpreted as principal components of the area variability

Conclusion

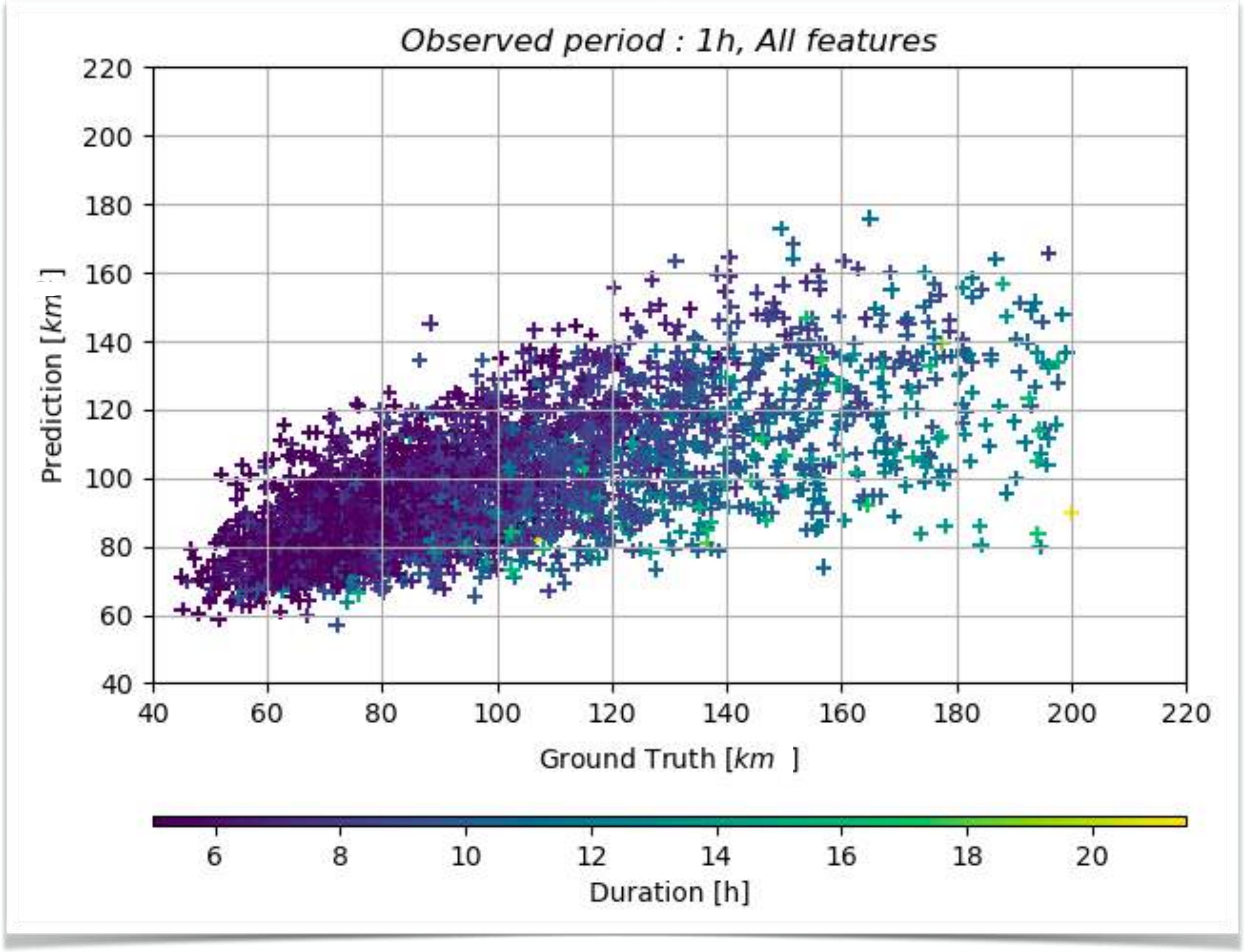
1. With 1.5h of only cloud shield observation a RF regressor can predict the maximal extension with R^2 =0.63 score and a mean error of 20km



Conclusion

1. With 1.5h of only cloud shield observation a RF regressor can predict the maximal extension with R^2 =0.63 score and a mean error of 20km

2. Adding features of the system and its environment including the shape, physical fields, trajectory and influence of neighbors we can reach R^2 =0.70 in 1h only

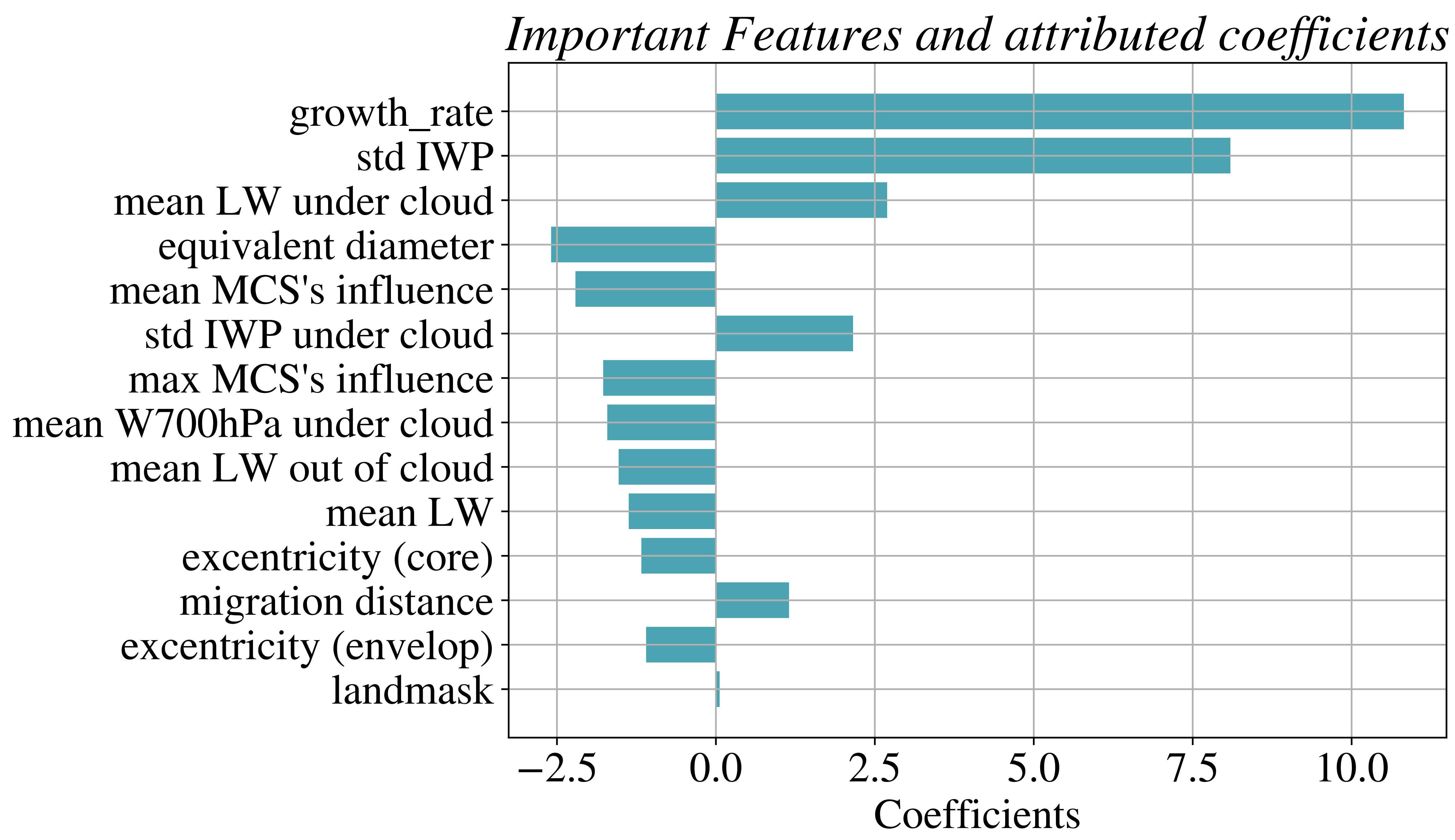


Conclusion

1. With 1.5h of only cloud shield observation a RF regressor can predict the maximal extension with R^2 =0.63 score and a mean error of 20km

2. Adding features of the system and its environment including the shape, physical fields, trajectory and influence of neighbors we can reach R^2 =0.70 in 1h only

4. Features at stake are mainly the the growth rate intensity, presence of ice in the system and in the environment, and the interaction with neighbors



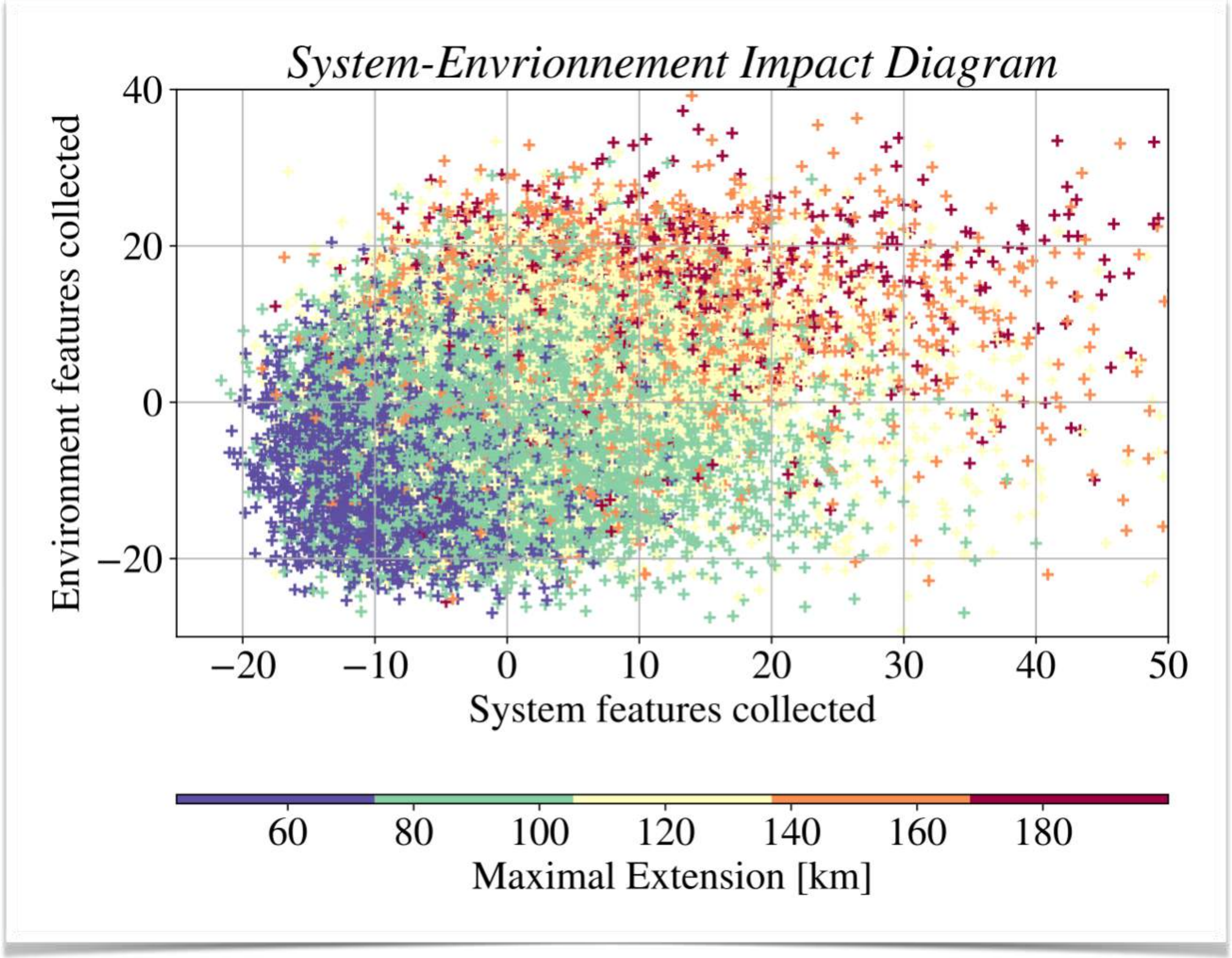
Conclusion

1. With 1.5h of only cloud shield observation a RF regressor can predict the maximal extension with R^2 =0.63 score and a mean error of 20km

2. Adding features of the system and its environment including the shape, physical fields, trajectory and influence of neighbors we can reach R^2 =0.70 in 1h only

4. Features at stake are mainly the the growth rate intensity, presence of ice in the system and in the environment, and the interaction with neighbors

5. Multilinear model allows a principal component analysis based on features related to the environnement and those to the system



Abramian et al 2024 (In preparation)

Oultines

Introduction

*Muller C. & **Abramian S.** 2023, Physics Today*

Part 1

Idealized Simulations

What sets tropical squall lines orientation and why ?

***Abramian S.**, Muller C., Risi C., 2022, GRL*

How does the orientation of the line impact extreme precipitation ?

