“Standing back from all your natural fussings and frettings; coming in out of the wind.”

- C. S. Lewis

Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

IMPRS
on Earth System Modelling
INTERNATIONAL MAX PLANCK RESEARCH SCHOOL

RAIN EVAPORATION BELOW SHALLOW TROPICAL TRADE-WIND CUMULI AS PREDICTED BY A NEW SUPER-DROPLET MODEL

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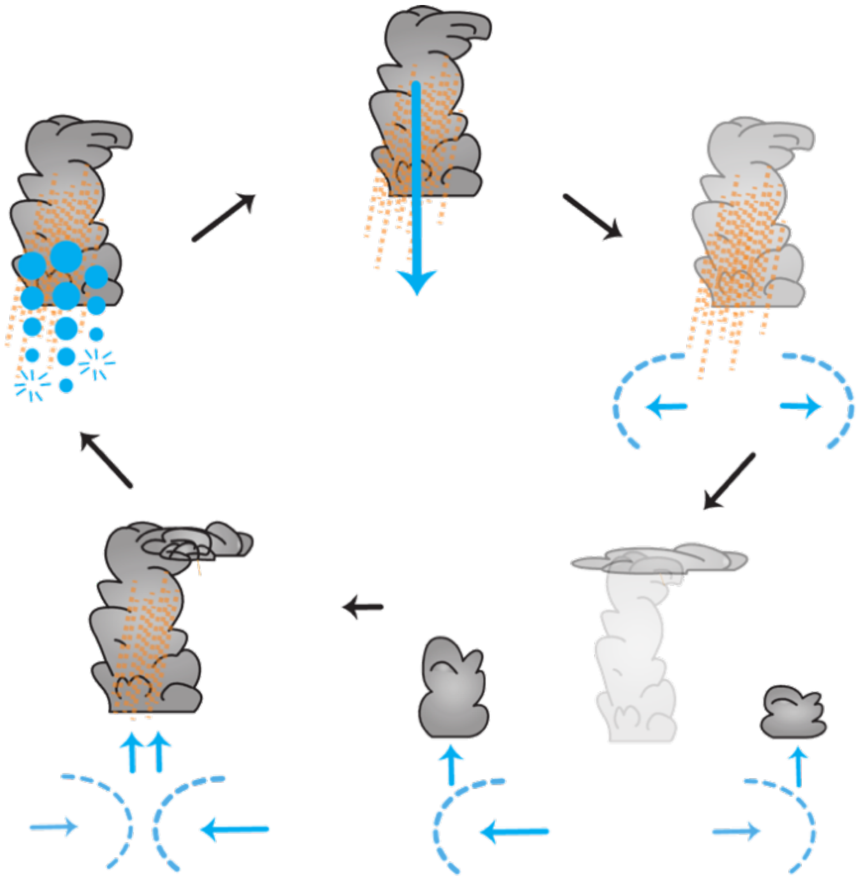
WARM-RAIN AND SHALLOW MESOSCALE CIRCULATIONS INTERACT WITH EACH OTHER

- **Rain evaporation in the sub-cloud layer drives downdraughts and cold pools and hence shallow mesoscale organisation**
  (Seifert and Heus 2013).
- **Conversely, shallow mesoscale organisation determines cloud and sub-cloud layer conditions**
  (Snodgrass et a. 2009).



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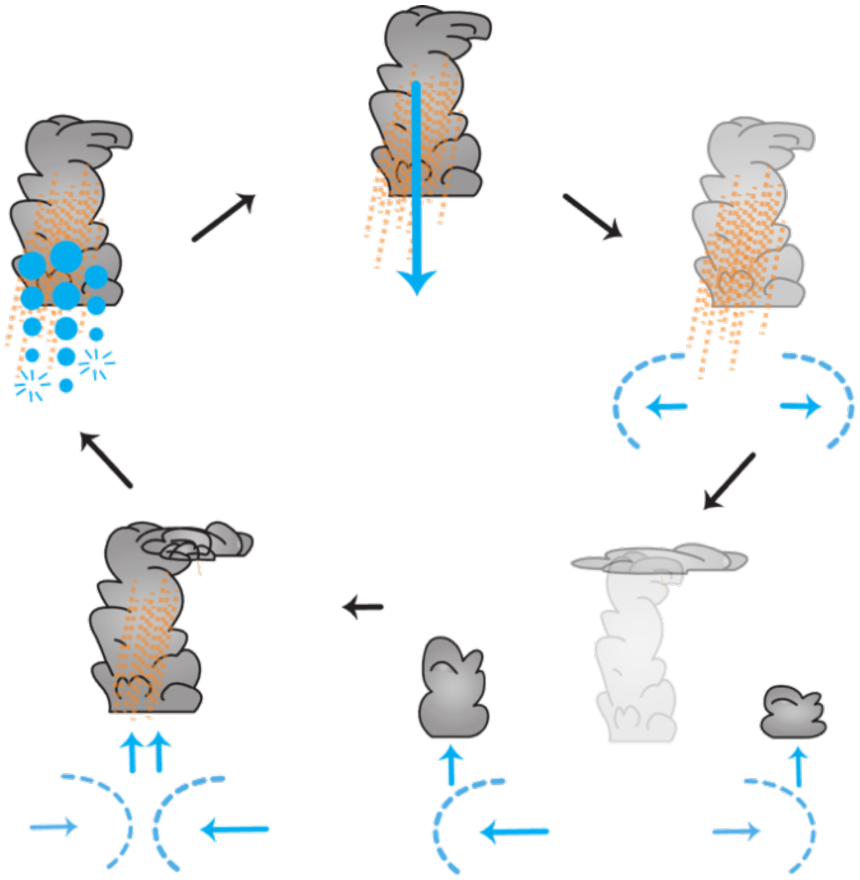
  (Tridon et al. 2017 & Sarkar et al. 2021, 2023)



SDM = Super-Droplet Model

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Use the Super-Droplet Model (SDM) to…

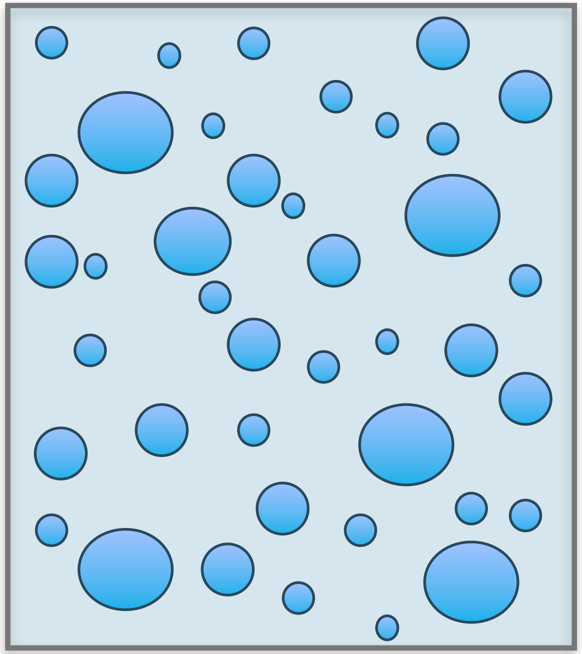
- ***analyse parts of microphysics important for cloud organisation***
- ***compare with existing models and upcoming remote sensing observations***

SDM = Super-Droplet Model

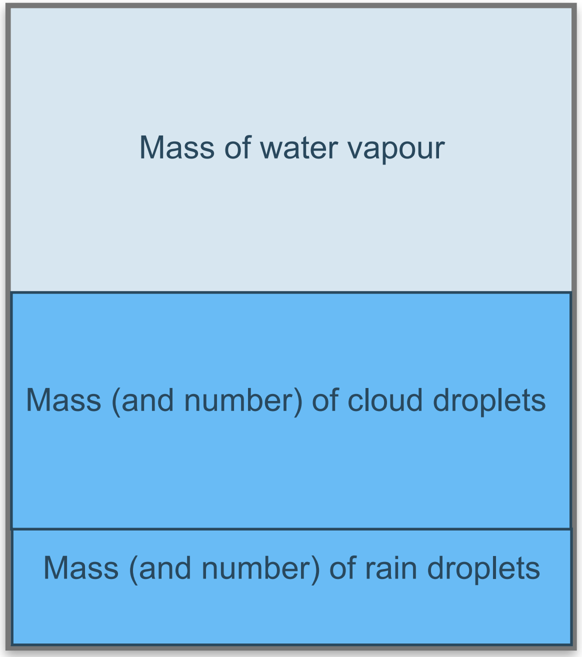
THE SUPER-DROPLET MODEL (SDM) IS A FUNDAMENTALLY DIFFERENT VIEW OF CLOUD MICROPHYSICS

Reality

$N = 10^{15}$



Bulk



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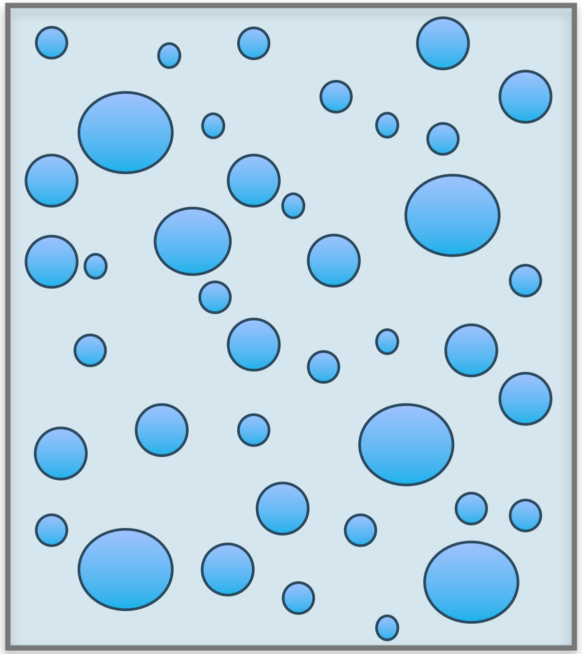
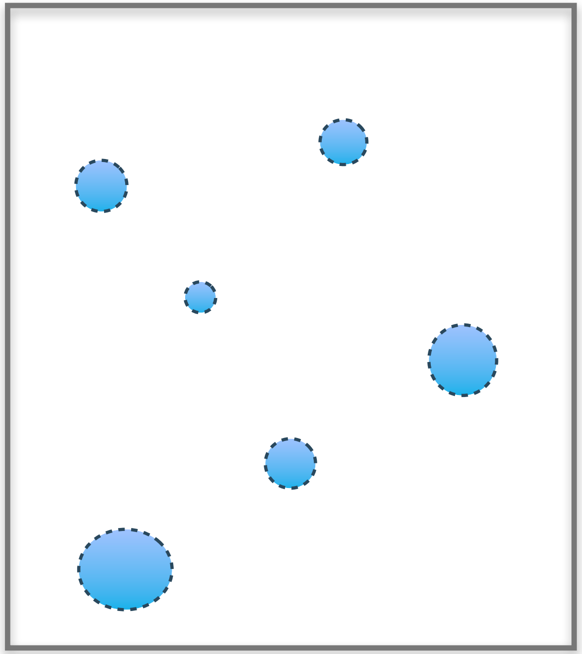


SDM

$N = 10^{15}$ $\quad N_{\mathrm{SD}} = 10$



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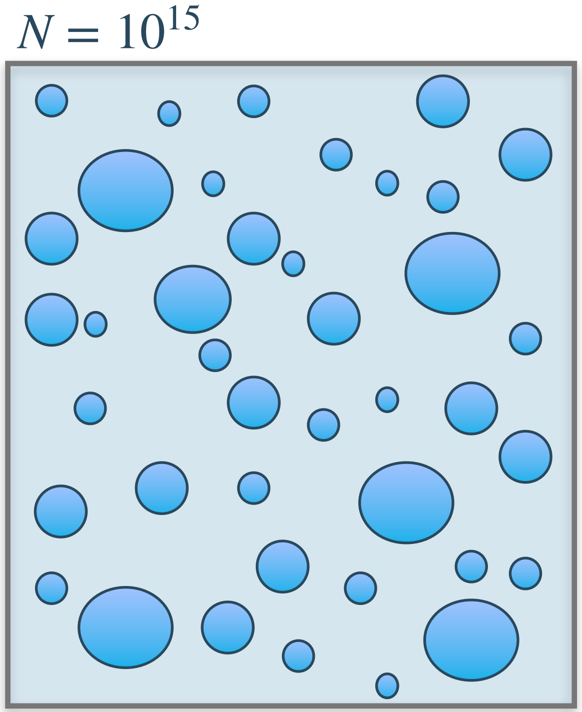
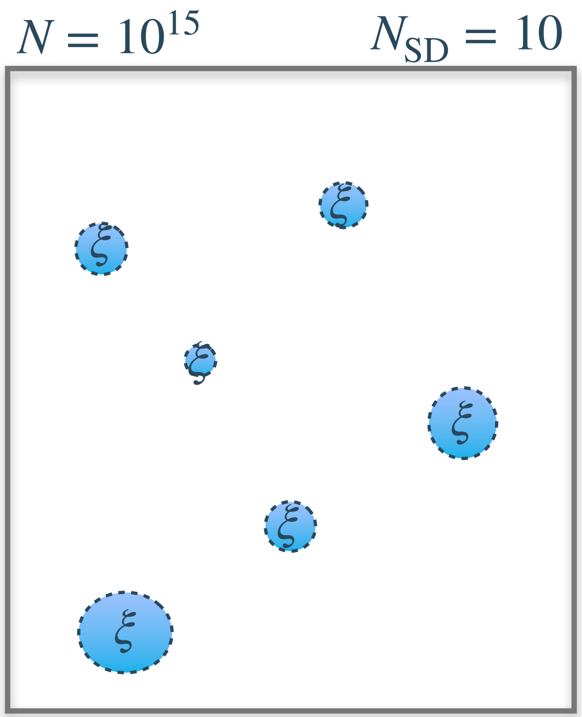


