c. 1963 - 20??

The death of autoconversion?

Kaitlyn Loftus (Columbia / NSF LEAP STC)

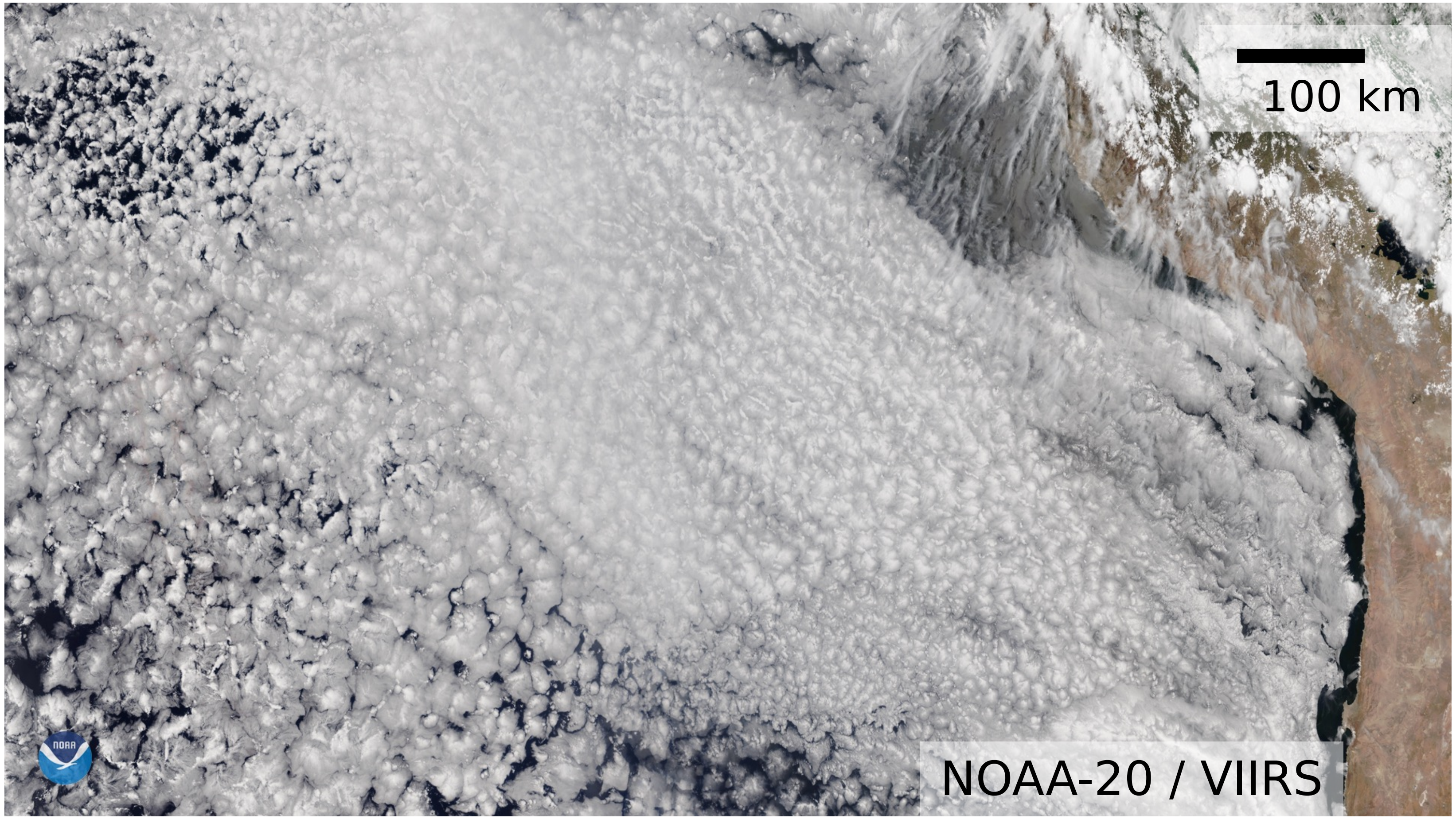
Marcus van Lier-Walqui, Hugh Morrison, & Robin Wordsworth

Cloud drop collisional growth shapes Earth’s water cycle & energy budget.

Albrecht (1987), Slingo (1990), Rotstayn (2000), Quaas et al. (2009), Posselt & Lohmann (2009), Suzuki et al. (2013), Michibata & Takemura (2015), Mülmenstädt et al. (2020,2021)

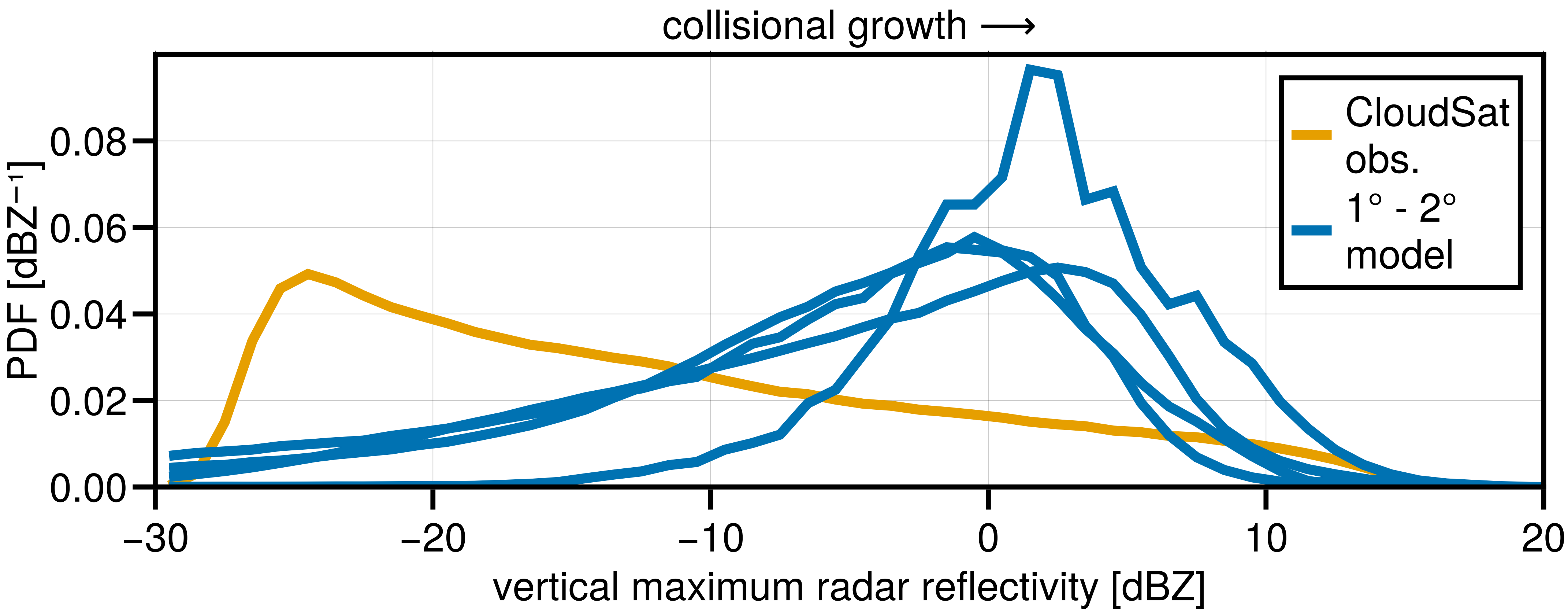
- Initiates warm rain
- Regulates warm cloud precipitation efficiency
- Shapes cloud radiative & precipitation properties

Beard & Ochs (1993), Wood (2000, 2012), H. Wang & Feingold (2009), Feingold et al. (2013), Yamaguchi et al. (2017), Gettelman et al. (2021)



Global climate models overestimate drop collisional growth relative to satellite obs.

*Suzuki et al. (2013, 2015), **Jing et al. (2017)**, Mülmenstädt et al. (2020)*



warm, marine clouds from 60°S – 60°N

adapted from Xianwen Jing et al. (2017)

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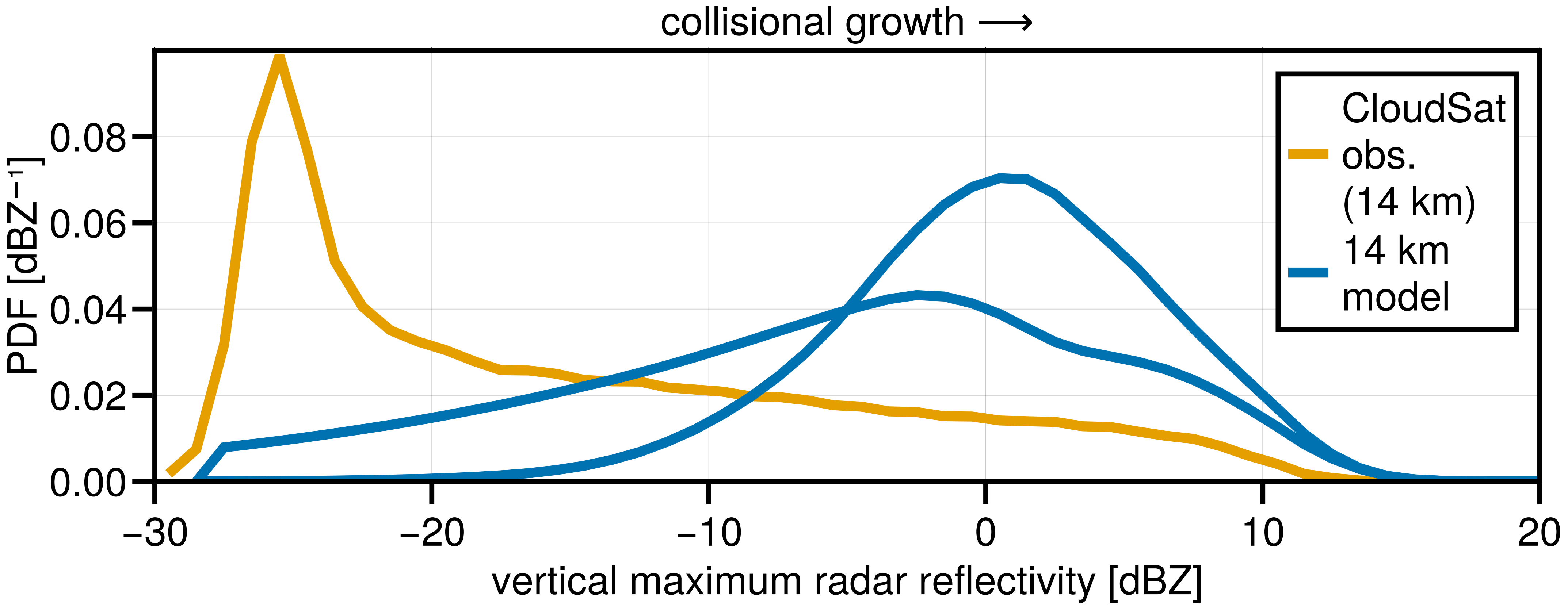

