



Impacts of Secondary Ice Production on the Microphysics and Dynamics of Deep Convective Clouds in Different Environments

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Abstract.

This study numerically investigates the impact of secondary ice production (SIP) on cloud microphysical, and diabatic properties in continental and marine deep convective clouds (DCCs). Four cases are simulated using the Icosahedral Nonhydrostatic (ICON) model with a 2-moment cloud microphysics scheme at 2 km horizontal grid spacing. ICON forms secondary ice via rime splintering, fragmentation during raindrop freezing (RDF), ice-ice collision, and sublimational breakup. A more detailed RDF scheme is implemented and compared to the existing simpler scheme. Both schemes predict similar overall properties in the simulated DCCs, suggesting that a simpler scheme can represent RDF in numerical models.

In the simulated DCCs, SIP processes accurately reproduce observed ice number concentrations. SIP enhances ice numbers by $10\text{--}10^3$, decreasing (increasing) supercooled-liquid (ice) mass by 10-30%, leading to sustained upper-level glaciation and prolonged convective activity. Including SIP increases surface precipitation by 4% in marine DCCs, with no significant change in continental DCCs. SIP enhance longwave absorption in the mixed-phase region and increased (20 % in continental and 40 % in marine DCCs) cloud radiative heating. SIP intensifies latent heating by up to 20 %, reaching $20\text{--}40\text{ K d}^{-1}$ in continental and 80 K d^{-1} in marine DCCs, from increased depositional growth of ice particles. This enhanced diabatic heating increases buoyancy, leading to a 10 % rise in mean vertical velocity, strengthening convection. These findings highlight the pivotal role of SIP in shaping the microphysical structure and dynamical behavior of deep convection, highlighting the need for its representation in numerical models.

1 Introduction

Clouds play a crucial role in Earth's energy balance by influencing radiative fluxes and latent heating (Lohmann et al., 2016).

The latent heat released during cloud formation modifies atmospheric circulation and vertical energy distribution. Clouds influence both incoming shortwave (SW) and outgoing longwave (LW) radiation (Trenberth et al., 2009), affecting atmospheric



heating rates at different heights. This interaction of clouds with radiation is quantified as ‘cloud radiative heating’ (CRH), which is the difference between atmospheric radiative heating rates in cloudy and clear-sky conditions, explaining how clouds locally heat or cool the atmosphere. This vertical redistribution of radiative energy depends on cloud properties (Sullivan et al., 2023; Keshtgar et al., 2024).

Deep convective clouds (DCCs) can produce heavy precipitation via convective cores and stratiform regions, while their associated long-lived and extensive, non-precipitating cirrus anvils play a crucial role in the radiation budget (Feng et al., 2011). DCCs range from small individual cells (≤ 1 km) to large ($\sim$ few hundred km) mesoscale convective systems (MCS) and can form in the tropics, subtropics, and midlatitudes (Wilcox et al., 2023). An MCS evolves through three phases: early growth, mature, and dissipation (Houze, 1982). The early growth phase is associated with individual cells that transport the condensate to higher levels and produce intense surface precipitation. In its mature stage, these cells organize into convective cores and a broad stratiform region that produces light precipitation. In the dissipation phase, both of these regions remain surrounded by persistent cirrus anvil clouds. In the tropics, MCSs significantly influence latent heating and radiative forcing (Roca et al., 2017; Wilcox et al., 2023), thereby modifying the thermodynamic structure of the atmosphere (Bouniol et al., 2016).

On a global scale, the majority of surface precipitation is from the ice-crystal (‘cold rain’) process (Lau and Wu, 2003; Field and Heymsfield, 2015). The ice-crystal process involves the growth of ice-crystals through vapour deposition, in which water vapour directly deposits onto ice-crystals or through riming, in which supercooled cloud droplets and drizzle freeze upon collision with ice-crystals. These processes form larger snowflakes or heavily rimed ice particles (e.g., graupel/hail) that may melt and form cold rain.

The processes governing ice formation in clouds are also crucial for understanding their radiative properties. Ice formation in clouds can occur through 1) the homogeneous nucleation of aqueous aerosol particles (APs) and supercooled cloud droplets, which typically occur above the -38°C level. In contrast, at mixed-phase levels (between 0 and -38°C), mostly insoluble APs, known as ice nucleating particles (INPs), initiate ice through 2) heterogeneous ice nucleation (DeMott et al., 2010; Kanji et al., 2017). However, in the mixed-phase region, it is often reported that the measured ice particle number concentration (INC) is about $10^2 - 10^4$ times higher than the available active INP number concentration (Sotiropoulou et al., 2020; Lawson et al., 2015; Waman et al., 2022). This discrepancy can be explained by the multiplication processes that involve secondary ice production (SIP) from pre-existing ice (Takahashi et al., 1995; Field et al., 2017; Korolev and Leisner, 2020).

Several SIP processes have been proposed so far (Korolev and Leisner, 2020). For example,

1. The rime-splintering process (HM, Hallett and Mossop, 1974)
2. Fragmentation of freezing raindrops or drizzle (RDF) (Phillips et al., 2018; Kleinheins et al., 2021)
3. Fragmentation upon ice-ice collision (IIC) (Vardiman, 1978; Takahashi et al., 1995)
4. Sublimational fragmentation of dendritic snow and graupel (SBF) (Oraltay and Hallett, 1989; Bacon et al., 1998; Deshmukh et al., 2022)



55 SIP through rime-splintering happens between -3 and -8°C , and involves ejection of ice splinters when supercooled droplets freeze upon collision with ice particles (Hallett and Mossop, 1974). The HM process has been recognized as important for rapid ice enhancement in the early growth of DCCs (Patade et al., 2016; Jackson et al., 2018; Lasher-Trapp et al., 2021; Waman et al., 2022; Han et al., 2024). Although a laboratory experiment by Seidel et al. (2024) mimicking convective conditions found no clear fragmentation via the HM process, the occasional observations of splinters in this experiment indicate
60 the mechanism may remain active in natural clouds with more complex dynamics and a broader range of droplet sizes.

Furthermore, IIC describes SIP from a collision between two ice particles (Grzegorzczuk et al., 2023; Gautam et al., 2024). Previous modelling studies (Zhao and Liu, 2021; Han et al., 2024; Yang et al., 2024; Patade et al., 2025) suggest that IIC can account for over 60 % of secondary ice in the simulated DCCs, especially in their mature stage (Waman et al., 2022). Two parameterizations are available to represent SIP via IIC in numerical models: 1) a temperature-dependent scheme by Takahashi
65 et al. (1995), 2) a more extensive parameterization, based on the principle of energy conservation by Phillips et al. (2017). The rate of IIC depends on the properties of the colliding particles, such as size, shape, density, roughness, temperature, and fall velocity.

SIP via RDF occurs during the freezing of drizzle or raindrops, as evident from laboratory studies by Mason and Maybank (1960) and Keinert et al. (2020). In RDF, the internal pressure from trapped liquid causes the ice shell to break, ejecting secondary ice splinters and liquid splashes that may later freeze. Lawson et al. (2015), using aircraft observations and a modelling approach, shows that in the studied marine DCCs, RDF dominates SIP between -4 and -15°C and may facilitate rapid cloud glaciation. Furthermore, recent modelling studies of DCCs (Huang et al., 2021; Waman et al., 2022; Patade et al., 2025) reported that RDF dominates overall SIP in their early stages.
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The importance of SBF in deep convective clouds, which occurs in unsaturated cloudy air (Korolev and Leisner, 2020), remains uncertain. While laboratory experiments (Oraltay and Hallett, 1989; Bacon et al., 1998; Dong et al., 1994) demonstrated fragmentation of sublimating dendrites and rimed particles under relative humidity with respect to ice (RH_i) 50–90%, field observations (Korolev and Issac, 2004) and modeling studies (Waman et al., 2022; Yang et al., 2024) found minimal contribution of SBF to total ice formation in clouds. Deshmukh et al. (2022) developed a theoretical parameterization for SBF during sublimation of dendritic snow and graupel based on the laboratory findings, though its applicability to different natural DCCs
80 remains to be validated.

SIP may also occur from INP activation in transient supersaturation around a freezing drop, where the release of latent heat warms the surface of the drop, causing vapor diffusion and local supersaturation (Korolev and Leisner, 2020). Also, rapid temperature changes during riming can cause thermal shocks in ice crystals, leading to fracturing and splintering. However, these processes remain poorly understood and lack parameterizations in current numerical models.

85 SIP can alter diabatic heating in DCCs through increased growth of ice splinters via deposition and riming, which may strengthen updrafts and modify dynamics (Qu et al., 2022; Grzegorzczuk et al., 2025). Recent modelling studies show that SIP can influence cloud dynamics, precipitation production, and radiative properties. Zhao and Liu (2021) reported that on a global



scale, SIP increases the net cloud radiative forcing by 1.1 W m^{-2} annually via microphysical changes. Moreover, in tropical convection, Qu et al. (2022) reported that SIP produces the observed ice mass and number, enhances buoyancy, and prolongs cloud lifetime. In contrast, an idealized simulation by Grzegorzczuk et al. (2023) found that SIP may lower the cloud top height without notably altering ice mass and buoyancy. These findings suggest that SIP plays a key role in the microphysics, dynamics, and radiative properties of clouds under different atmospheric conditions.

Hence, SIP can induce positive feedback in DCCs, where increased growth of extra ice particles enhances diabatic heating and updrafts, intensifying convection. This affects their development, organization, precipitation efficiency, and radiative properties. Yet, its impact on DCCs remains insufficiently well quantified across diverse environmental regimes. Previous studies have largely focused on idealized or isolated cases, leaving gaps in our understanding of how SIP modulates cloud dynamics and radiative effects in both continental and marine DCCs. Therefore, this study aims to investigate the possible impact of SIP on the dynamics, convective intensity, and radiative properties of DCCs, using simulations of three continental and one marine DCCs with the Icosahedral Nonhydrostatic (ICON, Zängl et al., 2015) model in limited area mode (LAM). Section 2 describes the observed DCCs and numerical model setup. Results are presented in Sec. 3, followed by conclusions in Sec. 4. The acronyms and symbols used are defined in Tables A1 and A2 respectively.

