Intercomparison of Model Simulations of Cloudy Rayleigh-Bénard Convection in a Laboratory Chamber

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Introduction

Michigan Tech Cloud Chamber: "The Pi Chamber"

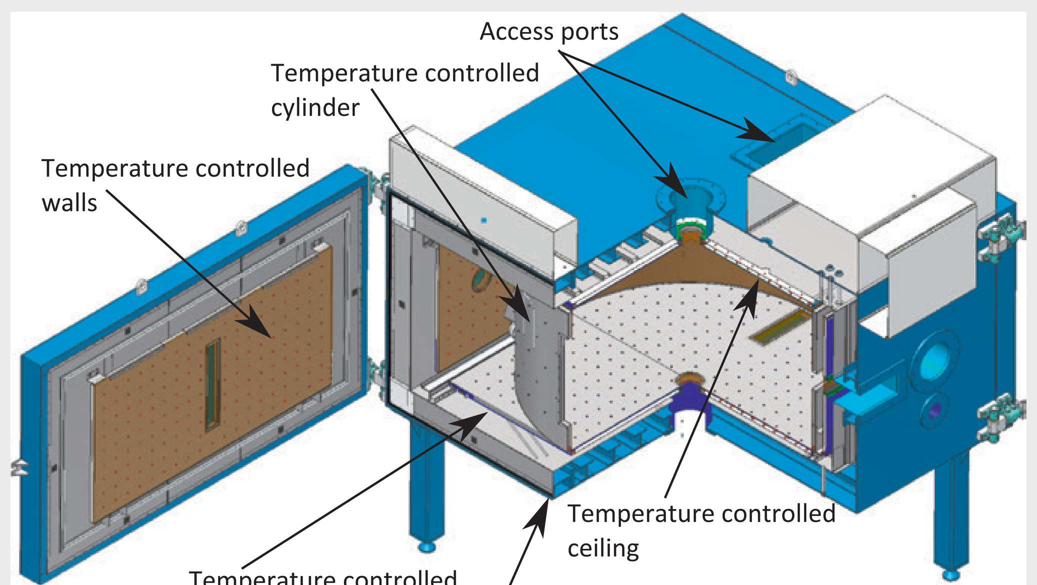
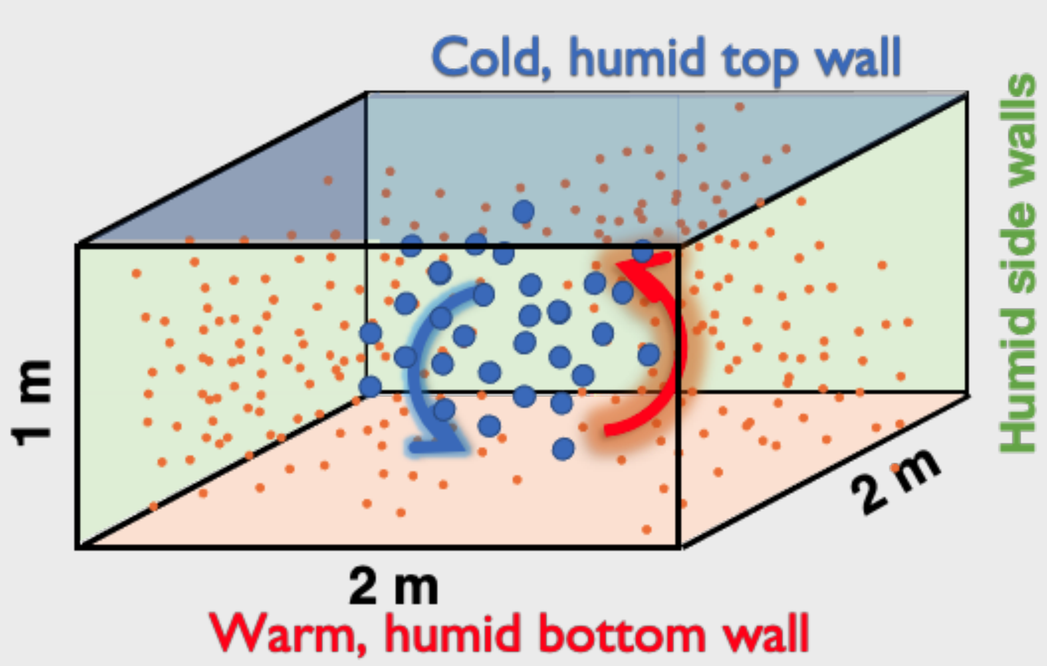
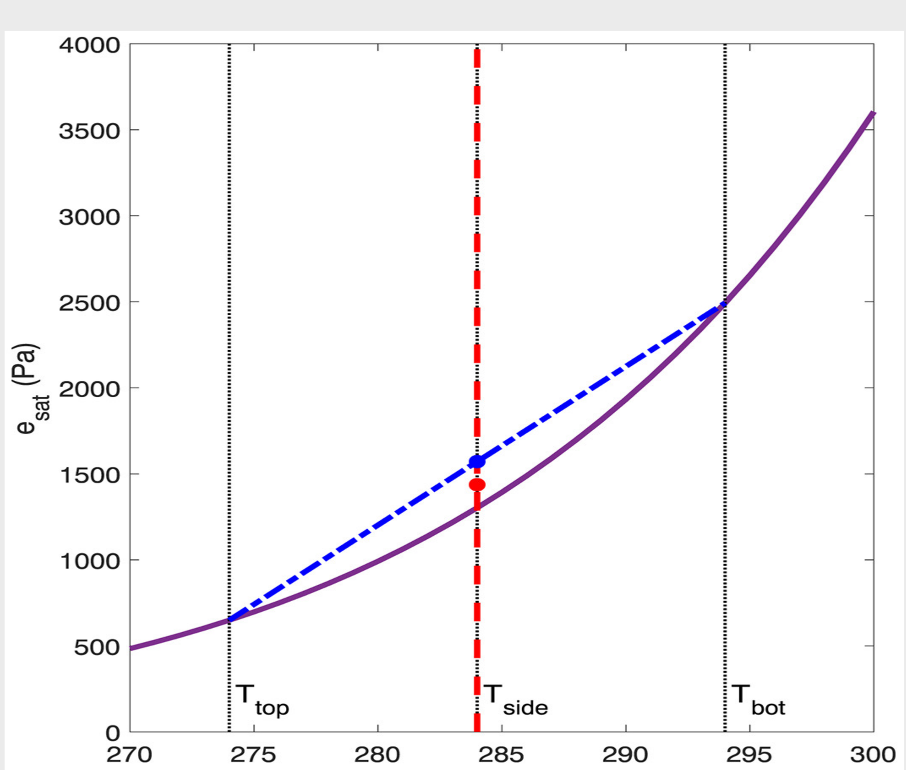


