Evolution of Droplet Size Distributions During the Transition of an Ultraclean Stratocumulus Cloud System to Open Cell Structure

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Atmospheric System Research

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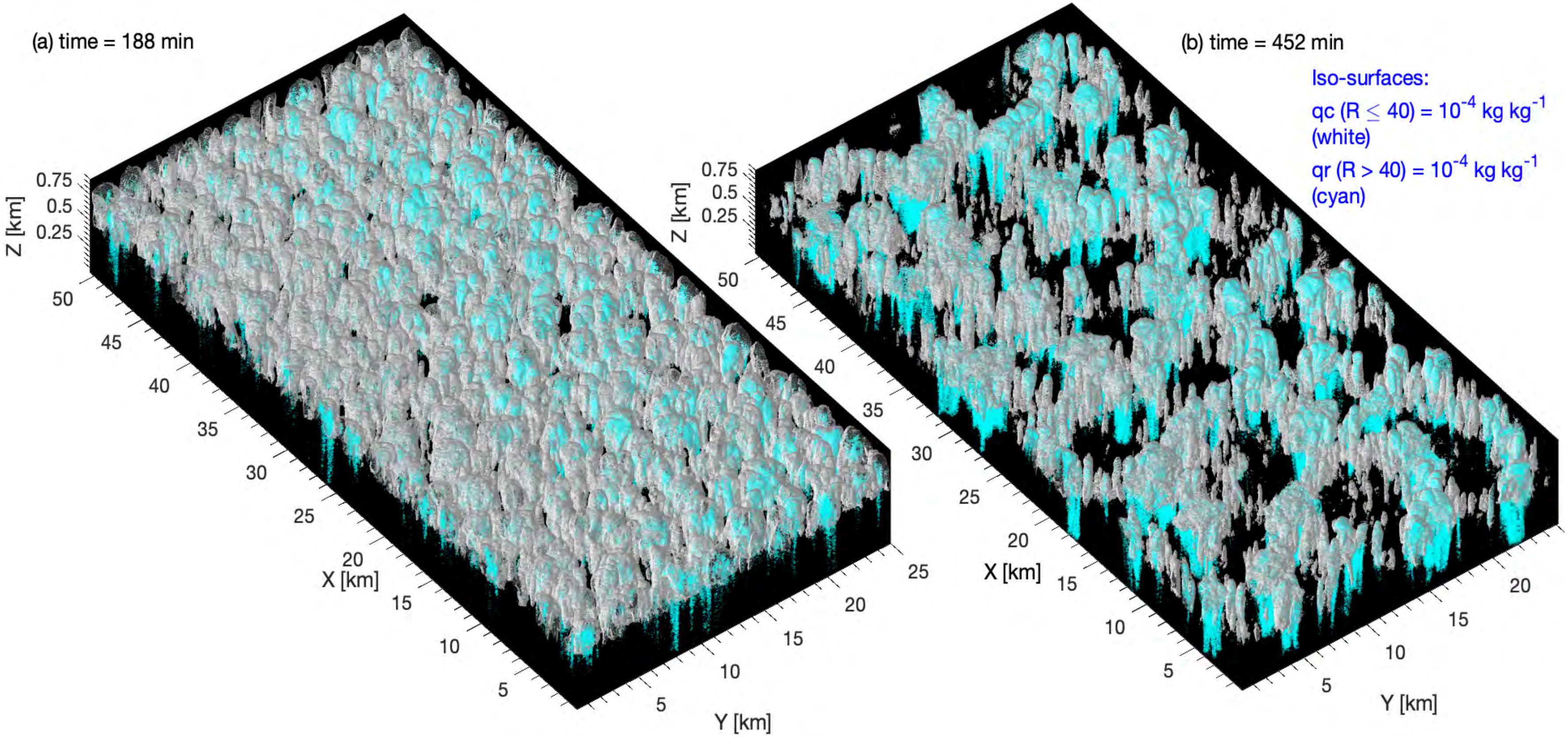
Motivation

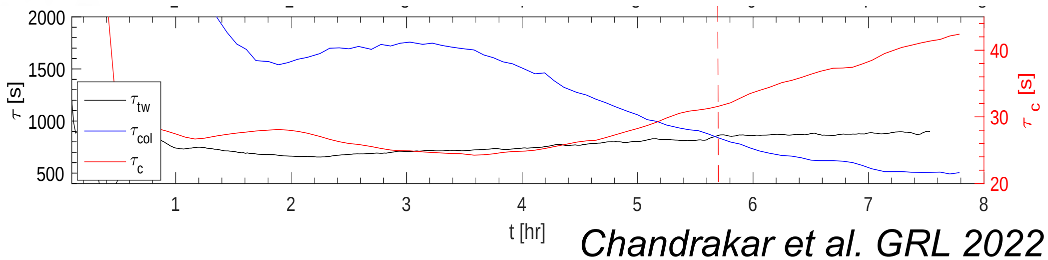
Credit: NASA Visible Earth-MODIS image

How do droplet size distributions (DSDs) vary spatially and temporally during the closed-to-open cell transition and contribute to the precipitation flux driving the cellular transition?

Closed to Open Cell Transition: Investigation using Lagrangian microphysics in LES

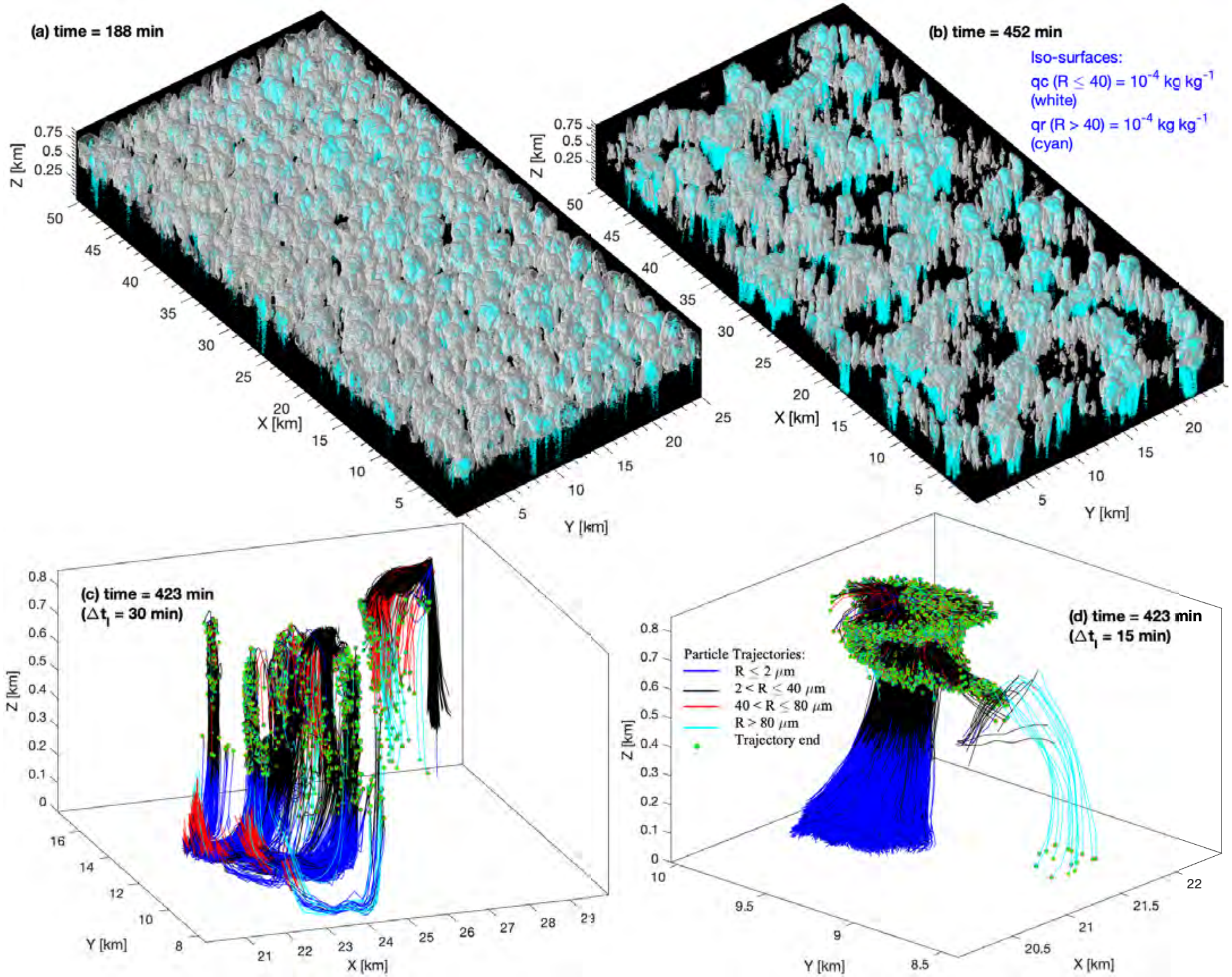


Open cell Transition ➔ Coalescence timescale < Eddy turnover timescale



Chandrakar et al. GRL 2022

Variability in droplet lifetime and growth history



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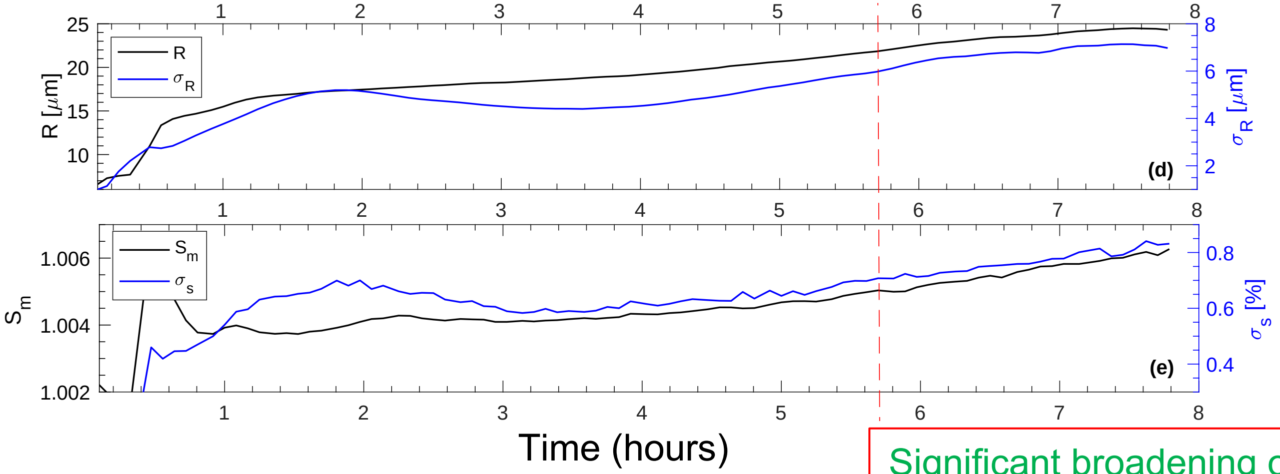
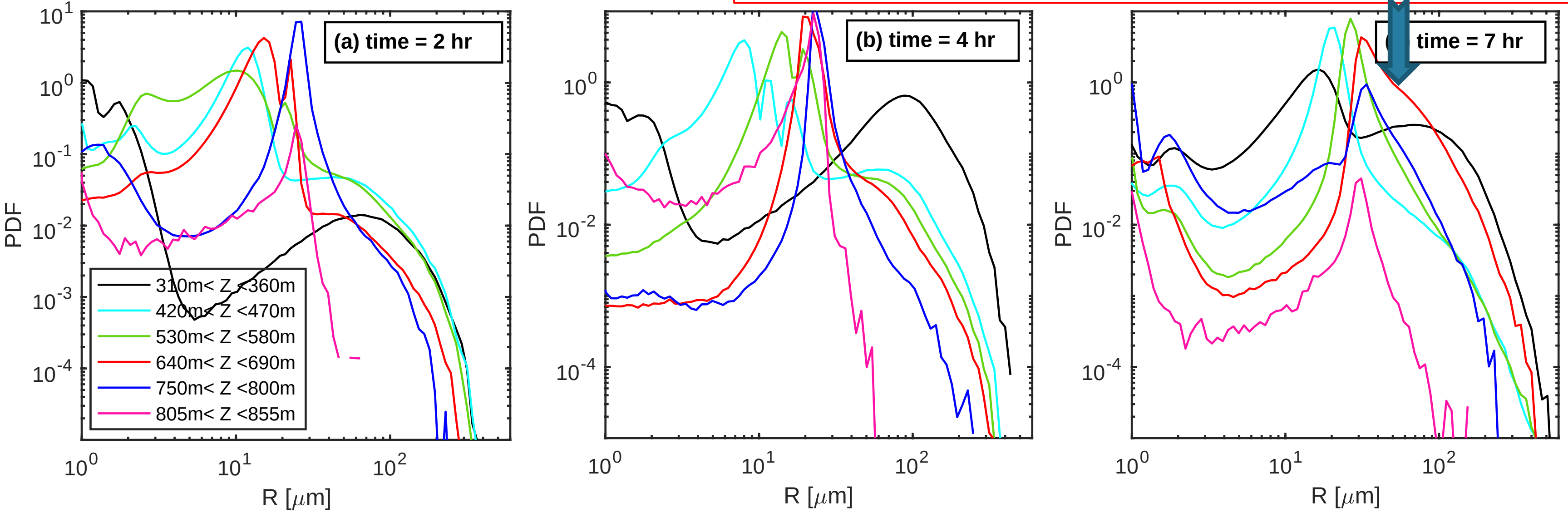
Evolution of DSDs during the closed-to-open cell transition



The mean and standard deviation of droplet radius follows in-cloud supersaturation mean and standard deviation.

