Progress and challenges in modeling dynamics-microphysics interactions: from the Pi chamber to Monsoon convection

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Information box contents begin
What: More than 120 cloud modeling researchers participated in a virtual workshop to discuss recent progress in representing dynamics-microphysics interactions in numerical models and pathways to improve our understanding across a variety of scales.
When: 26 - 30 July 2021
Where: The 10th ICMW was organized through a virtual platform (gather.town) by the Indian Institute of Tropical Meteorology, Pune.

Information box contents end

Introduction:
Following tradition, the 10th International Cloud Modeling Workshop (ICMW) was planned to be held at the Indian Institute of Tropical Meteorology (IITM) in Pune, India in July 2020, the week before the International Conference on Clouds and Precipitation (ICCP). Due to the COVID-19 pandemic, both ICMW and ICCP were postponed to 2021 and held online. For the 10th ICMW, more than 120 cloud modeling researchers from all around the world met online through the gather.town platform from 26 - 30 July 2021 to discuss recent progress and challenges in modeling dynamics-microphysics interactions.

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Early Online Release: This preliminary version has been accepted for publication in Bulletin of the American Meteorological Society, may be fully cited, and has been assigned DOI 10.1175/BAMS-D-22-0018.1. The final typeset copyedited article will replace the EOR at the above DOI when it is published.

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In recent ICMWs, dynamics-microphysics interactions were identified as a research focus by the cloud modeling community (Morrison et al. 2020). Techniques such as running different microphysics schemes in a kinematic framework (Szumowski et al. 1998; Morrison and Grabowski 2008; Shipway and Hill 2012; Hill et al. 2015) and using the microphysics piggybacking approach (Grabowski 2014; 2015) were proposed and applied to tackle this question. In ICMW 2021, a novel approach was used in one of the four case studies for this topic. The case was set up to reproduce the warm cloud experiment in the Michigan Technological University's Pi cloud chamber (Chang et al. 2016). The steady states of the turbulent chamber environment and microphysical properties provide a great testbed for models with different dynamic frameworks and microphysics approaches. It is the first time in the ICMW history that multiple models were used to simulate such a small-scale “cloud” phenomenon.

Another unique aspect of this ICMW is the applications of Lagrangian or particle-based microphysics approaches in many of the case studies (Grabowski et al. 2019). The single congestus case was set up to compare the Lagrangian and Eulerian microphysics methods in representing the cloud droplet size distribution (DSD) in a turbulent cloud environment. The COPE (Convective Precipitation Experiment) sheared convection case was designed to investigate the wind shear impact on clouds, secondary ice formation, and precipitation. The CAIPEEX (Cloud Aerosol Interaction and Precipitation Enhancement Experiment) monsoon convective clouds case was designed to explore the impacts of environmental and cloud condensation nuclei (CCN) conditions on monsoon convection. These four carefully-designed cases addressed dynamics-microphysics interactions at a large range of scales, from the small-scale turbulence within the Pi chamber and within a cumulus congestus, to the effects on storms from environmental vertical wind shear, and to the dynamics/microphysics of the Indian Monsoon.

The workshop provided a platform for the cloud modeling community to discuss the current issues, progress and challenges based on the four cases. Each case was assigned a full day, which included plenary presentations and discussion sessions. The fifth day was designated for general discussions and a special topic on cloud seeding research. Details on the workshop including case descriptions and recorded proceedings of the meeting can be found online (at https://iccp2020.tropmet.res.in/Cloud-Modeling-Workshop-2020).

