Broadening of adiabatic droplet spectra through eddy hopping: Polluted versus pristine environments

Wojciech W. Grabowski,

with Kamal Kant Chandrakar and Hugh Morrison

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submitted to JAS

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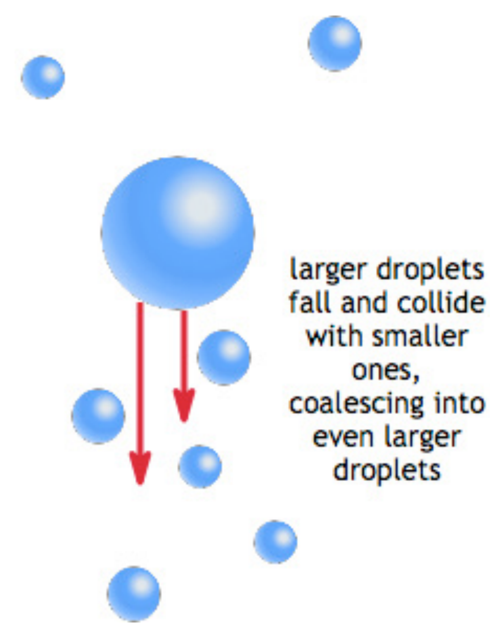
Width of the cloud droplet spectrum in warm clouds is an important parameter.

It affects transfer of solar radiation through a cloud and collision/coalescence that leads to rain formation…

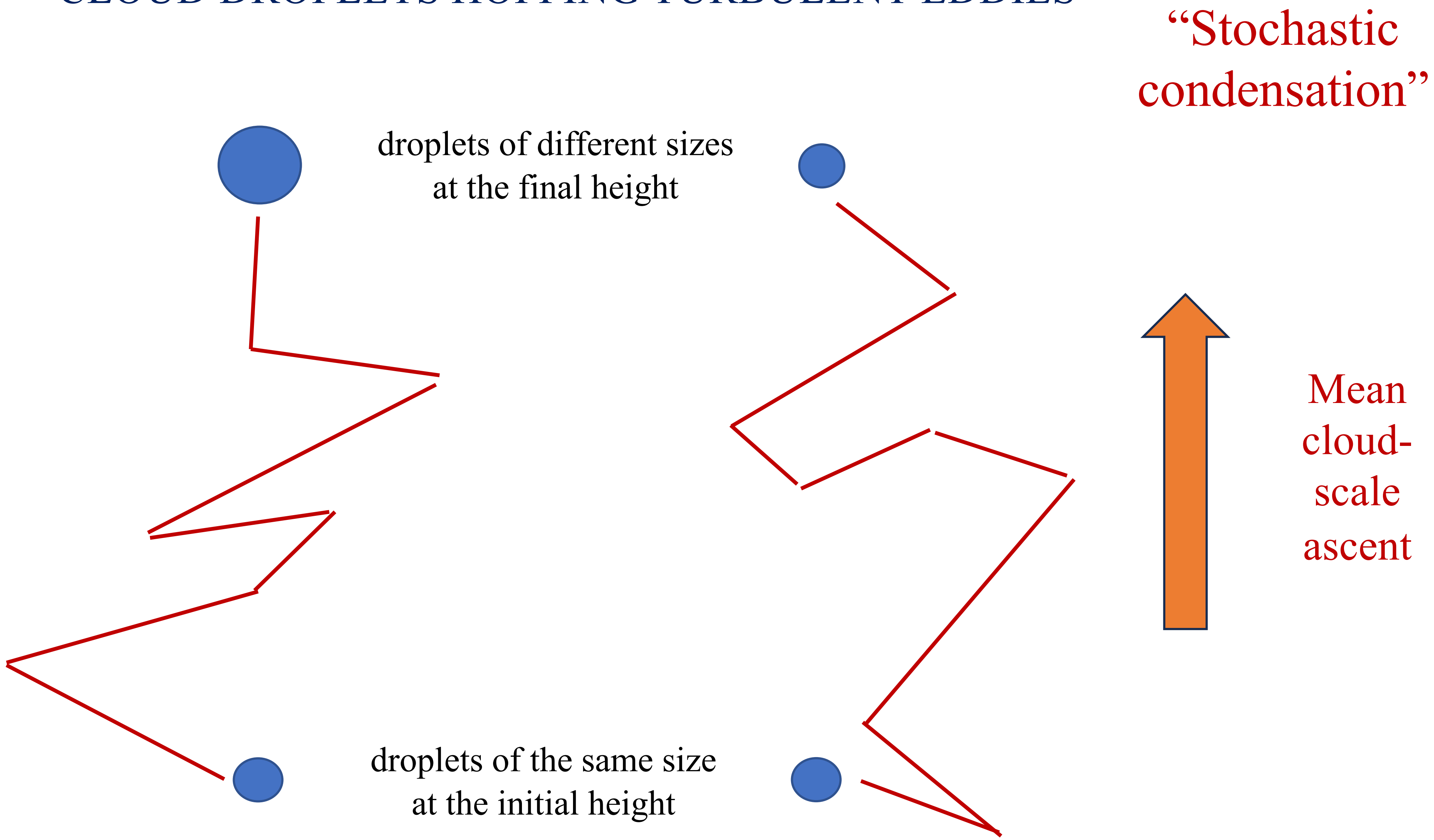
Effective radius r_e:

$$r_e = \frac{\int_0^\infty \pi r^3 \cdot n(r)\, dr}{\int_0^\infty \pi r^2 \cdot n(r)\, dr}$$

Gravitational droplet collisions:



CLOUD DROPLETS HOPPING TURBULENT EDDIES



Observed and/or simulated adiabatic droplet spectra in different CCN environments:

Fitzgerald, PhD dis., 1972: comparison between observed and simulated droplet spectra (sic!)

Jensen et al. *J. Atmos. Sci.*, 1985: CCOPE project: observed (and simulated) droplet spectra

Miles et al. *J. Atmos. Sci.*, 2000: database of observed stratus cloud droplet size distributions

Brenguier and Chaumat, *J. Atmos. Sci.*, 2001, adiabatic broadening theory and observations

Yum and Hudson *Atmos. Res.* 2005: observed and simulated droplet spectra from several projects

Pawlowska et al. *Geophys. Res. Let.*, 2006: observed droplet spectra from ACE2 field project

Prabha et al. *J. Geophys. Res.*, 2012: observed droplet spectra from CAIPEEX field project

Chandrakar et al. *Proc. Nat. Ac. Sci.* 2016: Pi chamber observations

Thomas et al. *JAMES*: 2019: Pi chamber observations and simulations

Grabowski *J. Atmos. Sci.*, 2020: Pi chamber simulations with monodisperse dry CCN

Grabowski et al. *J. Atmos. Sci.*, 2024: Pi chamber simulations with CCN distribution

Chandrakar et al. *J. Atmos. Sci.* 2020, 2021, 2022: cumulus congestus simulations

Grabowski et al. *J. Atmos. Sci* 2025: 1D model of eddy hopping with superdroplets

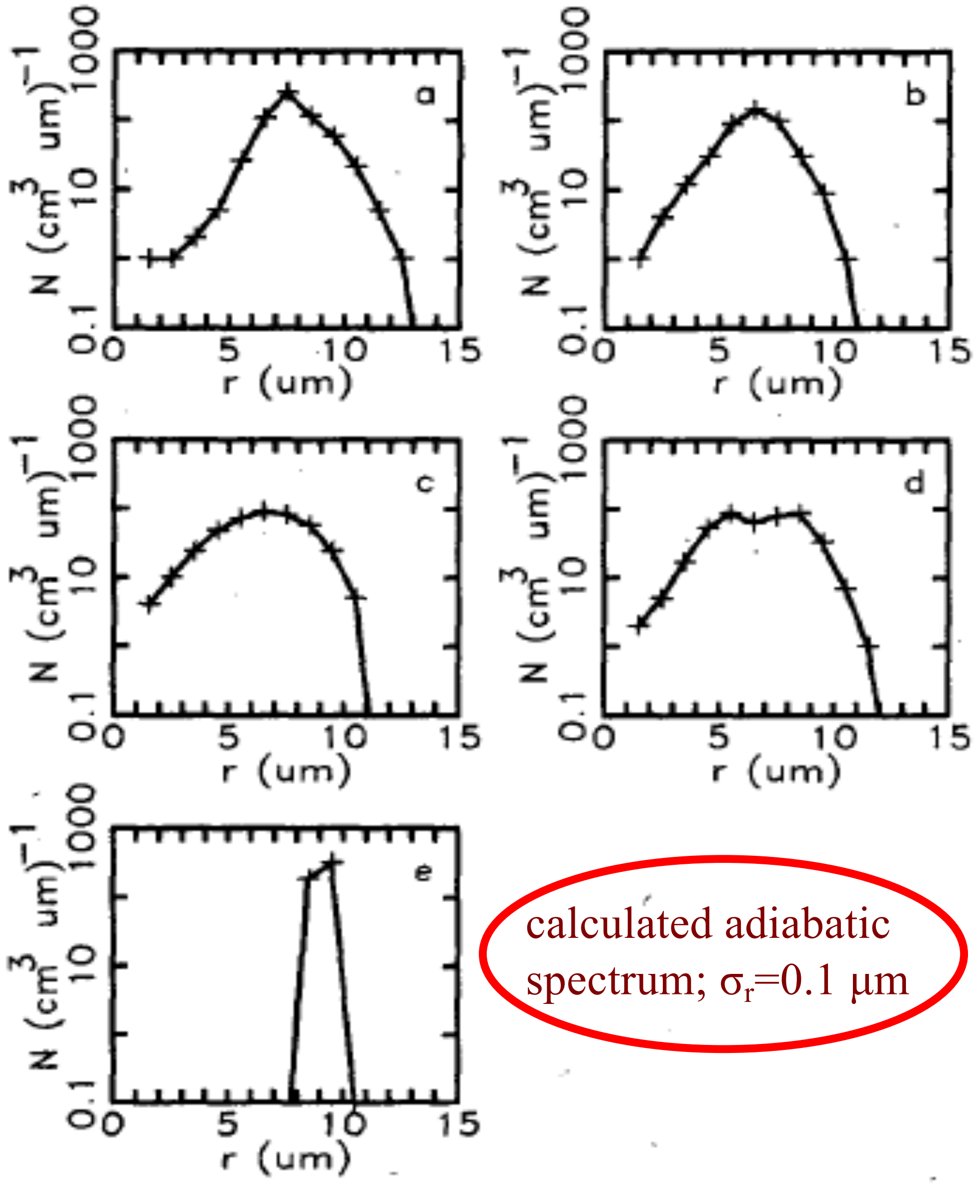
Observed close-to-adiabatic cloud droplet spectra in a cumulus averaged over ~100 m (1 Hz, FSSP data) around 1 km above the cloud base:

observed, adiabatic fraction AF ≈ 1; σ_r=1.3 μm

observed, AF ≈ 0.8; σ_r=1.3 μm

observed, AF ≈ 0.8; σ_r=1.8 μm

observed, AF ≈ 1; bimodal



calculated adiabatic spectrum; σ_r=0.1 μm

(Jensen et al. *JAS* 1985)

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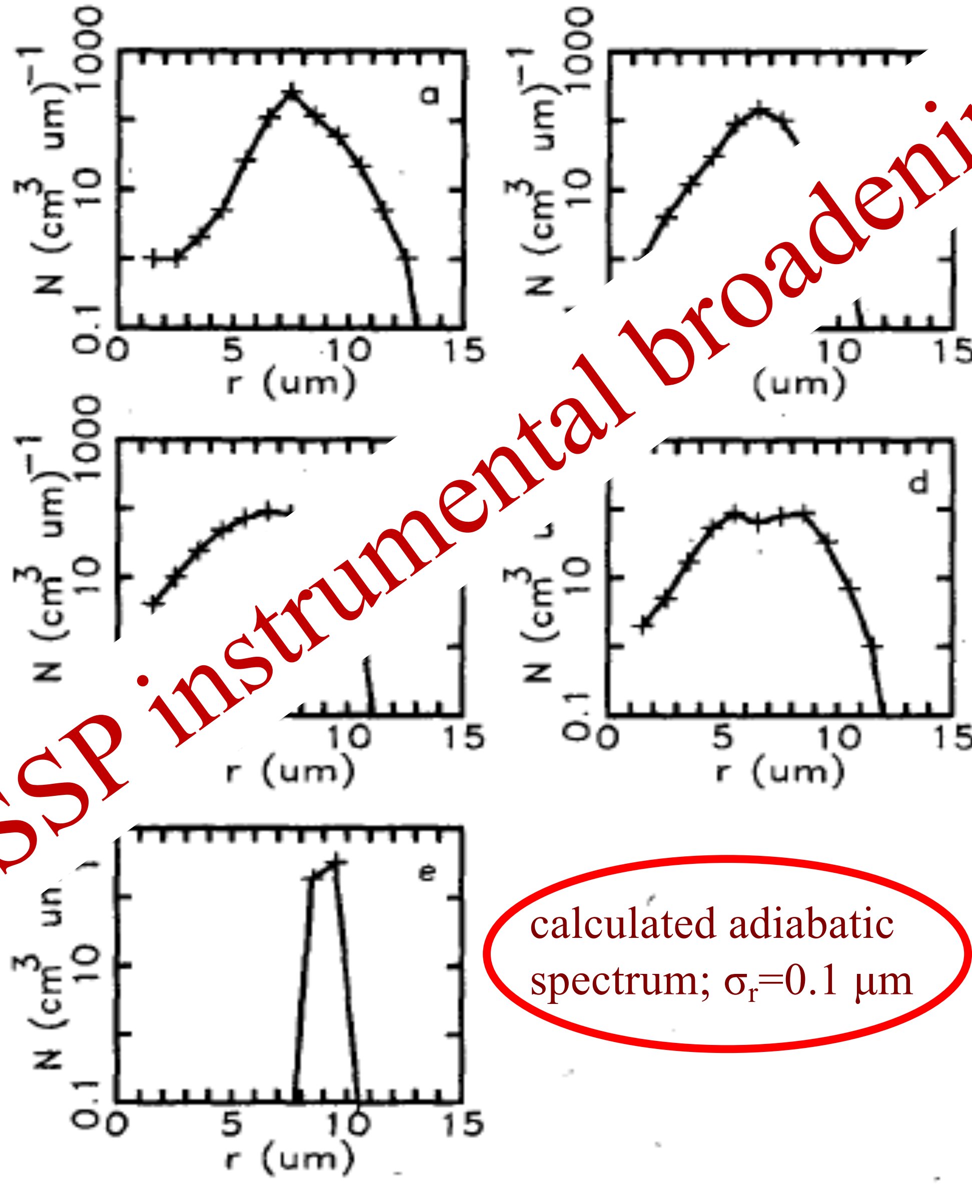


FSSP instrumental broadening?

calculated adiabatic spectrum; σ_r=0.1 μm

(Jensen et al. *JAS* 1985)

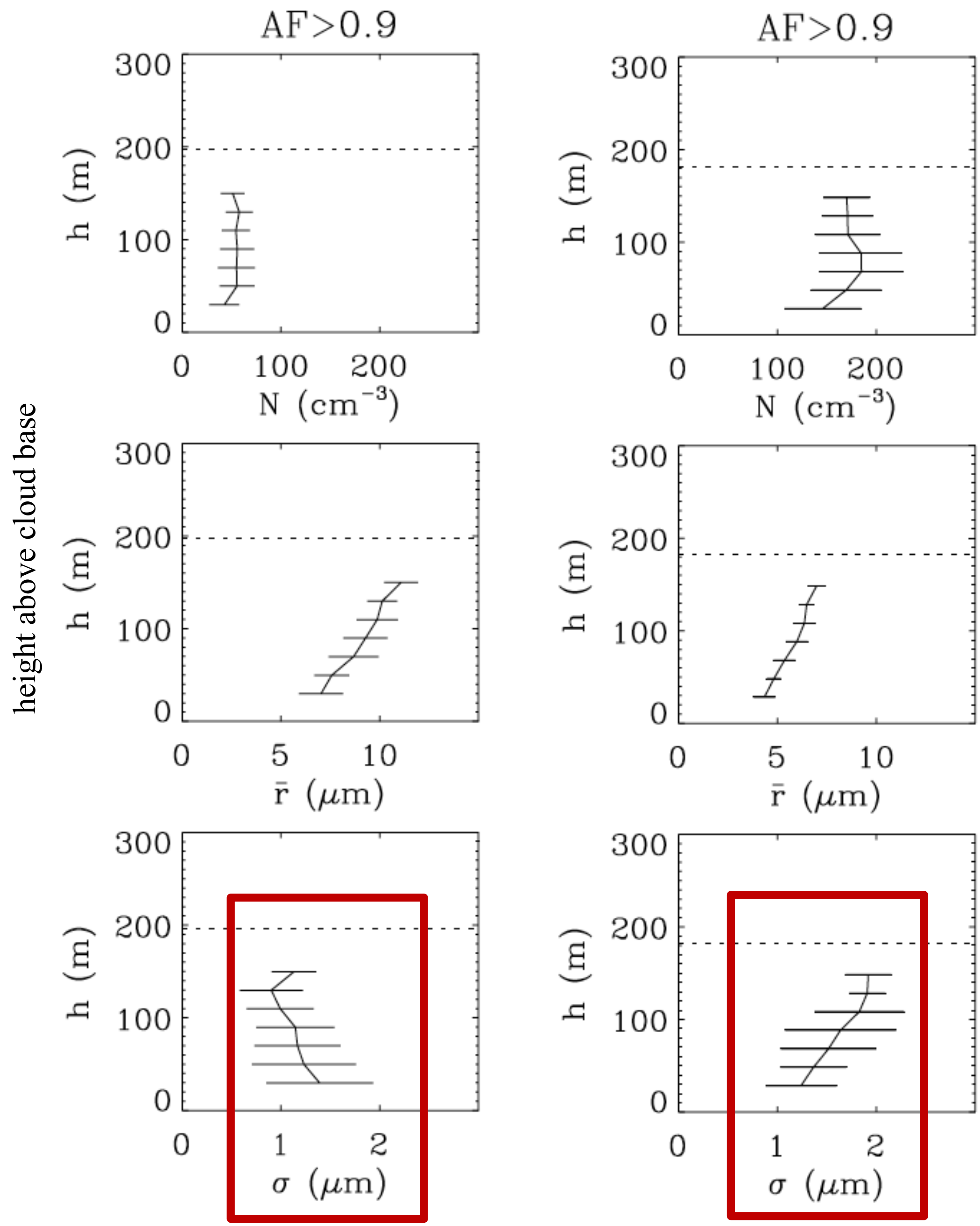
Observed close-to-adiabatic cloud droplet spectra in stratocumulus averaged over ~10m (10 Hz, Fast FSSP; Pawlowska et al. *GRL* 2006):

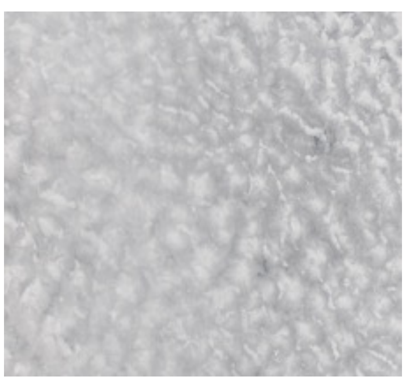
"almost adiabatic"

droplet concentration

mean radius

spectral width





Yum and Hudson *Atmos. Res*. 2005

Field projects

Table 2

Same as Table 1 except the parameters are measured or estimated averages of all data for each of the eight different field projects or air masses

Project name	N_{CCN} (cm^{-3})	S_{eff} (%)	N_c(ave) (cm^{-3})	MD (μm)	σ_c (μm) diameter
Sc	1411	0.100	312	10.9	4.6
Xc	1061	0.040	183	8.0	3.7
Sm	359	0.095	150	15.0	4.8
A	202	0.150	58	13.6	4.3
Xm	195	0.310	86	11.9	4.9
S2	191	0.180	70	13.9	5.0
F	122	0.080	41	15.0	4.8
S1	32	0.920	28	17.1	6.7

The S_{eff} is the effective supersaturation (Hudson, 1984) based on the average droplet concentration, N_c(ave).