Significant broadening of mean DSDs toward the right (large) tail after transitioning to the open cell



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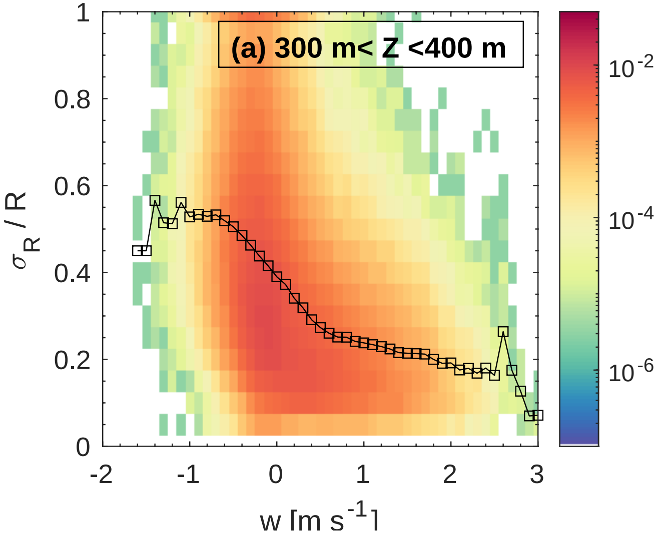
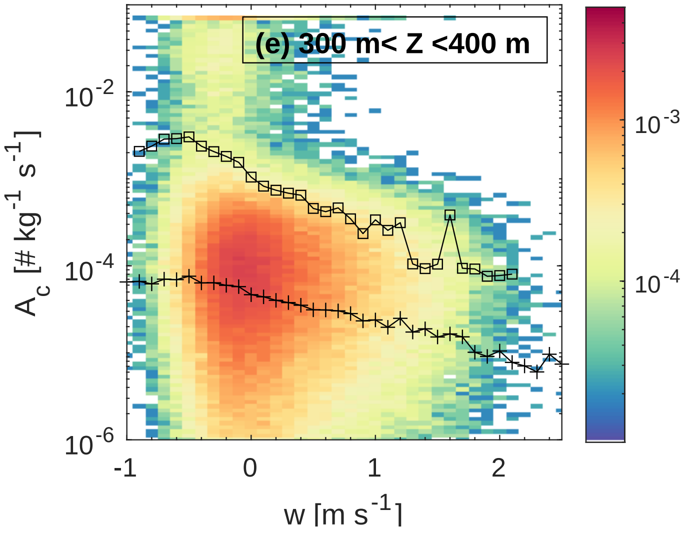
Dependence of droplet size distributions on vertical velocity

Longer drop lifetime (and higher variability) ➡ broader DSDs and higher drop collision-coalescence in downdrafts

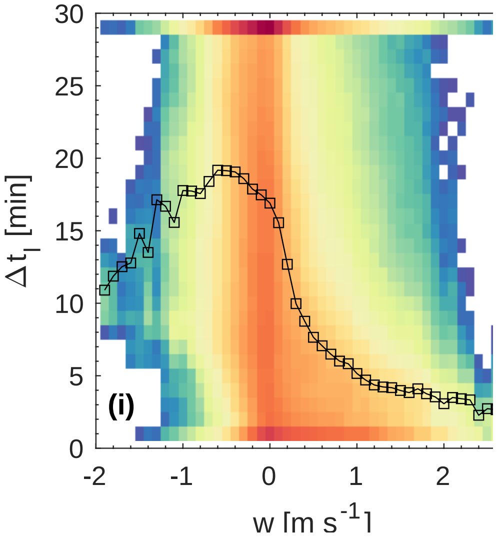
Relative radius dispersion versus vertical velocity



Coalescence rate versus vertical velocity



Droplet lifetime versus vertical velocity



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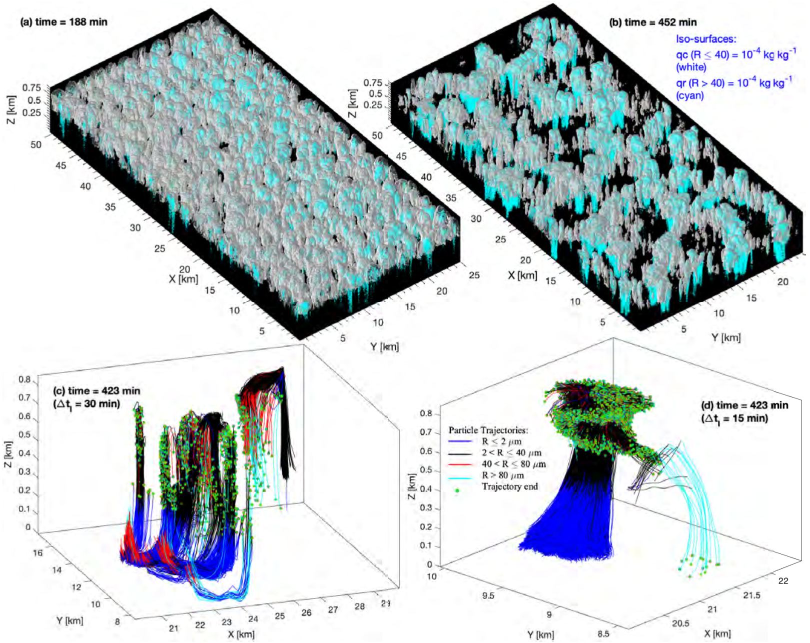
Conclusions



- ➢ Processes controlling precipitation development, which is a key to the transition, are analyzed by leveraging unique benefits of Lagrangian microphysics.
- ➢ During the transition, the rain rate increases sharply as the coalescence timescale decreases relative to the large eddy turnover.
- ➢ Drop size distributions in open cell stratocumulus are broader in downdrafts than updrafts from coalescence, evaporation and drop mixing.
- ➢ Sufficient time is needed for coalescence growth of cloud drops to drizzle within the updraft-downdraft cycle of large eddies. This favors broad drop size distributions (DSDs) and drizzle growth in downdrafts, where drops are typically much older than in updrafts.

Aerosol–Boundary Layer Interaction Modulated Entrainment Process

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University of Maryland at College Park

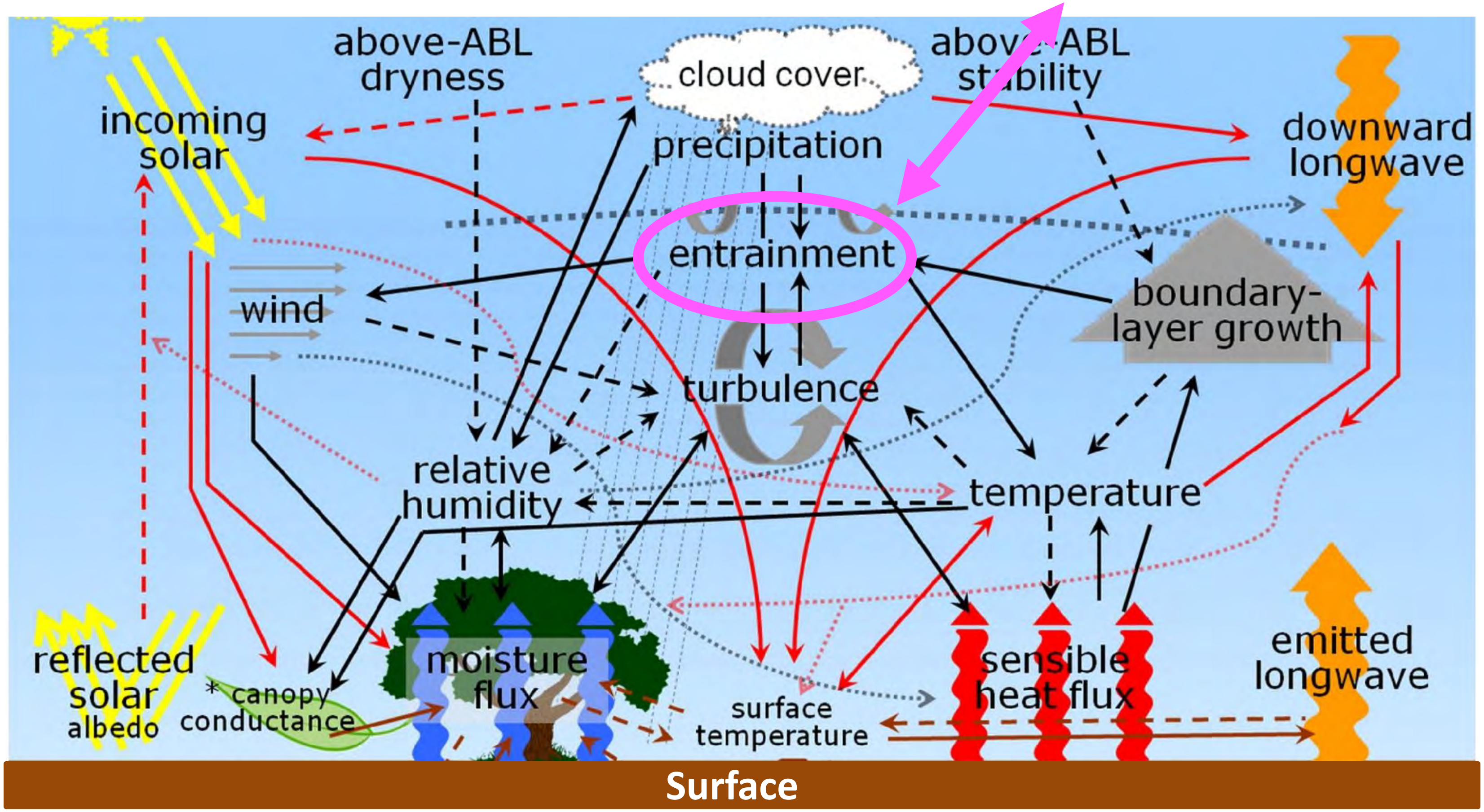
Collaborators: Youtong Zheng, Tong Wu, Hao Wu, Jianping Guo

Warm Boundary Layer Process Working Group

Why is entrainment crucial for PBL processes?

Coupled land-atmosphere system:
a ***chaotic system***

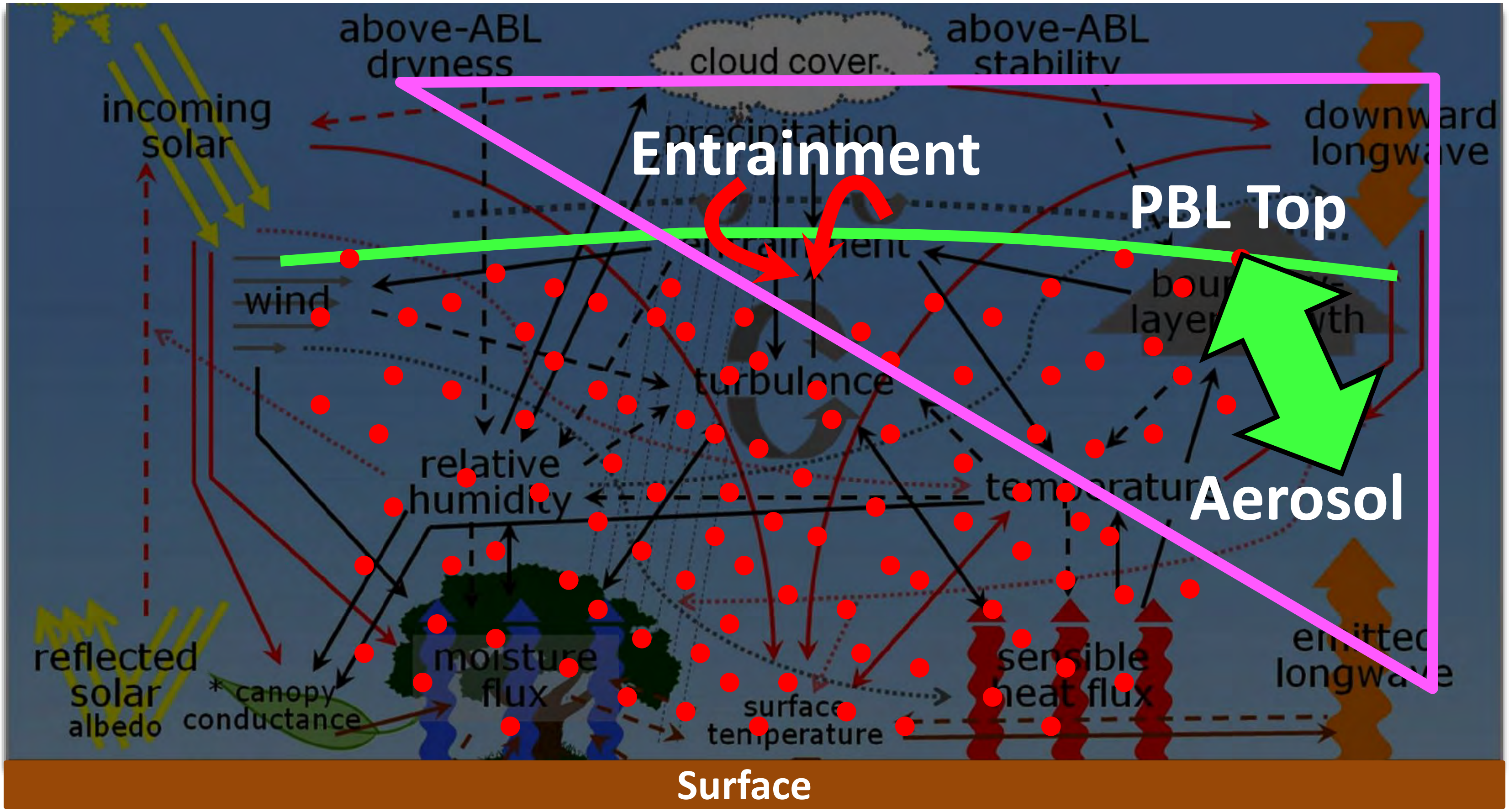
A key process to connect all



Santanello et al., 2018
(Adapted from Ek and Holtslag, 2004)

Why is entrainment crucial for PBL processes?

Intertwined interactions?