SDM



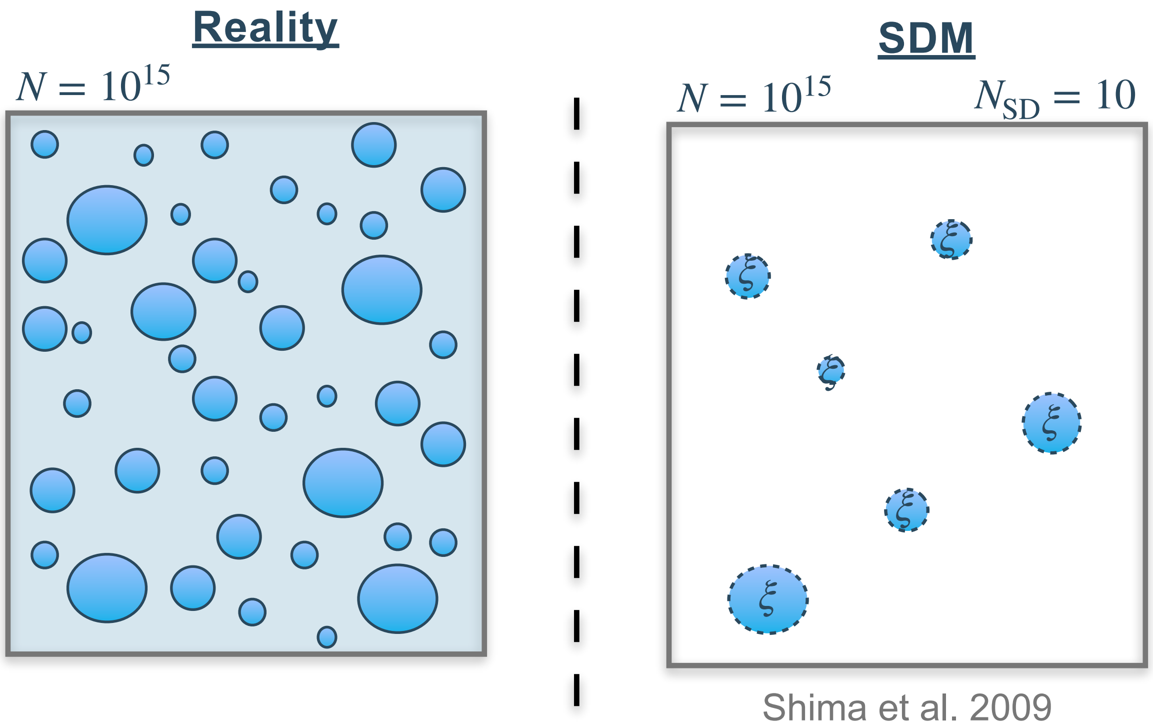
Shima et al. 2009

Each superdroplet has its own multiplicity, ξ,

$$\xi = 1, 2, 3, \ldots \xi$$

1 superdroplet = ξ real droplets

SDM HAS A NUMBER OF ADVANTAGES OVER BIN/BULK SCHEMES FOR CLOUD MICROPHYSICS

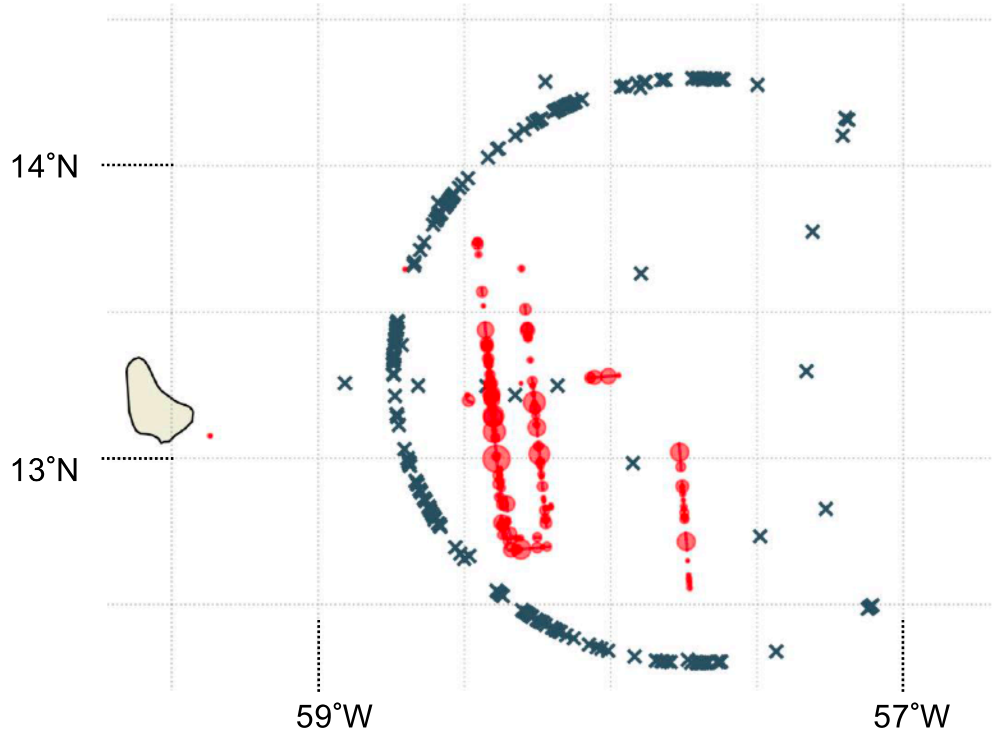


Shima et al. 2009

- **Numerical properties (non-diffusive)**
- **Increasing accuracy as you increase the number of super-droplets**
- **No assumptions on the shape of the droplet size distribution**
- **Exceptionally clear relation of model to underlying theory**

USING CLEO AND EUREC⁴A:
A 1-D RAIN-SHAFT FOR SUB-CLOUD RAIN EVAPORATION

EUREC⁴A winter field campaign in downstream North Atlantic (Bony et al. 2017, Stevens et al. 2021)



Niebaum et al. 2025 (in prep.)

USING CLEO AND EUREC4A: A 1-D RAIN-SHAFT FOR SUB-CLOUD RAIN EVAPORATION

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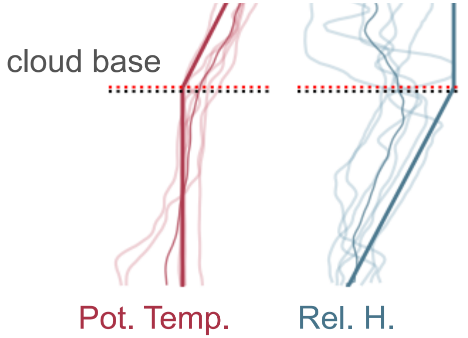
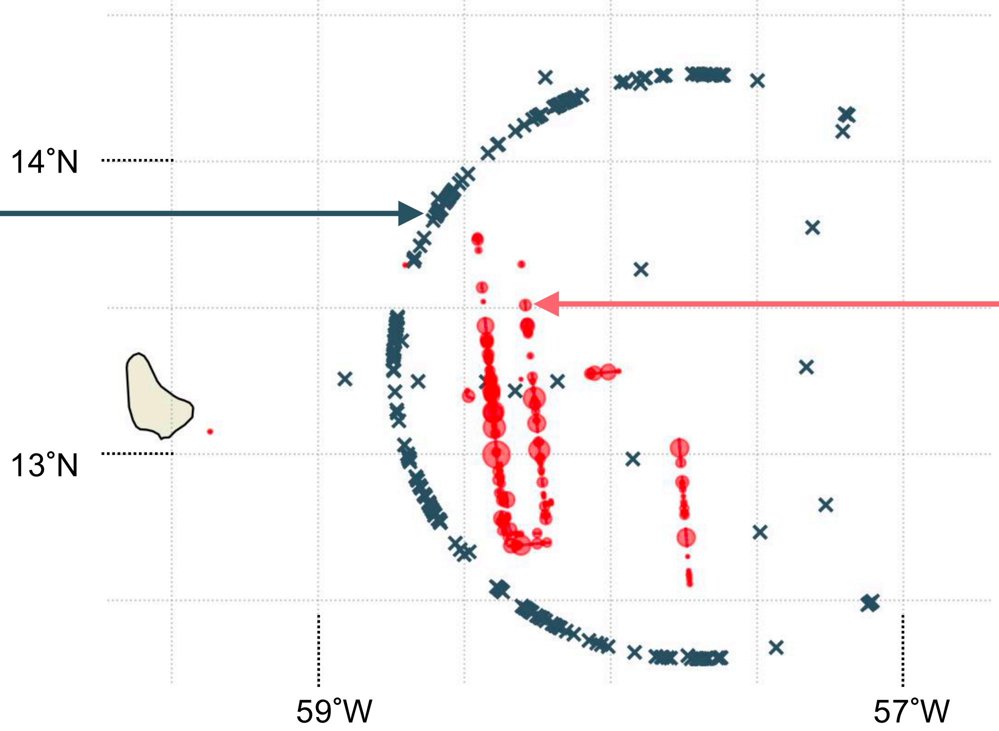
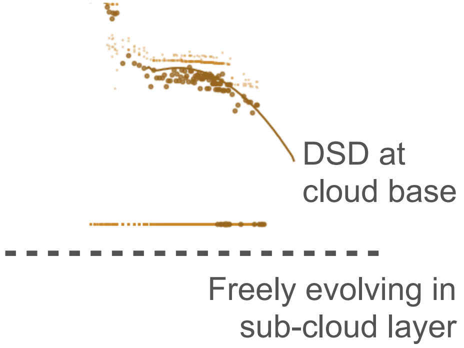
× **Fixed vertical profiles of temperature and relative humidity** from dropsondes

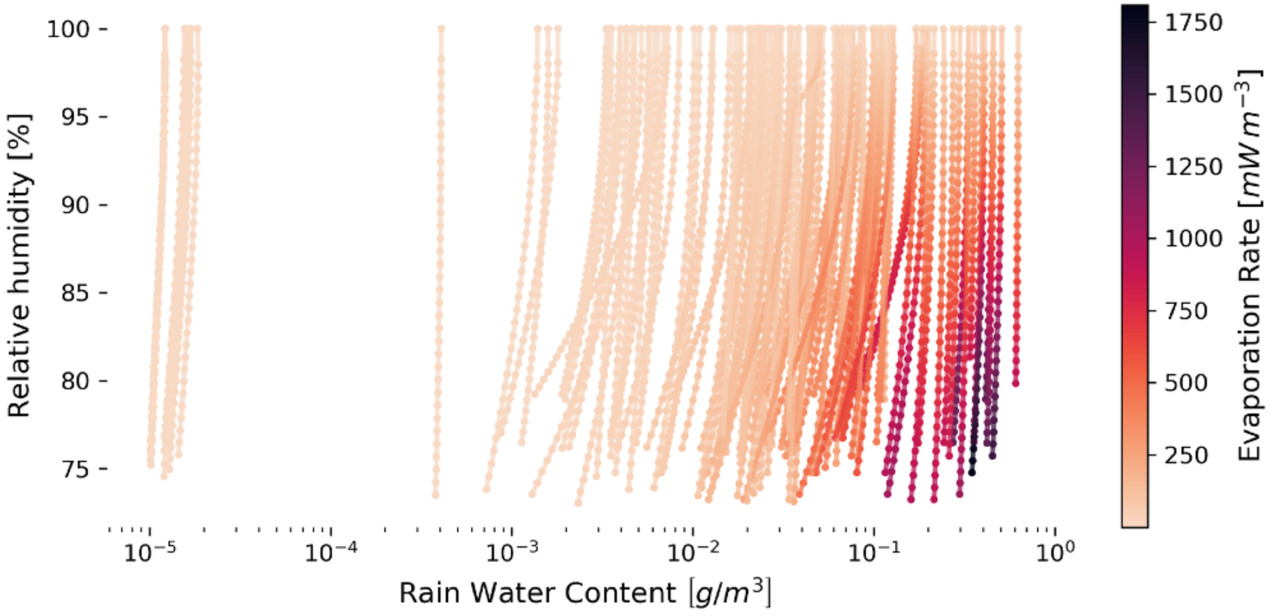




Fixed Cloud Base Droplet Size Distributions from in-situ aircraft measurements



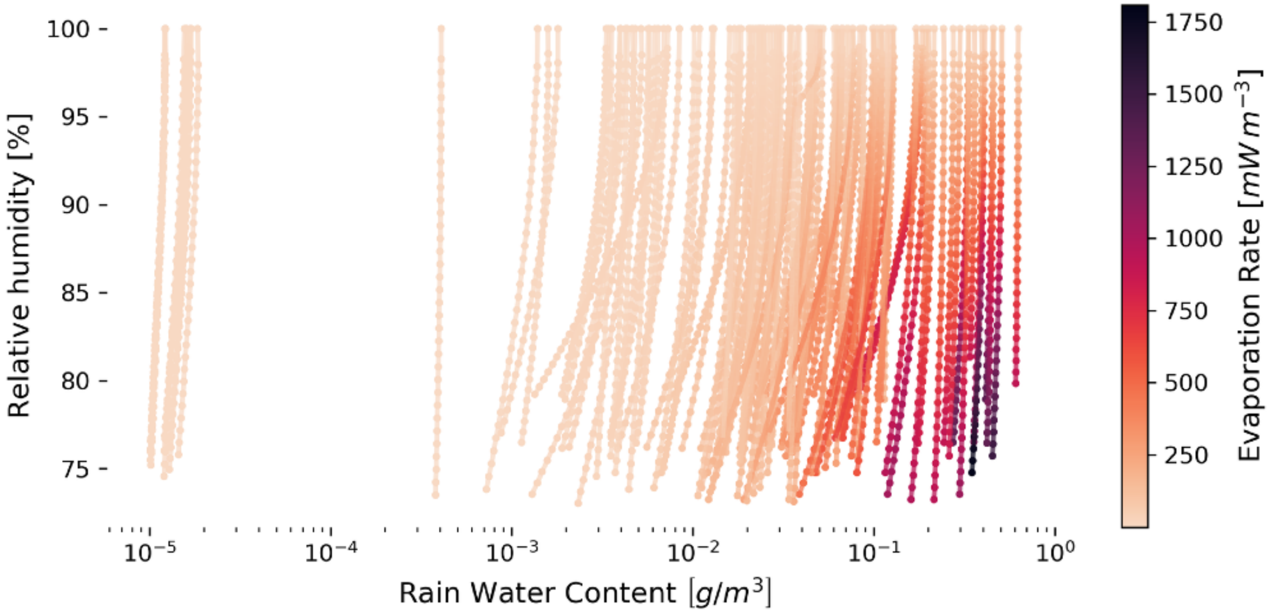
RELATIVE HUMIDITY CONTROLS THE VERTICAL PROFILE OF EVAPORATION



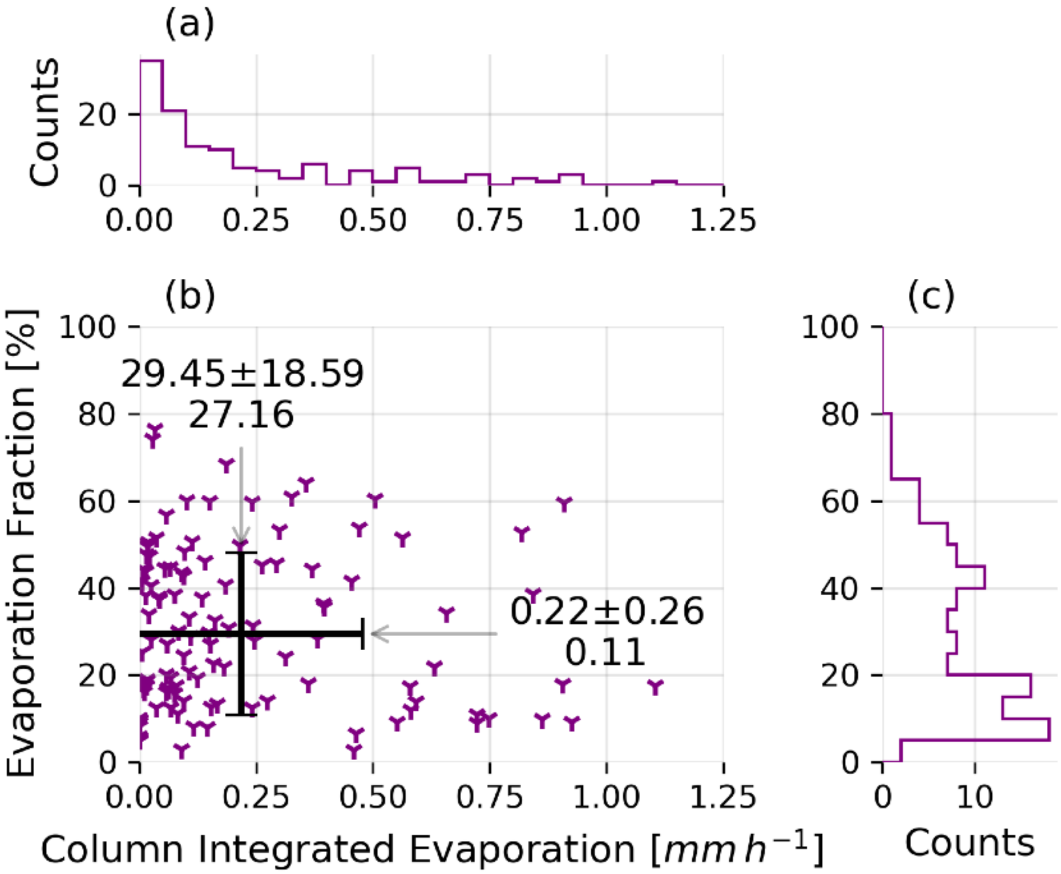
RELATIVE HUMIDITY CONTROLS THE VERTICAL PROFILE OF EVAPORATION

- **Constant lapse rate of relative humidity causes bottom heavy evaporation profile**