Adiabatic parcel simulations

Table 1

Average CCN concentrations at 1% S (N_{CCN}) for the eight field projects or air masses used in this study and cloud microphysical parameter values [maximum supersaturation (S_{max}), activated cloud droplet concentration (N_c), cloud droplet mean diameter (MD) and standard deviation of cloud droplet diameter (σ_c)] obtained from the Robinson (1984) model runs after 150 m ascent with 50 cm s^{-1} updraft

Project name	N_{CCN} (cm^{-3})	S_{max} (%)	N_c (cm^{-3})	MD (μm)	σ_c (μm) diameter
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Xc	1061	0.236	542	10.5	1.8
Sm	359	0.313	220	14.4	1.3
A	202	0.489	127	17.3	1.1
Xm	195	0.477	158	16.1	1.0
S2	191	0.493	130	17.2	1.0
F	122	0.517	98	18.9	1.0
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diameter

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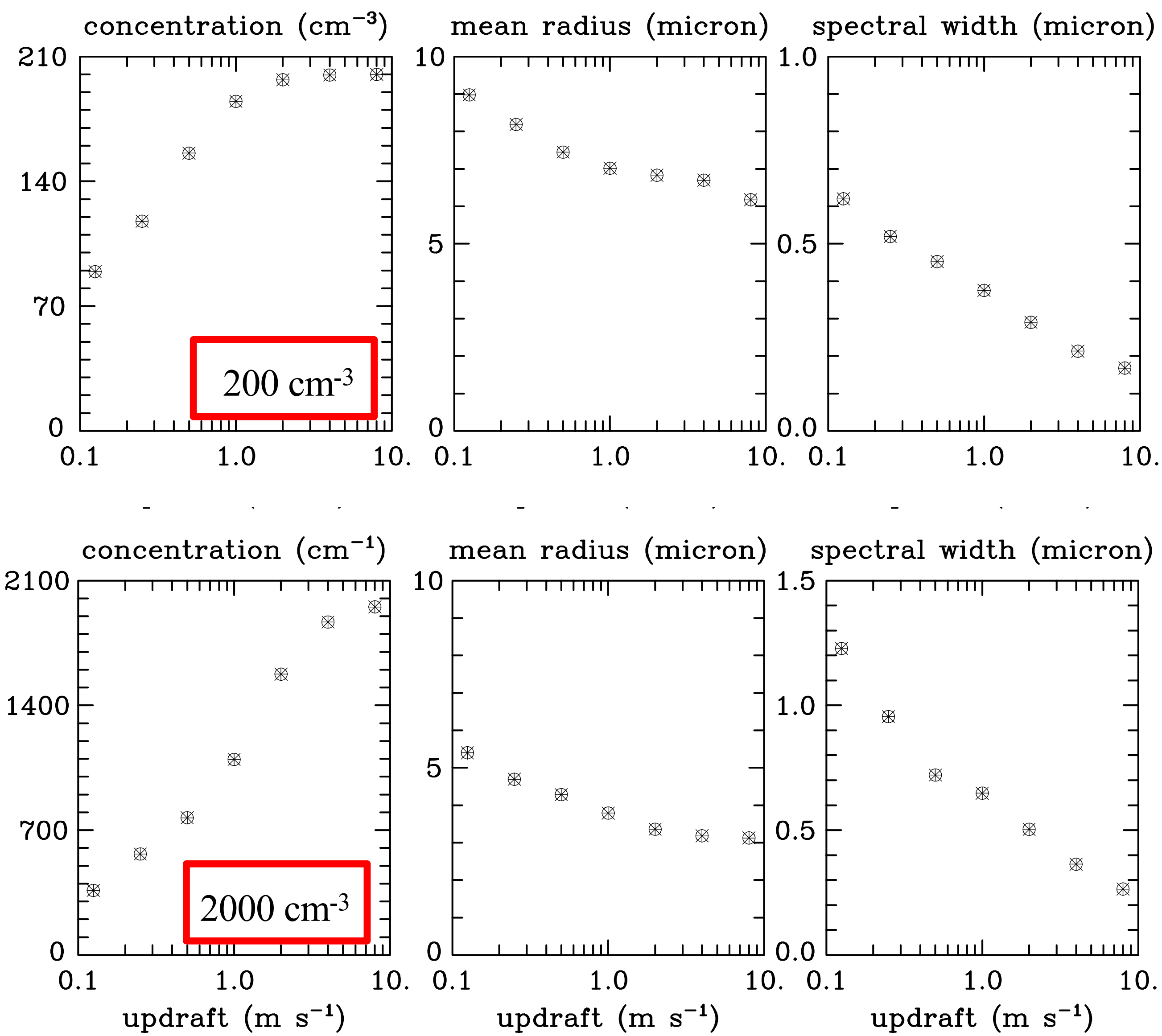
diameter

Larger values in observations (but instrumental uncertainty).
Opposite trends in observations and adiabatic parcel simulations?

Adiabatic parcel simulations with different updrafts: larger widths in polluted cases



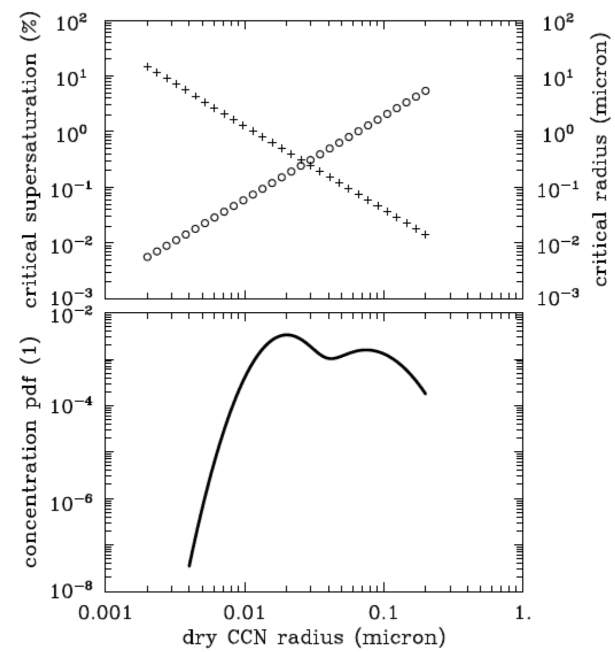
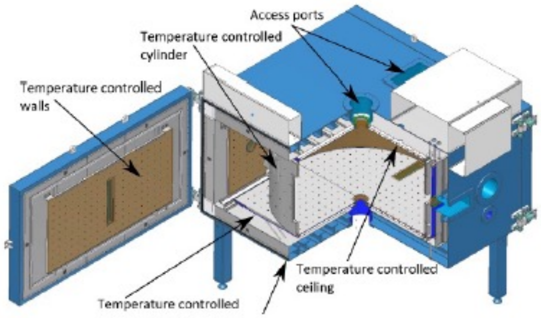


FIG. 2. (bottom) CCN distribution applied in simulations described in this paper. The distribution is not shown down to 2 nm (0.002 μm) as the values are smaller than the lowest value on the vertical axis. (top) Critical (activation) supersaturation (plus symbols) and critical (activation) radius (circles) as a function of the CCN dry radius. Horizontal scale is as in the bottom panel.

Grabowski et al. *J. Atmos. Sci*. 2022

Pi chamber (Michigan Tech. U.) observations and simulations



$\dot{n}_a$, cm^{-3} min^{-1}	$n_{a,int}$, cm^{-3}	n, cm^{-3}	$\bar{d}$, μm	diameter σ_d, μm
1	2	21.3	16.6	6.7
2	10	76.9	15.1	5.7
4	36	201.2	12.7	4.5
12	372	564.6	8.6	2.4
1,515	22,000	1,944.3	7.6	2.1

Observations: Chandrakar et al. *Proc. Nat. Ac .Sci.* 2016: monodisperse dry CCN

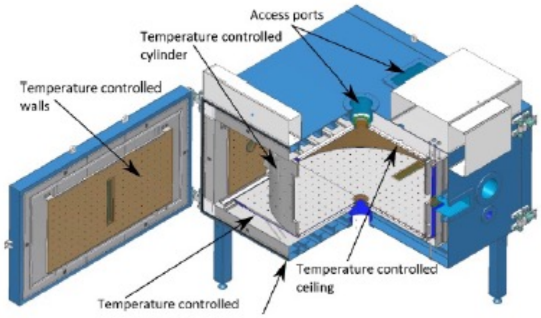
TABLE 1. Cloud water mixing ratio including all droplets (q_c) and its mean spatial distribution standard deviation (in parentheses), TKE, mean droplet concentration, mean radius, and mean spectral width (the last three derived including only droplets with radius larger than the critical for each CCN bin) averaged over the last 10 min of model simulations.

	q_c (std dev) (mg kg^{-1})	TKE (10^{-3} m^2 s^{-2})	Concentration (cm^{-3})	Radius (μm)	Spectral width (μm) radius
C40	50.4 (34.8)	2.85	30.5	5.7	3.1
C200	60.1 (47.3)	3.07	107	4.0	2.1
C1000	53.8 (52.8)	3.23	300	2.6	1.4
CROK	39.6 (44.5)	3.32	1330	1.3	0.7

Simulations: Grabowski et al. *J. Atmos. Sci.* 2024: dry CCN distributions

Smaller widths in polluted cases in both observations and simulations: the impact of turbulence?

Pi chamber (Michigan Tech. U.) observations and simulations



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Smaller widths in polluted cases in both observations and simulations: the impact of turbulence?

Can small-scale cloud turbulence explain the width of the droplet spectra in undiluted cloudy volumes?

Can small-scale cloud turbulence explain the width of the droplet spectra in undiluted cloudy volumes?

The two papers that started it all. Other followed…

Microscopic Approach to Cloud Droplet Growth by Condensation. Part I: Model Description and Results without Turbulence

P. A. VAILLANCOURT* AND M. K. YAU

Department of Atmospheric and Oceanic Sciences, McGill University, Montreal, Quebec, Canada

W. W. GRABOWSKI

National Center for Atmospheric Research, Boulder, Colorado

JAS 2001

Microscopic Approach to Cloud Droplet Growth by Condensation. Part II: Turbulence, Clustering, and Condensational Growth

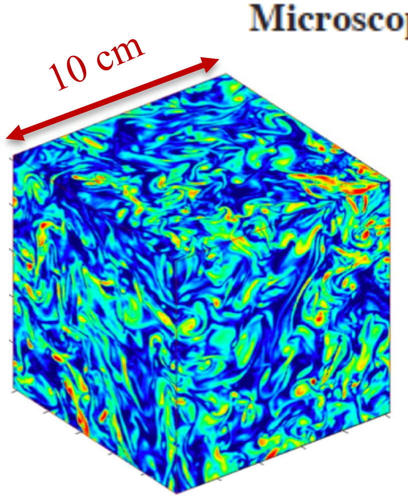
P. A. VAILLANCOURT, M. K. YAU, AND P. BARTELLO

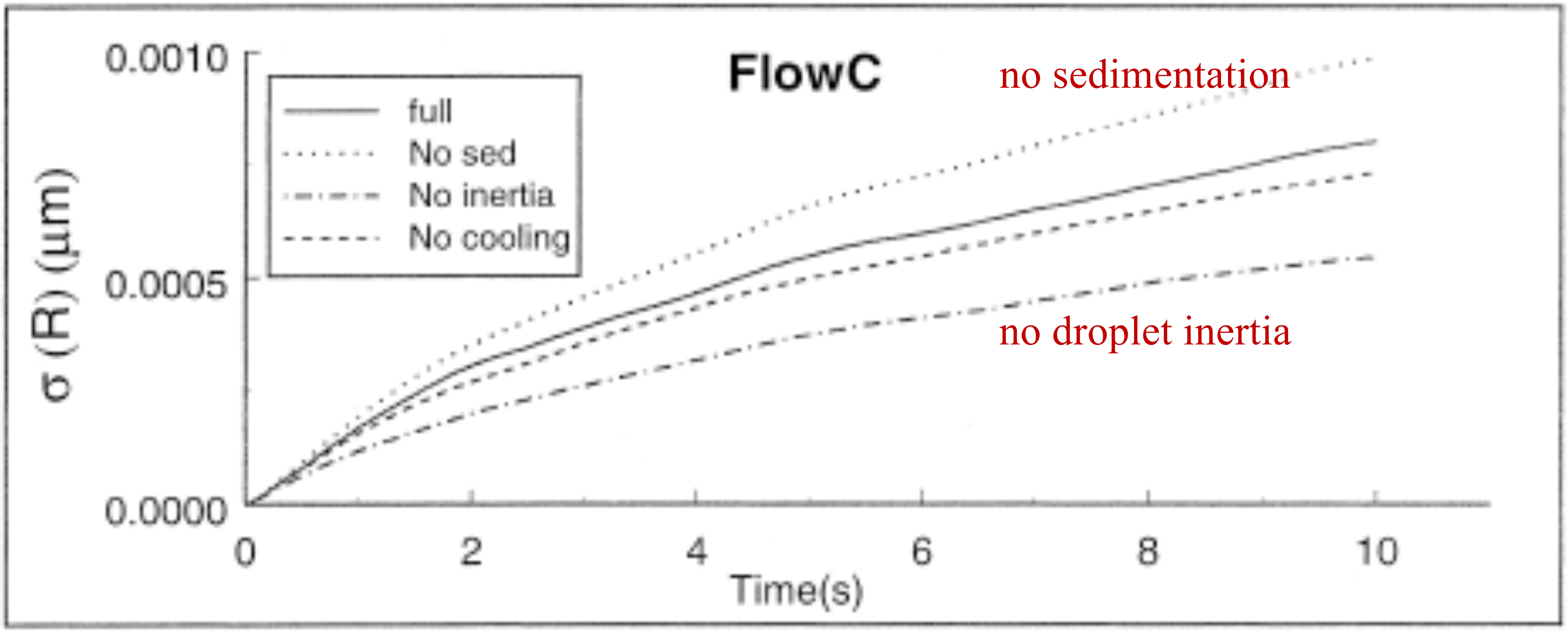
McGill University, Montréal, Québec, Canada

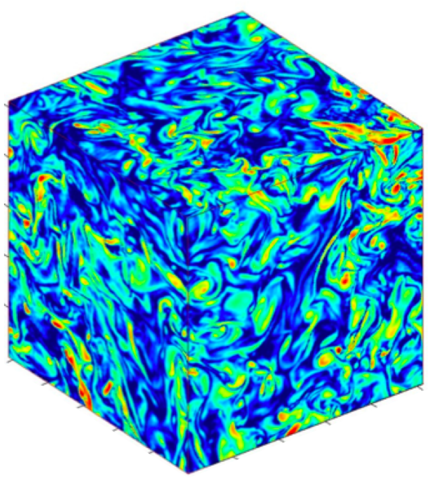
W. W. GRABOWSKI

National Center for Atmospheric Research, Boulder, Colorado

JAS 2002





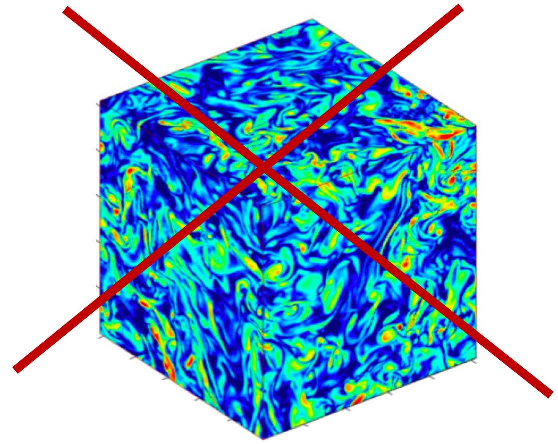


Several subsequent studies
pursued this line of research…
(see a review in Grabowski *JAS* 2025)

Vaillancourt et al. *JAS* 2002

Broadening of Cloud Droplet Spectra through Eddy Hopping: Why Did We All Have It Wrong?