Santanello et al., 2018
(Adapted from Ek and Holtslag, 2004)

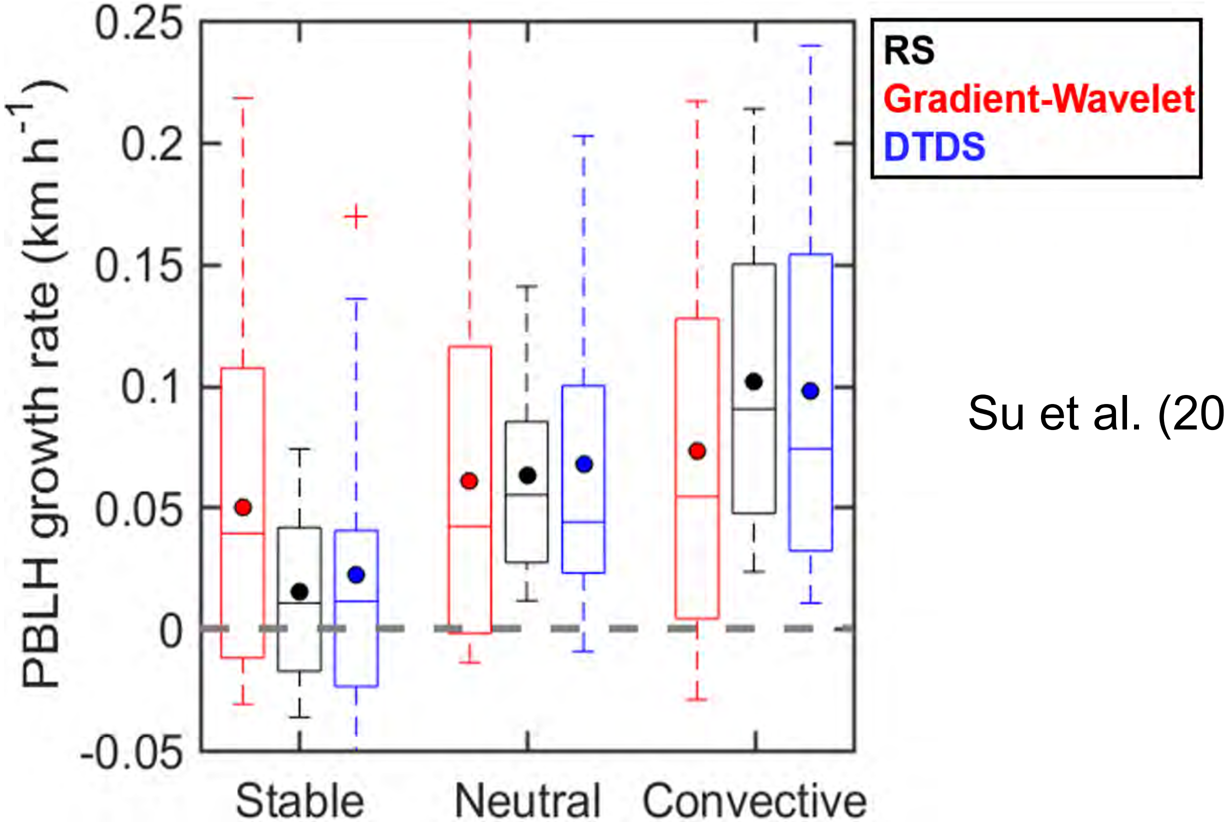
Datasets

Datasets:

Beijing site: there are multi-source measurements over Beijing metropolitan area.
Radiosonde, micropulse lidar (MPL), Sun photometer, eddy covariance technique
Data period: 2017-2019

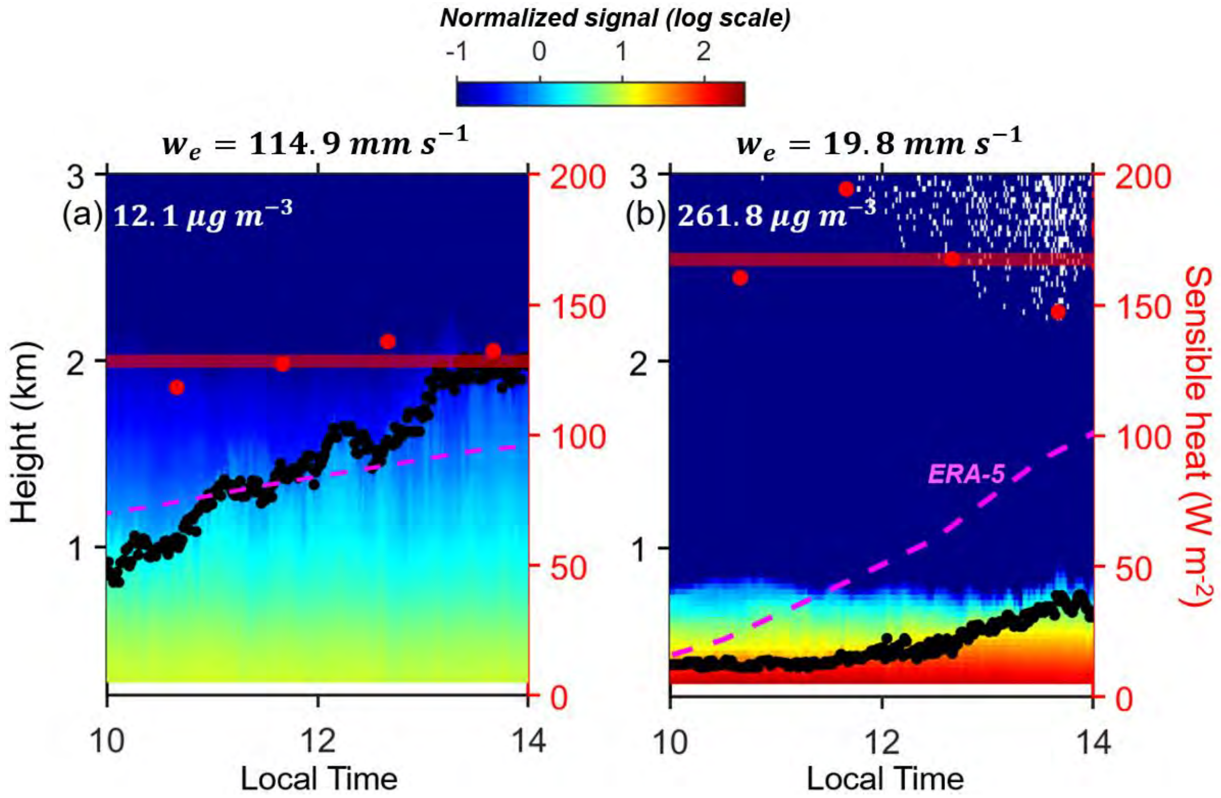
ERA-5: the new generation reanalysis data provides hourly estimates of atmospheric variables (PBLH, large-scale vertical velocity…) (Hersbach, 2020)

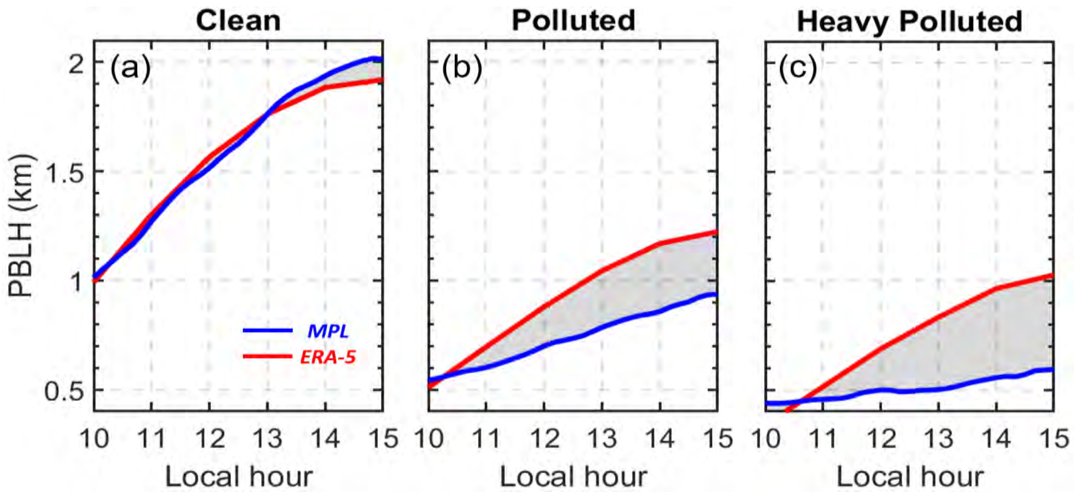
Method:



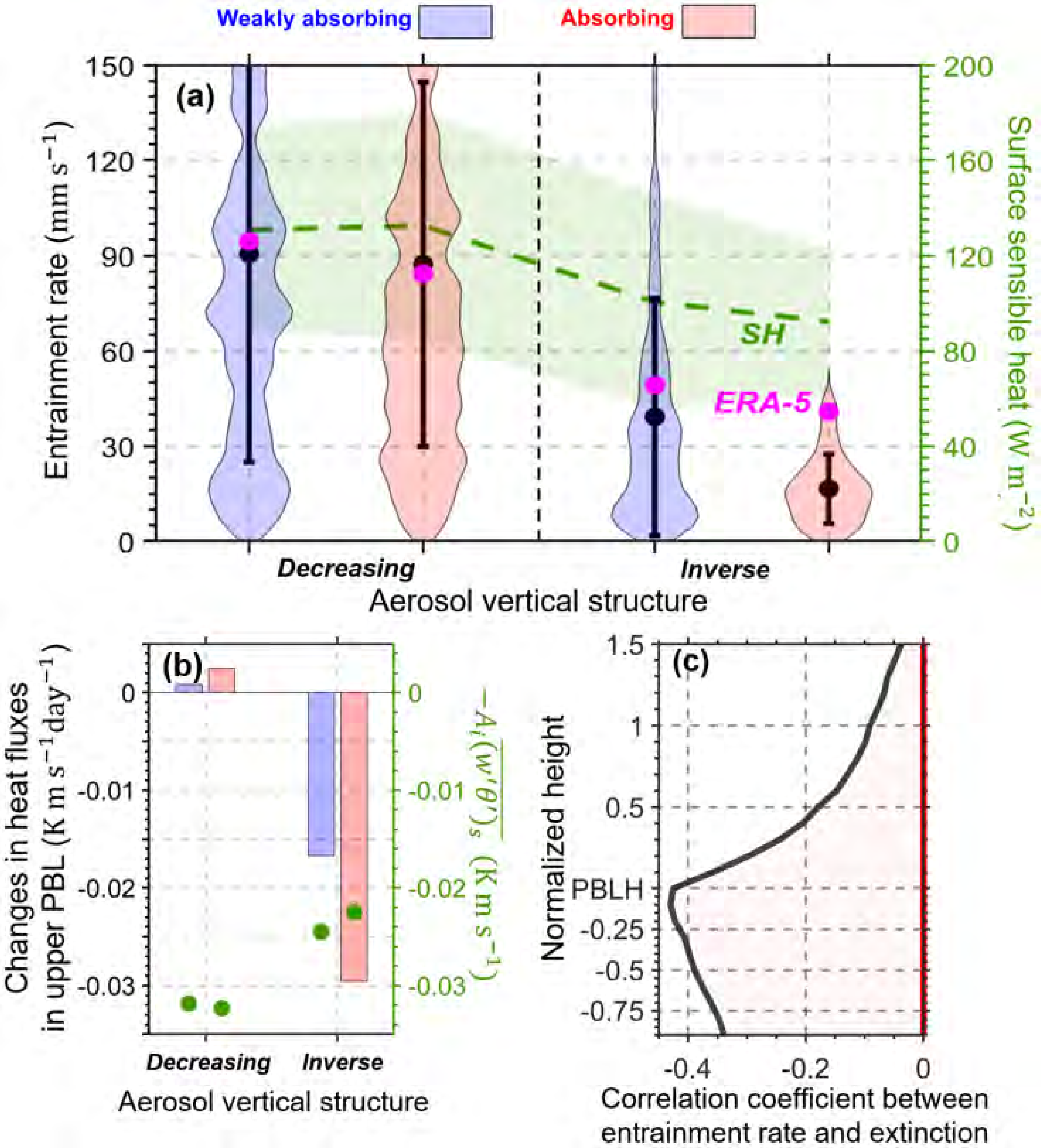
Su et al. (2020,RSE)

PBL variations for variable pollution levels





Entrainment associated with aerosol vertical structure



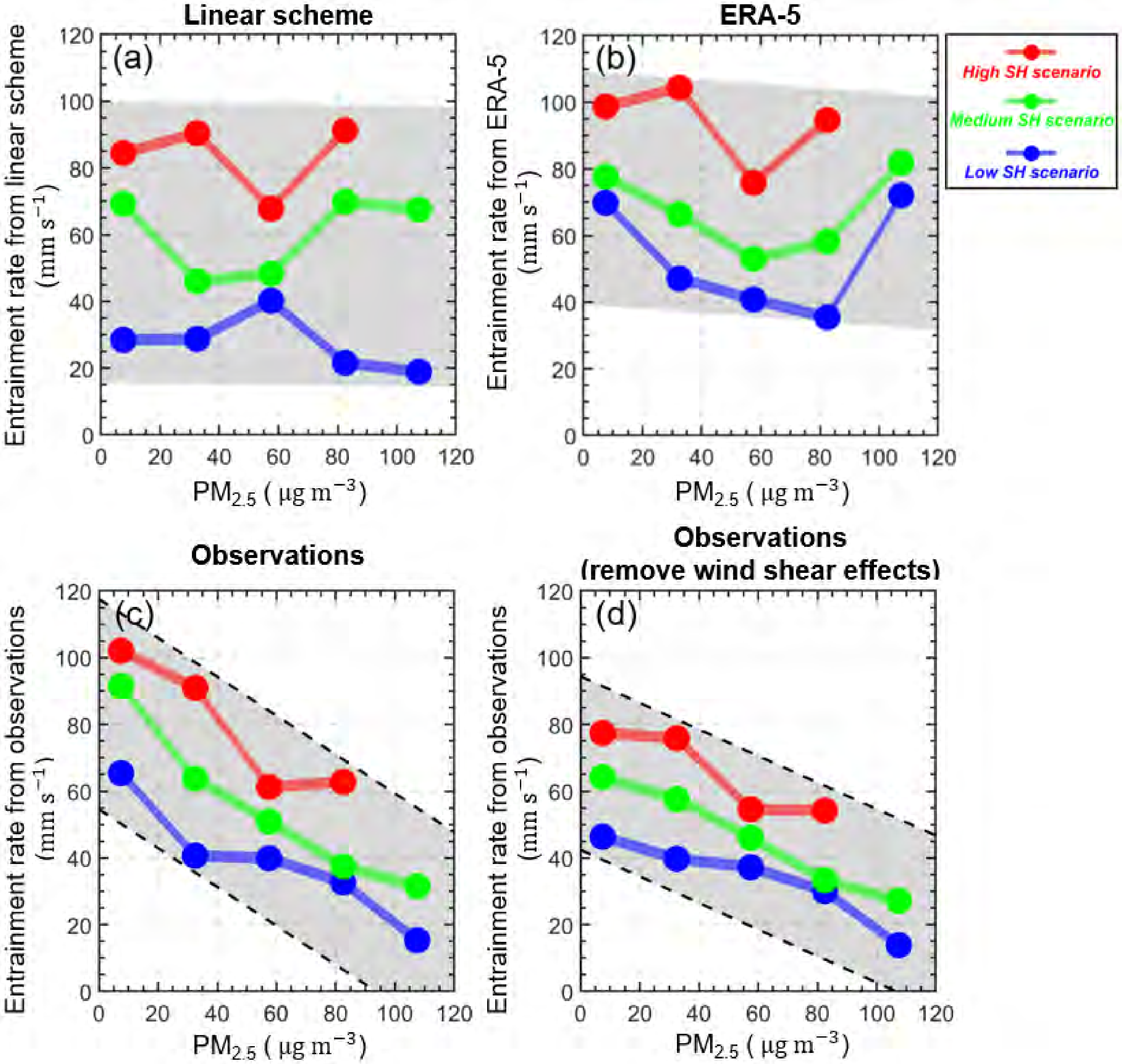
Sensitivity of the entrainment rate to aerosol loading

