On our Ability to Infer Process-level Understanding from Snapshots of Atmospheric Fields

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The challenge: Inferring Process from Snapshots

Can we learn the rules of football from (infrequent) snapshots of the game?

- Assuming the rules of the game do not change!

The challenge: Inferring Process from Snapshots

- Polar orbiting satellites
  - 1-2 x per day
- Aircraft flyby

Snapshots □ statistics of system state

Temporal evolution □ process understanding

Can we learn the rules of football from (infrequent) snapshots of the game?

- Assuming the rules of the game do not change!

1. Profiling drop effective radius using cloud top retrievals

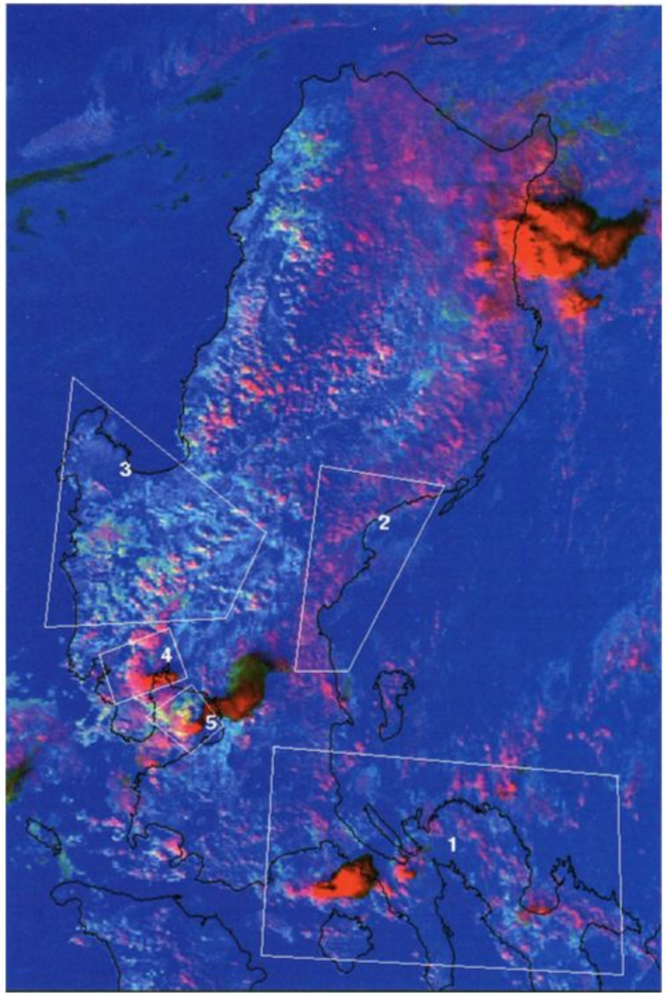
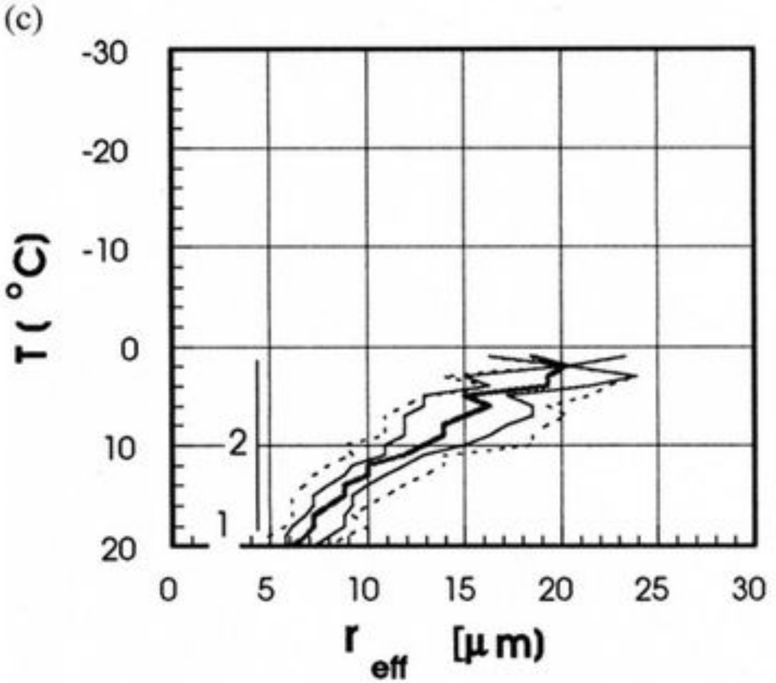


FIG. 8. As Fig. 1, but for a 400 × 650 km area over the northern half of the Philippines,

