PI Chamber Simulation Case: Modeling Aerosol-Cloud-turbulence Interactions in the Cloud Chamber

Last updated on Oct 27, 2020

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New timeline

Dec, 2019	**Announcements & invitations**
Feb, 2020	**Confirmation of participation**
Oct 12, 2020	**Results received from the participants**
Oct-Nov, 2020	**Data post-processing & communication with participants**
21:00-24:00 UTC Nov 16-17, 2020	**Online workshop for current participants**
Post online workshop	**Report summarizing the case**
Summer 2021	**International Cloud Modeling Workshop**
Post workshop	**Paper summarizing the case**

Agenda

Agenda of ICMW Virtual Workshop: Pi Chamber Case

Time 21:00 – 24:00 UTC Monday, Nov 16, 2020 (3 hours)

The workshop will take place via Zoom. It will start at:

- 1:00 p.m., Nov 16 US PT (Seattle)
- 2:00 p.m., Nov 16 US MT (Boulder)
- 4:00 p.m. Nov 16 US ET (New York, Houghton)
- 9:00 p.m., Nov 16 UTC / GMT
- 10:00 p.m. Nov 16 Berlin, Warsaw
- 2:30 a.m. Nov 17 Pune
- 5:00 a.m. Nov 17 Beijing
- 6:00 a.m. Nov 17 Kobe

The duration of the workshop will be about 3 hours. It will include three sessions with opening keynote, case discussions, and invited presentations, see agenda below:

UTC time (duration)	Session	Speaker(s)

21:00-21:15pm (15min)	Welcome & updates on ICMW 2021 plan	Steven Krueger *University of Utah* Sisi Chen, Lulin Xue *NCAR*
21:15-21:45pm (30min)	Keynote on Pi Chamber	Raymond Shaw *Michigan Technological University*
21:45-21:50pm (5min)	Break	
21:50-23:00pm (1hr10min)	Intercomparison study discussion	All participants
23:00-23:05pm (5min)	Break	
23:05-23:20 pm (15min)	Invited talk on Turbulent Leipzig Aerosol Cloud Interaction Simulator (LACIS-T)	Silvio Schmalfuß *The Leibniz Institute for Tropospheric Research (TROPOS)*
23:20-23:35 pm (15min)	Invited talk on University of Warsaw Lagrangian Cloud Model (UW-LCM)	Piotr Dziekan *University of Warsaw*
23:35-23:50 pm (15min)	Invited talk on Pi Chamber transient case	Theodore MacMillan *University of Notre Dame*
23:50-24:00 pm (10min)	Closing	

Case coordinators:

Dr. Sisi Chen (sisichen@ucar.edu)
Dr. Steven Krueger (Steve.Krueger@utah.edu)

Group mailing address: icmw2021-pi-chamber-case@googlegroups.com

Case overview

Motivation

- Cloud-aerosol-turbulence interactions in fine scales are not well-understood. Cloud modeling contains a large uncertainty from microphysical parameterizations.
- Due to the chaotic nature of clouds, in-situ measurement of cloud microphysics properties often comes with large uncertainty and the condition during measurement is often not controllable. Therefore, finding a good case based on measurements to compare with model results is challenging.
- Measurements for creating and evaluating parameterizations are sparse, boundary conditions are often poorly constrained, and atmospheric systems are rarely statistically stationary.
- Therefore, a turbulent mixed-layer formed within a cloud chamber provides an ideal environment for comparing measurements to simulations. Many of the thermodynamic, turbulence and microphysical properties in the Pi Chamber are comparable to those observed in stratocumulus clouds. The experiments also have reasonably well-characterized boundary conditions and achieve a statistical steady-state, and the detailed aerosol, cloud, and thermodynamic properties are available.
- On the other hand, high-resolution modeling provides alternative tools to look at small-scale cloud processes unresolved by traditional cloud models.
- 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 model in return can be used to better understand the details of physical processes that are challenging to measure with existing instruments.

Objective

- The objectives of the base cases in this case study are to answer:
    - What are the key processes/parameters that impact the shape of the droplet size distribution (DSD), e.g., turbulence, fluctuation of supersaturation, mean supersaturation, aerosol number concentration, droplet sedimentation and fall out, and the interactions of the above processes?
    - How do the size distribution properties vary as the aerosol injection rate is changed? Do they capture the observed dispersion indirect effect?
    - Can simulations qualitatively or quantitatively capture the steady-state cloud droplet size distribution with realistic properties?
- The objectives of the variation cases are to determine:
    - How sensitive are the model results to the variation/perturbation of the initial conditions/model configurations?
    - What is the model uncertainty due to the level of uncertainty in the measurements?
- By model comparisons, we aim to figure out:
    - What are the key differences in the results of different models when imposing the same set of constraints from laboratory measurements? What causes the differences?