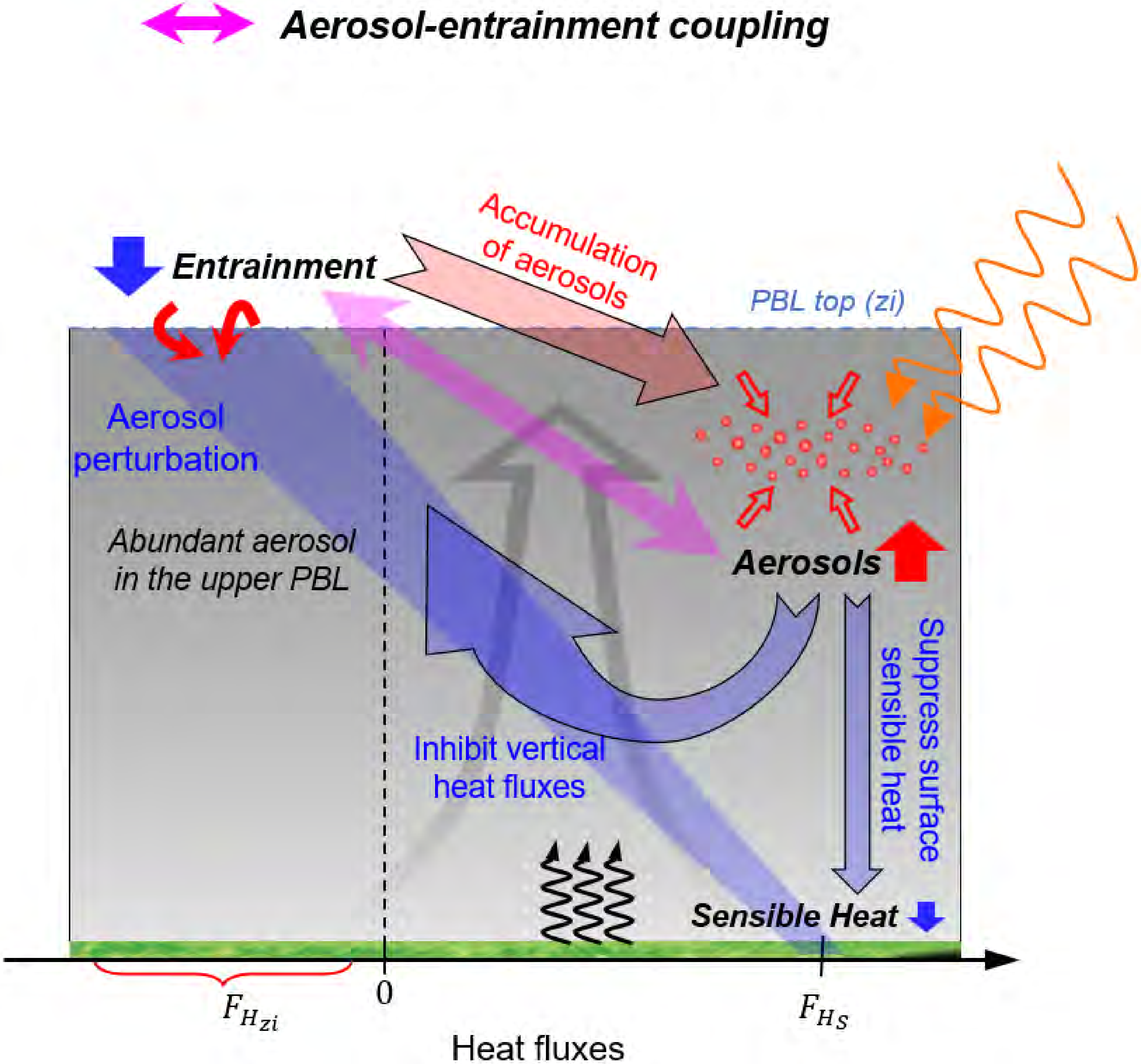
Linear relationship:

$$w_e = A_i \frac{\overline{(w'\theta')_s}}{\Delta\theta}$$

Observed entrainment rates:

$$\frac{dz_i}{dt} = w_e + w_i$$




Aerosol-entrainment coupling
Entrainment
Accumulation of aerosols
PBL top (zi)
Aerosol perturbation
Abundant aerosol in the upper PBL
Aerosols
Suppress surface sensible heat
Inhibit vertical heat fluxes
Sensible Heat
$F_{H_{zi}}$
0
F_{H_S}
Heat fluxes

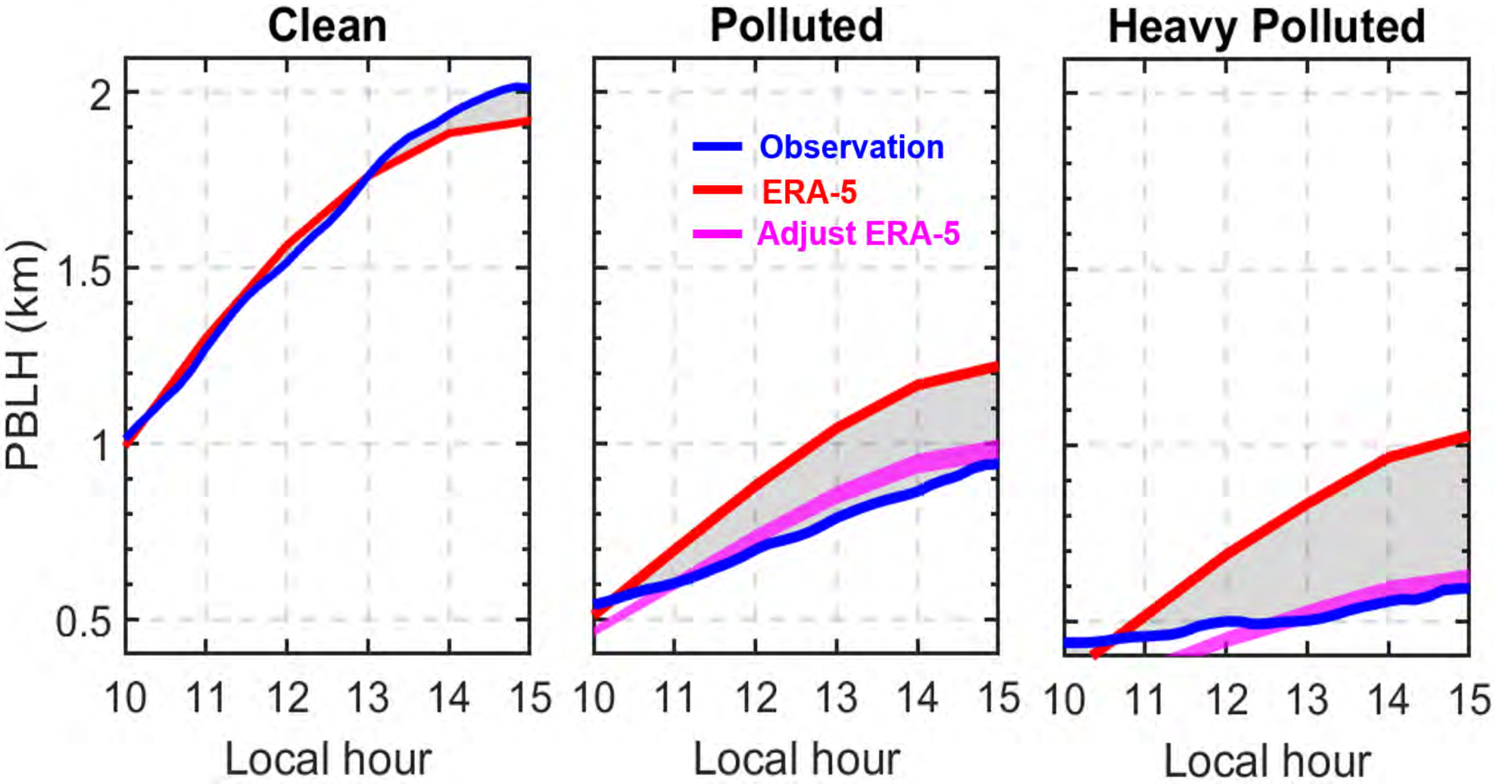
Revisit entrainment parameterization

Responses of entrainment rates to PM2.5:
(remove wind shear effects)

- High SH scenario: -0.31 ± 0.47
- Medium SH scenario: -0.36 ± 0.19
- Low SH scenario: -0.32 ± 0.23

(unit: $mm\ s^{-1}\ \mu g^{-1} m^{3}$)

Adjust the PBL growth rate in ERA5 under polluted conditions:



Summary

(1) Aerosol can suppress the entrainment process, especially for the inverse aerosol structure.

(2) This mechanism of aerosol-entrainment interactions can be a key ingredient for air pollution formation.

(3) Aerosol-entrainment interactions can explain the great sensitivity of observed entrainment rates to aerosols.

We need better entrainment parameterization under polluted conditions

Thank you!

Image courtesy: https://www.istockphoto.com/photo/clean-and-dirty-air-over-a-big-city-gm639753678-115490907

Using ARM's Spectroradiometer Observations to Study Cloud Mixing Processes and Near Cloud Aerosols

Alexander Marshak (GSFC)
Guoyong Wen (USRA)
Weidong Yang (USRA)

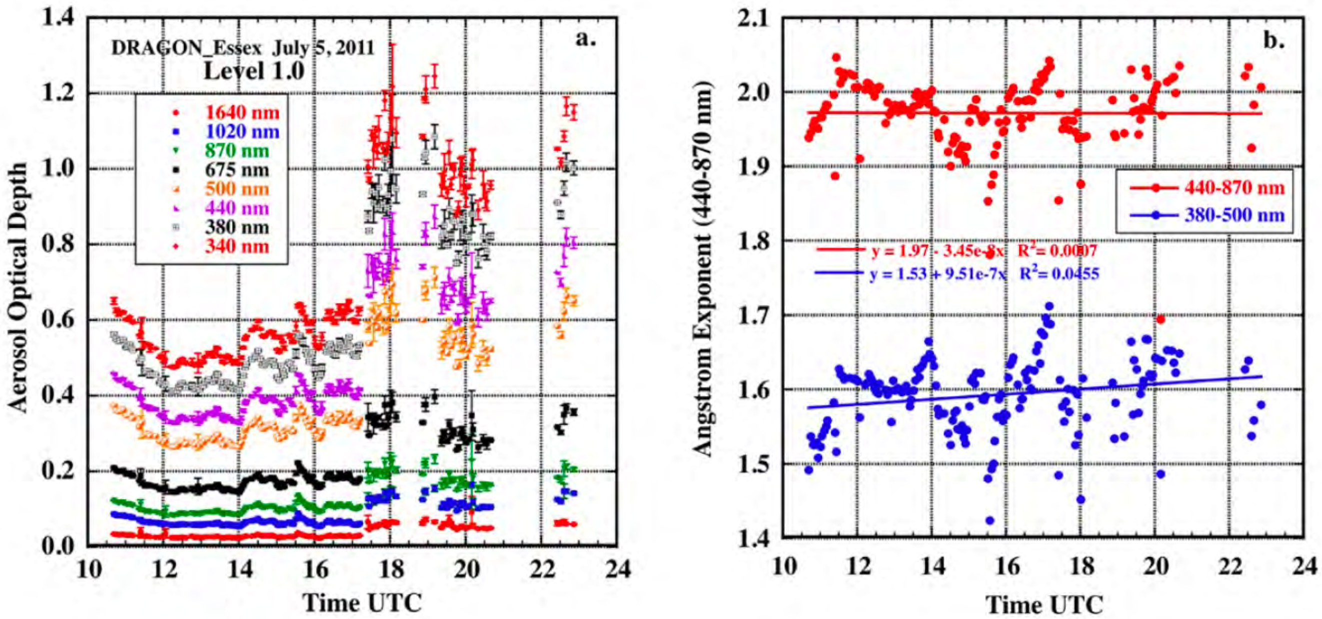
Background (Transition Zone, TZ)

- The TZ between cloudy and clear air is a region of **strong aerosol-cloud interactions** where aerosol CCN **humidify** and **swell** when approaching the cloud, while cloud drops **evaporate** and **shrink** when moving away from the cloud.

- There is a dynamic dance between CCN and cloud drops in this region, but this dance is extremely difficult to study with current aircraft, satellite and with most surface remote sensors because they just **don't have the time and/or spatial resolution** to do so.

Motivation

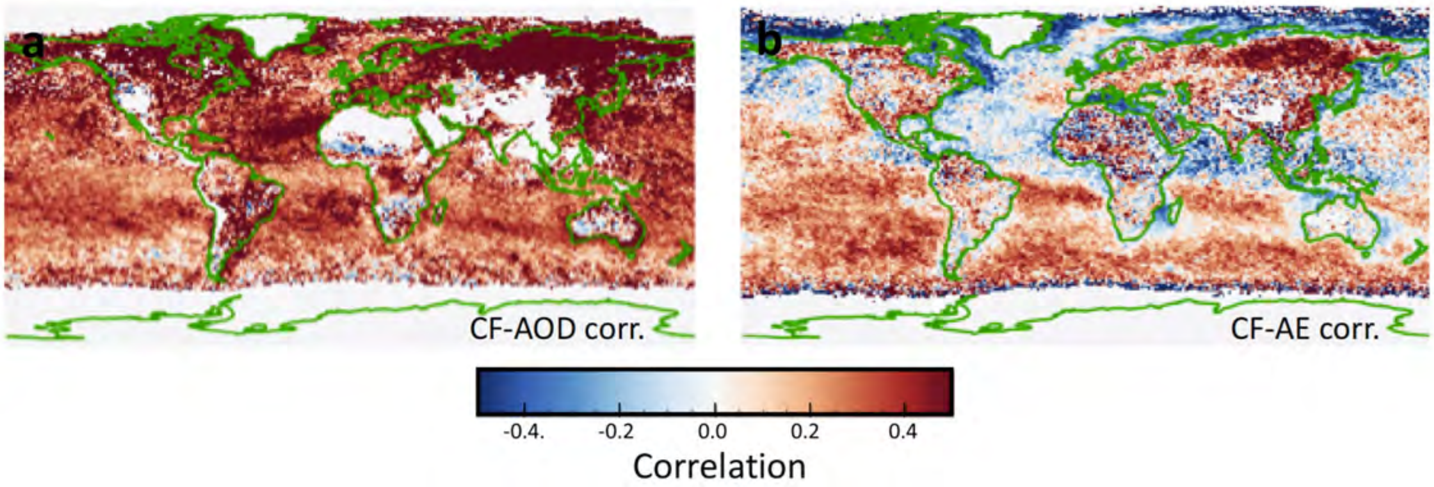
from Eck et al., 2014



Left: The time series of spectral AOD measured at AERONET site on 5 July 2011.