- **Except in rare cases when mean radius of droplet size distribution is very small**



EVAPORATION FRACTION AND COLUMN INTEGRATED AMOUNT ARE ONLY VERY WEAKLY CORRELATED



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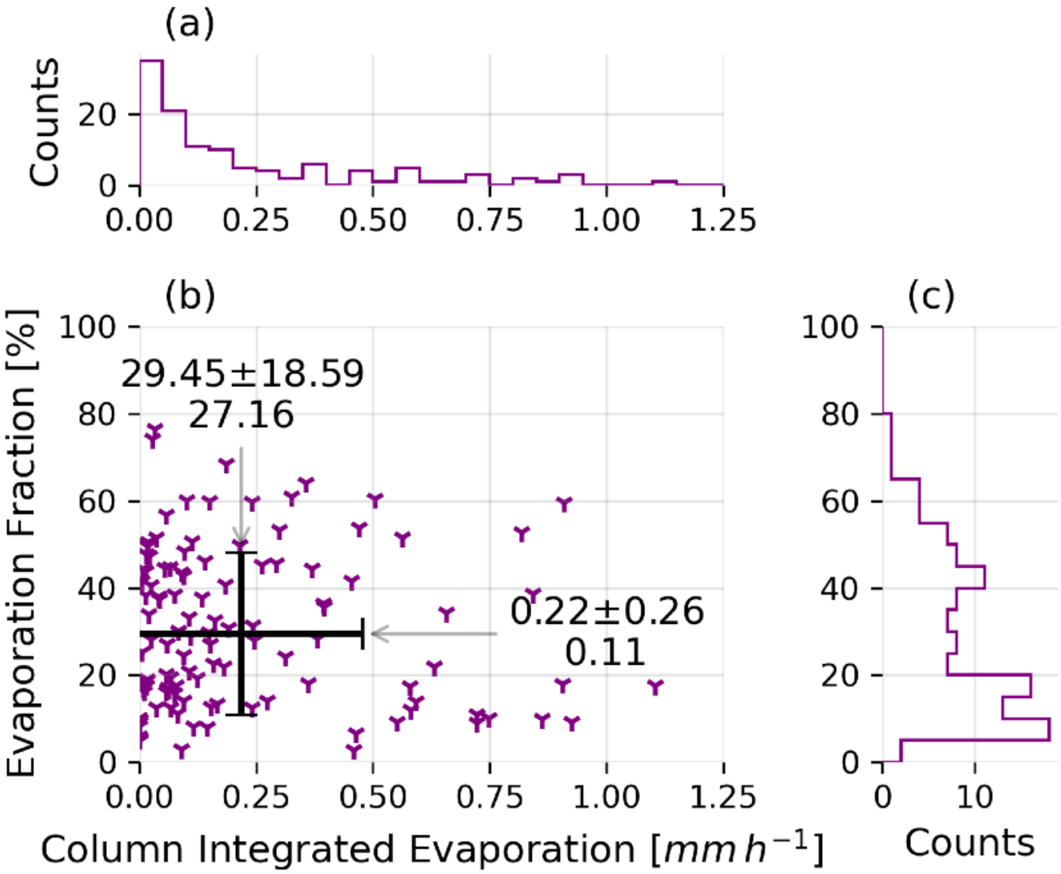
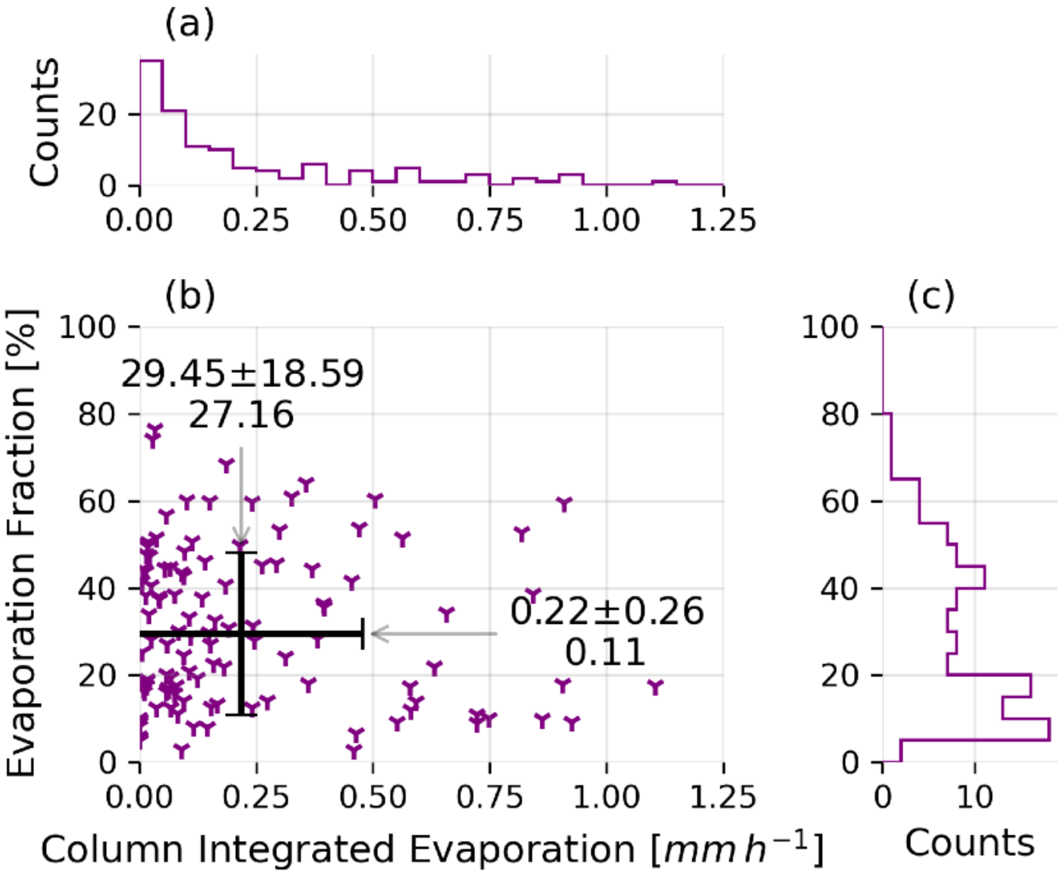


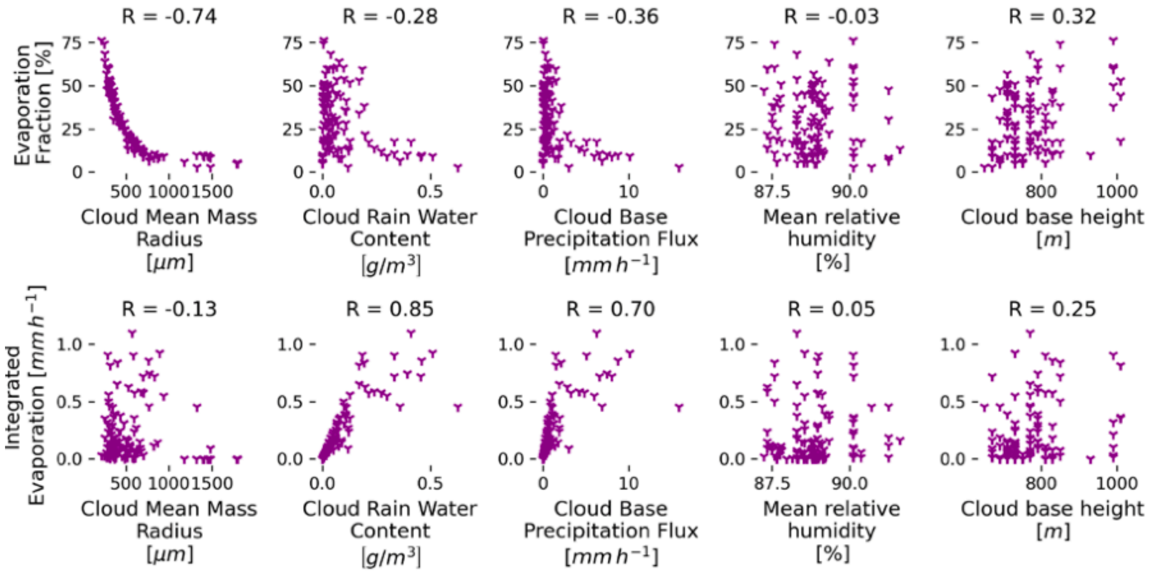
- **Absolute amount of evaporation:**
  - **very positively skewed**
  - **median = 0.11 mm/hour**

- **Evaporation fraction:**
  - **~uniformly distributed between 5-60%**
  - **median = 27%**

DSD = Droplet Size Distribution
RWC = Rain Water Content

RAIN WATER CONTENT CONTROLS TOTAL EVAPORATION, DROPLET SIZE DISTRIBUTION CONTROLS FRACTION





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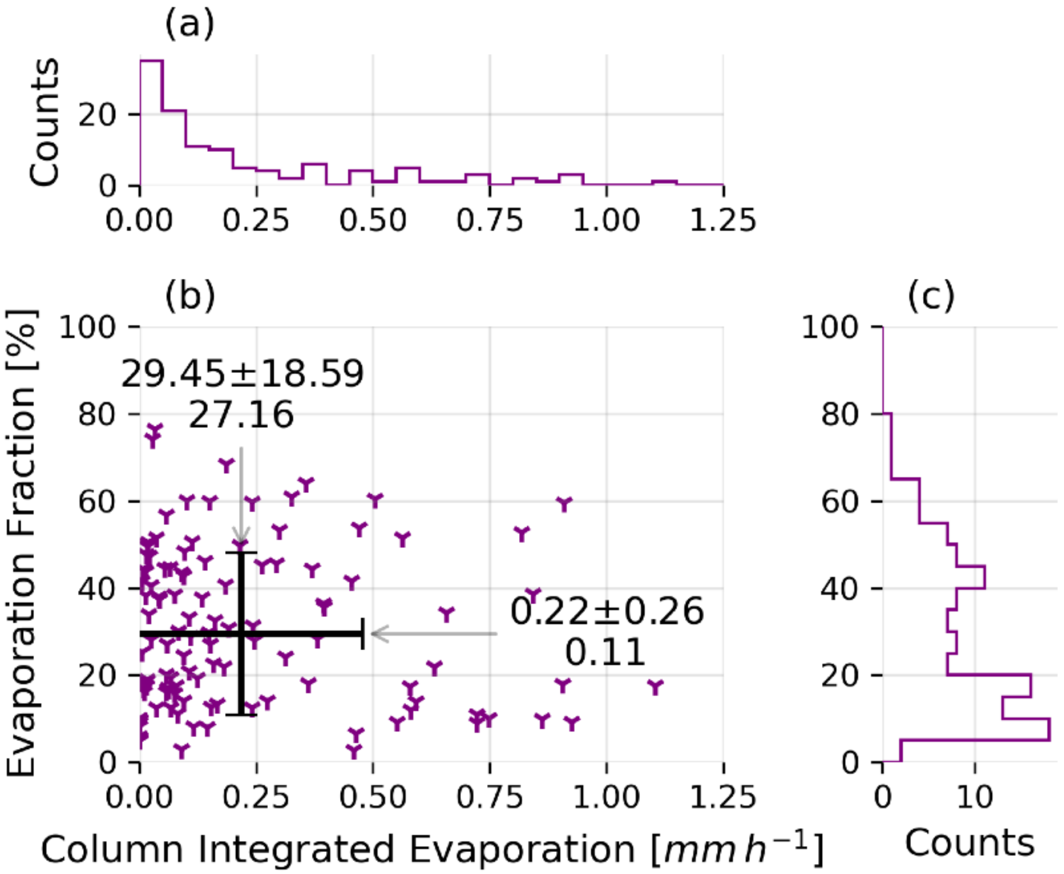