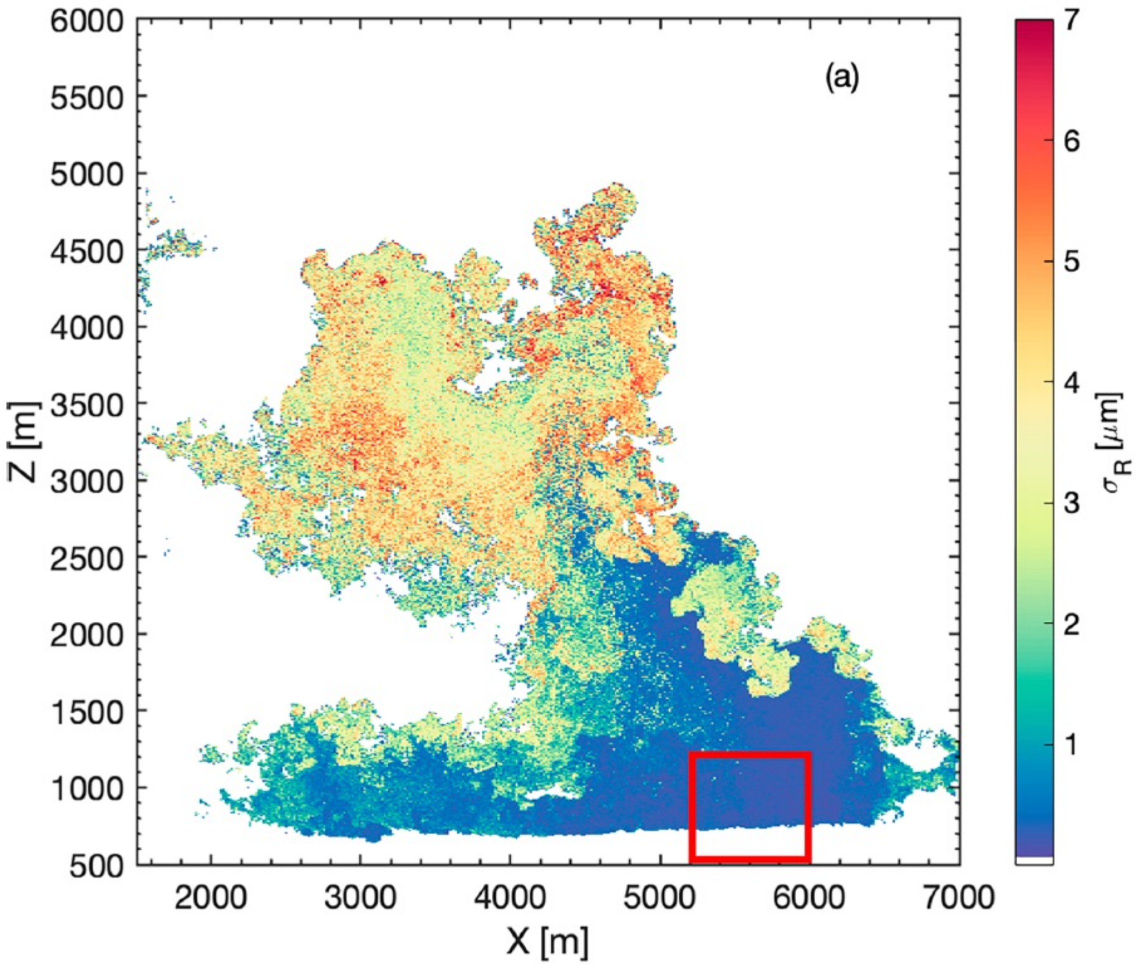
WOJCIECH W. GRABOWSKI[a]
[a] *NSF NCAR, Boulder, Colorado*



DNS-type studies do not really help understanding broadening droplet spectra in adiabatic volumes of natural clouds…

Untangling the Broadening of Adiabatic Cloud Droplet Spectra through Eddy Hopping in a High-Resolution Cumulus Congestus Simulation

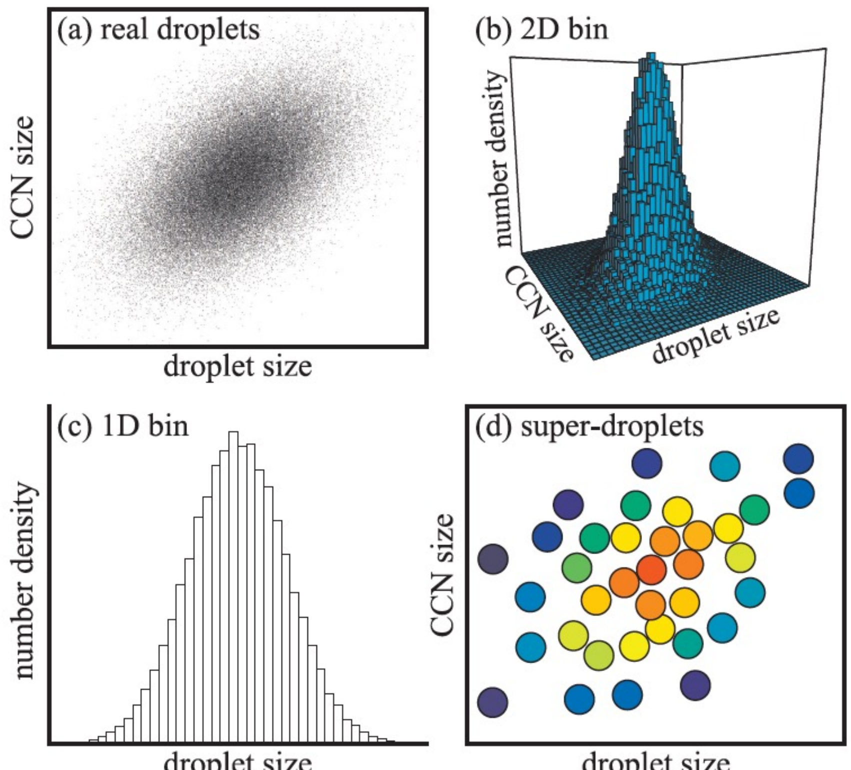
WOJCIECH W. GRABOWSKI,[a] KAMAL KANT CHANDRAKAR,[a] AND HUGH MORRISON[a]
[a] MMM Laboratory, NSF National Center for Atmospheric Research, Boulder, Colorado



Lasher-Trapp et al. (2005) used an elaborate scheme to calculate individual droplet growth along their trajectories through a turbulent cloud.

This is not needed when cloud model applies Lagrangian particle-based microphysics because each superdroplet follows its own trajectory.

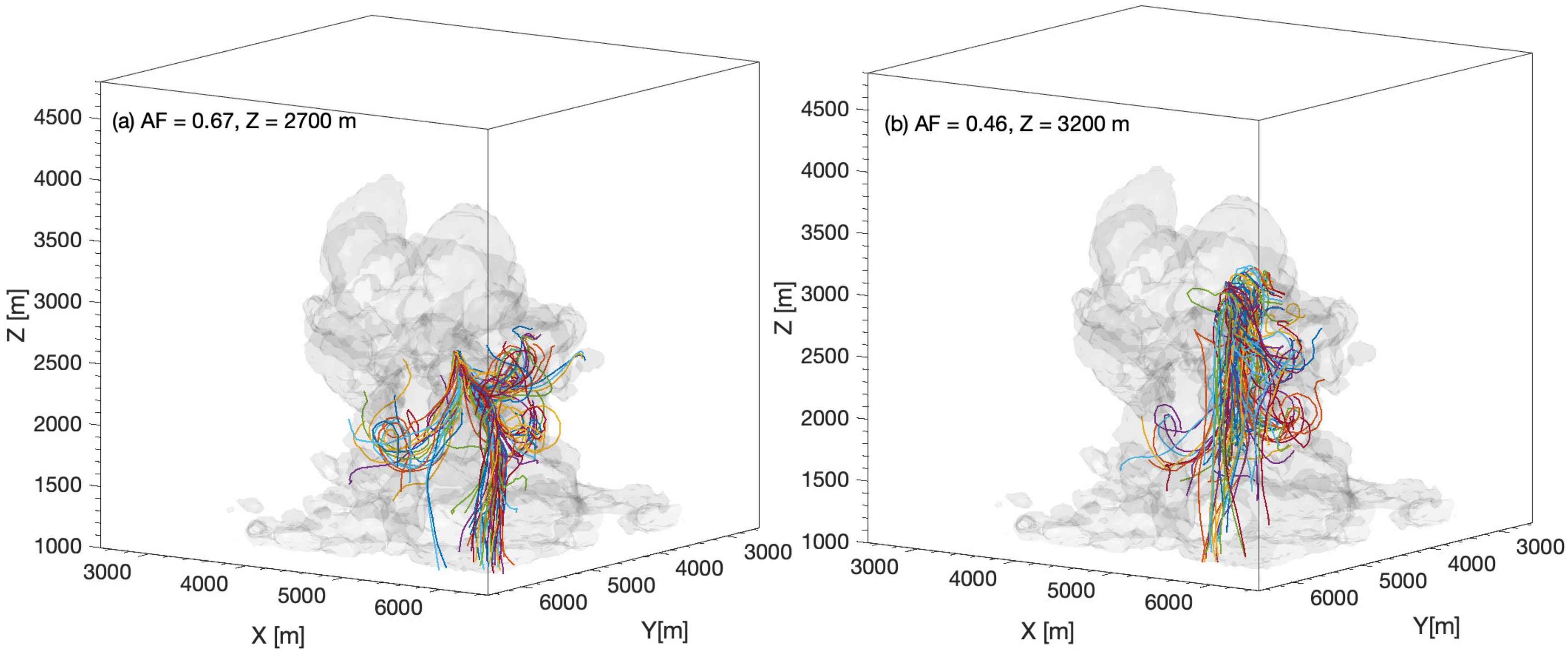
However, high spatial resolution is needed to appropriately simulate the the impact of cloud turbulence on the droplet growth.



blue - low multiplicity
red - high multiplicity

Grabowski et al. *BAMS* 2019

3D cloud simulations applying Lagrangian particle-base methodology, the superdroplet method (Shima et al.)

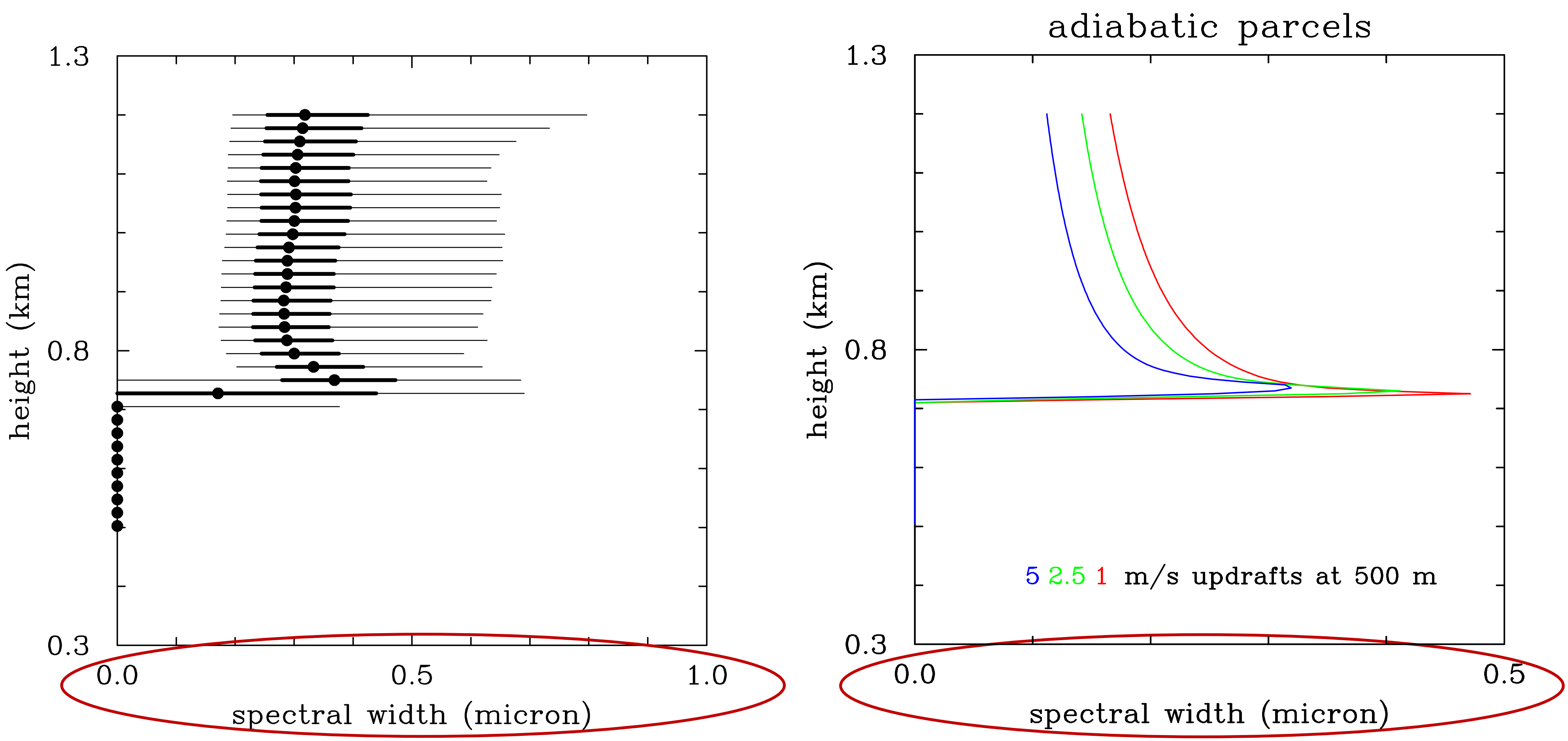


Chandrakar et al. *JAS* 2021

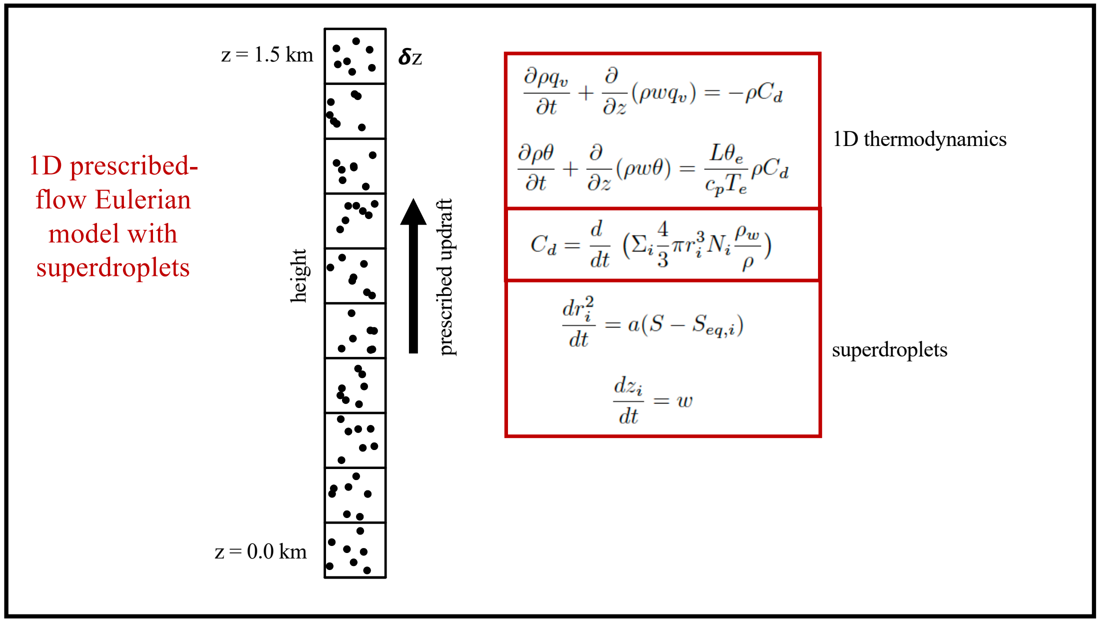
Trajectories of selected "super-droplets" arriving at a given location (different in right and left panels) above the cloud base. Example of "eddy hopping" at the cloud scale…

Can "eddy hopping" in a turbulent cloud lead to the spectral width increase even if there is no cloud dilution (i.e., adiabatic fraction close to 1)?