Right: The time series of the Ångström exponent computed for two wavelength intervals from the same data as in (a)

A rapid increase in AOD in the vicinity of cumulus clouds while the AE remained relatively constant throughout the day



Maps of correlation between MODIS CF and (**left**) AOD or (**right**) AE. The local correlation values are shown for each 1° x 1° region, for June-August in 2012-14

from Vánai and Marshak, 2018

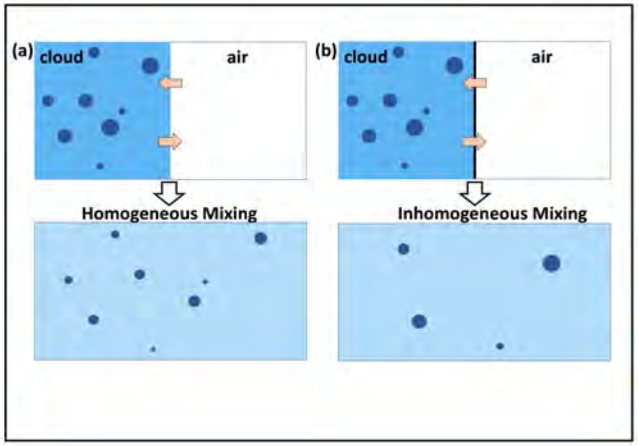
Mixing Processes

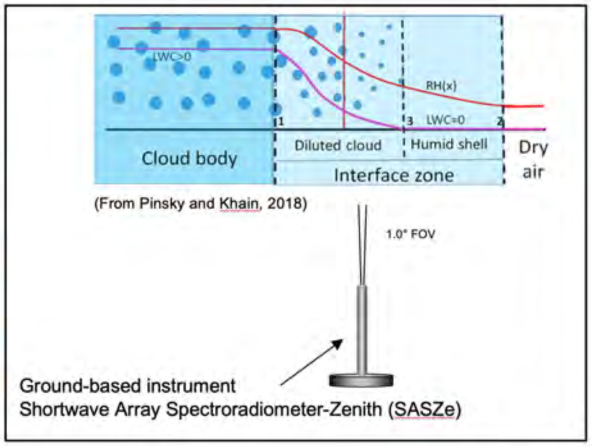
- The difference between homogeneous and inhomogeneous mixing is attributed to the **different timescales of mixing and evaporation.**

- We use **ground-based spectral observations** to test the inhomogeneous mixing hypothesis in **low clouds**.

- Data from shortwave spectrometers provide a **unique opportunity** to study the cloud mixing processes.

ARM’s Spectroradiometer Observations



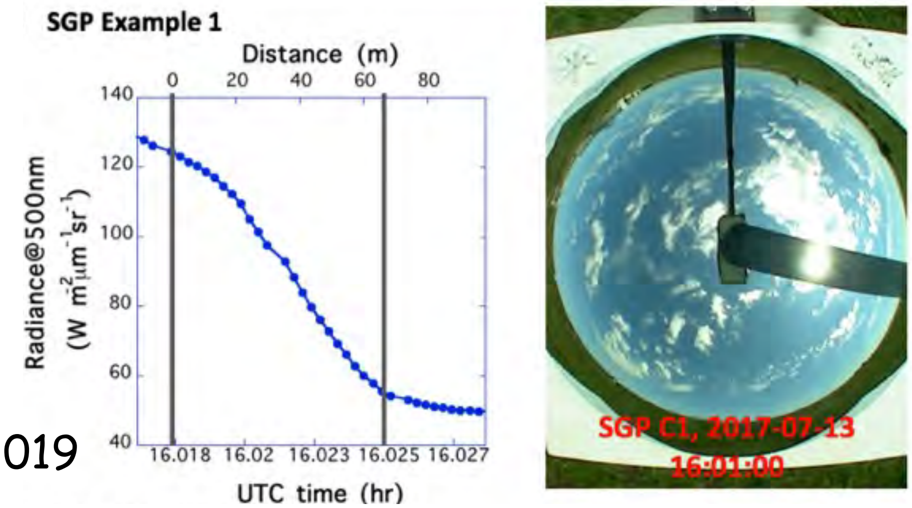


(From Pinsky and Khain, 2018)

Ground-based instrument
Shortwave Array Spectroradiometer-Zenith (SASZe)

Left: Two limiting scenarios of the air entrainment and mixing processes: the homogeneous vs inhomogeneous mixing:
(*i*) Drier air penetrates the cloud before cloud drop evaporates. Reduction in size of *all* droplets but no substantial change in the number of cloud droplets. (*ii*) Cloud drop evaporates before dry air penetrates the entirety of the cloud. Reduction in the droplet number concentration for droplets of *all* sizes but no change in the cloud drop spectrum.

Right: The scheme of changes of microphysical variables within the interface zone near cloud edge.

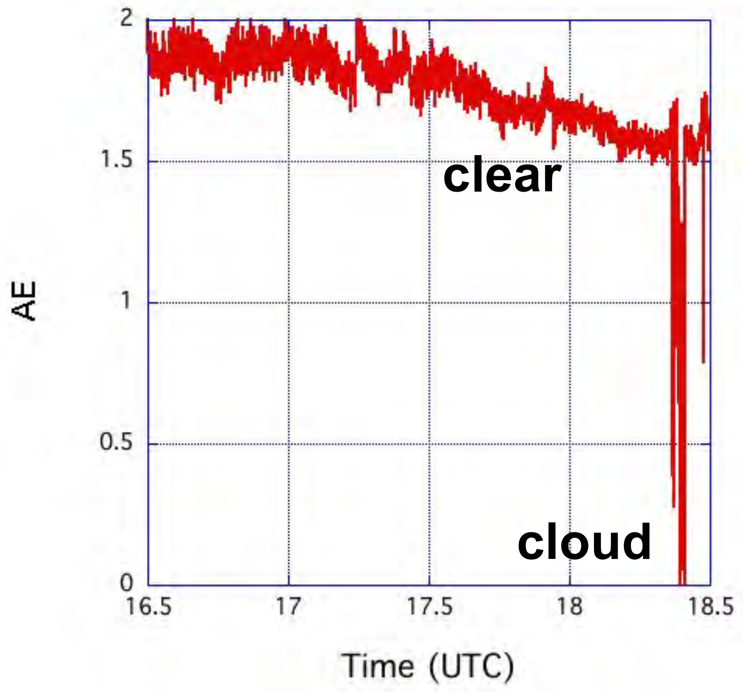


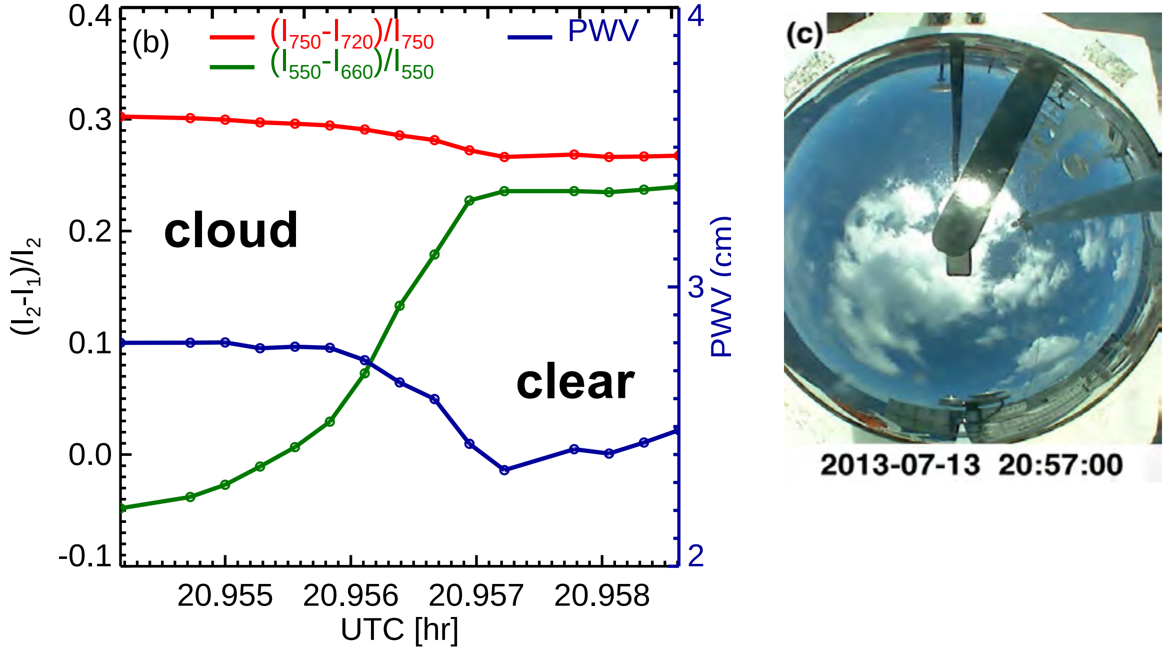
from Yang et al., 2019

An example of ARM’s Shortwave Array Spectroradiometer-Zenith (SASZe) observed 500-nm zenith radiance variation for cloudy-to-clear transition cases at the SGP site with corresponding total sky imager images on 13 July 2017.

Droplet size and PWV Variations

From Wen & Marshak, 2022





AE is proportional to radiance ratio – $\log(I_{500}/I_{860})$. SASZe zenith radiance can be used to study the variation of droplet size near clouds.

The ratio of SASZe zenith radiance at 720 nm (weak H_2O absorption) and 750 nm (non-absorbing) can be used to estimate water vapor variation near clouds.

Stratocumulus-surface decoupling prolongs cloud lifetime: the mechanism

Haipeng Zhang (UMD), Youtong Zheng (Princeton/GFDL), Zhanqing Li (UMD)

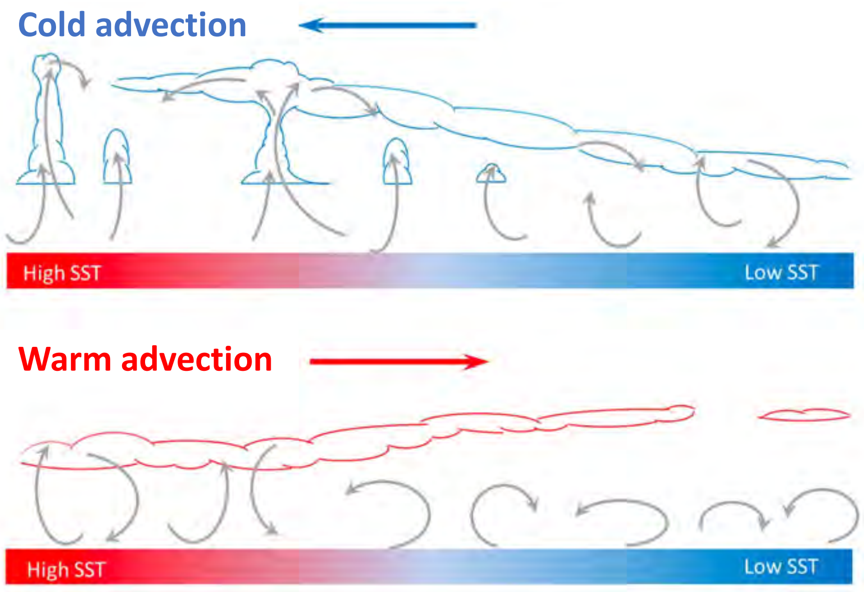
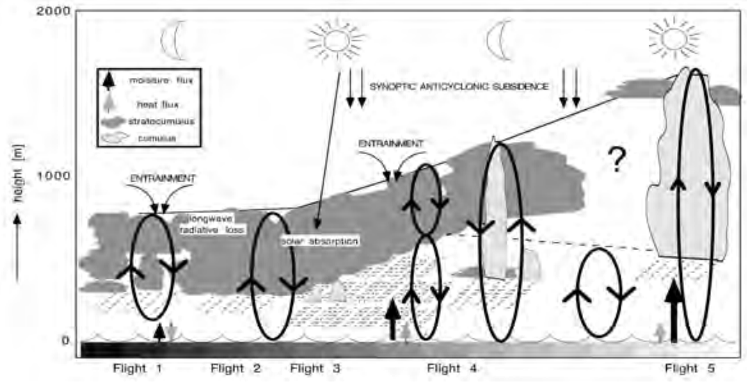


Figure 1. Schematic diagram of response of MBL coupling state to the external forcing of thermal advection. Adapted from Zheng et al. (2018b).

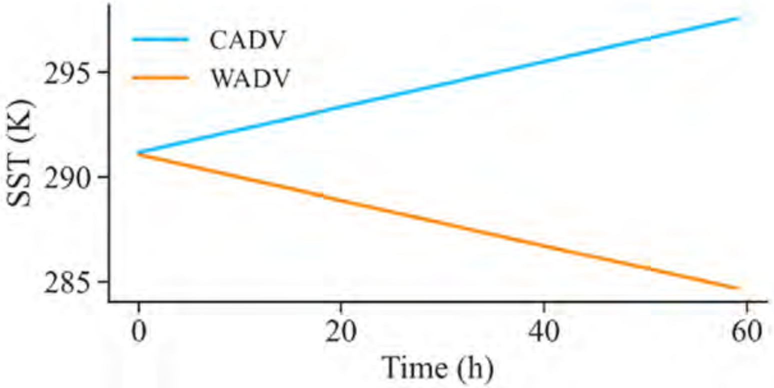
1. LCF decreases from cold to warm advection as the greater cloud-surface decoupling cuts off moisture supply. (Klein et al. 2017; Scott et al. 2020)

2. The opposite relationship is observed by Zheng & Li (2019) because the weaker entrainment drying helps sustain the cloud decks.

