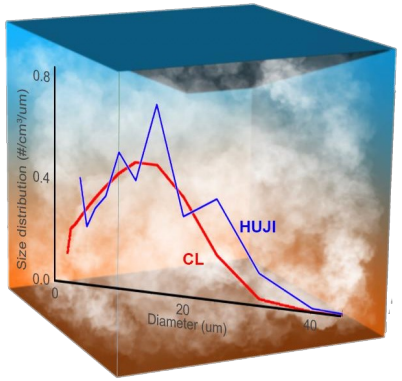
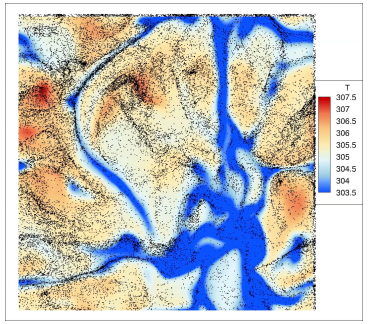
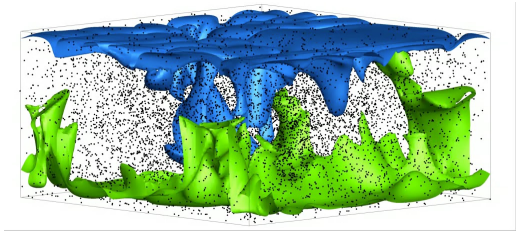
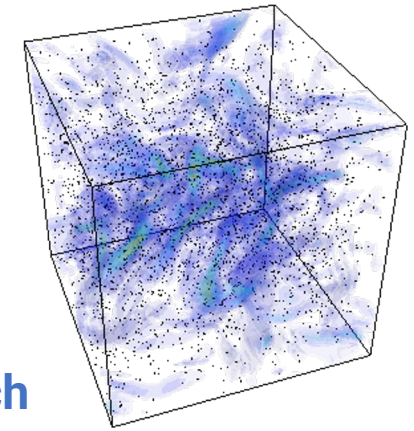
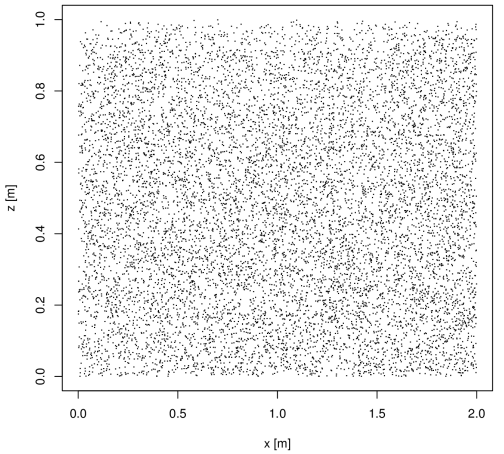


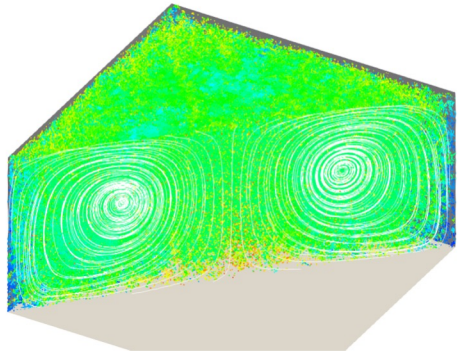





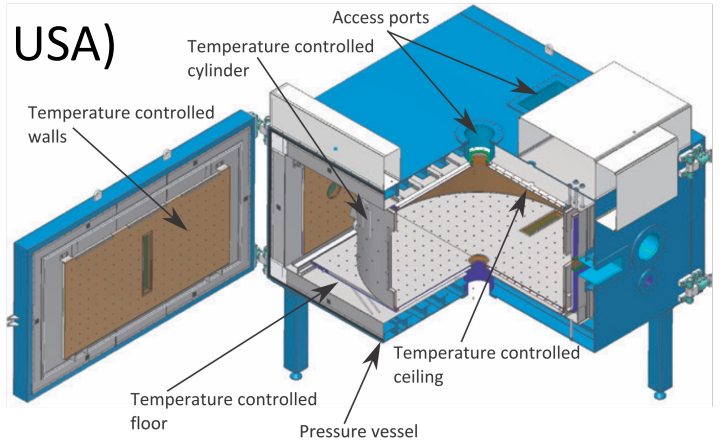



**Workshop on laboratory facilities for cloud research**
**Sep 22-24, 2021**



# Model intercomparison study of aerosol-cloud-turbulence Interactions in the Pi Chamber

Pi Chamber




Sisi Chen (NCAR, USA) and Steve Krueger (University of Utah, USA)

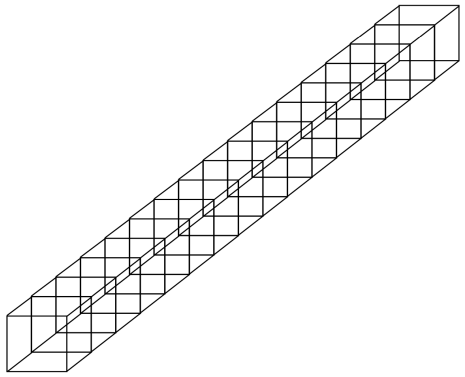
**Case participants:** Piotr Dziekan (University of Warsaw, Poland)

Silvio Schmalfuß (TROPOS, Germany)

Shin-ichiro Shima (University of Hyogo, Japan)

Fan Yang (Brookhaven National Laboratory, USA)

Theodore MacMillan and David Richter (University of Notre Dame, USA)



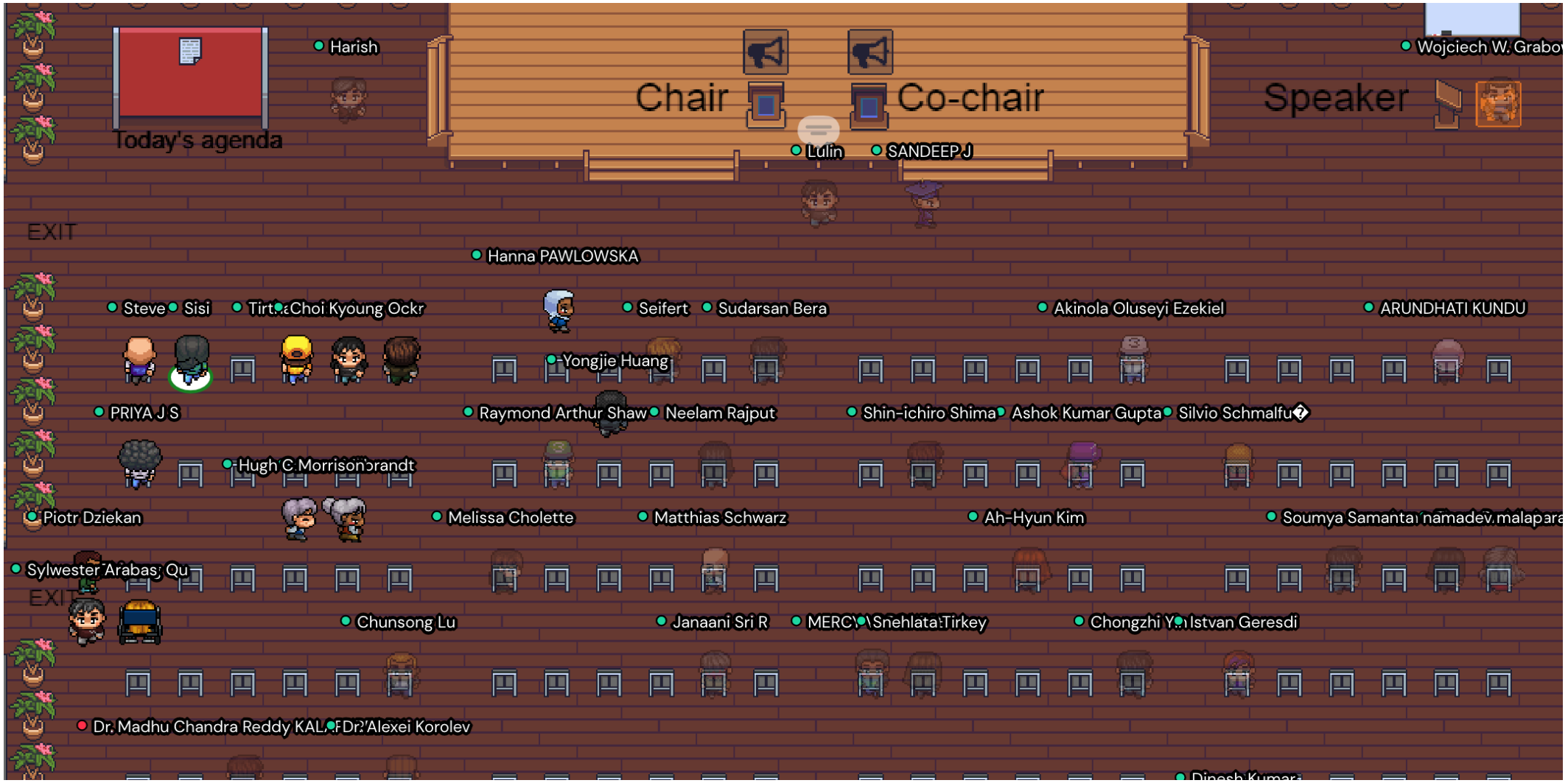
**Acknowledgement:** Raymond A. Shaw, Will Cantrell, Prasanth Prabhakaran, Subin Thomas (Pi Chamber Laboratory, Michigan Technological University, USA)