***Abramian S.**, Muller C., Risi C., 2023, JAMES*

Part 2

Realistic Global Simulations

What sets the maximal extension of MCSs ?

*In Prep. **Abramian S.**, Muller C., Risi C., Roca R., Fiolleau T.,*

How convective systems are recorded in past climate archive ?

*Risi C., Muller C., Vimeux F., Blossey P., Védeau G., Dufaux C., **Abramian S.**, 2023, JAMES*

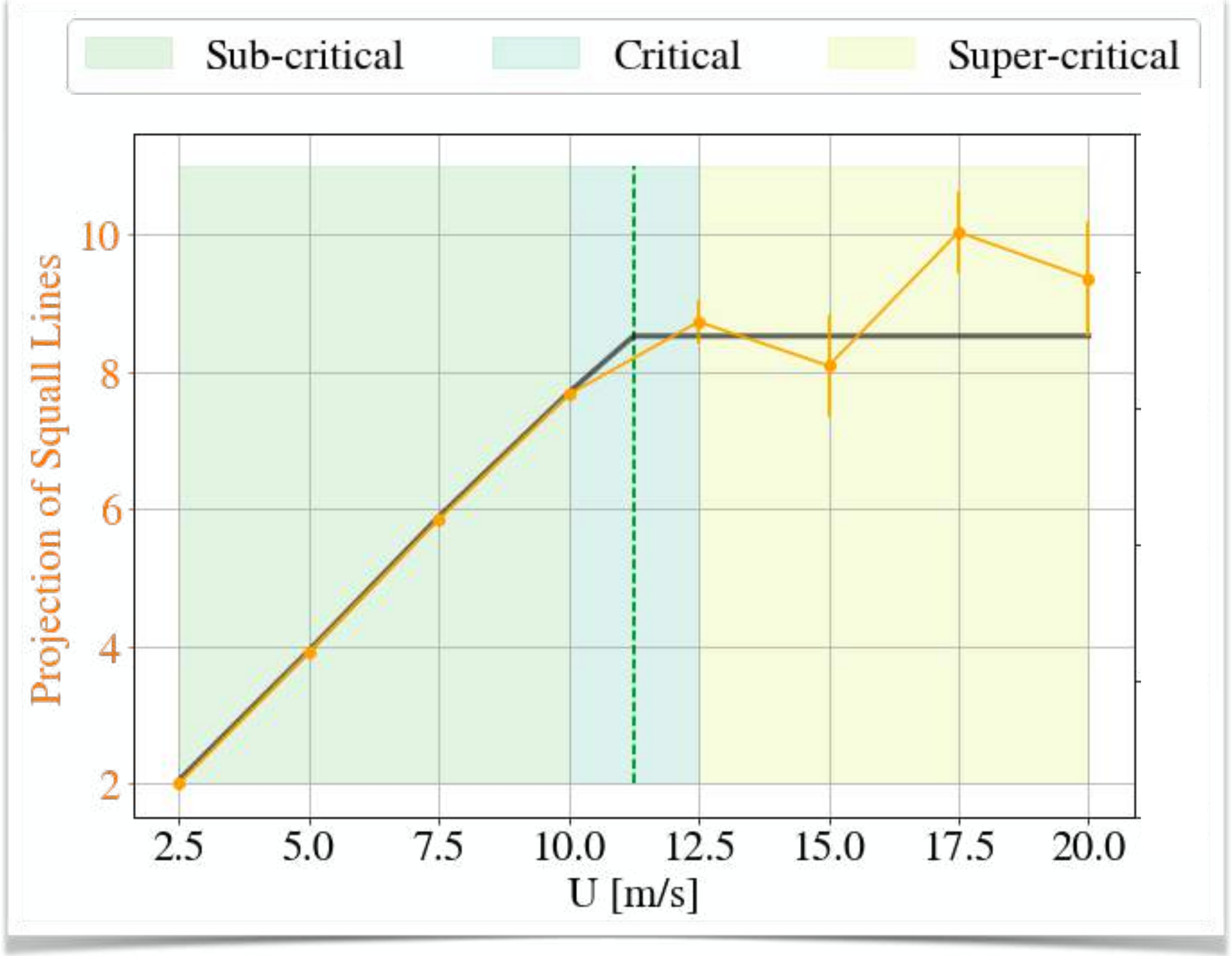
Conclusion and Perspectives

Take home messages

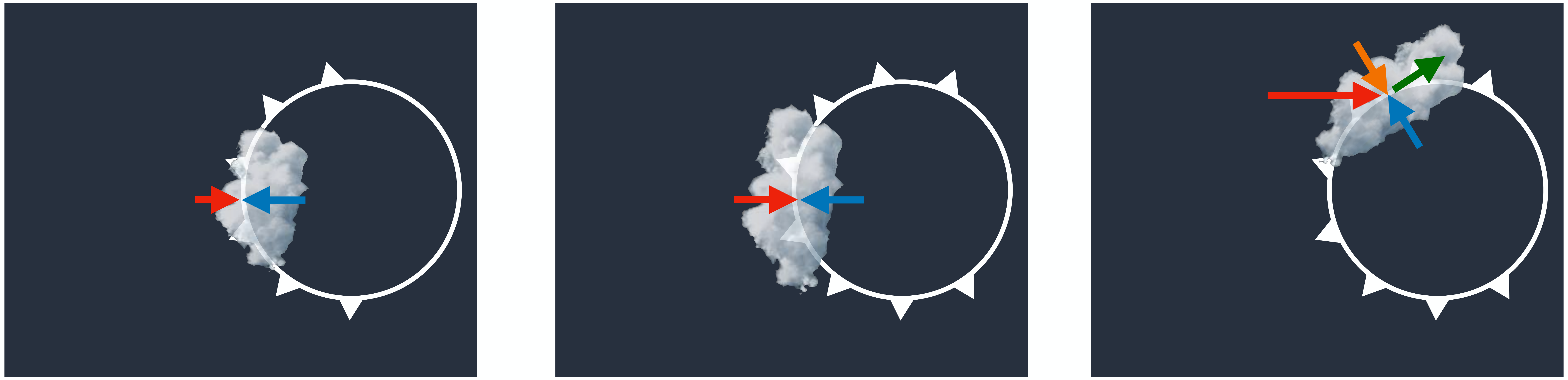
Part 1 What sets tropical squall lines orientation and why ?

- In the supercritical regime, the orientation of the squall lines reduces the incoming wind shear, and maintains the equilibrium
- Precipitation extremes are enhanced by about 30%–40% in optimal and superoptimal squall lines compared to random convection
- The enhancement of extremes is due to reduced dilution by entrainment and enhanced initial vertical velocity of updrafts in optimal and superoptimal regimes

Abramian S., Muller C., Risi C., 2022, GRL *Abramian S., Muller C., Risi C., 2023, JAMES*



Suboptimal **Optimal** **Superoptimal**



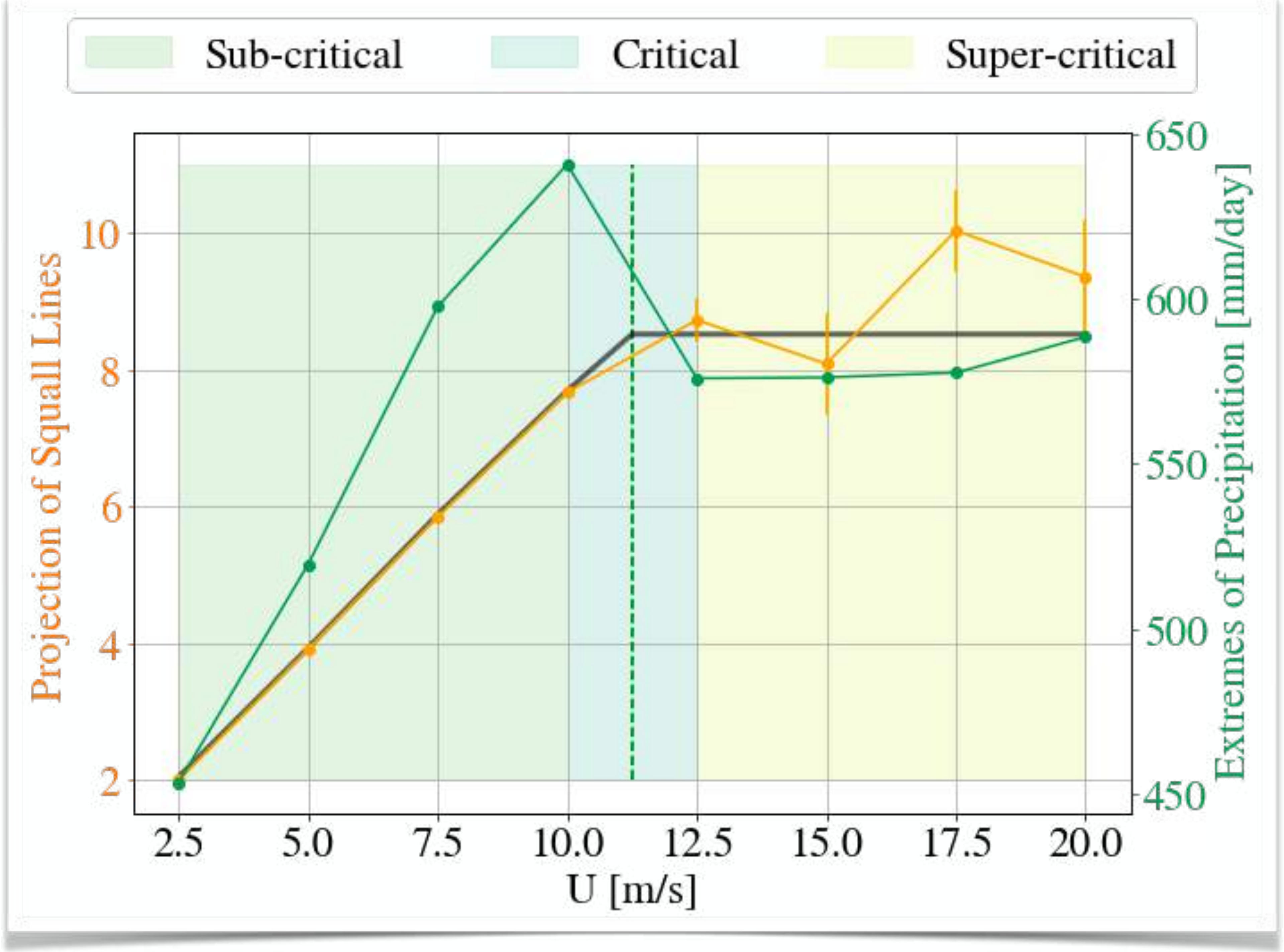
Take home messages

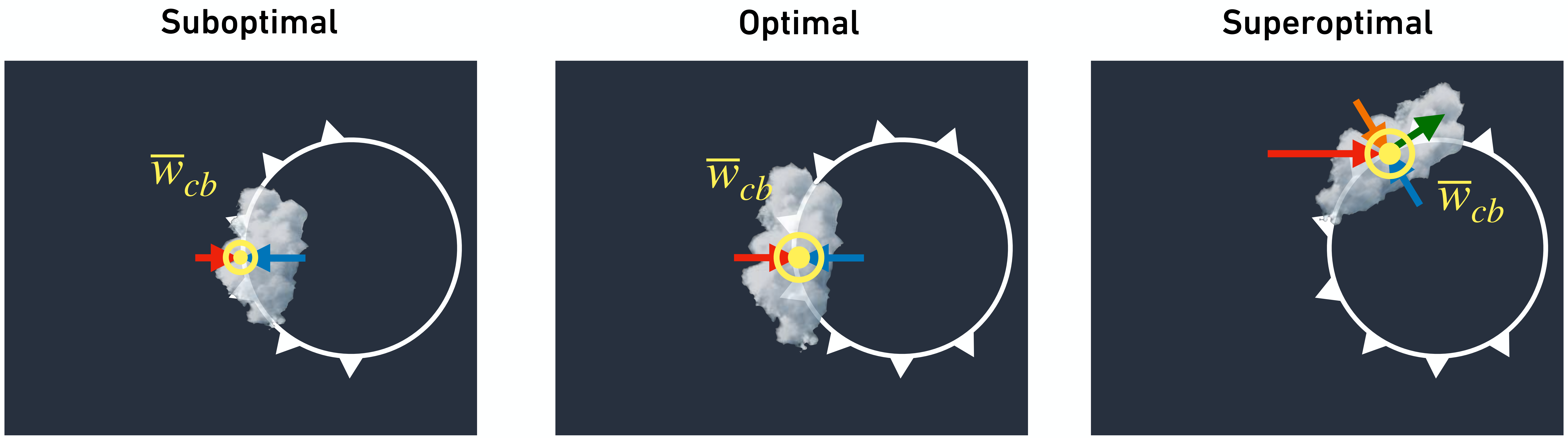
Part 1

How does the orientation of the line impact extreme precipitation ?