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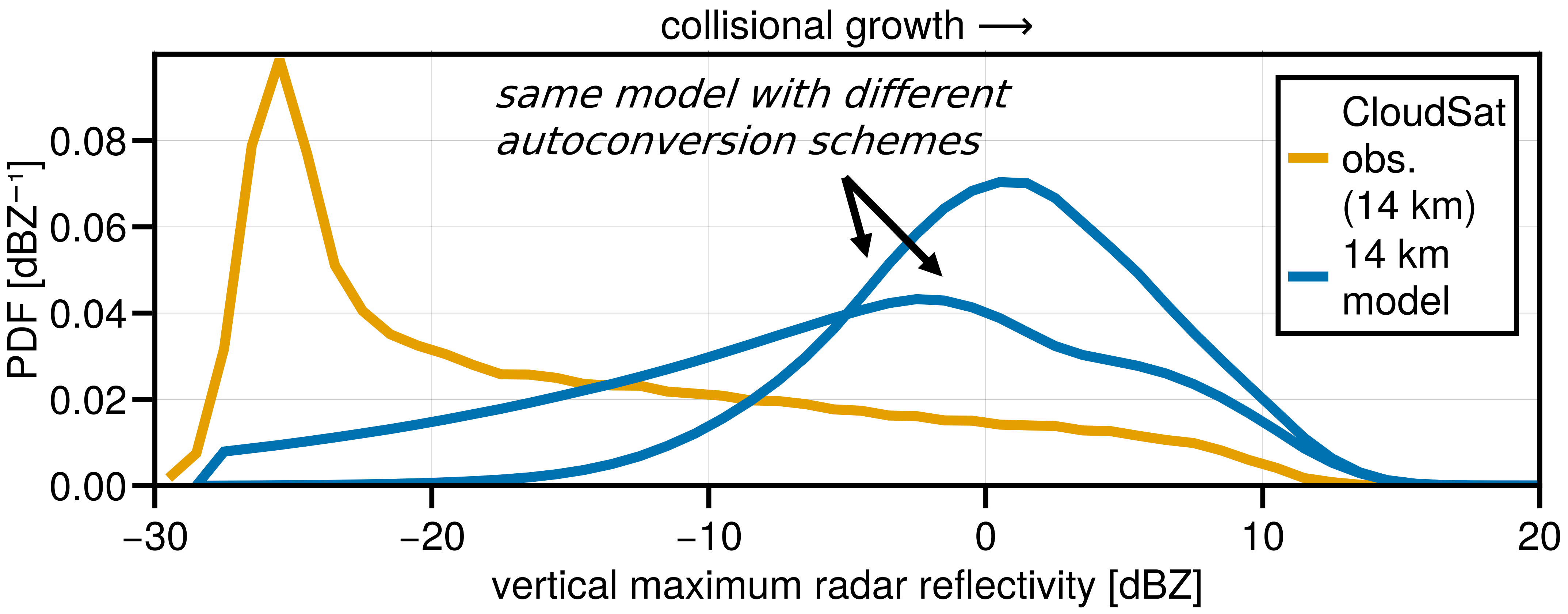

warm, marine clouds from 60°S – 60°N

adapted from Xianwen Jing et al. (2017)

We catalog CMIP6 global models' representations of collisional growth.

Coupled Model Intercomparison Project Phase 6 (CMIP6)

	atm component(s)	#	L_1	L_2	N_1	N_2	auto	auto ref	acc	acc ref	sc1	sc2	n_2	doc
1	CAM6;CAM6-Nor;E3Mv1.0	10	P	P	P	P	L_1,N_1	KK00	L_1,L_2	KK00	–	L_2,N_2	e	both
2	ECHAM6.3	7	P	D	P	–	L_1,N_1	KK00	L_1,L_2	KK00	L_1?	–	e-MP	both
3	CAM5.3;CIESM-AM	6	P	D	P	D	L_1,N_1	KK00	L_1,L_2	KK00	–	L_2,N_2	e	both
4	MetUM-GA7.1	5	P	P	A	–	L_1,N_1	KK00	L_1,L_2	KK00	–	–	e-AB	both
5	GISS-E2-1;GISS-E2-2	4	P	D	A?	–	L_1?	D96?	L_1?,L_2?	D96?	–	–	–?	IPCC
6	AGCM3	3	P	D	A	–	L_1,N_1,L_2^*	CC87,RK98	L_1,L_2	TC80	–	–	e-MP	IPCC
7	Arpege6.3	3	P	P	–	–	L_1	K69	L_1,L_2	L02	–	–	e-MP?	both
8	CCSR AGCM	3	P	D	P	–	L_1,N_1	B68	L_1,L_2	T18	L_1	–	–?	both
9	GFDL-AM4.0	3	P	D	P	–	L_1,N_1	MC77	L_1,L_2	R97	–	–	e-MP	both
10	IFS Cy36r4	3	P	P	A	–	L_1,N_1?	S78	L_1,L_2	S89	–	–	–	both
11	CAM4	2	P	D	–	–	L_1,L_2^*	CC87,RK98	L_1,L_2	TC80	–	–	e-MP	IPCC
12	CanAM5	2	P	D	A?	–	L_1,N_1?	KK00	L_1,L_2	B94	–	–	e-MP	both
13	INM-AM4-8;INM-AM5.0	2	–	D	–	–	–	–	–	–	–	–	–	IPCC
14	LMDZ APv5;LMDZ NPv6	2	P	D	–	–	L_1	S78	–	–	–	–	–	both
15	MRI-AGCM3.2	2	P	D	–	–	L_1	S78	L_1?,L_2?	S89?	–	–	–	es-doc
16	ECHAM5-CAMS	1	P	D	D	–	L_1,N_1	LR96,B94	L_1,L_2	B94	–	–	e-MP	IPCC
17	FAMIL2.2	1	P	P	–	–	L_1	B68,L83	L_1,L_2	L83	–	–	e-MP	IPCC
18	GAMIL3	1	P	D	P	D	L_1,N_1	KK00	L_1,L_2	KK00	–	L_2,N_2	e	IPCC
19	GFDL-AM2.0	1	P	D	–	–	L_1	MC77	L_1,L_2	R97	–	–	e-MP	IPCC
20	HadGAM2 r1.1	1	P	D	A?	–	L_1,N_1?	TC80	L_1,L_2	WB99	–	–	e-MP	both
21	IFS Cy43r1	1	P	P	–	–	L_1	KK00	L_1,L_2	KK00	–	–	e-AB	es-doc
22	IITM-GFS	1	P	D	–	–	L_1	S78	L_1,L_2	ZC97	–	–	–	both
23	Manabe R30L14	1	–	D	–	–	–	–	–	–	–	–	–	both
24	MRI-AGCM3.5	1	P	D	P	–	L_1,N_1	MC77	L_1,L_2	R97	–	–	e-MP	both
25	NICAM16-9S	1	P	P	A	–	L_1	B68,L83	L_1,L_2	L83	–	–	e-MP	es-doc

Loftus (2023) – Chapter 4

CMIP6 microphysics parameterizations share fundamental structural assumptions.

Coupled Model Intercomparison Project Phase 6 (CMIP6)

	atm component(s)	#	L_1	L_2	N_1	N_2	auto	auto ref	acc	acc ref	sc1	sc2	n_2	doc
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4	MetUM-GA7.1	5	P	P	A	–	L_1,N_1	KK00	L_1,L_2	KK00	–	–	e-AB	both
5	GISS-E2-1;GISS-E2-2	4	P	D	A?	–	L_1?	D96?	L_1?,L_2?	D96?	–	–	–?	IPCC
6	AGCM3	3	P	D	A	–	L_1,N_1,L_2^*	CC87,RK98	L_1,L_2	TC80	–	–	e-MP	IPCC
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9	GFDL-AM4.0	3	P	D	P	–	L_1,N_1	MC77	L_1,L_2	R97	–	–	e-MP	both
10	IFS Cy36r4	3	P	P	A	–	L_1,N_1?	S78	L_1,L_2	S89	–	–	–	both
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15	MRI-AGCM3.2	2	P	D	–	–	L_1	S78	L_1?,L_2?	S89?	–	–	–	es-doc
16	ECHAM5-CAMS	1	P	D	D	–	L_1,N_1	LR96,B94	L_1,L_2	B94	–	–	e-MP	IPCC
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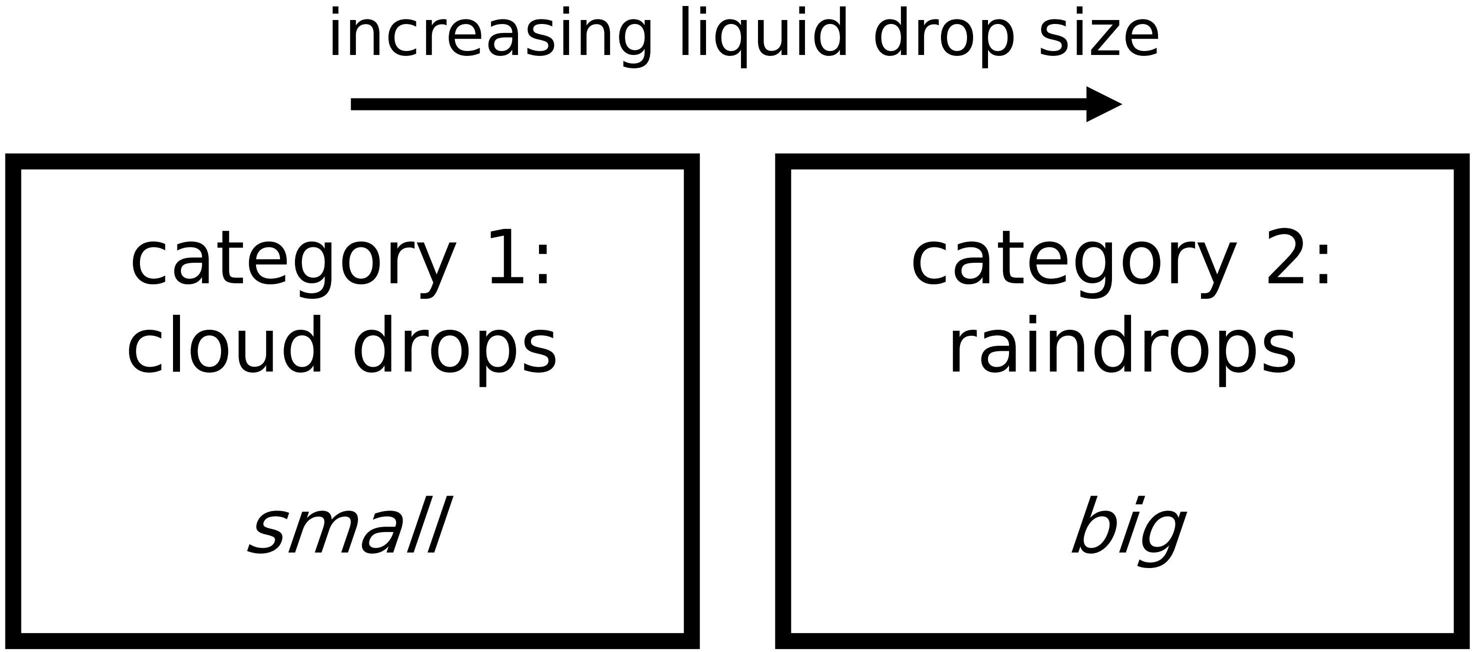
22	IITM-GFS	1	P	D	–	–	L_1	S78	L_1,L_2	ZC97	–	–	–	both
23	Manabe R30L14	1	–	D	–	–	–	–	–	–	–	–	–	both
24	MRI-AGCM3.5	1	P	D	P	–	L_1,N_1	MC77	L_1,L_2	R97	–	–	e-MP	both
25	NICAM16-9S	1	P	P	A	–	L_1	B68,L83	L_1,L_2	L83	–	–	e-MP	es-doc