Fig. 1. A cutaway schematic of the cloud chamber with one door open and the cylindrical thermal panel in place.



Cloudy Rayleigh-Bénard Convection
Droplets grow on injected aerosol particles.
Droplets fall out due to settling.



Mixing of saturated air parcels at the top, bottom, and sidewall temperatures produces supersaturation.

The Intercomparison Protocol

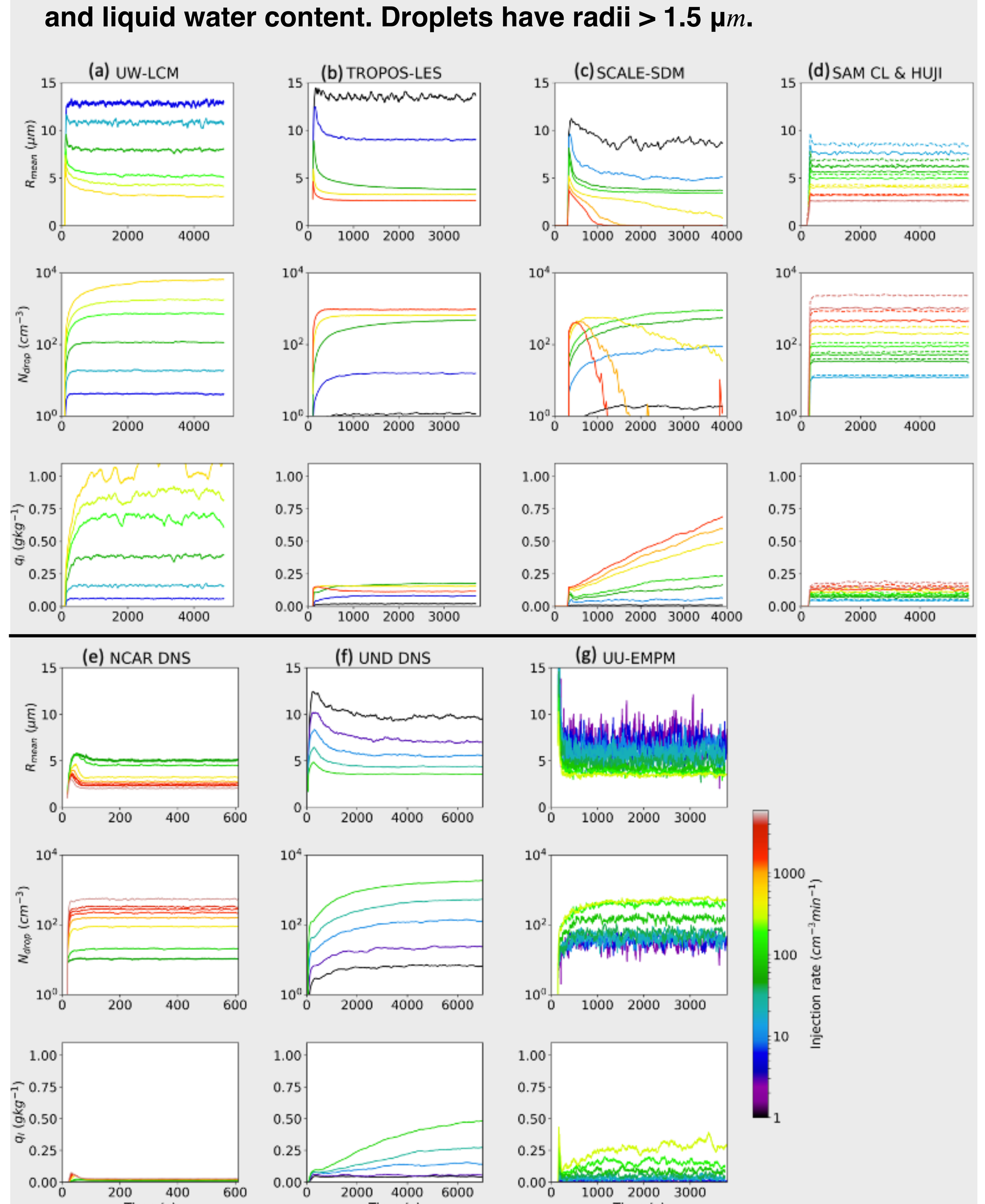
The model configuration for the steady-state intercomparison

a. **Boundary conditions:** The top wall temperature is 299 K, the bottom temperature is 280 K, the side wall temperature is 285 K. The relative humidity of the top and bottom walls is 100 %. The relative humidity of the side wall is adjusted in the models with side walls such that the supersaturation inside the chamber is ~3 % in steady-state before aerosols are injected into the chamber. After reaching steady-state, the aerosols (brown dots in the diagram) are injected into the chamber to form droplets (blue dots).
b. **Aerosol injection:** Continuously inject sodium chloride aerosols with a dry diameter of 125 nm for a range of rates.
c. **Duration**: Run simulation for 1 to 2 h after injection commences, to achieve a steady state.