2 Details of field Campaigns and Model

The present study focuses on four different campaigns (Table 1) involving DCCs from various locations and periods. These are the three continental cases, including 1) the fourth phase Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX-IV) over Solapur, India, 2) Deep Convective Microphysics Experiment (DCMEX) over Magdalena Mountains, New Mexico, 3) Midlatitude Continental Convective Clouds Experiment (MC3E) over Oklahoma, USA, and one marine deep convection observed during 4) Organized Convection and EarthCARE Studies over the Tropical Atlantic (ORCESTRA).

These cases are described in the following section.



Table 1. Summary of the selected convective cases (continental cases are denoted by * and marine by †), the associated cloud base and top temperatures, convective available potential energy (CAPE) from ICON control runs (Figs. 1–4b), and the instruments used during the campaigns, mounted on aircraft (marked with *) and satellite (denoted by †). The particle sampling range used in the present study for the optical probes (Cloud-liquid and ice probes are denoted with ⊗ and ⊕ respectively) mounted on the aircraft is also shown.

Case/Region/Time	CAPE (J kg ⁻¹)	Cloud base (°C)	Cloud top (°C)	Aircraft*/ Satellite†	Cloud-liquid [⊗] Ice particle [⊕] probes
CAIPEEX* (Peninsular India, 30 September 2019, 06–20 UTC)	1210	20	–60	Beechcraft B200*	CDP [⊗] (0.002–0.05 mm) CIP [⊕] (0.4–0.93 mm), PIP [⊕] (0.4–6 mm)
DCMEX* (New Mexico, USA 2 August 2022, 18–23 UTC)	669	5	–60	BAe-146*	CDP [⊗] (0.002–0.05 mm) 2DS [⊕] (0.1–1.28 mm), CIP [⊕] (0.1–0.93 mm) Nevrozov ^{⊕⊗} (0.1–2 g m ⁻³)
MC3E* (Oklahoma, USA, 11 May 15 UTC –12 May 2011 03 UTC)	1224	17	–60	Citation*	CDP [⊗] (0.002–0.05 mm) CIP [⊕] (0.2–1.5 mm), HVPS-3 [⊕] (0.2–19.2 mm)
ORCESTRAT† (Tropical Atlantic, 3 September 00 UTC –4 September 2024 00 UTC)	1006	23	–60	EarthCARE†	CPR ^{⊗⊕} (EarthCARE)

2.1 Field Campaigns

110 2.1.1 CAIPEEX

During CAIPEEX-IV, the Beechcraft B200 aircraft (Fig. 1a) measured aerosol and cloud properties, along with meteorological parameters, between cloud base and –15 °C. The B200 aircraft performed multiple passes near stratus layers with embedded convection (Prabhakaran et al., 2023; Patade et al., 2025). Details of the optical probes mounted on the B200 during CAIPEEX are summarized in Table 1. The cloud droplet probe (CDP) sampled cloud droplet properties, such as cloud droplet number



115 concentration (CDNC) and liquid water content (LWC). The cloud imaging probe (CIP) and precipitation imaging probe (PIP)
measured drizzle and ice properties, including INC, whereas ice water content (IWC) is derived using the mass-size relationship
from PIP's size distribution (Patade et al., 2025). The CIP was equipped with anti-shatter tips (Korolev et al., 2011), whereas
the PIP data were processed following Patade et al. (2025). To minimize biases from artificial shattering (collision with probe
tips), only ice particles larger than $400\text{ }\mu\text{m}$ ($N_{I,400}$) from PIP and CIP are used to validate the simulated INC. In CAIPEEX-IV,
120 a dual-polarization, C-band radar ($75\text{--}76^\circ\text{ E}$, $17\text{--}18^\circ\text{ N}$) observed the convective system (Prabhakaran et al., 2023).

To minimize biases from artificial shattering (collision with probe tips), only ice particles larger than $400\text{ }\mu\text{m}$ ($N_{I,400}$) from
PIP and CIP are used for model validation.

The case examined here was observed on 30 September 2019 during CAIPEEX-IV over Solapur, primarily involving DCCs.
The pre-convective air and dewpoint temperatures from the control run (Sec. 2.2, Table 3) are shown in Fig. 6b. For CAIPEEX
125 case, the lifting condensation level (LCL) is at 20°C with tops reaching up to -60°C (Fig. 1b), with convective available
potential energy (CAPE) of 1210 J kg^{-1} (Table 1).

Figure 1c shows the particle habits at different cloudy levels observed by the CIP during the CAIPEEX campaign. It is seen
that, in this post-monsoon convection, the warm levels ($> 0^\circ\text{C}$) were dominated by drizzles and raindrops of diameters between
 0.1 and 0.9 mm . Also, between 0 and -10°C , the coexistence of both liquid and ice particles was observed, indicating the
130 presence of well-developed, mixed-phase conditions. At -4°C , ice particles were chiefly needles/columns, plates, and heavily
rimed graupels, suggesting possible formation of secondary ice via rime-splintering. Furthermore, colder levels were highly
populated with relatively large ($>0.7\text{ mm}$ in diameter) rimed particles, highlighting the presence of both warm and cold rain
processes in such clouds.

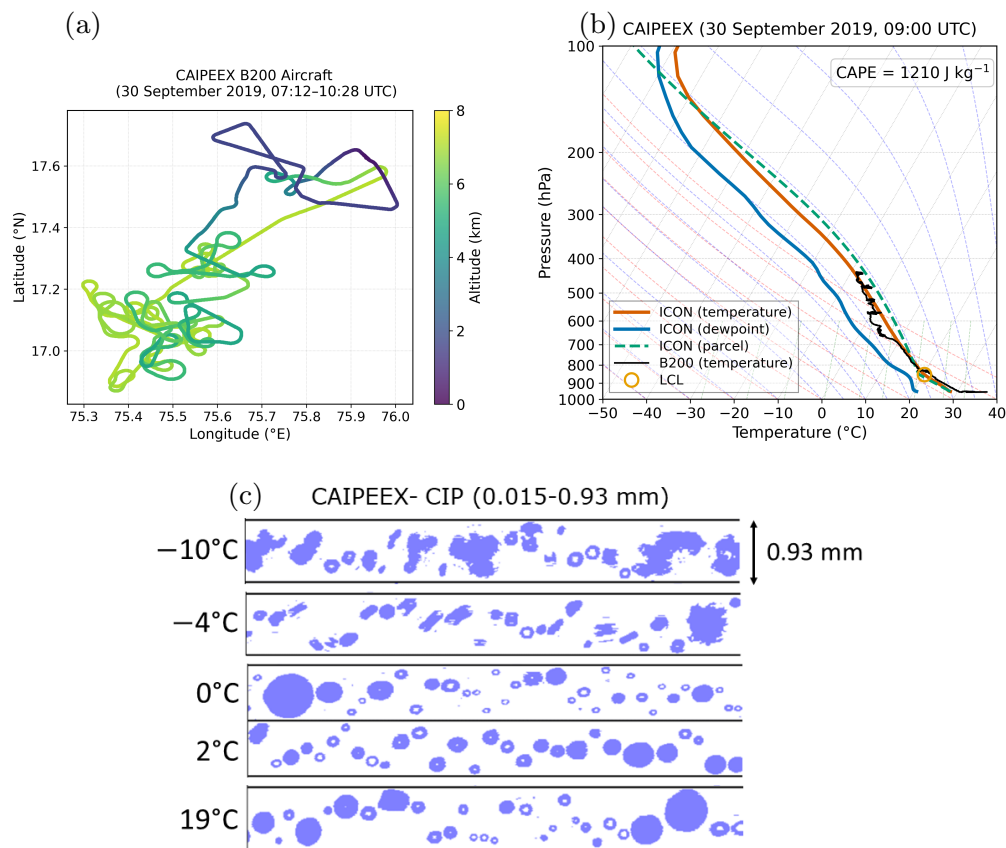


Figure 1. (a) Flight track of the B200 aircraft, (b) simulated (red line) and B200 observed (black line) vertical profile of the air temperature, simulated dew point temperature (blue line), and LCL (orange circle) at 09 UTC on 30 September 2019. In (b), the simulated temperature profiles are from the control run (Table 3) of the CAIPEEX case. Also (c) hydrometeor images by the CIP probe observed at different levels during the CAIPEEX convection.



2.1.2 DCMEX

135 The DCMEX was conducted during July–August 2022 over the Magdalena Mountains, New Mexico, USA, by the UK National Environment Research Council to understand the aerosols, microphysics, and dynamics involved in the development of DCCs (Finney et al., 2024). The DCMEX aimed to enhance the understanding of microphysical processes and their representation in climate models, to address uncertainties associated with cloud-radiative effects.

The DCMEX case analyzed here was observed on 02 August 2022. On this day, the measurements of aerosols and cloud
140 microphysics were made by the UK’s BAe146 aircraft between 1526 and 2000 UTC (Fig. 2a). The INC was measured by the optical probes mounted on the BAe146 aircraft (Finney et al., 2024), such as the 2-dimensional stereo probe (2DS), and CIP (ice particles larger than $100\ \mu\text{m}$ (NI_{100})), corrected for any possible artificial shattering (Field et al., 2006) (Table 1). Furthermore, the CDP measured CDNC, whereas the Nevzorov hot wire probe was used to measure their LWC and IWC (Finney et al., 2024). Also, the ground-based C-band, dual-polarimetric Shared Mobile Atmospheric Research and Teaching
145 radar, unit 1 (Finney et al., 2024) was deployed at Socorro Airport (34.022° N , 106.898° W), which provided continuous monitoring of cloud evolution before, during, and after the aircraft observations.

For the selected DCMEX case, the simulated LCL is at 5°C , and the cloud tops are reaching up to -60°C , whereas the CAPE is $670\ \text{J kg}^{-1}$ (Fig. 2b).