Loftus (2023) – Chapter 4

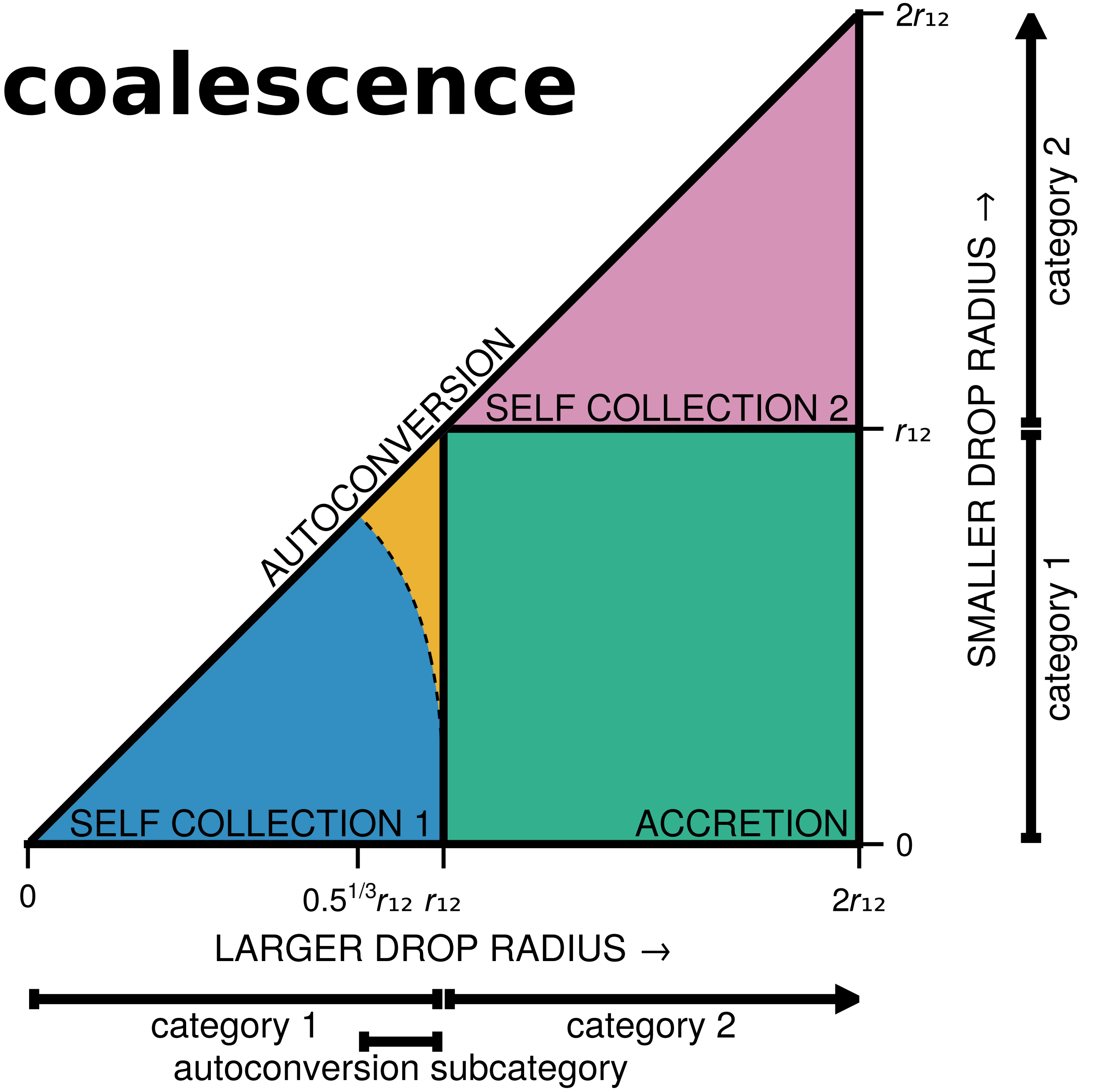
Condensed liquid water is divided into 2 categories loosely based on drop size.

CMIP6 shared assumption 1



2 category collision-coalescence has 4 components:

- self collection 1: cat. 1 + cat. 1 = cat. 1
- autoconversion: cat. 1 + cat. 1 = cat. 2
- accretion: cat. 1 + cat. 2 = cat. 2
- self collection 2: cat. 2 + cat. 2 = cat. 2

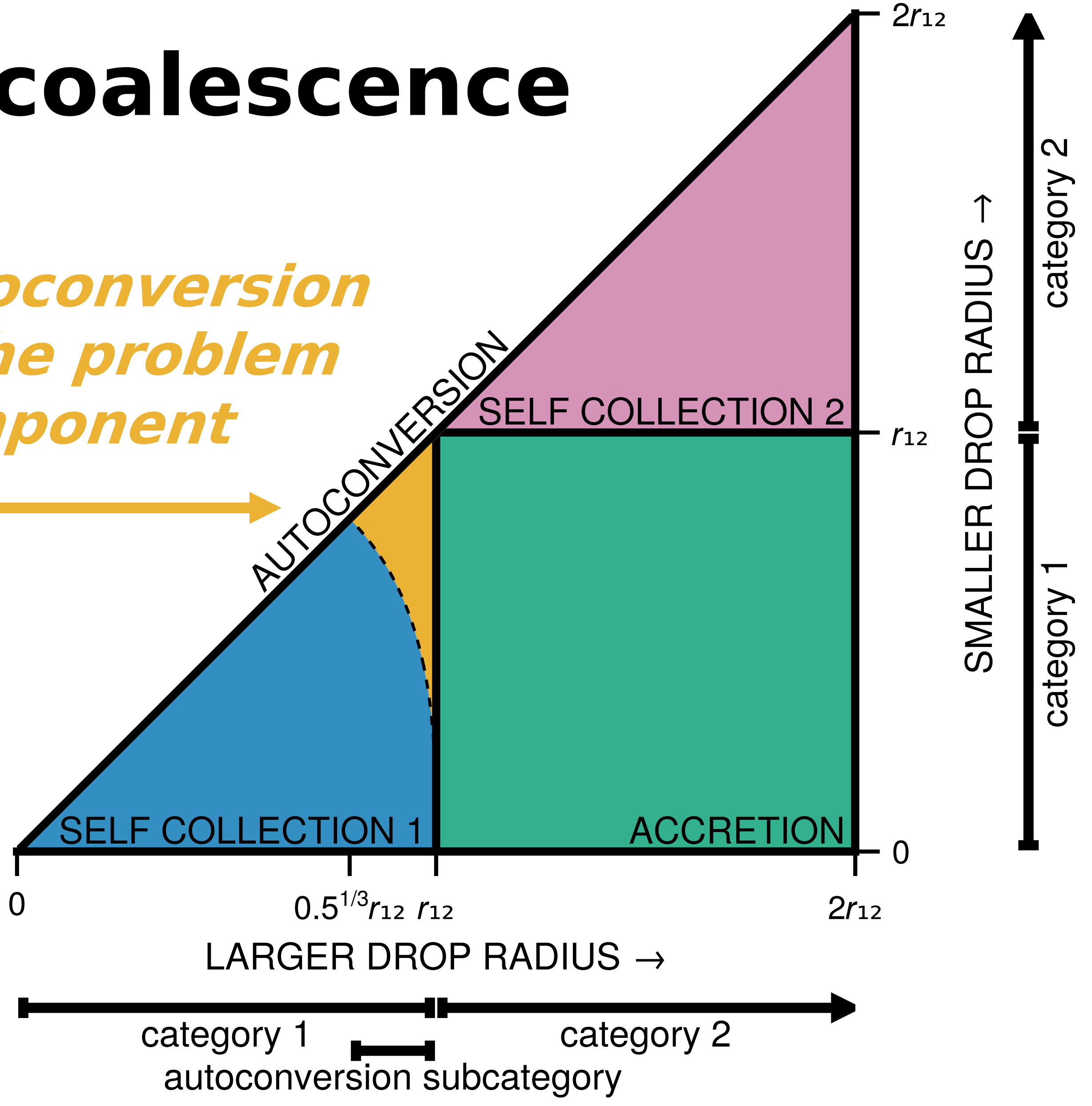


after Wood & Blossey (2005), Beheng (2010)

2 category collision-coalescence has 4 components:

- self collection 1: cat. 1 + cat. 1 = cat. 1
- autoconversion: cat. 1 + cat. 1 = cat. 2
- accretion: cat. 1 + cat. 2 = cat. 2
- self collection 2: cat. 2 + cat. 2 = cat. 2

autoconversion is the problem component



after Wood & Blossey (2005), Beheng (2010)

Why is autoconversion the problem component?

Berry (1967), Long (1974), Kokubo & Ida (1996, 1998), Kostinski & Shaw (2005)

early collisional growth:
~autoconversion (r ≲ 40-60 µm)

- highly nonlinear
  - $< \dot{m} > \propto m^3$
  - "lucky" drops can runaway from smaller drop mode
- sensitive to small changes in DSD
  - probability of collision *extremely* sensitive to both drop sizes