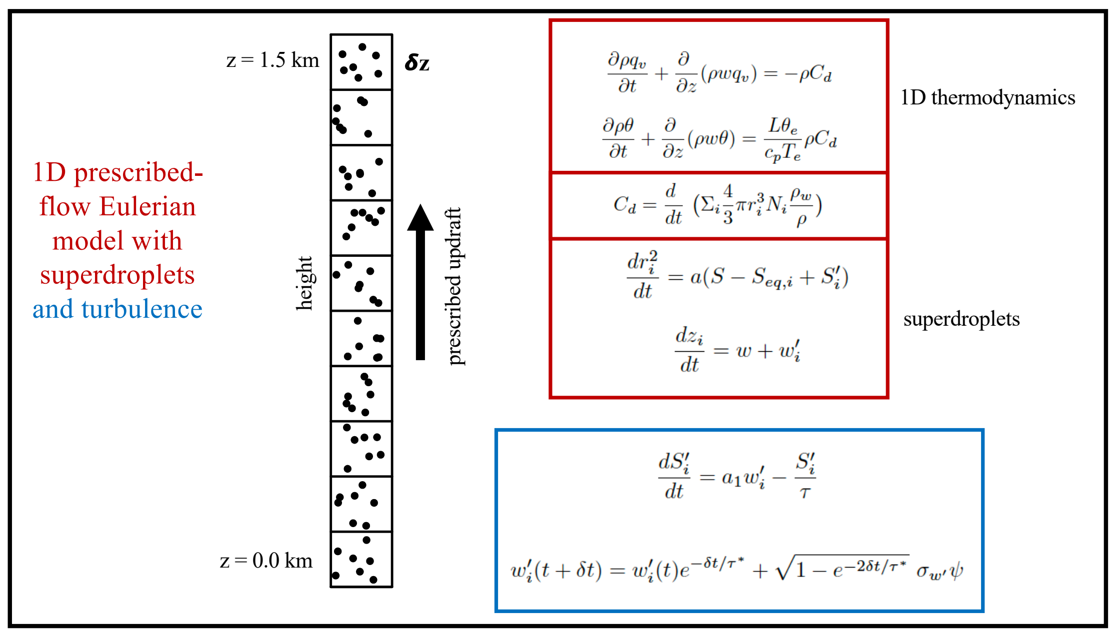
Adiabatic droplet spectra in 3D cloud simulation with polluted dry CCN distributions versus adiabatic parcels:



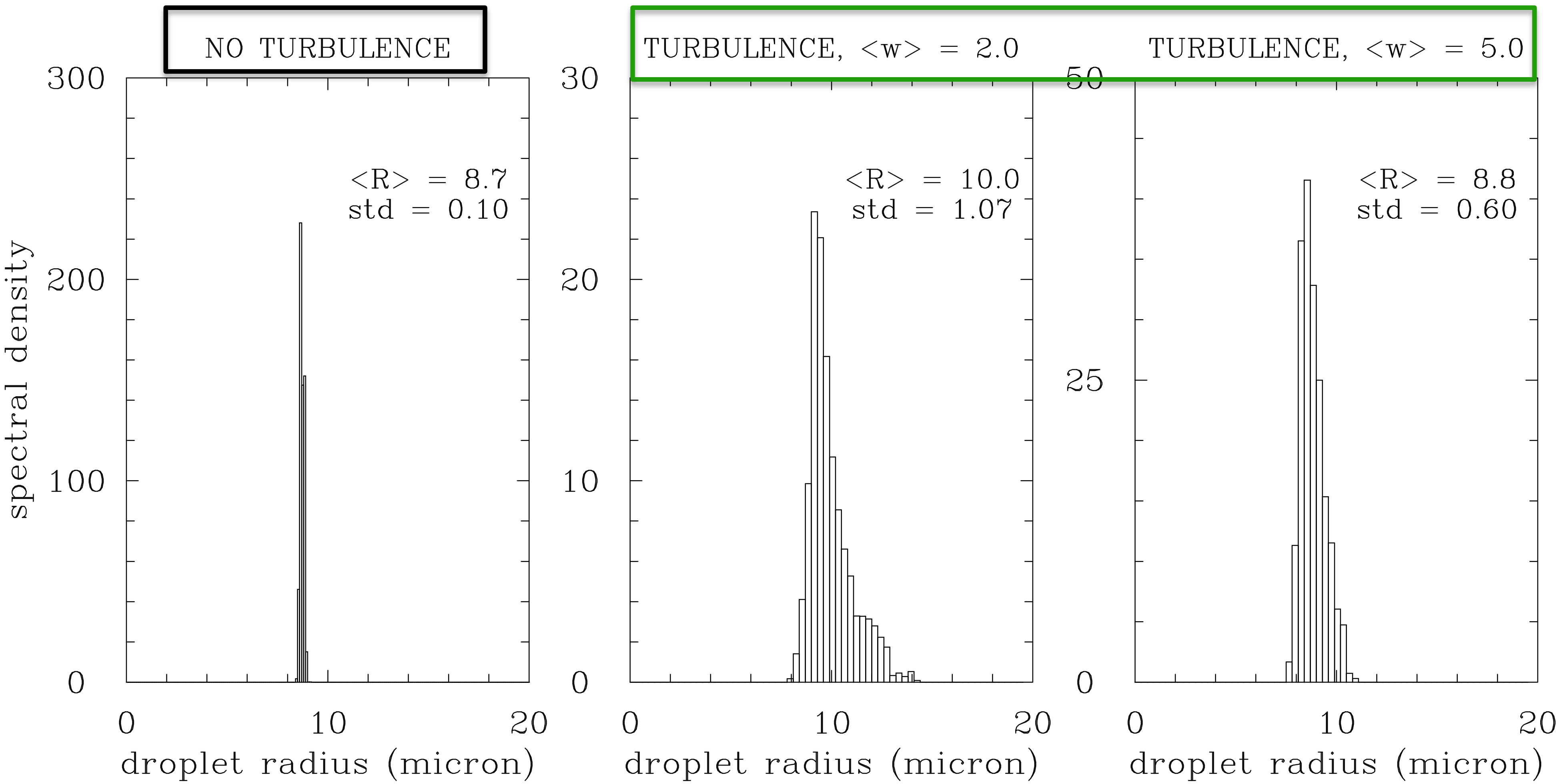
No turbulence: each superdroplet grows in exactly the same supersaturation S



With turbulence: in addition to mean S, each superdroplet experiences turbulence-driven S'



Spectra at 1.5 km height from 1D Eulerian-Lagrangian simulations without and with effects of cloud turbulence (based on 3D simulation conditions).



Using the 1D Eulerian-Lagrangian framework, we address two questions:

How to understand larger spectral widths in observations when compared to adiabatic parcel simulations?

How to understand what seems to be opposite polluted vs pristine trends in observations and adiabatic parcel simulations?

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How to understand larger spectral widths in observations when compared to adiabatic parcel simulations?

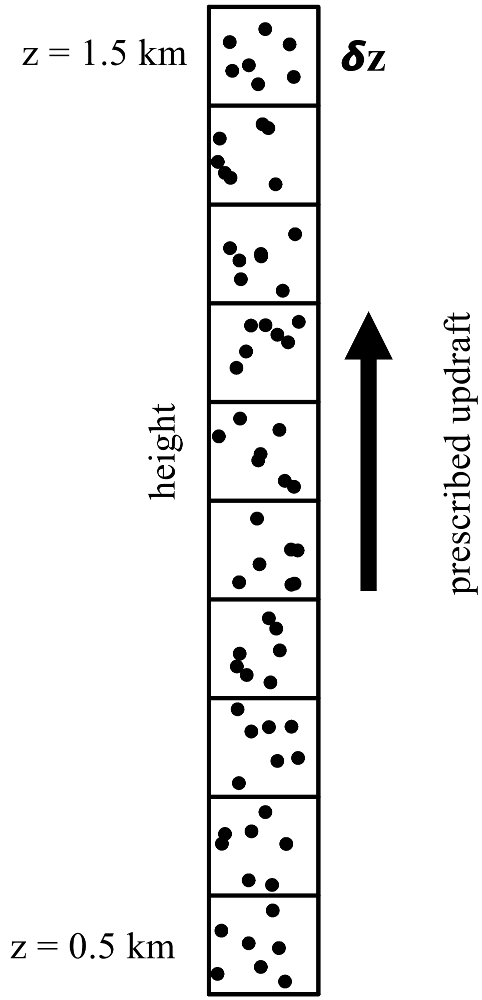
How to understand what seems to be opposite polluted vs pristine trends in observations and adiabatic parcel simulations?

The answer to both questions:

Impact of cloud turbulence on formation and growth of cloud droplets!

No turbulence:

1D prescribed-flow Eulerian model with superdroplets



1D thermodynamics

$$\frac{\partial \rho q_v}{\partial t} + \frac{\partial}{\partial z}(\rho w q_v) = -\rho C_d$$

$$\frac{\partial \rho \theta}{\partial t} + \frac{\partial}{\partial z}(\rho w \theta) = \frac{L\theta_e}{c_p T_e}\rho C_d$$

$$C_d = \frac{d}{dt}\ (\Sigma_i \frac{4}{3}\pi r_i^3 N_i \frac{\rho_w}{\rho})$$

superdroplets

$$\frac{dr_i^2}{dt} = a(S - S_{eq,i})$$

$$\frac{dz_i}{dt} = w$$

No turbulence:

1.5 km deep 1D domain, 300 grid points, constant updraft of 1, 2, and 4 m s^{-1}
dz = 5 m, dt = 0.1 sec (sub-stepping for droplet growth)

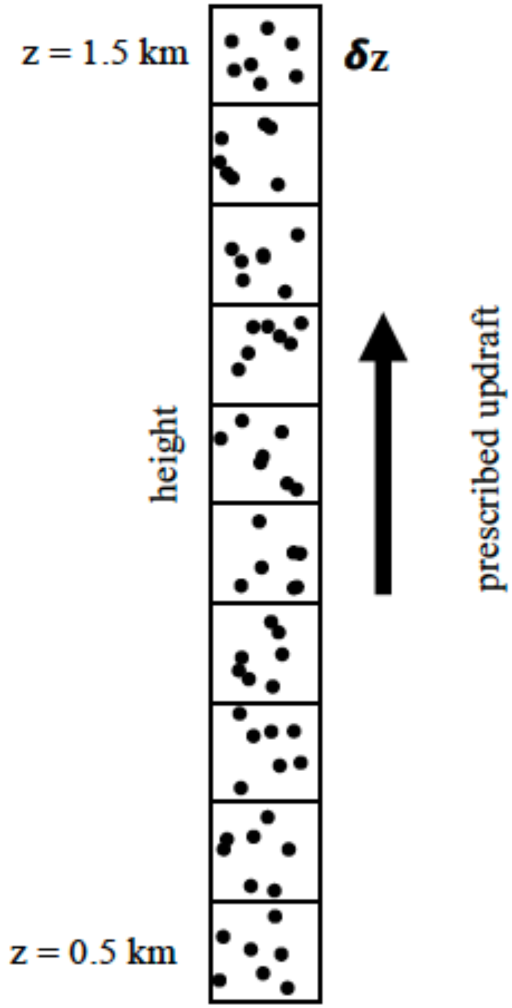
1D advection: MPDATA scheme (Smolarkiewicz et al.)
inflow – constant in time
outflow – unimportant

Superdroplets (SDs):

- 100 CCN bins (5-500 nm), each bin with 32 SDs per grid volume (total 963,200 SDs)
- SDs randomly positioned at onset with initial radius at equilibrium with local supersaturation
- SDs advected with the mean updraft
- SDs moved to the bottom grid volume when leaving top of the domain with radius reset to the initial radius
- all SDs within a given grid volume grow in the same supersaturation $S(q_v, T)$

With turbulence:

1D prescribed-flow Eulerian model with superdroplets and turbulence



1D thermodynamics

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$$C_d = \frac{d}{dt}\left(\Sigma_i \frac{4}{3}\pi r_i^3 N_i \frac{\rho_w}{\rho}\right)$$

superdroplets

$$\frac{dr_i^2}{dt} = a(S - S_{eq,i} + S_i')$$

$$\frac{dz_i}{dt} = w + w_i'$$

$$\frac{dS_i'}{dt} = a_1 w_i' - \frac{S_i'}{\tau}$$

w', S' – turbulence!

$$w_i'(t+\delta t) = w_i'(t)e^{-\delta t/\tau^*} + \sqrt{1 - e^{-2\delta t/\tau^*}}\ \sigma_{w'}\psi$$

Adding turbulence:

Each SD grows in the supersaturation
that comes from the combination of the mean $S(q_v, T)$
and fluctuations S' driven by the stochastic model

Stochastic model parameters similar to 3D cloud simulation:

mean TKE dissipation $\boldsymbol{\varepsilon}$ = 10 $cm^2\ s^{-3}$

L (integral length scale): 240 m

Height-dependent phase relaxation time τ the same for all SDs
(derived from turbulence-free simulation)

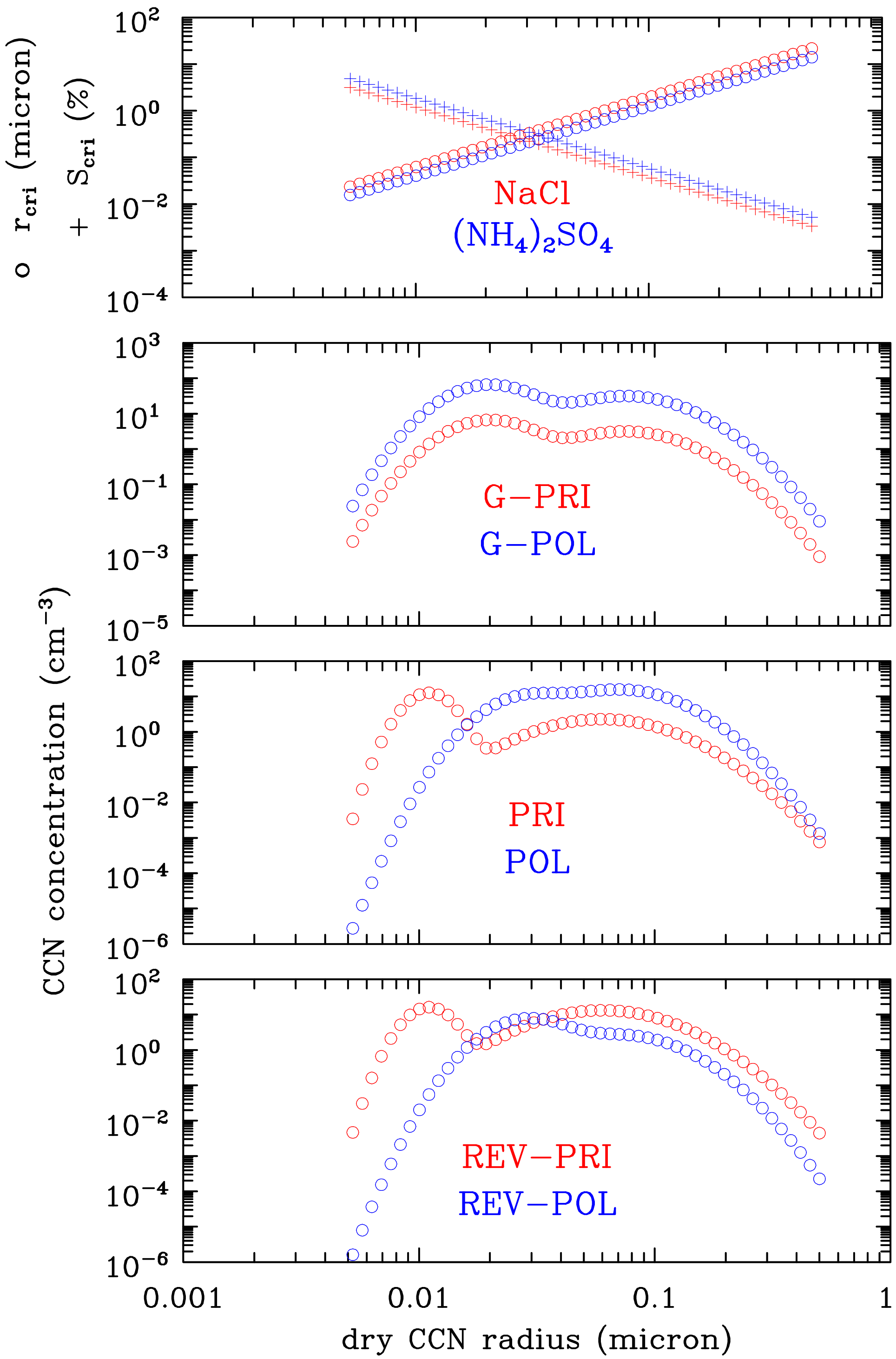
vertical velocity standard deviation ~0.5 $m\ s^{-1}$
turbulence integral time scale τ^* ~ 240 s
the same for all simulations

Bimodal dry CCN distributions: pristine versus polluted

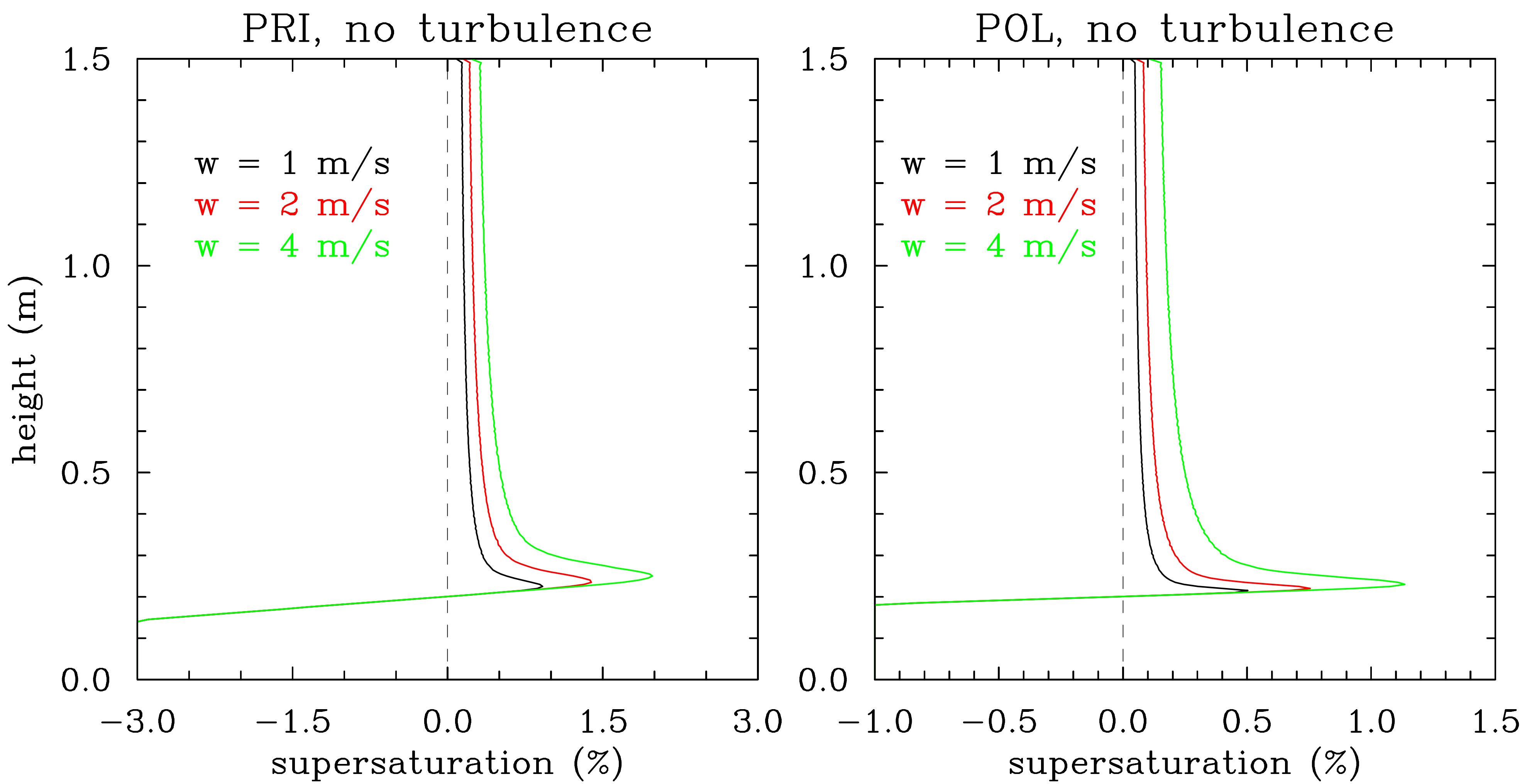
CCN distribution	Reference	Comments
POL	Grabowski et al. 2011, Grabowski and Pawlowska 2023	Polluted CCN from VOCALS field project
PRI	Grabowski et al. 2011, Grabowski and Pawlowska 2023	Clean CCN from DYCOMS field project
REV-POL	Grabowski and Pawlowska 2023 (supporting information)	CCN spectral shape of POL with N_1 and N_2 concentrations from PRI
REV-PRI	Grabowski and Pawlowska 2023 (supporting information)	CCN spectral shape of PRI with N_1 and N_2 concentrations from POL
G-POL	Arabas et al. 2015, Grabowski et al. 2022	Spectral shape similar to POL, polluted N_1 and N_2 concentrations
G-1000	Arabas et al. 2015, Grabowski et al. 2022	As G-POL, but 2 times smaller N_1 and N_2 concentrations
G-PRI	Arabas et al. 2015, Grabowski et al. 2022	As G-POL, but 10 times smaller N_1 and N_2 concentrations