    - How can we justify/mitigate the divergence between the model results.
    - What are the implications for model parameterization/development at sub-grid scales?
- Out of this case study, we will formulate a test case for future model development & verification.

Introduction to the Pi chamber facility

What is the PI Chamber?

The Pi chamber is a turbulent, multiphase reaction chamber developed at Michigan Technological University. The cloud chamber is capable of generating and sustaining cloud formation in simulated tropospheric conditions for minutes to days.

Chamber schematics & capacity

Schematics of the PI Chamber structure are illustrated below (Figure 1 and Figure 2). The pressure shell is rectangular. The internal volume is 1 m high and 2 m wide. Two front-opening hinged doors give full access to the internal workspace. The thermal panels, which regulate the temperature within the chamber, are controlled on three separate circuits, corresponding to the top, bottom, and sidewall sections of the chamber internal workspace. All panels are capable of maintaining thermostatic conditions. For more detailed technical specification, see Chang et al. (BAMS 2016) https://journals.ametsoc.org/doi/full/10.1175/BAMS-D-15-00203.1

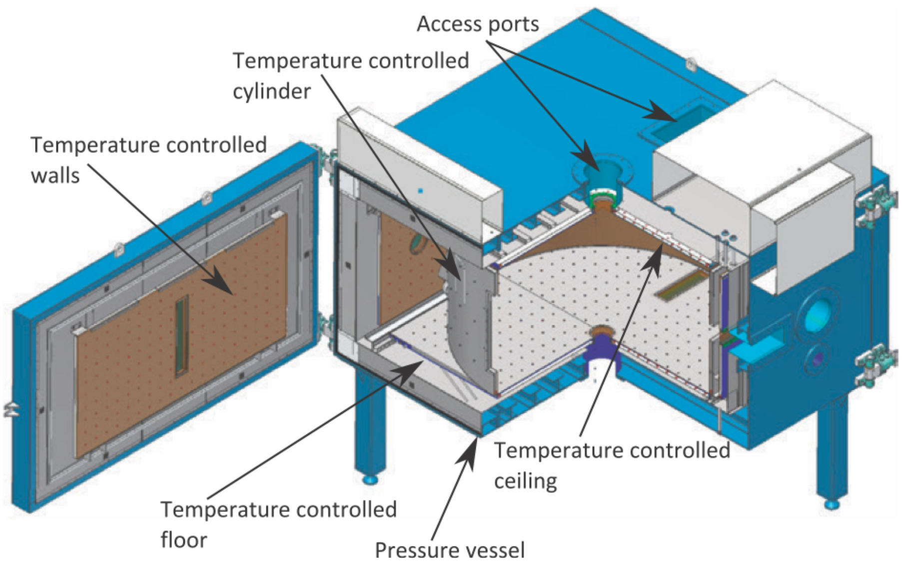

FIG. 1. A cutaway schematic of the cloud chamber with one door open and the cylindrical thermal panel in place.

Fig.1: Cutaway view of the PI Chamber (Chang et al., 2016)

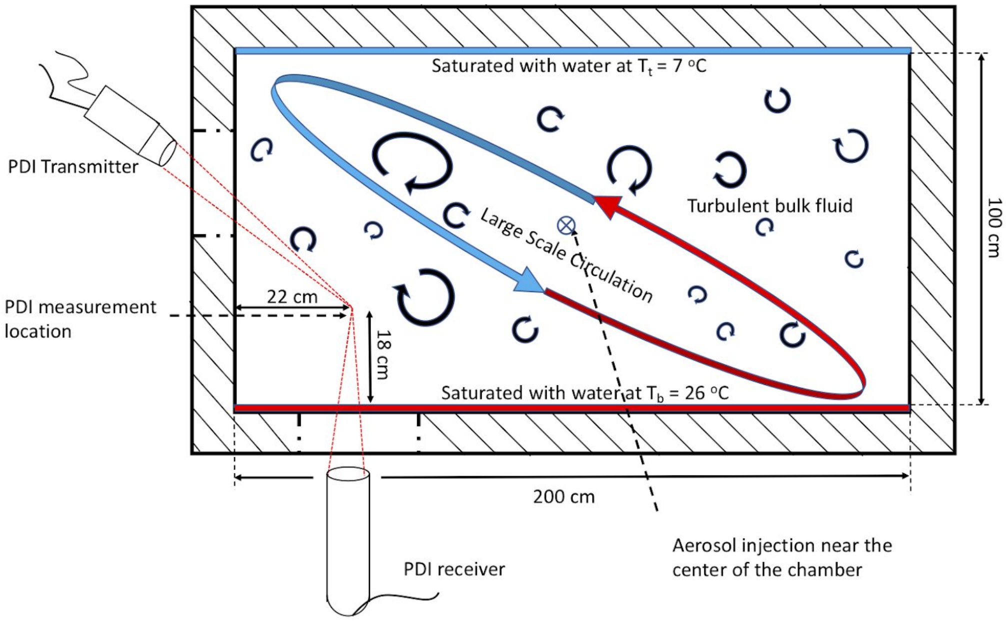

Fig. 2: Vertical cross-section of the PI Chamber (Chandrakar et al., 2019 QJRMS)