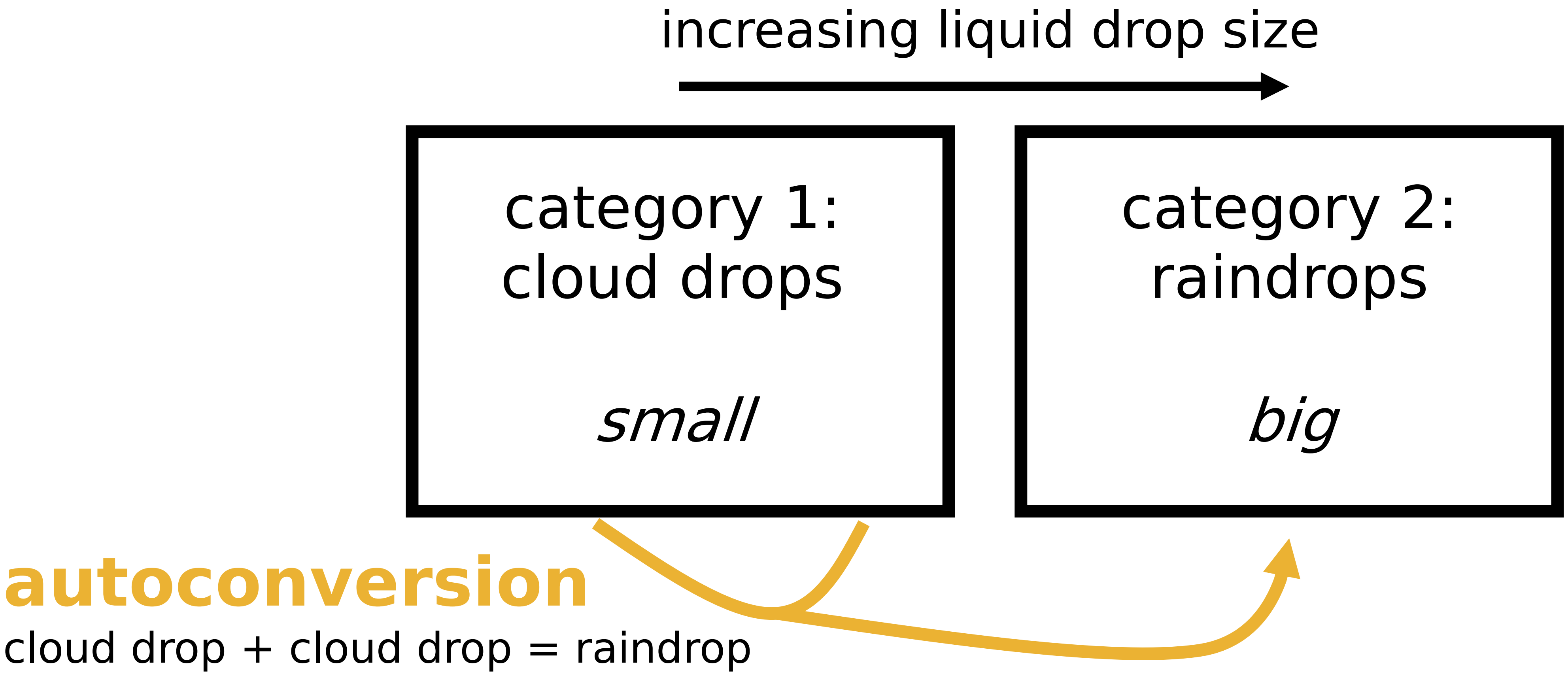
late collisional growth:
~accretion (r ≳ 40-60 µm)

- approximately linear
  - $< \dot{m} > \propto m$
- not sensitive to small changes in DSD
  - probability of collision *not* sensitive to smaller drop size

DSD = drop size distributions

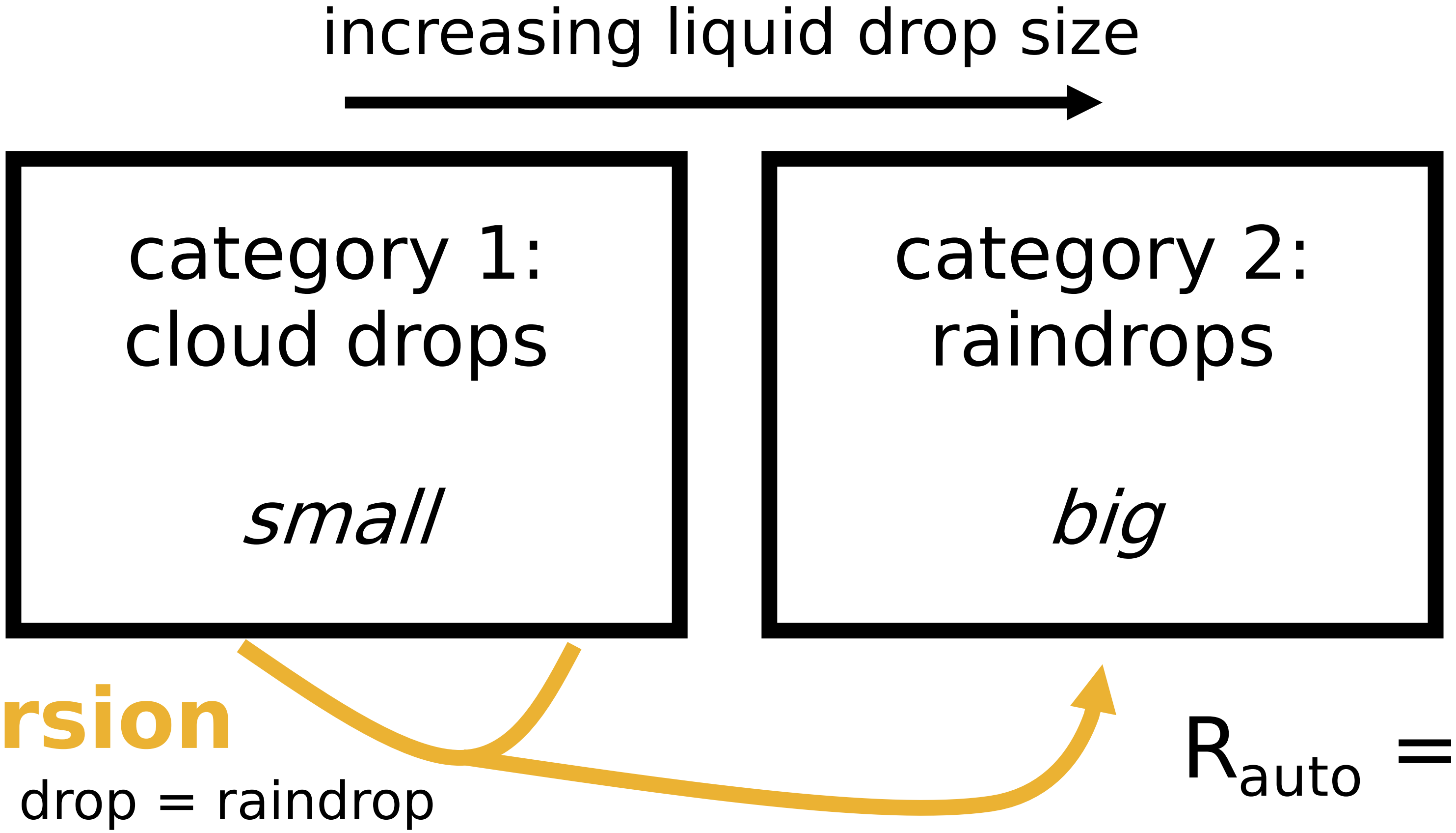
Autoconversion is the only “process” that can create raindrops in warm clouds.

CMIP6 shared assumption 2



Autoconversion rate is a function of cloud category mass & number conc.

CMIP6 shared assumption 3



autoconversion

cloud drop + cloud drop = raindrop

$$R_{auto} = f(L_1, N_1)$$

Cotton (1972) critiqued autoconversion schemes for neglecting “cloud aging.”

> One possible qualitative explanation for the discrepancy between eq (4) and observation is that neither eq (4) nor (1) specifies any time dependence for the rate of autoconversion whereas experience has shown that, regardless of the LWC, initial droplet dispersion, concentration, etc., a certain “aging” time is required before the distribution can be expected `to form precipitation particles.

many other critiques tied to this issue

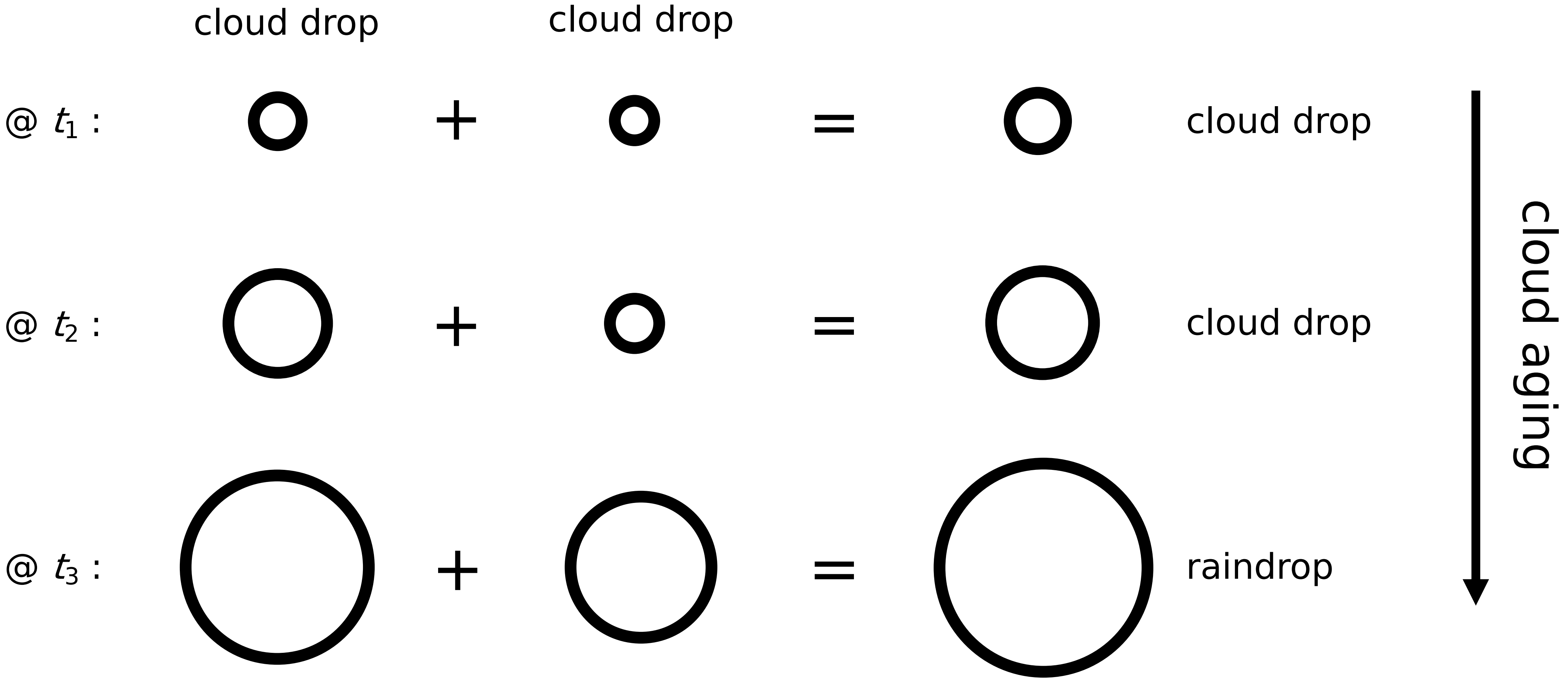
e.g., Seifert & Beheng (2001), Liu & Daum (2004), Seifert & Rasp (2020), Igel et al. (2022)

Cotton (1972) critiqued autoconversion schemes for neglecting “cloud aging.”

> One possible qualitative explanation for the discrepancy between eq (4) and observation is that neither eq (4) nor (1) specifies any time dependence for the rate of auto-conversion whereas experience has shown that, regardless of the LWC, initial droplet dispersion, concentration, etc., a certain ‘‘aging’’ time is required before the distribution can be expected `to form precipitation particles.