CCN distribution	N_1 (cm^{-3})	r_1 (nm)	σ_1 (1)	N_2 (cm^{-3})	r_2 (nm)	σ_2 (1)	chemical composition
POL	160.	29.	1.36	380.	71.	1.57	$(NH_4)_2SO_4$
PRI	125	11.	1.20	65.	60.	1.70	NaCl
REV-POL	125.	29.	1.36	65.	71.	1.57	$(NH_4)_2SO_4$
REV-PRI	160.	11.	1.20	380.	60.	1.70	NaCl
G-POL	1,200.	20.	1.40	800.	75.	1.60	NaCl
G-1000	600.	20.	1.40	400.	75.	1.60	NaCl
G-PRI	120.	20.	1.40	80.	75.	1.60	NaCl

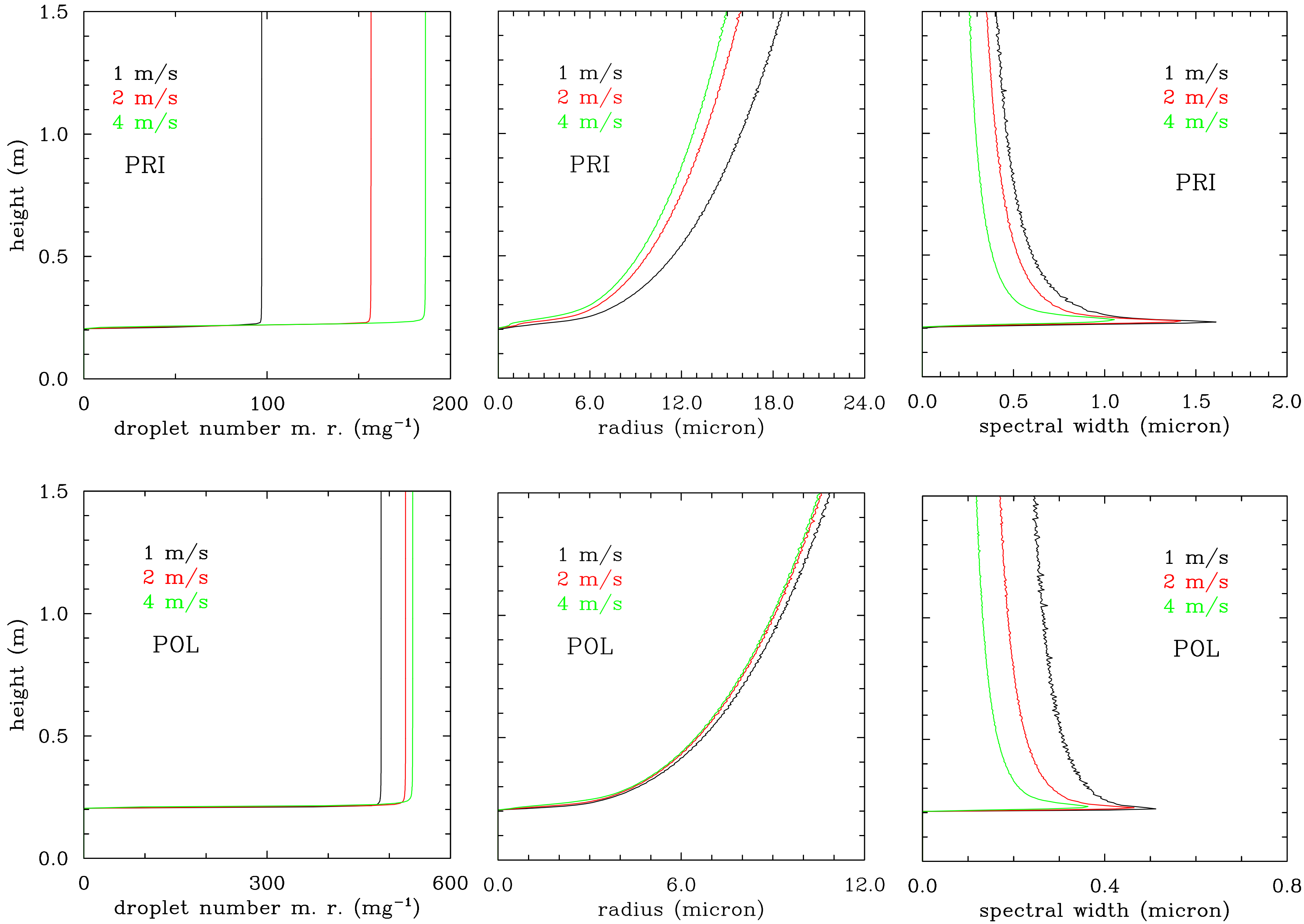
Dry CCN distributions:
pristine
versus
polluted



WITHOUT TURBULENCE

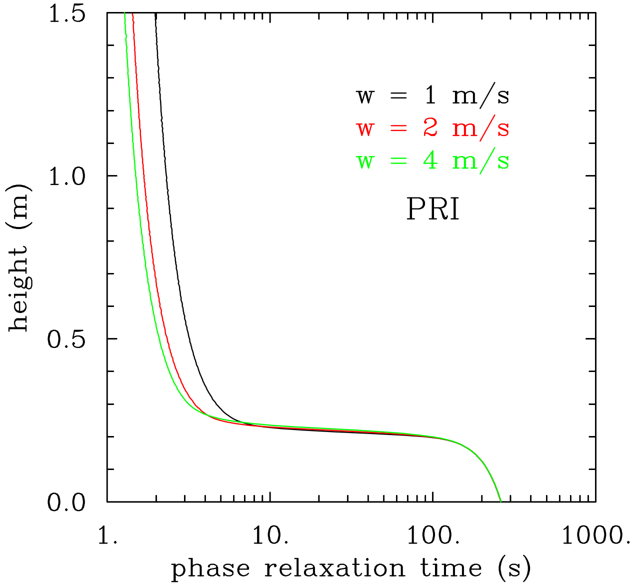


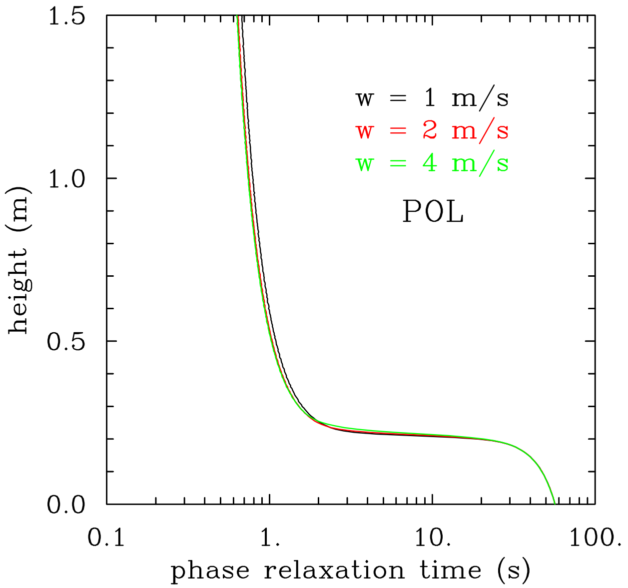
WITHOUT TURBULENCE



ADDING TURBULENCE

we need information about the phase relaxation time

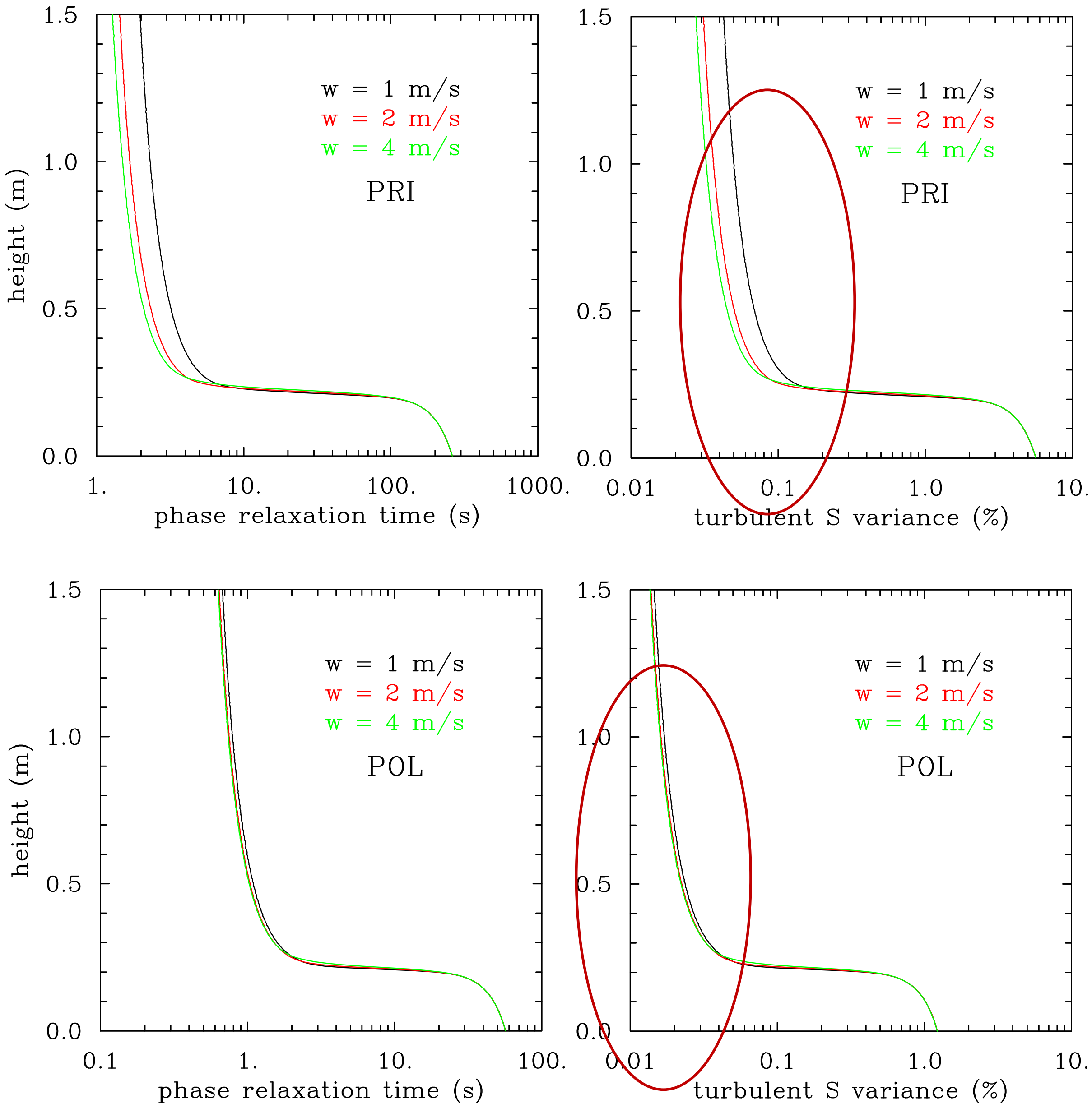




$$\frac{dS_i'}{dt} = a_1 w_i' - \frac{S_i'}{\tau}$$

ADDING TURBULENCE

we need information about the phase relaxation time



$$\frac{dS'_i}{dt} = a_1 w'_i - \frac{S'_i}{\tau}$$

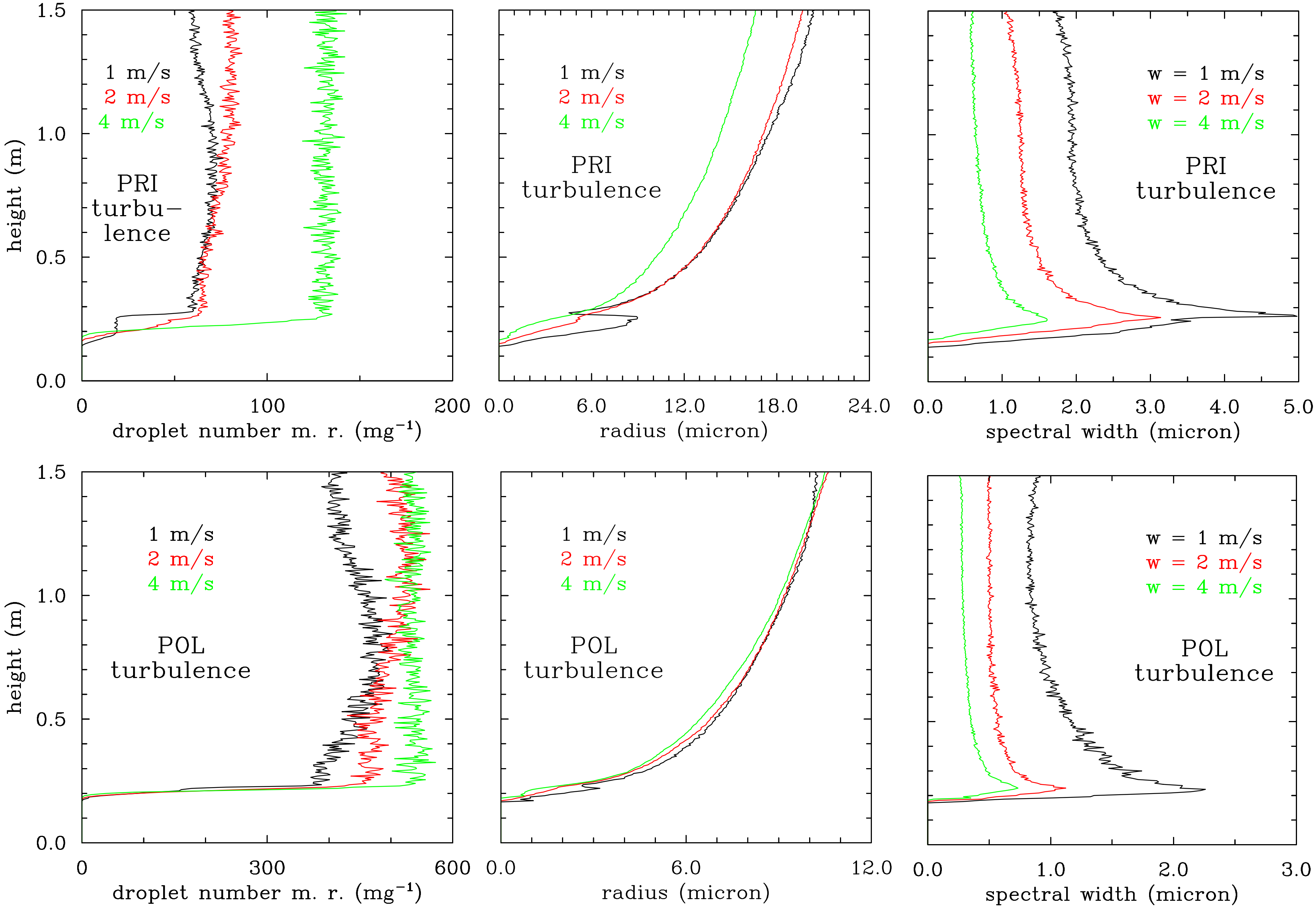
For the quasi-equilibrium supersaturation:

$$S_{qe} = a_1 \ \tau \ w$$

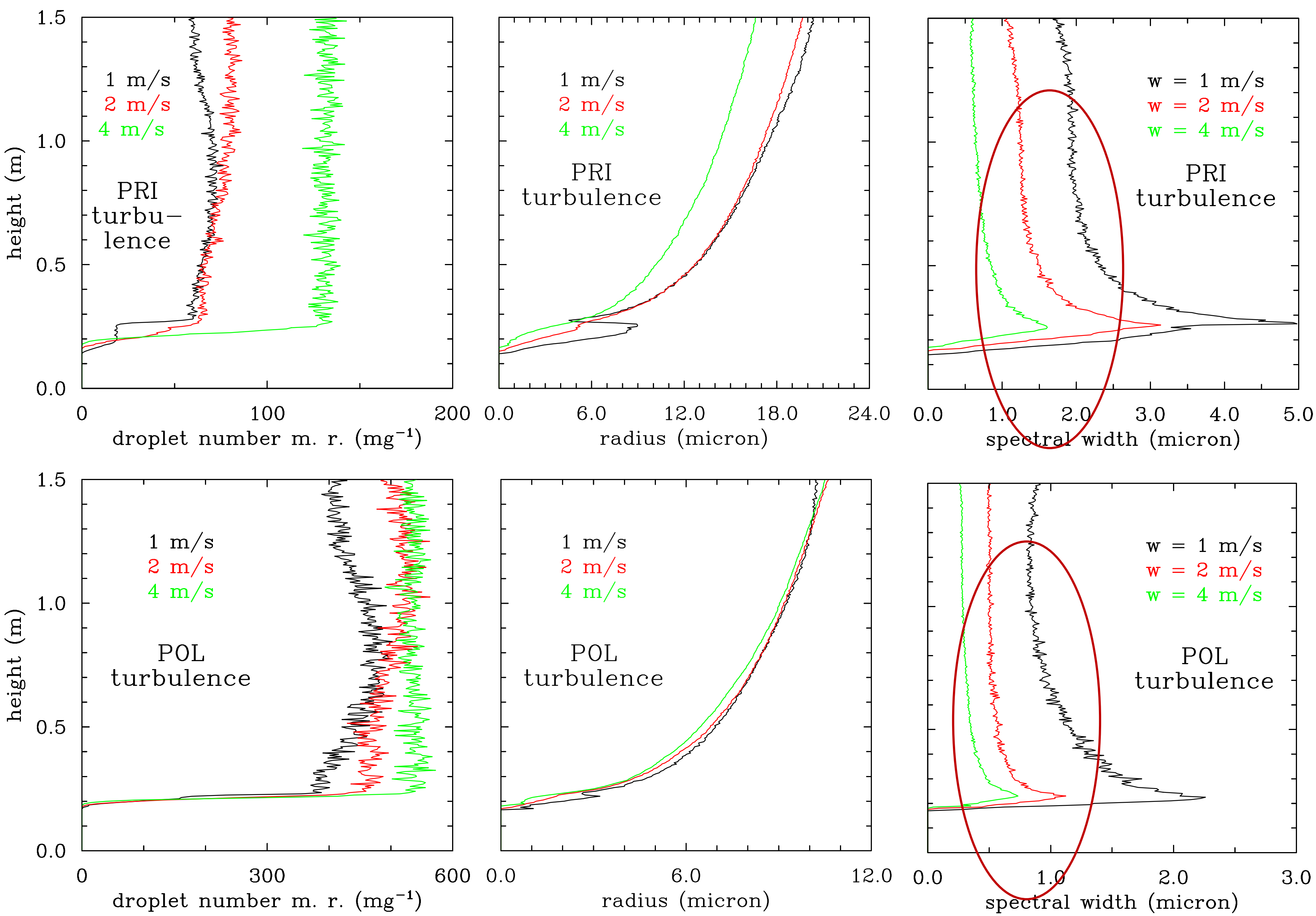
$$\sigma_S = a_1 \ \tau \ \sigma_w$$

$\sigma_w = 0.54 \text{ m sec}^{-1}$ is the vertical velocity standard deviation

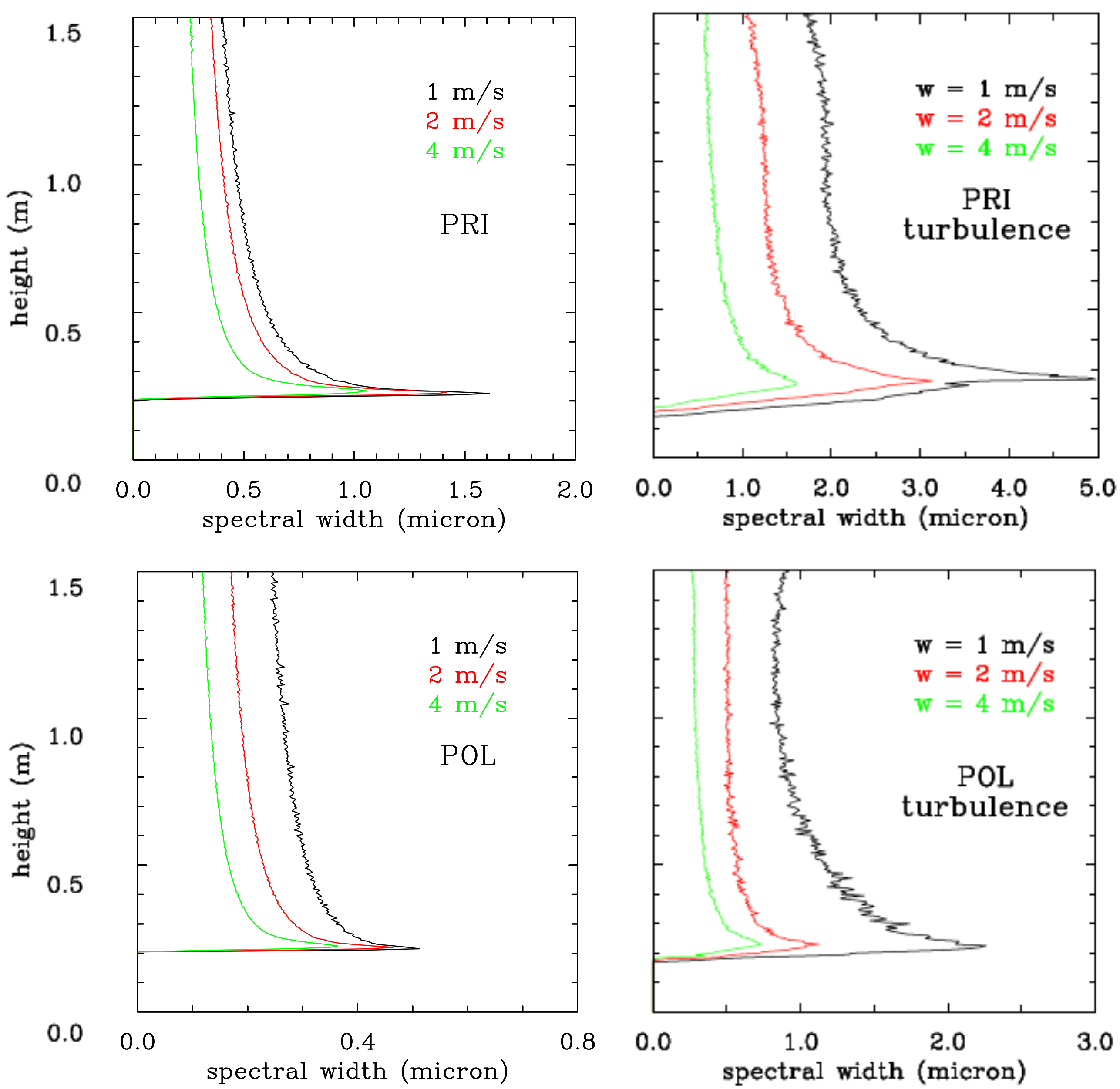
WITH TURBULENCE



WITH TURBULENCE



WITHOUT TURBULENCE WITH TURBULENCE

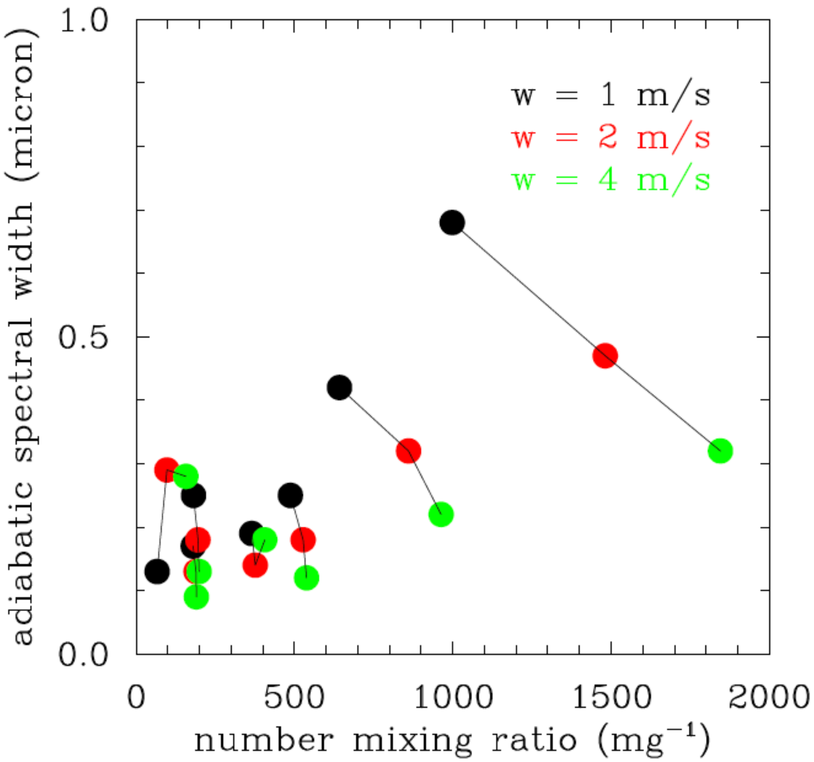


Results for all dry CCN distributions

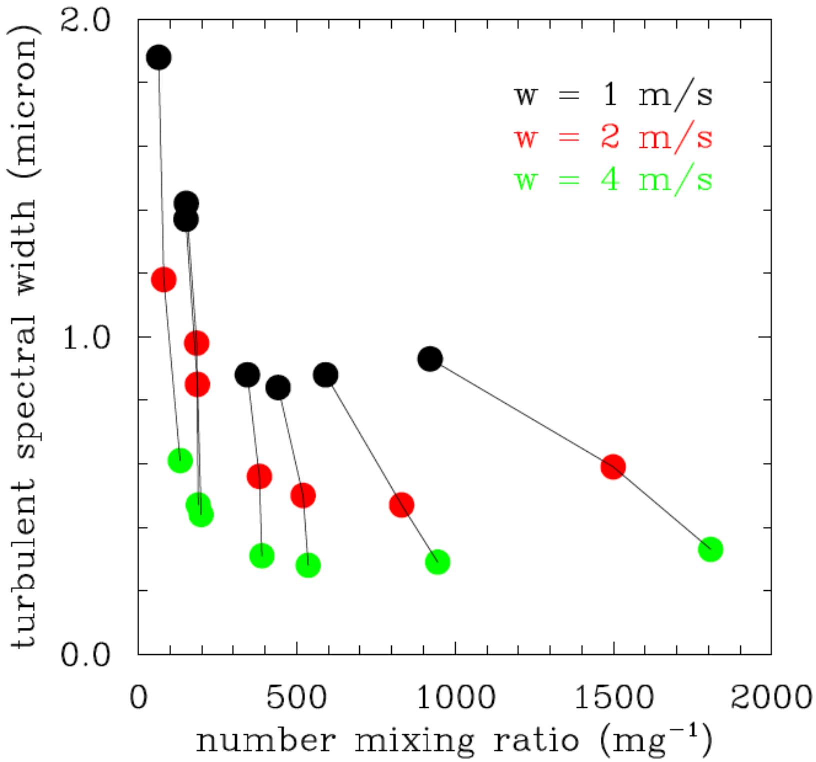
simulation	w (m/s)	NO TURB	Number m.r. (1/mg)	Width (micron)	WITH TURB	Number m.r. (1/mg)	Width (micron)	Turb. width enhmt.
POL	1		487	0.25		441	0.84	3.4
	2		527	0.18		520	0.50	2.8
	4		538	0.12		526	0.28	2.3
PRI	1		66	0.13		64	1.88	14.5
	2		97	0.29		80	1.18	4.1
	4		157	0.28		132	0.61	2.2
REV-POL	1		180	0.17		151	1.42	8.4
	2		189	0.13		184	0.98	7.5
	4		190	0.09		189	0.47	5.2
REV-PRI	1		365	0.19		344	0.88	4.6
	2		376	0.14		382	0.56	4.0
	4		406	0.18		390	0.31	1.7
G-POL	1		998	0.68		921	0.93	1.4
	2		1481	0.47		1499	0.59	1.3
	4		1845	0.32		1807	0.33	1.0
G-1000	1		642	0.42		591	0.88	2.1
	2		860	0.32		831	0.47	1.5
	4		963	0.22		945	0.29	1.3
G-PRI	1		181	0.25		150	1.37	5.5
	2		195	0.18		186	0.85	4.7
	4		199	0.13		198	0.44	3.4

