Mapping Meteorological Conditions to Predator Prey Dynamics

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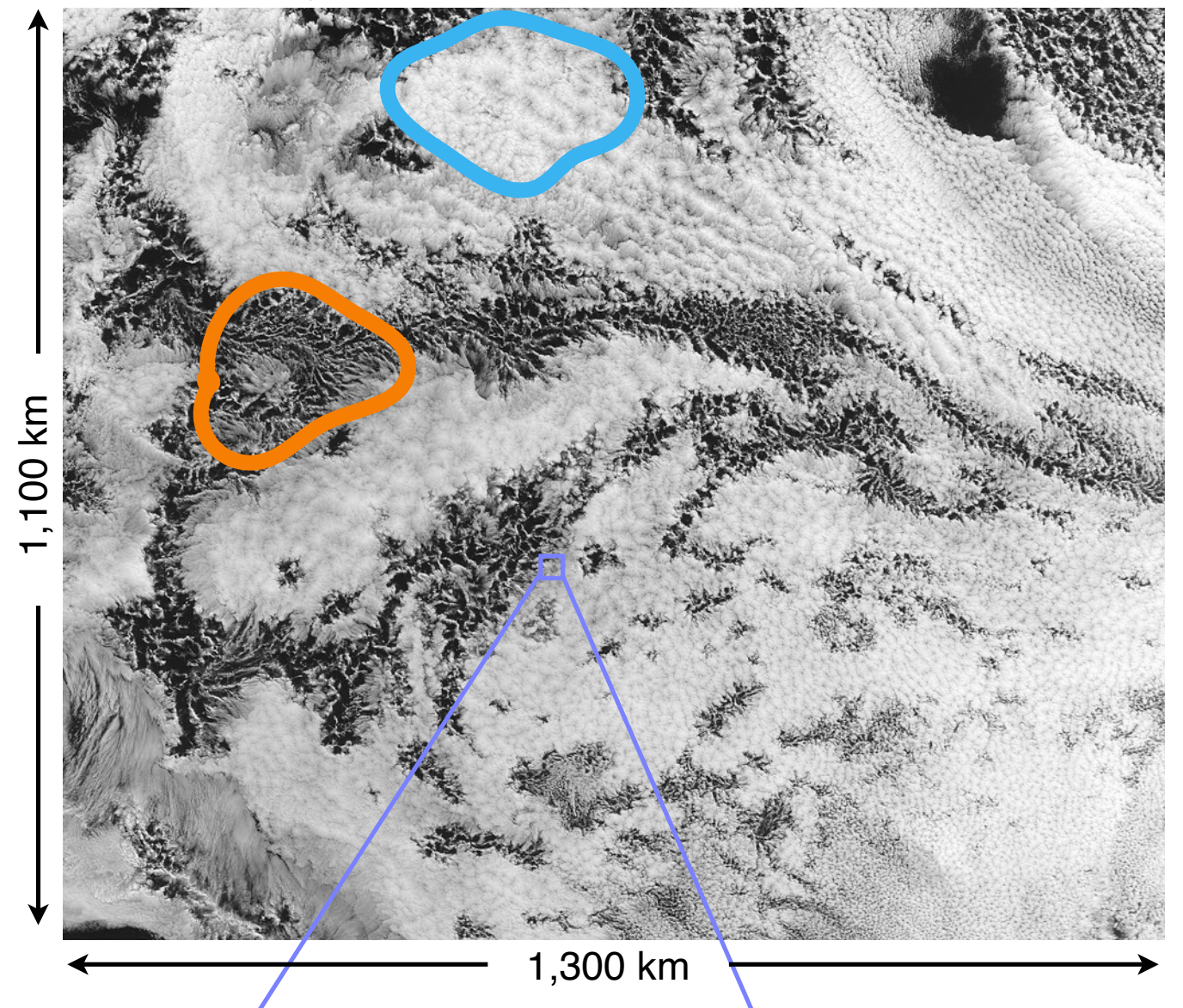
Stratocumulus clouds

- Cloud decks can cover immense stretches of subtropical oceans that can reach 1000's of km in scale
- Cover approximately 20% of the Earth's surface
- Have two different configurations:
  - *"Open cell"* (less reflective) 🟧
  - *"Closed cell"* (more reflective) 🟦
- Significant contributor to Earth's energy budget
- Large source of uncertainty in climate projections

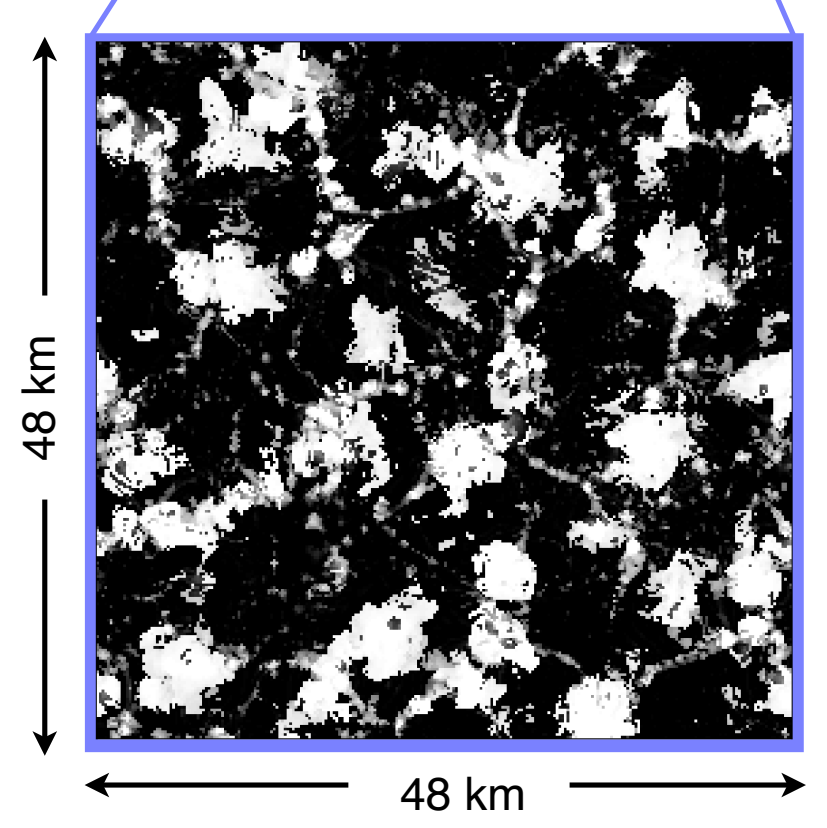
Satellite image of stratocumulus clouds over Atlantic Ocean[1]