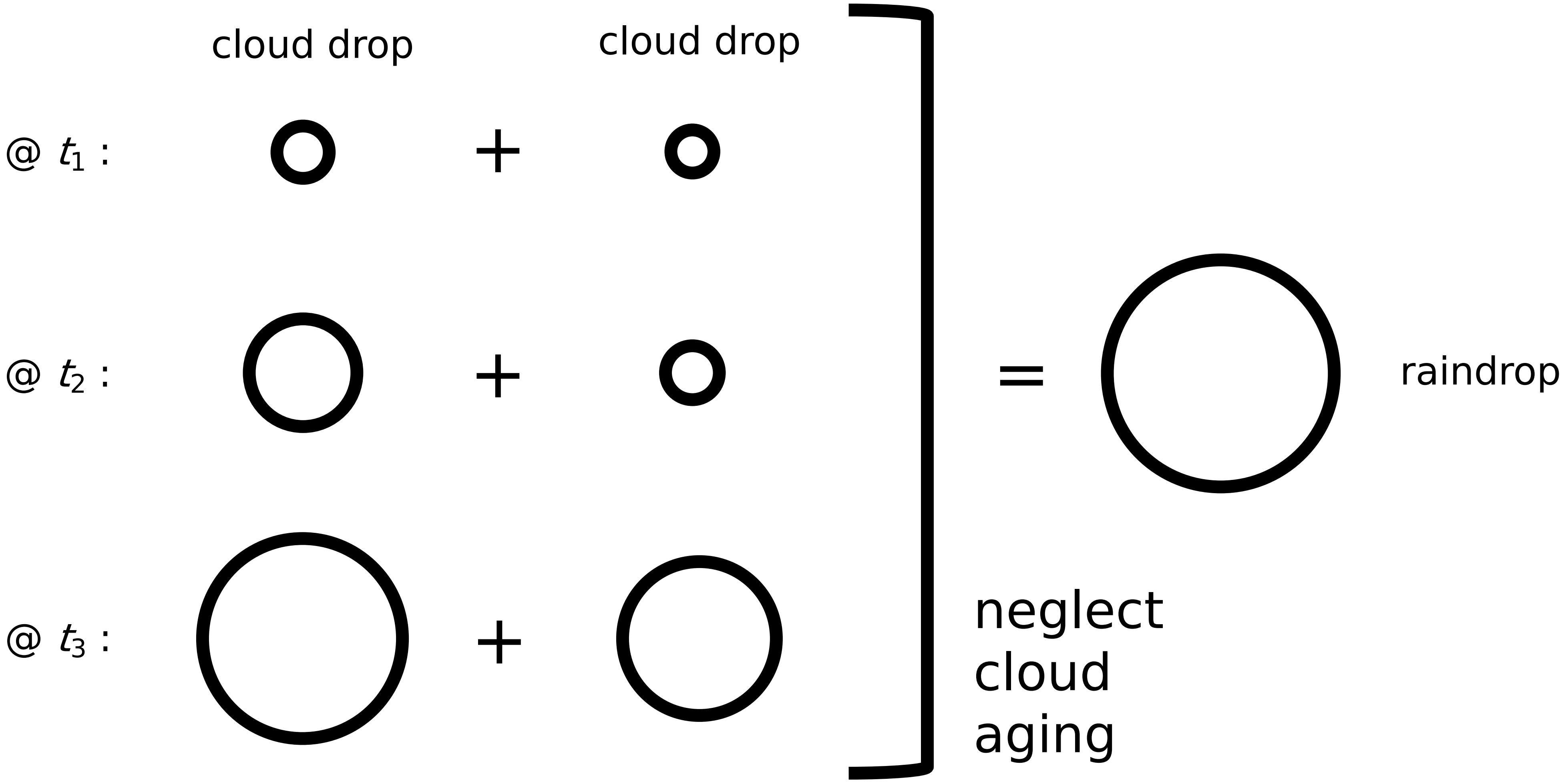
50+ years later, this critique is still applicable to CMIP6 models.

CMIP6 assumptions ⟹ neglect autoconversion's evolution with cloud aging.



SCHEMATIC.

CMIP6 assumptions ⟹ neglect autoconversion's evolution with cloud aging.

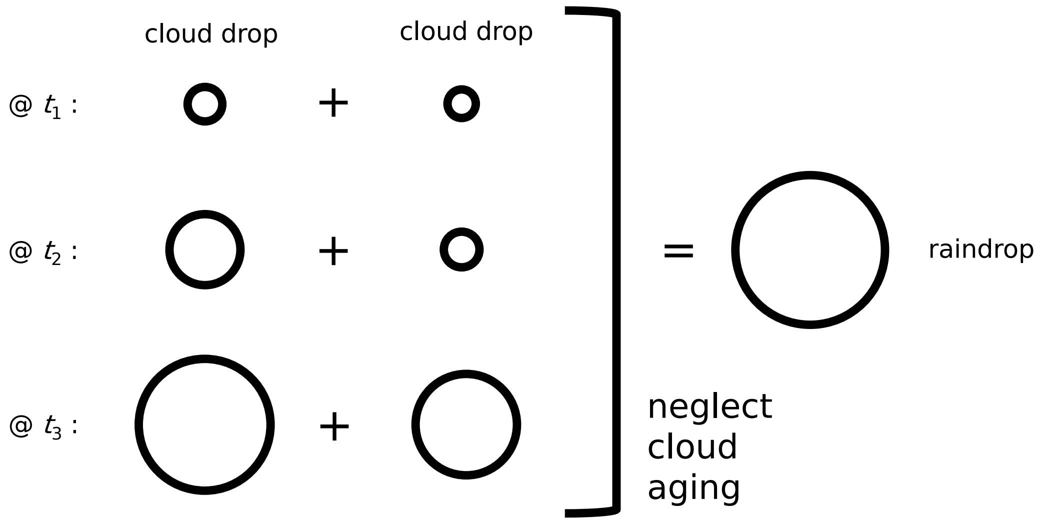


SCHEMATIC.

If cloud aging is slow relative to drop lifetime against evaporation, warm clouds will not rain.

e.g., Seifert & Stevens (2010), Feingold et al. (2013)

MICRO



2

MACRO

NASA

Are shared CMIP assumptions about **autoconversion** an **important** structural error in climate models?

Do we need to kill the flawed but resilient autoconversion paradigm?

Test CMIP6 autoconversion assumptions via

1) in situ observations
2) process model (LES) CPE framework

.
.
.

n) CMIP-class global model

LES = large eddy simulation
CPE = calibrated physics ensemble

1) Is the neglected aging regime important? Test with observations!

Use in situ DSD observations from HOLODEC instrument

- measure drop radii (5-1000 µm) in ~10 cm^{-3} volume

in warm marine boundary layer clouds

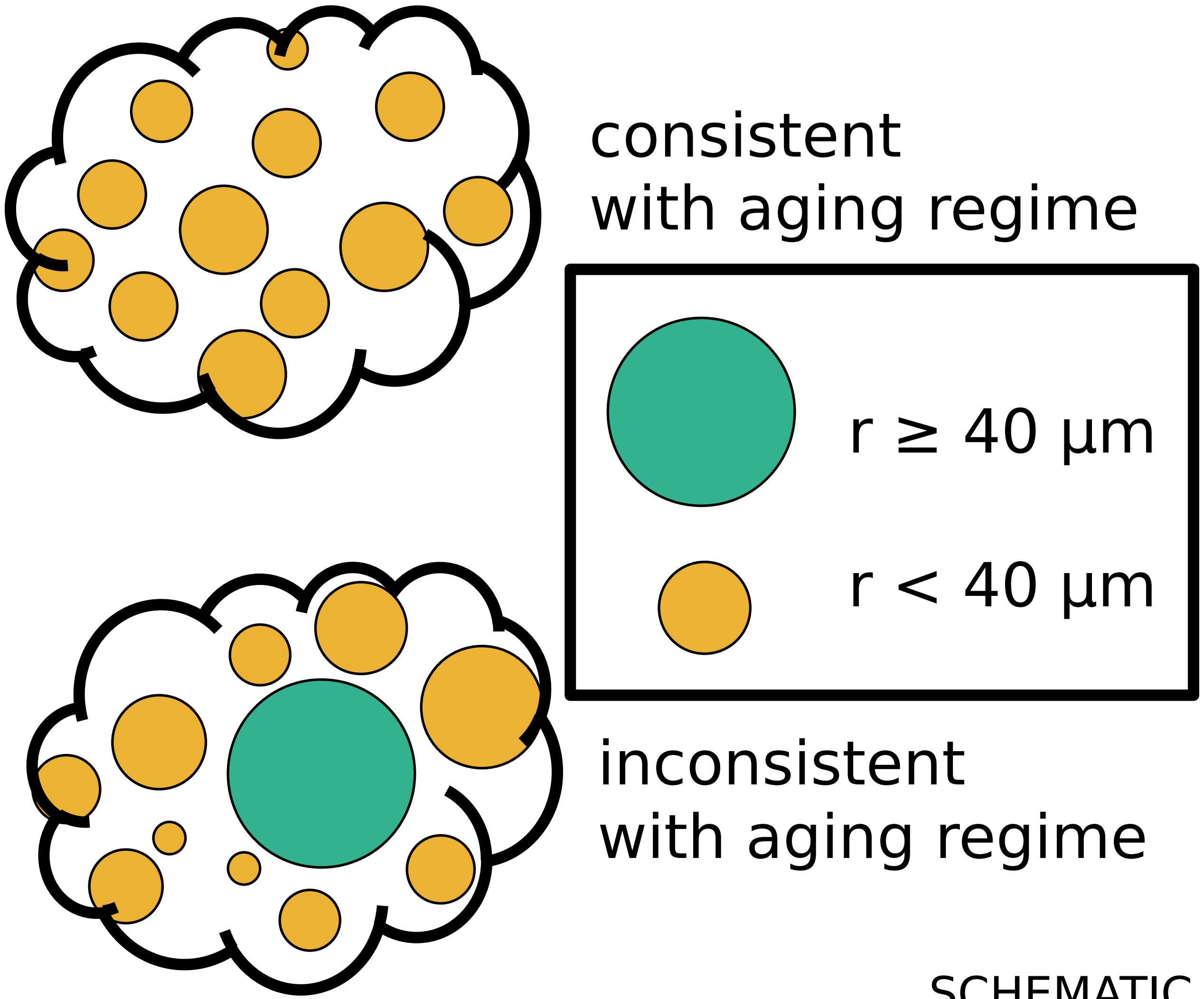
- ACE-ENA (North Atlantic)
- CSET (East Pacific)