The chamber is also accompanied by a suite of instrumentation allowing for the generation and characterization of aerosol and cloud particles, measurement of thermodynamic and turbulence conditions, and sampling of particles for subsequent chemical and morphological analysis.
The research problems that can be addressed with this facility range from aerosol formation and optical properties to turbulent clouds and ice nucleation. Fig. 3 illustrates the spatial structures of aerosol and cloud drop distribution inside the chamber corresponding to different aerosol injection rates.

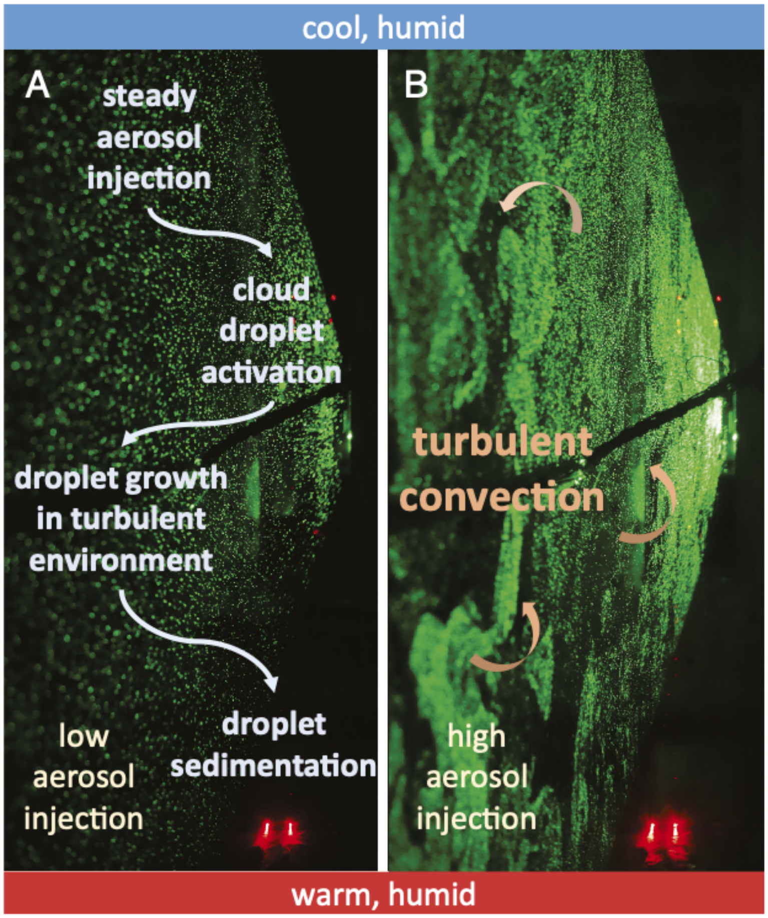

Fig. 3. Snapshot inside the PI Chamber with aerosols injected (Chang et al. 2016 BAMS)

Case description

The cases proposed here are focused on cloud-aerosol-turbulence interactions in a warm cloudy environment, i.e., no ice particles. Modeling results from DNS, LES, and other numerical/theoretical models are all welcome.

Two **base cases** are provided, with an emphasis on the steady state.

1) Steady-state case (primary emphasis)
Aerosols are constantly injected with a prescribed injection rate to form a steady-state droplet size distribution (DSD) in a steady-state thermal and turbulent environment, given the thermostatic wall conditions, i.e., fixed wall temperature and near wall humidity. The detailed numerical configurations are listed in the Section of "*Model configuration for the steady state case*"

2) Transient state case (optional)
Aerosol injection is switched off after the steady-state is achieved. The boundary condition and turbulent intensity, i.e., any forcing will remain the same except for the aerosol injection is switched off.

3) We also highly recommend that the participants perform some **variation cases** to look at **the response/sensitivity to various processes/conditions within each model**:
Examples of variations/perturbations in the configuration/parameters are turbulence intensities, $\bar{Q}v, \bar{T}$, Qv', T', aerosol size/composition, switch on/off collision-coalescence, model resolution, microphysics schemes (bin, bulk, and Lagrangian particles), with/without droplet losses due to contacting the side walls, and results on DSDs with/without the sidewall, etc.