Modeling stratocumulus clouds

Large Eddy Simulations (LES)

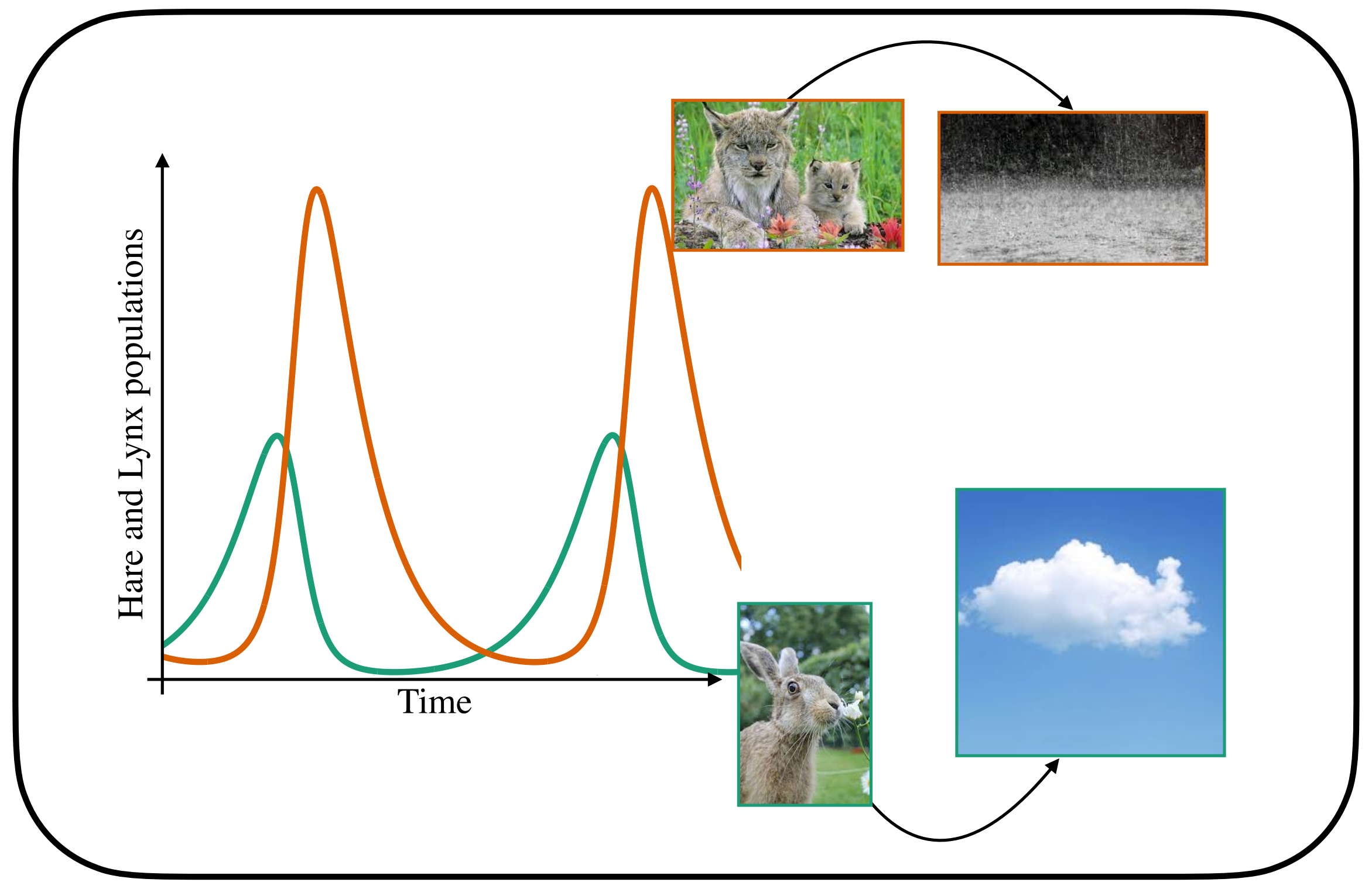
- Realistic 3D and time atmospheric simulation that resolves clouds and relies on governing equations
- Computationally expensive and produces GBs of output on atmospheric conditions over time



Snapshot of LES grid representing cloud depth values (white represents high cloud depth and black represents low cloud depth)

Predator-Prey dynamics and KTF17

- Predator-Prey dynamics lead to oscillations because of "competition" between predator and prey
- We can port this idea to cloud modeling: interpret cloud as the prey and rain as the predator and we should observe cycles of cloud growth and decay



- KTF17 (nonlinear cloud and rain equation)[1,2] model is based off this idea
- KTF17 is a simple delay differential equation model