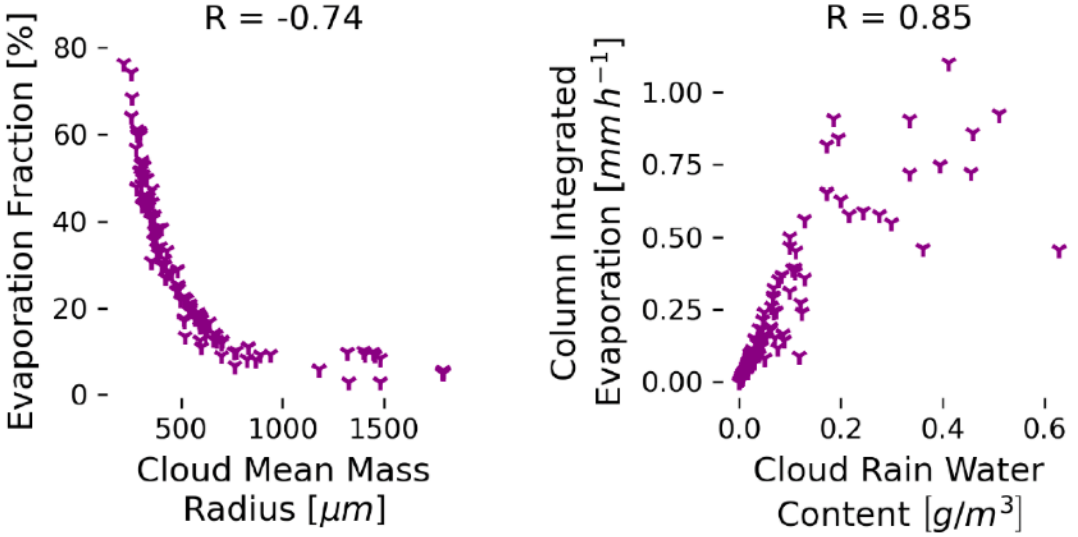

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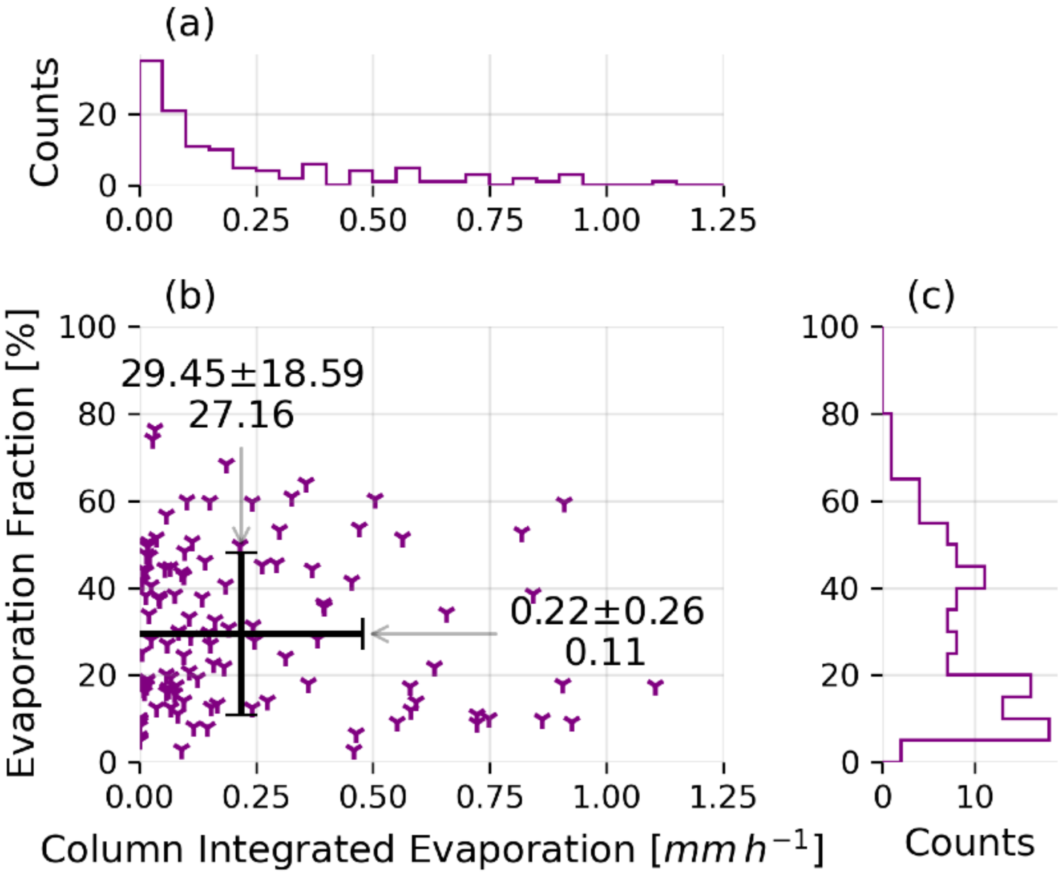
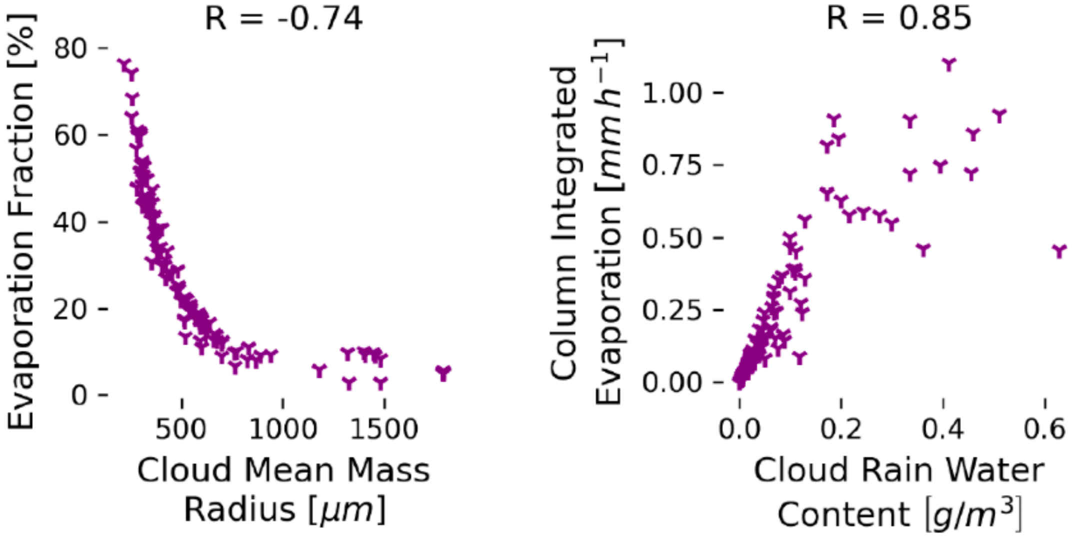
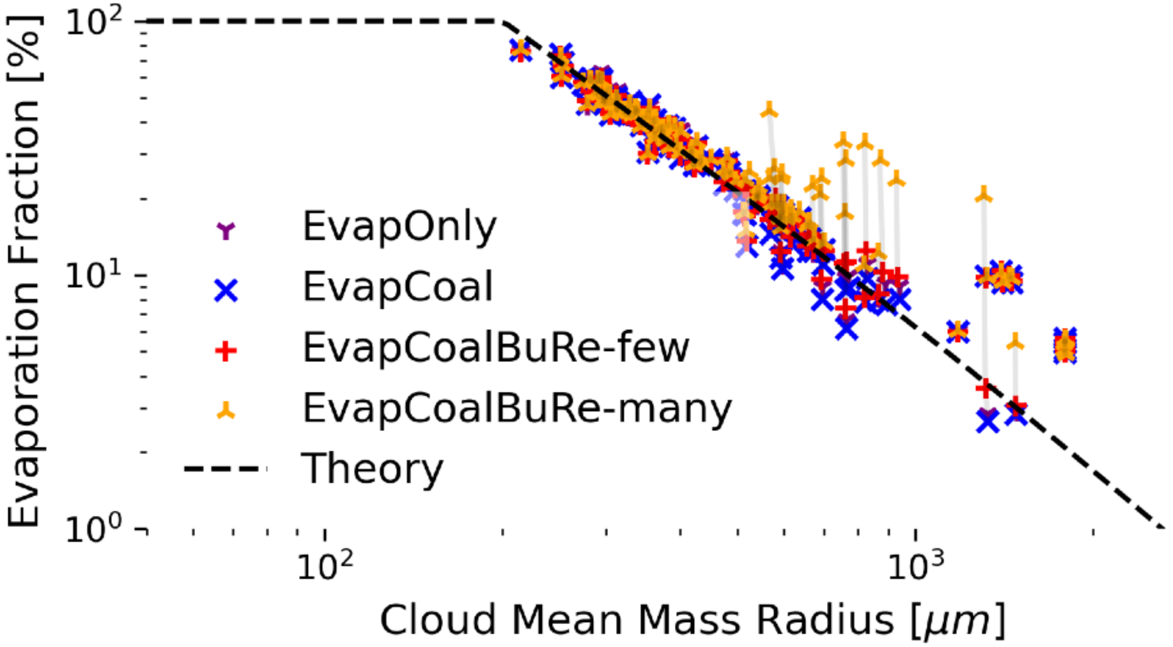


Need better than bulk scheme to accurately model cloud droplet size distribution!



In agreement with Sarkar et al. 2025 (sub. GRL)

INSIGNIFICANT IMPACT OF COLLISIONS BETWEEN DROPLETS ON SUB-SHALLOW-CLOUD LAYER EVAPORATION



- O(1%) change in evaporated fraction by including collisions between droplets
- Larger changes in limit of excessive breakup, but only for narrow size distributions of mm-size droplets

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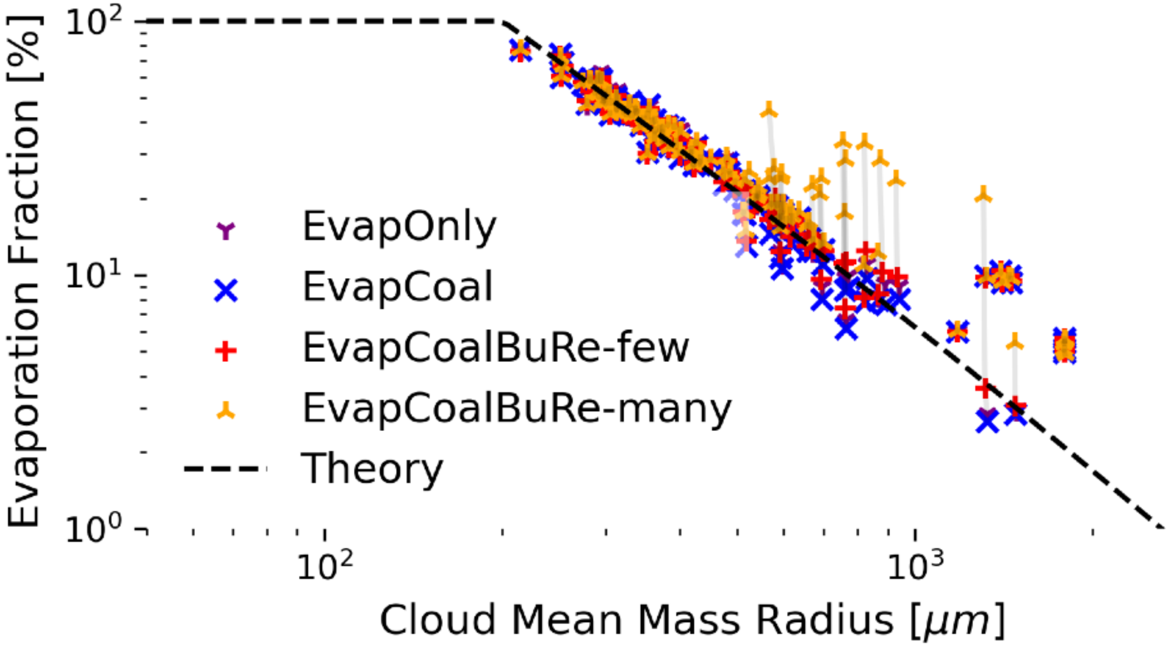

- **O(1%) change in evaporated fraction by including collisions between droplets**
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Collisions may still be important for more variable, broader DSDs (heavier rain) and when feedback on thermodynamics is included

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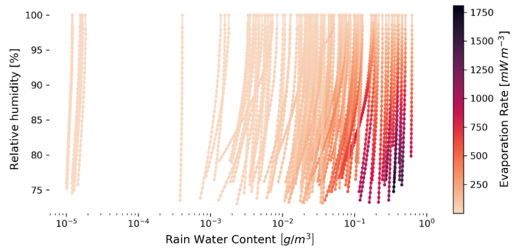
RAIN EVAPORATION BELOW SHALLOW TROPICAL TRADE-WIND CUMULI AS PREDICTED BY A NEW SUPER-DROPLET MODEL (SDM)

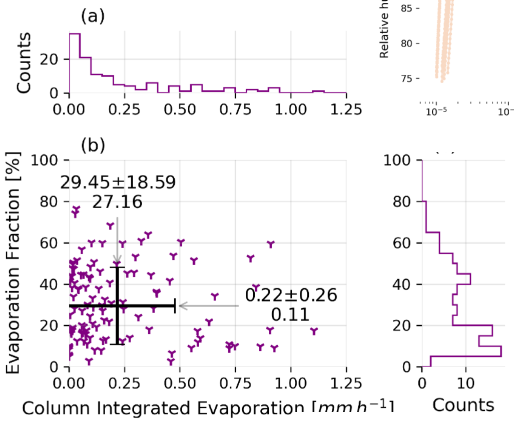
Open source!
yoctoyotta1024/CLEO

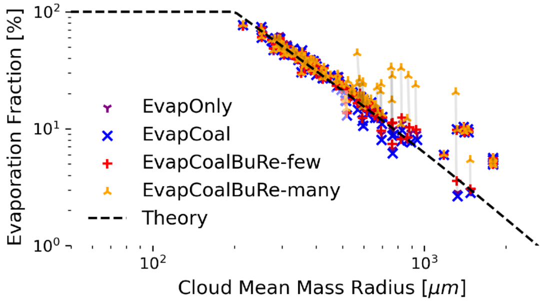
New SDM called CLEO combined with EUREC[4]A observations, 1-D rainshaft shows evaporation…

- **vertical profile is function of RWC and relative humidity**
- **fraction is ~uniformly distributed, median at 27%, sensitive to mean radius of DSD**
- **column integral is positively skewed, median at 0.11 mm/hour, sensitive to cloud RWC**
- **robust to collisions between droplets, but their importance in cases of heavier rainfall cannot be ruled out**

Niebaum et al. 2025 (in prep.)







Appendices

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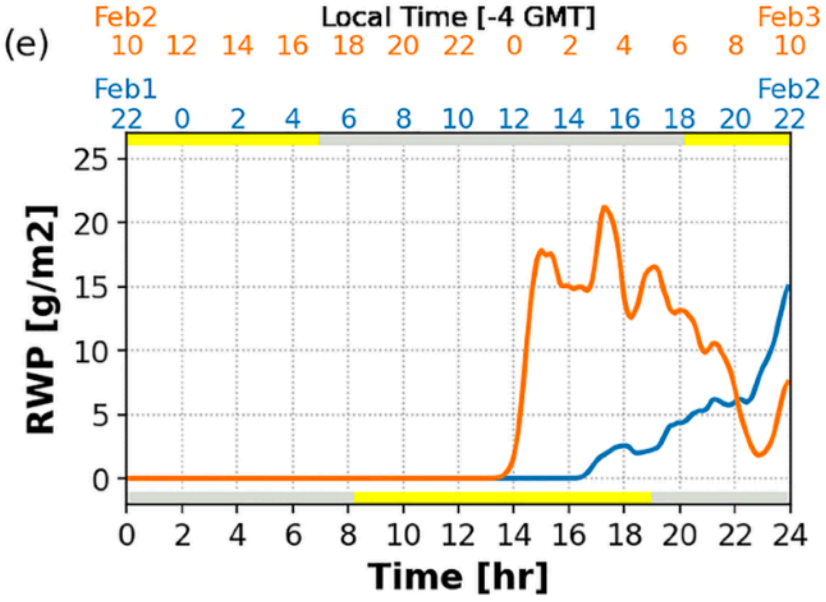
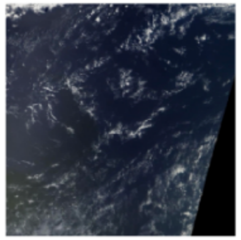


Delay diurnal cycle by 12 hrs

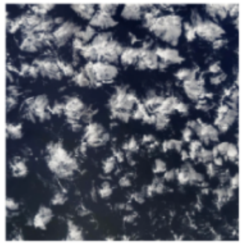
Control

(Narenpitak et al. 2022 and Bony et al. 2019)

Sugar (MODIS/Terra 23 Feb 2010)



Flowers (MODIS/Aqua 9 Feb 2017)



MICRO- MESO-SCALE CLOUD INTERACTIONS LACK DATA SO LET'S USE THE SUPER-DROPLET MODEL (SDM)

- **No long-term observations** of rain evaporation and precipitating downdrafts yet
- **Existing observations and models have not been compared,** so we lack a robust quantification of rain evaporation *(Tridon et al. 2017 & Sarkar et al. 2021, 2023)*

Use the Super-Droplet Model (SDM) to …

- ***analyse which parts of microphysics are important for cloud organisation***
- ***compare with other models and upcoming remote sensing observations***

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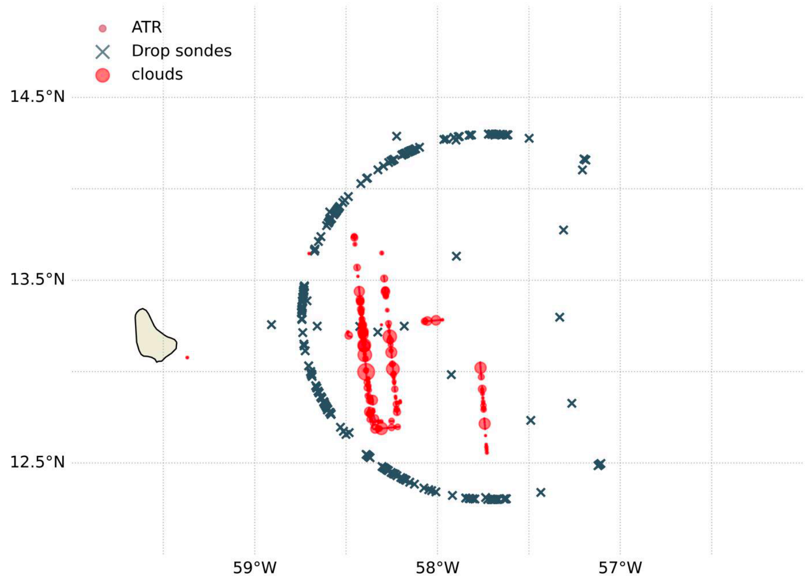
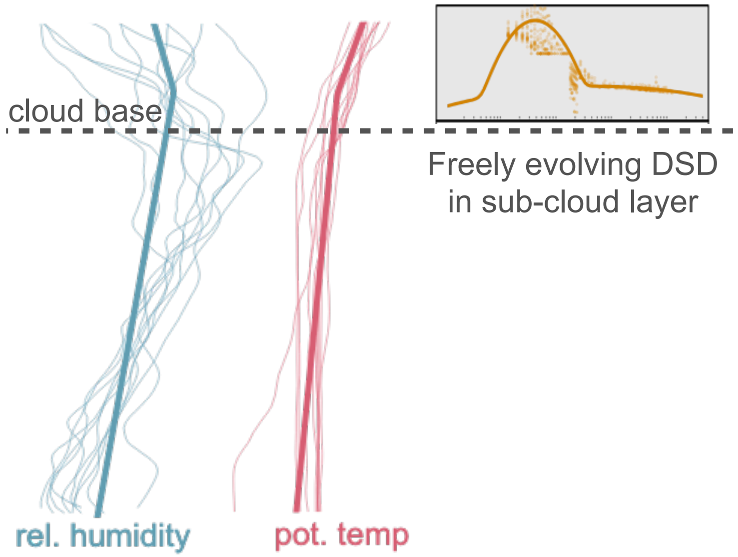
- **Droplet Size Distributions in range 2 µm - 2.55 mm** from in-situ aircraft measurements