# Purpose of this presentation

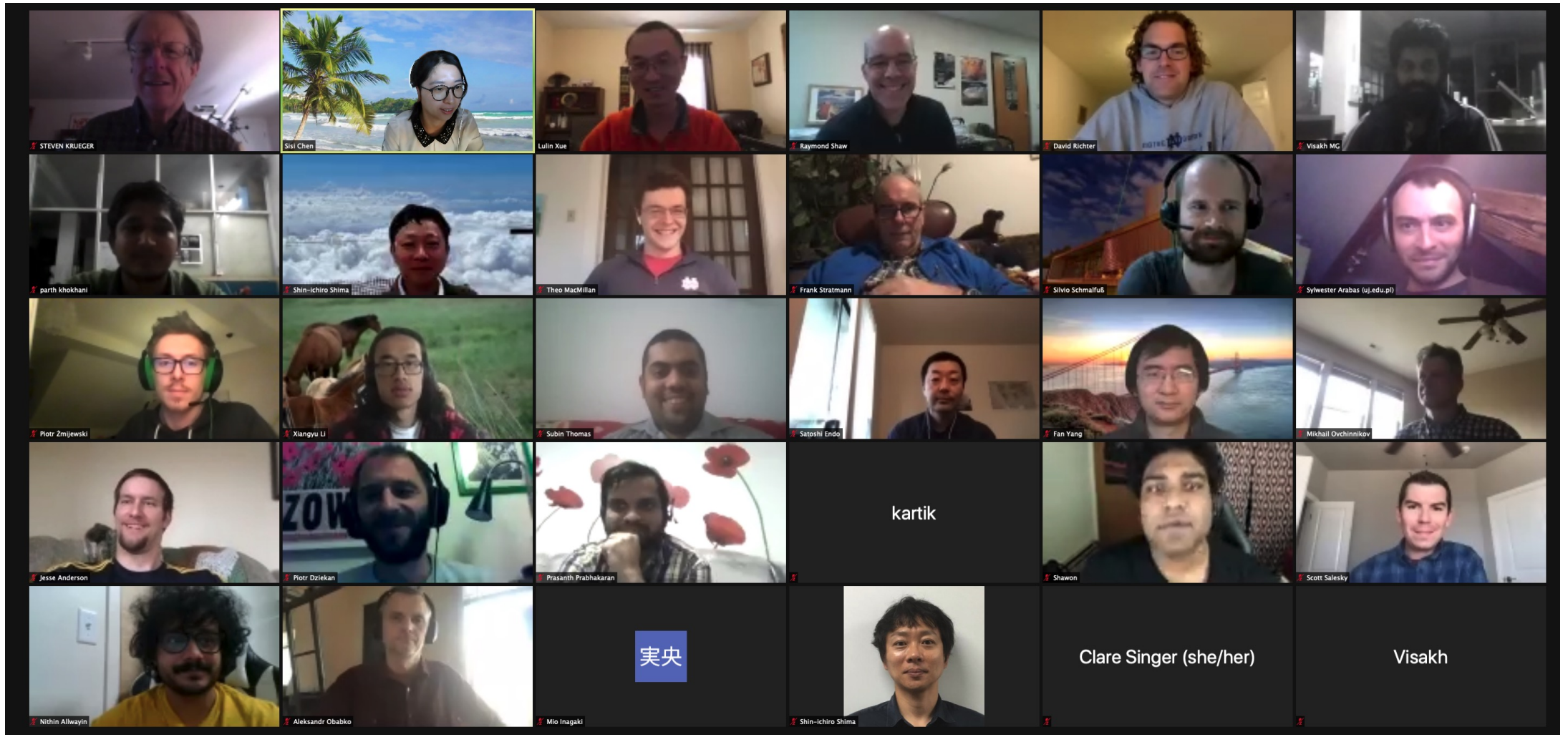
- Summary and future work of the model intercomparison study

- How laboratory facility could help improve cloud physics modeling
- How modeling can also provide insights for designing future cloud-aerosol laboratory facilities and new laboratory experiments.

# International Cloud Modeling Workshop, Jul 2021



# Pi Chamber Inter-comparison mini workshop in Nov 2020



# Motivation

- Cloud-aerosol-turbulence interactions in fine-scales are not well-understood.
- Cloud chamber measurements are valuable for comparing to simulations given the chamber's well-characterized boundary conditions, controlled environment, detailed microphysical & thermodynamic properties, etc.
- High-resolution models provide detailed information that is challenging to obtain by measurements.
- In the long run, comparing the results of high-resolution models to laboratory measurements helps to verify physics in the model. And the well-validated models in return can be used to better understand the details of physical processes that are challenging to measure with existing instruments.