The brief descriptions of motivations, setup, and preliminary conclusions of each case are provided below. The summary of all cases is listed in Table 1.
Table 1. Summary of the 10th ICMW cases

<table>
<thead>
<tr>
<th>Case leaders</th>
<th>Goal</th>
<th>Case participants</th>
<th>Scale of the case</th>
<th>Model resolution</th>
<th>Dynamical framework</th>
<th>Microphysics</th>
<th>Workshop participants</th>
<th>Highlights</th>
<th>Future plan</th>
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<tr>
<td>Sisi Chen (NCAR)</td>
<td>Simulate Pi chamber controlled environments and explore physics at the droplet native scale</td>
<td>7 (4 countries)</td>
<td>~ O(1 m)</td>
<td>~ O(1 mm to 1 cm)</td>
<td>DNS, LES, and LEM</td>
<td>Particle by particle, Super droplet, Bin</td>
<td>120 + 221 YouTube views</td>
<td>Both super saturation mean value and fluctuation are important for DSD, and neither dominates</td>
<td>Analyze wall effect, particle settling timescale, large-scale circulation, and particle Lagrangian history</td>
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<td>Steve Krueger</td>
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<td>~ O(1 km to 10 km)</td>
<td>~ O(10 to 100 m)</td>
<td>LES</td>
<td>Super droplet, Bin</td>
<td>94 + 666 YouTube views</td>
<td>Large differences among results are due to varieties of dynamical framework, microphysics, and model assumptions</td>
<td>Investigate the reasons of the wider droplet spectrum of bin models, in particular the effect on the vertical resolution</td>
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<td>(University of Utah)</td>
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<td>~ O(10 to 100 km)</td>
<td>~ O(100 m)</td>
<td>LES</td>
<td>Bulk, hybrid super droplet (with ice)</td>
<td>74 + 260 YouTube views</td>
<td>The spectral width simulated by the bin scheme is consistently wider than the corresponding particle-based model results</td>
<td>Investigate the effect of cloud forcing and different microphysics in the same dynamical framework</td>
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<td>Shin-ichiro Shima</td>
<td>Compare the Lagrangian and Eulerian microphysics approaches at the single cloud scale</td>
<td>7 (6 countries)</td>
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<td>~ O(100 m)</td>
<td>LES and CRM</td>
<td>Bulk, Bin</td>
<td>61 + 408 YouTube views</td>
<td>The results appeared sensitive to the method of cloud forcing</td>
<td>Investigate the large-scale forcing impact and the sensitivity of results to the graupel representation</td>
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<td>(University of Hyogo)</td>
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<td></td>
<td>~ O(100 m to 1 km)</td>
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<td>Impact of moisture is more dramatic than CCN effect on clouds and precipitation</td>
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<td>Wojciech Grabowski</td>
<td>Investigate the impact of shear on clouds, secondary ice formation, and precipitation at the storm scale</td>
<td>4 (2 countries)</td>
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<td>Lower environmental RH leads to lower entrainment rate and mass flux and stronger updraft</td>
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<tr>
<td>Sonia Lasher-Trapp</td>
<td>Exp lore the impacts of environmental and CCN conditions on monsoon convection at the storm scale</td>
<td>7 (3 countries)</td>
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Case 1: Pi chamber warm cloud case

The scientific objectives are (1) to demonstrate the model capability of representing the detailed microphysical processes happening in the cloud chamber and how different models behave in different aerosol injection rates, (2) to reveal the model uncertainties and limitations in the existing modeling tools, and (3) to provide guidance and recommendations for future work to improve cloud chamber simulations and model-laboratory comparisons. The cloud chamber configurations from the Pi cloud chamber were used to set up the simulation.

Chamber-averaged statistics of microphysics and thermodynamics during the steady-state in response to different levels of aerosol injections were compared. Models were able to qualitatively capture the general behavior of the DSD corresponding to the high and low injection rates. However, it was also found that the model results exhibit numerous differences in both microphysics and thermodynamics, which were not yet well understood and require further investigation.