- In the supercritical regime, the orientation of the squall lines reduces the incoming wind shear, and maintains the equilibrium
- Precipitation extremes are enhanced by about 30%–40% in optimal and superoptimal squall lines compared to random convection
- The enhancement of extremes is due to reduced dilution by entrainment and enhanced initial vertical velocity of updrafts in optimal and superoptimal regimes

Abramian S., Muller C., Risi C., 2022, GRL *Abramian S., Muller C., Risi C., 2023, JAMES*





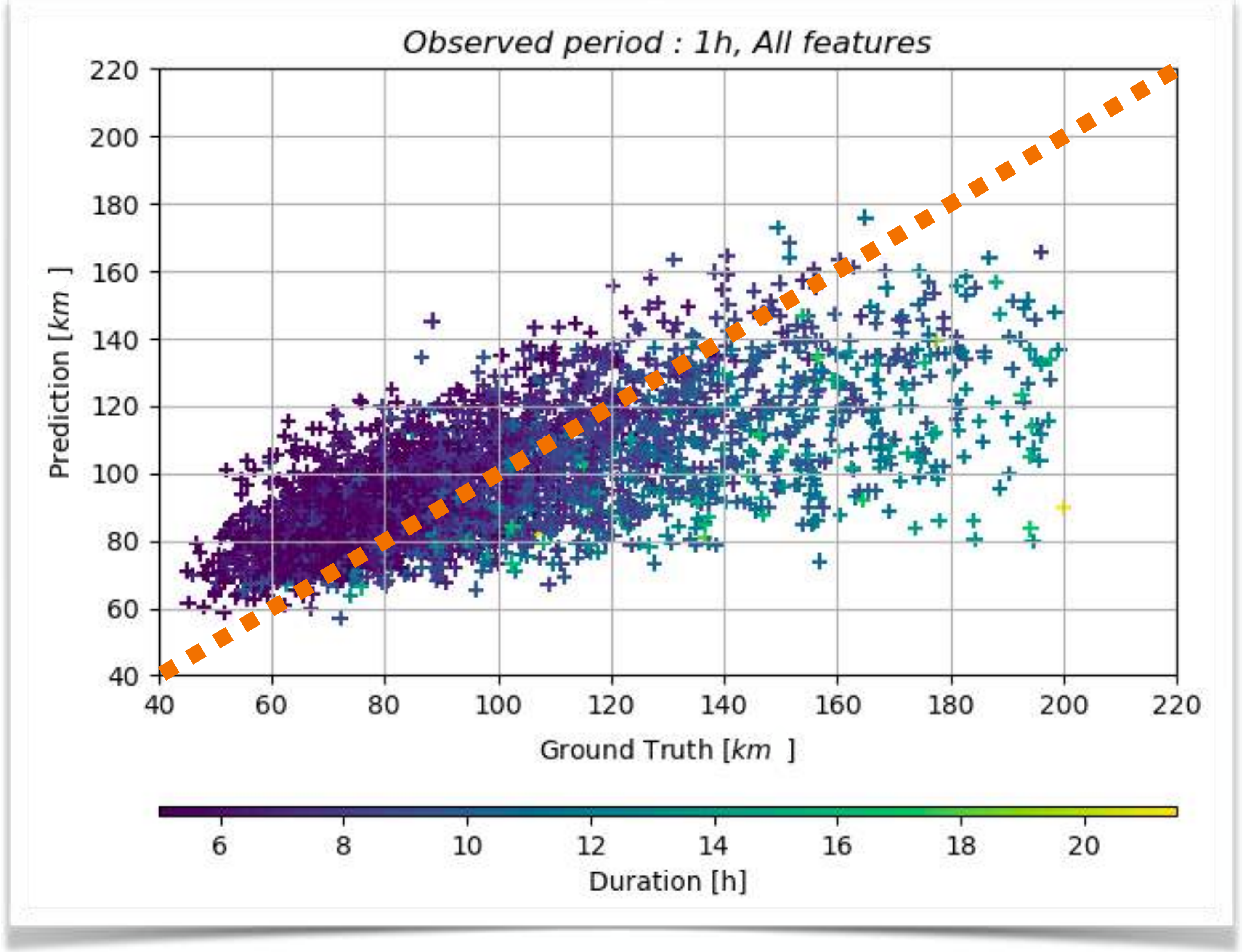
Take home messages

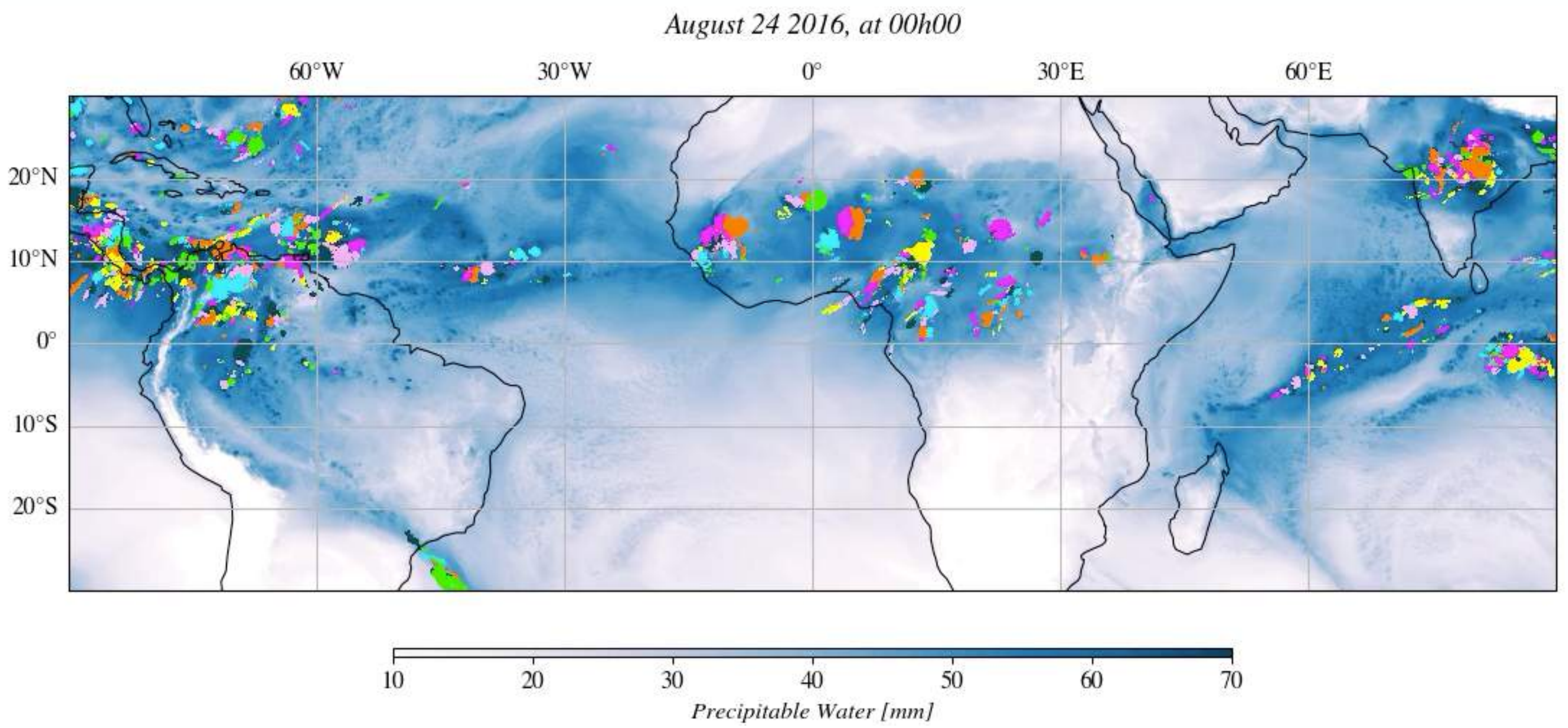
Part 2

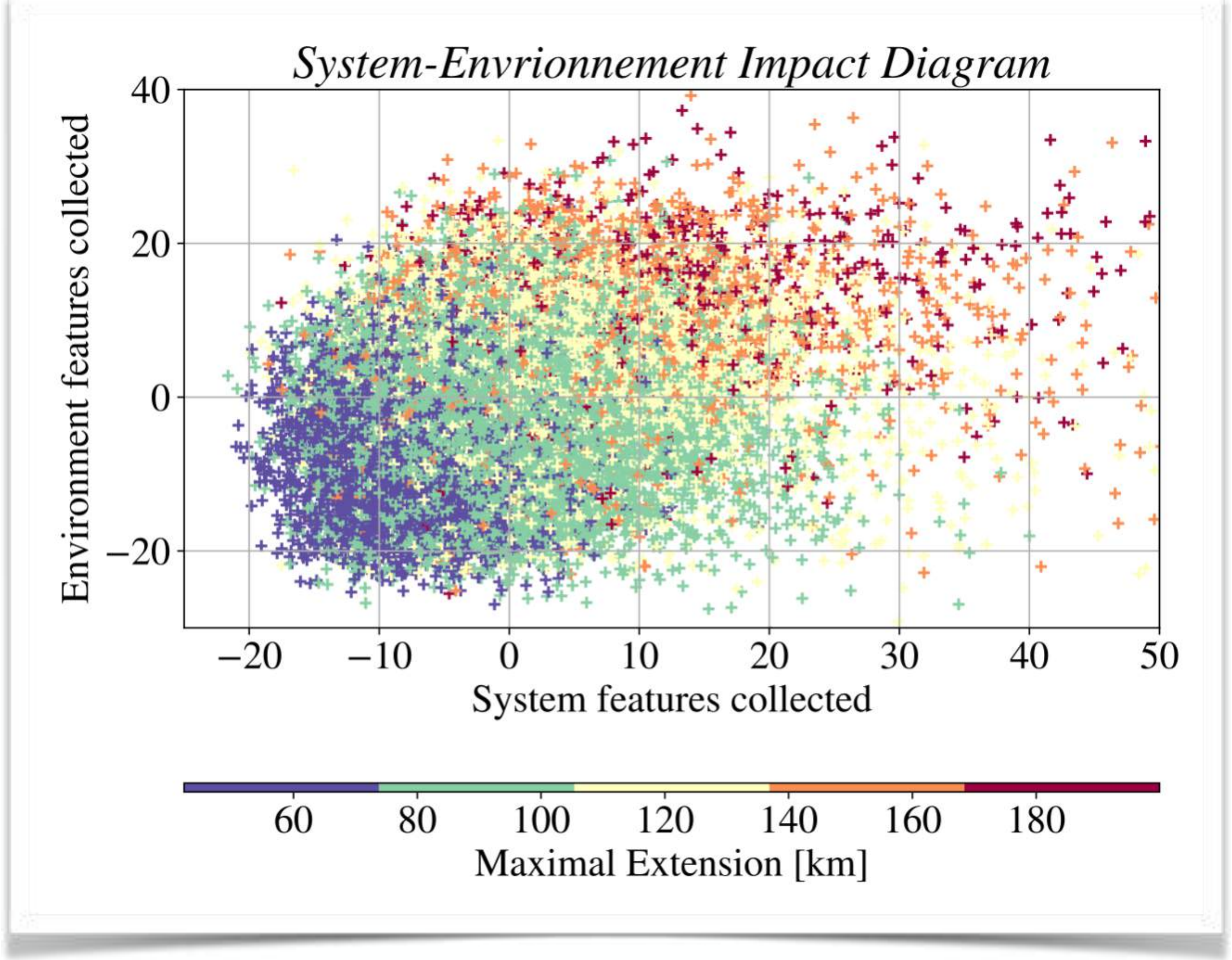
What sets the maximal extension of MCSs ?