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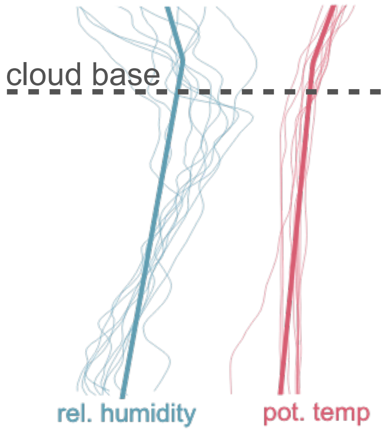

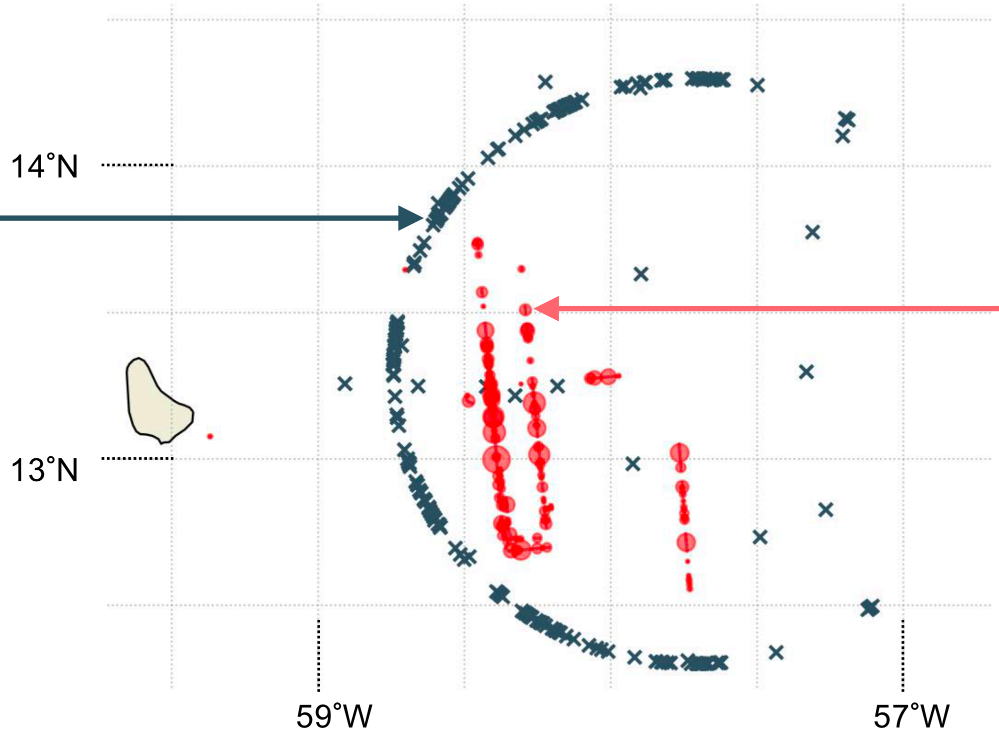

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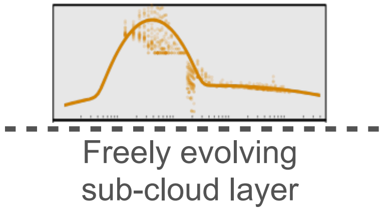

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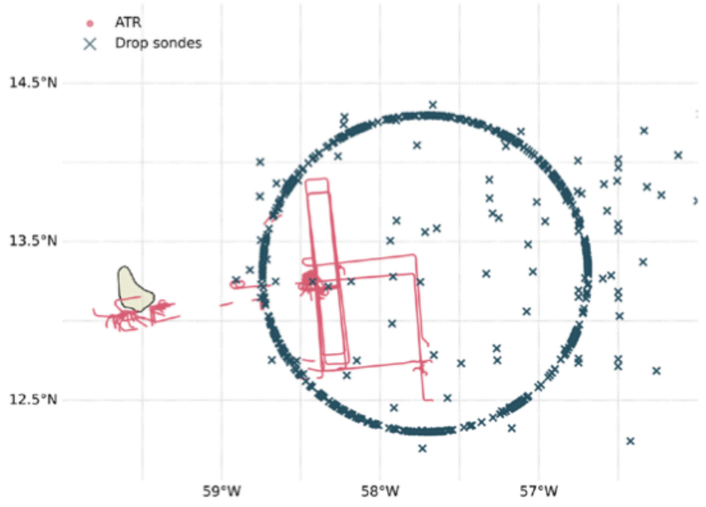
EUREC⁴A PROVIDES DATA TO CONSTRAIN RAIN EVAPORATION



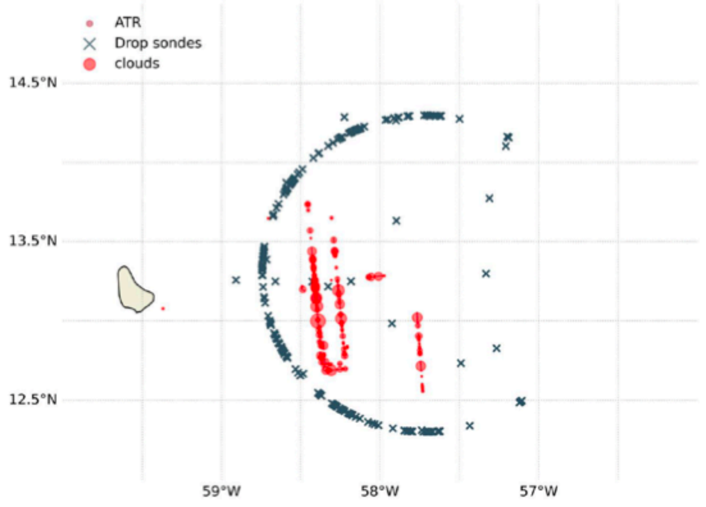
SAFIRE ATR42: PMA/Cloud composite dataset

- Dataset: Coutris, P. 2021
- Paper: Bony S. et al. 2022

JOANNE : Joint dropsonde Observations [...]

- Dataset: George, G. 2021
- Paper: George, G. et al. 2021

DATA FROM RAIN CLOUDS AT CLOUD BASE IS OF INTEREST



Cloud identification

- ATR measurement within 500 – 1200m altitude
- Rain drops need to be present
- At least 3 consecutive measurements fulfilling this property -> 300m min. cloud length

Dropsondes:

- Max. 3 hour
- 100 km radius

EUREC4A AND BCO OBSERVATIONS

Table 1. Table showing median $\pm$ IQR of various cold-pool properties for the *noprevWI* set of cold pools as well as the 25 % strongest ($\Delta T < -1.39$ K) and weakest ($\Delta T > -0.61$ K) cold pools of this set. The computation of the diagnostics is explained in Sect. 2.5.

	noprevWI	Strong	Weak
#	3889	972	972
ΔT (K)	-0.89 ± 0.78	-1.82 ± 0.67	-0.5 ± 0.1
$\Delta T_{\mathrm{unfil}}$ (K)	-1.2 ± 0.8	-2.16 ± 0.66	-0.79 ± 0.17
Δq_{min} (g kg^{-1})	-0.43 ± 0.65	-0.55 ± 0.81	-0.36 ± 0.54
Δq_{max} (g kg^{-1})	0.2 ± 0.41	0.29 ± 0.51	0.12 ± 0.3
$\Delta \theta_{\mathrm{e,min}}$ (K)	-2.05 ± 2.08	-3.3 ± 2.25	-1.35 ± 1.35
$\Delta \theta_{\mathrm{v,min}}$ (K)	-0.96 ± 0.81	-1.92 ± 0.7	-0.55 ± 0.14
Δp_{max} (hPa)	0.09 ± 0.29	0.2 ± 0.44	0.04 ± 0.19
ΔU_{max} (m s^{-1})	1.14 ± 1.55	2 ± 1.97	0.7 ± 0.99
$\Delta U_{\mathrm{max,unfil}}$ (m s^{-1})	2.81 ± 2.36	4 ± 2.52	2.02 ± 1.69
$\Delta \mathrm{wdir}_{\mathrm{mean}}$ (°)	0.48 ± 12.57	3.33 ± 18.34	-0.32 ± 8.59
R_{int} (mm h^{-1})	0.9 ± 1.76	1.45 ± 2.42	0.41 ± 0.95
$\mathrm{RR}_{\mathrm{mean}}$ (mm h^{-1})	0.05 ± 0.38	0.39 ± 1.06	0 ± 0.04
$\mathrm{CTH}_{\mathrm{max}}$ (km)	3.04 ± 1.11	3.56 ± 1.2	2.66 ± 0.96
$\mathrm{CTH}_{\mathrm{mean}}$ (km)	2.32 ± 0.88	2.74 ± 0.81	2.03 ± 0.89
w_{minSCL} (m s^{-1})	-0.55 ± 1.56	-1.89 ± 2.42	-0.27 ± 0.51
w_{maxSCL} (m s^{-1})	0.91 ± 0.62	1.1 ± 0.7	0.78 ± 0.54
w_{max450} (m s^{-1})	0.98 ± 0.81	1.27 ± 0.99	0.79 ± 0.66
Length (km)	13.3 ± 9.5	18.6 ± 10.9	10 ± 6
$\Delta t_{\mathrm{nextcp}}$ (min)	117 ± 426	85 ± 245	158 ± 725
Dur (min)	33 ± 22	47 ± 29	25 ± 12
Front dur (min)	19 ± 12	29 ± 19	15 ± 4

Vogel et al. 2021

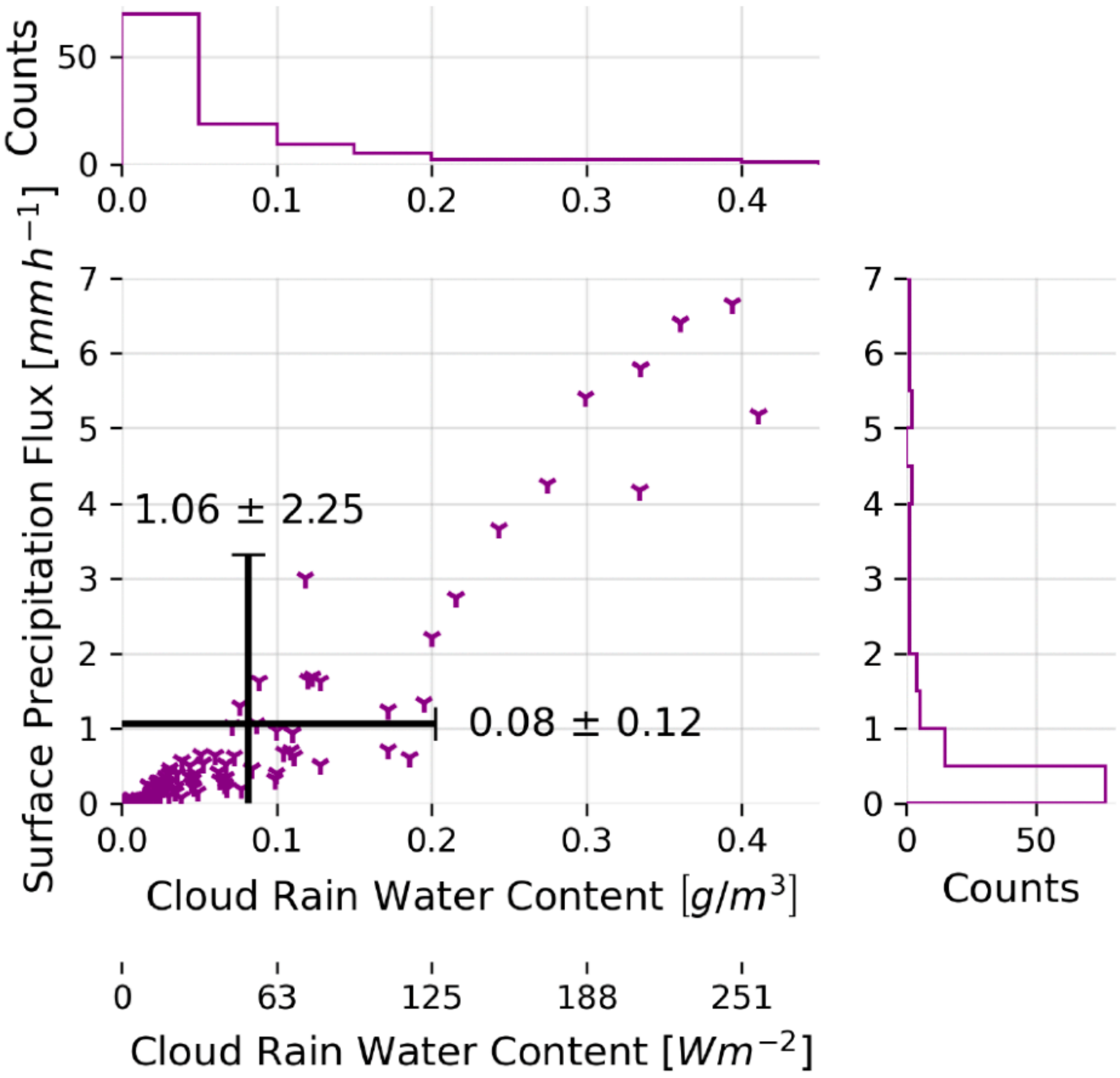
46 C. Acquistapace et al.: EU

Table 3. Daily mean values of the main surface variables observed on the *MS Merian* during the EUREC^{4}A campaign: T2m is the air temperature 2 m above the radar base, which is approximately 20 m a.s.l. (above sea level), RR is the rain rate. The liquid water path (LWP) is derived from the collocated 89 GHz channel microwave radiometer, and RH and P are the relative humidity and air pressure from a weather station positioned next to the radar equipment.