Fig. 2c presents the particle habits observed by the CIP probe at different levels for DCMEX clouds. At levels near cloud
150 base, between 1 and -2°C , drizzles were observed. At levels colder than -2°C , the presence of irregular, large ice particles was prominent, along with small, pristine, column-like structures.

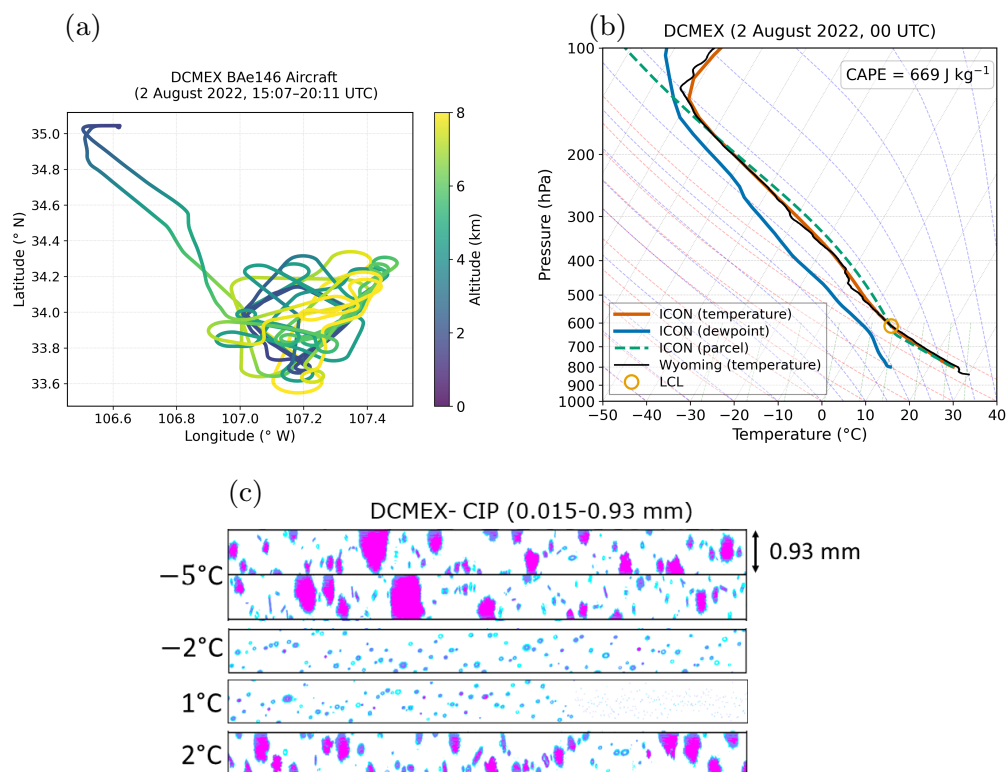


Figure 2. As in Fig. 1, but in (a) the flight path is for the BAe146 aircraft. In (b), observed air temperature (black line) is from the University of Wyoming archive [35.038° N, 106.623° W] at 00 UTC on 02 August 2022.



2.1.3 MC3E

The MC3E campaign (Jensen et al., 2016) was conducted from 22 April to 6 June 2011 over the Southern Great Plains, Oklahoma, USA, to study the complex physical processes that drive midlatitude DCCs and associated precipitation. It was jointly
155 organized by the U.S. Department of Energy Atmospheric Radiation Measurements (ARM) and the National Aeronautics and Space Administration's (NASA) Global Precipitation Measurement (GPM) mission.

During MC3E, the University of North Dakota Citation aircraft (Table 1) measured the cloud microphysical properties at levels between cloud base (17°C) and -30°C (Fig. 3a). Mounted on the Citation aircraft, the high volume precipitation spectrometer version 3 (HVPS-3) and CIP measured the IWC and INC, whereas the CDP measured the LWC and CDNC. During
160 MC3E, the HVPS-3 was equipped with anti-shattering tips (Korolev et al., 2011). The possible bias due to artificial shattering of ice particles is minimized by considering ice concentrations of particles larger than $200\text{ }\mu\text{m}$ (NI_{200}). Additionally, the simulated radar reflectivity is validated against the reflectivity measured by the Ka-band ARM zenith radar (KAZR, Widener et al., 2012).

Here, an MCS observed on 11 May 2011 during the MC3E campaign, characterized by relatively high CAPE (1224 J kg^{-1}),
165 is analyzed. For this MCS, the LCL was at 17°C and the tops were extending up to -60°C (Fig. 3b, Table 1).

For the observed MCS during MC3E, Fig. 3c shows the hydrometeor habits from the CIP measurements at different levels. The levels near cloud base (17°C) were dominated by liquid particles larger than 0.2 mm , indicating the presence of smaller drizzle drops or raindrops. At -5°C , the co-existence of large aggregates, with rare pristine ice crystals, and supercooled liquid was observed, favoring mixed-phase cloud processes such as riming. The presence of larger aggregates at these levels chiefly
170 suggests stratiform cloud conditions. Also, at colder mixed-phase levels, between -16 and -22°C , hydrometeors appeared to be more irregular, with dendritic and aggregated particles observed, suggesting vigorous ice crystal growth via aggregation at these levels.

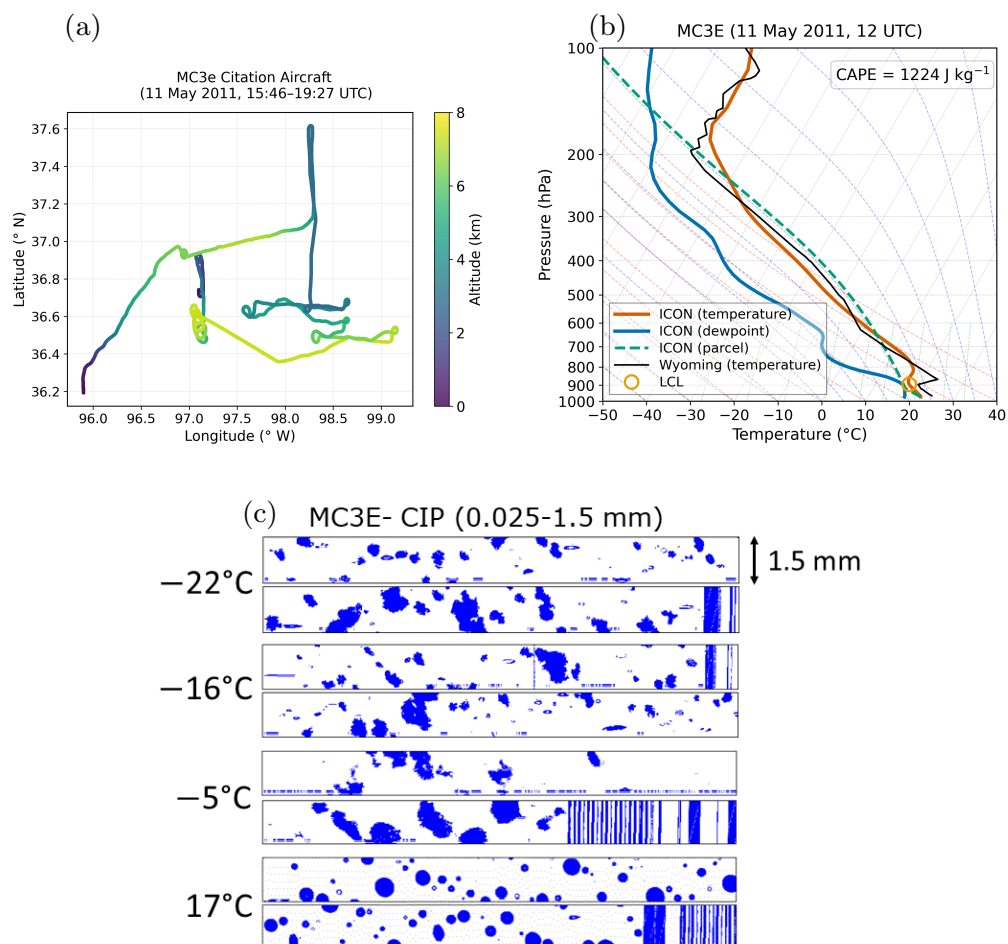


Figure 3. As in Fig. 1, but in (a) the flight path is for the Citation aircraft. In (b), the observed air temperature (black line) is from the University of Wyoming archive [35.18° N, 97.44° W] at 12 UTC on 11 May 2011.



2.1.4 ORCESTRA

The ORCESTRA campaign (Stevens et al., 2025), conducted over the tropical Atlantic (Fig. 4a) from 10 August to 30 September 2024, was led by the Max Planck Institute for Meteorology (MPI-M). Its main objective was to improve the understanding of the mesoscale organization of tropical convection, including its interactions with tropical waves and air–sea processes, and its impacts on climate, the Earth’s radiative budget, and tropical cyclogenesis. During ORCESTRA, aircraft and ground-based observations were carried out across the tropical Atlantic Ocean, including regions near Barbados and the Cape Verde Islands (Fig. 4b). These observations are also used to calibrate measurements from the European Space Agency and Japan Aerospace Exploration Agency (JAXA) Cloud Aerosol Radiation Explorer satellite ((EarthCARE, Wehr et al., 2023).

The present study analyzes an MCS observed on 3 September 2024, during ORCESTRA (Fig. 4a). The ICON simulated air temperature profile is compared with the corresponding observations for 00 UTC on 3 September 2024 (Fig. 4b). For these clouds, the base and top temperatures were at about 23 °C, and –60 °C respectively, with CAPE of about 1100 J kg^{–1}.

The EarthCARE (Table 1) is a sun-synchronous satellite, launched on 28 May 2024, and is equipped with the cloud profiling radar (CPR, Wehr et al., 2023). The main aim of EarthCARE is to study the vertical structure of clouds and aerosols and the radiation budget at the top of the atmosphere to enhance understanding of how aerosols and clouds influence the Earth’s climate and to improve the accuracy of climate models through these observations.