- Initial growth rate of MCSs strongly anticipated their eventual maximum area
- Incorporating additional features allow to predict the maximal area of MCSs with just one hour of observation (R-squared 0.7)
- Noteworthy factors are the growth rate, the presence of ice in the system's environment and proximity to surrounding systems

In Prep. Abramian S., Muller C., Risi C., Roca R., Fiolleau T.,





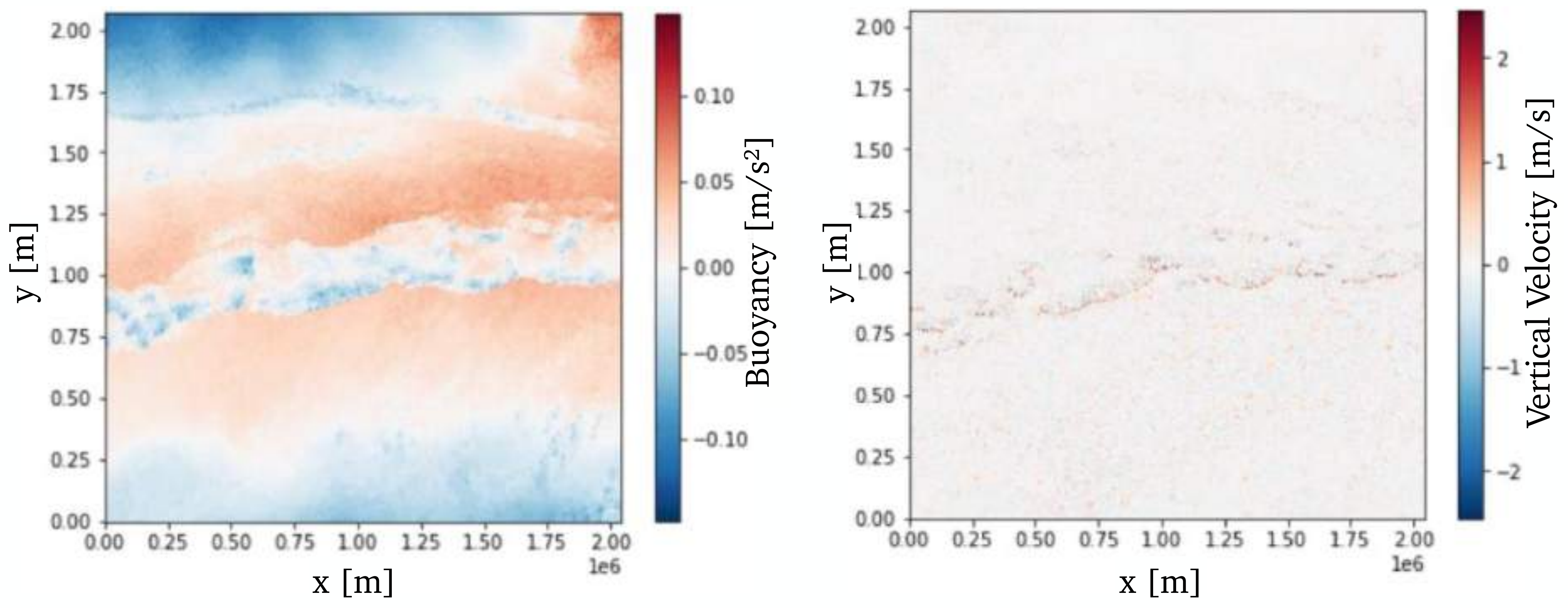


Short term perspectives

Part 1

Intern Marin Siron, master student

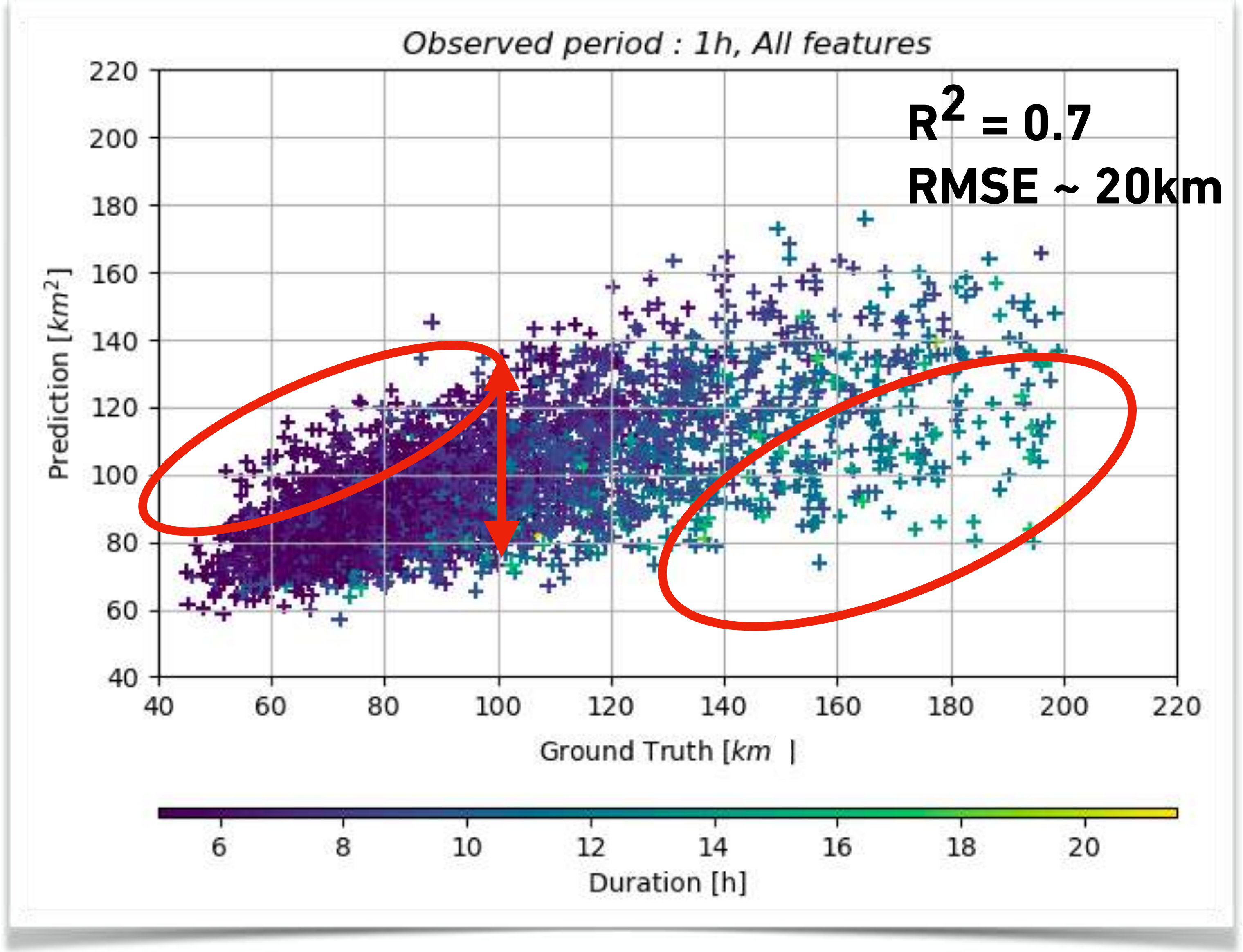
- ***Can we extend these results to more realistic data ?***
  - How to characterize squall lines in GCRMs (and not mistake them for the ITCZ) ?
    Beucler et al 2020, Windmiller and Stevens 2023
  - Do they show different regimes of development ? What does the cold pools properties look like ?
    Grant et al 2020, Liu and Moncrieff 2017



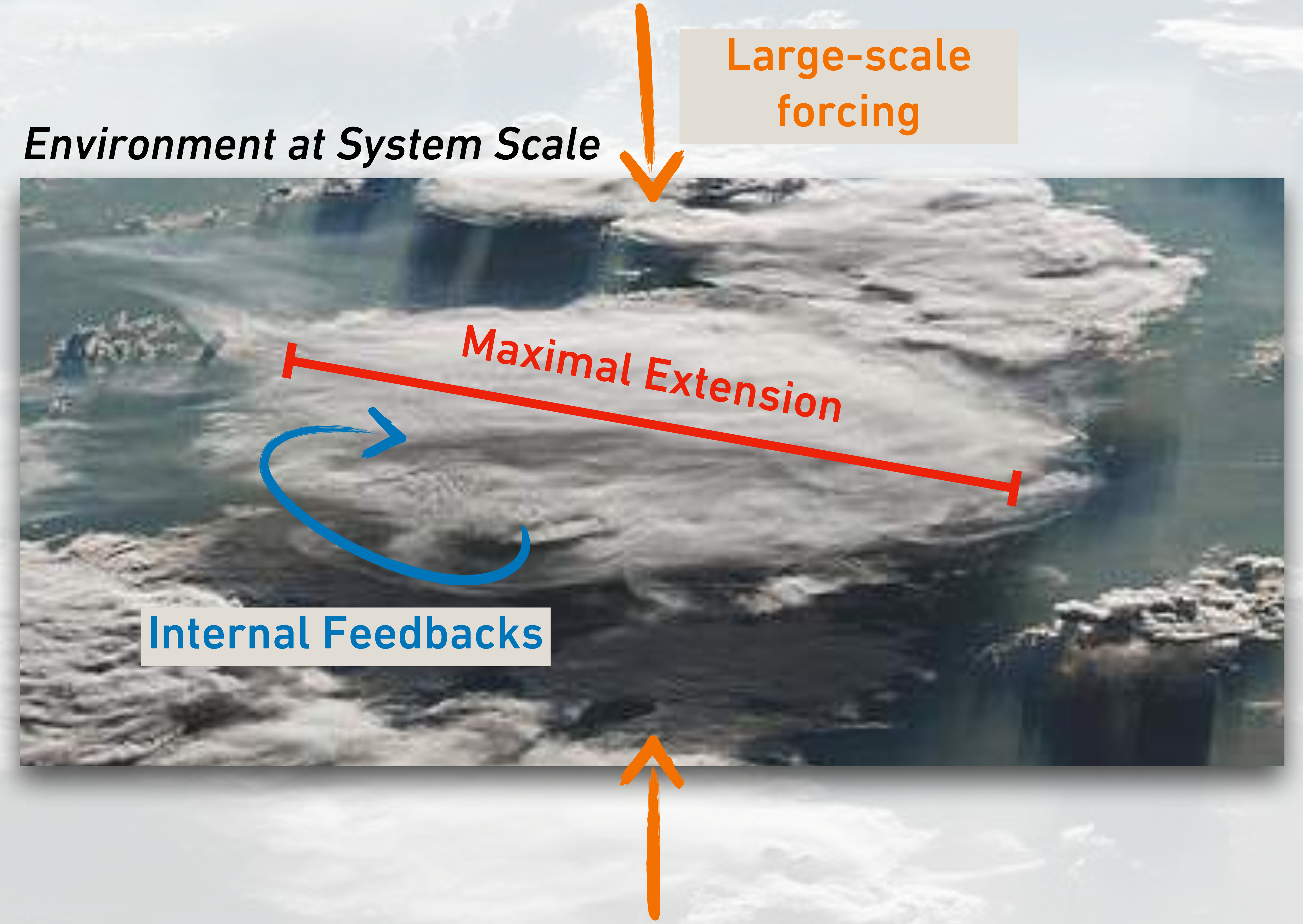
Part 2

- ***Can the prediction of maximum MCSs area be applied to observational data ?***
  - Database (*Fiolleau et al. 2020*) provides 5-year period of observational data for different regions in the tropics
  - Preliminary discussions with researchers from Meteo-France and NOAA have been started to application for nowcasting

- ***What is the archetype of unpredictable MCSs ?***
  - Some MCSs are difficult to predict which can suggest that boundary conditions balance initial growth; but how and why ? *Roca et al 2017*
  - Does the spatial structure improve the prediction ?



System Scale : what did we learn ?



Part 1

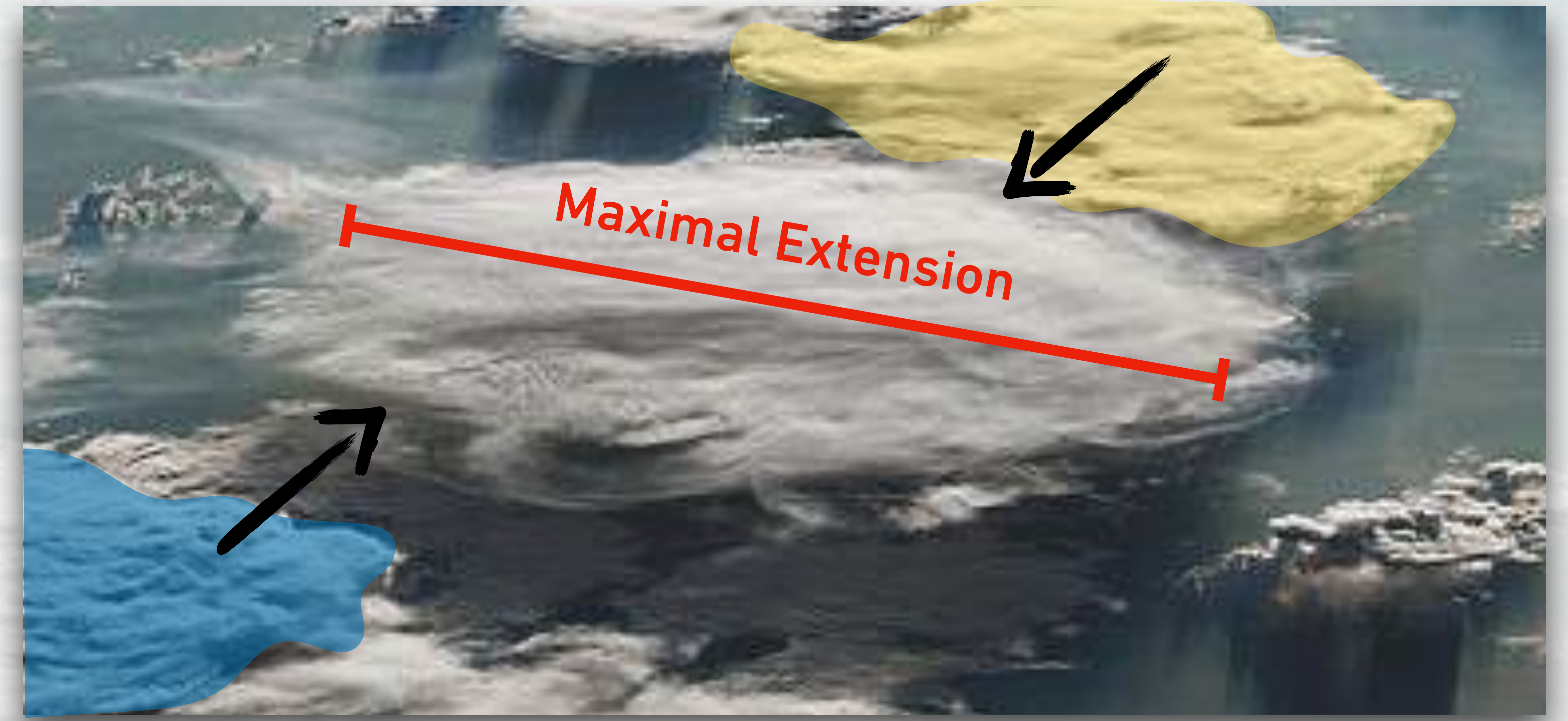
Physical processes controlling the morphological properties of MCSs also control precipitation extreme at the scale of the system

Long term perspectives

System Scale : what did we learn ?