Summary of the Models

Model Type	Model Name	Simulated Chamber Geometry/region	dx, dy, dz (cm)	Microphysics scheme	Aerosol injection rates ($cm^{-3}\ min^{-1}$)	Side wall RH	Top/bottom wall temperature	Top/bottom wall Qv or RH	Initial supersaturation	Standard deviation of supersaturation	Participanting institute
Large-eddy simulation (LES)	UW-LCM	The entire chamber with top, bottom, and side walls (1 m, 2 m, 2 m)	3.125	super-droplet method (SDM)	6-600	80%	Ttop=280K Tbot=299K	RH=100%	3.30%	7.20%	University of Warsaw, Poland
	SCALE-SDM		6.25	SDM	1-1500	65%		RH=100%	3.90%	0.93%	University of Hyogo, Japan
	TROPOS-LES		3.125	SDM	1-1500	82.00%		Qv_top = 7.6683 g/kg; Qv_bot = 24.139 g/kg	2.30%	2.50%	Leibniz Institute for Tropospheric Research, Germany
	SAM		3.125	Two bin schemes (Chen & Lamb; HUJI)	15-4500	81%		Qv_top=6.1562g/kg, Qv_bot=21.5865g/kg	3.00%	2.40%	Brookhaven National Laboratory, USA
Direct numerical simulation (DNS)	UND-DNS	The entire chamber without side walls (1 m, 2 m, 2 m)	dx, dy = 1.5625; dz = 0.78125	SDM and particle-by-particle method	1-100	100%		RH=100%	2.30%	1.50%	University of Notre Dame, USA
	NCAR-DNS	The core region of the chamber (1 m, 2 m, 2 m)	0.15625	SDM and particle-by-particle method	50-5000	No top/bottom walls. Constant external forcing was applied to the Qv and T field to address the wall impact.			3.10%	0.73%	National Center for Atmospheric Research, USA
1D Linear-eddy model (1D-LEM)	UU-EMPM	One-dimensional vertical column of the chamber (1 m, 2 m, 2 m)	dz=0.1667	particle-by-particle method	2.5-320	100%	Ttop=280K Tbot=299K	RH=100%	1.70%	3.00%	University of Utah, USA

Time series of droplet mean radius, droplet number concentration, and liquid water content. Droplets have radii > 1.5 μm.



Expectations from Theory

Steady-state distribution of droplet radius

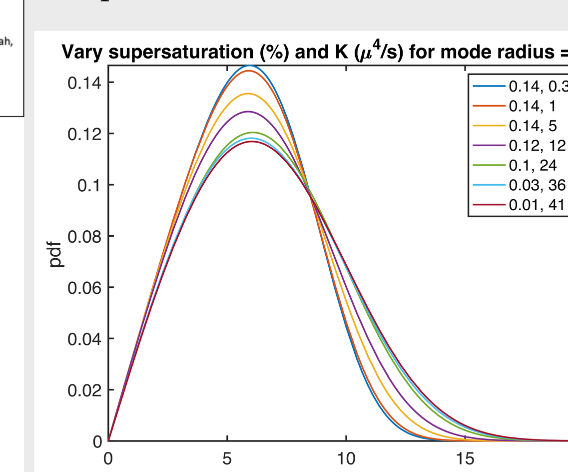
Let $v(r)\,dr$ be the number of cloud droplets per unit mass of air with droplet radius r in the interval $(r, r + dr)$.

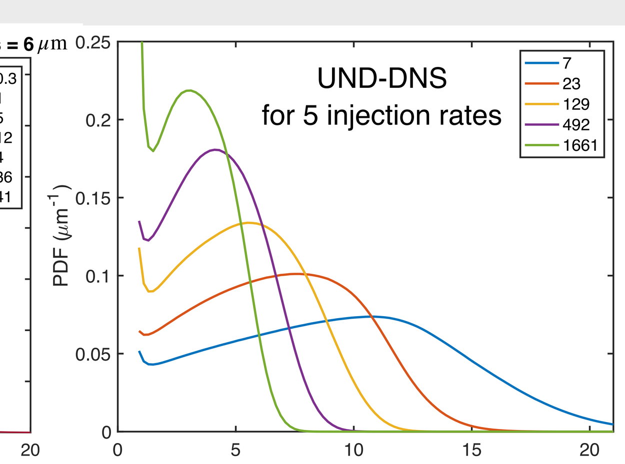
The processes that determine $v(r)$ in a cloud chamber are:

- aerosol injection
- condensation growth due to mean saturation
- condensation growth due to supersaturation fluctuations
- droplet fall out