Rather than sample snapshots at different times, look at clouds in a field at the same time, but at different stages of evolution

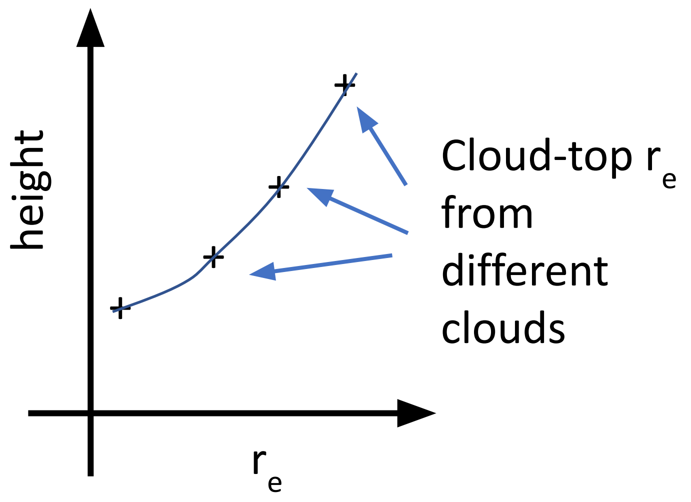


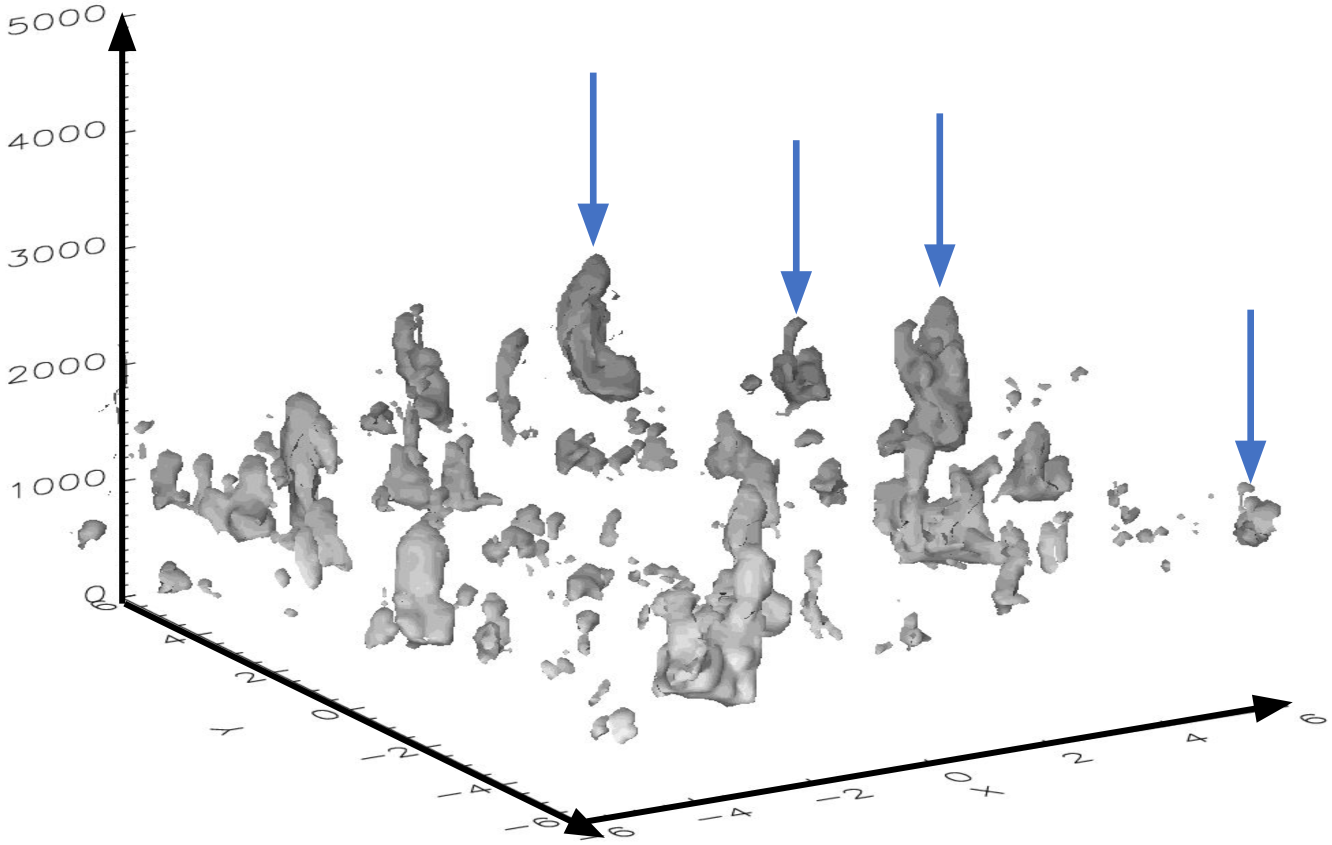
Assumption:
Negligible variability in meteorology/boundary layer properties across the image
or
The rules of the game don't change