# Pi Chamber

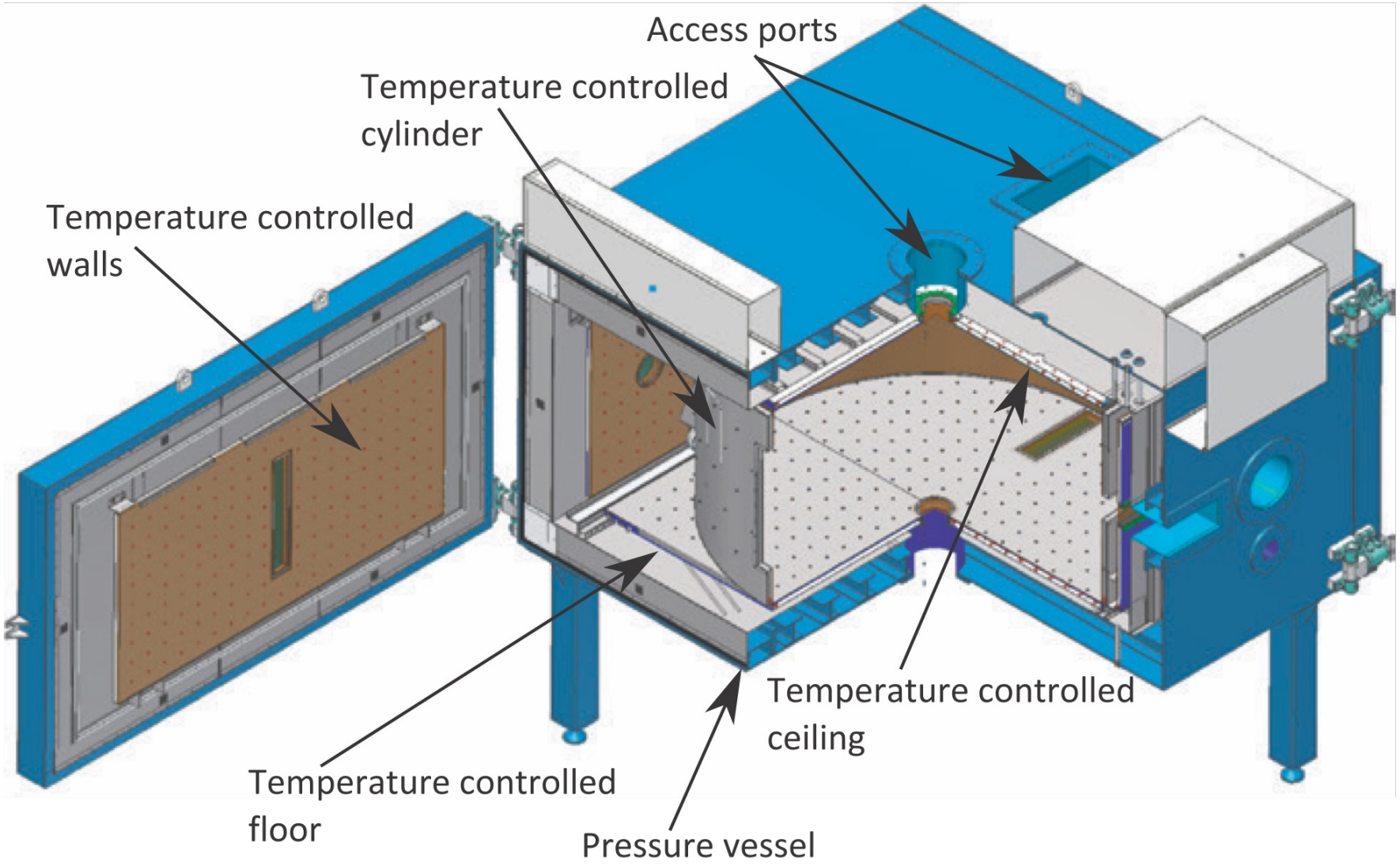
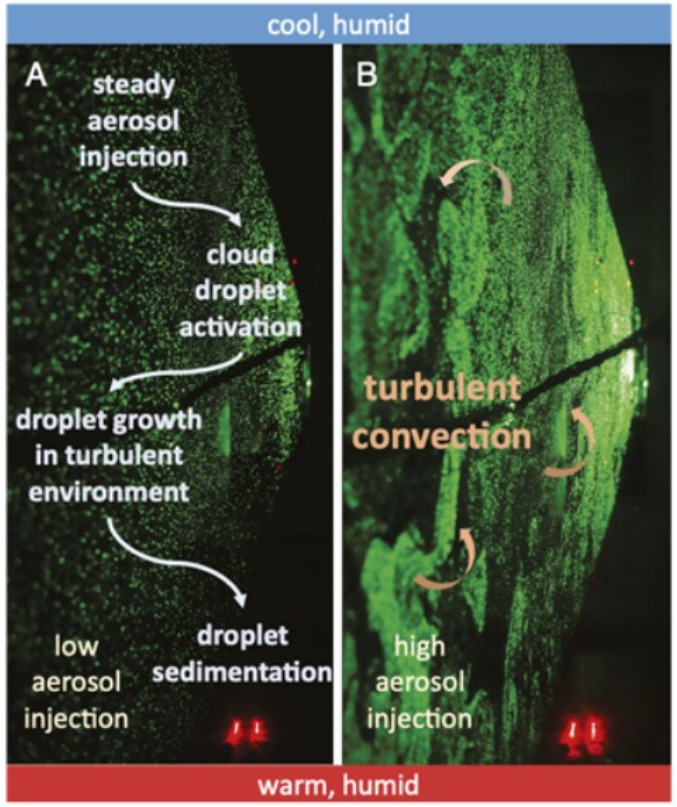