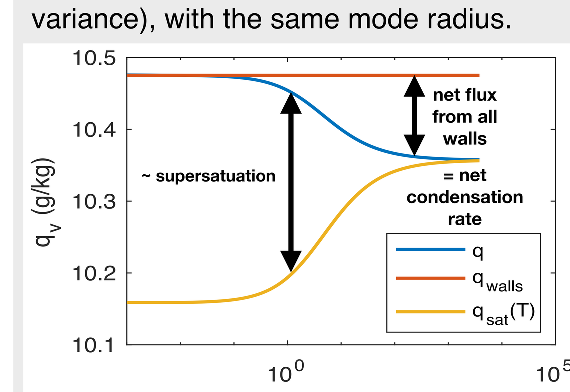
If we neglect solute and curvature effects in the droplet growth equation, the resulting analytic steady state DSD depends on three flow parameters: mean supersaturation, the supersaturation variance, and the Lagrangian autocorrelation time scale of the supersaturation, as well as on the aerosol injection rate, the chamber height, and the Stokes' fall speed parameter. For fixed flow parameters, the corresponding PDF does not depend on the injection rate.

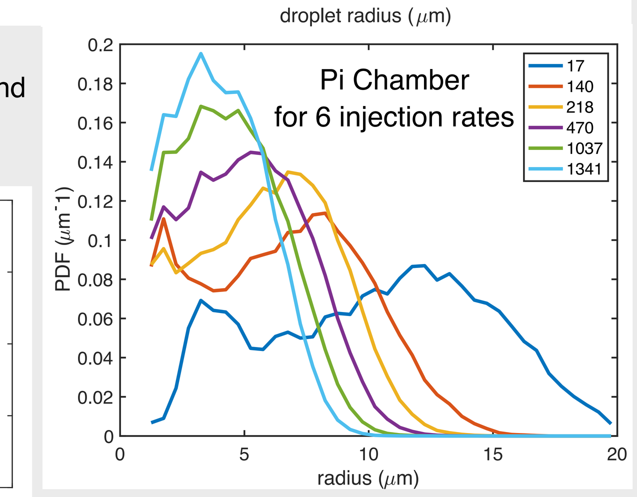
The PDF shape has only a weak dependence on the relative magnitudes of the mean supersaturation and the supersaturation variance, which combined with the difficulty of measuring supersaturation in the Pi Chamber, has made quantifying the role of supersaturation fluctuations from measurements challenging. Recent efforts by the MTU Pi Chamber group used the impacts of supersaturation fluctuations on droplet activation to infer the role of supersaturation fluctuations.





(Above) Theoretical PDFs for seven combinations of mean supersaturation and spectral diffusivity, K, (~ supersaturation variance), with the same mode radius.





(Left) From bulk model.