In summary, this case presented the first example of the model intercomparison of cloud chamber simulations. The comparison was performed among a diverse set of model categories: including four types of LES models (Dziekan et al. 2019; Shima et al. 2009, 2020; Niedermeier et al. 2020; Khairoutdinov and Randall 2003) performed by the University of Warsaw, University of Hyogo, Leibniz Institute for Tropospheric Research, and Brookhaven National Laboratory, two types of DNS models (Chen et al. 2021; Richter et al. 2021) by the National Center for Atmospheric Research (NCAR) and the University of Notre-Dame, and the Linear Eddy Model (LEM, Su et al. 1998) by the University of Utah. Most of the models simulated the entire chamber with or without side walls, except for one DNS model by NCAR that focused on the core region of the chamber, and the LEM that simulates the chamber as a 1D column. Different microphysics schemes (Bin schemes and Lagrangian microphysics) were used by the case participants to explore the numerical differences produced by the Eulerian and Lagrangian methods.

Case 2: Single congestus case

The width of the DSD affects radiative properties of warm (ice-free) clouds and likely impacts formation of precipitation through collision-coalescence. One can argue that warm rain formation in Eulerian spectral bin microphysics schemes is affected by artificial DSD broadening (Morrison et al. 2018; Grabowski 2019; Pardo et al. 2020; Olesik et al. 2021; Lee et al. 2021).
Lagrangian particle-based schemes, on the other hand, are free from this problem, but may impact simulated cloud properties because of the limited (and typically relatively small) number of super-droplets that can be used.

This model intercomparison case study aims at comparing cloud DSD simulated by various bin and particle-based schemes in a cumulus congestus cloud. The numerical setup is based on previous simulations of a case from the Small Cumulus Microphysics Study field campaign that took place in 1995 in Florida (USA) as described in Lasher-Trapp et al. (2005).

Seven groups from six countries participated in this case study. The results of nine different models were compared, out of which five were spectral bin schemes (Bryan and Fritsch 2002; Feingold et al. 1988; Grabowski 2020; Nishizawa et al. 2015; Sato et al. 2015; https://scale.riken.jp/; Skamarock et al. 2008; Khain et al. 2004, 2015; Geresdi 1998; Geresdi et al. 2014) performed by Hokkaido University, Nanjing University of Information Science and Technology, NCAR, University of Pécs, University of Washington, and Yonsei University; and four were Lagrangian particle-based schemes (Chandrakar et al. 2021; Grabowski 2020; Shima et al. 2009, 2020; Dziekan et al. 2019) performed by NCAR, RIKEN Center for Computational Science, University of Hyogo, and University of Warsaw.

The initial conclusions were as follows: 1) Both approaches capture the observed broadening of convective cloud DSD with height due to entrainment and turbulence. 2) Bin and particle-based schemes produce qualitatively similar results except for the DSD width; DSDs in bin models are consistently wider than that in particle-based models. The clear difference of DSD width seems to be originating from the inherent limitations of the two schemes, and further careful investigations need to be carried out to understand the underlying mechanism.

**Case 3: COPE sheared convection case**

In July-Aug 2013, the Convective Precipitation Experiment (COPE) was held in Southwest England to collect data on the dynamics and microphysics of convective precipitation in order to help improve numerical weather prediction of heavy rainfall events. The 2 August case from this field campaign consisted of a line of thunderstorms occurring in an environment with strong vertical wind shear. This case was numerically simulated by Lasher-Trapp et al. (2018) with an idealized model, where the strong vertical wind shear limited secondary ice production (specifically, rime-splintering) and surface rainfall. The goals of this case were to evaluate the
extent of vertical wind shear effects upon different representations of microphysical processes used across a range of idealized numerical models.