The present study uses cloud properties observed by the EarthCARE CPR (Fig. 4a) to evaluate and validate the corresponding ICON simulation. The CPR was jointly developed by JAXA and the National Institute of Information and Communications Technology, Japan, and operates at a high frequency of 94 GHz (Wehr et al., 2023). It is designed to measure the cloud properties, moisture content, the vertical structure, and motions of the hydrometeors. Additionally, the simulated surface precipitation is validated against the coincident observations from the GPM satellite measurements, which uses the dual-frequency radar and multi-channel radiometer. Launched in February 2014, the GPM is led by NASA and JAXA and designed to provide global observations of rain and snow.

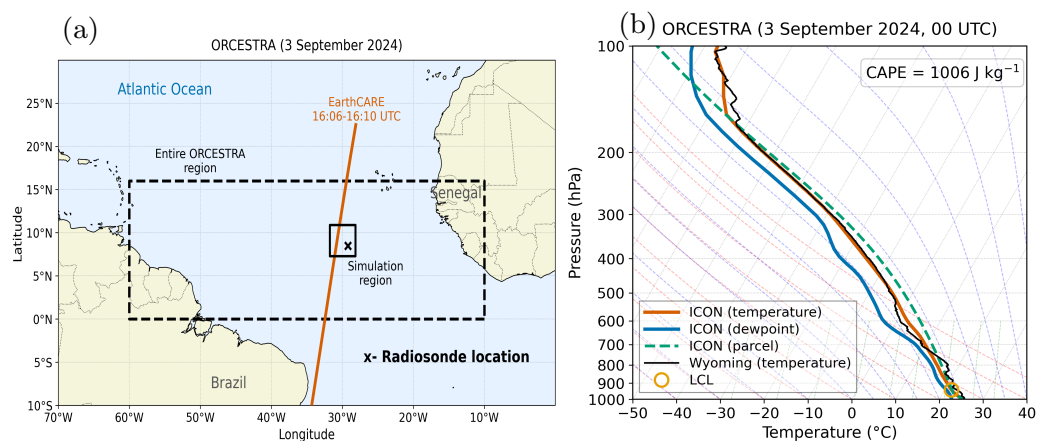


Figure 4. (a) Geographical location of the entire ORCESTRa campaign (dashed black box). The red line shows the EarthCARE overpass over the selected ORCESTRa region (solid black box), and 'x' shows the Radiosonde location on 3 September 2024. Also shown are the vertical profiles of (b) the simulated (red line) and observed (black line, Wyoming Sonde archive [8.47° N, 29.206° W]) air and simulated dew point temperature (blue line) at 00 UTC on 03 September 2024. In (b), the orange circle denotes LCL, and the simulated temperature profiles are from the control (Table 3) run of the ORCESTRa case.



195 2.2 Numerical Model

The present study uses the ICON (Zängl et al., 2015) model to simulate the convective cases (Sec . 2.1). ICON is developed by the German weather service (Deutscher Wetterdienst), in collaboration with the MPI-M, German Climate Computing Center (Deutsches Klimarechenzentrum, DKRZ), Center for Climate Systems Modeling, and Karlsruhe Institute of Technology. The non-hydrostatic dynamical core of ICON solves fully compressible, non-hydrostatic primitive equations (Gassmann and Herzog, 2008) on an unstructured triangular grid and with a C-type staggering based on successive refinement of a spherical icosahedron (Wan et al., 2013), to avoid singularity issues at the poles.

Here, the ICON NWP physics package is used, with a 2-moment bulk microphysics scheme (Seifert and Beheng, 2006) which follows the generalized gamma distribution to describe the particle size distributions (PSD) of hydrometeors. The diameter-mass and fall velocity-mass relationships are parameterized with power laws (Han et al., 2024, Table 1 therein). In the 2-moment microphysics scheme, ICON predicts the mass and number mixing ratios of cloud droplets and ice ('crystal'), snow, graupel, hail, and rain.

ICON uses the ecRad radiation scheme (Hogan and Bozzo, 2018), where SW and LW radiative transfer are governed by the effective radii of cloud liquid and ice-crystal. In this study, these effective radii are derived from both their mass mixing ratios and number concentrations, enabling a more consistent coupling between radiation and microphysics.

In ICON, the CCN activation scheme by Segal and Khain (2006) initiates cloud droplets based on aerosol properties (CCN concentration and log-normal size distribution width) and vertical velocity at the cloud base. This scheme uses regression equations and lookup tables derived from a 2000-bin microphysics parcel model, separating clouds into four regimes: maritime, continental, intermediate, and polluted continental. Furthermore, at subzero levels warmer than -38°C , ICON forms primary (heterogeneous) ice by activating INP through immersion freezing and deposition nucleation (Hande et al., 2015), depending on the temperature and saturation ratio with respect to ice (S_i). Also, above the -38°C level, ICON initiates homogeneous ice through freezing of water droplets (Jeffery and Austin, 1997; Cotton and Field, 2002) and aqueous aerosols. Homogeneous freezing of raindrops is not considered, as raindrops freeze rapidly at warmer levels before reaching the threshold for homogeneous nucleation (Seifert and Beheng, 2006). The heterogeneous raindrop freezing is parameterized following Bigg (1953).

220 2.2.1 Secondary ice processes implemented in ICON

ICON initiates secondary ice through four ice multiplication processes. These are

1. Hallett-Mossop (HM) process of rime-splintering

In ICON, the rate of splinter formation during riming of supercooled cloud droplets larger than $24\text{ }\mu\text{m}$, through the HM



process, is represented as,

$$\frac{\partial N_{sec}}{\partial t} = \aleph_{hm} \times w_{hm}(T) \times q_{rime} \quad (1)$$

Here, N_{sec} is the number of secondary ice fragments from the HM process, $\aleph_{hm}$ is a constant (3.5×10^8 fragments per kg, Table A2), q_{rime} is the rimed ice mixing ratio, and $w_{hm}(T)$ is a temperature-dependent function given by,

$$w_{hm}(T) = \begin{cases} 0 & T < 256 \text{ K} \\ \left(\frac{T-256}{3} \times \frac{T-270}{-2} \right) & 256 \text{ K} < T < 270 \text{ K} \\ 0 & T > 270 \text{ K} \end{cases} \quad (2)$$

2. Fragmentation in raindrop freezing

In the ICON model, SIP is also initiated via RDF, following the parameterization by Sullivan et al. (2018, hereafter SUL18). The SUL18 is a simplified scheme that forms secondary ice during the immersion freezing of raindrops, dependent on the temperature and shattering probability of a freezing raindrop. More details are from Sullivan et al. (2018) and Han et al. (2024).

To examine how the existing parameterizations of RDF impact ice formation, dynamics, and radiative properties in the simulated clouds, a new, more detailed parameterization, proposed by Phillips et al. (2018, hereafter PHIL18), is implemented in ICON and compared with the predictions of SUL18.

The RDF proposed by PHIL18 forms secondary ice through two different modes. The first mode involves SIP in collisions between supercooled drops (0.05 – 5 mm diameter (D)) and a less massive ice particle or in immersion freezing of a raindrop. The number of secondary ice fragments (N_{sec}) from mode 1 is given by,

$$N_{sec} = \Xi_{RDF}(D) \times \Omega(T) \left[\frac{\zeta \eta^2}{(T - T_0)^2 + \eta^2} + \beta_{RDF} \times T \right] \forall m > m_i, D < 1.6 \text{ mm} \quad (3)$$

Here, T is temperature in °C, and the quantities such as Ξ_{RDF} , β_{RDF} , ζ , and η are dependent on D , and Ω is a function of T (Phillips et al., 2018, Sec. 4 and Appendix B therein).

In mode 1, both small and big fragments can be formed, denoted as ‘S’ and ‘B’ respectively, during freezing of a raindrop. The number of big fragments, added to the graupel category, is given as,

$$N_B = \min \left\{ \Xi_{RDF}(D) \Omega(T) \left[\frac{\zeta_B \eta_B^2}{(T - T_{B,0})^2 + \eta_B^2} \right], N_{sec} \right\} \quad (4)$$

And, the number of small fragments, identified as ice-crystals, can be derived as,

$$N_S = N - N_B \quad (5)$$

In mode 2, secondary ice splinters are initiated via the emission and eventual freezing of splashes formed during the collision between a larger ice particle and a raindrop. The number of fragments (N_{sec}) from the second mode is given by,

$$N_{sec} = 3\Phi(T) \times [1 - f(T)] \times \max(DE - DE_{crit}, 0) \forall m < m_i \text{ and } D > 0.15 \text{ mm}. \quad (6)$$



Here, Φ is the probability of any drop fragment in a splash containing ice, which is set to 0.3 following James et al. (2021). And, DE is dimensionless energy defined by,

$$DE = \frac{K_0}{\gamma_{liq}\pi D^2} \quad (7)$$

and, the collision kinetic energy (CKE, K_0) is,

$$K_0 = \frac{1}{2} \frac{mm_i}{(m + m_i)} (v - v_i)^2 \quad (8)$$

where m and m_i are the masses of liquid and ice particles, respectively. Table A2 describes the other symbols, and additional details are from PHIL18.

3. Fragmentation in ice-ice collision

Fragment formation during collisions between ice particles is included as a SIP process in ICON following Phillips et al. (2017). This formulation links SIP in IIC to the CKE available during collision. In ICON, this scheme is applied within the bulk microphysics framework, by discretizing each colliding ice particle into emulated bins that follow a gamma size distribution (Han et al., 2024). The rime fraction is assumed to be constant and set to 0.4. The fragments from the collision between all possible pairs of bins are added together to obtain the total number of fragments from ice-ice collisions. For a collision between two ice particles, the expected number of secondary ice fragments (N_{sec}) is given as,

$$N_{sec} = \alpha A(M) \left[1 - \exp \left(- \left(\frac{CK_0}{\alpha A(M)} \right)^\gamma \right) \right] \quad (9)$$

Here, K_0 is the CKE (Eq. 8) of the colliding ice particles, α is the surface area of the smaller particle, γ is the shape parameter, and C is the asperity-fragility coefficient. The other symbols are described in Table A2. In ICON, fragments are formed in collisions between ice particles of different or the same habits, except for the crystal-crystal collision. Further details of the physical assumptions and parameter choices are described in Phillips et al. (2017, Sec. 4 and Table 1 therein) and Han et al. (2024).