**FIG. 1. A cutaway schematic of the cloud chamber with one door open and the cylindrical thermal panel in place.**

# Model intercomparison case

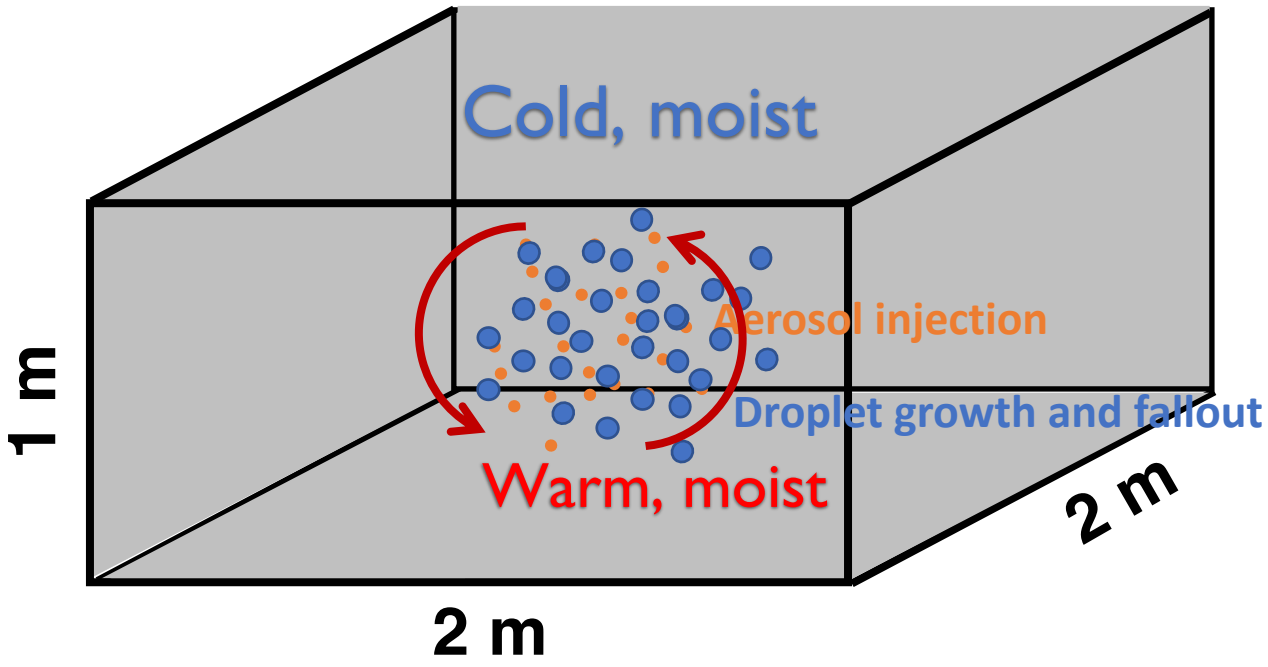



Interior snapshot of the Pi Chamber

**Steady-state case in the Pi Chamber**

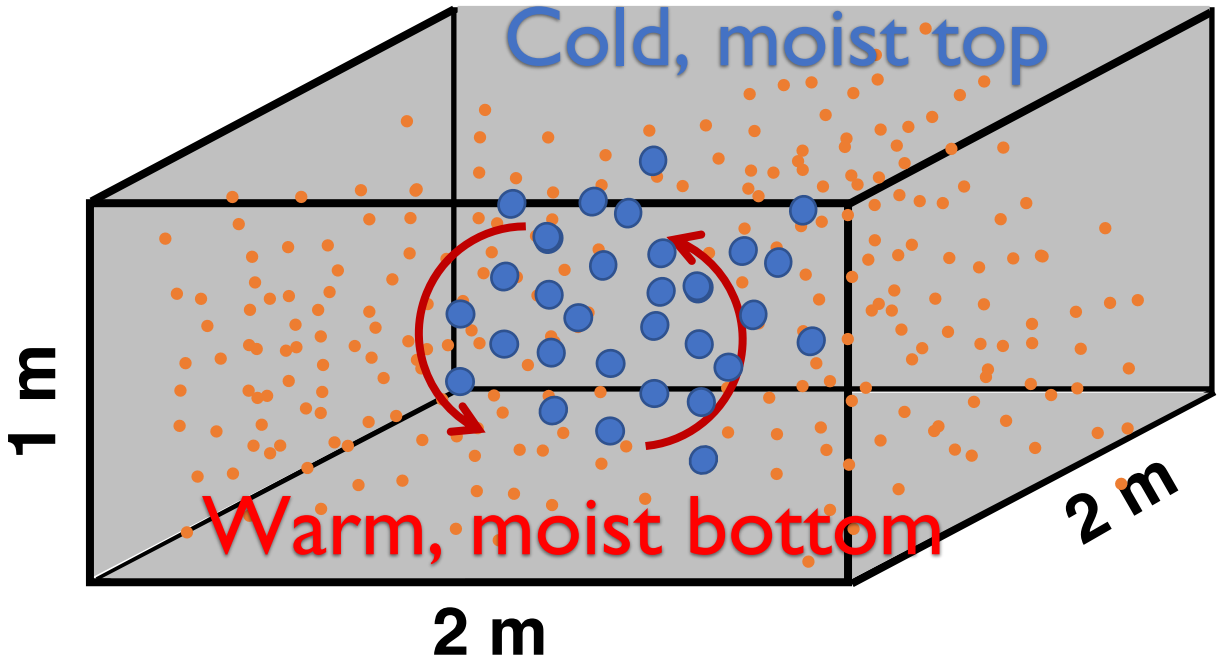
- Steady aerosol injection (prescribed injection rates)
- Thermostatic wall conditions (fixed wall temperature and near wall humidity)
- Steady-state droplet size distribution
- Steady-state thermal and turbulent environment

# Steady-state case in the Pi Chamber




- **Temperature is controlled at all walls** (bottom, top, and sides).
- **Turbulence** is generated by the vertical temperature gradient.
- **Supersaturation is produced** by mixing of air saturated at $T_{bot}$ and $T_{top}$
- **Constant aerosol injections.**
- **Droplets grow and fall out.**

# Steady-state case in the Pi Chamber




- **Temperature is controlled at all walls** (bottom, top, and sides).
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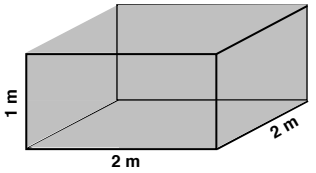
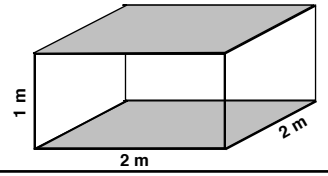
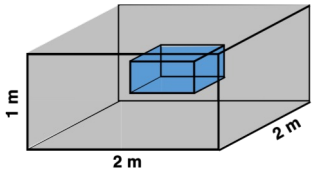
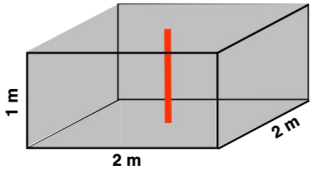
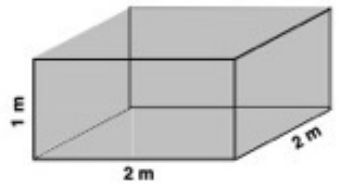
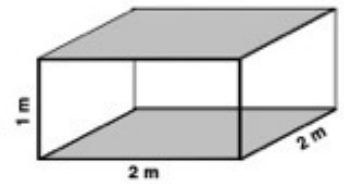
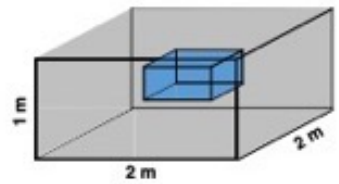
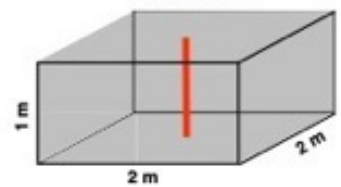
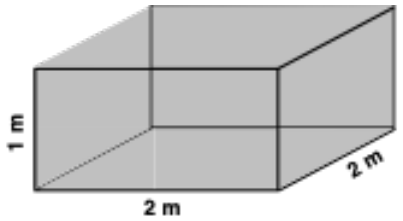
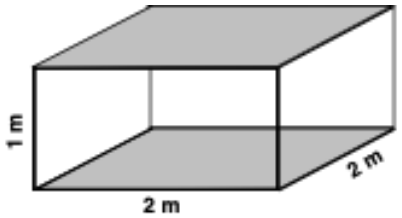
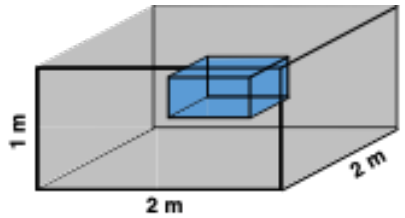
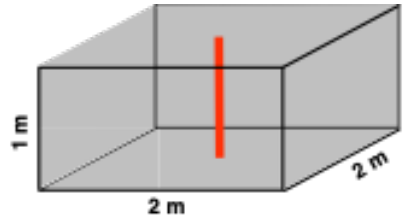
- **Supersaturation is produced** by mixing of air saturated at $T_{bot}$ and $T_{top}$
- **Constant aerosol injections.**
- **Droplets grow and fall out.**