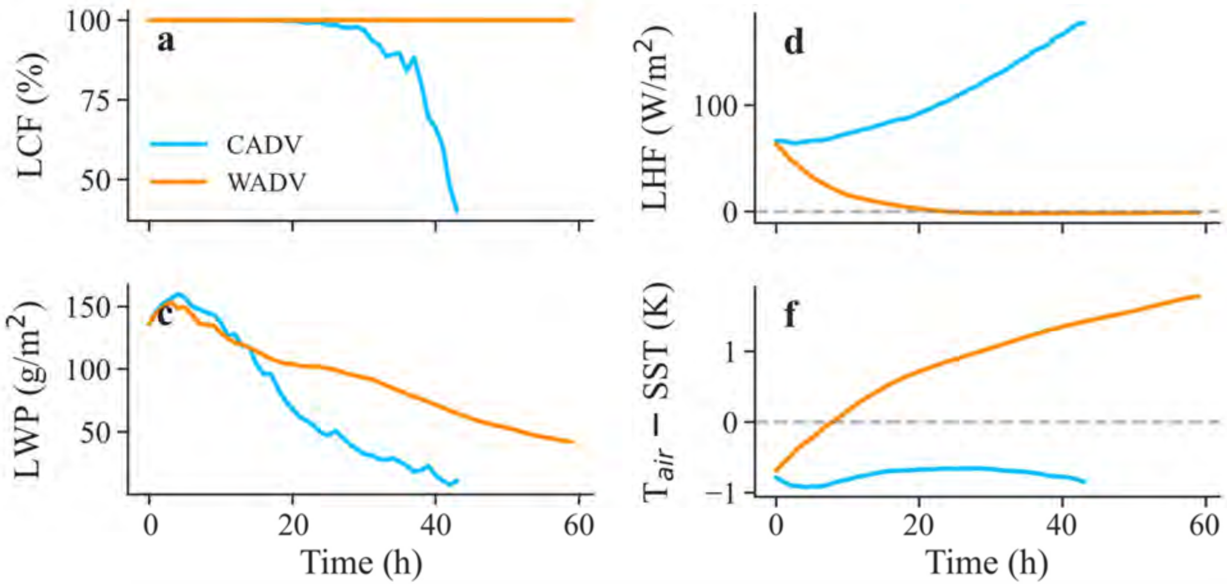
Two idealized LES Lagrangian simulations



(ASTEX, Albrecht et al., 1995)



Longer persistence of cloud deck in WADV

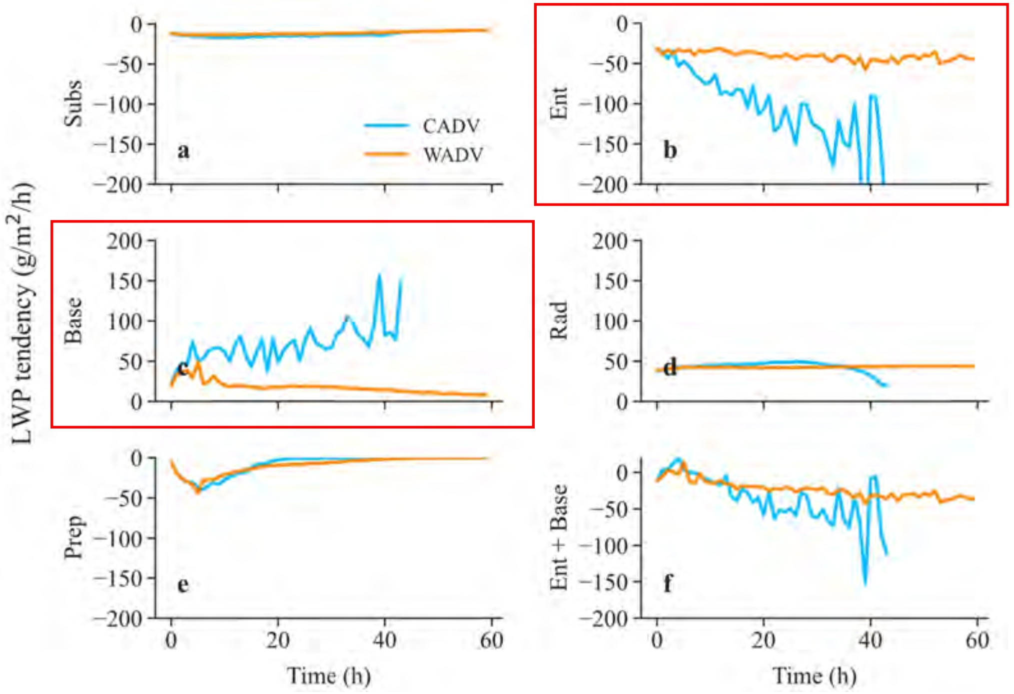


- Quick cloud breakup in CADV ***versus*** long persistence in WADV
- Increasing surface fluxes in CADV ***versus*** significant suppression of surface fluxes in WADV

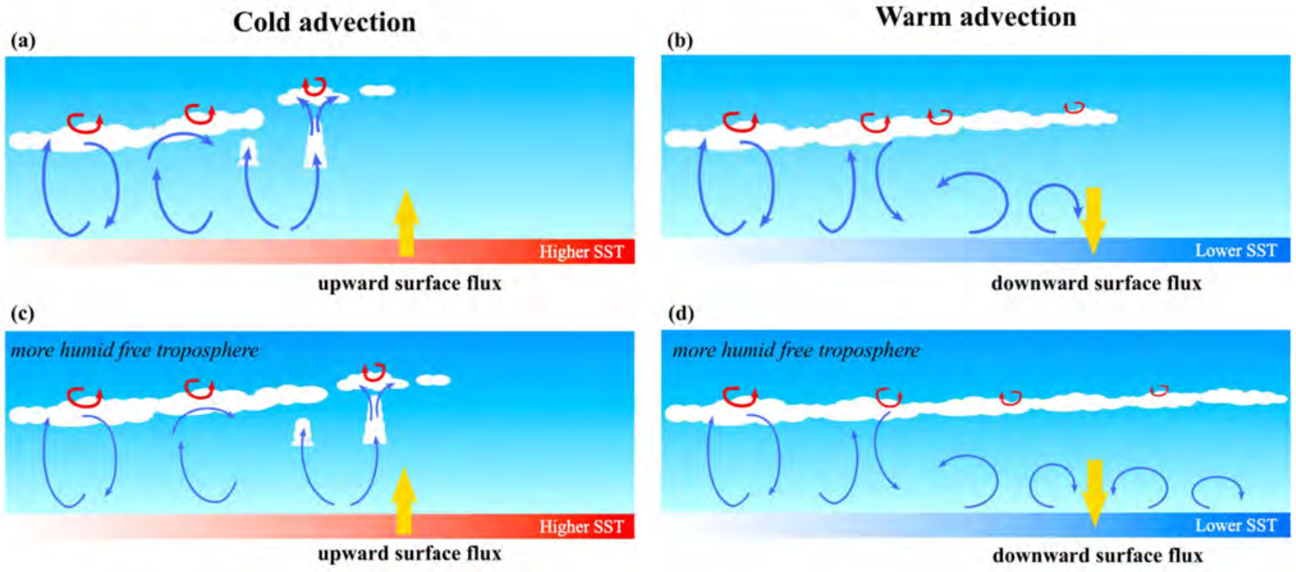
LWP budget analysis

$$\frac{\partial \mathrm{LWP}}{\partial t} = \mathrm{Ent} + \mathrm{Base} + \mathrm{Rad} + \mathrm{Prec} + \mathrm{Subs}$$

(Dussen et al., 2016)



Physical mechanisms



- The persistence in WADV is because the decoupling-induced reduction in entrainment drying outweighs the decrease in cloud-base moisture transport
- It is more significant in a more humid free troposphere
- The results are robust across varied environmental conditions and modeling settings.

Stratocumulus susceptibility across time and cloud scales

Xiaoli Zhou[1], Graham Feingold[1], David Painemal[2], Christine Chiu[3]

[1]NOAA/CIRES, [2]SSAI/NASA Langley, [3]CSU

@ ARM-ASR PI Meeting (WBLP WG breakout), Oct. 27, 2022

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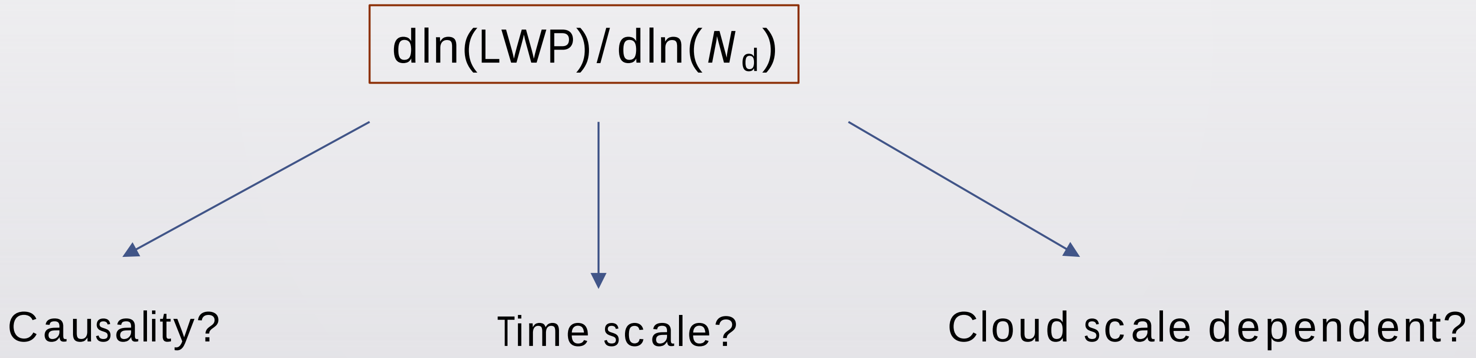
Cloud susceptibility

Cloud susceptibility: cloud liquid water adjustment to aerosol-induced perturbation

Why we care:

- Climatic relevance (the most uncertain anthropogenic forcing of the climate system)
- Marine cloud brightening



$\mathrm{dln}(\mathrm{LWP})/\mathrm{dln}(N_d)$

Causality?

Time scale?

Cloud scale dependent?

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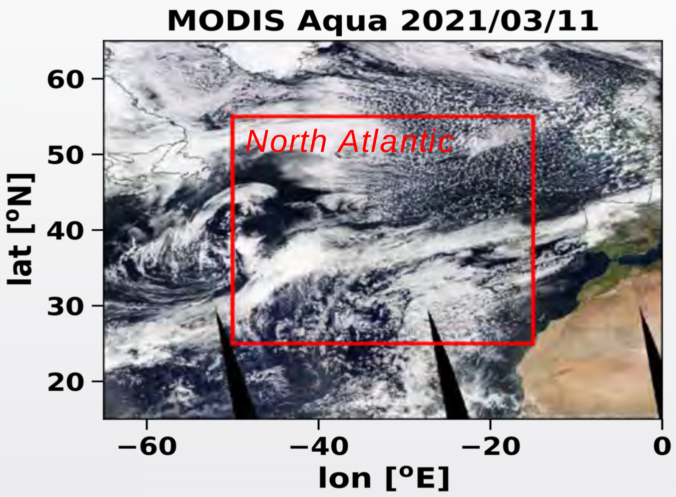
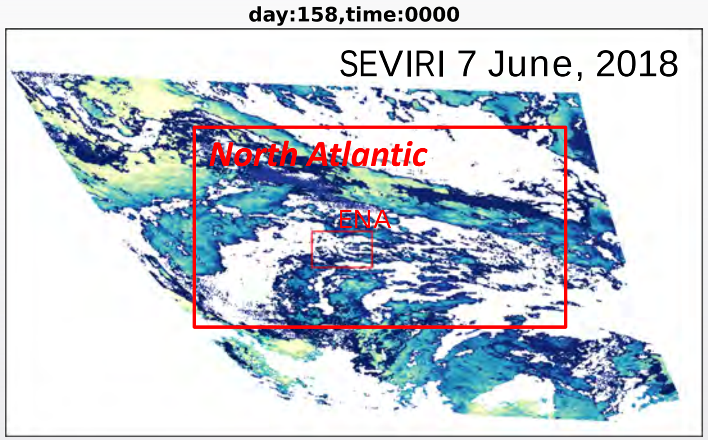
Dataset & Methodology



Temporally

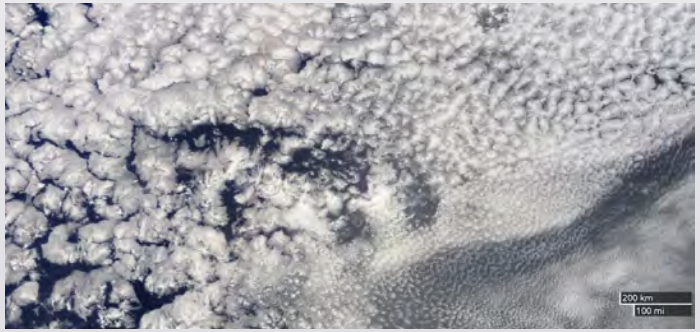


☐ How fast does cloud respond to the changes in aerosols, by what factors?

☐ Causal relationship between LWP and N_d

- Meteosat-11 (SEVIRI)
- June, 2018 (one month data)
- 15 min temporal resolution
- 2^ox2^o scene average LWP & N_d (daytime only)
- 25 multi-scenes
- 1D wavelet transform

Spatially



☐ Is LWP adjustment sensitive to mesoscale cell size?

- MODIS 2005-2011 (7 years)
- 2^ox2^o scene average LWP & N_d
- MCC cell sizes classified by 2D wavelet transform

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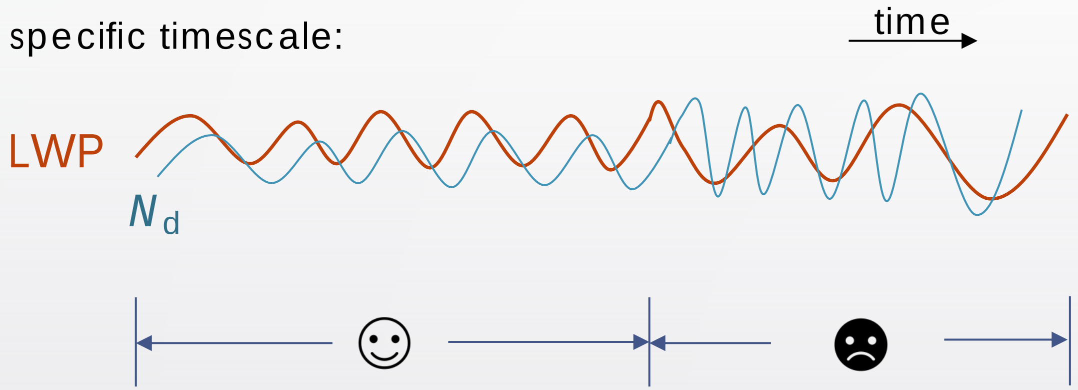
Stratocumulus susceptibility across timescales

For a specific timescale:



1d Continuous Wavelet analysis --- coherence analysis

- Find coherent time periods
- Compute dln(LWP)/dln(N_d)
- Compute phase of the wavelet cross-spectrum between LWP and N_d

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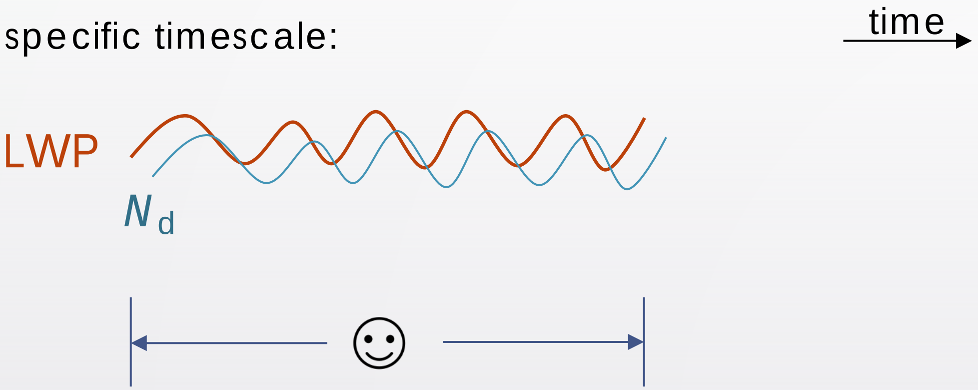
Stratocumulus susceptibility across timescales