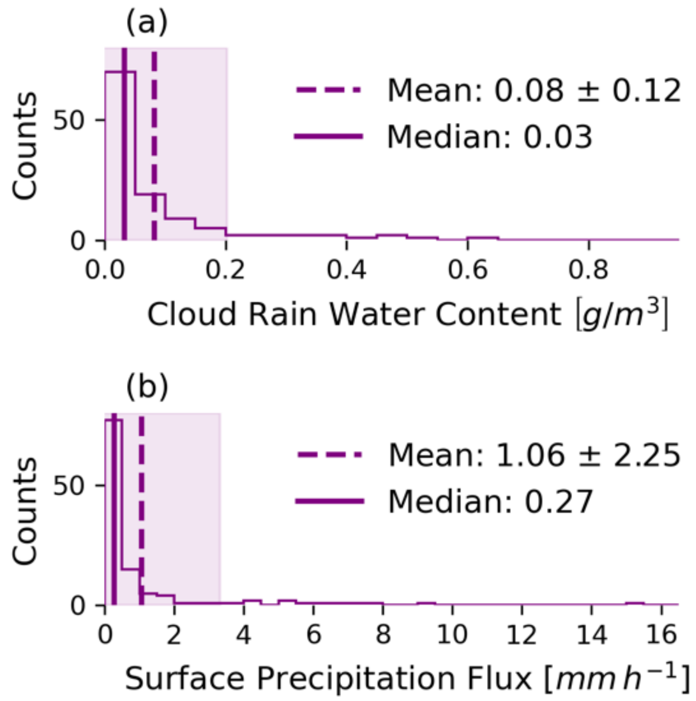
Day	T2m [°C]	RR [mm h^{-1}]	LWP [g m^{-2}]	RH [%]	P [hPa]
19 Jan 2020	26.35	0.0	1	63.6	1013.9
20 Jan 2020	25.95	0.57	30	72.4	1013.3
21 Jan 2020	26.85	1.0	71	67.2	1011.7
22 Jan 2020	27.25	1.42	0	63.2	1010.3
23 Jan 2020	26.85	0.99	12	69.2	1009.7
24 Jan 2020	26.15	0.57	318	76.2	1010.4
25 Jan 2020	26.85	0.67	13	67.5	1011.9
26 Jan 2020	26.65	0.0	23	67.4	1012.2
27 Jan 2020	26.95	1.37	391	75.2	1012.0
28 Jan 2020	27.25	0.0	50	74.9	1010.8
29 Jan 2020	27.15	0.32	26	72.4	1010.9
30 Jan 2020	27.55	0.0	20	71.5	1011.7
31 Jan 2020	27.35	0.0	8	70.0	1012.7
1 Feb 2020	27.45	0.31	13	64.8	1013.0
2 Feb 2020	27.45	0.49	6	62.3	1012.0
3 Feb 2020	27.05	0.0	3	68.2	1013.3
4 Feb 2020	27.25	0.0	8	69.2	1013.1
5 Feb 2020	27.05	0.45	10	68.3	1014.1
6 Feb 2020	27.15	0.0	11	65.7	1013.9
7 Feb 2020	26.75	1.77	31	63.7	1013.9
8 Feb 2020	26.55	7.43	35	65.8	1013.6
9 Feb 2020	26.85	1.38	4	66.3	1015.3
10 Feb 2020	26.65	0.80	106	67.3	1015.1
11 Feb 2020	26.55	0.30	54	68.7	1014.6
12 Feb 2020	26.35	0.43	85	70.3	1014.1
13 Feb 2020	26.55	0.70	51	68.5	1012.7
14 Feb 2020	27.35	3.24	53	67.3	1012.9
15 Feb 2020	26.85	0.89	22	68.0	1012.1
16 Feb 2020	26.75	1.06	47	70.2	1011.3
17 Feb 2020	27.05	0.33	15	68.6	1011.9
18 Feb 2020	26.75	4.22	312	71.4	1013.2
19 Feb 2020	26.05	0.62	319	74.1	1013.1

Acquistapace et al. 2022

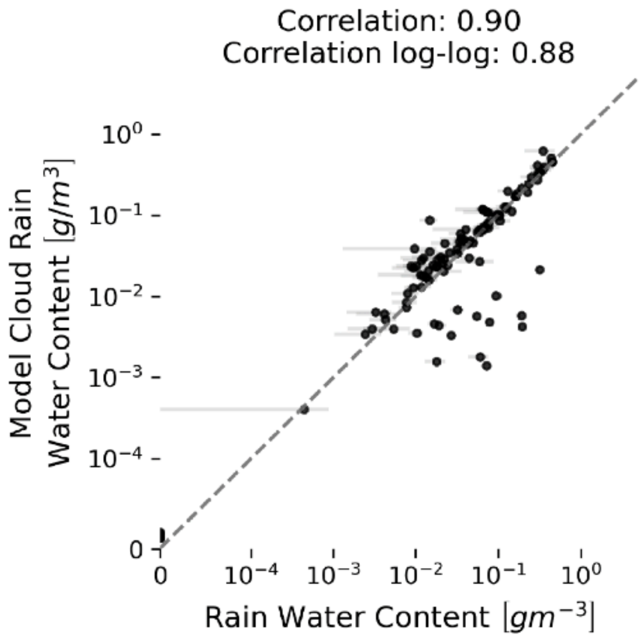
RWC AND PRECIPITATION ARE REALISTIC



- **Surface precipitation flux mean ~1 mm/hr**
- **In line with BCO and ship (slightly lower as we capture lots of light rain)**

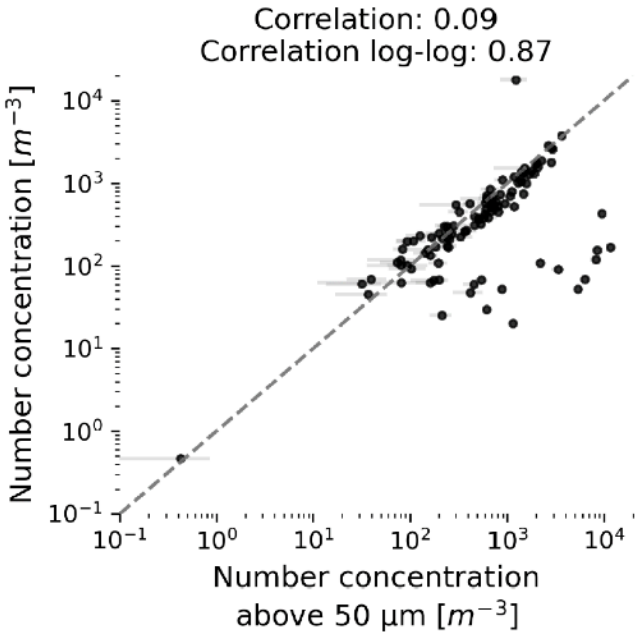


OBSERVATIONS – RAIN WATER CONTENT



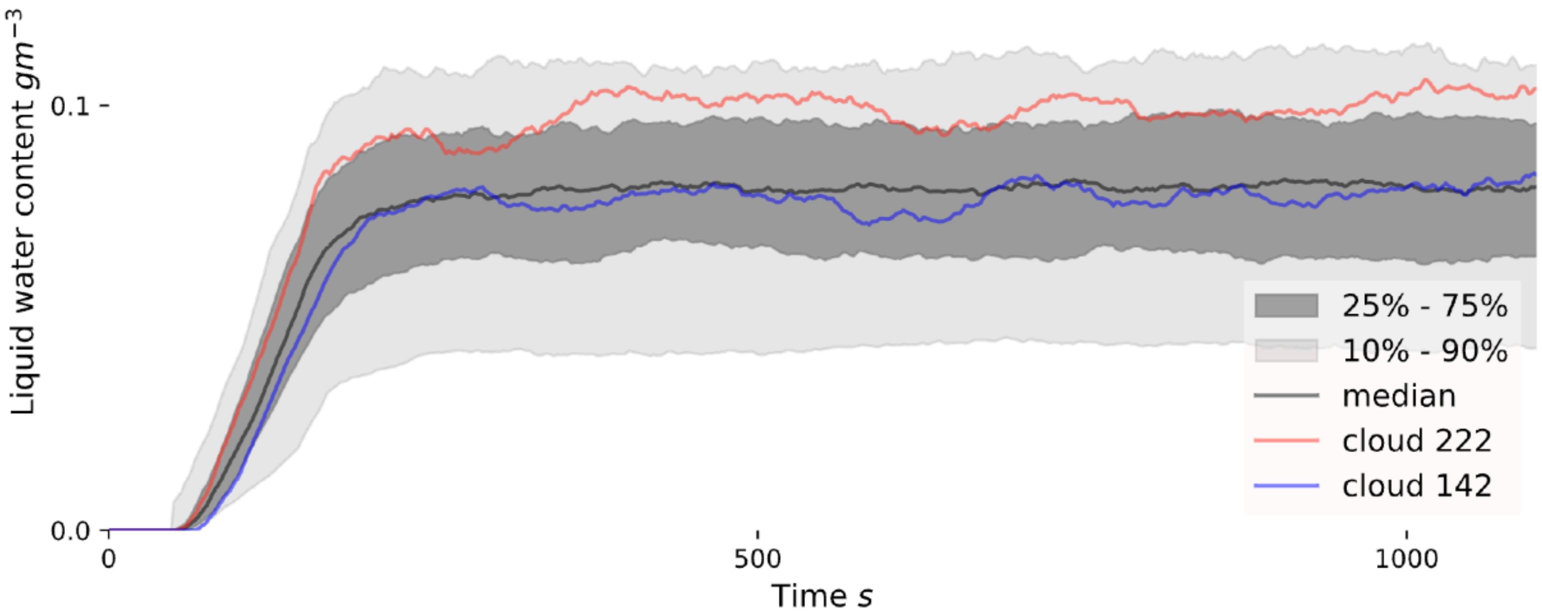
- Rain water content on x-axis is measured by ATR.
- It is all LWC for radii bins above 50µm

OBSERVATIONS – NUMBER CONCENTRATION

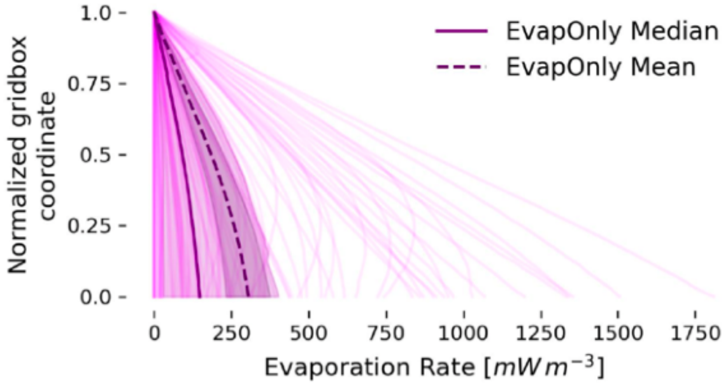


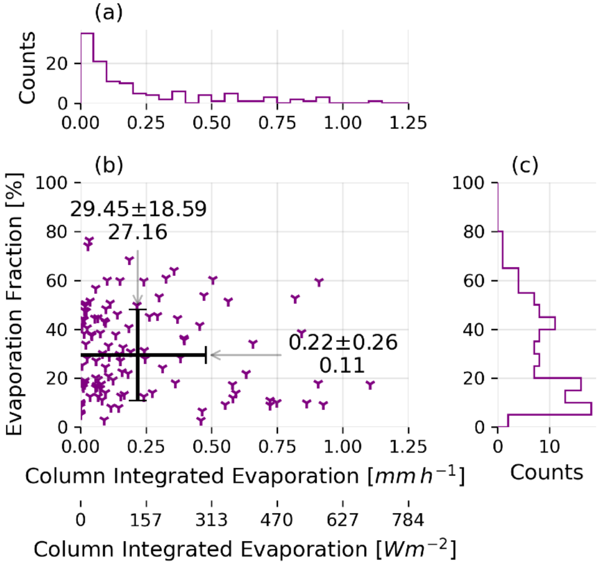
- Droplet number concentration on x-axis is measured by ATR.
- It is all DNC for radii bins above 50µm