Dimensional form

$$\frac{\mathrm{d}H}{\mathrm{d}t} = \frac{H_0 - H(t)}{\tau} - \rho H^2(t-T)$$

$H(t) - cloud\ depth$
$H_0 - cloud\ depth\ carrying\ capacity$
$\tau - time\ scale$
$T - delay$
$\rho - scaling\ factor$

Non-dimensional form

$$\frac{\mathrm{d}h}{\mathrm{d}x} = 1 - h - \frac{1}{\mu}h^2(x-D)$$

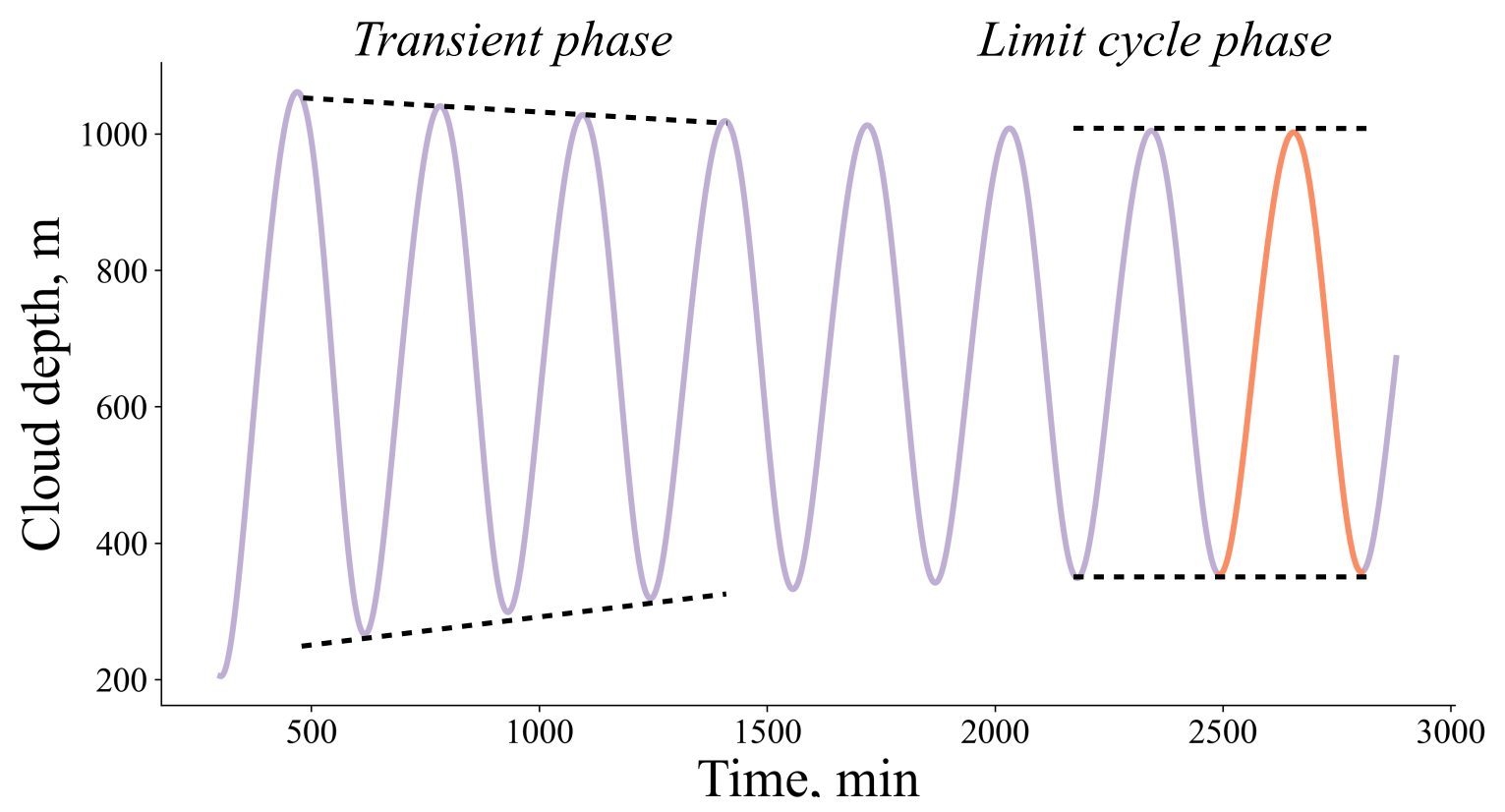
$h - normalized\ height$
$x - normalized\ time$
$D - non\text{-}dimensional\ delay$
$\mu = \frac{1}{\rho H_0 \tau}$

Main Science Questions

- Can KTF17 represent aspects of one LES?
- Can KTF17 represent varying meteorological conditions?
- Can KTF17 be useful for learning about stratocumulus clouds?