Part 2

Among the mechanisms modulating these properties, the presence and size of neighboring systems seems to play an important role



To understand how system organizes and expands one must understand how systems organize themselves in relation with each other

Long term perspectives

Synoptic Scale : what questions does this raise ?

Long term perspectives

Synoptic Scale : what questions does this raise ?

Environment at Synoptic Scale

Kiladis et al 2019, Cheng et al 2023

Physical origins of the properties of mesoscale convective systems and implications for high impact events

PhD Defense, Université Paris Science Lettre

Sophie Abramian

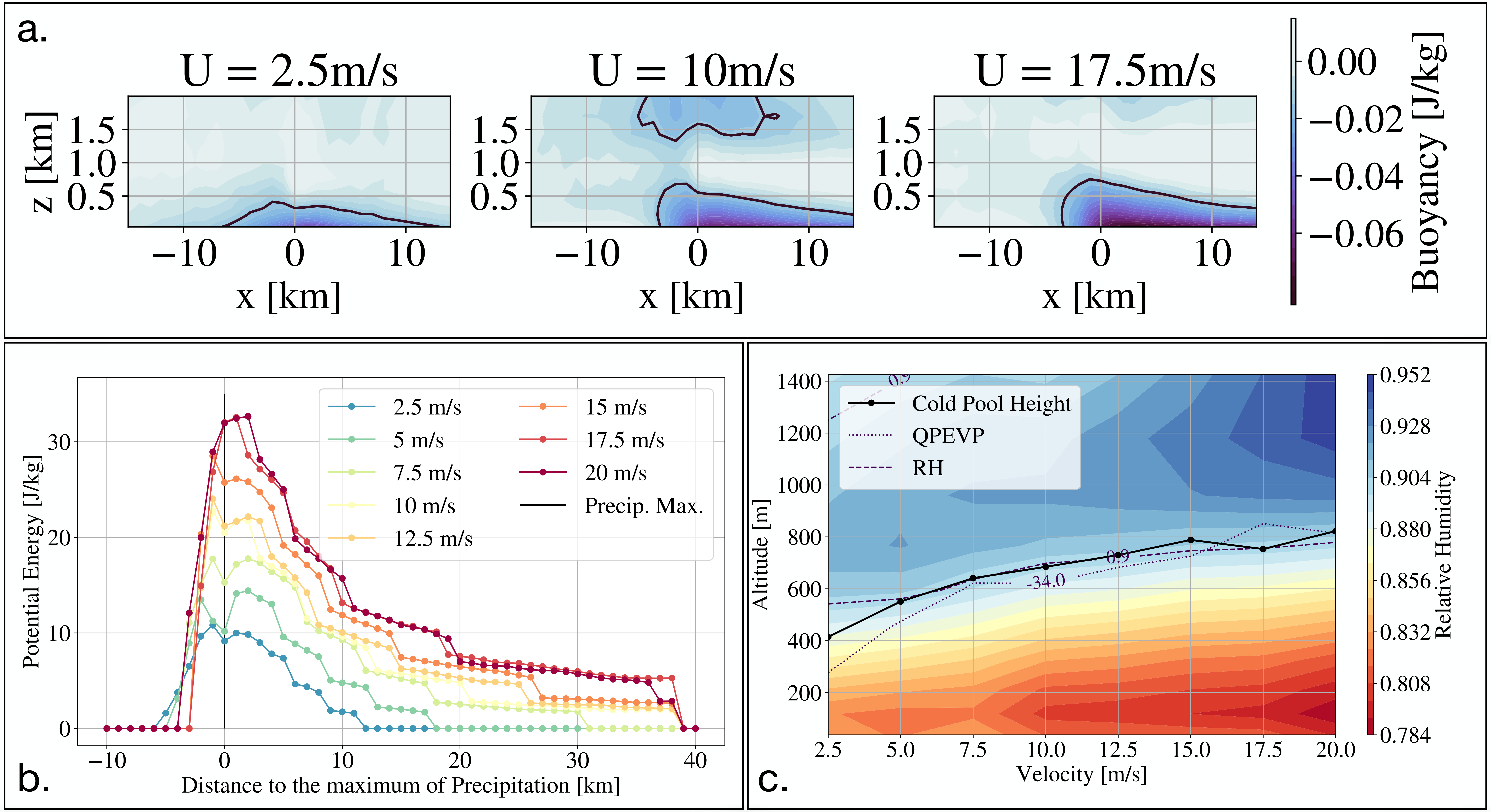
under the supervision of **Caroline Muller** (ISTA) & **Camille Risi** (LMD, Sorbonne Université)

Laboratoire de Météorologie Dynamique, Ecole Normale Supérieure de Paris, Ecole Doctorale 129

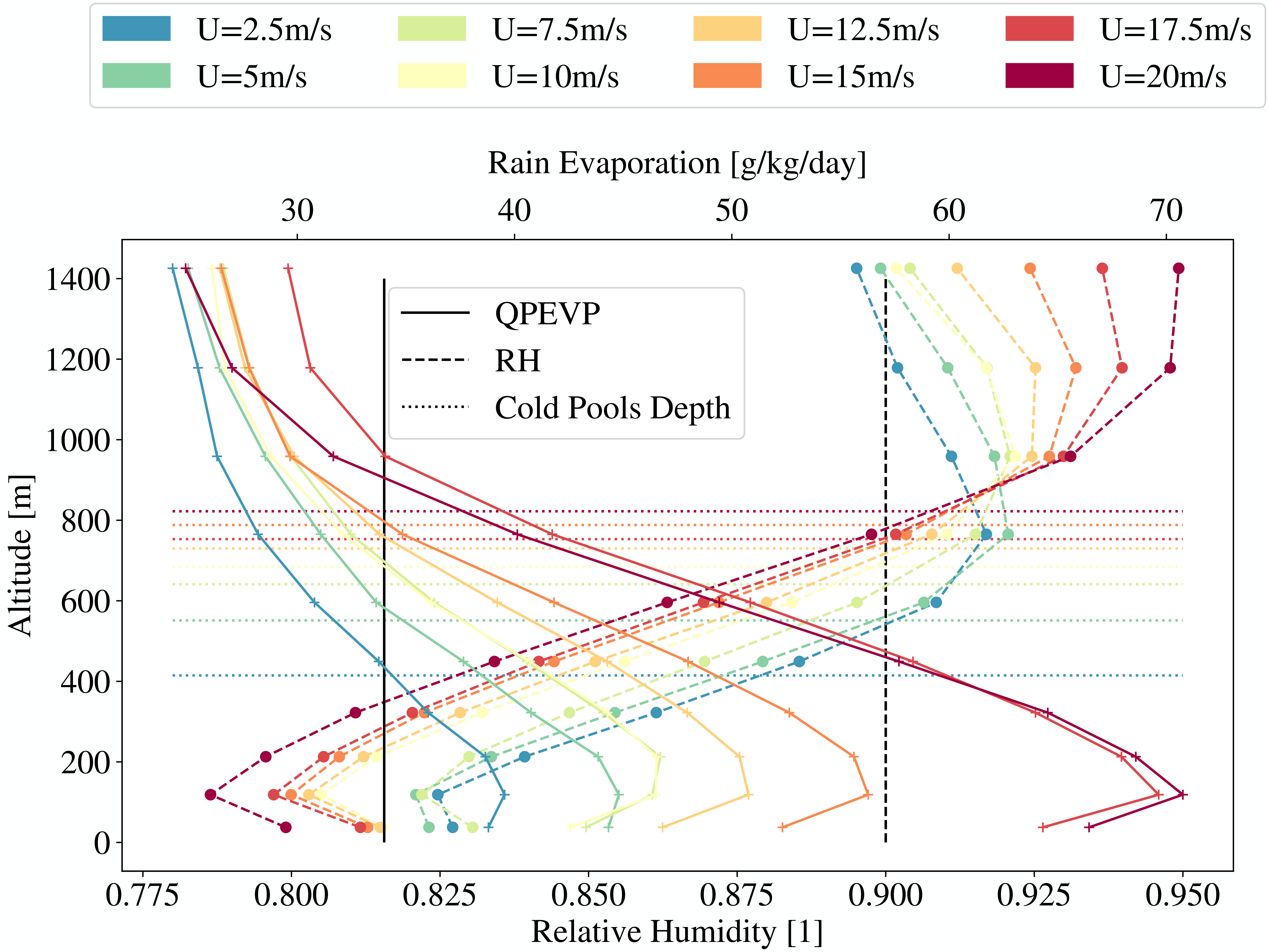
Thank you for your attention !