Philippines

Rosenfeld and Lensky (1998)

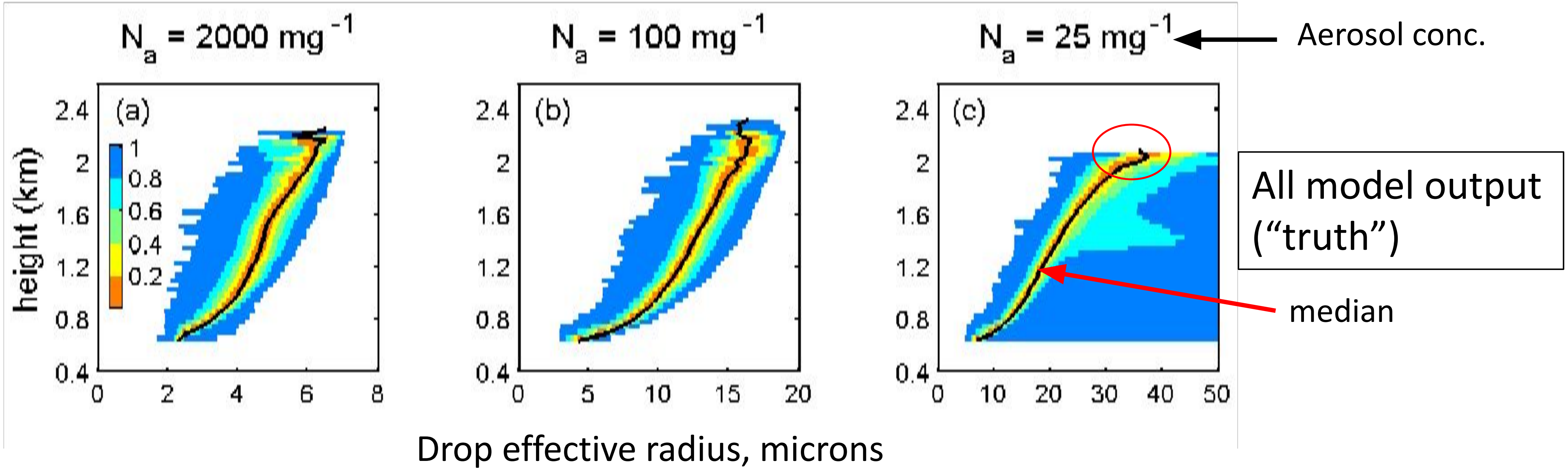
- Each cloud is at a different stage of its lifecycle
- Sample r_e at cloud top
- Build r_e profile by connecting all the individual cloud-top r_e





Testing this idea using LES:

Large Eddy simulation of shallow marine cumulus



S. Zhang et al. 2011

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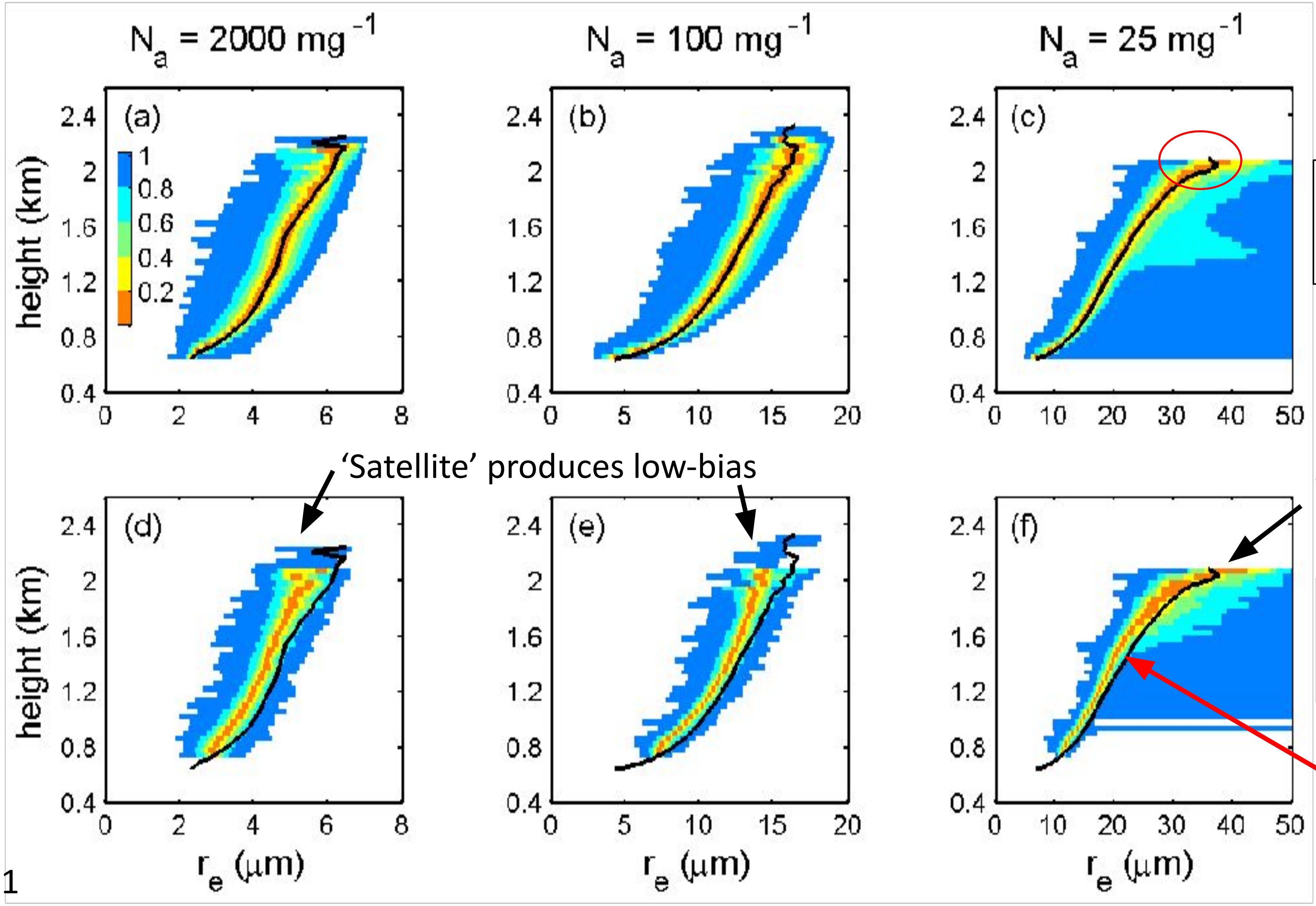

All model output ("truth")

'Satellite' produces low-bias

Higher variability when c-c growth and precip occurs

Profiling using cloud-top r_e

Median from plots above

Mimic Rosenfeld/ Lensky method; assume perfect retrievals

S. Zhang et al. 2011

Ergodicity

A sufficiently large collection of random samples from a process can represent the average statistical properties of the entire process.

Often thought of as a ‘time-space exchange’

Ergodicity

Practical examples:

1) Whether one person rolls a die 100 times or 100 people roll a die once, the expected outcome is the same (**ergodic**)

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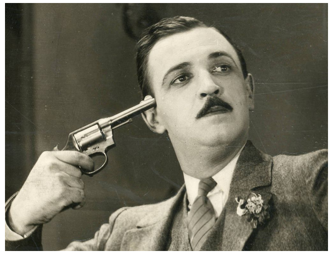
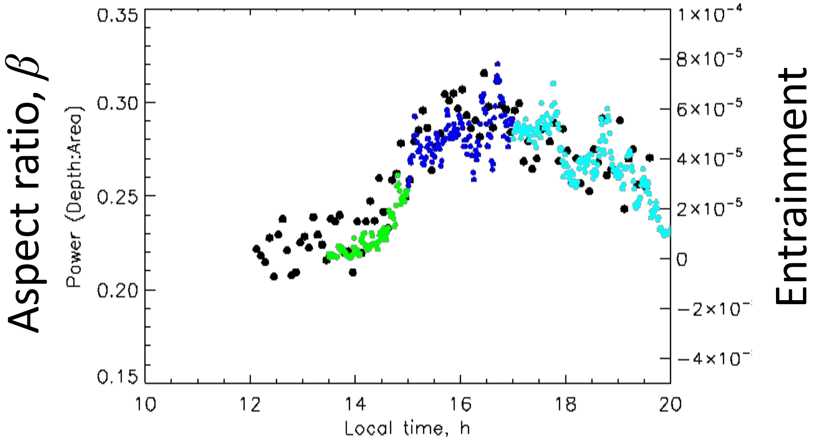


2) Whether one person plays Russian roulette 6 times or 6 people play Russian roulette once, the outcome is very different
(**non-ergodic**)

What does this success in r_e profiling mean?