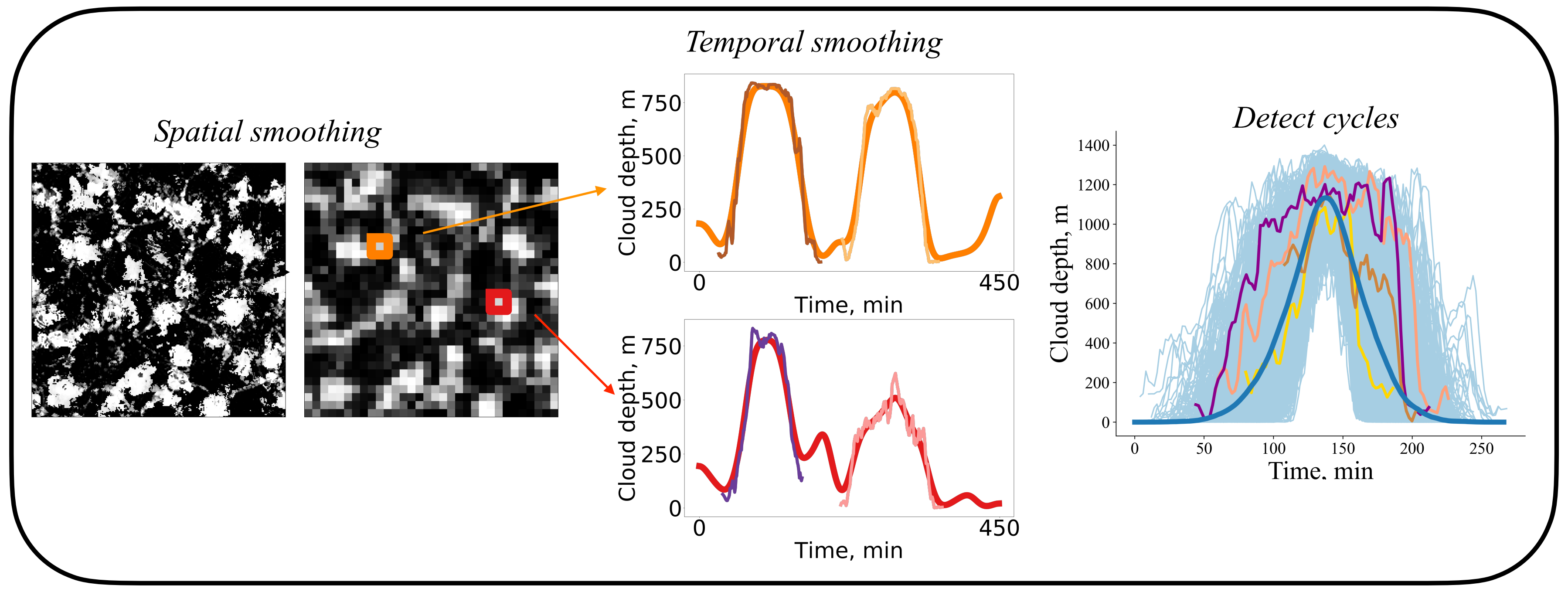
KTF17 model (contd.)

- Models two regimes
  1. Constant cloud depth: cloud rains out at the same rate as it replenishes
  2. **Limit cycles:** cloud grows until it can produce rain, then shrinks as rain depletes cloud



Extracting cycles from LES

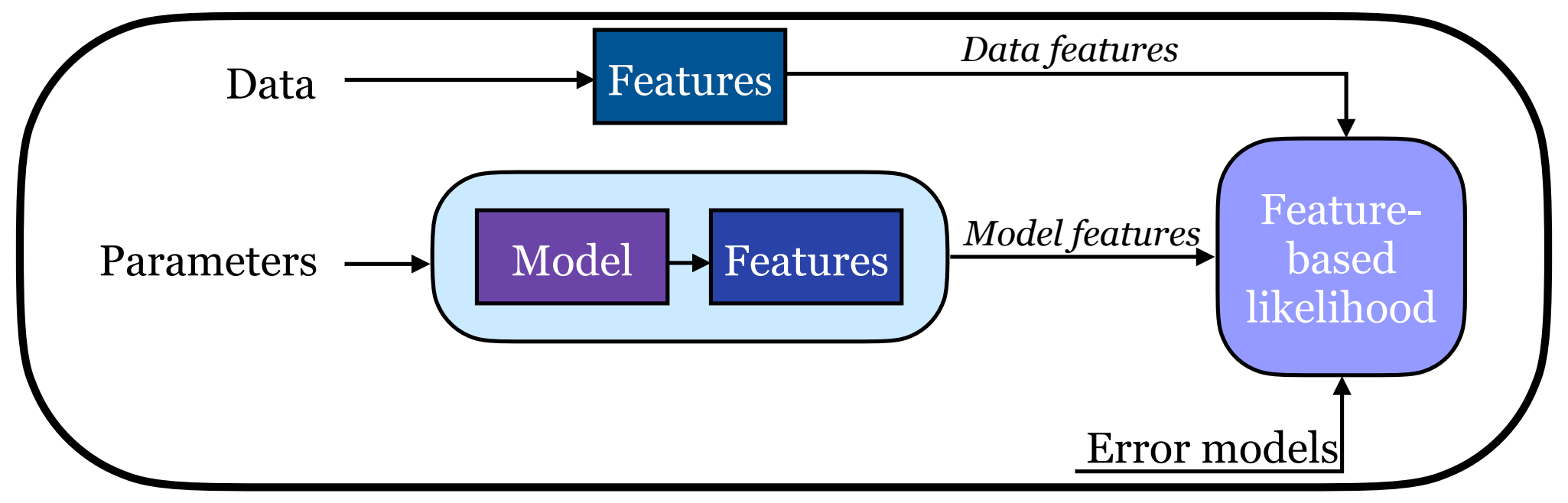
- We can define an **LES feature** as the average of all detected cycles within an LES
- An LES feature is computed by executing a three step process:



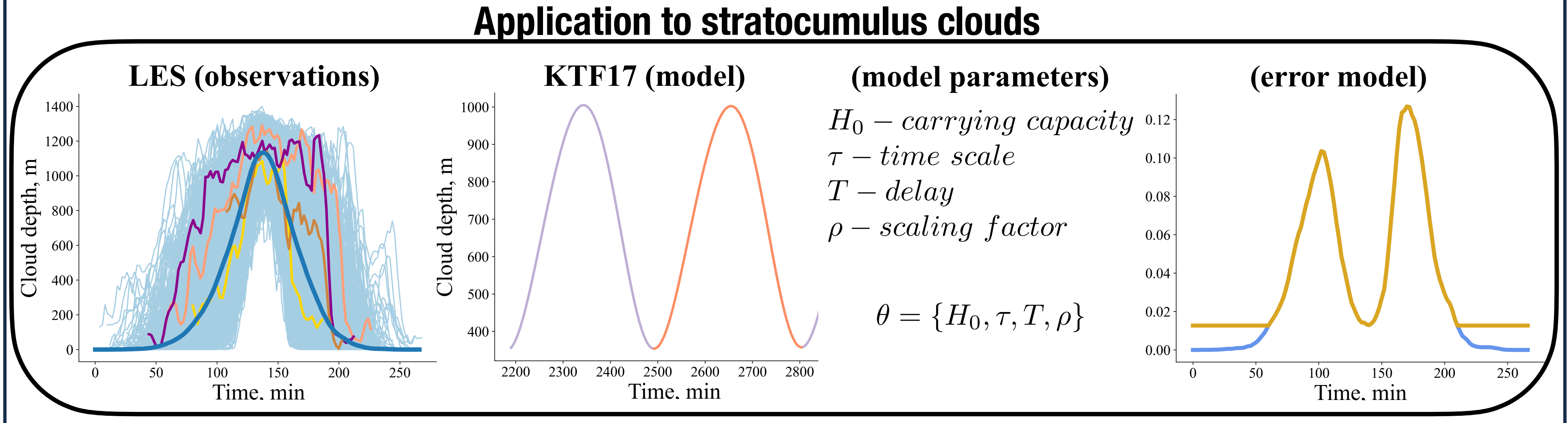
Feature-based inversion

- Match only selected aspects (features) of data
- Define likelihood based on these features
- Infer model parameters using feature-based likelihood

Basic ideas of feature-based inversion



Application to stratocumulus clouds



(model parameters)

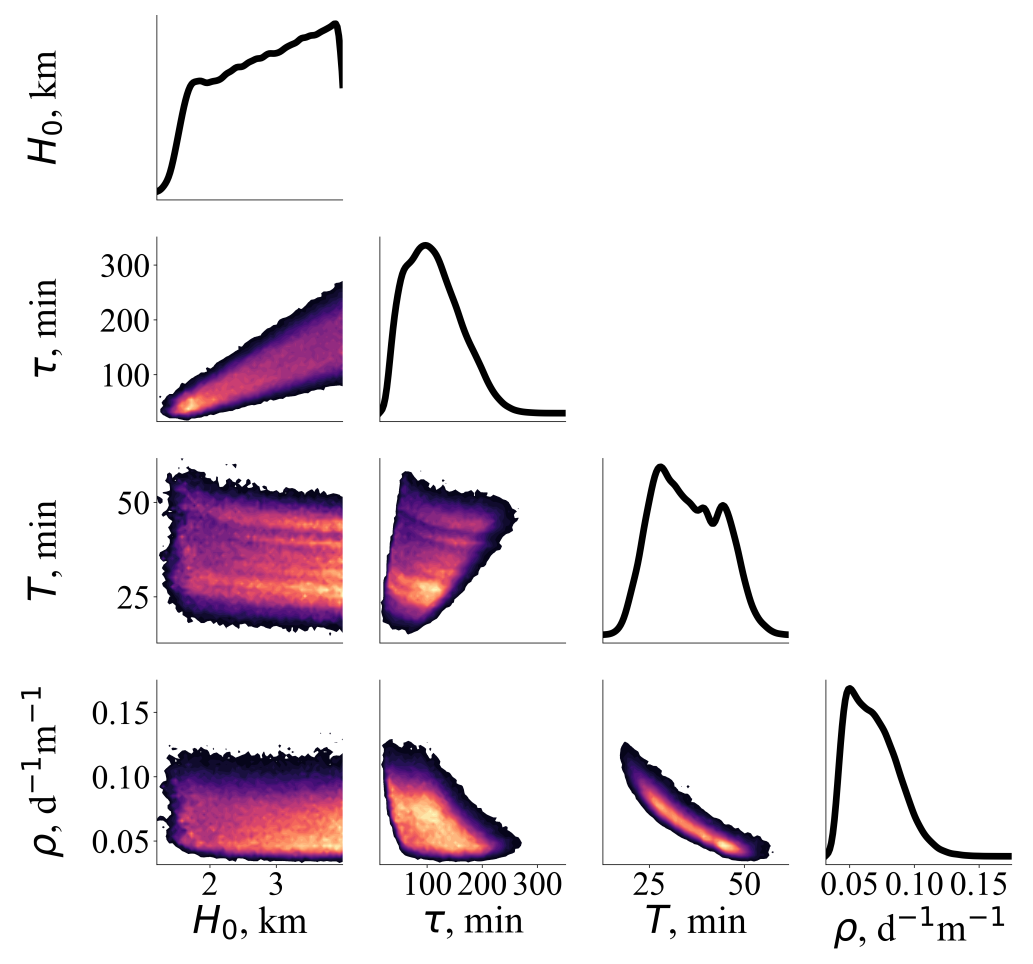
$H_0 - carrying\ capacity$
$\tau - time\ scale$
$T - delay$
$\rho - scaling\ factor$