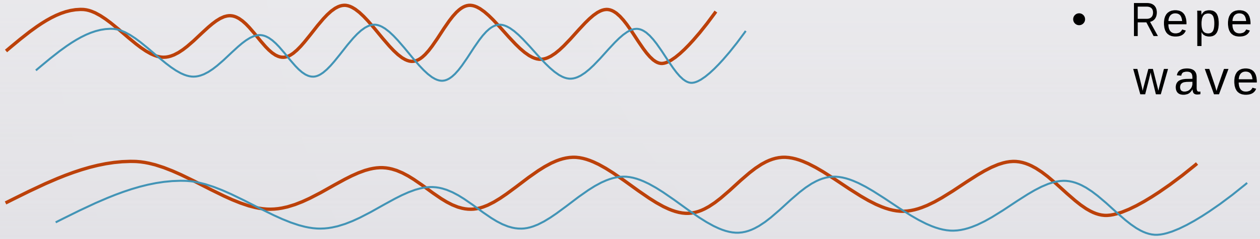
For a specific timescale:



1d Continuous Wavelet analysis --- coherence analysis

- Find coherent time periods
- Compute dln(LWP)/dln(N_d)
- Compute phase of the wavelet cross-spectrum between LWP and N_d

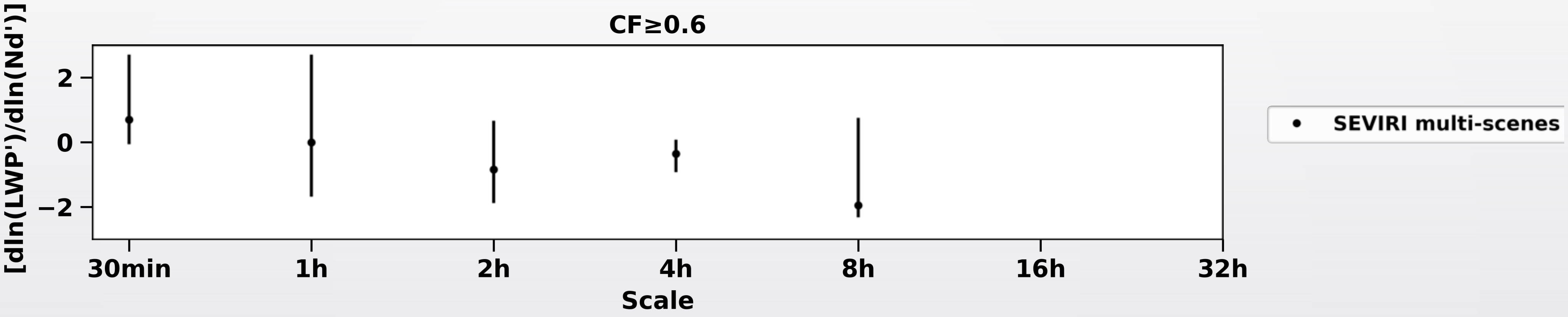
Other timescales:



- Repeat for all timescales segregated by wavelet analysis (30 min, 1 h, 2h, 4h, 8h)

How LWP and N_d correlate cross timescales?

For stratocumulus: CF≥0.6



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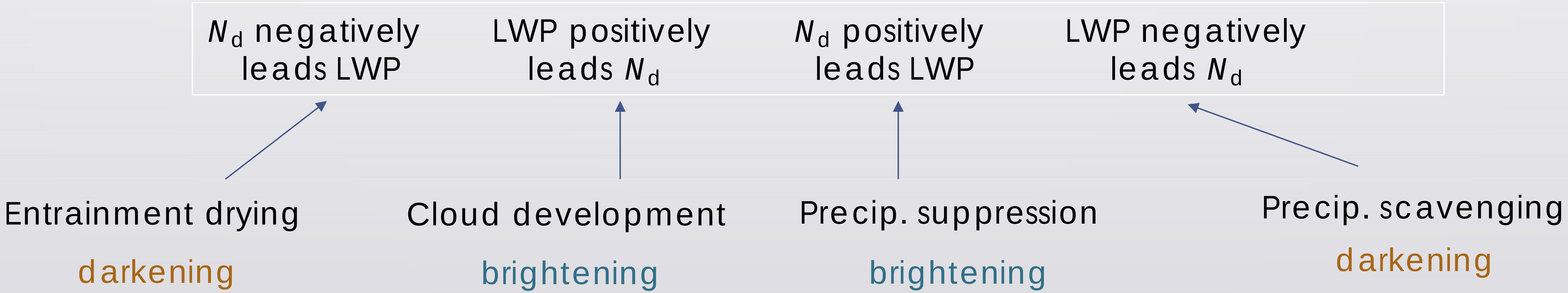
Causal relationship between LWP and N_d



N_d negatively leads LWP

LWP positively leads N_d

N_d positively leads LWP

LWP negatively leads N_d

Entrainment drying

darkening

Cloud development

brightening

Precip. suppression

brightening

Precip. scavenging

darkening

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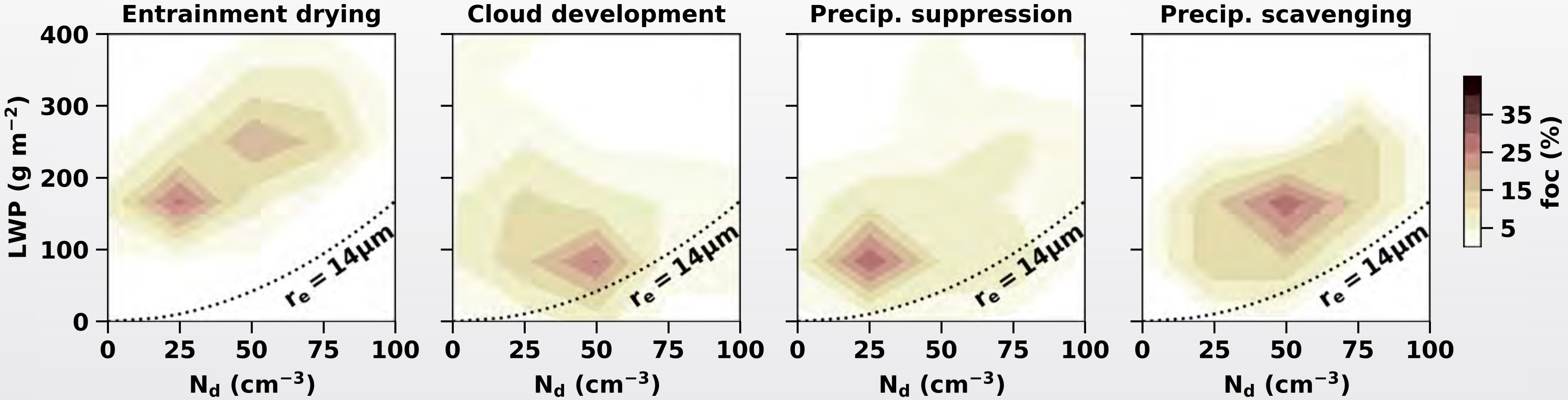
Causal relationship between LWP and N_d

CF≥0.6



N_d negatively leads LWP

LWP positively leads N_d

N_d positively leads LWP

LWP negatively leads N_d

Entrainment drying

darkening

Cloud development

brightening

Precip. suppression

brightening

Precip. scavenging

darkening

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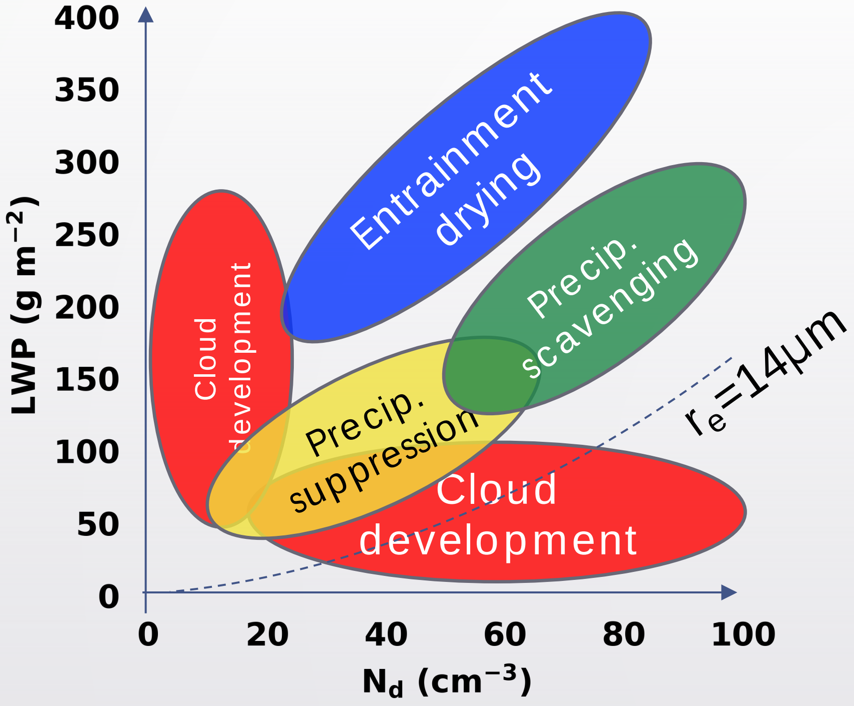
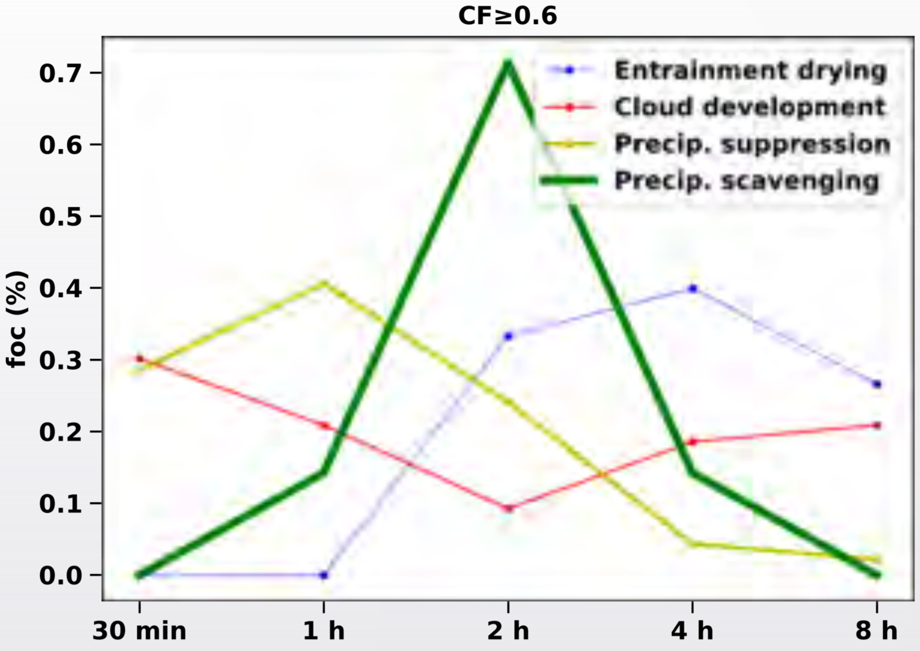
Causal relationship between LWP and N_d across timescales





- A new scenario [cloud development] is found to cause positive correlation between LWP and N_d
- Scenarios depend on LWP & N_d. Clouds with low LWP and/or low N_d tend to show brightening effect due to cloud development and precipitation suppression
- The brightening scenarios respond faster than the darkening scenarios
- The darkening scenarios (precip. scavenging, entrainment drying)are the most frequent at the timescale of 2-4h

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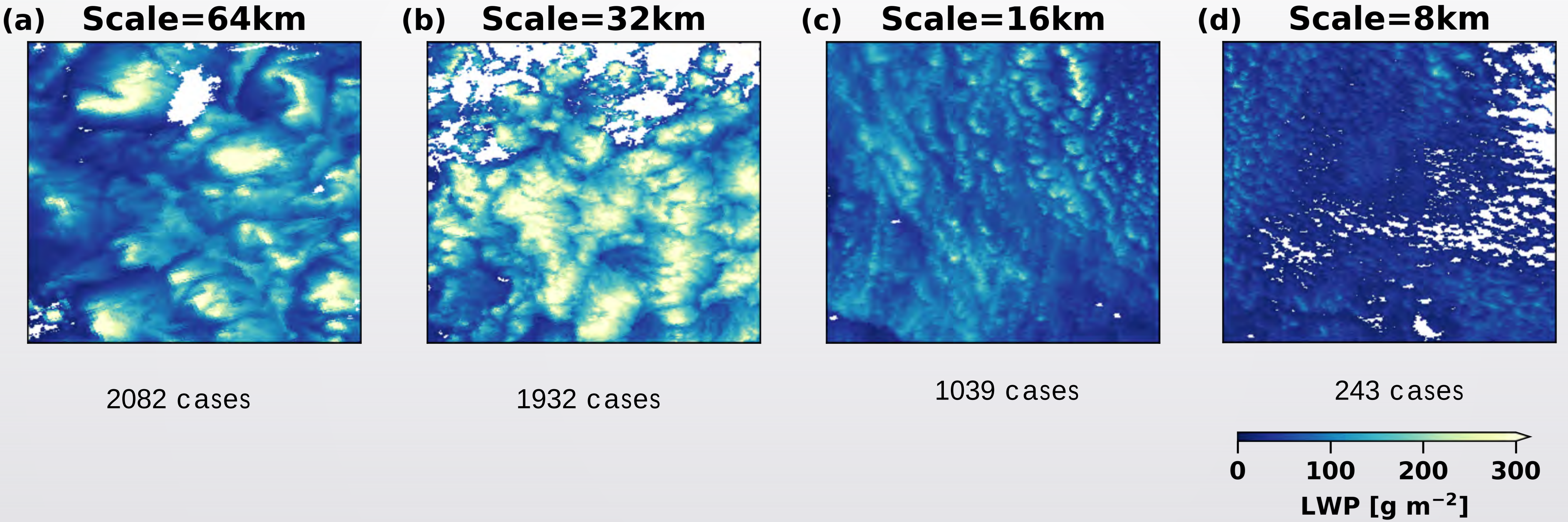
Stratocumulus susceptibility across cloud scales

Mesoscale Cellular Convection (MCC)



2082 cases

1932 cases

1039 cases

243 cases

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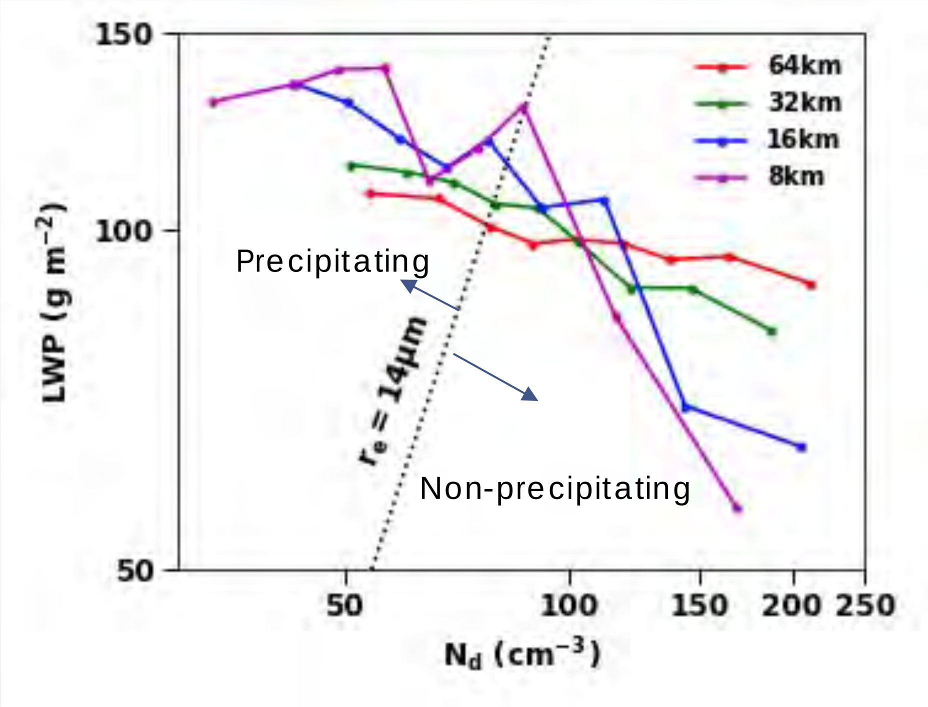
Stratocumulus susceptibility is sensitive to MCC cell scale!