Results from the two base cases will be used to do inter-model comparisons. For the attendants presenting in the workshop, **model results of the steady-state case are required.**

1) Model configuration for the steady state case

No droplet collision-coalescence in the base cases (both steady-state case and transient case), and droplets grow by condensation only. We mainly provide the configurations for DNS and LES models. Attendants may adjust configurations for other types of models accordingly.

1.1) DNS simulating the core region of the chamber

Assume homogeneous and isotropic turbulence in the core region of the PI chamber. This assumption is ideal for the spectral DNS models due to their requirement for periodicity of the boundary conditions.

For **spectral DNS models**, one may use forcing in the low wavenumber band to maintain the fluctuations of the **v**, T, and Qv fields. For more information on forcing T and Qv in the DNS, one may refer to the method in Saito et al. (2019) or Paoli & Shariff (2009).

For **DNS with a finite difference scheme**, we strongly encourage participants to construct the full geometry of the PI chamber with explicit wall boundary conditions (see LES configurations in (1.2)).

<table>
<tr><th colspan="2">variables</th><th>methods/calculations</th><th>values</th></tr>
<tr><td colspan="2">Initial mean T, Qv, and p in the core region</td><td>Derived from the flux balance model (*)
(Thomas et al. 2019)</td><td>$\bar{T}_0 = 287.25\ K$
$\bar{Qv}_0 = 0.0104126\ kg\ kg^{-1}$
$P = 1000.0\ hPa$</td></tr>
<tr><td colspan="2">Diagnostic mean and standard deviation of supersaturation</td><td>The diagnostic statistics $\bar{S}$ are calculated based on $\bar{T}_0$ and $\bar{Q}_{v0}$:
$S \approx Qv/Qv_{sat} - 1$.
$Qv_{sat} = eps \frac{e_{sat}}{(P - e_{sat})}$, $eps \approx 0.615$.
$e_{sat} = 2.53 \times 10^{11} exp(-5.42 \times 10^3/T)$.
cf. equation (2.12) in Rogers & Yau (1989).</td><td>$\bar{S} = 3.11\%$
$\sigma S = 1.4\%$</td></tr>
<tr><td>Forcing on the fluctuations and the mean of the scalar fields
(T, Qv).</td><td>Apply the external forcing to the fluctuation fields to maintain steady-state σT & σQv</td><td>The intensity of the forcings are determined based on the observed steady-state σT & σQv in the case without particles (i.e., before aerosols are injected into the chamber).
The participants shall first conduct the simulation without injecting aerosols to determine the forcing intensity to obtain the desired standard deviation (σ) of T and Qv fields.
Then, the same forcing intensity will be applied to the case when aerosols are injected.
As σT & σQv will respond to the condensation/evaporation of droplets, their values are expected to change accordingly.

Forcing schemes on scalar fields are similar to forcing on the turbulence. Participants can refer to Paoli and Shariff (2009).</td><td>$\sigma T = 0.5633\ K$
$\sigma Qv = 0.4775\ g/kg$</td></tr>
</table>

	Nudge the mean T & Qv to approach $\bar{T}_0$ and $\bar{Qv}_0$	Nudge the mean value with the relaxation timescale τ (eqn (28-29) in Saito et al. 2019): $\frac{\partial \bar{T}}{\partial t} = -\frac{1}{\tau}(\bar{T}(t) - \bar{T}_0) + \frac{L}{C_p}\bar{C}_d$ $\frac{\partial \bar{Qv}}{\partial t} - \frac{1}{\tau}(\bar{Qv}(t) - \bar{Qv}_0) - \bar{C}_d$ The last term on the RHS of both eqns is the condensation term	$\tau = 60\ s$
Turbulence level		Mean eddy dissipation rate ε	$\varepsilon = 0.001\ m^2 s^{-3}$
Spatial resolution $\Delta x\, \Delta x$		The grid size is required to resolve the smallest turbulence scale (Kolmogorov length-scale, η), i.e., $k_{max}\eta > 1$. k_{max} is the maximum resolvable wavenumber. Or $\Delta x < \eta$	
Initial wind velocity mean			$\bar{U}_0 = \bar{V}_0 = \bar{W}_0 = 0\ m/s$
Model spin-up time		Spin up the model to reach steady-state (in droplet number concentration, mean size, etc); If steady-state is not observed, then at least 1min of spin-up time is required.	$T_{spin} > 1min$
(**Minimum**) simulated time duration **after reaching steady-state;**			$T_{tot} > 5min$
Domain size			$L_x = L_y = L_z =$ $20\ cm \times 20\ cm\ \times 20\ cm$