4. Fragmentation in sublimation of graupel and dendritic snow

In ICON, an empirical formulation proposed by Deshmukh et al. (2022) is used to represent fragmentation during sublimation of dendritic snow and graupel. According to this formulation, the rate of fragment production during sublimation of dendritic snow is,

$$\frac{\partial N_{sec}}{\partial t} = \beta_{SBF} \times d^\gamma \times v' \times (100 - RH_i) \times f_v \times \Xi_{SBF} \quad \forall 261K > T > 256K \quad (10)$$

and, during sublimation of graupel,

$$\frac{\partial N_{sec}}{\partial t} = \left(\frac{\rho_{D0}}{\rho_r} \right) \times \beta_{SBF} \times d^\gamma \times v^* \times (100 - RH_i) \times f_v \times \Xi_{SBF} \quad (11)$$

Where d is the crystal diameter. Further details on the symbols are given in Table A2. Additional details are from Deshmukh et al. (2022).



The fragments formed in these four SIP processes are added to the cloud-ice category, allowing for a possible cascade effect. Also, the contribution to the total ice from homogeneous and heterogeneous nucleation, and the four SIP processes, is estimated using their process rates.

2.2.2 Experimental Design

285 In this study, each case (Sec. 2.1) is simulated in the LAM of ICON, with four two-way nested domains (Fig. 5), with the horizontal grid spacing halved from 13 km in the outermost (2500 km × 2500 km) domain to 1.6 km in the innermost (500 km × 500 km) domain. With a 21 km model top, the vertical grid spacing is gradually increased from the surface to the model top using 65 vertical levels. The model integration time step is 10 s. For the simulated DCCs, the initial and lateral boundary conditions (LBCs) are derived from the ECMWF atmospheric reanalysis version 5 (ERA5, Hersbach et al., 2020) data and
290 updated every three hours at the lateral boundaries for the outer domain. These nested domains are coupled online, and the LBCs for the inner domain are derived from the corresponding outer domain. In addition, all domains are simulated with the 2-moment microphysics scheme (Seifert and Beheng, 2006). For the inner two domains (3.2 and 1.6 km), shallow convection (Sakradzija et al., 2015) is parameterized, and deep convection is assumed to be explicitly resolved.

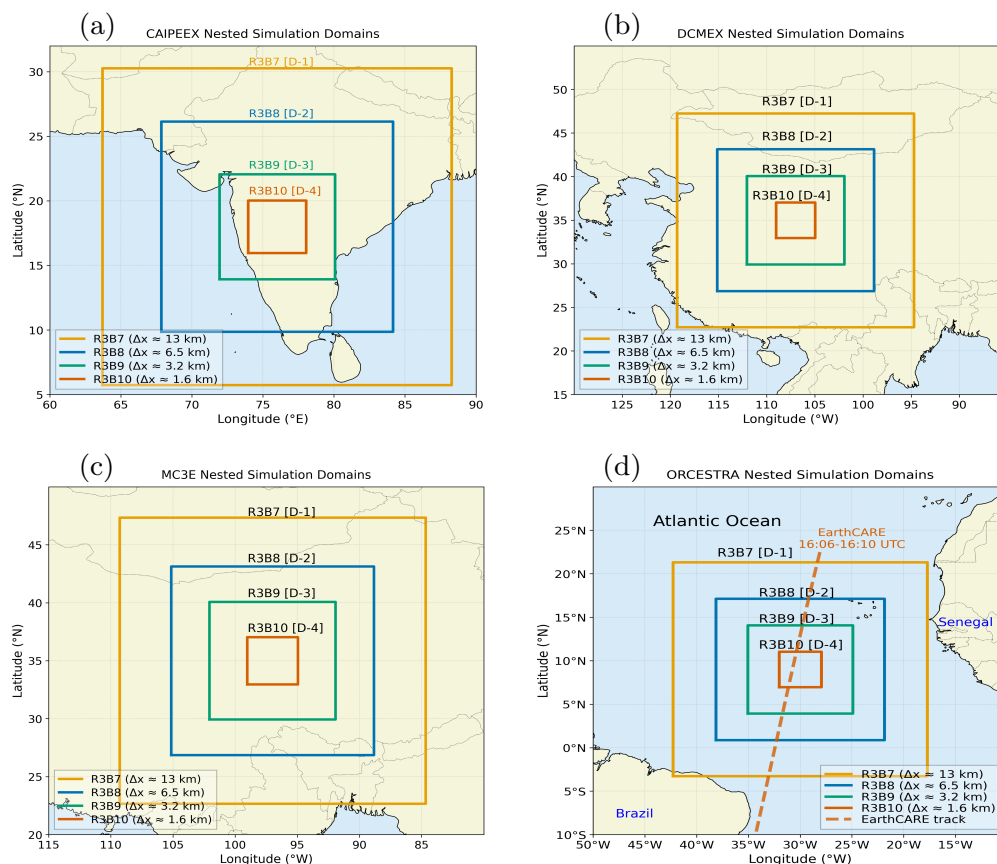


Figure 5. Outlines of the geographical areas used as domains for the simulated events of convection during (a) CAIPEEX, (b) DCMEX, (c) MC3E, and (d) ORCESTRA. The dashed red line in (d) shows the EarthCARE overpass over the study location between 1606 and 1610 UTC on 3 September 2024.

Due to their similar aerosol conditions, the simulated CAIPEEX, DCMEX, and MC3E cases are classified as ‘continental’, while ORCESTRA is categorized as ‘marine’ convection. Table 2 summarizes the details of the simulation time for each convective case. For the continental DCCs, the spin-up time is 3-6 h. In contrast, no spin-up time is considered for the ORCESTRA simulation, as ICON realistically reproduces the observed convection that was already present at initialization (Fig. 9f).

Here, the control run (Table 3) is performed with four SIP processes (Sec. 2.2.1), with RDF represented using the SUL18 scheme. Also, to assess the role of SIP on cloud and radiative properties, a sensitivity run (‘No SIP’ run) is performed in which SIP is turned off and compared with the control run. Furthermore, to examine the influence of the choice of RDF scheme on the simulated cloud properties, another sensitivity run (PHIL18 run) is performed in which the SUL18 scheme is replaced with the PHIL18 scheme.

The results discussed in the following sections are from the innermost (1.6 km) domain.



Table 2. Summary of simulation and spin-up time of the simulated DCCs.

Case	Spin-up time (h)	Simulation analysis start/end time
CAIPEEX	6	06-20 UTC 30 September 2019
DCMEX	6	16 UTC 2 August to 00 UTC 3 August 2022
MC3E	3	12 UTC 11 May to 12 UTC 12 May 2011
ORCESTRA	0	00 UTC 3 September to 00 UTC 4 September 2024

Table 3. Details of the simulations performed.

Case	Simulation analysis start/end time
Control	Includes all four SIP processes with RDF represented with the SUL18 scheme
No SIP	Excludes all four SIP processes
PHIL18	Includes all four SIP processes with RDF represented with the PHIL18 scheme

3 Results from the control simulations

305 3.1 Model Validation

This section compares the micro- and macrophysical properties of the simulated DCCs (Sec. 2.1), with aircraft (for CAIPEEX, DCMEX, MC3E) and satellite (for ORCESTRA) observations that are temporally and spatially coincident.

3.1.1 CAIPEEX

For the simulated convection in CAIPEEX, Fig. 6 shows a comparison of the control simulation (Table 3) with the coincident
 310 aircraft observations, conditionally averaged over the cloudy updrafts ($w > 1 \text{ m s}^{-1}$). The simulated properties of cloud-liquid (LWC and CDNC, Fig. 6 (a, b)) are seen to be in good agreement with observations from the CDP, with errors less than $\pm 30\%$. Furthermore, overall, the simulated total INC agrees well with the coincident observations of NI_{400} from CIP and PIP (Fig. 6d), with their means differing less than $\pm 40\%$ at all sampling levels. The same agreement is reported between the simulated and observed IWC (Fig. 6c).

315 As shown in the contoured frequency by altitude diagrams (CFADs), the simulated radar reflectivity (Fig. 6 f) shows the general vertical structure of CAIPEEX clouds as observed by the C-band radar (Fig. 6 e). The observed reflectivity shows a distinct bright band at about 5 km with a maximum reflectivity exceeding 25 dBZ. Although the simulation underestimates the high reflectivity values below 6 km, it adequately reproduces the overall shape and vertical distribution of reflectivity, with



both showing cloud tops at similar altitudes (16 km). The median profiles show that both simulated and observed reflectivities
320 decrease with height above the melting level (5 km), the simulated convection exhibits slightly weaker reflectivity, chiefly at
higher (> 6 km) altitudes, suggesting possible differences in ice-phase processes.