Self-similarity in a cloud field growing in ~homogeneous environmental conditions

Aspect ratio tells us something about net entrainment



Aspect ratio parameter β

$(z \sim a^{\beta})$

z = depth

a = area

Black dots: mean cloud-field aspect ratio parameter β

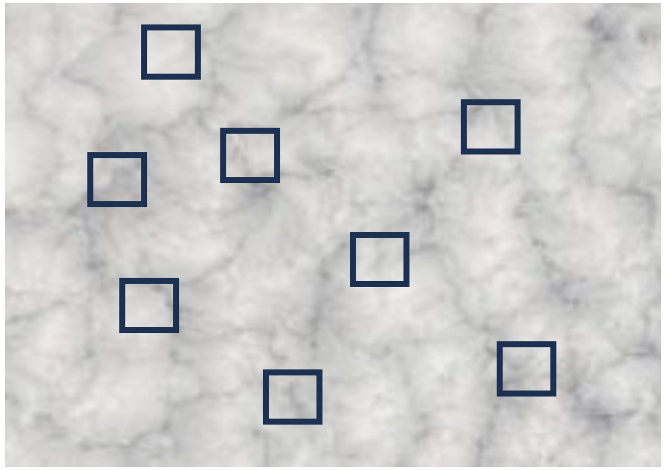
Colored dots: mean cloud-field entrainment rates

Feingold et al. 2024, in progress
See also Hoffmann et al. 2023

2. Compositing of a stratocumulus cell from a snapshot

Hypothesis: The processes in a canonical Sc cell can be understood by compositing samples of many different Sc cloud cells

Spatial sampling process understanding



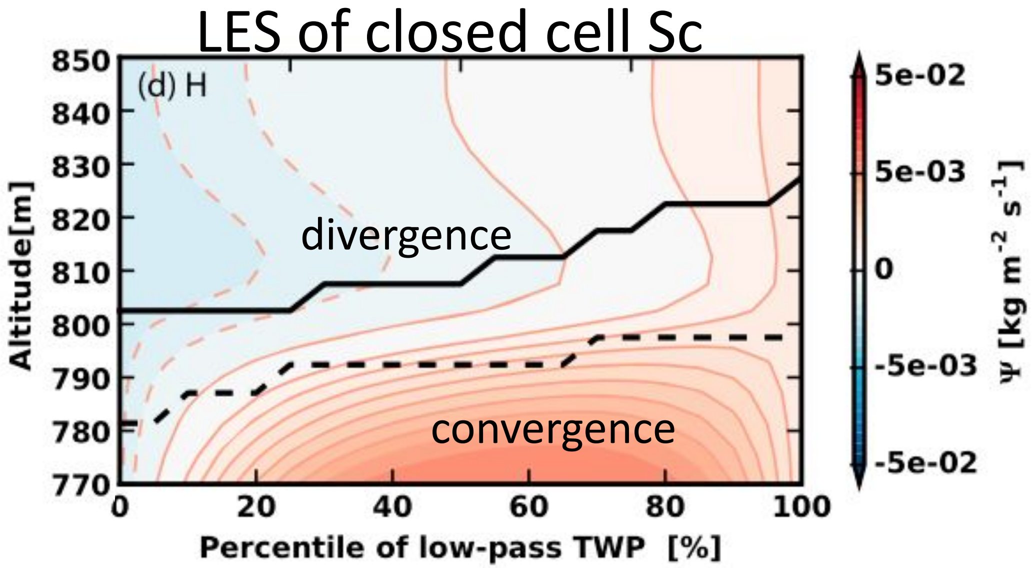
Closed-cell stratocumulus

Assumption:
Negligible variability in meteorology/boundary layer properties across the image

2. Compositing of a stratocumulus cell from a snapshot

Hypothesis: The processes in a canonical Sc cell can be understood by compositing samples of many different Sc cloud cells