Results for all dry CCN distributions

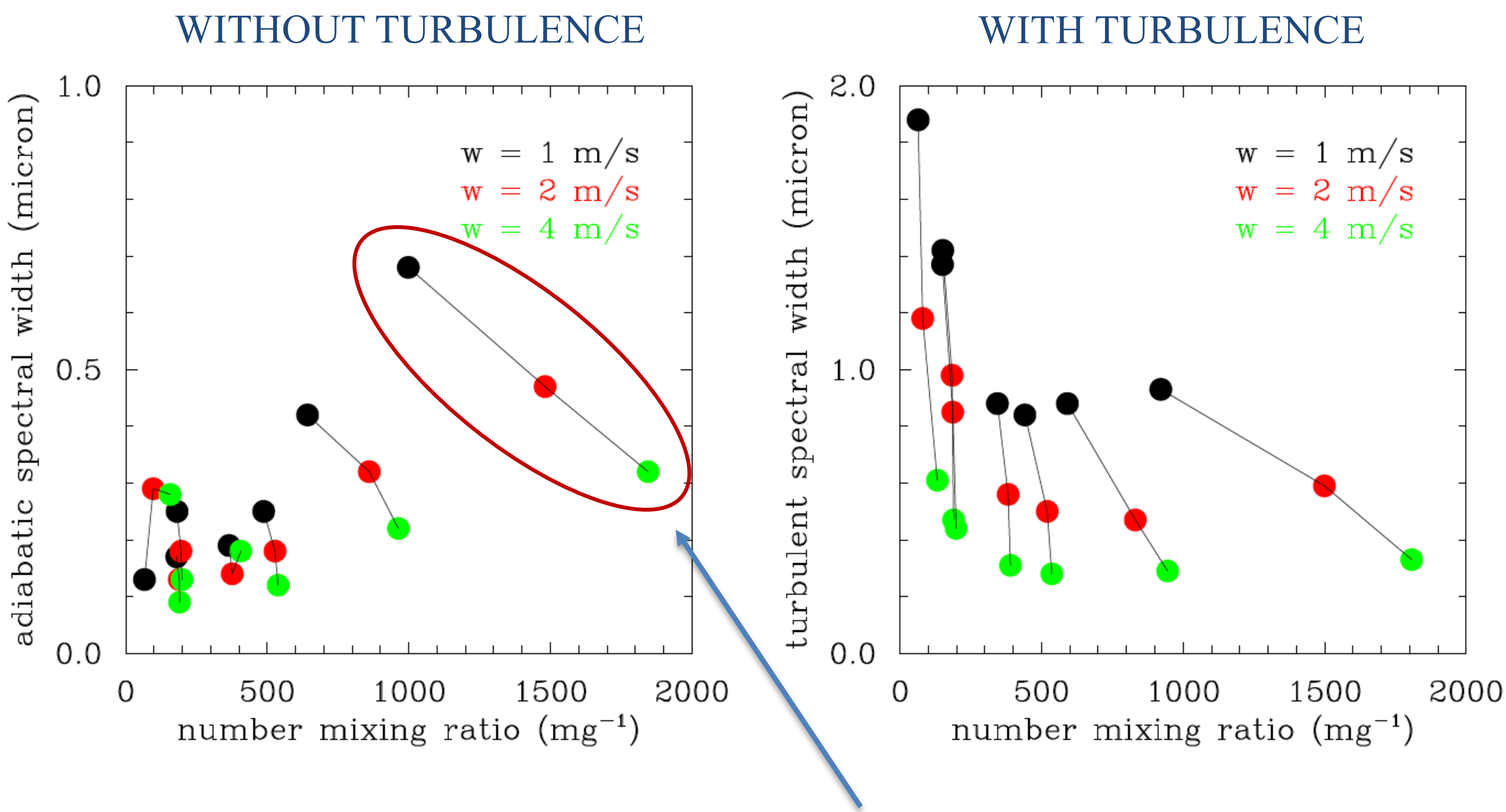
WITHOUT TURBULENCE



WITH TURBULENCE

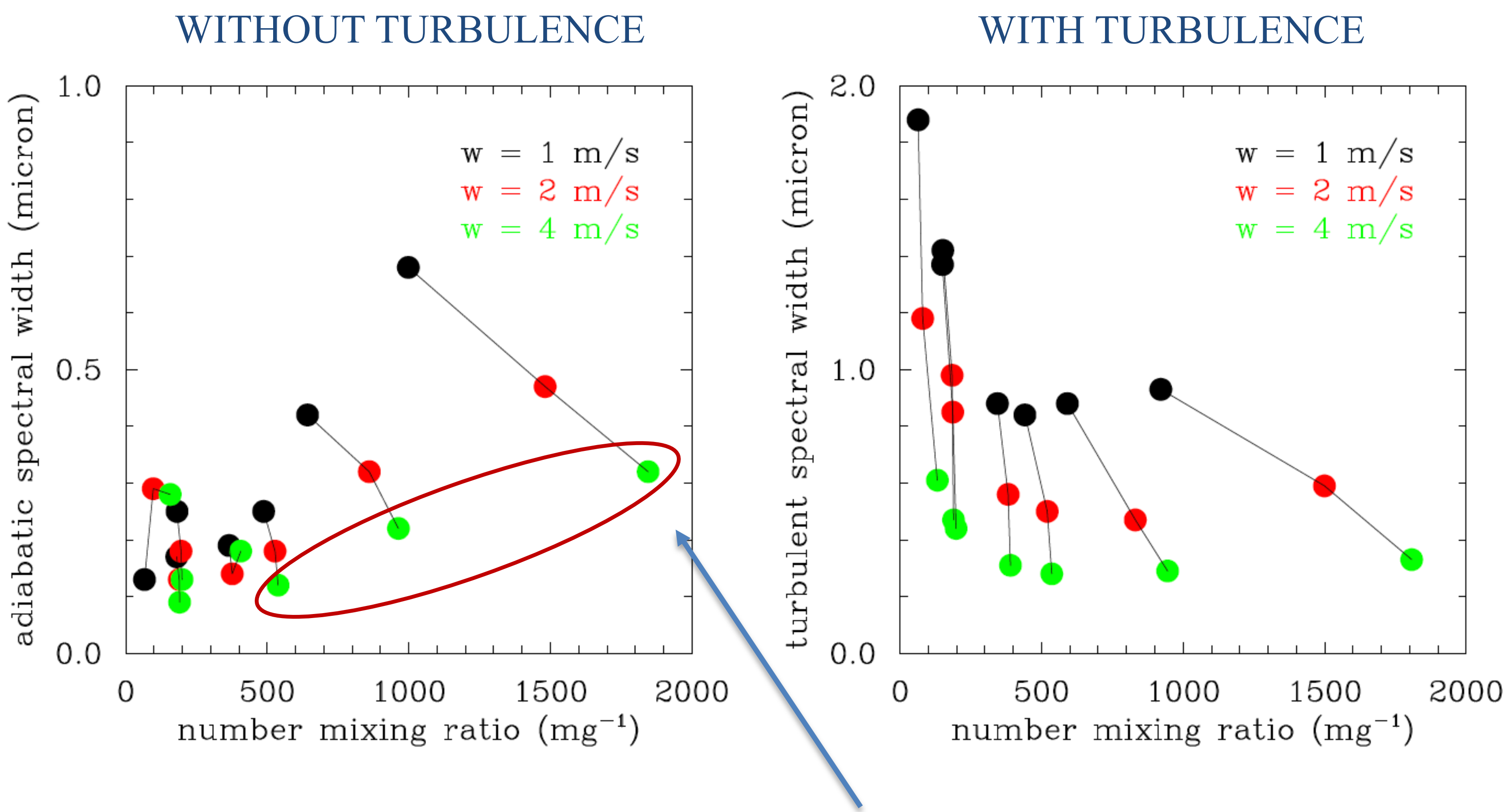


Results for all dry CCN distributions



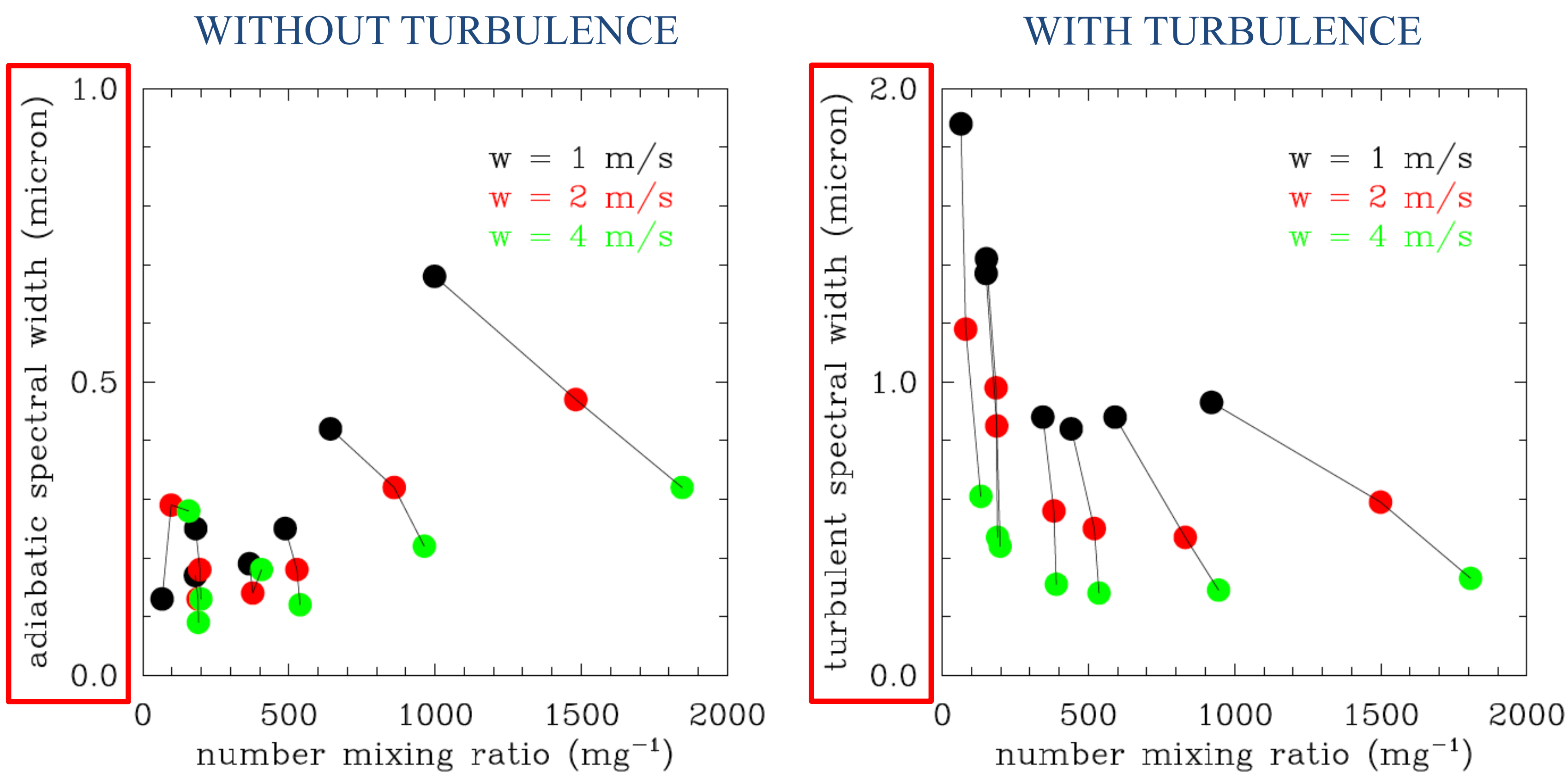
the same CCN, different updrafts

Results for all dry CCN distributions

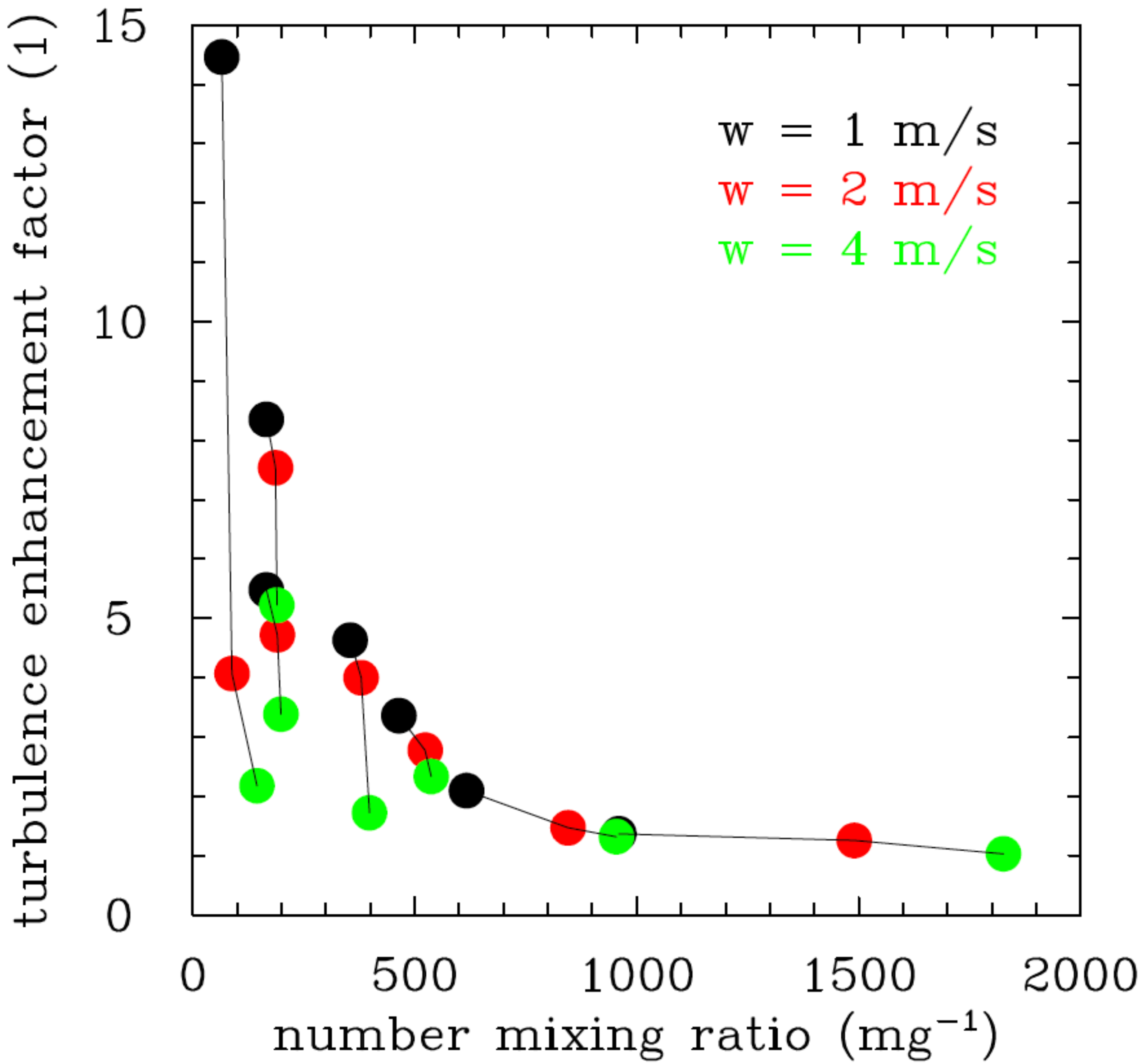


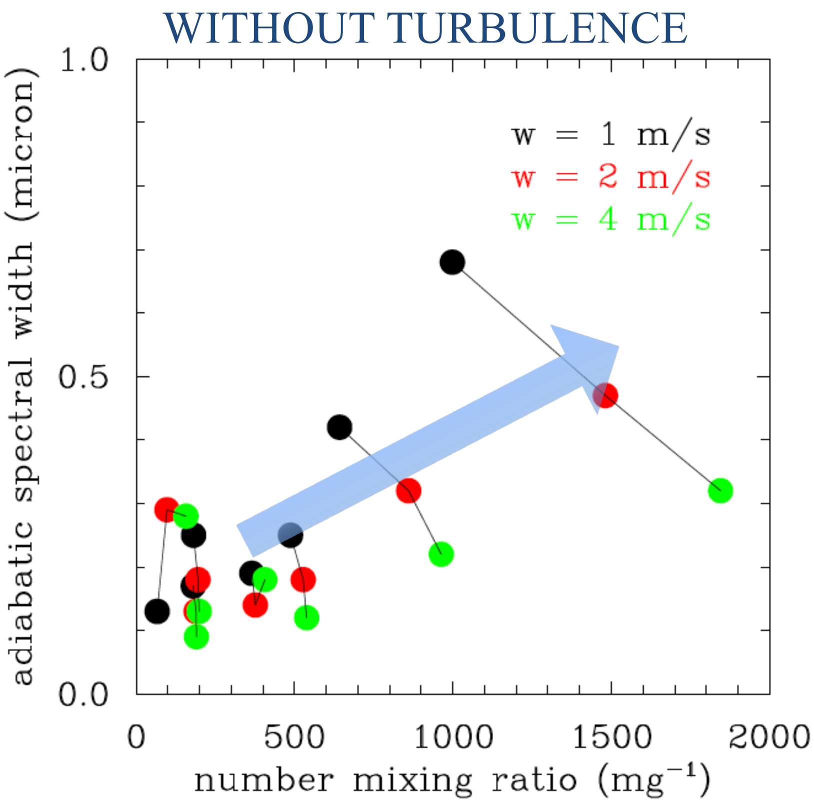
different CCN, the same updrafts

Results for all dry CCN distributions

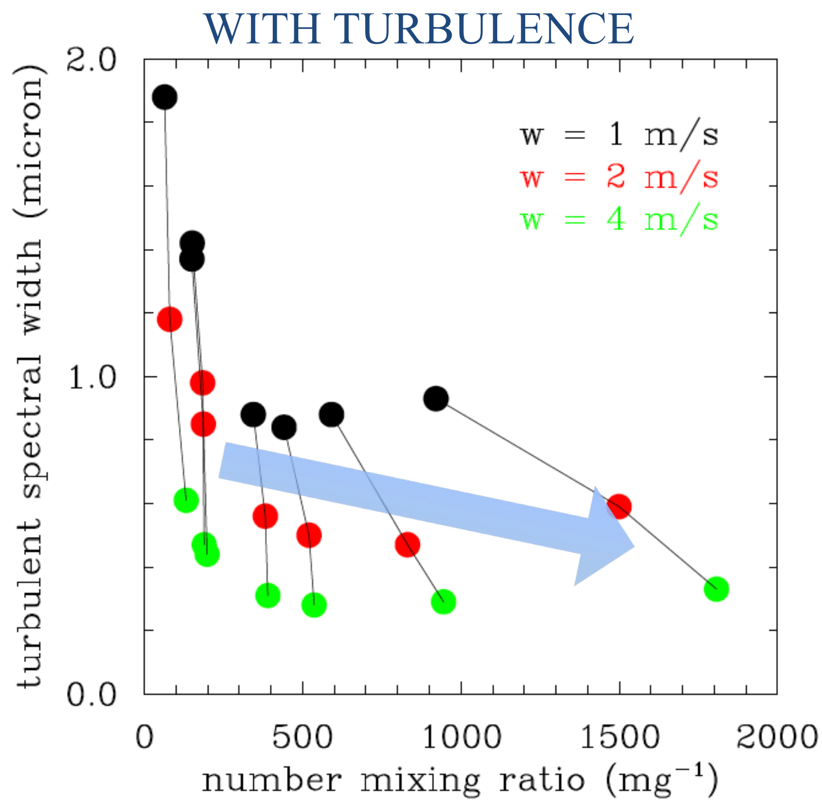


Results for all dry CCN distributions





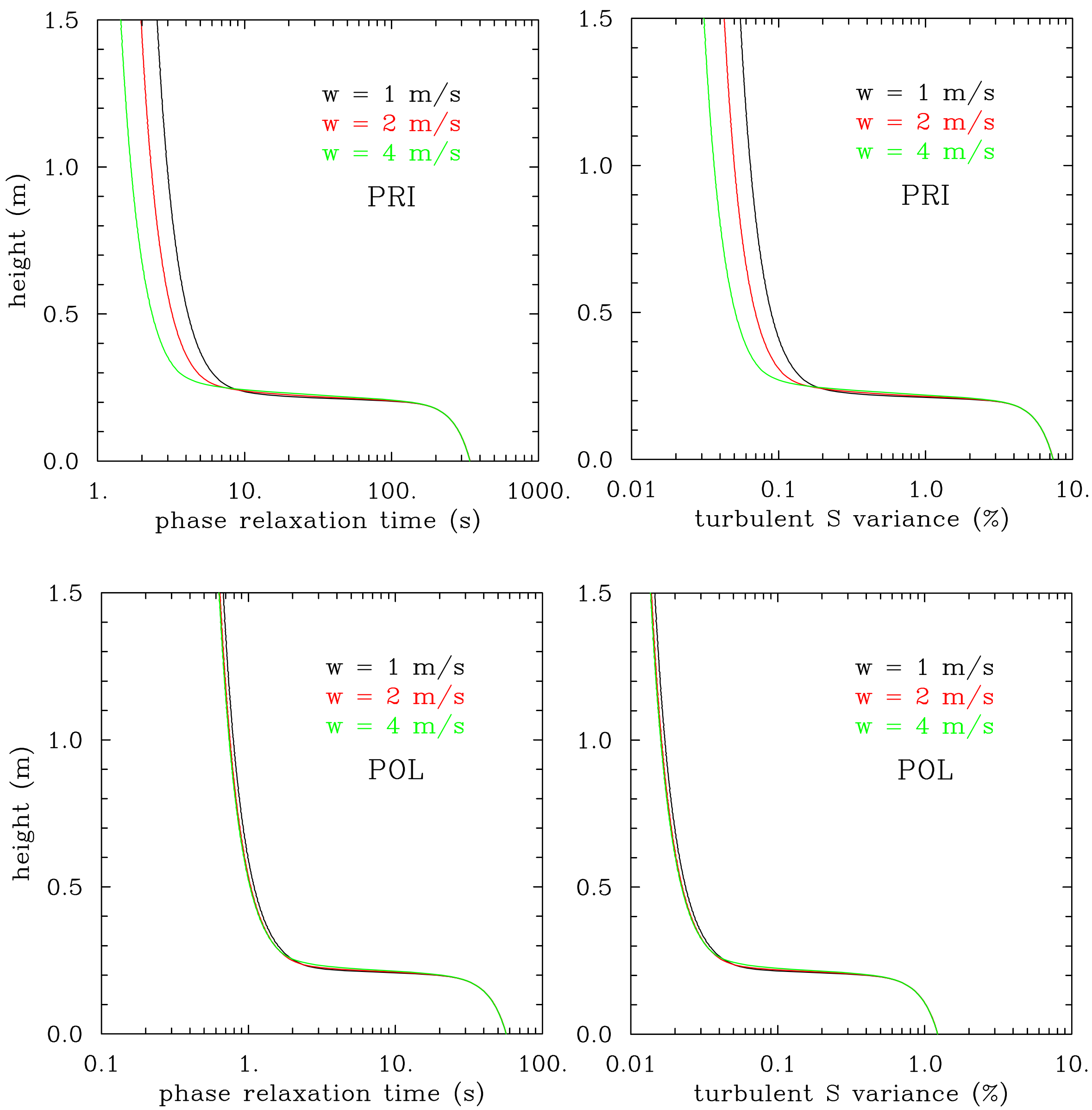
Spectral width tends to increase with droplet concentration



Spectral width tends to decrease with droplet concentration

Where the reversal comes from?

Pristine clouds feature longer phase relaxation time and thus larger supersaturation fluctuations!



$$\frac{dS_i'}{dt} = a_1 w_i' - \frac{S_i'}{\tau}$$

For the quasi-equilibrium supersaturation:

$S_{qe} = a_1\ \tau\ w$

$\sigma_S = a_1\ \tau\ \sigma_w$

$\sigma_w = 0.54\ \mathrm{m\ sec^{-1}}$ is the vertical velocity variance

How to understand larger spectral widths in observations when compared to adiabatic parcel simulations?