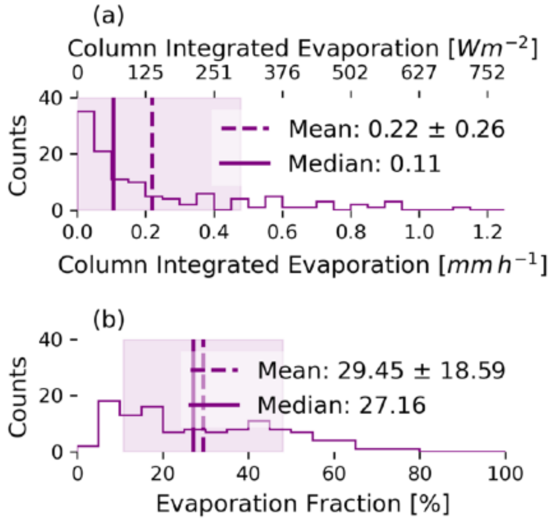
STEADY STATE REACHED AFTER 4-5 MINUTES WHEN MM-SIZED DROPLETS REACH THE SURFACE



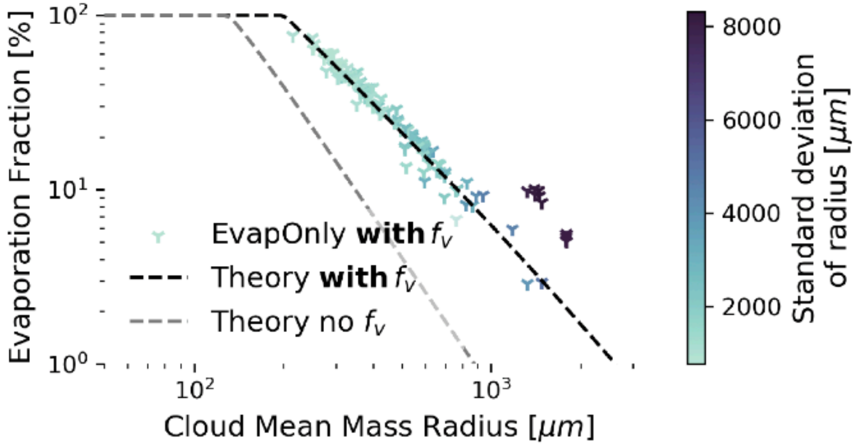
RESULTS



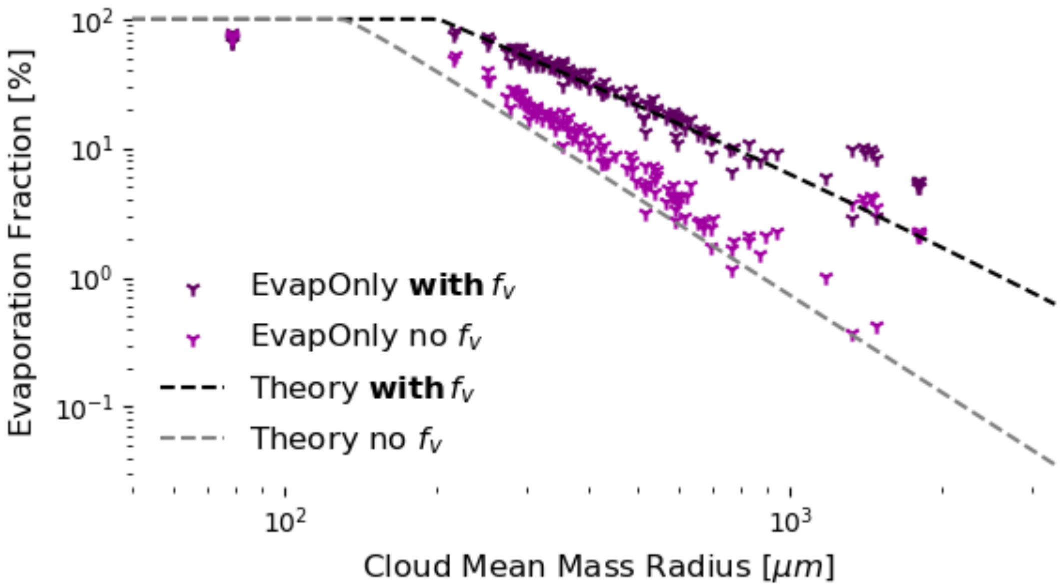




OUTLIERS IN EVAPORATION FRACTION ARE MAINLY DUE TO SPREAD IN DISTRIBUTION



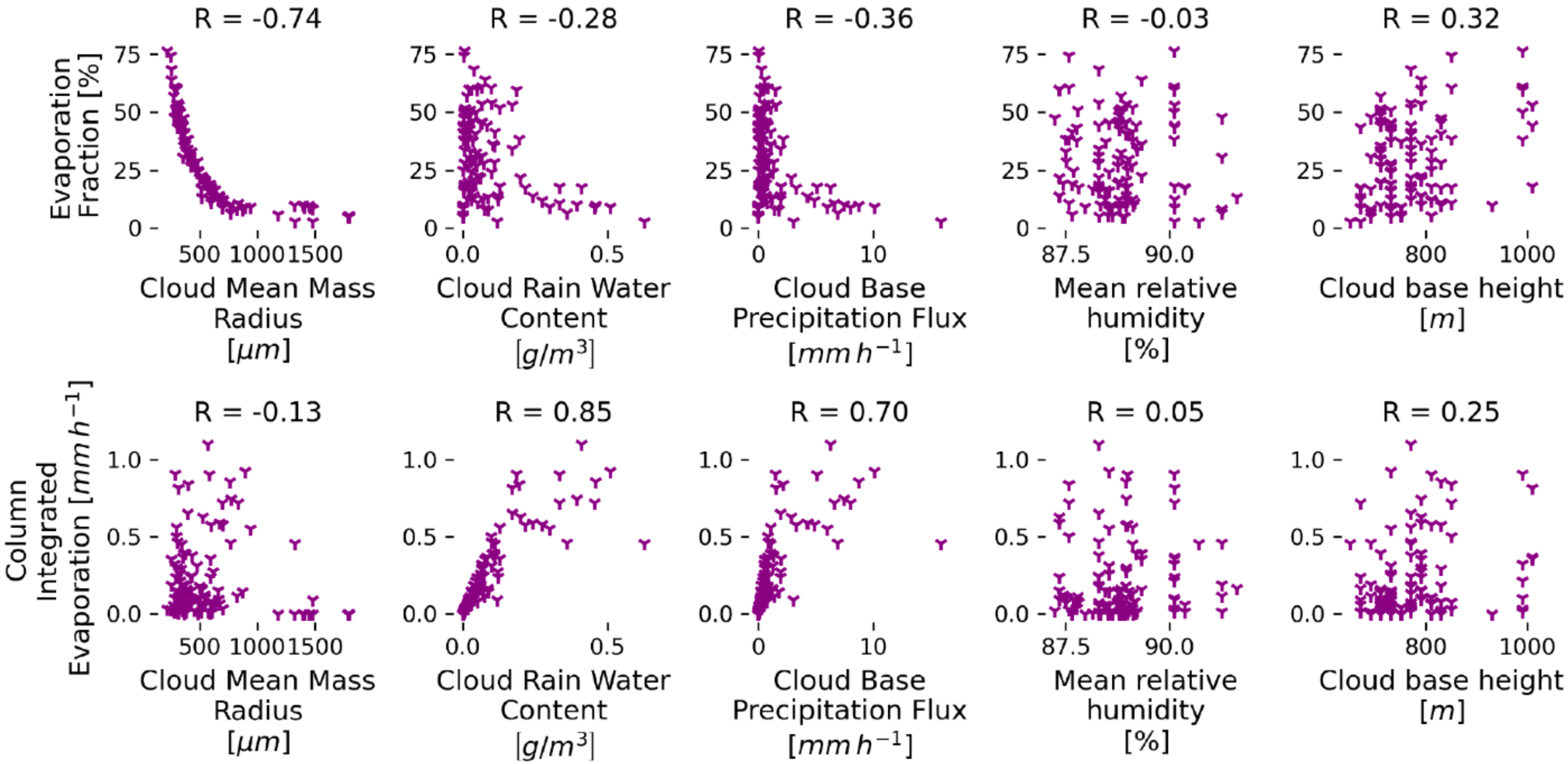
COLLISIONS BETWEEN DROPLETS PLAY A VERY MINOR ROLE IN SUB-SHALLOW-CLOUD LAYER EVAPORATION



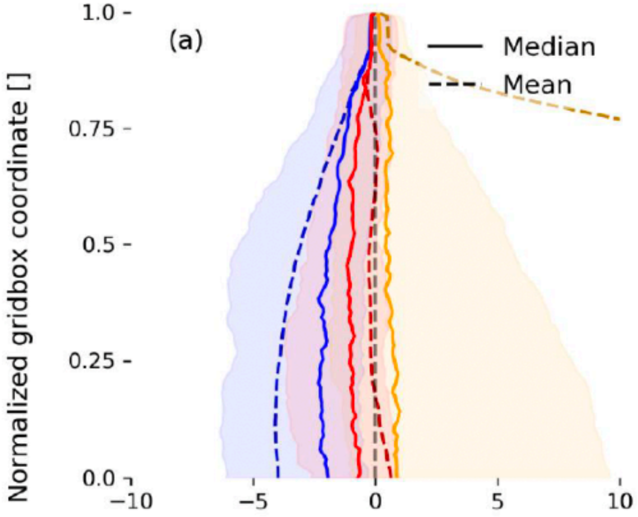
- **Only O(1%) change in evaporated fraction by including collisions between droplets**
- **Larger changes in limit of excessive breakup, but only for narrow size distributions of mm-size droplets**
- **Ventilation effects are extremely important, increasing evaporation rates ten-fold**

RESULTS

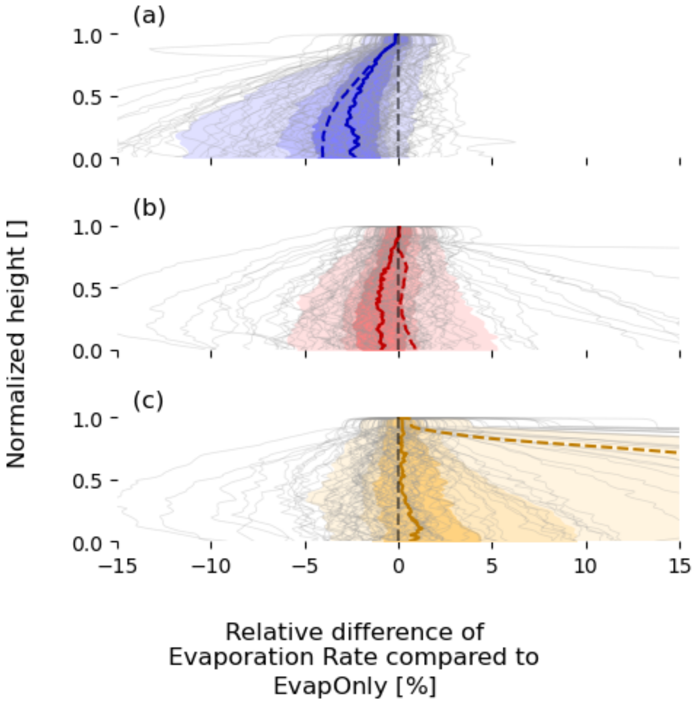
ALL CORRELATIONS WITH EF AND CIE



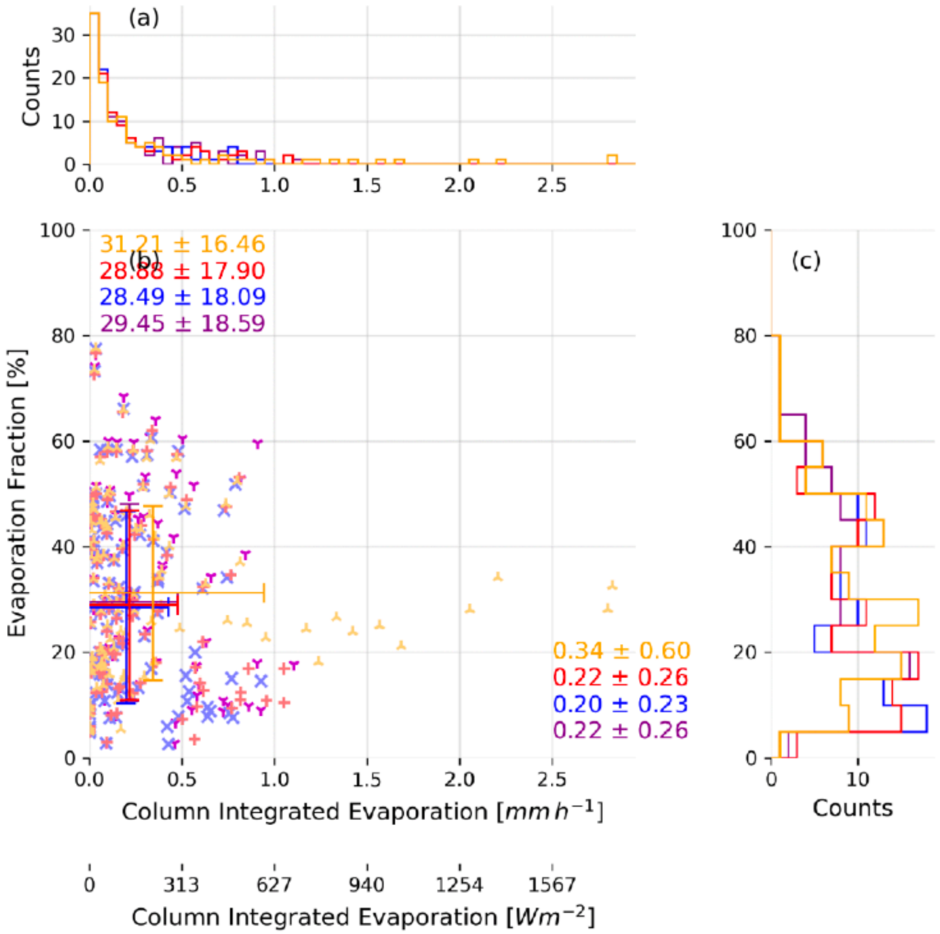
RESULTS



(a)
Median
Mean
Normalized gridbox coordinate []
1.0
0.75
0.5
0.25
0.0
−10
−5
0
5
10

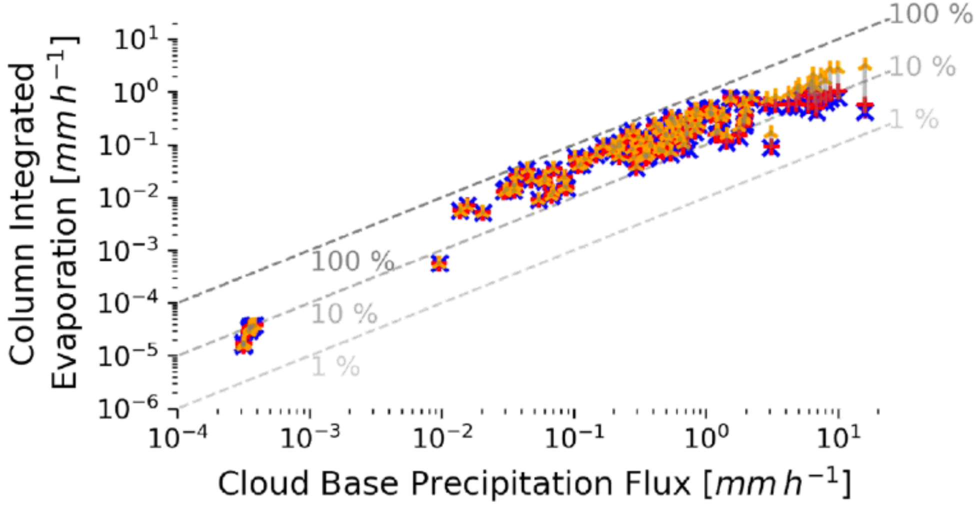


(a)
(b)
(c)
Normalized height []
1.0
0.5
0.0
−15
−10
−5
0
5
10
15
Relative difference of Evaporation Rate compared to EvapOnly [%]

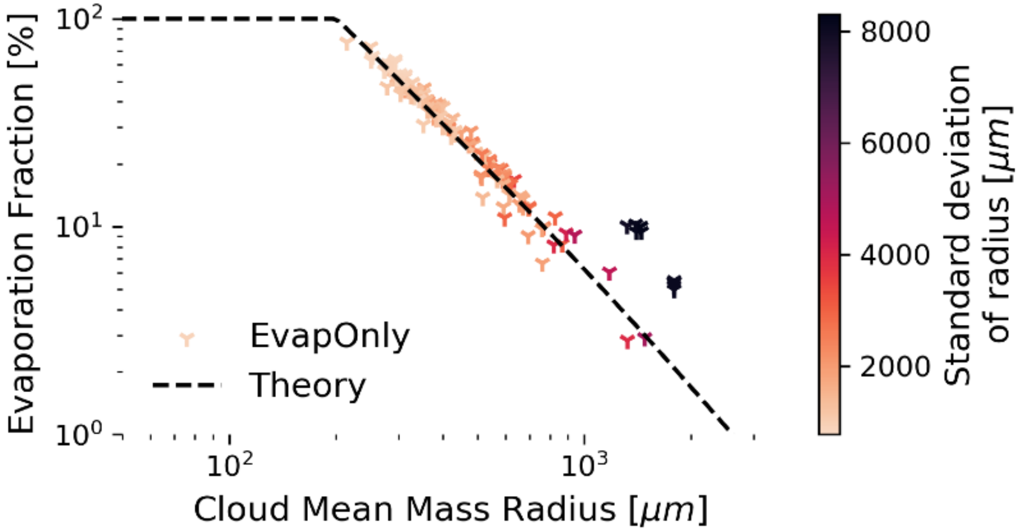


(a)
Counts
30
20
10
0
0.0
0.5
1.0
1.5
2.0
2.5
(b)
31.21 ± 16.46
28.88 ± 17.90
28.49 ± 18.09
29.45 ± 18.59
Evaporation Fraction [%]
100
80
60
40
20
0
0.34 ± 0.60
0.22 ± 0.26
0.20 ± 0.23
0.22 ± 0.26
Column Integrated Evaporation [$mm\,h^{-1}$]
0
313
627
940
1254
1567
Column Integrated Evaporation [Wm^{-2}]
(c)
0
10
Counts