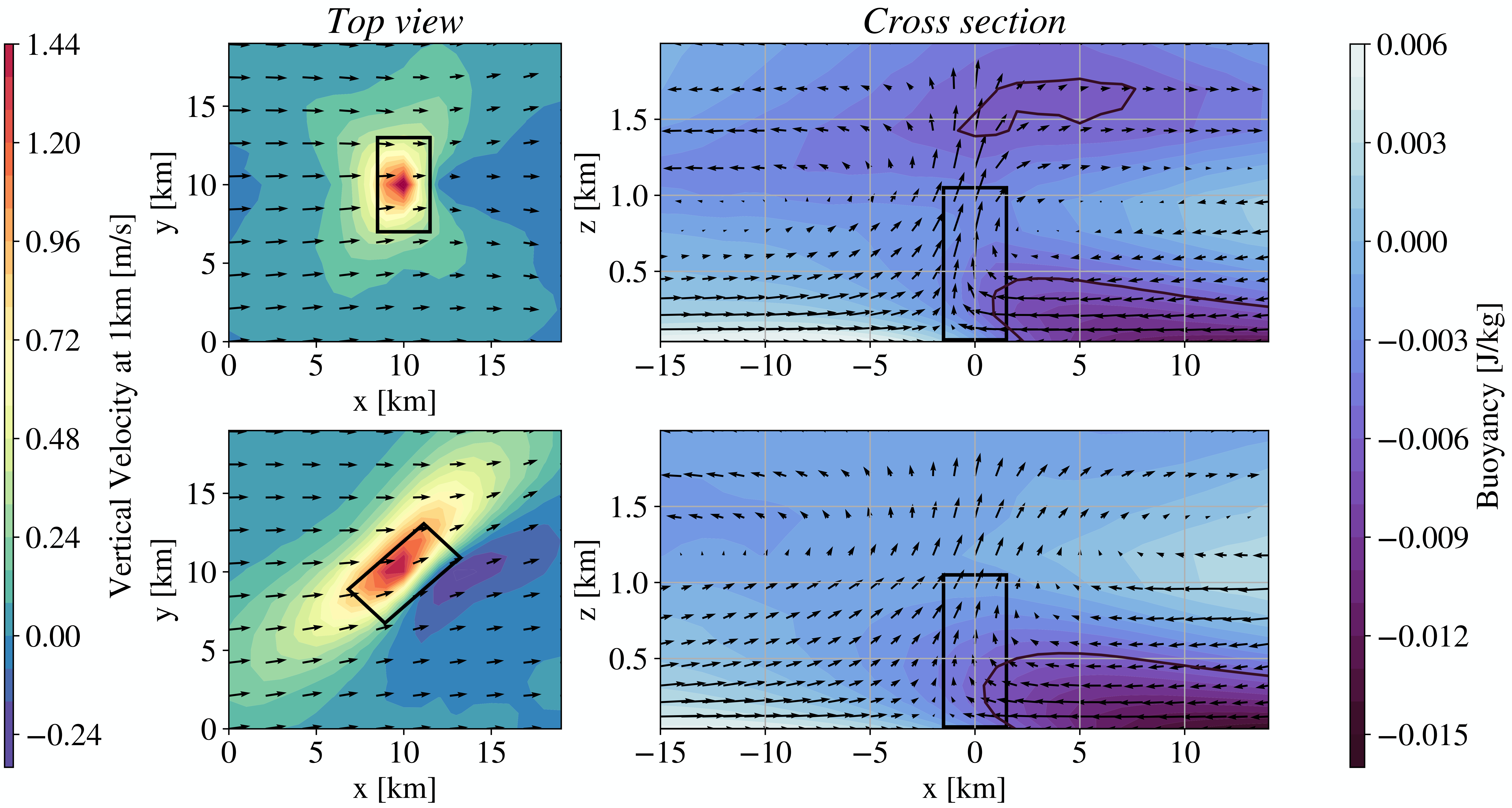
Tuesday, December 5th 2023

Supplementary

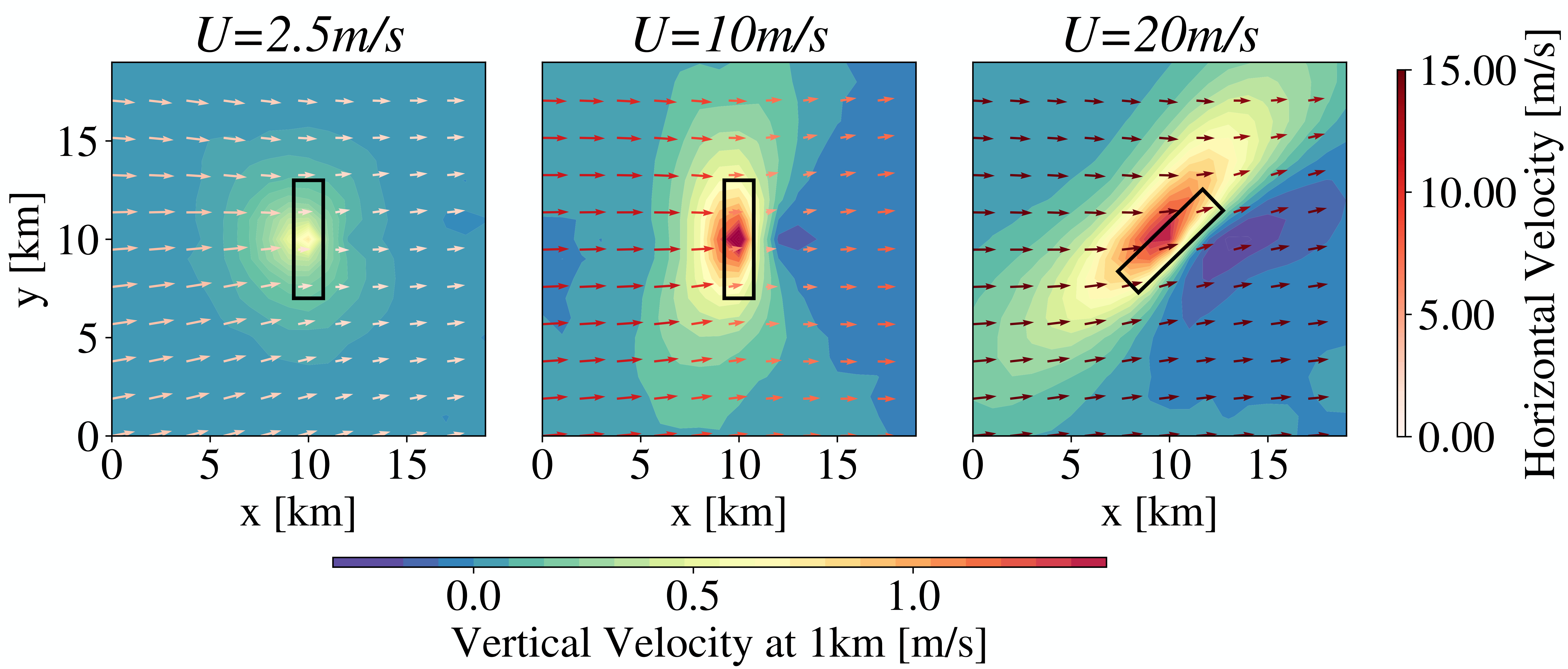


Supplementary

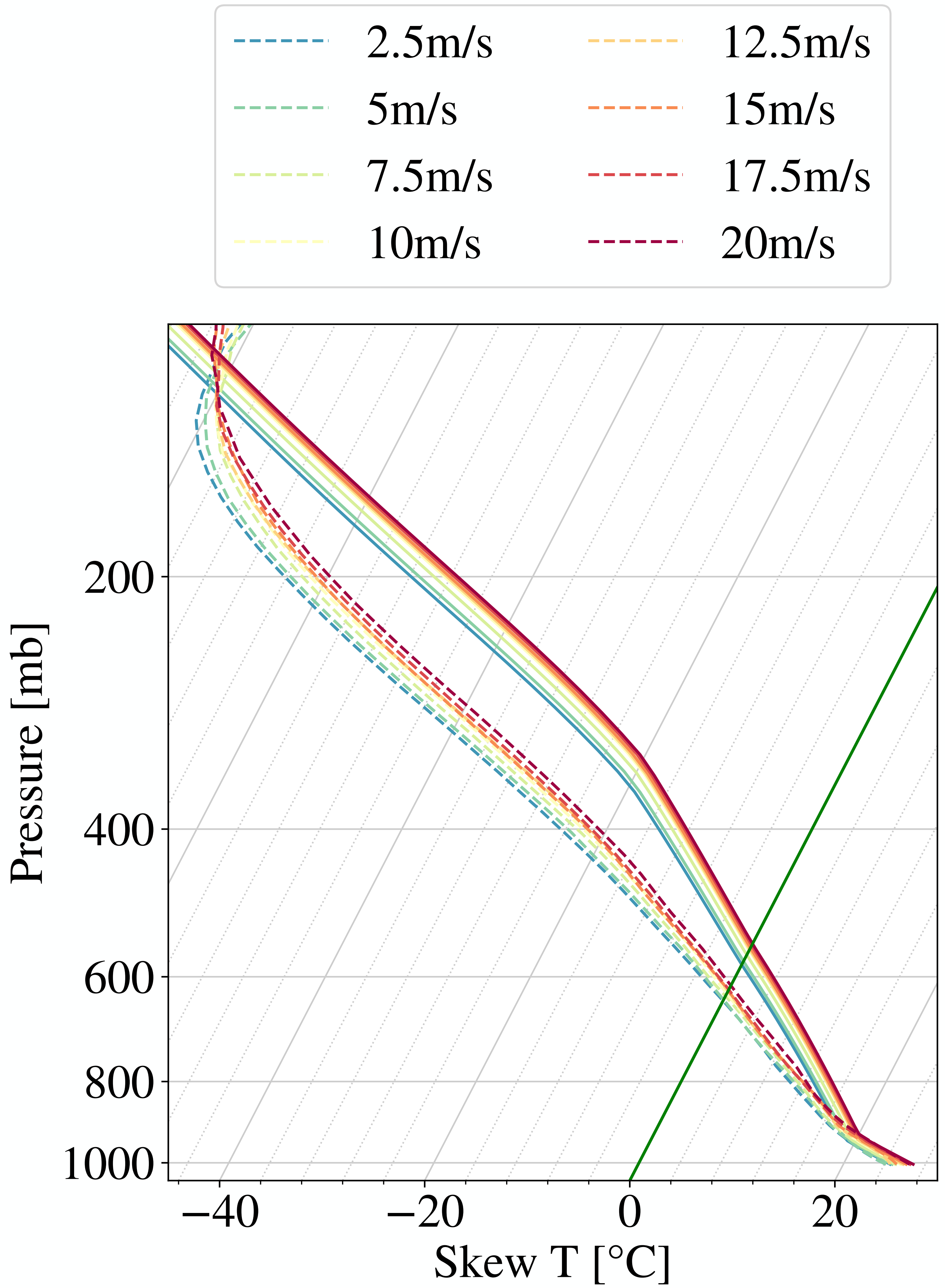



Top view
Cross section
1.44
1.20
0.96
0.72
0.48
0.24
0.00
−0.24
Vertical Velocity at 1km [m/s]
y [km]
x [km]
z [km]
0.006
0.003
0.000
−0.003
−0.006
−0.009
−0.012
−0.015
Buoyancy [J/kg]