Zoom in close to inversion



Ψ= stream function

TWP = total water path

Method

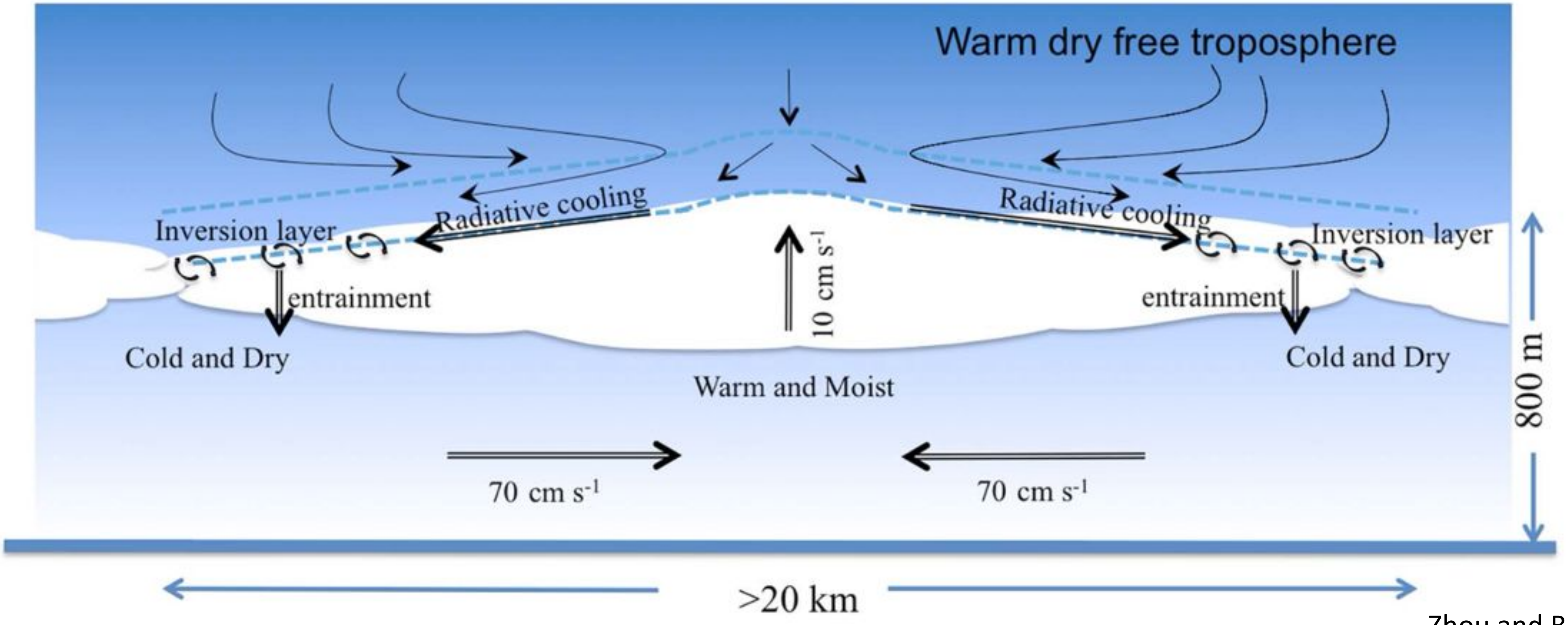
- Sample a large number of cells in this scene
- Sort them by quantiles of a variable such as TWP
- Composite all samples

Bretherton and Blossey (2017)

Zhou and Bretherton (2019)

2. Compositing of a stratocumulus cell from a snapshot

The structure of a closed stratocumulus cell can be explained by the composite of many closed cells sorted by TWP

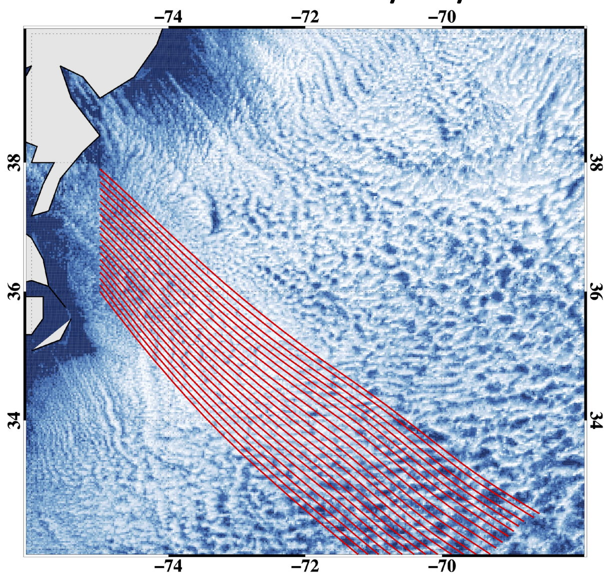


Zhou and Bretherton (2019)