Bulk model for cloudy Rayleigh-Bénard convection in a laboratory chamber

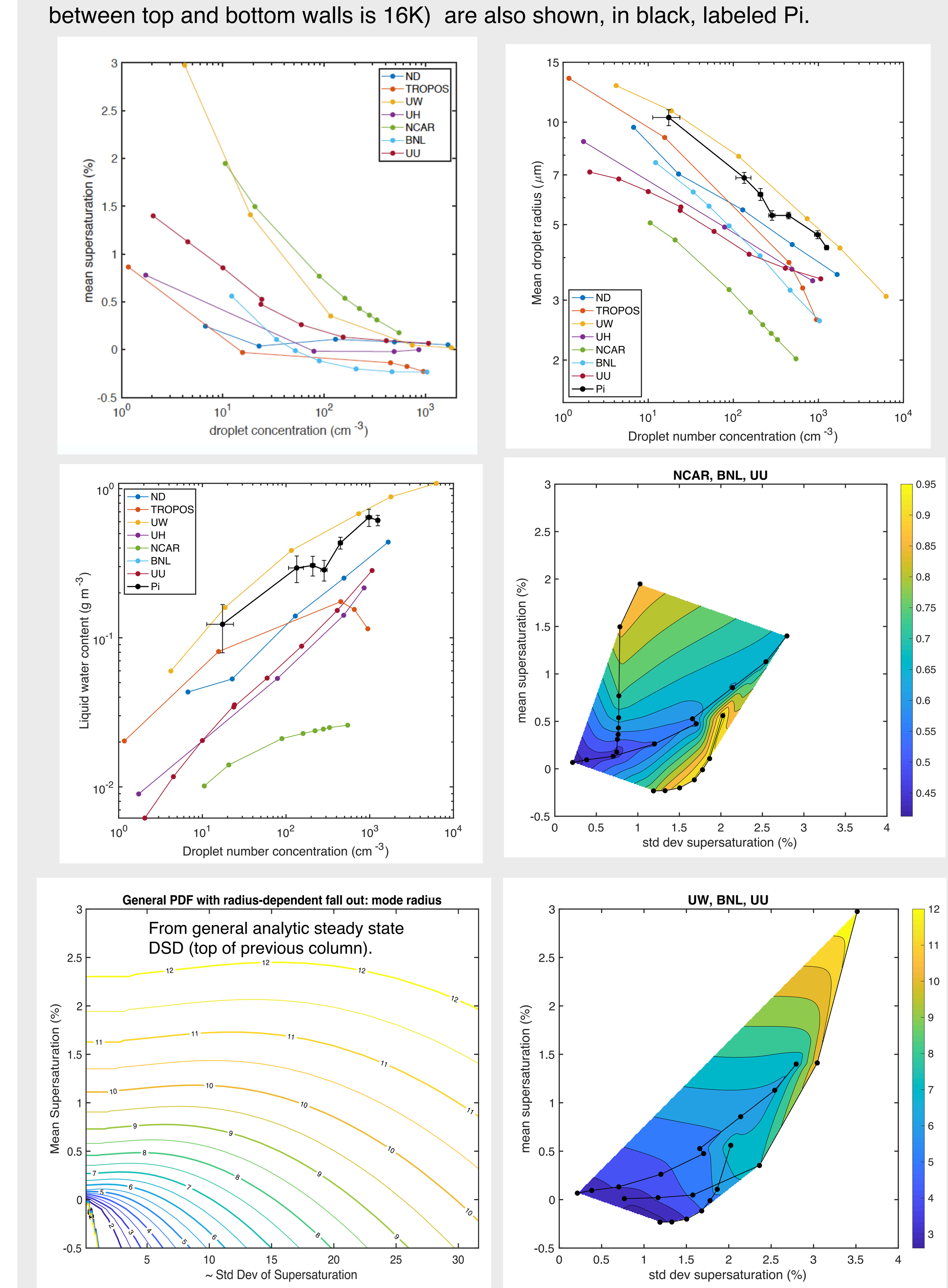
In the absence of fluctuations, the mean supersaturation, $\bar{s}$, in the Pi Chamber is a function of the mean temperature, $\bar{T}$, and mean water vapor mixing ratio, $\bar{q}$. The latter are determined by the net fluxes of sensible and latent heat from the walls and droplets.

We model the flux of $\bar{T}$, for example, as $-V(\bar{T} - T_{\mathrm{wall}})$, and determine the velocity scale V from the flux implied by the Nusselt number.

The net condensation rate (net vapor fluxes to droplets) is proportional to $\bar{s}$, droplet number concentration, N_d, and mean radius, $\bar{r}$, a function of $\bar{s}$ only. Given N_d, the model predicts $\bar{s}$, and therefore the DSD.

Steady-state Model Results

Pi Chamber measurements from 16K experiments (i.e., temperature difference between top and bottom walls is 16K) are also shown, in black, labeled Pi.



Summary

- The statistics of the numerical models, measurements, and theory agree qualitatively, but there are considerable differences in the quantitative results.
- The droplet radius PDFs agree qualitatively in shape and in dependence of mean radius on droplet number concentration.
- This dependence on droplet number concentration is a result of the changing balance of fluxes from the walls and droplets, as revealed by the theoretical bulk model.
- The mean (and fluctuating, not shown) supersaturation both increase as droplet number concentration decreases.
- The mean radius decreases and the LWC increases as both mean and fluctuating supersaturation increase.
- The activated fraction of particles increases as both mean and fluctuating SS increase.

Scan the QR code for references and further information.

ACKNOWLEDGEMENT. This material is partly based upon work supported by the National Science Foundation Science and managed by Michigan Technological University under Grant 2133229.