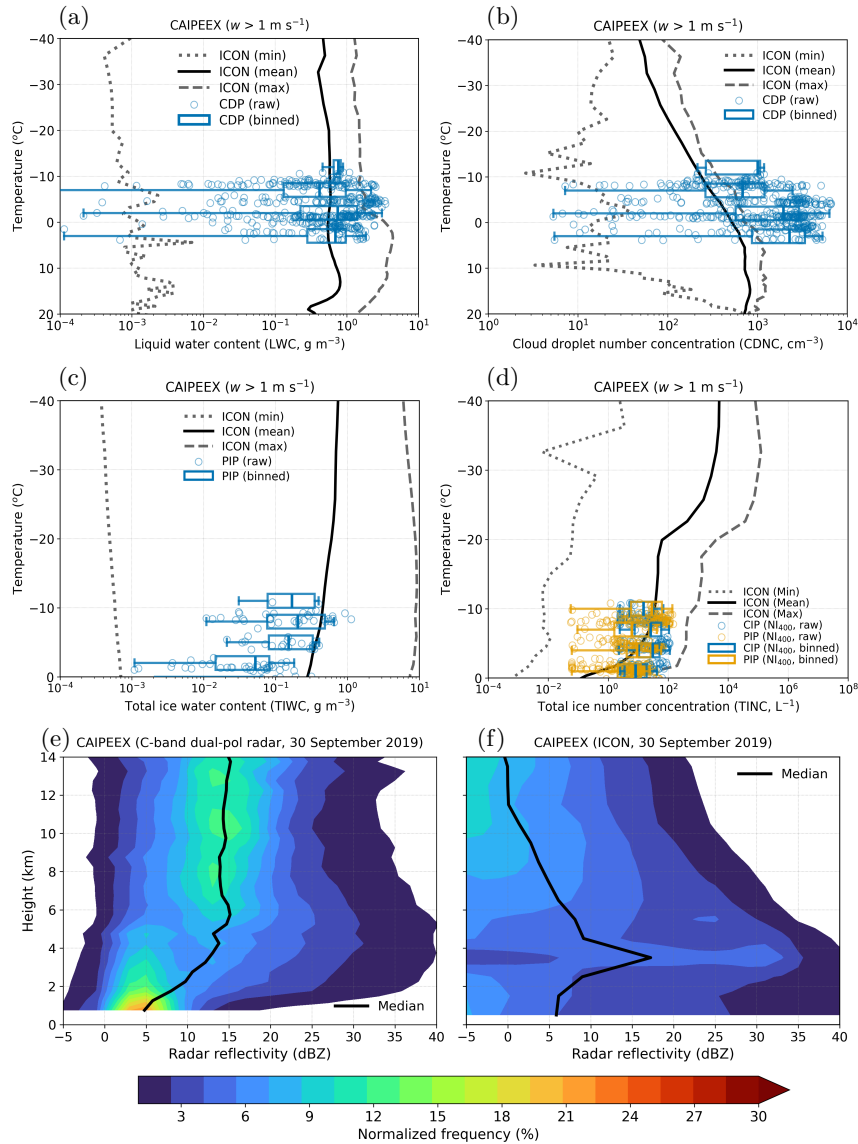


Figure 6. Conditionally averaged predictions (minimum (dotted lines), mean (solid lines) and maximum (dashed lines)) from the control simulation of the CAIPEEX case, over cloudy convective updrafts ($w > 1 \text{ m s}^{-1}$) for the (a) liquid water content (LWC), and (b) cloud droplet number concentration (CDNC), compared against the coincident CDP observations, and (c) ice water content (IWC) and (d) total ice particle number concentration (INC) compared with the corresponding observations from PIP probe (for IWC), and CIP and PIP (for INC) probes mounted on the B200 aircraft during CAIPEEX. In (d), only particles larger than 0.4 mm are shown from both CIP and PIP probes. Also, the simulated radar reflectivity from the control run (f) is compared with the corresponding observations (e) from the C-band dual polarization ground-based radar operational during CAIPEEX, averaged over $75\text{--}76^{\circ}\text{E}$ and $17\text{--}18^{\circ}\text{N}$ in both the simulation and the observations.



3.1.2 DCMEX

Figure 7 compares the results from the control simulation of DCMEX DCCs on 2 August 2022 with BAe146 aircraft observations, focusing on the cloudy updraft regions ($w > 1 \text{ m s}^{-1}$). The model simulates the magnitude of observed cloud-liquid
325 (mean droplet sizes, LWC, CDNC) properties at levels between the cloud base (5°C) and -10°C (Fig. 7 (a, b)). However, at colder levels ($< -10^\circ\text{C}$), limited sampling size (< 10) of the CDP results in larger model-observation discrepancies ($> 50\%$).

Also, at such cold levels, the simulated IWC is about four orders of magnitude higher than observed by the Nevzorov probe (Fig. 7c), whereas the medians differ by less than 50% at warmer subzero levels ($> -10^\circ\text{C}$). Simulated INC similarly agrees with CIP and 2DS observations (Fig. 7d). Notably, the observed INC differs by more than an order of magnitude at all
330 subzero levels. This discrepancy may partly result from ICON overestimating INC, especially below -15°C level, as well as significant uncertainties in the in-situ measurements, making it challenging to evaluate model performance against the observed ice properties.

The CFAD (Fig. 7 (e, f)) shows that the distribution of the simulated radar reflectivity agrees well with the observations from the dual-polarimetric, C-band Doppler radar, with both showing a similar cloud-top altitude of about 16 km. The maximum
335 radar reflectivity is up to 40 dBZ, both in the simulation and observation.

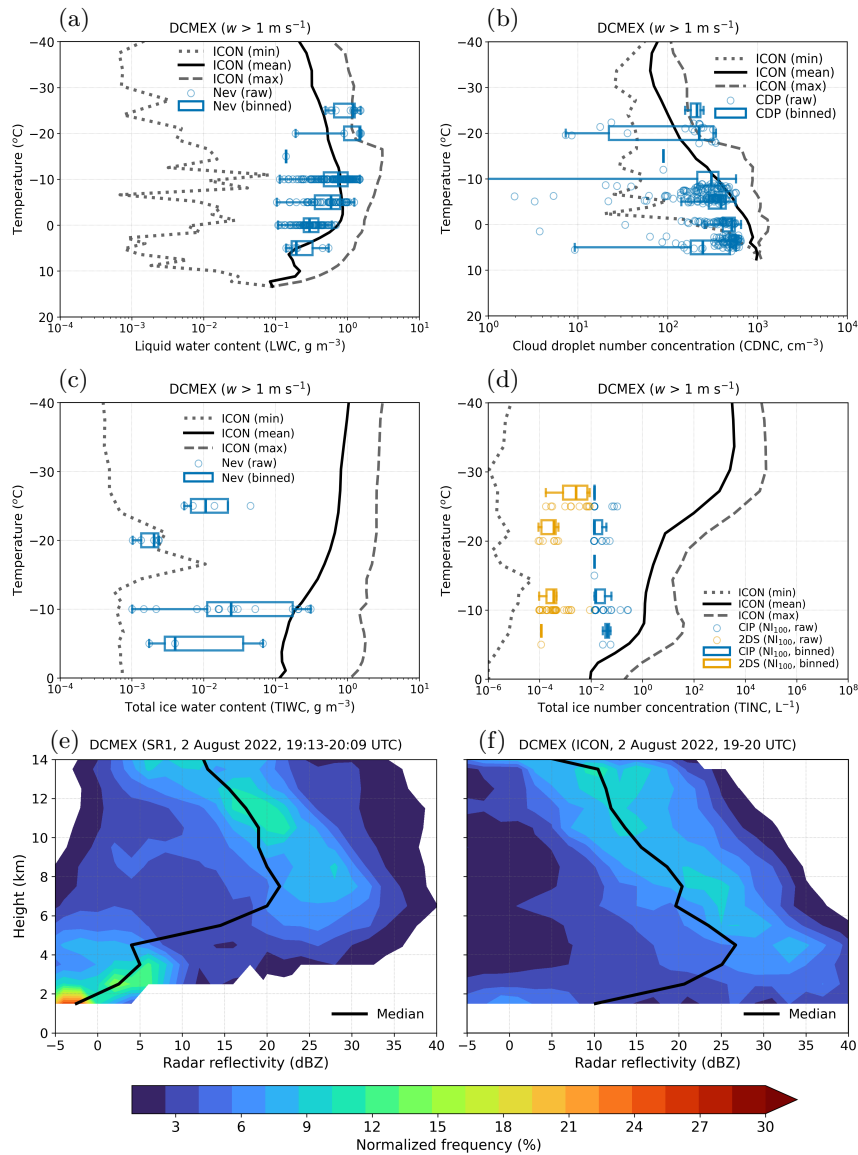


Figure 7. As in Fig. 6 but for DCMEX case observed on 2 August 2022. During DCMEX, the LWC, IWC, and CDNC were measured by the Nevzorov and CDP probes, respectively mounted on the BAe146 aircraft. The INC of particles larger than 0.1 mm was measured by CIP, whereas 2DS includes all particles. The radar observations are from the C-band, dual polarization, Shared Mobile Atmospheric Research and Teaching ground-based Doppler radar, unit 1, operational during DCMEX.



3.1.3 MC3E

For the simulated MCS, observed on 11 May 2011 during MC3E, Fig. 8 presents a comparison between the simulated cloud-liquid and ice properties and those measured by the Citation aircraft, in the cloudy updraft regions ($w > 1 \text{ m s}^{-1}$). The simulated and observed properties of cloud-liquid (LWC and CDNC) are in the same orders of magnitude, with the simulation consistently exhibiting slightly higher values than those measured (Fig. 8 (a, b)). Also, the simulated total INC is compared with the NI_{200} from HPVS-v3 and CIP (Fig. 8 (c, d)). The simulated INC at observational levels reaches 10 L^{-1} , comparable in magnitude to HPVS-v3 and CIP measurements.

In the control simulation of MC3E, the simulated reflectivity agrees well with the observation from the Ka-band Zenith radar, as evident in Fig. 8(e, f). The model adequately predicts the overall frequency distribution and the vertical extent of the observed reflectivity. In addition, the maximum reflectivity is located below the freezing level (4.5 km), both in observation (25 dBZ) and simulation ($> 40 \text{ dBZ}$), and the reflectivity values decrease with altitude.