Footnotes:

(*): flux balance model (use the evolution of the mean temperature, T, as an example)

The evolution of the mean temperature T inside the chamber is determined by the fluxes at the top/bottom boundaries (T_t and T_b) and the side wall T_s.

$$\frac{dT}{dt} = -\frac{1}{\tau}[2(T - T_0) + \hat{A}(T - T_s)]$$

,

here $T_0 = \frac{T_t + T_b}{2}$ and $\hat{A} = \frac{A_s}{A} = 2$ is the chamber geometry parameter defined by the area ratio between the side wall and the top/ bottom plates. A cuboidal geometry is assumed. The side length of the top/bottom walls = 2m, and the height of the chamber = 1m.

Assuming $\frac{dT}{dt} = 0$ in steady state, we then obtain

$T = \frac{\hat{A}T_s + 2T_0}{2+\hat{A}}$ $T = \frac{\hat{A}T_s + 2T_0}{2+\hat{A}}$

Plug in $T_s = 285K$, $T_0 = \frac{T_b + T_t}{2} = \frac{280K + 299K}{2} = 289.5K$, and $\hat{A} = 2$,

we get $T = T_s = 287.25K$ $T = T_s = 287.25K$

1.2) **LES/DNS** of the entire chamber environment

Note that for **DNS aiming to simulate the entire chamber**, same boundary and initial conditions as listed in the table below are applied, but some parameters and conditions such as dx and dt will be different to meet their specific CFL conditions, and for resolving more detailed dynamics and microphysics.

variables	method	values
Top, bottom, and side wall temperature	$\Delta T = 19K$ (299K bottom and 280K top)	$T_t = 280K,\ T_b = 299K,\ T_s = 285K$
Pressure	Standard atmospheric pressure	P=1000hPa
Water vapor mixing ratio at the walls	For the top and bottom, set to saturated Qv based on T_t *and* T_b And assume RH=82% at the side wall (i.e., $Qv_s \approx 82\%\ Qv_{sat}(T_s)$)) Note setting the RH=82% at the side wall is to ensure the mean supersaturation of the chamber $\bar{S} \approx 2.5\%$ (see Thomas et al., 2019). One can also adjust RH and Qv_s accordingly based on $\bar{S}$ value in the simulation.	$Qv_t = 6.1562\ \times 10^{-3} kg/kg$ $Qv_b = 0.0215865\ kg/kg$ $Qv_s = 7.1183\ \times 10^{-3} kg/kg$ (Qv_s is adjustable based on the $\bar{S} = 2.5\%$ assumption).
Initial vertical T & Qv profile in the chamber	A linear (unstable) profile of T and Qv between the top and bottom walls	$T(z) = 299K - 19K \times z/H$ [K] $Qv(z) = 0.0216 - 0.0154 \times z/H$ [kg/kg]
Geometry of the chamber and grid	Rectangular shape ($2m \times 2m \times 1m$)	H=1m (z direction) Lx=Ly=2m $\Delta x = 3.125\ cm$

spacing		$N = 64 \times 64 \times 32$
Boundary conditions	For **LES**: By providing T and Qv at the walls, we imply that fluxes are computed using some kind of similarity conditions	No-slip boundary conditions preferred. Roughness length for LES $z_0 = 0.000035\ m$
Total simulation time and time step		$T_{tot} = 2\ hr$, $\Delta t = 0.02\ s$ to satisfy CFL condition
Initial wind profile		U= V= W= 0m/s

Detailed information can be found in the LES study of Thomas et al. (2019):
https://doi.org/10.1029/2019MS001670

1.3) How to include droplet & aerosol processing

Definition of droplet, aerosol, particle:

Aerosols are referred to those not activated (i.e., for NaCl particle with $d_{dry} = 125\ nm$, r_{wet} below the critical radius of $r = 1.5\ \mu m$).
Droplets are defined as those over $r=1.5\ \mu m$.
Particles include both aerosols and droplets.

Mean & fluctuation scalar fields (T & Qv)	For DNS, same forcing for mean and fluctuations as described in (1.1)	
	For LES, same boundary conditions applied as in (1.2)	
Size of aerosol (dry)	Monodisperse r	$d_{dry} = 125\ nm$ (diameter)
Chemical composition		NaCl
Aerosol injection	Inject aerosols at rates to produce N_{drop} (activated droplet number concentrations) ranging from 10 to 3000 cm^{-3}. Droplets are defined as $r >= 1.5\ \mu m$, aerosols are defined as $r < 1.5\ \mu m$ given by the estimated critical droplet radius of the NaCl particle at $d_{dry} = 125\ nm$ is estimated around $r_{critical} = 1.5\ \mu m$ (cf. Rogers and Yau, 1989, p.88-89) (Suggested droplet number concentrations = 10, 30, 100, 300,1000, 3000 cm^{-3}) See Fig.4 below for the observed DSD in the Pi Chamber.	
Droplet removal /	Drop gravitational settling velocity (Rogers & Yau, 1989):	