3. Evolution of a Cold Air Outbreak

GOES snapshot
- ERA5 1000hPa winds;
- GOES16 LWP, N_d, A_c

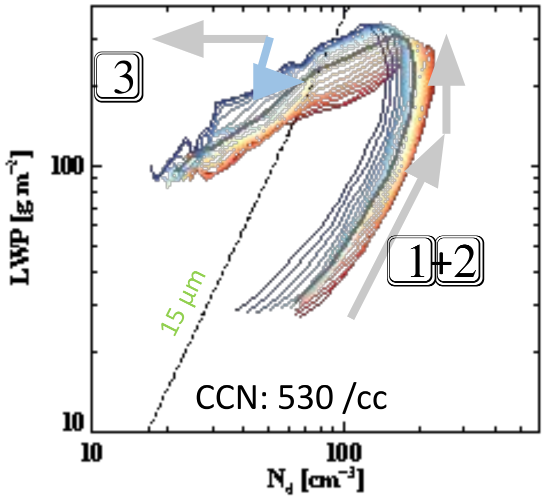
11am LST 01/29/2021



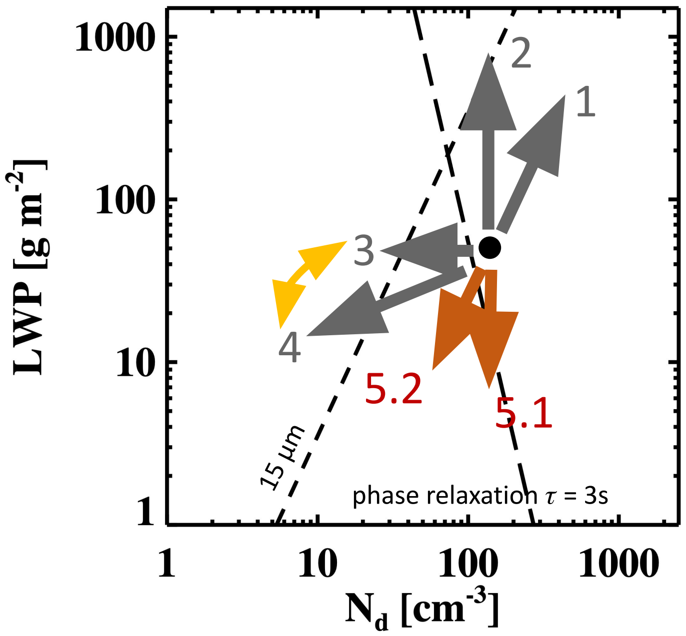
Cold air outbreak
Eastern USA

Can one infer processes driving cloud field evolution from a trajectory through a snapshot?

Shape encodes process
- Meteorological drivers
- Microphysical processes



LWP-N_d



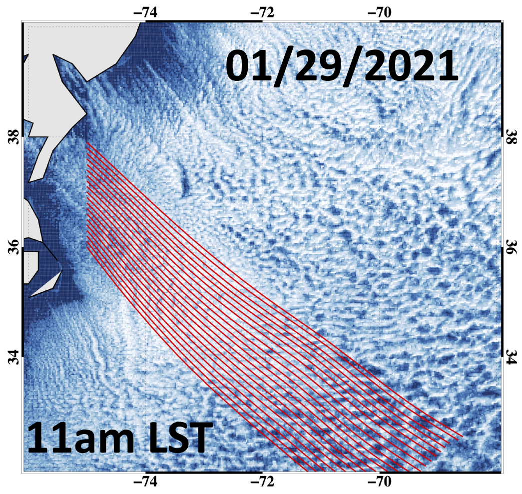
1. activation
2. condensation
3. collision-coalescence
4. precipitation
5. entrainment
   1) homogeneous
   2) inhomogeneous

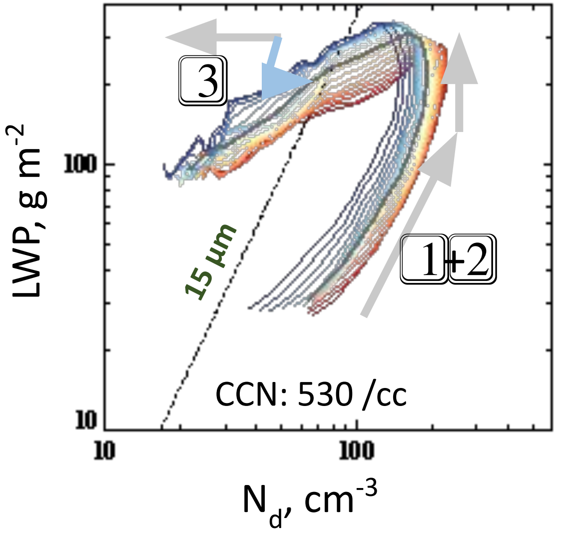
Jianhao Zhang

3. Evolution of a Cold Air Outbreak

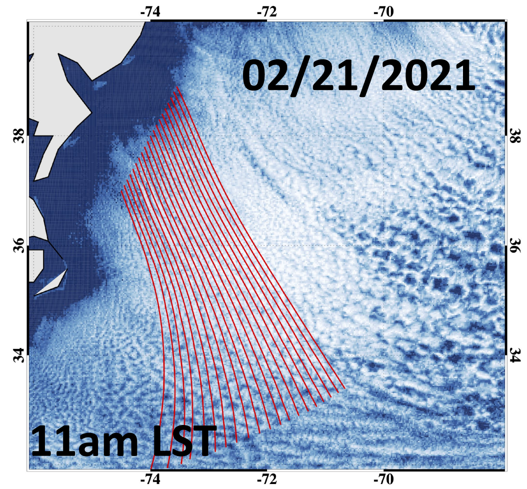
<u>2-D “trajectories” inferring cloud street evolution from a snapshot:</u> ERA5 1000hPa winds; GOES16 LWP, N_d, A_c