# Participating modelers

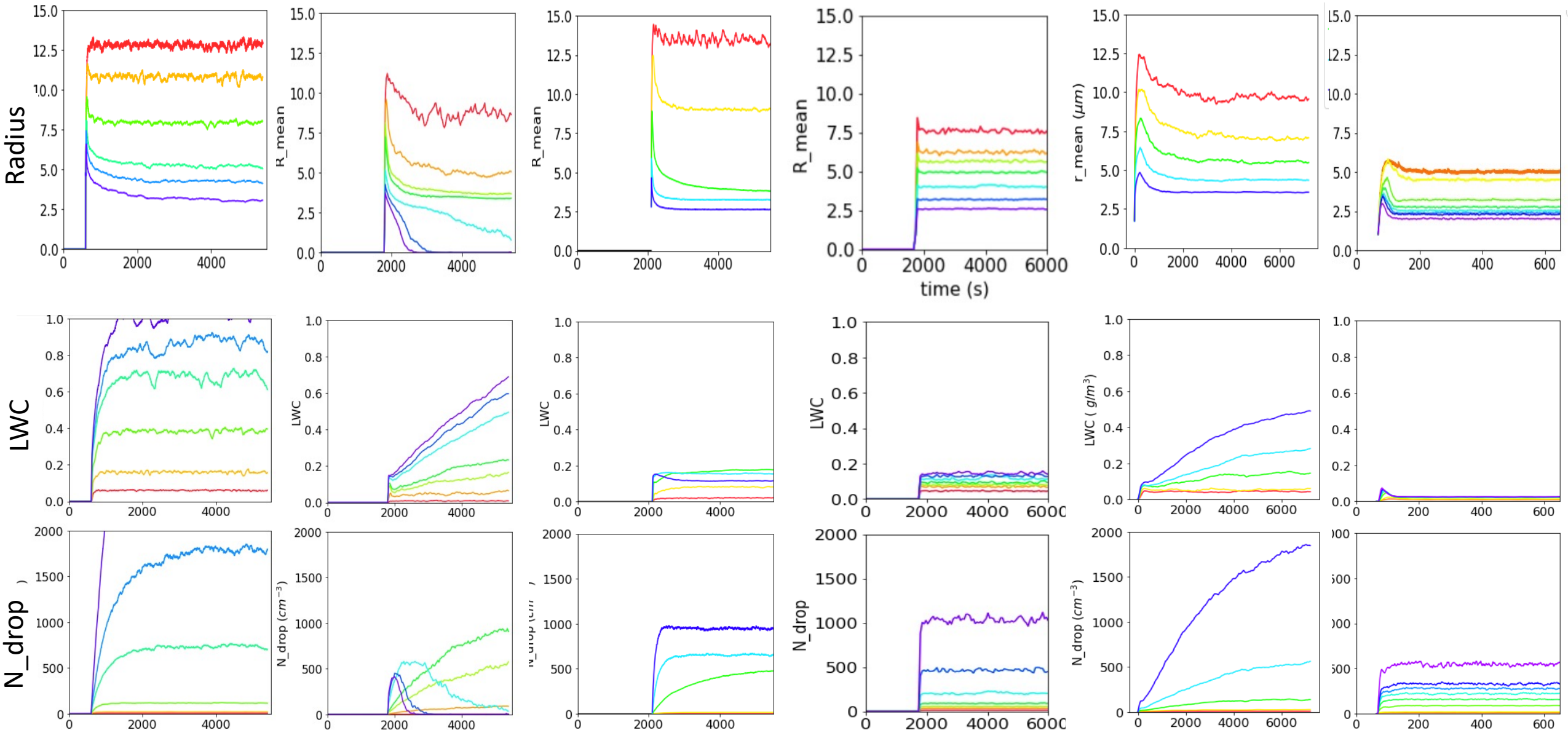
| Model Type | Participants | Model Name | Simulated Chamber Geometry |
|---|---|---|---|
| **LES** | **Piotr Dziekan** (University of Warsaw) | UWLCM |  |
| | **Shin-ichiro Shima** (University of Hyogo) | SCALE-SDM | |
| | **Silvio Schmalfuß** (Leibniz Institute for Tropospheric Research) | TROPOS-LES | |
| | **Fan Yang** (Brookhaven National Laboratory) | SAM | |
| **DNS** | **Theodore MacMillan/ David Richter** (University of Notre Dame) | DNS |  |
| | **Sisi Chen** (NCAR) | DNS |  |
| **1D-LEM** | **Steve Krueger** (University of Utah) | EMPM (1D) |  |

| Model Type | Participanting institute | Model Name | Simulated Chamber Geometry/region |
|---|---|---|---|
| Large-eddy simulation (LES) | University of Warsaw, Poland | UWLCM | The entire chamber with top, bottom, and side walls   |
| | University of Hyogo, Japan | SCALE-SDM | |
| | Leibniz Institute for Tropospheric Research, Germany | TROPOS-LES | |
| | Brookhaven National Laboratory, USA | System for Atmospheric Modeling (SAM) | |
| Direct numerical simulation (DNS) | University of Notre Dame, USA | UND-DNS | The entire chamber without side walls   |
| | National Center for Atmospheric Research, USA | NCAR-DNS | The core region of the chamber   |
| 1D Linear-eddy model (1D-LEM) | University of Utah, USA | EMPM | One-dimensional vertical column of the chamber   |

| Model Type | Participanting institute | Model Name | Simulated Chamber Geometry/region | Aerosol injection rates ( $cm^{-3}\ min^{-1}$ ) | dx, dy, dz (cm) | Microphysics scheme |
|---|---|---|---|---|---|---|
| Large-eddy simulation (LES) | University of Warsaw, Poland | UW-LCM | The entire chamber with top, bottom, and side walls   | 6-600 | 3.125 | super-droplet method (SDM) |
| | University of Hyogo, Japan | SCALE-SDM | | 1-1500 | 6.25 | SDM |
| | Leibniz Institute for Tropospheric Research, Germany | TROPOS-LES | | 1-1500 | 3.125 | SDM |
| | Brookhaven National Laboratory, USA | System for Atmospheric Modeling (SAM) | | 15-4500 | 3.125 | two bin schemes (Chen & Lamb; HUJI) |
| Direct numerical simulation (DNS) | University of Notre Dame, USA | UND-DNS | The entire chamber without side walls   | 15-1500 | dx, dy = 1.5625; dz = 0.78125 | SDM and particle-by-particle method |
| | National Center for Atmospheric Research, USA | NCAR-DNS | The core region of the chamber   | 50-5000 | 0.15625 | SDM and particle-by-particle method |
| 1D Linear-eddy model (1D-LEM) | University of Utah, USA | EMPM | One-dimensional vertical column of the chamber   | 10-320 | 1 | particle-by-particle method |