sedimentation 2 options	$k_1 = 1.233 \times 10^8\ m^{-1}s^{-1}$ $v_{drop} = k_1 r^2\ m\ s^{-1}$
	Simulation of the core region without walls: remove at a constant rate based on the Stokes settling: Use random droplet removal based on the probability of droplet fallout during certain time interval Δt, which is $v_{drop}/H\Delta t = k_1 r^2/H\Delta t$, $H = 1\ m$, where $k_1 r^2$ is the Stoke's Law droplet terminal velocity.
	Full chamber simulations: remove droplets when contacting the walls
Droplet growth	Grow by condensation (in base cases, droplet collision-coalescence is not considered)

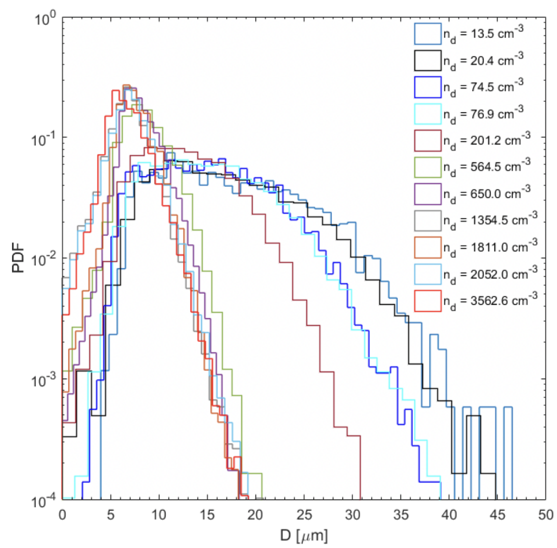

Fig. 4: Observed steady-state droplet size distribution in the Pi Chamber corresponding to different aerosol injection rates. n_d is the droplet number concentration (Fig. 1 in the supplementary material of Chandrakar et al. 2018 JAS)

1) (Optional) Model configuration of the transient case

Use the same condition as the steady-state case, but turn off the aerosol injection after reaching the steady-state. Measurements are taken after the aerosol injections are switched off. Simulated time for the transient period = 30 min for LES & 10 min for DNS.

Model output

1. Data Format

The model output should be submitted in **NetCDF** format, or **ASCII file** with code (in Fortran, python or matlab) to read the file(s) or with reading instructions. The output variables are listed in the tables below with the given **units**.

For the base cases, output from each aerosol injection scenario is required to be saved in separate files.

2. Output Variables

1) 1D data (for all models):

1.1) Output: Time series of domain average statistics

Frequency: every **1s**.

For LES, the domain average excludes regions within **12.5 cm (=4 grid points)** from the walls, i.e., grid points [5:60, 5:60, 5:28] in x, y, z direction.

Output variables	Output format	units
{time} - Time t		s
{T} - temperature		K
{Qv} - water vapor mixing ratio		g/kg
{RH} - relative humidity		%
{LWC} - liquid water content	defined as mass of liquid water per unit **volume** of dry air	gm^{-3}
{N_drop} - Droplet number concentration N_{drop}	Droplets are defined as the one grow beyond its critical radius, i.e., $r_{aerosol} > r_{critical}$, where $r_{critical}$ is the critical radius, here we set $r_{critical} = 1.5\ \mu m$	cm^{-3}
{N_aerosol} - aerosol number concentration	Defined as the number of aerosols which are unactivated: $r_{aerosol} < r_{critical}$	cm^{-3}
{N_removal} - droplet removal rate		$s^{-1}cm^{-3}$
{disp_r} - relative dispersion of	Defined as ratio between the standard	

droplet size distribution	deviation of droplet size distribution and the mean droplet size $= \frac{\sqrt{\Sigma(r-\bar{r})^2/N_{drop}}}{\bar{r}}$	
{r_mean1} - droplet mean radius	$= \Sigma r/N_{drop}$	μm
{r_mean2} - droplet effective mean radius	$= \frac{\Sigma r^3 n(r)}{\Sigma r^2 n(r)}$	μm
{Sigma2_S} - spatial variance of supersaturation $\sigma^2 S$		
{Sigma2_T} - spatial variance of temperature $\sigma^2 T$		
{Sigma2_Qv} - spatial variance of water vapor mixing ratio $\sigma^2 Qv$		
{epsilon} - eddy dissipation rate ε		$m^2 s^{-3}$
The above time series of variables can be saved in a single file, filename: ***AAA_Nxxx_1D****, AAA is model name (DNS or LES); xxx is the injection rate (e.g, 100, 200...)*		
Droplet size distribution (DSD) at **steady-state** in response to different injection rates (if steady-state were not obtained, please provide a time evolution of DSD as a 2D profile, see Table 2.2)	Bins of droplet size from 0-50 μm in **radius** with a bin width of 0.2 μm *Saved in a separate file filename:* ***AAA_Nxxx_dsd****, AAA is model name (DNS or LES); xxx is the injection rate (e.g, 100, 200...)*	cm^{-3} (number concentration in each bin)