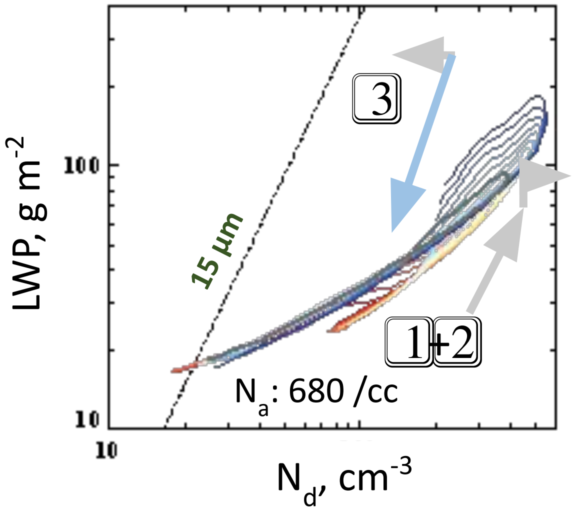
Precip-driven breakup





Entrainment-driven breakup





<u>Precip-driven breakup</u>

0) **Large scale meteorology sets the boundary layer depth**
1) activation
2) condensation
3) **collision-coalescence dominates**, while entrainment reduces LWP

temporal – spatial consistency, provided the trajectory through the domain is faster than the cold air outbreak event

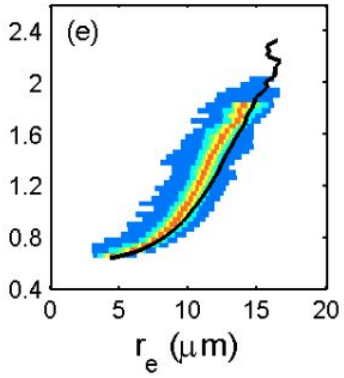
<u>Entrainment-driven breakup</u>

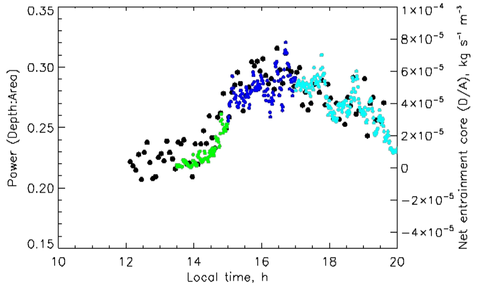
0) **Large scale meteorology sets the boundary layer depth**
1) activation
2) **Minimal condensation**
3) **Entrainment dominates**, while collision-coalescence increases r_e

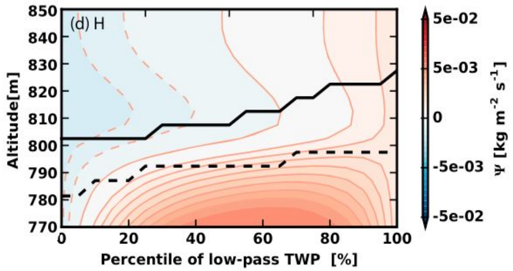
Summary

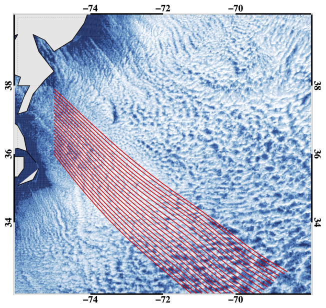
How well can we infer ‘Process’ from ‘Snapshots’?

- Profiling of r_e based on cloud-top r_e in a cloud field
  - Appears robust in shallow marine cumulus
  - Implies self similarity across a cloud field
  - Cloud aspect ratio □□ entrainment
- Stratocumulus compositing to infer process
  - Randomly sample field and sorting by Total Water Path provides insight into process
- Time-Space interchangeability in cold air outbreak
  - Dominant meteorological and μphysical processes can be identified
  - Largescale system evolution needs to be slower than the processes being explored









Some comments on Ergodicity

- Exploiting Ergodicity – to the extent that it exists – is a powerful way to utilize large samples of snapshots to infer process

- Strict definitions of ergodicity may not be necessary for snapshots to be useful for understanding processes

- Practical aspects may get in the way
  - E.g., ability to retrieve r_e, τ in broken clouds