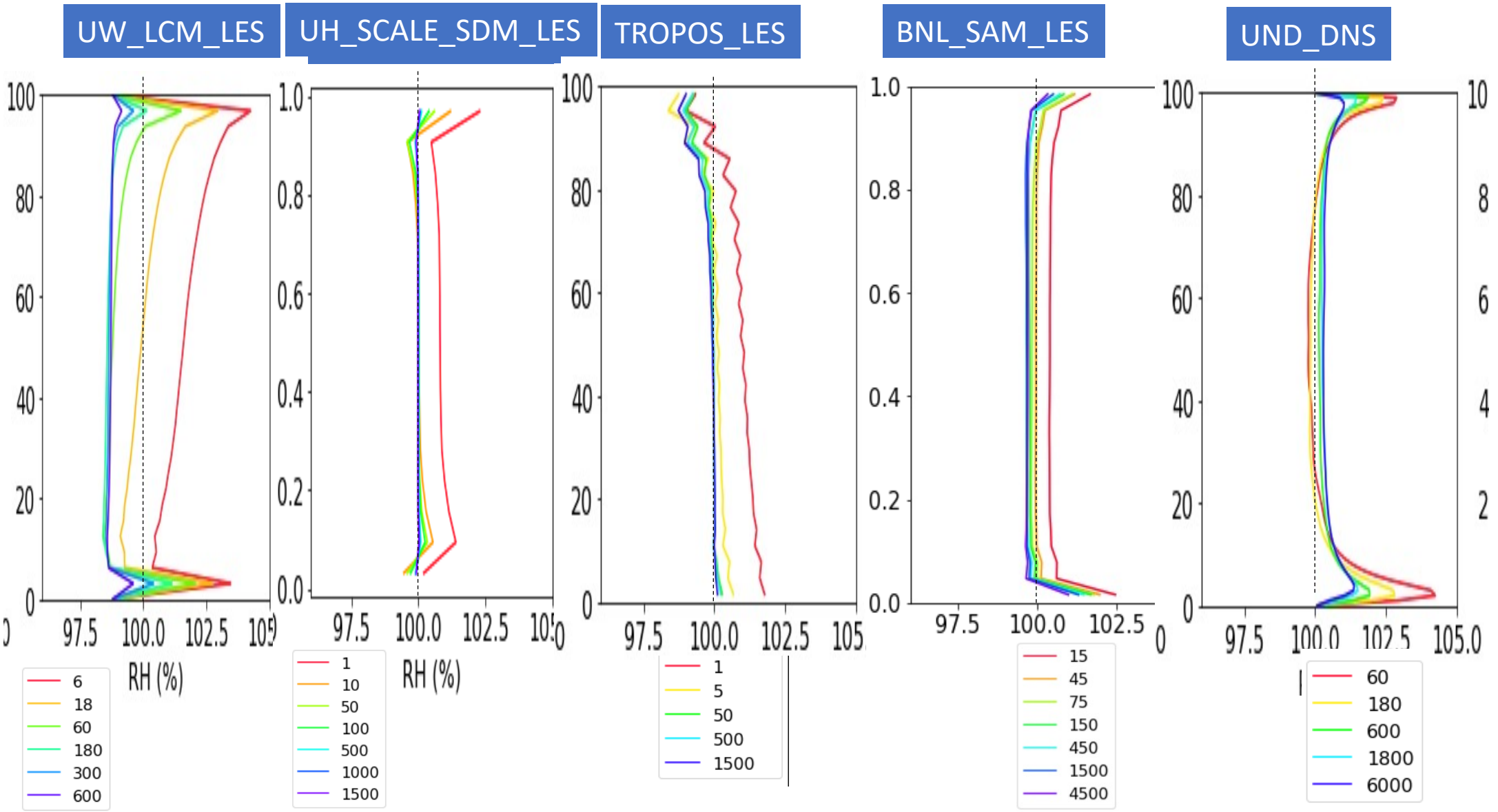
UW_LCM_LES | UH_SCALE_SDM_LES | TROPOS_LES | BNL_SAM_LES | UND_DNS | NCAR_DNS

**Low injection rates → High injection rates**



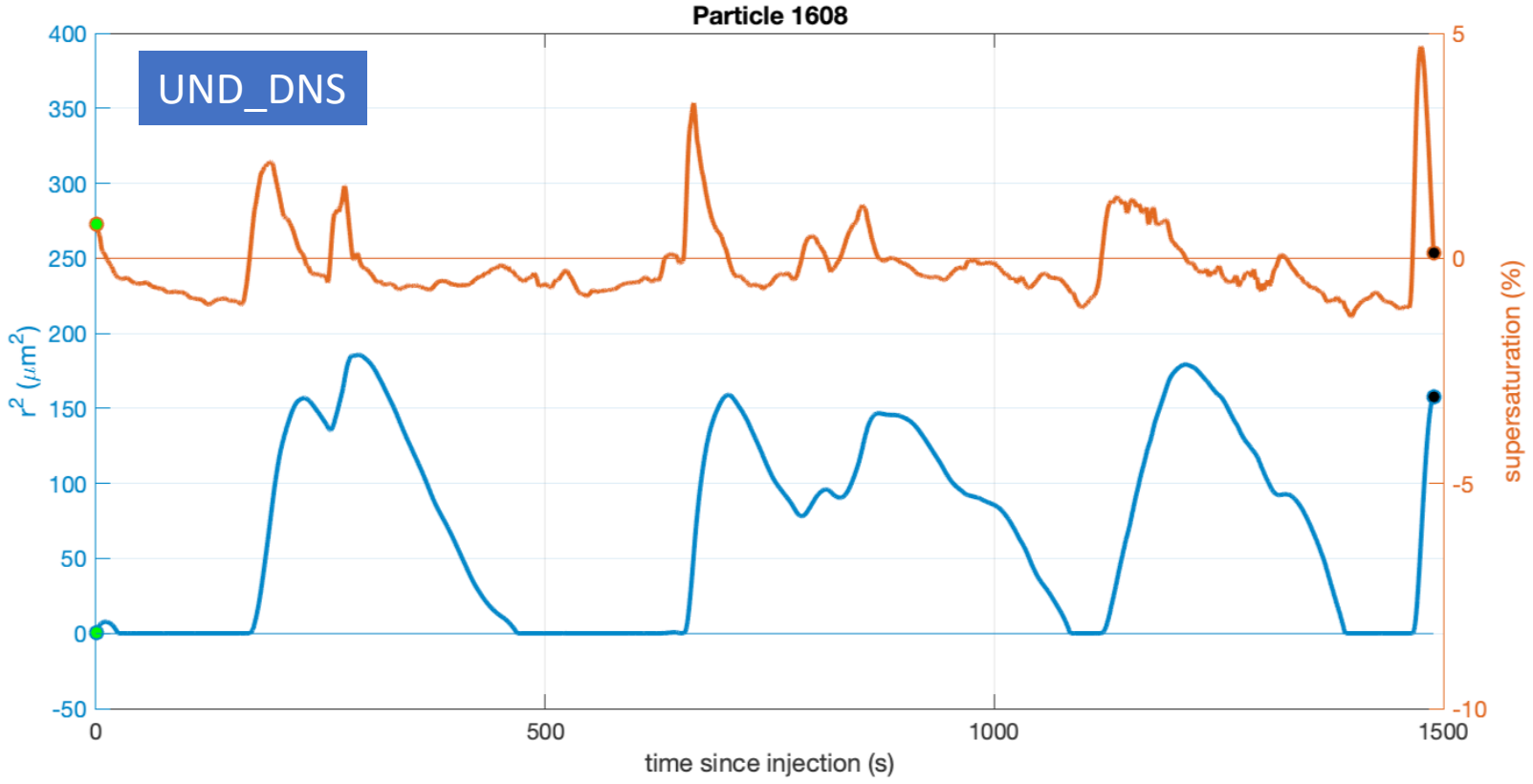
# RH vertical profiles

**clean → polluted**



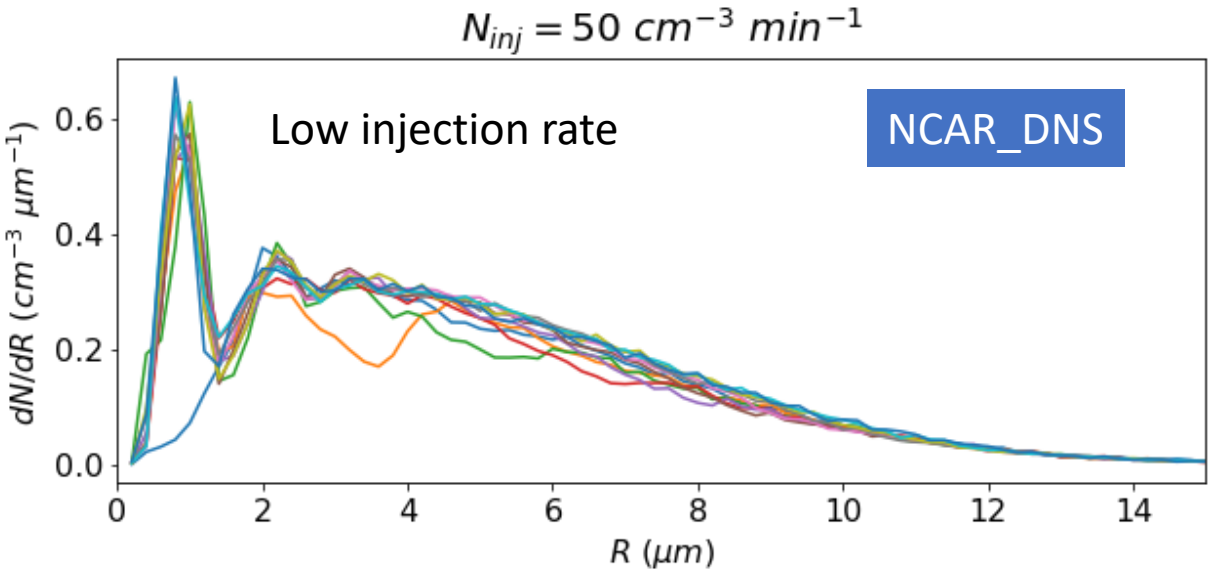
# Droplets' Lagrangian history

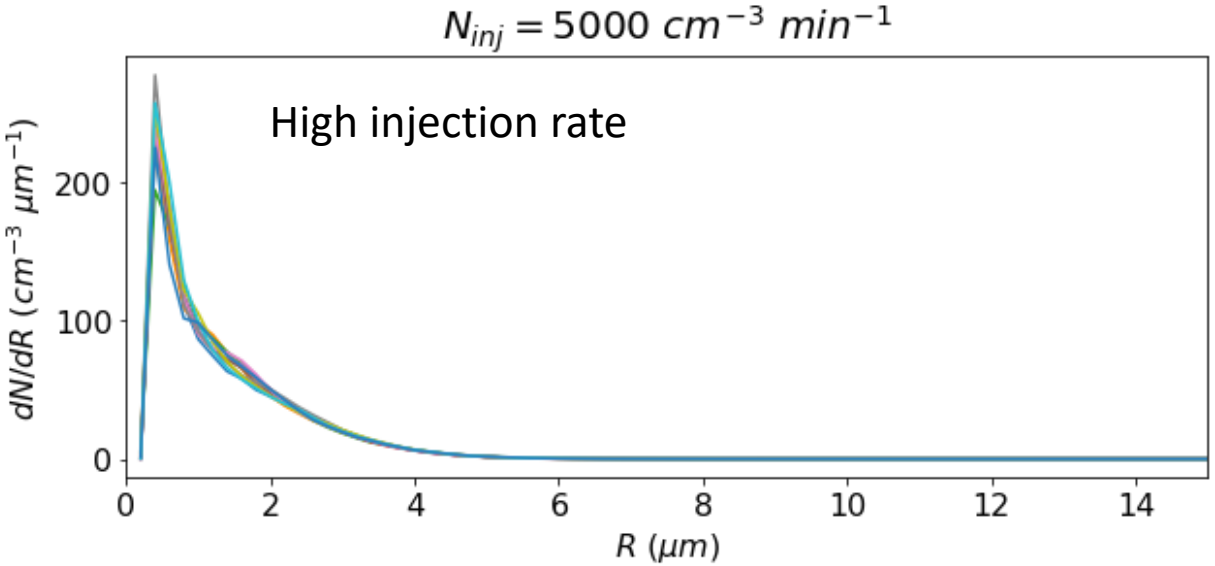
$r^2$ of an individual droplet along its trajectory,