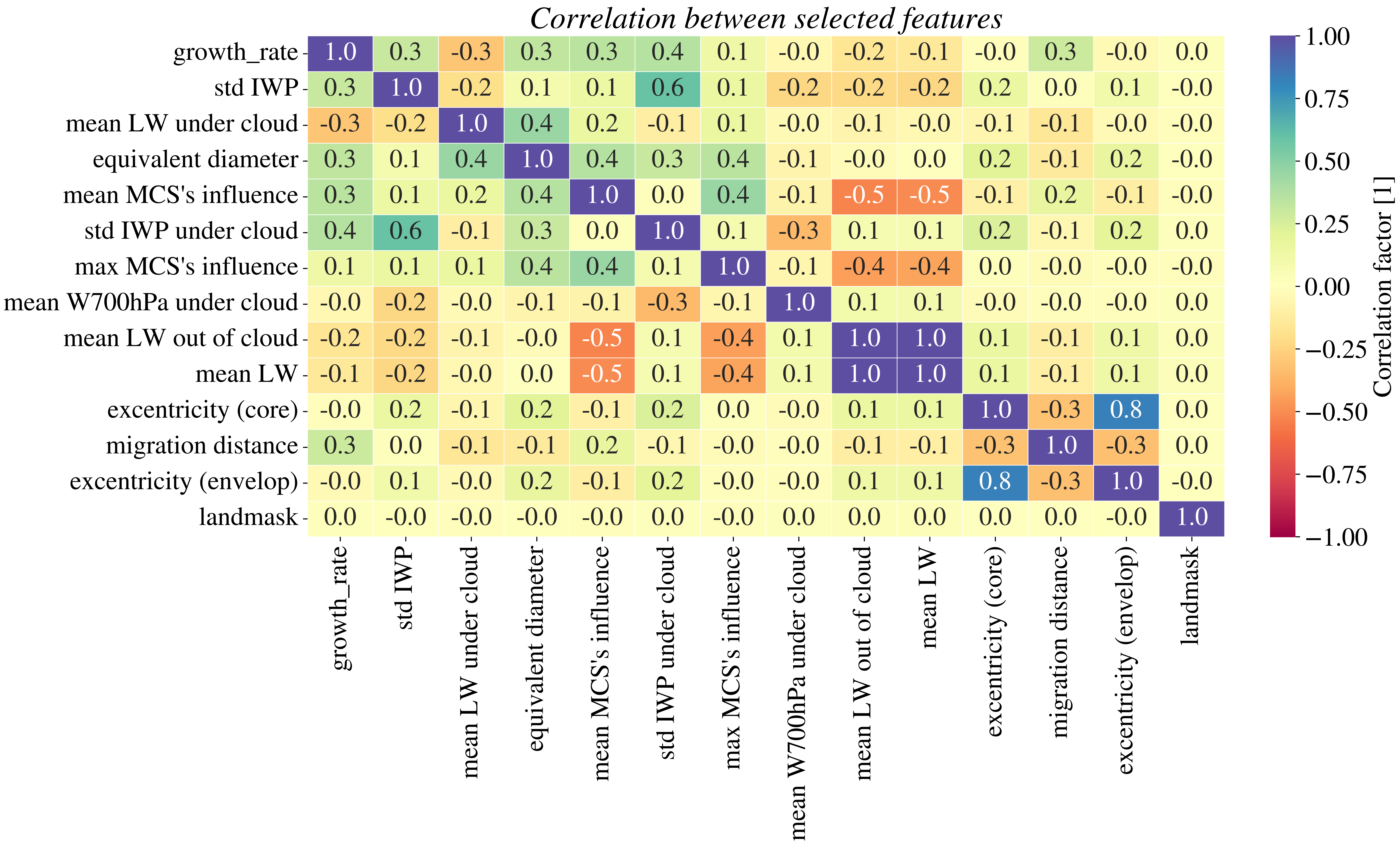
Supplementary



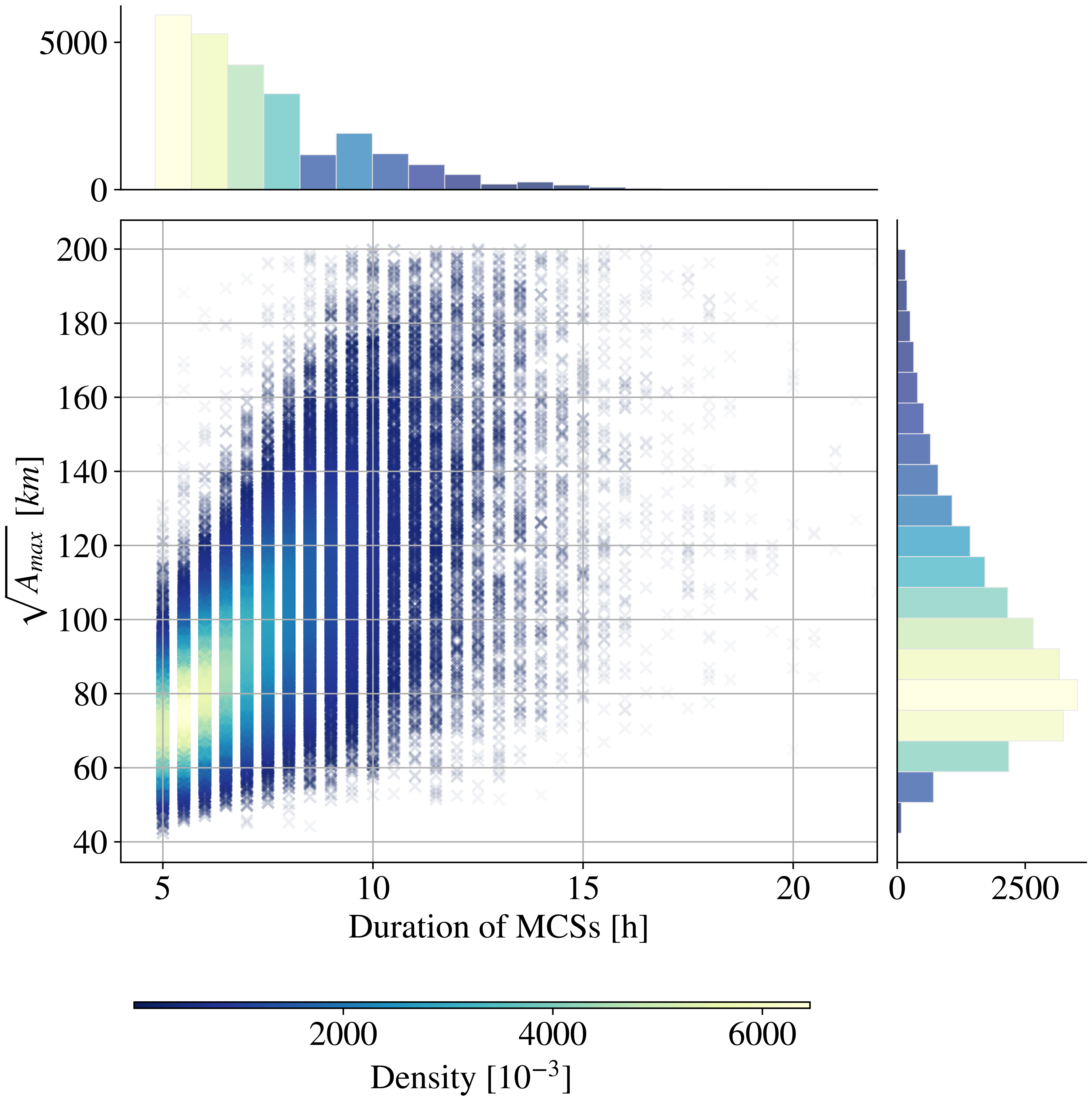
Supplementary

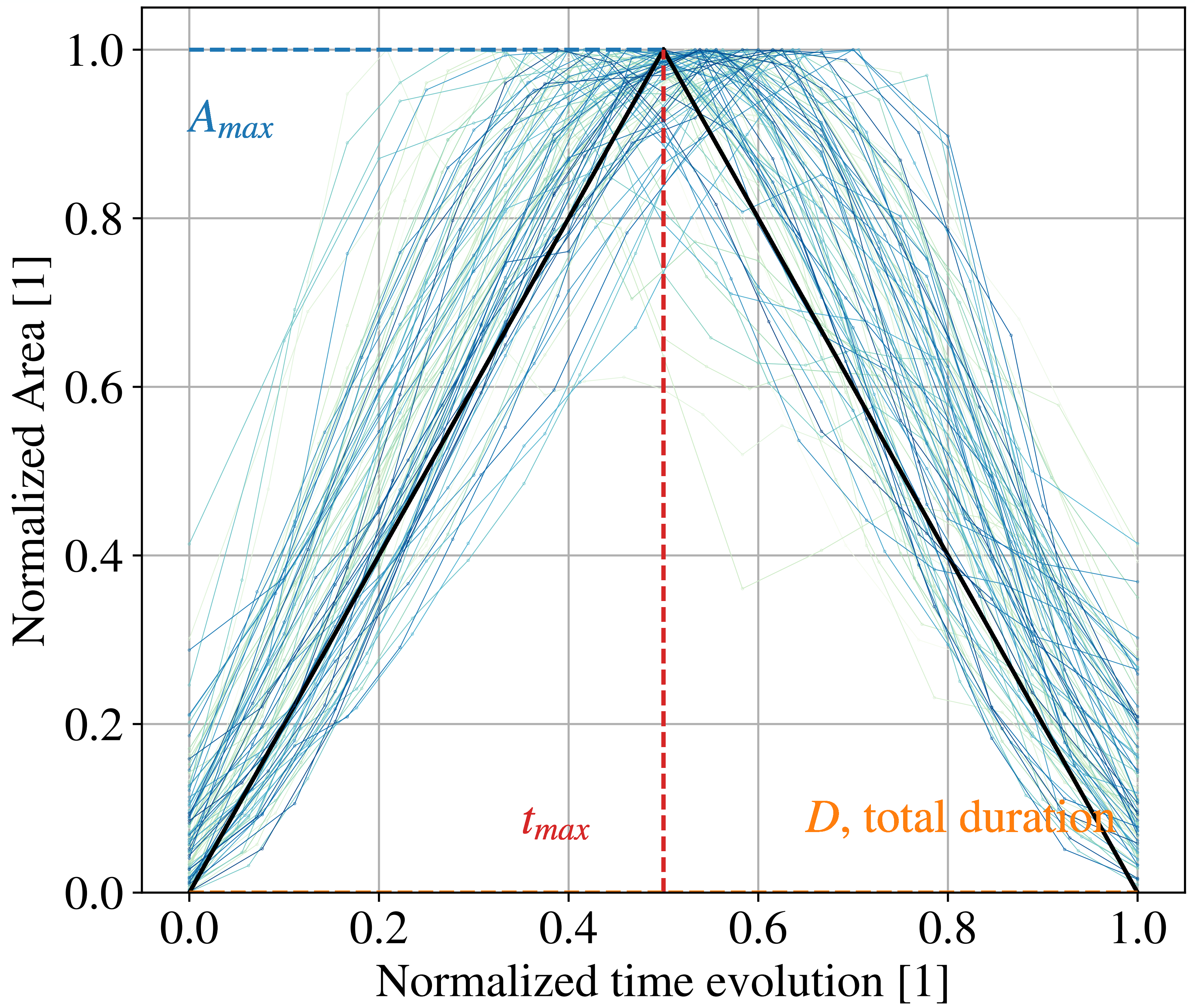


Supplementary

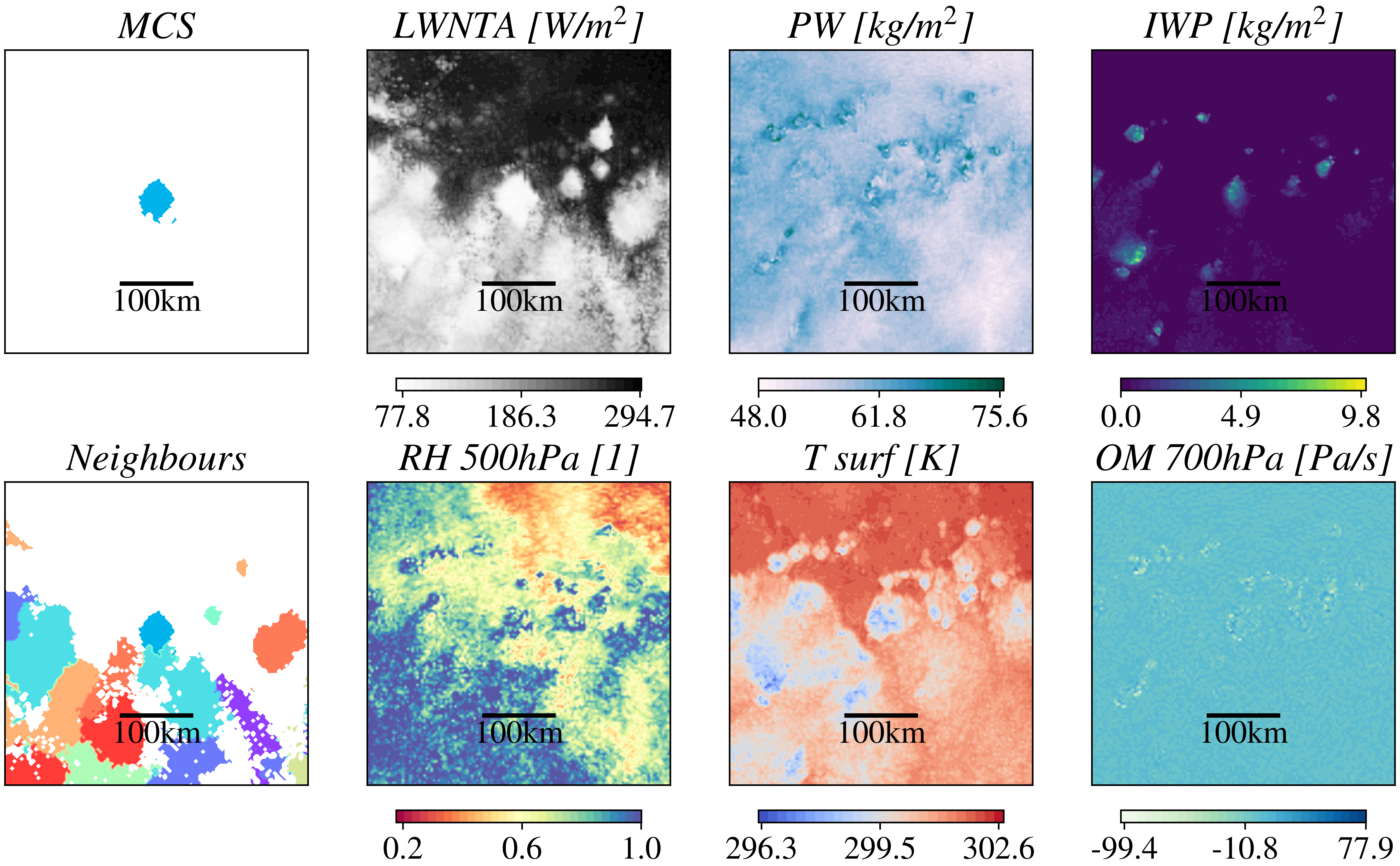


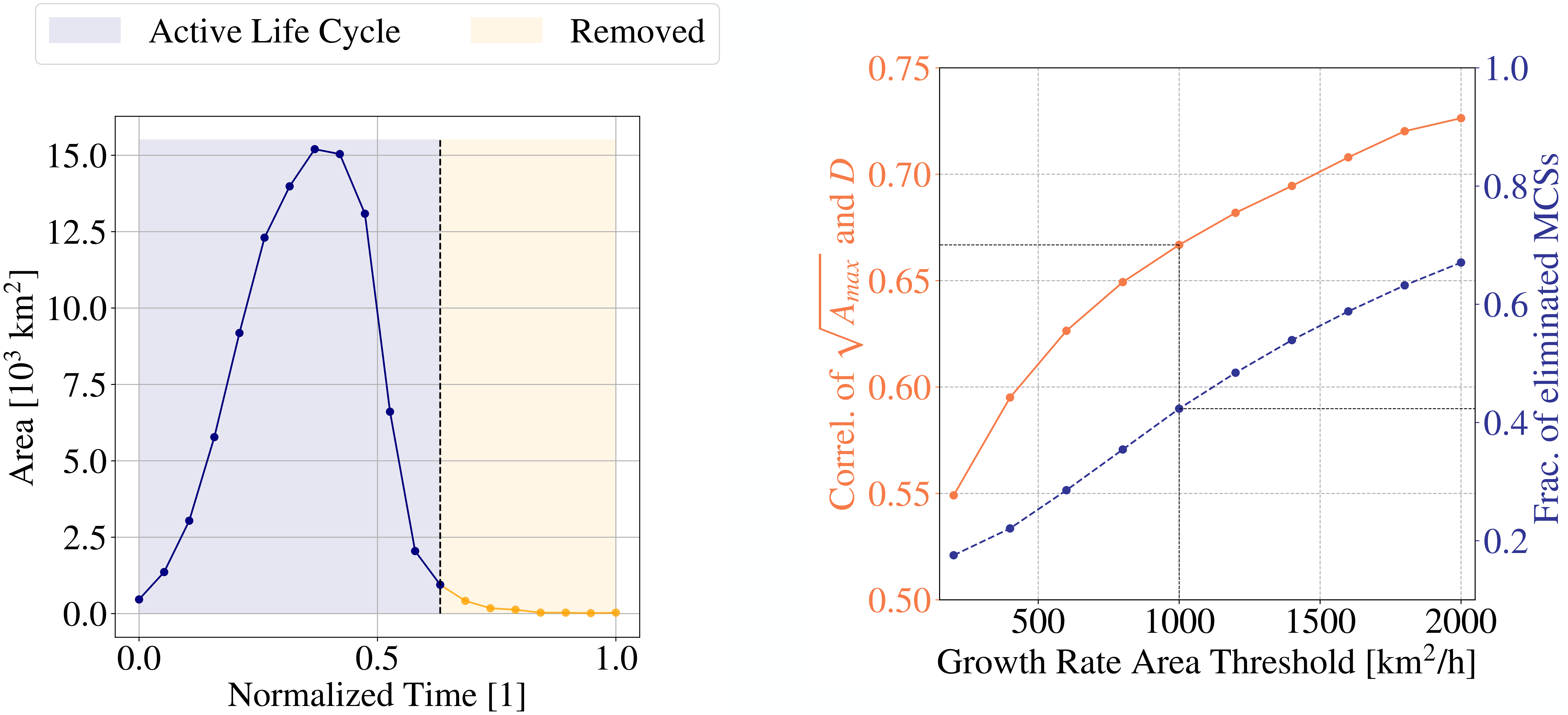
Supplementary

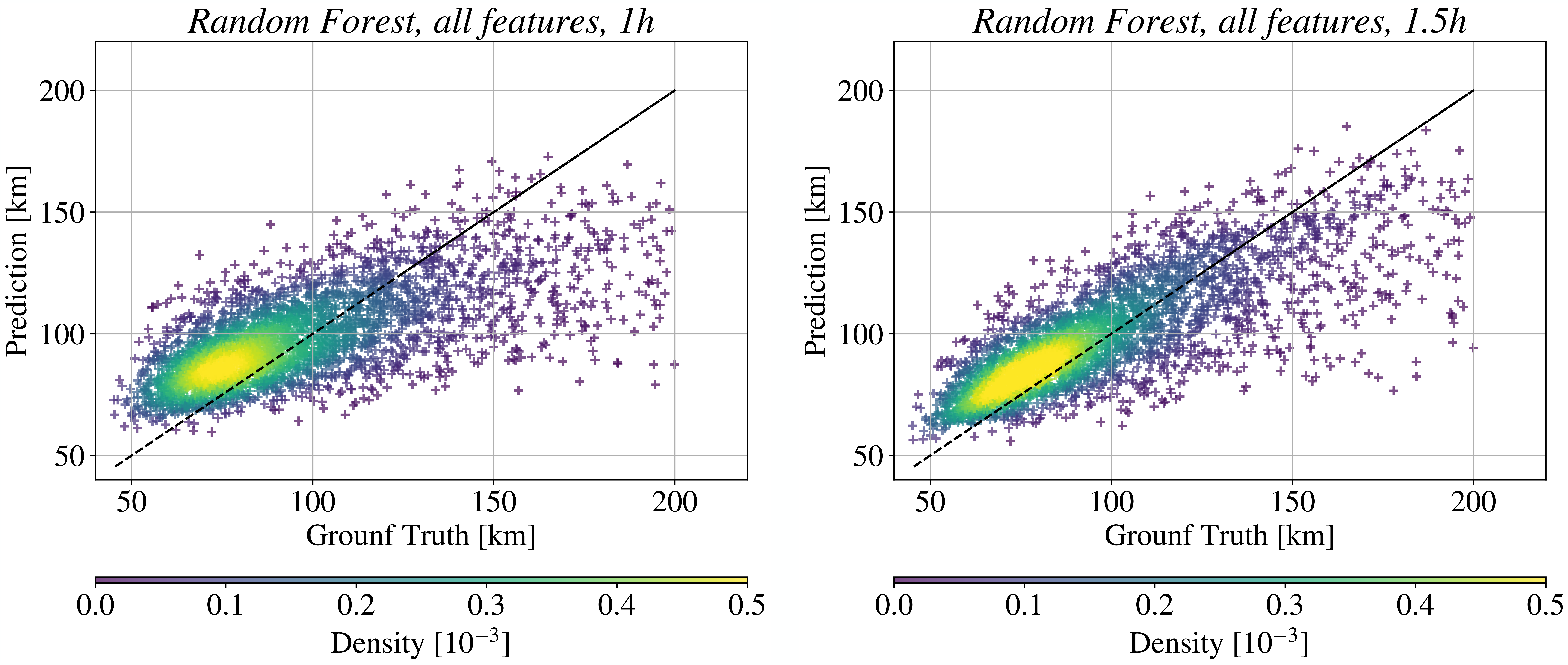




Supplementary




Active Life Cycle
Removed
Area [10^3 km^2]
15.0
12.5
10.0
7.5
5.0
2.5
0.0
0.0
0.5
1.0
Normalized Time [1]
Correl. of $\sqrt{A_{max}}$ and D
0.75
0.70
0.65
0.60
0.55
0.50
Frac. of eliminated MCSs
1.0
0.8
0.6
0.4
0.2
500
1000
1500
2000
Growth Rate Area Threshold [km^2/h]

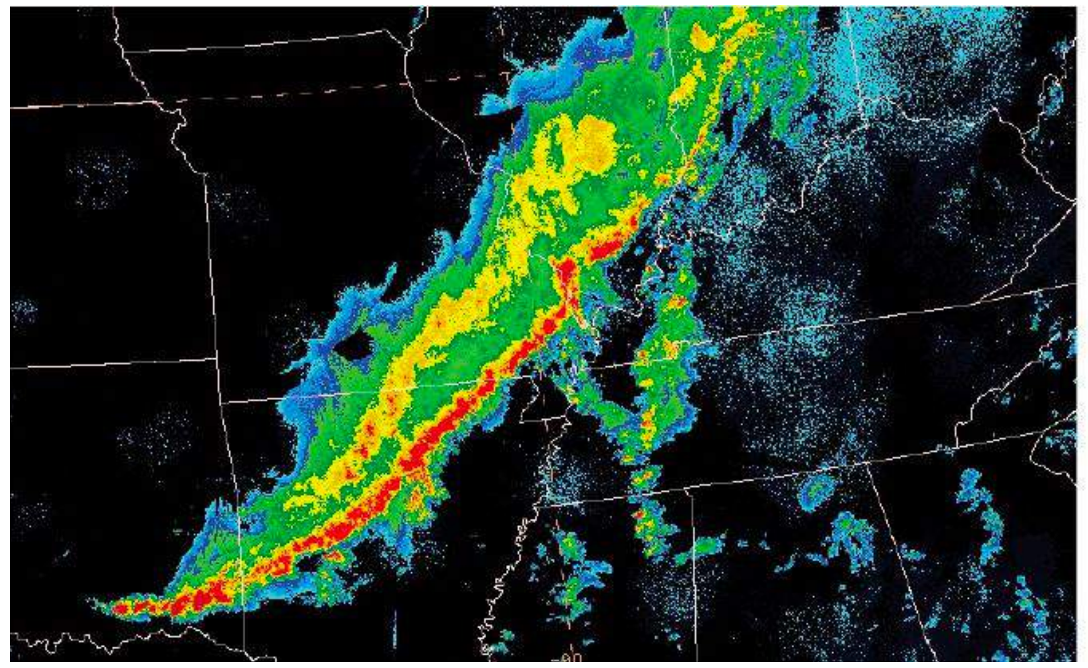

Random Forest, all features, 1h
Random Forest, all features, 1.5h
Prediction [km]
Grounf Truth [km]
50
100
150
200
Density [10^-3]
0.0
0.1
0.2
0.3
0.4
0.5

Supplementary

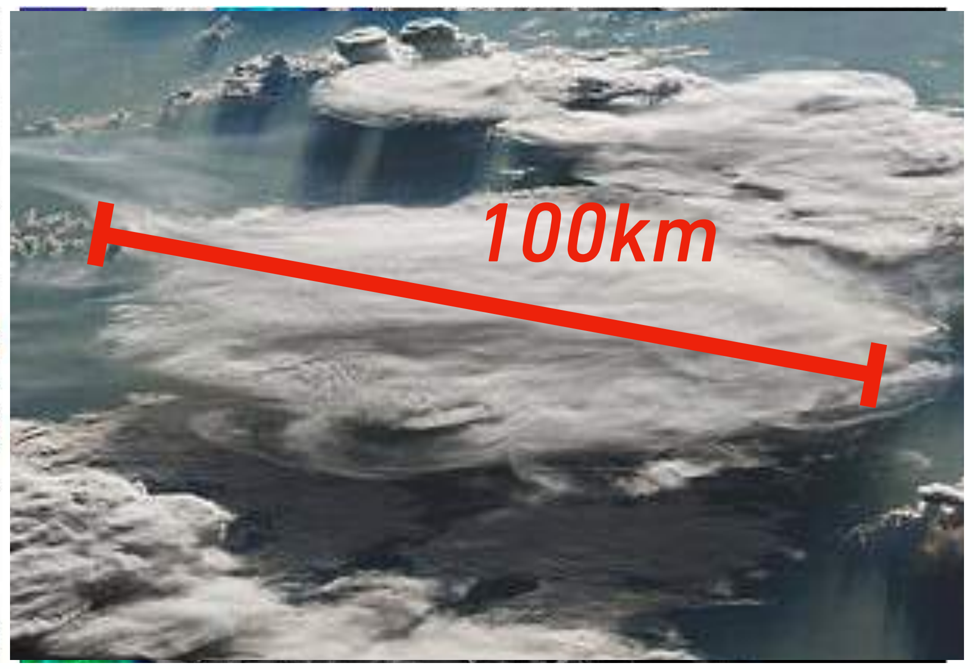
	System Scale : what did we learn ?	Synoptic Scale : what questions does this raise ?