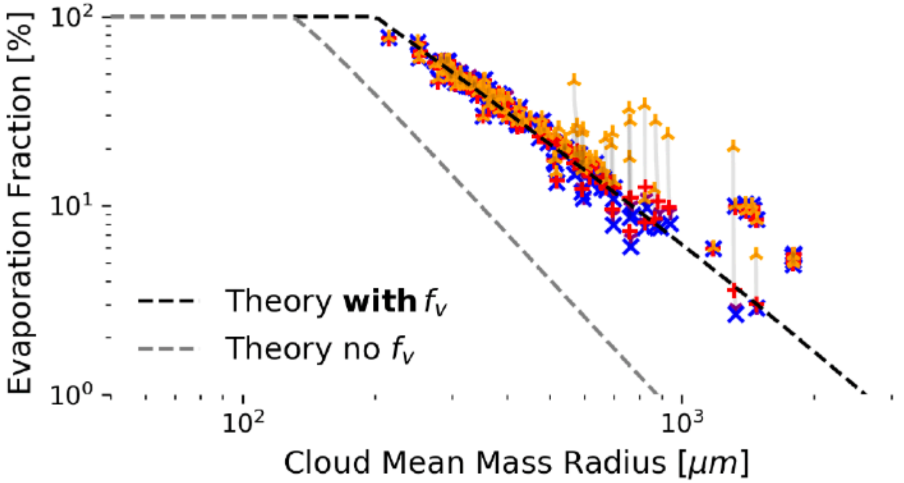
RESULTS



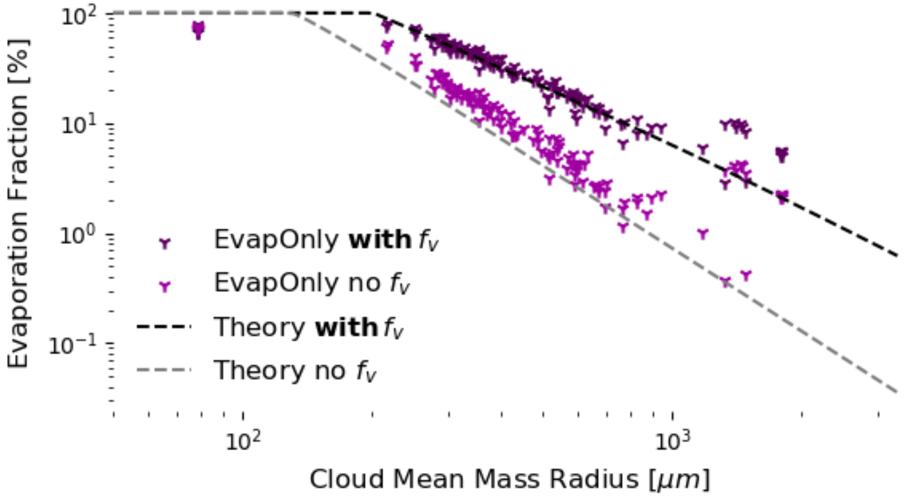
Column Integrated Evaporation [$mm\,h^{-1}$]
Cloud Base Precipitation Flux [$mm\,h^{-1}$]
100 %
10 %
1 %
100 %
10 %
1 %
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}



Evaporation Fraction [%]
Cloud Mean Mass Radius [μm]
EvapOnly
Theory
Standard deviation of radius [μm]
8000
6000
4000
2000
10^{2}
10^{1}
10^{0}
10^{2}
10^{3}

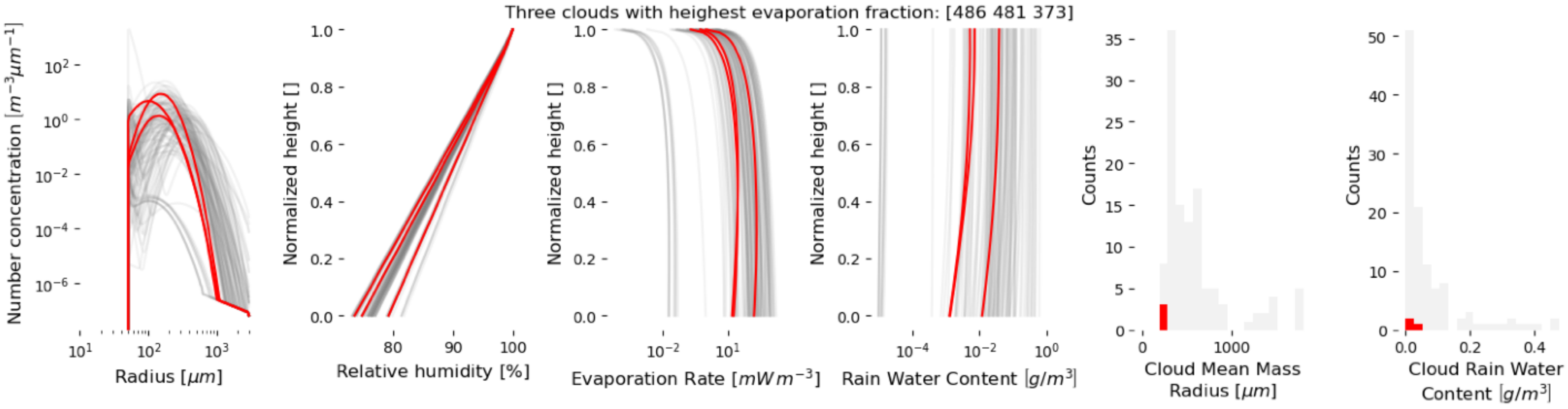


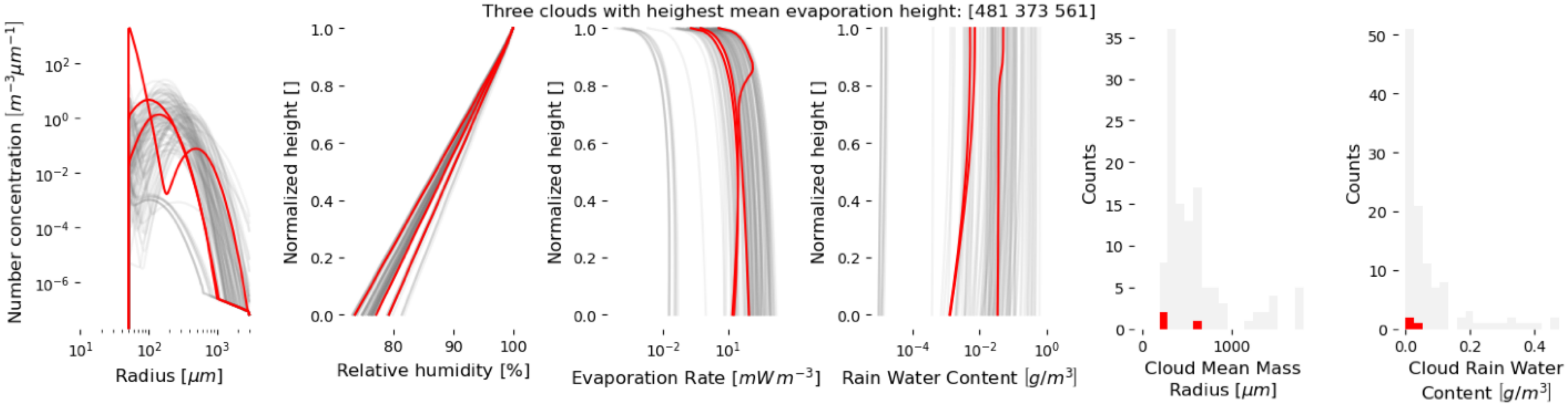
Evaporation Fraction [%]
Cloud Mean Mass Radius [μm]
Theory **with** f_v
Theory no f_v
10^{2}
10^{1}
10^{0}
10^{2}
10^{3}



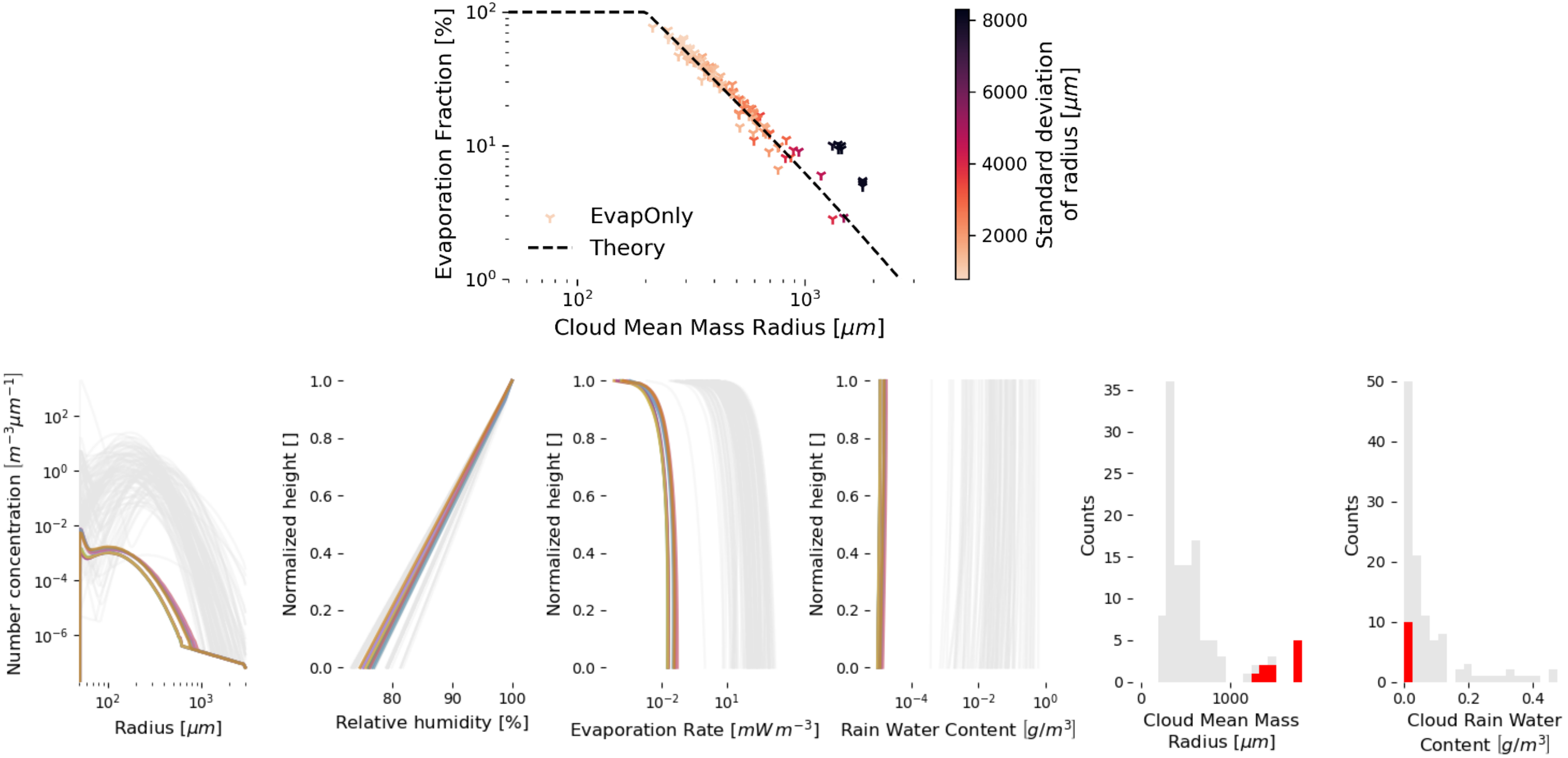
Evaporation Fraction [%]
Cloud Mean Mass Radius [μm]
EvapOnly **with** f_v
EvapOnly no f_v
Theory **with** f_v
Theory no f_v
10^{2}
10^{1}
10^{0}
10^{-1}
10^{2}
10^{3}

RESULTS: TOP-HEAVY EVAPORATION FROM SMALL MEAN RADIUS DISTRIBS

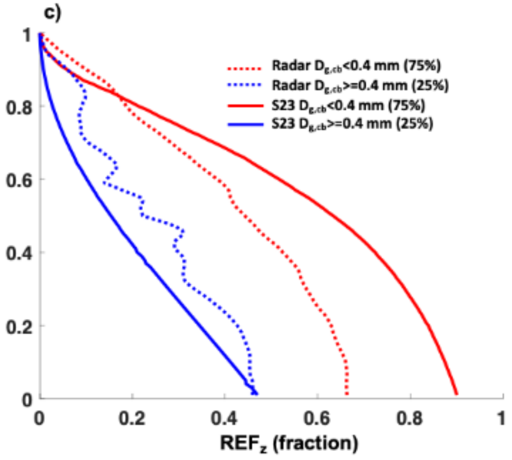


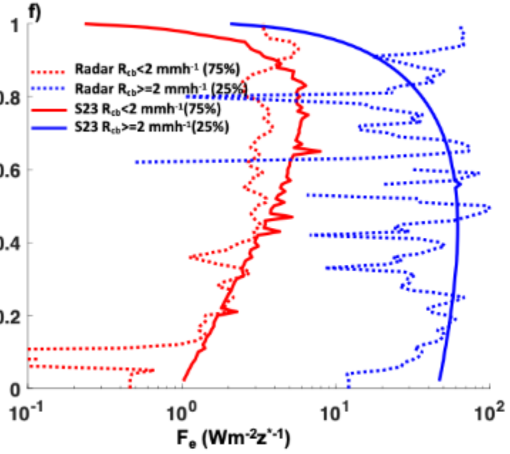


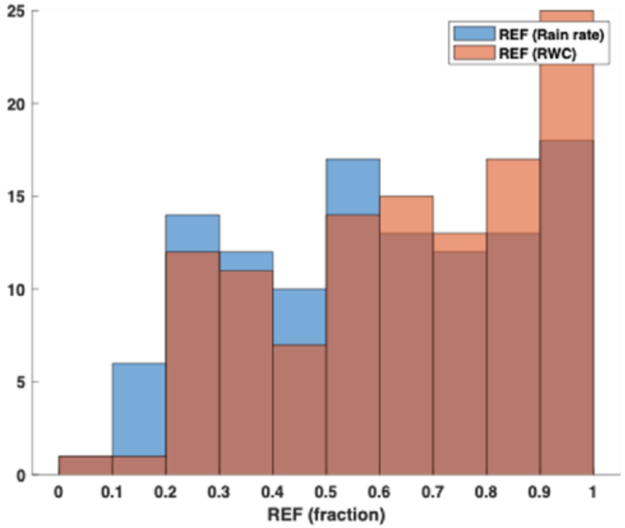
RESULTS: LARGER THAN EXPECTED EVAPORATION FRACTION FROM BROAD DSDS

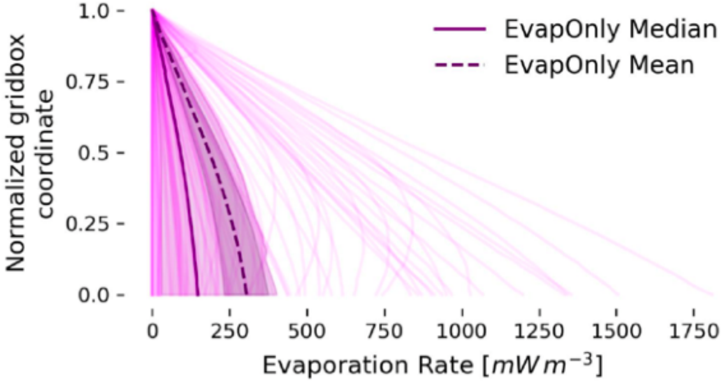


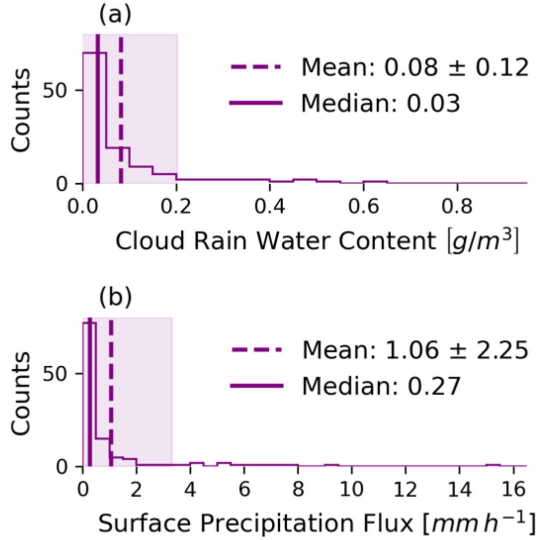
MAMPI COMPARISON? WORK IN PROGRESS











Color values Max Planck Institute for Meteorology from 2022

Main colors

text green, logo green
R0-G108-B102

background dark green
R0-G85-B85

Accompanying colors

dark grey
R119-G119-B119

grey
R167-G167-B167

light grey
R238-G238-B238

text white, logo white
R255-G255-B255

background black
R0-G0-B0

Accent colors

light green
R198-G211-B37

dark blue
R41-G72-B93

light blue
R0-G177-B234

orange
R239-G124-B0