The case was simulated with 4 different idealized modeling setups: CM1 (Cloud Model 1, Bryan and Fritsch 2002) with two-moment NSSL microphysics (Mansell et al. 2010), and ICON (Icosahedral Nonhydrostatic model, Zängl et al. 2015) run in either 2D or 3D with two-moment bulk microphysics (Seifert and Beheng 2006) or with McSnow Lagrangian microphysics (Brdar and Seifert 2018). Groups from the University of Illinois, Deutscher Wetterdienst, and Karlsruhe Institute of Technology participated. All simulations used grid spacing on the order of 100 meters. Across the range of models, enhanced rime-splintering and stronger surface precipitation resulted when storm updrafts were less tilted. Interestingly, however, the amount of updraft tilting was sensitive not only to the vertical wind shear used in the model, but also to the method of cloud initiation, i.e., forcing using warm bubbles or surface heat fluxes. The workshop participants decided that more study of cloud initiation mechanisms in idealized numerical models, and their effects upon the overall cloud dynamics, is warranted.

Case 4: CAIPEEX monsoon convective clouds case
The CAIPEEX case study is based on Gayatri et al. (2017), a study of a convective cloud over the Indian peninsula. The case study was motivated by the importance of convective clouds which contribute significantly (45-55%; Pokhrel and Sikka 2013) to monsoon rainfall that determines the agriculture-dependent economy of the country. The specific scientific objective is to investigate the impact of environmental moisture content and CCN concentration in mixed-phase monsoon clouds using the bin and bulk microphysical models in the LES/CRM (cloud-resolving model) framework.

The case was simulated by groups with several LES and CRM frameworks. The models were initialized with radiosonde or the domain averaged sounding from the simulations of Gayatri et al. (2017). Observations of aerosol size distribution and CCN spectra from CAIPEEX flights were used in the simulations.

The WRF (Weather Research and Forecasting) model simulations with spectral bin microphysics demonstrated that the moist and high CCN environment favored deeper clouds with more supercooled liquid, enhanced mixed-phase, and higher precipitation. However, the effect of moisture is more dramatic than the CCN effect. The Hallet-Mossop (H-M) process had
a significant contribution to the production of ice particles. However, the impact of H-M on precipitation was minimal. The contribution of the H-M process increased with an increase in both moisture and CCN. The Met Office NERC Cloud model (MONC, Brown et al. 2015) with Cloud AeroSol Interaction Microphysics (CASIM, Grosvenor et al. 2017) showed higher liquid water, ice water, and cloud depth for polluted clouds but produced the highest precipitation in the low CCN simulation. Dynamical cloud parameters like entrainment rate and mass flux have been investigated using WRF-LES (bulk microphysics scheme) under varying moisture and CCN conditions. A drier environment led to a decrease in fractional entrainment rate and mass flux at the upper half of cloud layers. However, results were insensitive to CCN changes. This emphasizes that environmental moisture has a dominant impact on cloud dynamical properties.

In summary, the monsoon convective clouds with top heights around 6-8 km were simulated by different models. It was found that the amount of moisture is a determining factor for dynamics-microphysics interactions (Gayatri et al. 2021). The dramatic impact of the mixed-phase cloud processes indicates the need for further investigation with other secondary ice production mechanisms.

General conclusions:
The four case studies of the 10th International Cloud Modeling Workshop demonstrate the advancements of technical approaches and innovation of experiment designs in recent years, and reveal challenges in modeling dynamics-microphysics interactions (Morrison et al. 2020). Based on the presentations, discussions and summaries at the workshop, the following main conclusions were drawn:

1) The innovative design of a laboratory chamber experiment case allows different dynamic frameworks and microphysics approaches to be thoroughly tested in a well-constrained turbulent environment and carefully validated against detailed observations.

2) The Lagrangian microphysics approach that offers a more natural way to study aerosol-cloud-precipitation interactions is becoming increasingly mature, and is ready for simulations at sub-cloud and single cloud scales.

3) The simulated cloud structure and precipitation properties are not only sensitive to dynamic frameworks and microphysical representations but can also be sensitive to the method of cloud initiation/forcing in idealized models.
4) Aerosol effects on convective clouds and precipitation are strongly regulated by environmental conditions and large-scale forcing.

Interested readers are encouraged to contact the case leaders for possible collaboration. The scientific outcomes of each case will be presented in upcoming publications.

References


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