Susanne Glienke

HOLODEC PI: Raymond Shaw, HOLODEC data processing: Susanne Glienke

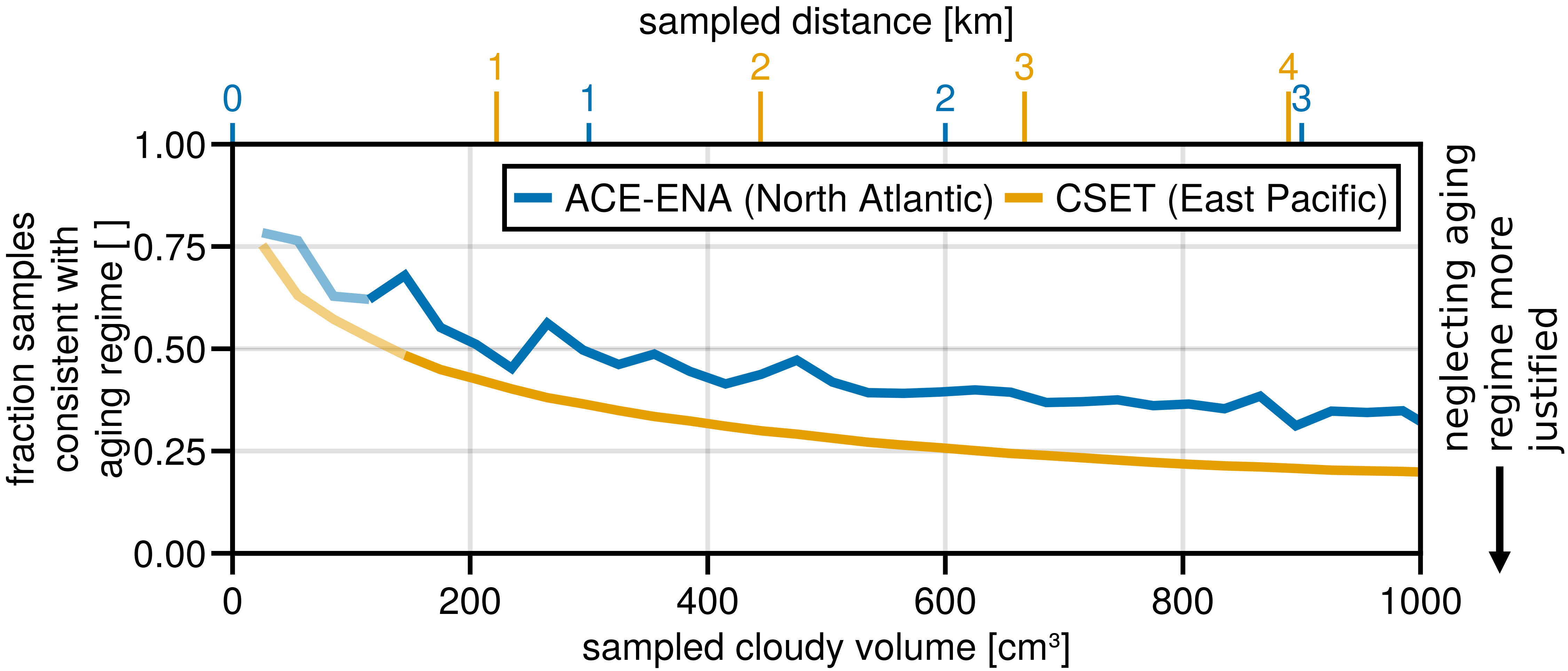
How to assess aging regime with only "snapshots" of cloud microphysical state?

- Drops of r ≳ 40-60 μm have exited highly nonlinear collisional growth regime
- Cloudy air samples with 1+ drop of r ≥ 40 μm are not consistent with being in aging regime



SCHEMATIC.

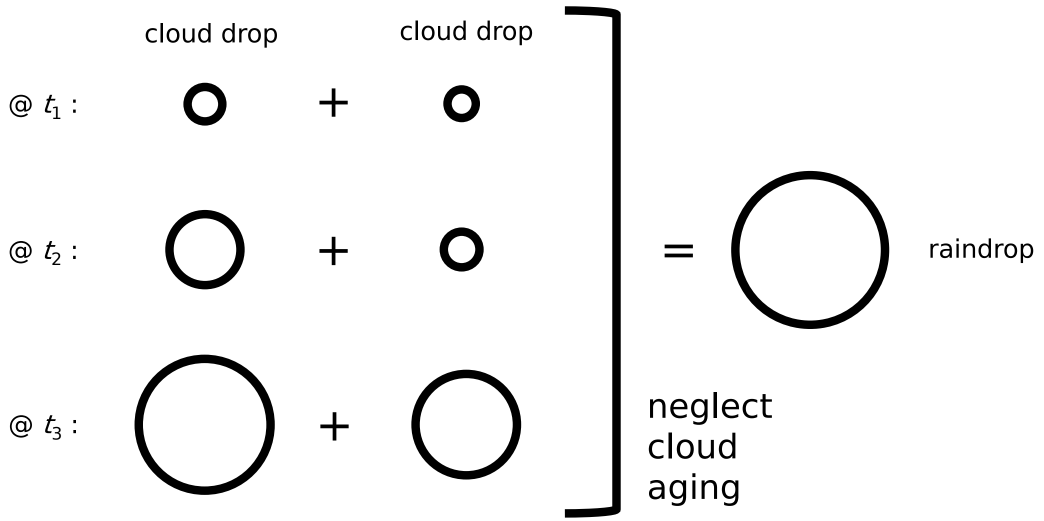
DSD observations are consistent with a frequently occurring aging regime.



sampled volume – spatial averaging tradeoffs

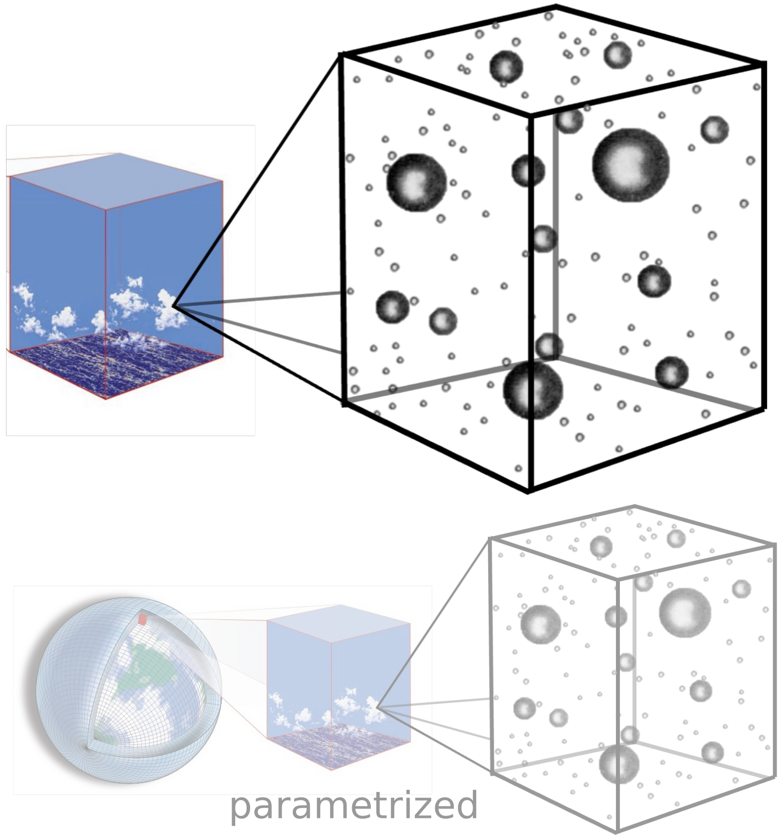
2) Attributing structural error to autoconversion via CPE framework in LES

MICRO



2

(more) MACRO

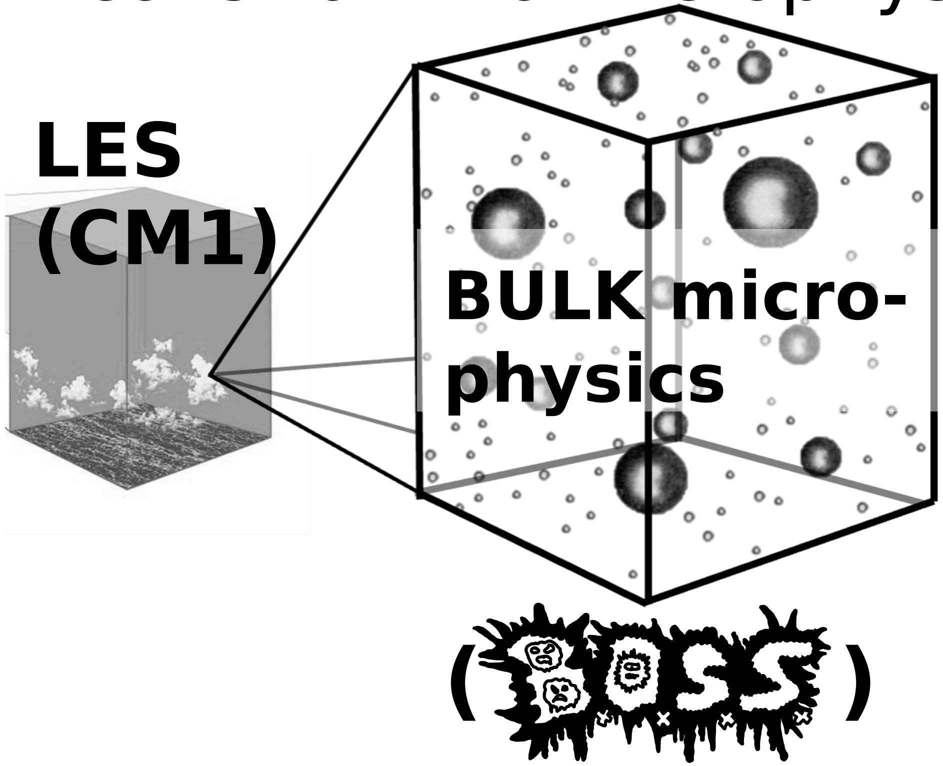


adapted from Tapio Schneider/Kyle Pressel/Momme Hell/Caltech + Pruppacher & Beard (1970)

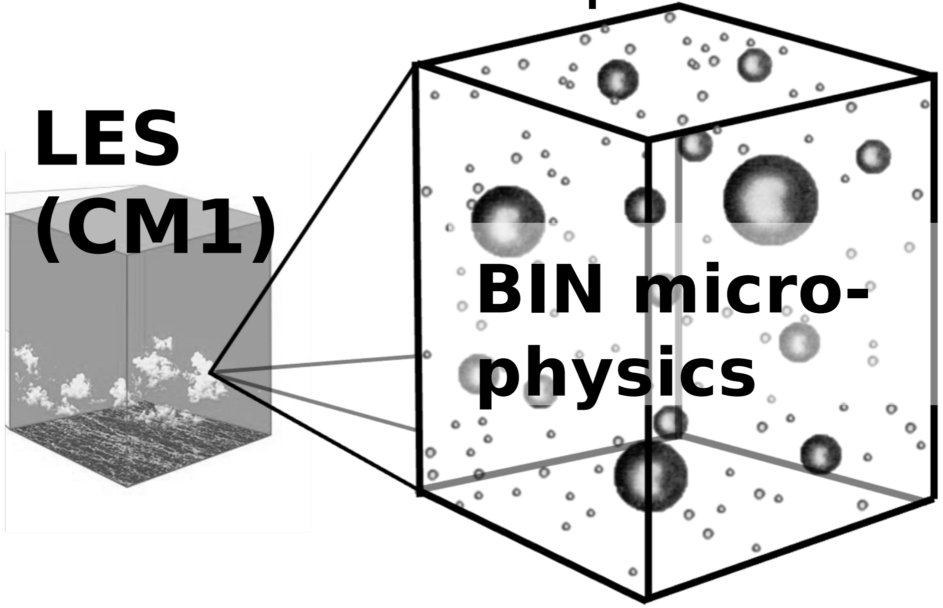
We constrain a CMIP-like bulk mp in LES based on a more complex bin mp using ML-enabled Bayesian inference.