How to understand opposite trends in observations and adiabatic parcel simulations?

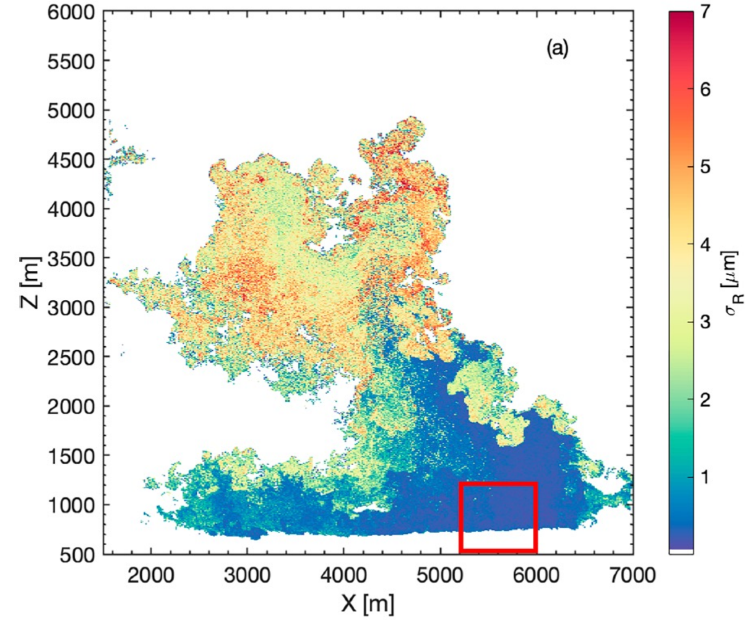
The answer to both questions:

Cloud turbulence impact on formation and growth of cloud droplets!

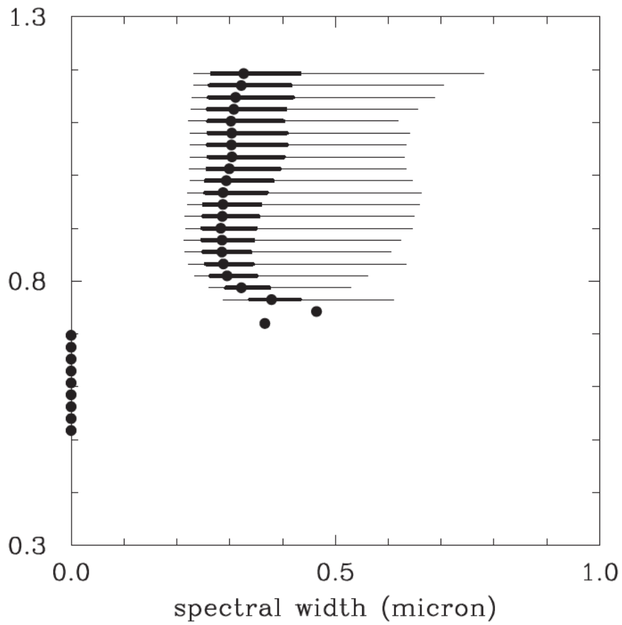
Is there a support for this claim in 3D cloud simulations?

Untangling the Broadening of Adiabatic Cloud Droplet Spectra through Eddy Hopping in a High-Resolution Cumulus Congestus Simulation

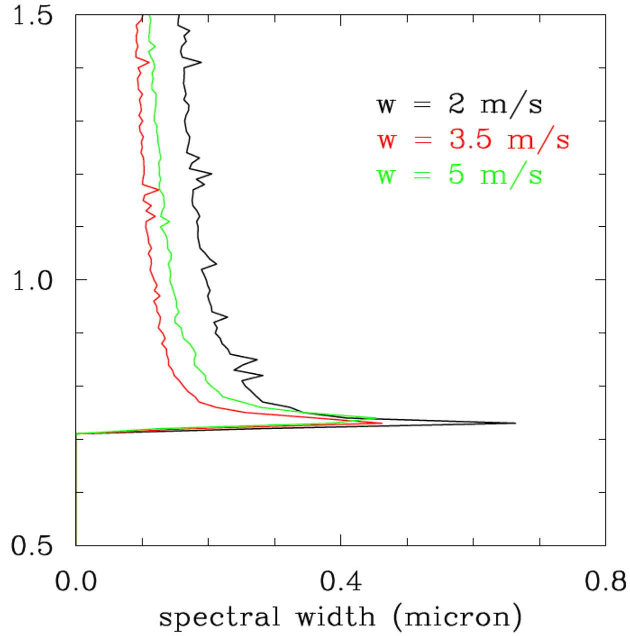
WOJCIECH W. GRABOWSKI,[a] KAMAL KANT CHANDRAKAR,[a] AND HUGH MORRISON[a]
[a] *MMM Laboratory, NSF National Center for Atmospheric Research, Boulder, Colorado*



3D cloud model



1D updraft model
without turbulence



1D updraft model
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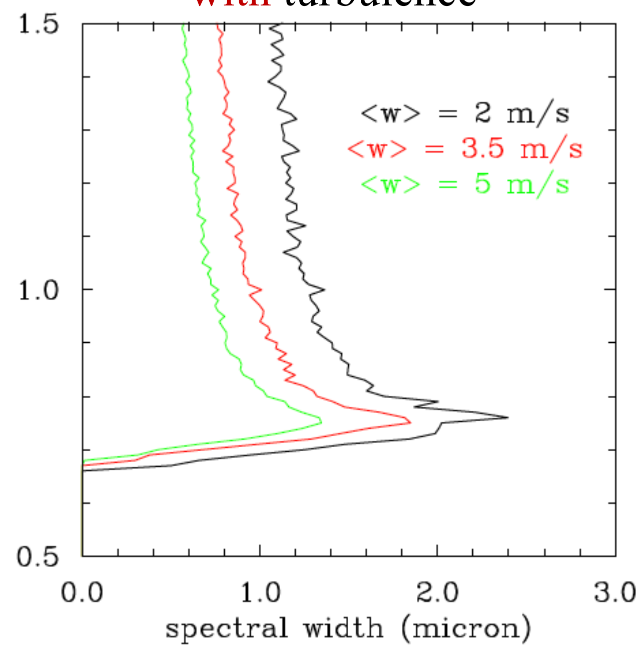

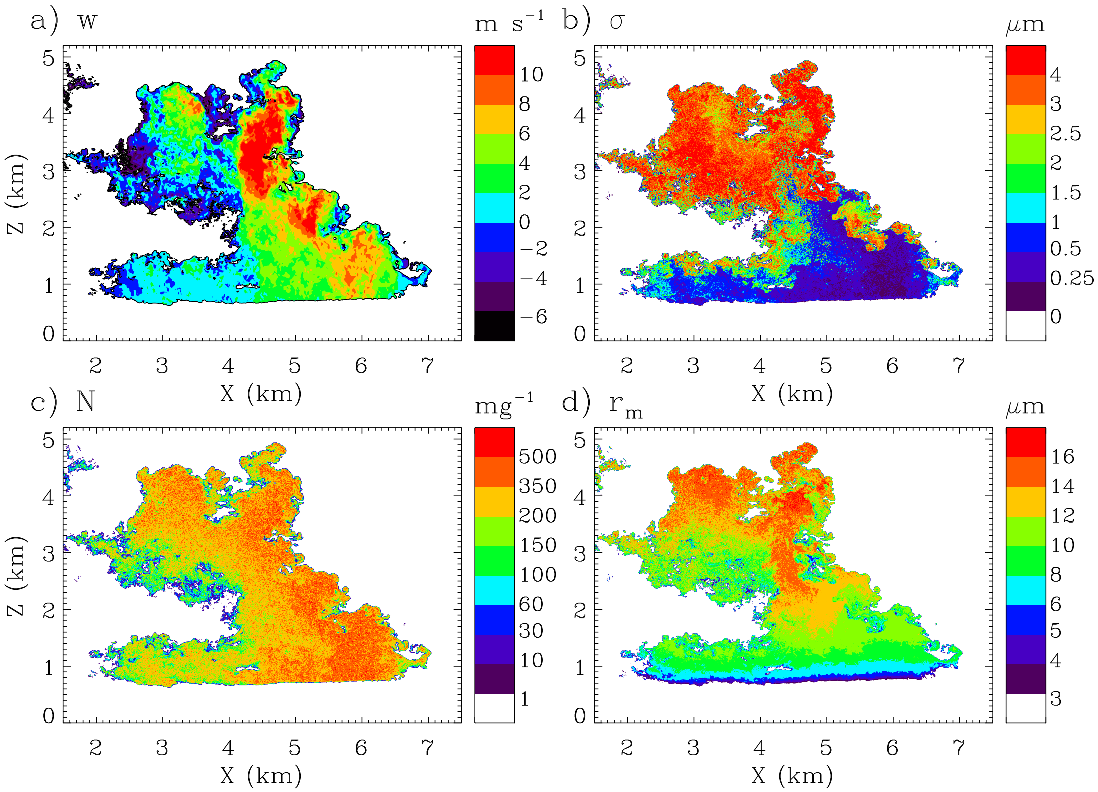

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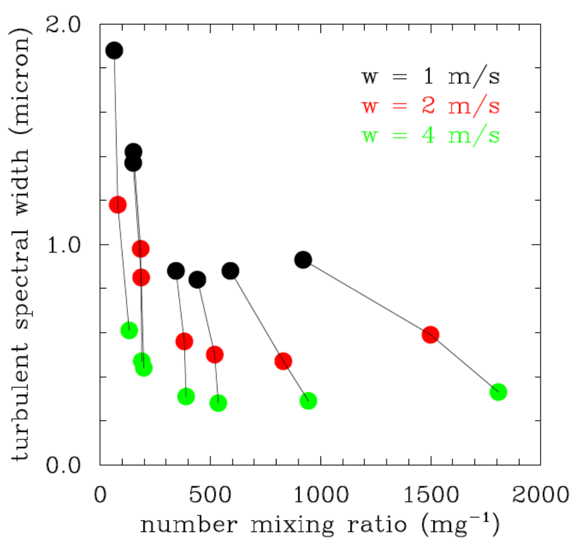
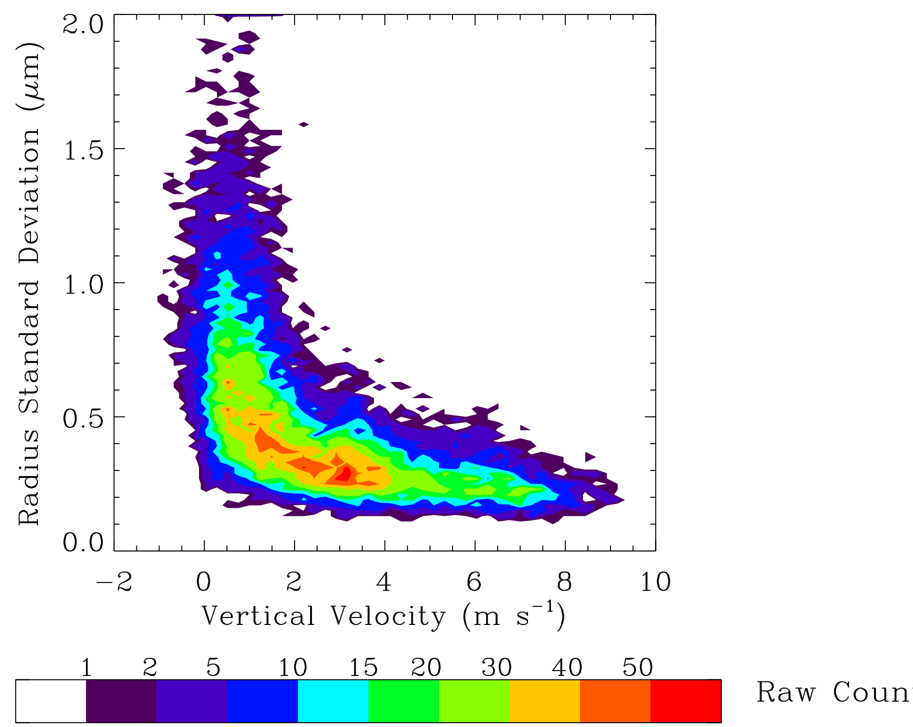
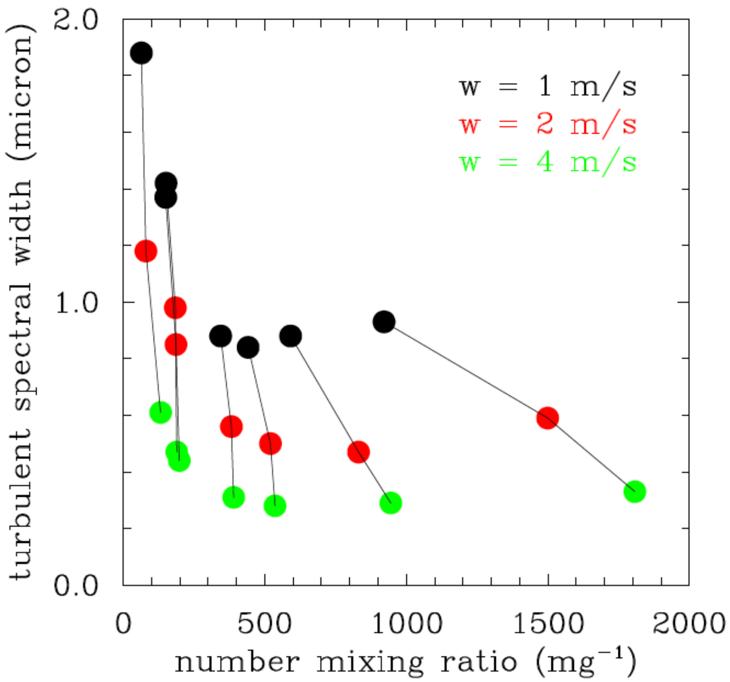
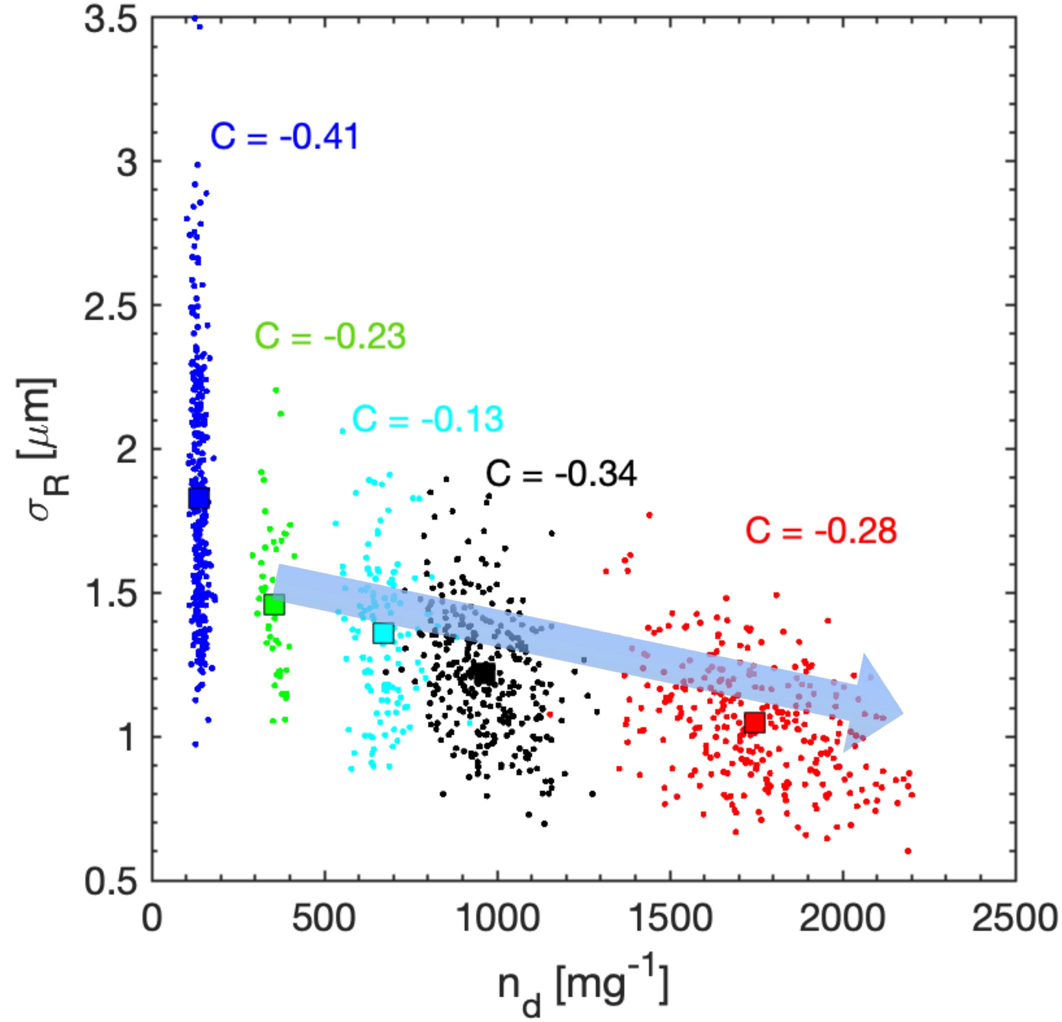
The same 3D high-res 3D simulation





Similar 3D lower-resolution cloud simulations with different dry CCN spectra: pristine to polluted conditions





Summary:

In agreement with previous studies, adiabatic spectra *without turbul*ence are typically narrow. Polluted CCN result in wider adiabatic droplet spectra.

With turbulence, droplet spectra simulated by the idealized 1D adiabatic Eulerian – Lagrangian vertical air current are wider, especially in pristine conditions. This agrees with observations of natural clouds and with observations and numerical simulations of turbulent laboratory clouds.

Larger turbulence impact in pristine conditions is explained by a longer phase relaxation time that implies larger turbulent supersaturation fluctuations for the same turbulent vertical velocity fluctuations.