Dots: Median LWP in 10% percentile bins of N_d

1. Negative cloud adjustment slope
2. The negative slope is likely dominated by entrainment drying—no significant changes in slope on each side of r_e=14μm line (precip. onset)
3. The slope is significantly less negative for large size MCCs

- Dynamically, weaker TKE hampers entrainment (Kazil et al., 2017)
- Microphysically, bigger cloud droplets reduces evaporation (not shown)

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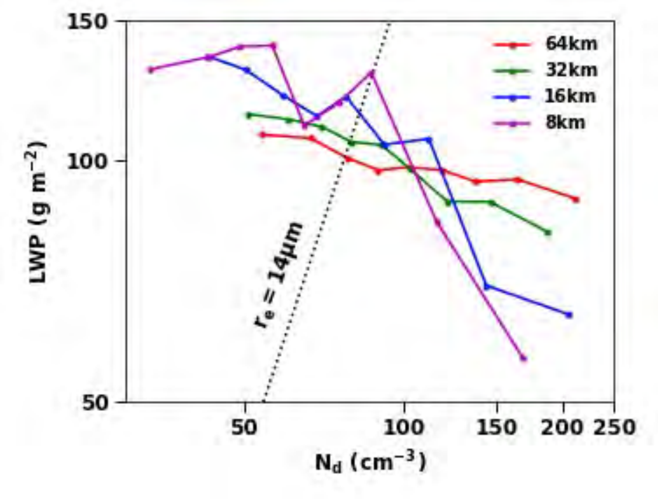
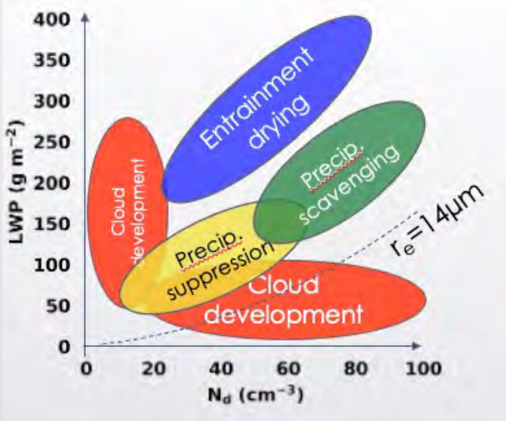
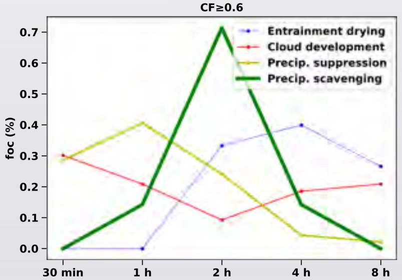
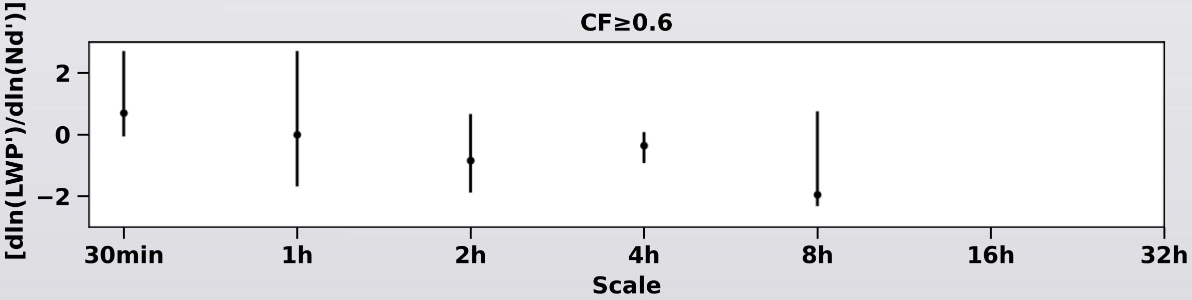
Take-home messages

- Cloud susceptibility is weaker for large-scale MCCs
- A new scenario [cloud development] is found to cause positive correlation between LWP and N_d
- Scenarios depend on LWP & N_d. Clouds with low LWP and/or low N_d tend to show brightening effect due to cloud development and precipitation suppression
- The brightening scenarios respond faster than the darkening scenarios
- The darkening scenarios (precip. scavenging, entrainment drying)are the most frequent at the timescale of 2-4h









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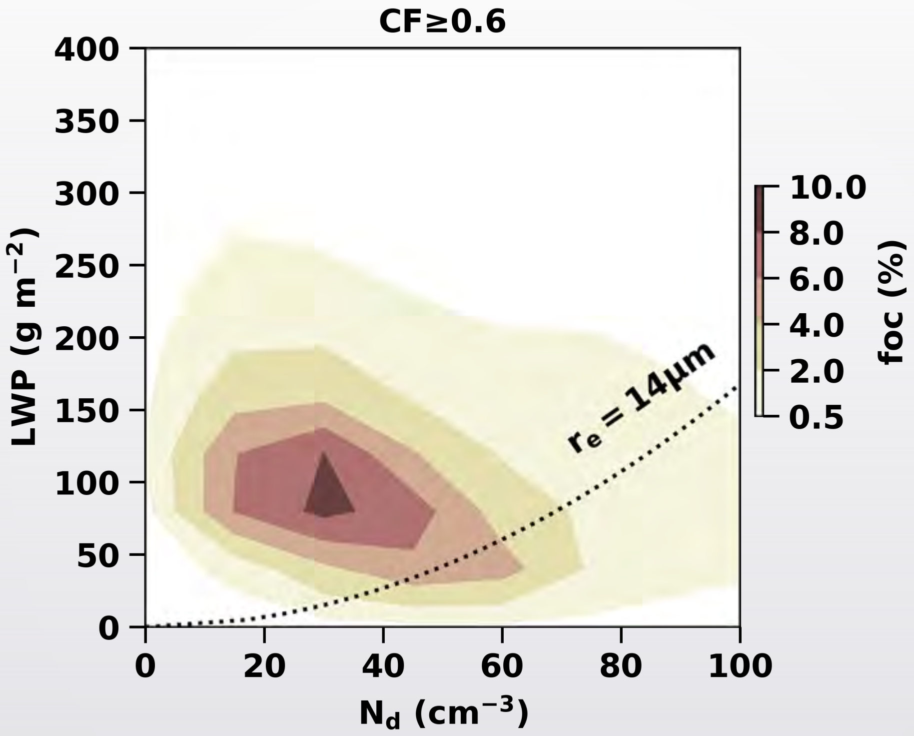
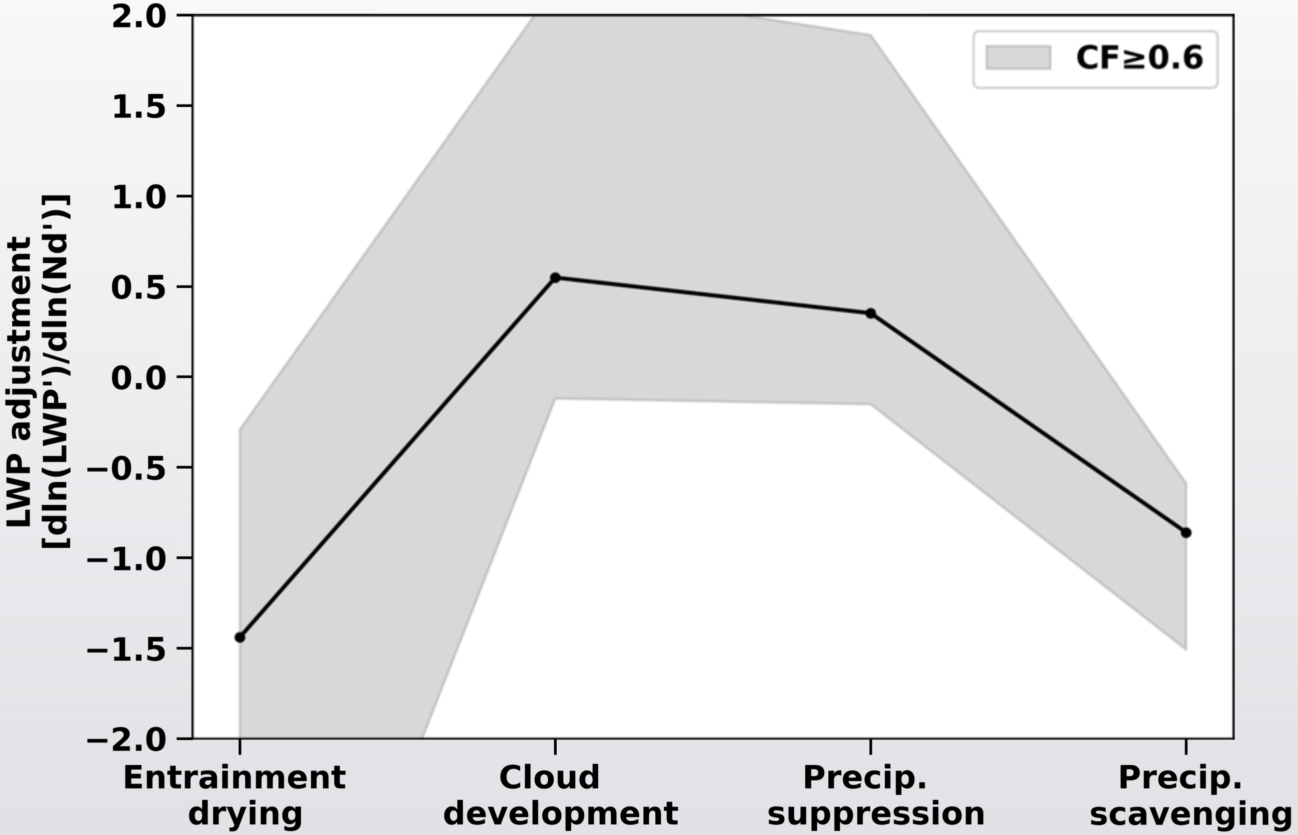
Additional figures



Additional figures



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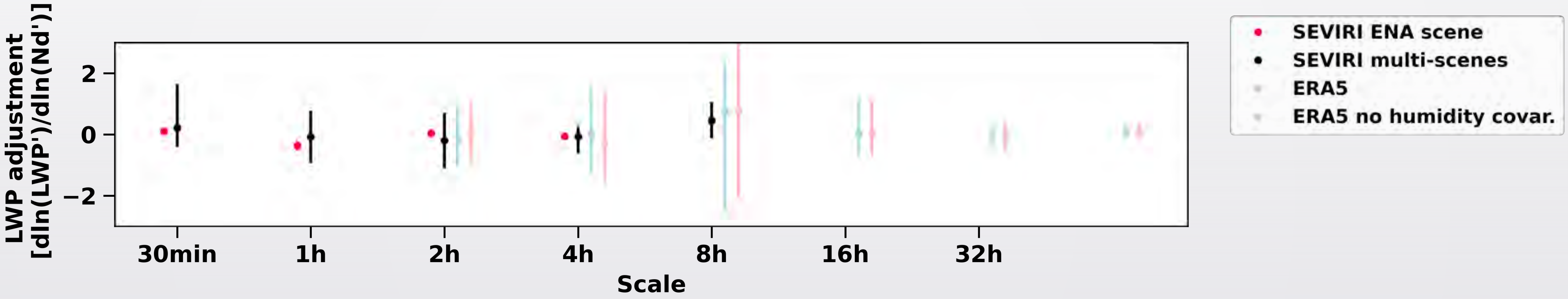

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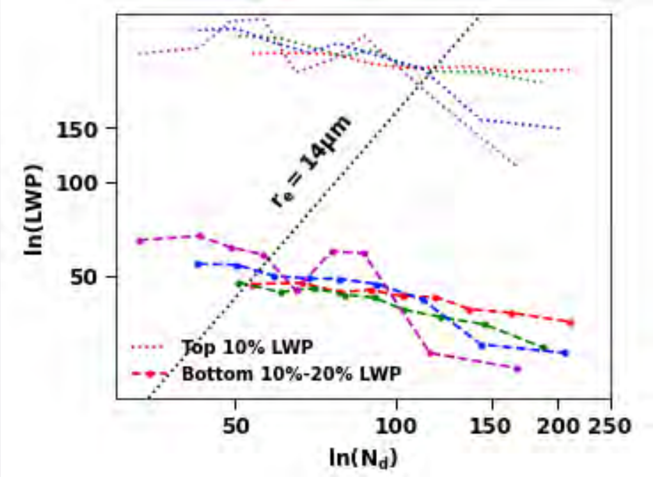

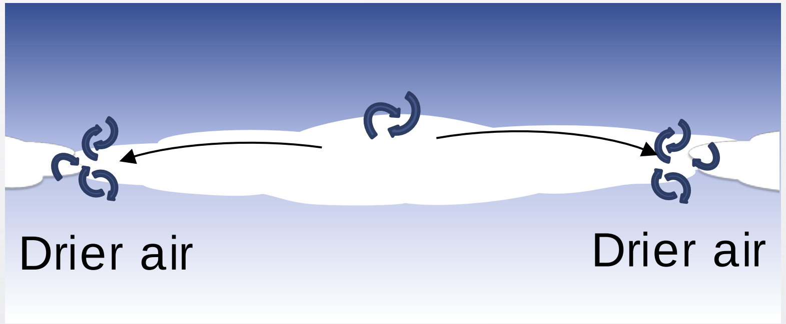

Cloud core or cloud edge?

- Entrainment at the top of cloud core also plays a role!