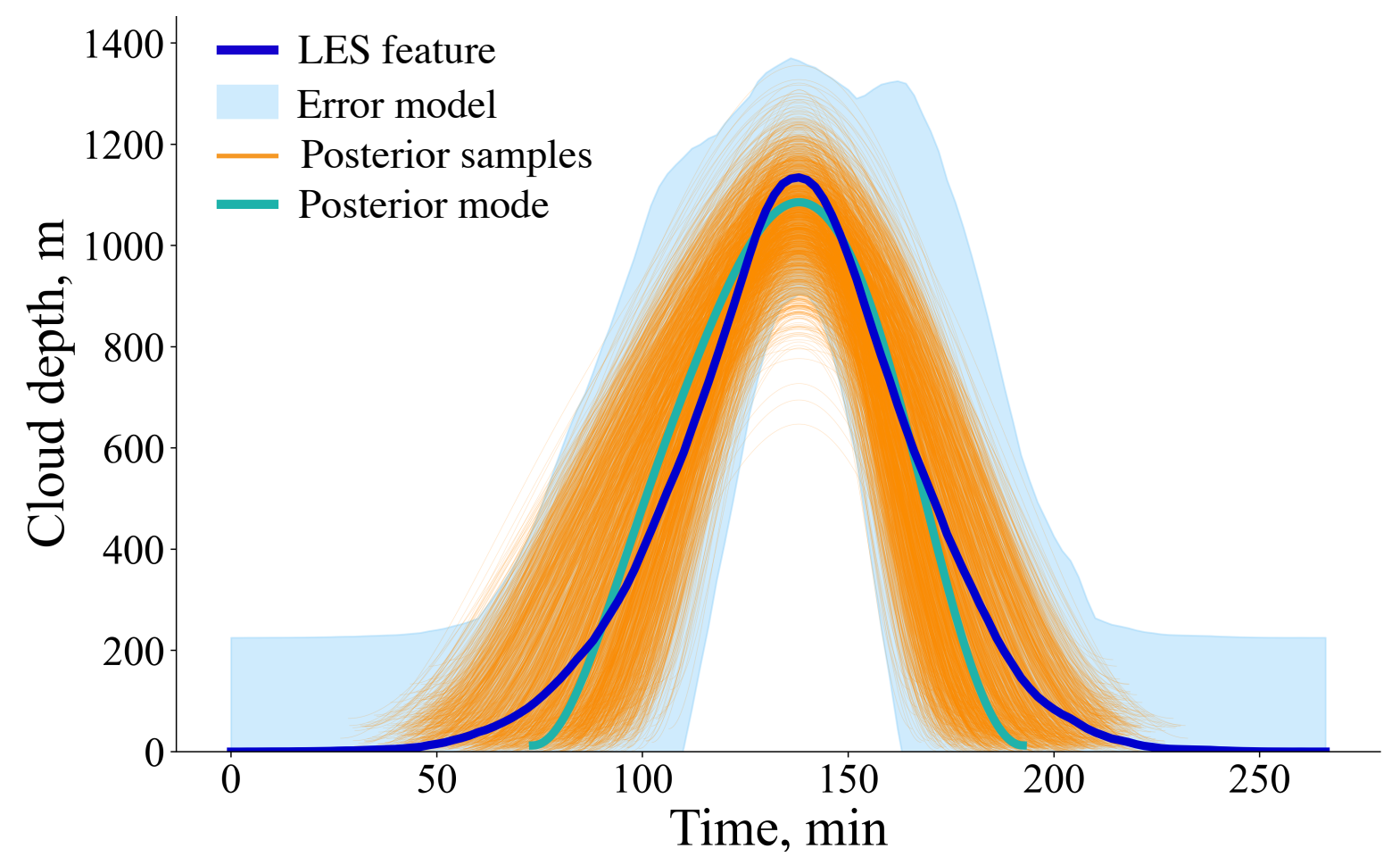
$$\theta = \{H_0, \tau, T, \rho\}$$

Feature-based posterior distribution:

$$\underset{\overset{\uparrow}{\text{observations}}}{y} = \underset{\overset{\uparrow}{\text{model}}}{\mathcal{M}}(\underset{\overset{\uparrow}{\text{model parameters}}}{\theta}) + \underset{\overset{\uparrow}{\text{error model}}}{\eta},\ \eta \sim \mathcal{N}(0, R) \qquad p(\theta|y) \propto \underset{\overset{\uparrow}{\text{prior}}}{p_0(\theta)}\underset{\overset{\uparrow}{\text{likelihood}}}{p_l(y|\theta)}$$