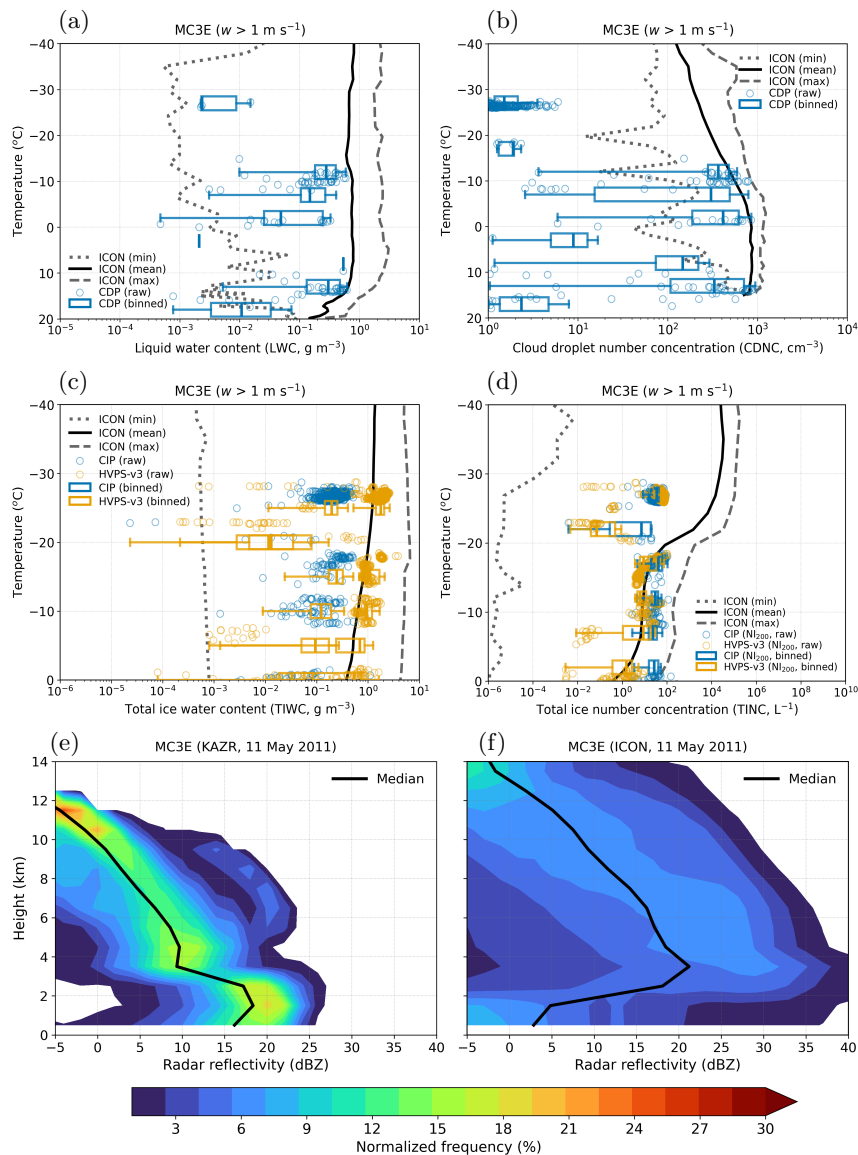


Figure 8. As in Fig. 6 but for MC3E case observed on 11 May 2011. During MC3E, the LWC and CDNC were measured by the CDP probes, respectively mounted on the Citation aircraft. NI_{200} was measured by CIP and HVPS-v3. The radar observations are from the Ka-band zenith radar (97.485° W, 36.605° N) operational during MC3E.



3.1.4 ORCESTRA

For the ORCESTRA case, the observed microphysical and radar properties are derived from the CPR onboard the EarthCARE satellite (Sec. 2.1, Fig. 9 (a-c, f)). Also, the simulated total precipitation is compared with the measurements from the GPM (Fig. 9d).

From these profiles, it is evident that ICON predicts the observed vertical distribution of the LWC (Fig. 9a) and total IWC (Fig. 9b) with reasonable accuracy. Also, the simulated total INC agrees well with the CPR observations at most altitudes (Fig. 9c). However, between -20 and -40°C levels, ICON predicts the total INC that is up to two orders of magnitude higher than those from the CPR. This discrepancy is likely because ICON overpredicts INC at these levels as well as the limited sensitivity of the CPR to large concentrations of small ice particles, which, despite being numerous, contribute little to radar reflectivity. This results in an underestimation by CPR of the total INC in cloudy regions dominated by small ice-crystals.

Furthermore, Fig. 9d shows a good agreement between the temporal evolution of the domain-averaged surface precipitation between the simulation and the GPM observation. ICON adequately captures the observed peak and decrease in precipitation with time, with generally higher precipitation than the corresponding observation. This is attributed to the fact that at such a higher spatial resolution (1.6 km) than GPM (10 km), ICON captures intense convective cores that may produce larger and more localized precipitation maxima (supplementary Fig. S1).

Also, for this convection, Fig. 9 (e, f) shows a CFAD comparison of the radar reflectivity between the control simulation and the CPR observations, between 16:00 and 16:15 UTC. The CPR CFAD shows a broad distribution of reflectivity, with a mean value of about 10 dBZ at most vertical levels. The median of the CPR reflectivity remains consistently below 10 dBZ at all levels, mainly due to its sensitivity to a wide range of hydrometeors, including stratiform precipitation, as well as its ability to detect localized and small-scale convection.

In contrast, the CFAD from the control simulation shows a relatively broader and higher reflectivity distribution, mainly below 8 km, with a median exceeding 10 dBZ. This is chiefly because at higher spatial resolution (1.6 km), ICON can capture strong and localized convective cores that may experience signal attenuation at the 94 GHz frequency of CPR, particularly in regions of heavy precipitation (Sasikumar et al., 2025). The simulation, therefore, may exhibit pronounced convective features, whereas CPR measurements may show stratiform features. Despite these differences, the overall vertical structure of the simulated reflectivity compares adequately with the CPR observations, with both showing a gradual decrease in reflectivity with altitude and maximum frequency between the lower and mid-troposphere. Notably, ICON shows the observed stratiform and embedded convective features of the ORCESTRA storm, as evident by regions of lower reflectivity (0-10 dBZ) at mid-levels (5-10 km).

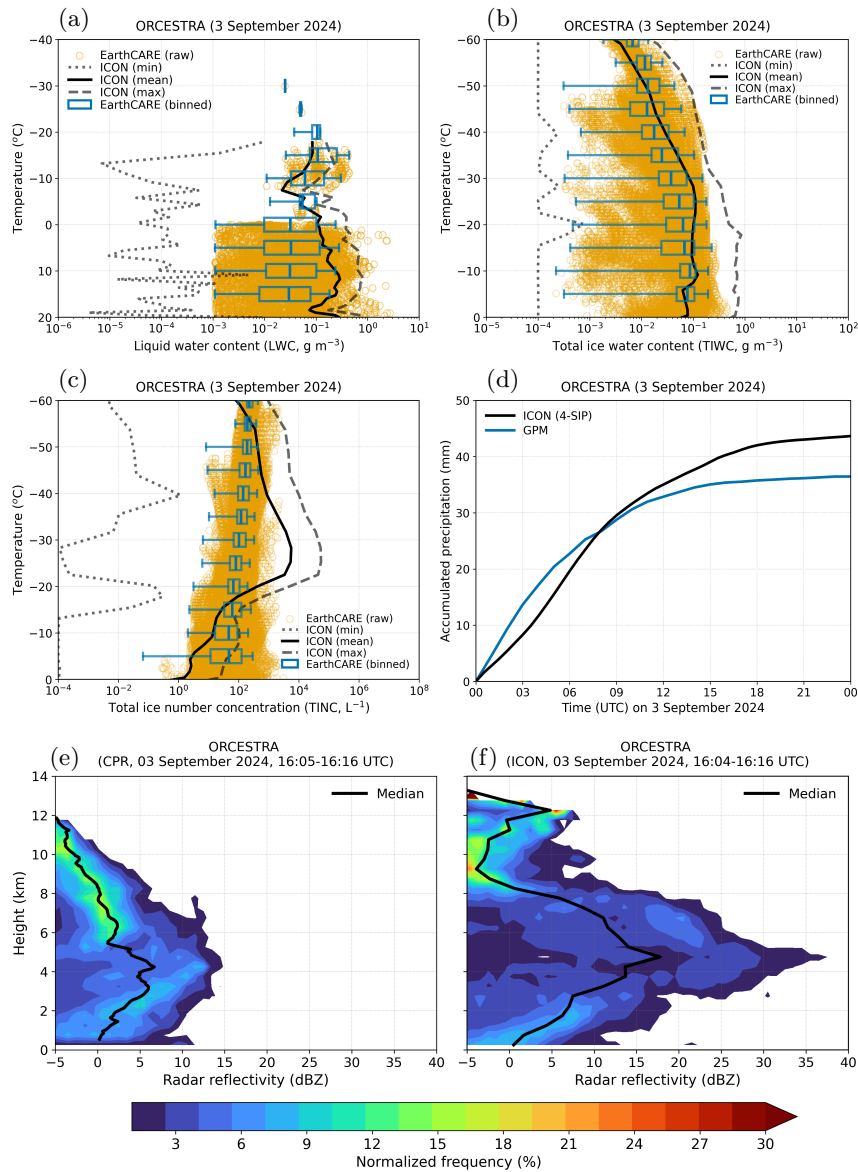


Figure 9. Comparison of the simulated properties (mean- solid lines, min- dotted lines, and max- dashed lines), such as (a) LWC, (b) total IWC, (c) total INC, with the coincident observations from EarthCARE CPR. Also, (d) the simulated domain-averaged surface precipitation rate (solid black line) is compared with the corresponding observations from the GPM (solid blue line). Furthermore, the contoured frequency by altitude diagram (CFAD) of radar reflectivity of the (e) EarthCARE-CPR is compared with the (f) control simulation of ORCESTR for the period between 16:05 and 16:16 UTC. The simulated microphysical properties in (a-c) and radar reflectivity are plotted corresponding to the region of EarthCARE pass, as shown in Fig. 4a.



In summary, ICON adequately reproduces the observed microphysical properties and distribution of radar reflectivity for the simulated DCCs. Also, in their mixed-phase regions (0 and -38°C), the combination of various SIP processes (Sec. 2.2.1) allows ICON to simulate the observed INC, which cannot be explained by heterogeneous ice nucleation alone in these DCCs (supplementary Fig. S2).