and the supersaturation at droplet's location

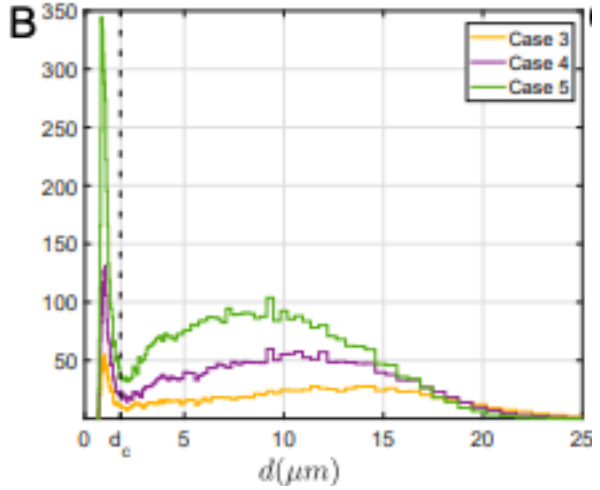



When the supersaturation is fluctuating, a particle may grow and shrink many times before falling out.

# DSDs responding to aerosol injections (NCAR DNS)

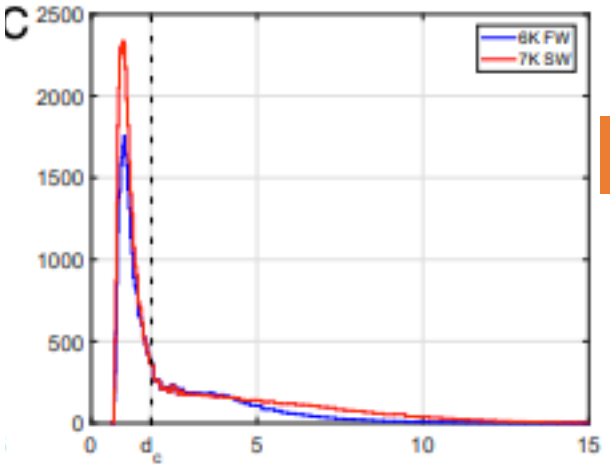


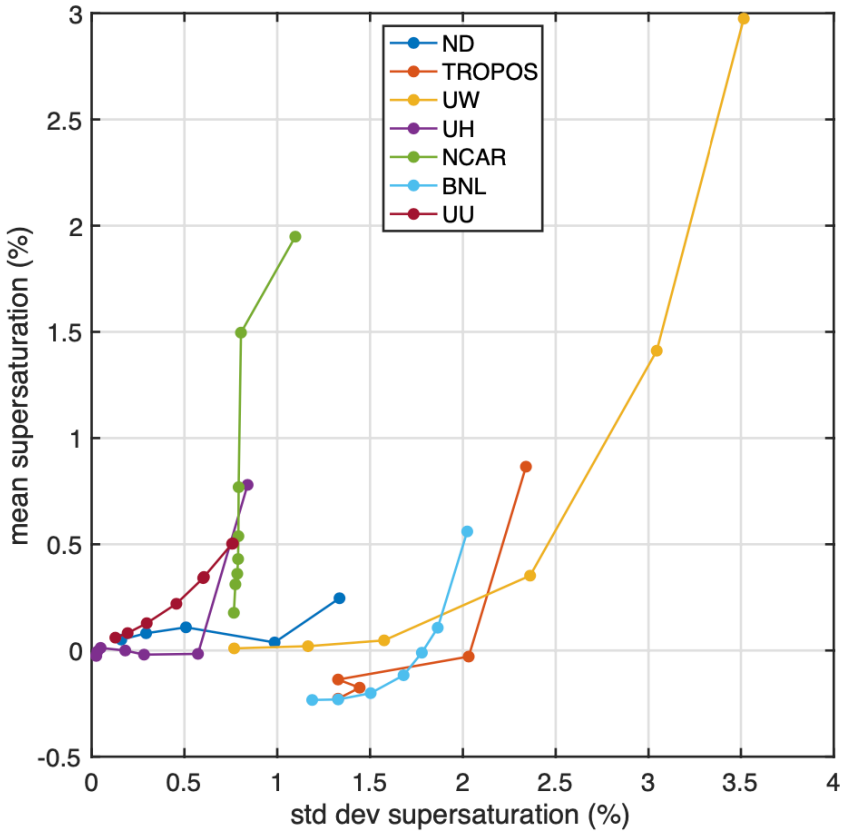

Pi chamber measurements
Prabhakaran et al. (2020 PNAS)