Feature-based inversion results

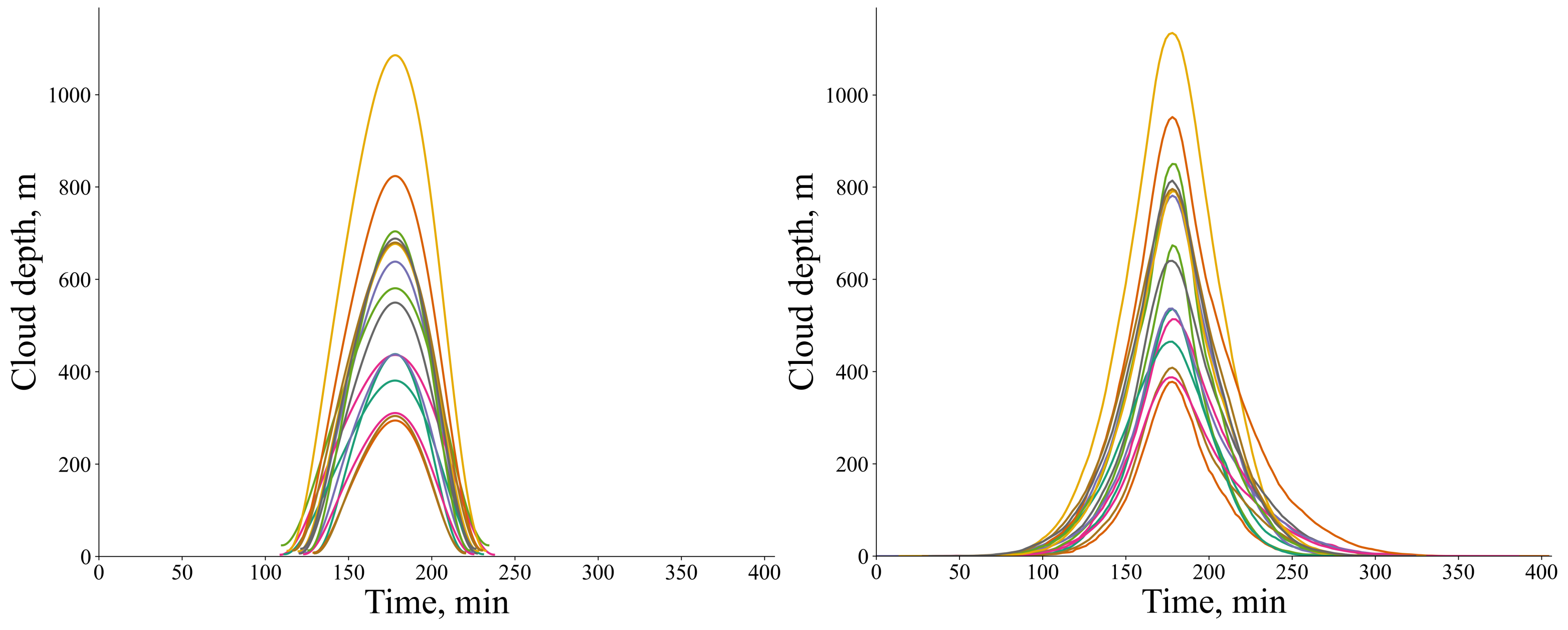




- We have 16 precipitating simulations (LES suite) that we perform our feature-based inversion on

Feature-based inversion results (contd.)

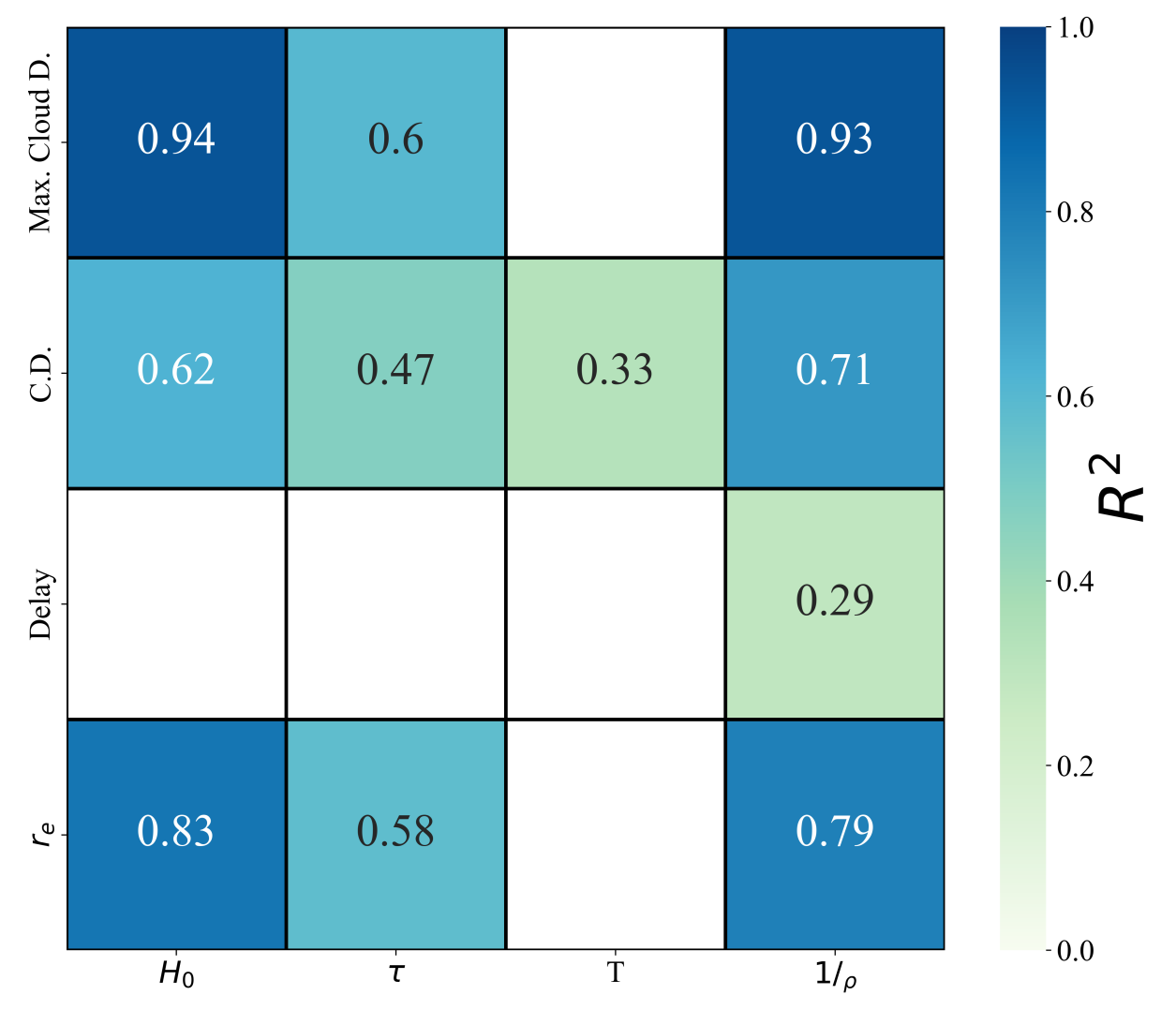
- Large variability within suite including:
  - Cloud cover
  - Droplet concentration (ranging from 10 cm^{-3} to 60 cm^{-3})
  - Maximum cloud depth (ranging from 400 m to 1,200 m)