Internal Feedbacks	**Aggregation feedbacks in the near environment** Radiative cooling *Fildier et al 2023* Convective Memory *Colin and Sherwood 2021* Cold pools dynamics *Haerter 2019, Feng et al 2015* Waves at the boundary layer *Mapes 1993*	**The System and its synoptic environment** Part 2 : Influence of neighboring systems? For a given environment what explains the MCSs variability ?
External Forcing	**Shear convection interaction** Part 1 : Squall Lines and Extremes	**Synoptic Forcing** What is the influence of equatorial waves ? *Kiladis et al 2019, Cheng et al 2023*

Better understand what controls MCSs properties

Squall Line



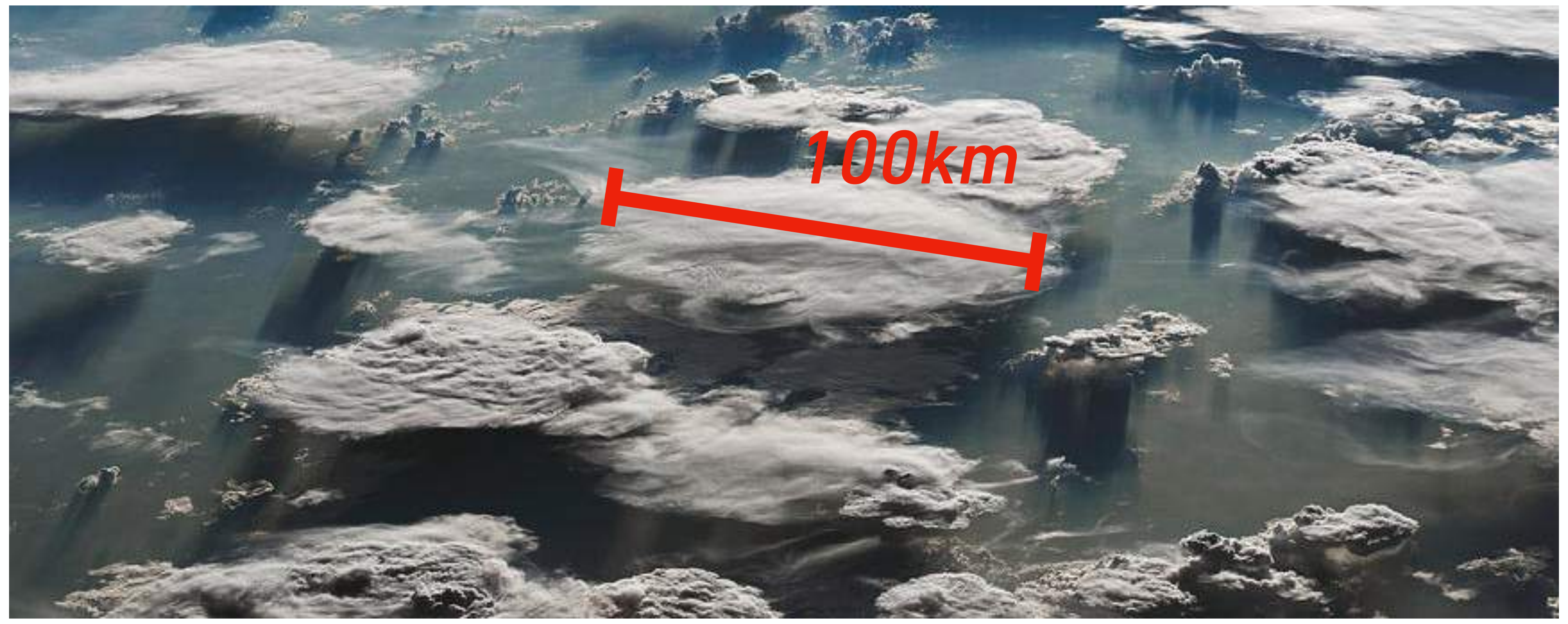
Mesoscale Convective Complex



Better predict local precipitation extreme

Better understand what controls distributions of MCSs population properties?

Population of Mesoscale Convective Systems



Better predict regional precipitation extreme ?

Supplementary