similar workflow discussed by Ken Carslaw & Greg Elsaesser yesterday

constrain 16 microphysics (mp) parameters



based on a more complex model



(TAU)

CM1: *Bryan & Fritsch (2002)*
TAU: *Tzivion et al. (1987,1989), Feingold et al. (1988)*

CMIP-like bulk microphysics scheme (similar process rate forms)

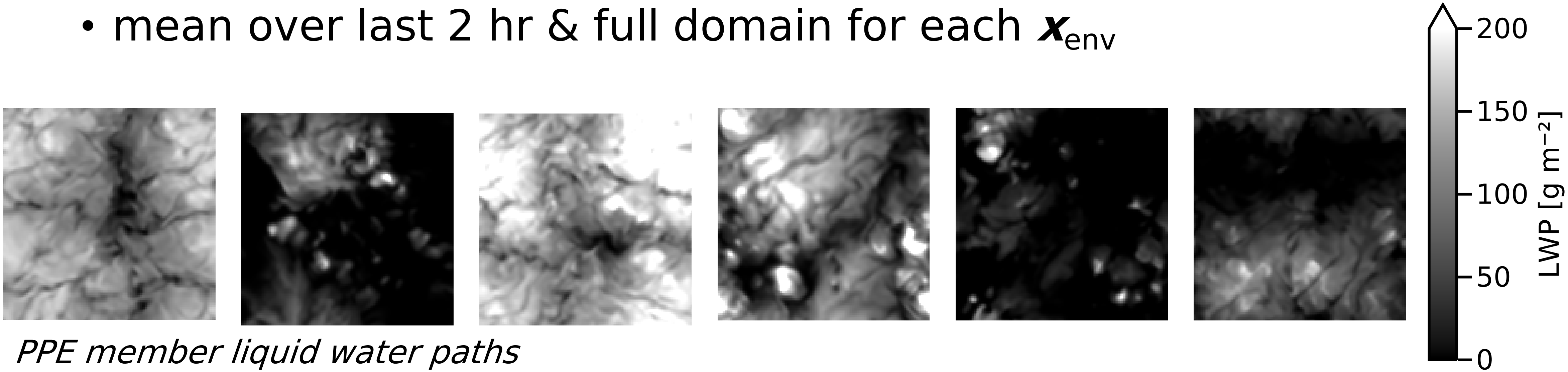
- warm 2 moment, 2 category (cloud & rain) bulk scheme
- power laws for collision coalescence & sedimentation velocity
  - 16 constrainable parameters
  - $\mathbf{R_{auto} = a\, q_1^{b}\, n_1^{2-b}}$
- other processes & numerical implementation follow P3 *Morrison & Milbrandt (2015)*

part of BOSS framework by Hugh Morrison, Marcus van-Lier Walqui, Sean Santos

Morrison et al. (2020), van Lier-Walqui et al. (2020)

Constraining “observations”: mean end state properties from 135 bin mp LES stratocumulus cases.

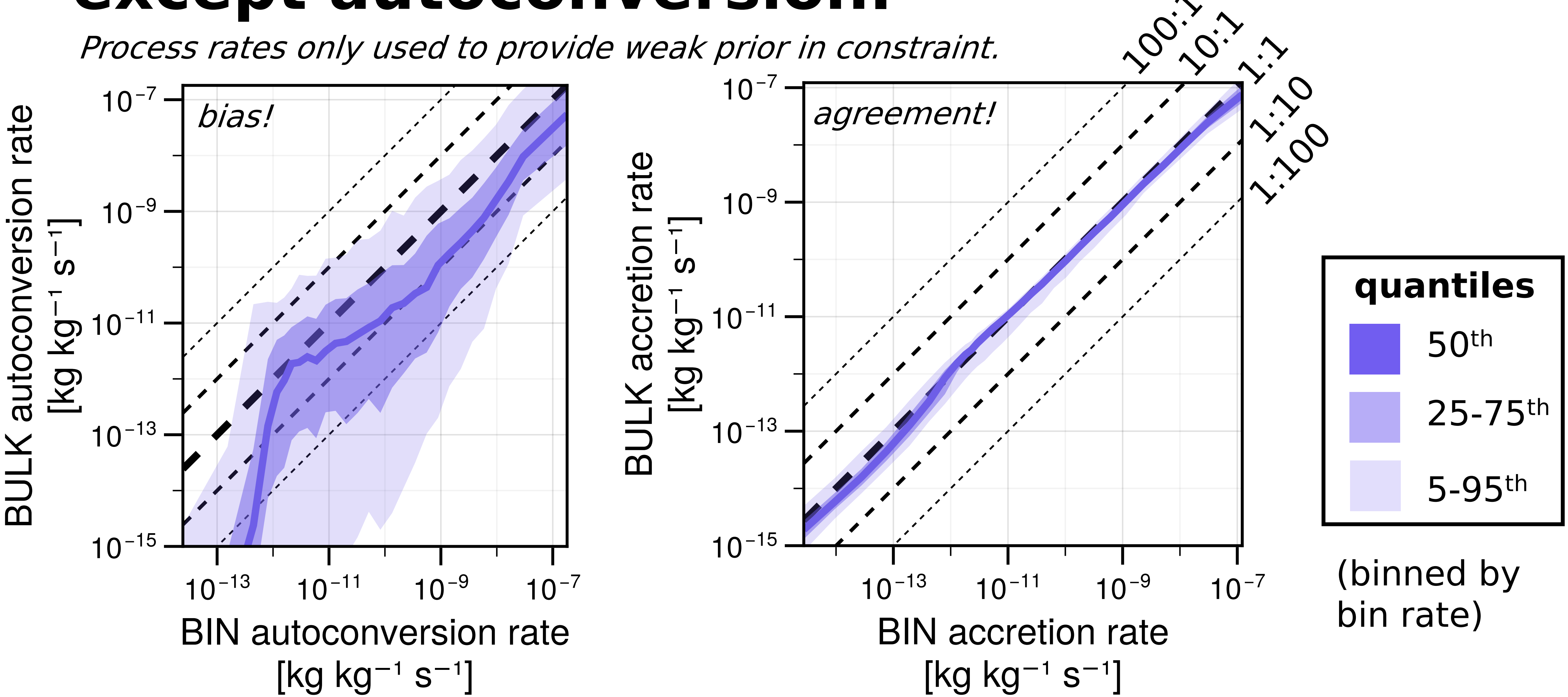
- 135 marine stratocumulus cases with variable $\boldsymbol{x}_{\text{env}}$
  - based on DYCOMS II RF 02 *Ackerman et al. (2009)*
  - varied environmental conditions $\boldsymbol{x}_{\text{env}}$:
    background aerosol + initial water & temperature profiles
    Feingold et al. (2016), Glassmeier et al. (2019)
- Observations: mean LWP & surface rain rate
  - mean over last 2 hr & full domain for each $\boldsymbol{x}_{\text{env}}$



PPE member liquid water paths

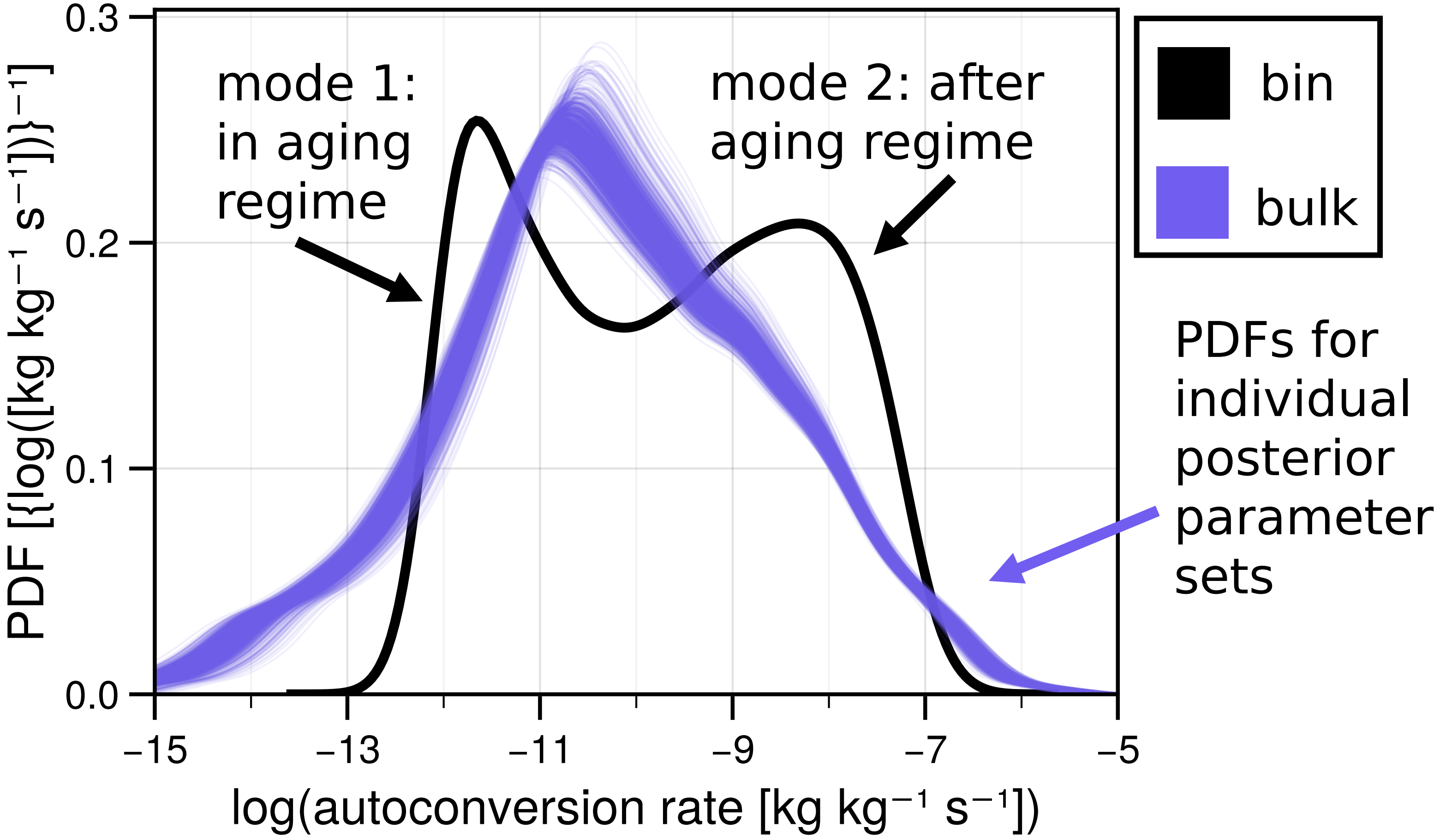
Process rates for constrained bulk scheme largely agree with bin rates—except autoconversion.