Fluctuation-influenced regime

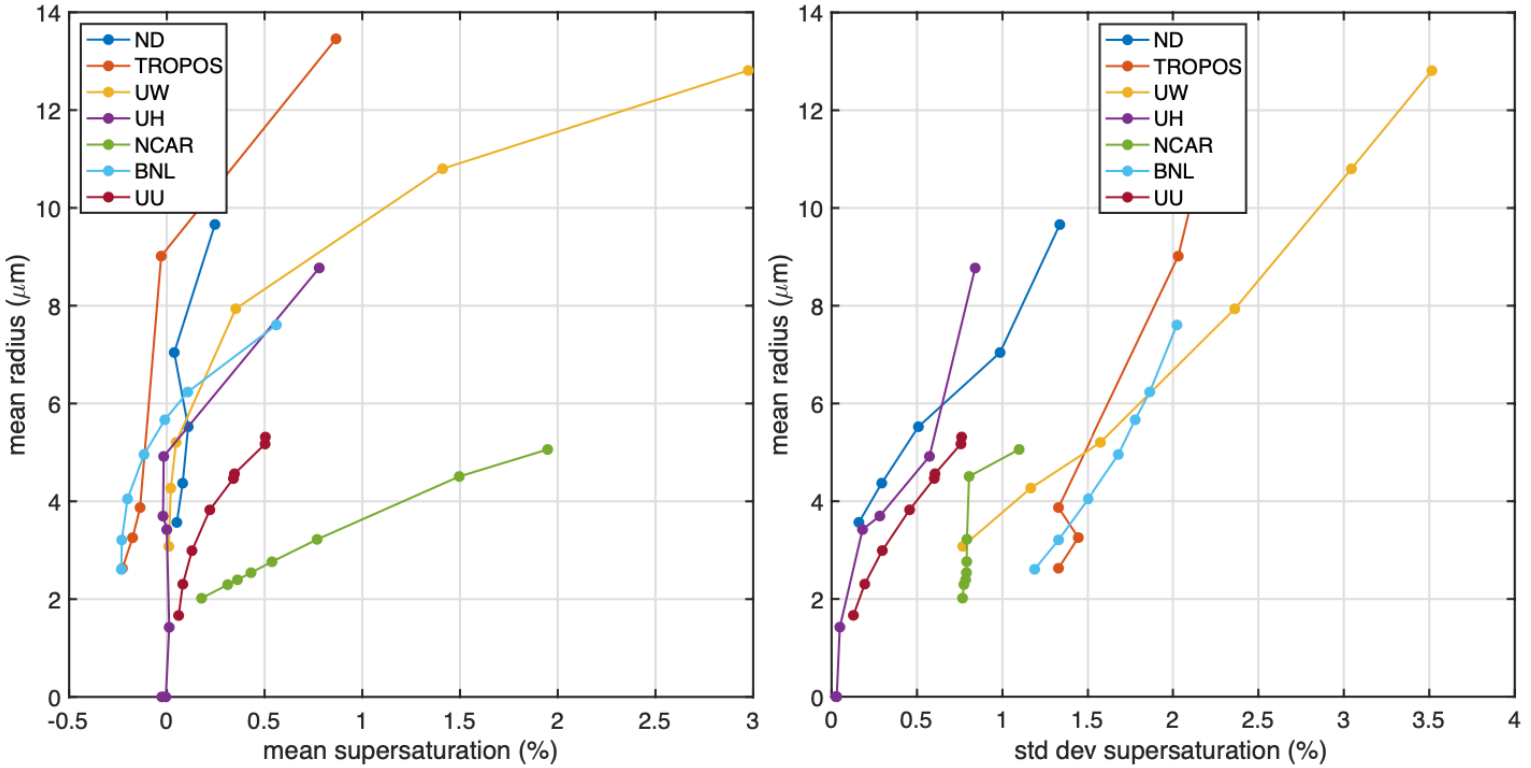



Fluctuation-dominated regime

**Different models occupy different regions of <s>-<s'>** space




**Mean radius depends on both <s> and <s's'>**

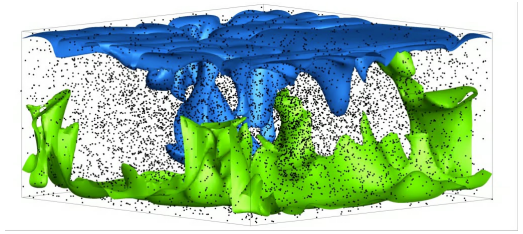



Different models occupy different regions of mean supersaturation <s> and fluctuations <s's'> space

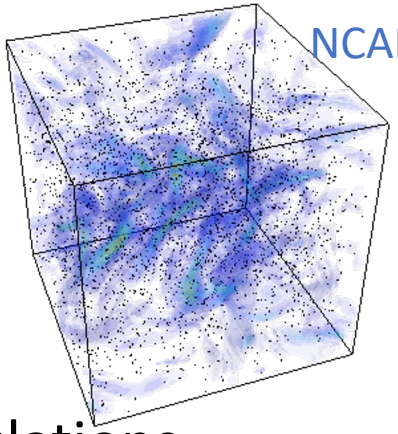
The mean radius depends on both <s> and <s's'>

# Summary

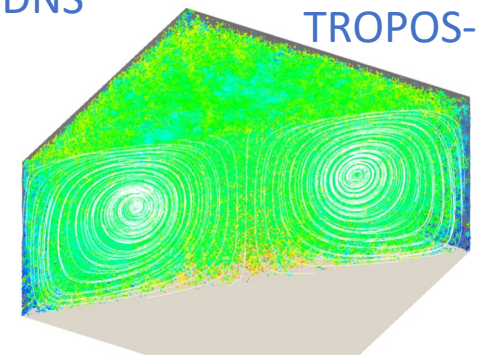
UND-DNS



NCAR-DNS

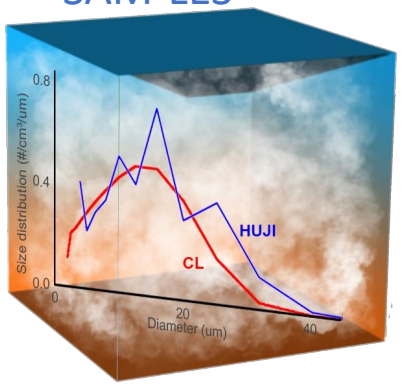


TROPOS-LES

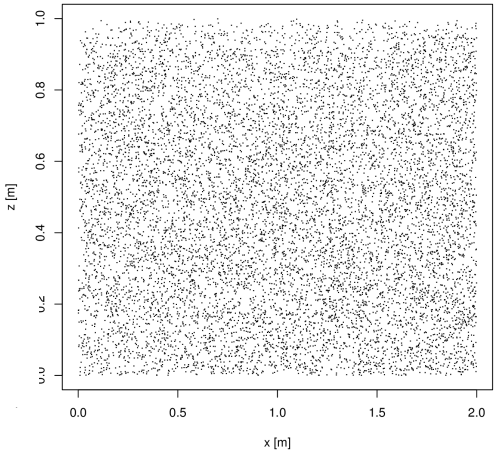


- First inter-comparison study on cloud chamber simulations
- A diverse set of model geometries
- Various microphysics schemes
- Each model inhabits different regions of <s>-<s’s’> space.
- Both of <s> and <s’s’> are important for determining the DSD, and neither dominates.
- The processes that determine LWC, DSD shapes, Nd, etc. in the Pi Chamber remain poorly quantified in simulations and measurements.
- The model results exhibit numerous differences that are not yet well understood.

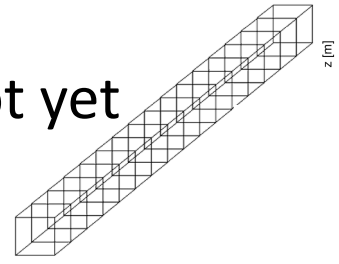
SAM-LES




SCALE-SDM




EMPM



# Future work

- Further analyze the simulated wall fluxes and the particle settling timescales
- Investigate the role of large-scale circulations inside the chamber
- Perform Lagrangian microphysics analysis
- Obtain more measurements from Pi Chamber to evaluate the model results
- Perform model-observation comparisons