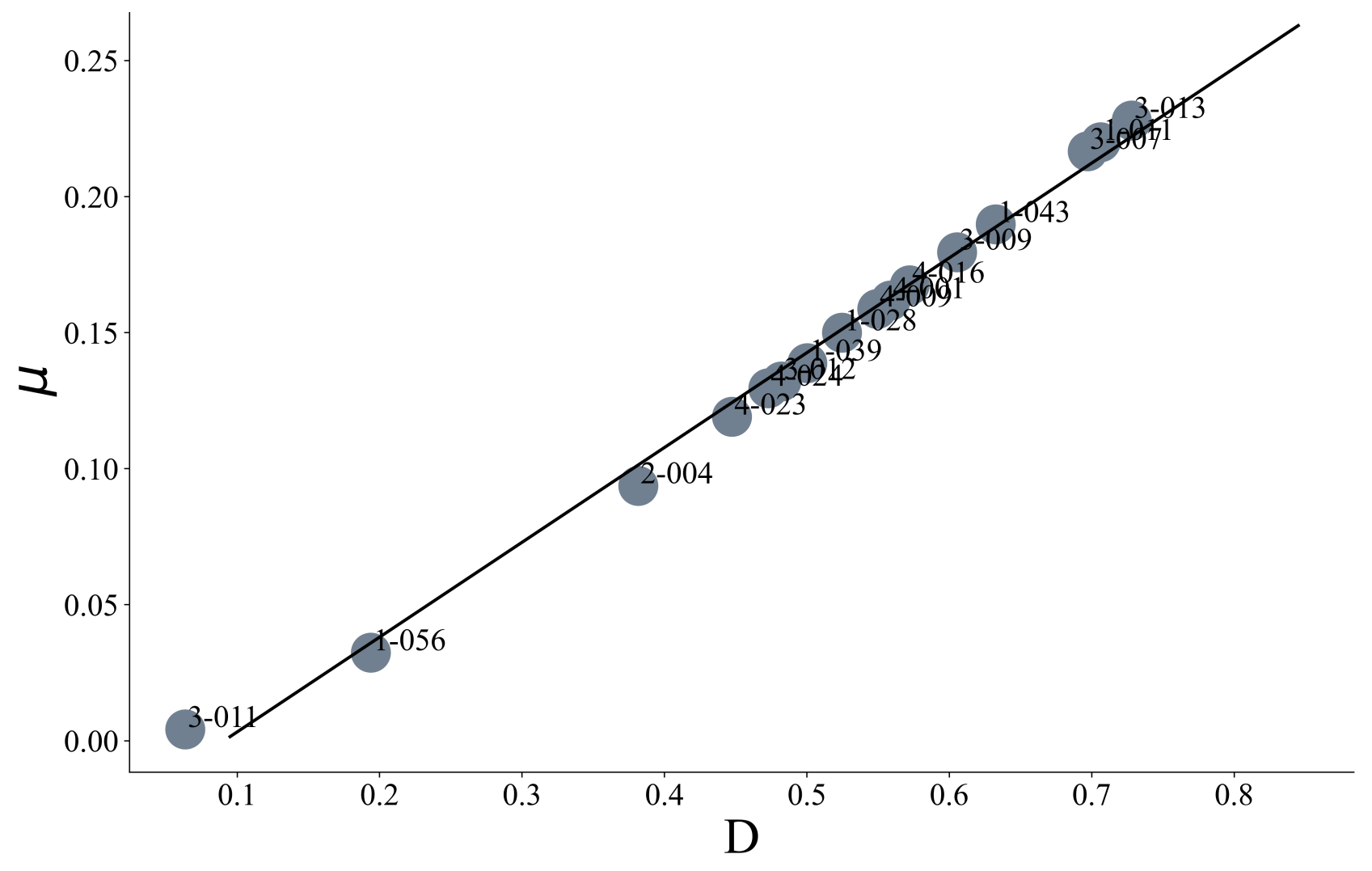
- After sufficiently sampling from the posterior distribution for each precipitating LES, we can identify the set of parameters that gives us the highest (mode) posterior probability

Trends between meteorological conditions and KTF17

- We identify relationships between the KTF17 parameters and the meteorology from the LES as well as relationships between the KTF17 parameters themselves



	H_0	τ	T	$1/\rho$
Max. Cloud D.	0.94	0.6		0.93
C.D.	0.62	0.47	0.33	0.71
Delay				0.29
r_e	0.83	0.58		0.79



Conclusions

- KTF17 can describe cycles of growth and decay within an LES
- KTF17 can describe all precipitating cases within our LES suite
- KTF17 parameters are dependent on each other and the maximum cloud depth from the LES is the main driver of these relationships
- LES meteorology overpowers KTF17 microphysical relationships

References

1. I. Koren, G. Feingold, *Aerosol–cloud–precipitation system as a predator-prey problem,* Proceedings of the National Academy of Sciences 108 (30) 12227 - 12232 (2011).
2. I. Koren, E. Tziperman, G. Feingold, *Exploring the nonlinear cloud and rain equation*, Chaos: An Interdisciplinary Journal of Nonlinear Science 27 103107 (2017).
3. S. Lunderman, M. Morzfeld, F. Glassmeier, G. Feingold, *Estimating parameters of the nonlinear cloud and rain equation from a large-eddy simulation*, Physica D: Nonlinear Phenomena 410 0167 - 2789 (2020).

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