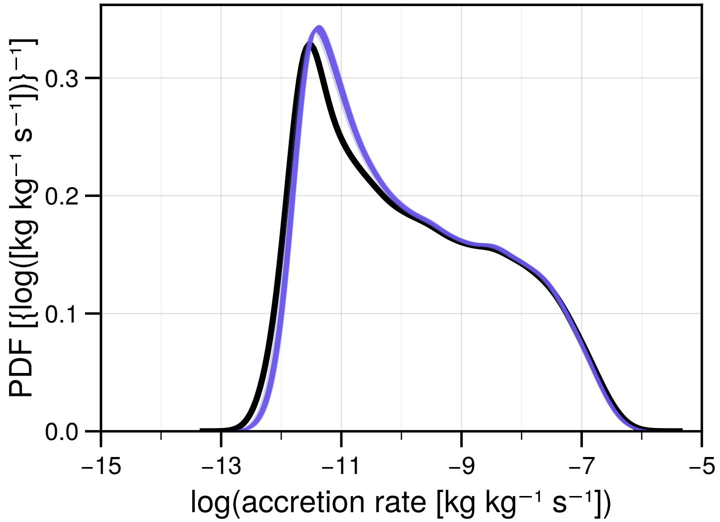
Process rates only used to provide weak prior in constraint.



(binned by bin rate)

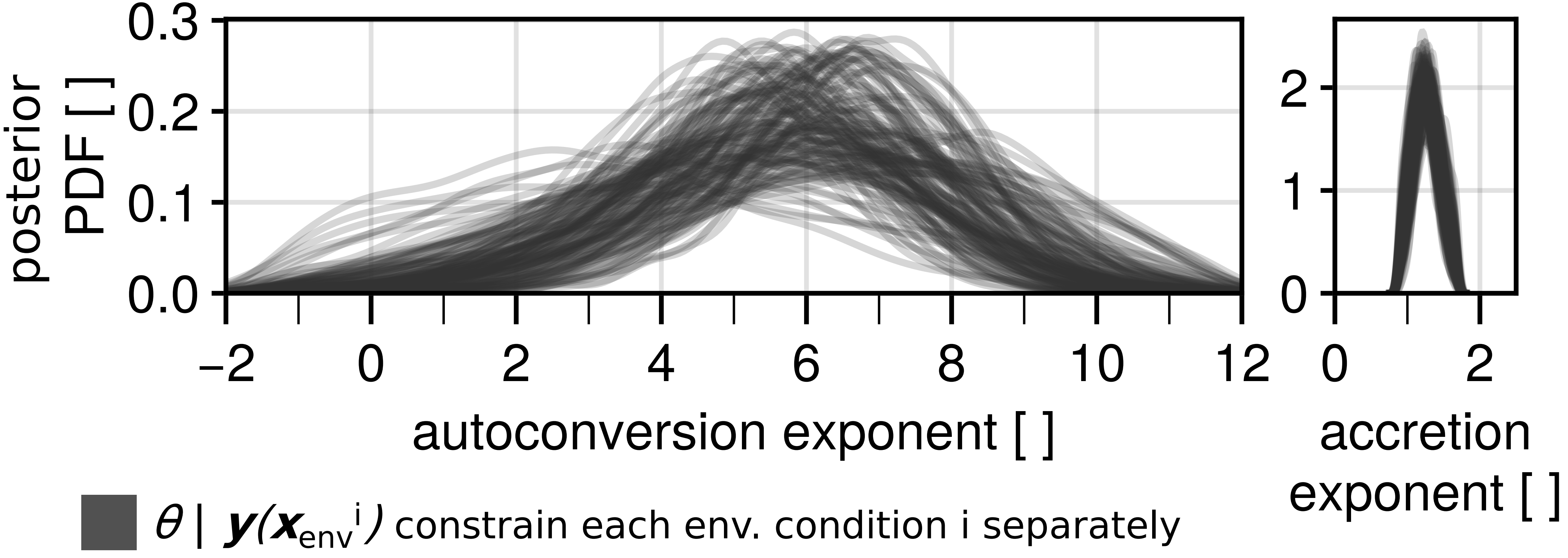
The constrained power law autoconverstion rate PDF straddles in/after cloud aging regime.





other process rate PDFs similar

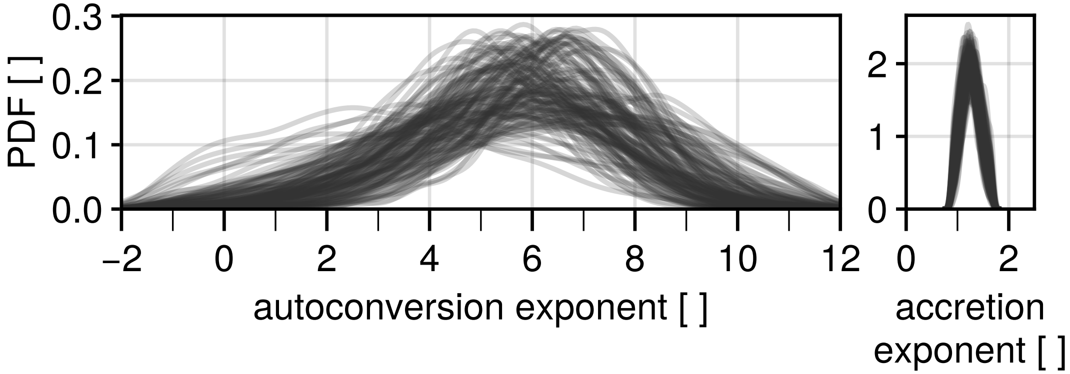
Constraint of autoconversion exponent parameter is the most sensitive to $\boldsymbol{x}_{\mathrm{env}}$.

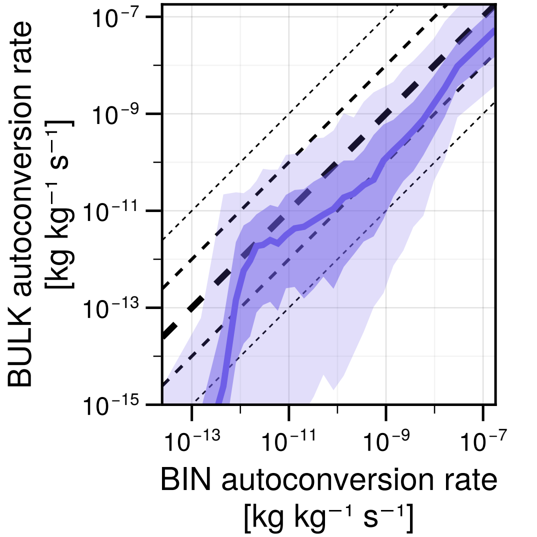


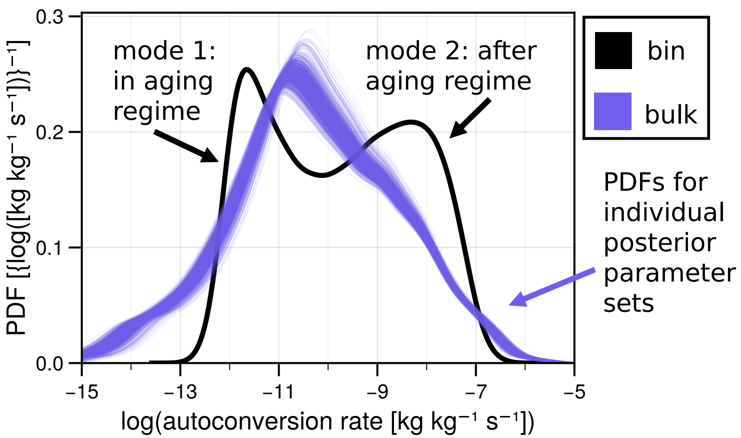
suggests insufficient complexity in autoconversion "process"

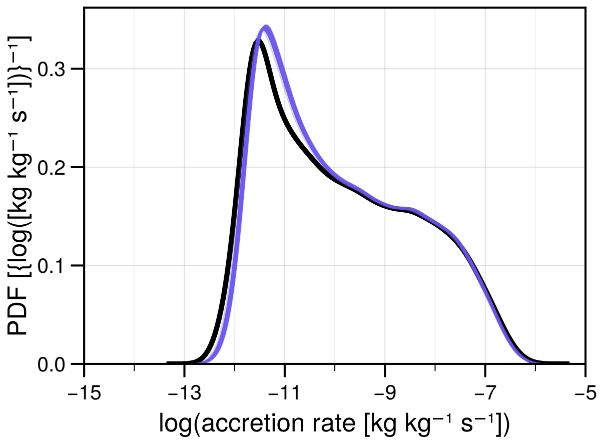
Golaz et al. (2007); Williamson et al. (2015)

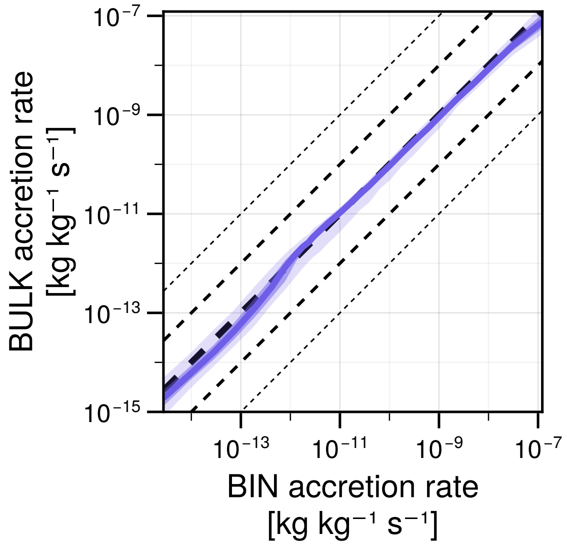
Autoconversion repeatedly emerges as a source of structural error.











Future: many strategies to improve early stages of parameterized collisional growth!

change process functional form, add prognostic variable(s), change prognostic variables

- 2 category
  - add stochasticity *Stanford et al. (2019), Vukicevic et al. (2022)*
  - add memory ***Seifert & Beheng (2001)****, Koren & Feingold (2012), Chiu et al. (2021)*
  - add third cloud category variable *Igel et al. (2022) ADD*
- 1 category
  - remove artificial categories & track full liquid DSD properties *Kogan & Belochitski (2013), Igel et al. (2022), Hu & Igel (2024)*
- 3 category
  - add drizzle category *Lüpkes et al. (1989), Saleeby & Cotton (2004), Sant et al. (2013*

additional considerations: other microphysical processes, numerical implementation, subgridscale variability, computational cost, coupling to other physics modules

Is it time to kill the flawed but resilient autoconversion paradigm?

- CMIP6 models share fundamental assumptions in their microphysics parameterizations
  - Autoconversion, their representation of early stages of collisional growth (needed to initiate warm rain), neglects cloud aging
- Are shared CMIP assumptions about autoconversion an important structural error in climate models?
- We add 2 lines of evidence to suggest we should be concerned about these assumptions
  - in situ observations
  - process model (LES) CPE framework

c. 1963 - 20??

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