1.2) **(optional output)** For LES & DNS that simulate the entire chamber, we also ask for time series of the variables **near the walls** at every 1s (wall average separately for top, bottom and side)

{time} - time		s
{T_s} - sidewall temperature		K

{T_b} - bottom temperature		K
{T_t} - top temperature		K
{Qv_s} - sidewall Qv		kg/kg
{Qv_t} - top Qv		kg/kg
{Qv_b} - bottom Qv		kg/kg
{RH_s} - sidewall relative humidity		%
{RH_t} - top relative humidity		%
{RH_b} - bottom relative humidity		%
{qv_flux_t} - moisture flux at the top		$kg\ kg^{-1} m s^{-1}$
{qv_flux_b} - moisture flux at the bottom		$kg\ kg^{-1} m s^{-1}$
{qv_flux_s} - moisture flux at the sidewall		$kg\ kg^{-1} m s^{-1}$
{H_flux_t} - heat flux at the top		$W m^{-2}$
{H_flux_b} - heat flux at the bottom		$W m^{-2}$
{H_flux_s} - heat flux at the sidewall		$W m^{-2}$
*The above time series of variables can be saved in a single file, filename: **AAA_Nxxx_1D_wall** AAA is model name (DNS or LES); xxx is the injection rate (e.g, 100, 200...)*		

1.3) For LES (optional) Time series of instantaneous values of S, T, Qv at the center of the domain.

2) 2D data (**height z, time t**) for models that simulate the entire chamber

2.1) time series of the mean vertical profile **at every 30s**. The value is averaged over the horizontal plane (also excluding 4 points or 12.5cm from the wall) and at a thickness of every **dz=1cm**. z is the distance from the bottom lid.

{time} - time		s
{T} - temperature $T(z,t)$		K
{Qv} - $Qv(z,t)$		kg/kg
{RH} - $RH(z,t)$	relative humidity	%
{Sigma2_S}	Profile of spatial variance of supersaturation $\sigma^2 S$ as a function of height	
{N_drop} - Droplet number concentration N_{drop}	Number concentration of droplets at each height.	cm^{-3}
*For **netcdf** output, the above time series of variables can be saved in a single file, filename: **AAA_Nxxx_2D,** AAA is model name (DNS or LES); xxx is the injection rate (e.g, 100, 200...);* *For **ASCII files**, each variable is saved in one file.* *Filename: **AAA_Nxxx_2D_var**, var is the name of the variable* *Data is saved in the following format: each row represents the profile at one time point, and each column is the time series at a given z location.*		

2.2) Time evolution of DSD (number concentration of each bin, time) if there is no steady-state DSD.

{dsd} - $DSD(r,t)$	The first dimension of the array contains the number concentration of each droplet size bin; The second dimension is time. You may include several DSDs if there is no steady-state DSD established in your simulations.	cm^{-3} (number concentration in each bin)
	DSD output bin resolution: Bin width is 0.2 μm, from 0 - 50 μm	
	Saved in a separate file *filename: **AAA_Nxxx_dsd**,* *AAA is model name (DNS or LES); xxx is the injection rate (e.g, 100, 200...)*	

2.3) Optional, so far we do not need the near-wall 2D field for model inter-comparison. Therefore, for now we suggest only calculating average & variances of the near-wall field (we will only need the top and bottom walls), which is already part of the profile data in (2.1)

Spatial distribution of instantaneous T and Qv near the top/bottom walls at every 1min
Filename: ***AAA_Nxxx_2D_wall*** *for* ***netcdf****.*
AAA_Nxxx_2D_var_top *and* ***AAA_Nxxx_2D_var_bottom*** *for* ***ASCII files****.*

3) 3D data (for all models)

A few 3D snapshots of the T, Qv, and S at steady-state (and at transient-state if available)
Filename: ***AAA_Nxxx_3D (in figure format or netcdf)***

List of symbols:

Symbol	Name of variable	Unit
Qv	Water vapor mixing ratio	kg/kg
Qv_t , Qv_b , Qv_s	Qv at the top, bottom, and side wall	kg/kg
$Qv_{sat}(T) = eps\frac{e_{sat}(T)}{P-e_{sat}(T)}$	Qv at saturated water vapor pressure e_{sat} is the saturated water vapor pressure. cf. eq. (2.12) in Rogers & Yau (1989) $eps \approx 0.615$	kg/kg
T_b, T_t, T_s	Temperature at the top and bottom, and side wall	K
$\Delta T = 19K$	Temperature difference of the top and bottom walls	K
P	Pressure inside the chamber	hPa
H=1	Height of the chamber	m
Lx, Ly=1	Width of the chamber in horizontal direction	m
dx, dz	Size of the grid box	m
σQv, σT	Standard deviation of Qv and T	
S	Supersaturation ratio $S = \frac{e}{e_{sat}} - 1 \approx \frac{Qv}{Qv_{sat}(T)} - 1$	
d_{dry}	Diameter of the dry aerosol	μm
r	Droplet radius	μm
ε	Eddy dissipation rate	$m^2 s^{-3}$
U, V, W	Wind speed in x, y, z	$m\ s^{-1}$

	direction	
N_{inj}	Aerosol injection rate	$s^{-1} cm^{-3}$
N_{drop}	Droplet number concentration	cm^{-3}
e_{sat}	Saturated water vapor pressure	hPa
$\bar{C}_d$	Mean condensation rate	$kg kg^{-1} s^{-1}$

References

[1] Chang, K., J. Bench, M. Brege, W. Cantrell, K. Chandrakar, D. Ciochetto, C. Mazzoleni, L.R. Mazzoleni, D. Niedermeier, and R.A. Shaw, 2016: A Laboratory Facility to Study Gas–Aerosol–Cloud Interactions in a Turbulent Environment: The Π Chamber. *Bull. Amer. Meteor. Soc.,* **97**, 2343–2358, https://doi.org/10.1175/BAMS-D-15-00203.1

[2] Thomas, S., Ovchinnikov, M., Yang, F., Voort, D., Cantrell, W., Krueger, S. K., & Shaw, R. A. (2019). Scaling of an atmospheric model to simulate turbulence and cloud microphysics in the Pi Chamber. *Journal of Advances in Modeling Earth Systems*, 11, 1981– 1994. https://doi.org/10.1029/2019MS001670

[3] Chandrakar, K.K., Cantrell, W., Chang, K., Ciochetto, D., Niedermeier, D., Ovchinnikov, M., Shaw, R.A. and Yang, F., 2016. Aerosol indirect effect from turbulence-induced broadening of cloud-droplet size distributions. *Proceedings of the National Academy of Sciences*, *113*(50), pp.14243-14248. https://doi.org/10.1073/pnas.1612686113

[4] Chandrakar, K.K., Cantrell, W., Ciochetto, D., Karki, S., Kinney, G. and Shaw, R.A., 2017. Aerosol removal and cloud collapse accelerated by supersaturation fluctuations in turbulence. *Geophysical Research Letters*, *44*(9), pp.4359-4367. https://doi.org/10.1002/2017gl072762

[5] Chandrakar, K.K., W. Cantrell, and R.A. Shaw, 2018: Influence of Turbulent Fluctuations on Cloud Droplet Size Dispersion and Aerosol Indirect Effects. *J. Atmos. Sci.,* **75**, 3191-3209., https://doi.org/10.1175/JAS-D-18-0006.1

[6] Saito, I., Gotoh, T. and Watanabe, T., 2019. Broadening of Cloud Droplet Size Distributions by Condensation in Turbulence. *Journal of the Meteorological Society of Japan. Ser. II*. https://doi.org/10.2151/jmsj.2019-049

[7] Paoli, Roberto, and Karim Shariff. Turbulent condensation of droplets: direct simulation and a stochastic model. *J. Atmos. Sci.,* 66, no. 3 (2009): 723-740.https://doi.org/10.1175/2008jas2734.1

[8] Grabowski, W.W., 2020: Comparison of Eulerian Bin and Lagrangian Particle-Based Schemes in Simulations of Pi Chamber Dynamics and Microphysics. *J. Atmos. Sci.,* **77**, 1151–1165, https://doi.org/10.1175/JAS-D-19-0216.1

[9] Park, H.J., O'Keefe, K. and Richter, D.H., 2018. Rayleigh-Bénard turbulence modified by two-way coupled inertial, nonisothermal particles. *Physical Review Fluids*, *3*(3), p.034307. https://doi.org/10.1103/physrevfluids.3.034307

[10] Rogers, R.R. and Yau, M.K., 1989. A Short Course in Cloud Physics, Int. Ser. Nat. Philos, 113, p.290.