380 3.2 Microphysical analyses of the control runs

In Fig. 10, the process rates of INCs from the primary (heterogeneous) ice and from various SIP processes are analyzed from the control runs of the simulated DCCs.

In the mixed-phase region of these DCCs, IIC dominates the overall ice formation (Fig. 10), whereas primary ice contributes least to the total ice. Also, in all simulated clouds, it is seen that each SIP process exhibits a peak at different altitudes. For
385 example, IIC peaks at much colder levels (-30°C) forming about 99% of the total secondary ice there. Furthermore, RDF peaks at relatively warmer temperatures (-20°C) and forms about 1% of the total secondary ice.

The HM process is found to peak at much warmer levels (between -8 and -10°C), contributing over 30% to the total secondary ice at these levels. Moreover, SBF produces ice splinters at a quasi-steady rate at all subzero levels warmer than -38°C , forming less than 1% of the total secondary ice. Hence, depending on their contribution to the total secondary ice, IIC
390 can be ranked as the first, the HM process as the second, RDF as the third, and SBF as the fourth most important SIP process, as also reported by Waman et al. (2022).

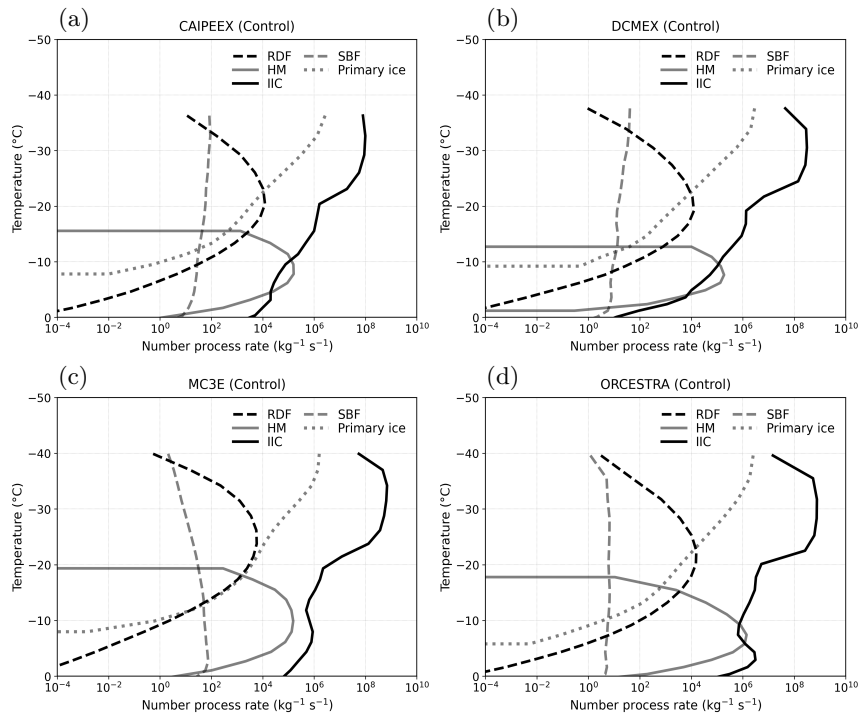


Figure 10. Profiles of the number process rates of various SIP processes, such as fragmentation in raindrop freezing (RDF, dashed black lines), Hallett-Mossop rime-splintering (HM, solid gray lines), ice-ice collision (IIC, solid black lines), and sublimation (SBF, dashed gray lines), averaged over convective ($w > 1 \text{ m s}^{-1}$) cloudy grid points for the control simulations of the DCCs, such as (a) CAIPEEX, (b) DCMEX, (c) MC3E, and (d) ORCESTRA. Also shown is the process rate for heterogeneously nucleated ice (Primary ice, dotted gray lines). Process rates represent time-integrated values over the simulation period, while vertical velocity corresponds to instantaneous model output.



3.3 Impact of SIP on microphysics, precipitation and dynamics of DCCs

To assess the role of ice multiplication (Sec. 2.2.1) in modulating the microphysical, dynamical, and radiative properties of the simulated DCCs, a sensitivity test was performed. This involved modifying the control run to create a perturbation simulation
395 ('No SIP' run), in which all SIP processes are excluded, which is then compared with the control run.

3.3.1 Impact of SIP on microphysical properties

For the simulated CAIPEEX convection, Fig. 11 illustrates the time-height evolution of the simulated microphysical properties (LWC, total IWC, and INC) in the control and No SIP simulations. Additionally, corresponding changes due to SIP (control minus No SIP) are also shown in the same figures. In the mixed-phase region of the simulated CAIPEEX DCCs, supercooled
400 liquid is about 40% higher without SIP than with it, chiefly due to decreased depositional growth of ice crystals there (Fig. 11 (a-c)). In contrast, in the mixed-phase levels in this monsoon convection, the exclusion of SIP predicts a 20% and 70% decrease in the total IWC and INC, respectively, than those with SIP (Fig. 11 (d-i)).

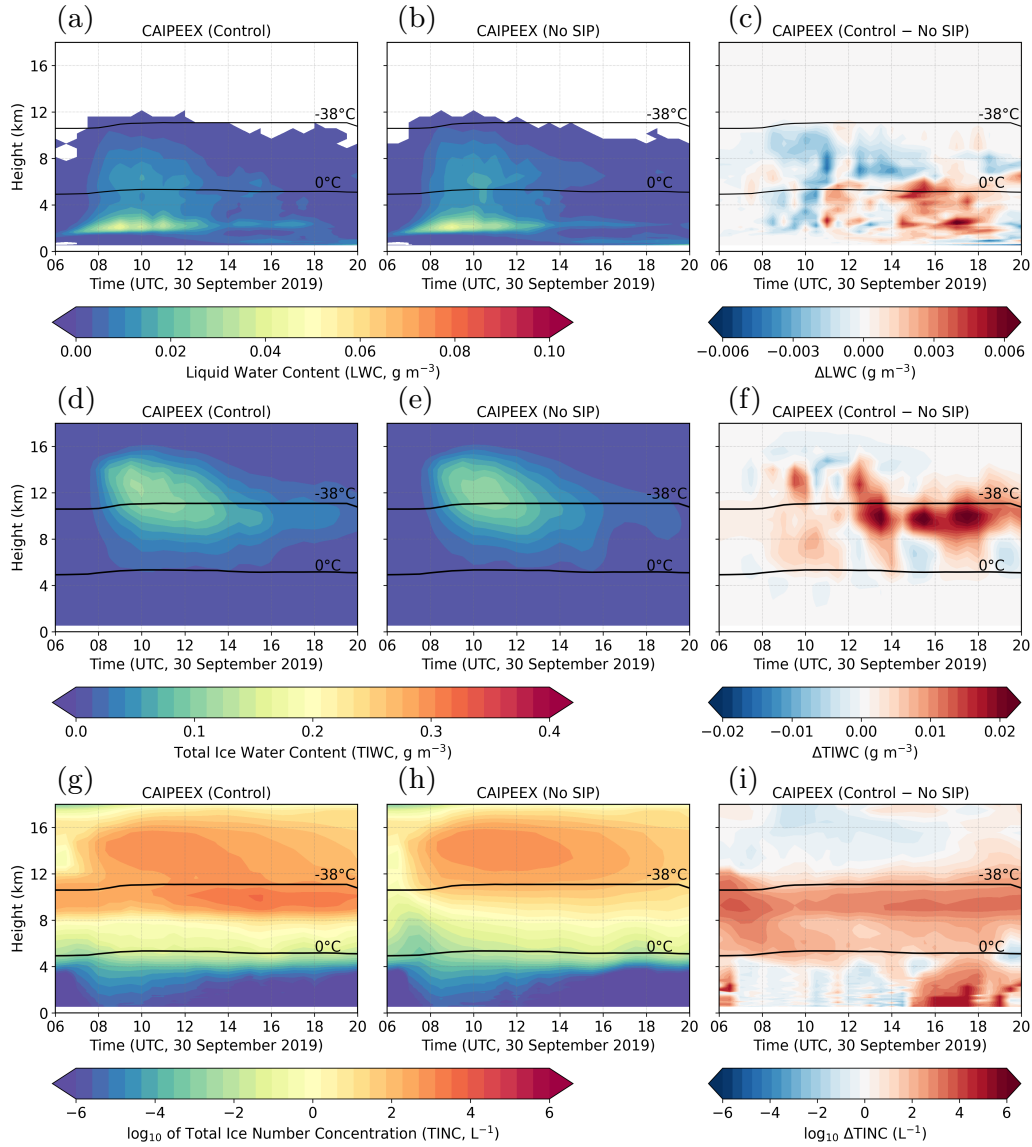


Figure 11. Domain averaged time-height profiles of the (a) LWC, (d) total IWC, and (g) total INC from the control simulation of CAIPEEX convection. The same information is shown from the No SIP run in (b, d, h). Furthermore, the change (control minus No SIP) in LWC, total IWC, and total INC is shown in (c), (f), and (i), respectively. Also, in these plots, the freezing and -38°C levels are denoted by the horizontal black and gray lines. In (i), the color bar scale is plotted as $\text{sign}(\Delta\text{Total INC}) \times \log(1 + |\Delta\text{Total INC}|)$, where Δ denotes change.



In the mixed-phase region of the simulated DCMEX clouds, during convection (18-23 UTC), the absence of SIP causes about a 20% increase (decrease) in the supercooled liquid (total ice) mass (Fig. 12 (a-f)). Furthermore, at these levels, when present, SIP produces as high as 10^3 L^{-1} ice number concentration over a broad vertical extent (4.2 to 16 km) and a prolonged period (18-23 UTC, Fig. 12 (g-h)). In contrast, without SIP, the maximum INC is 50 L^{-1} at homogeneous levels, with a more confined vertical extent and a relatively shorter duration of enhancement.

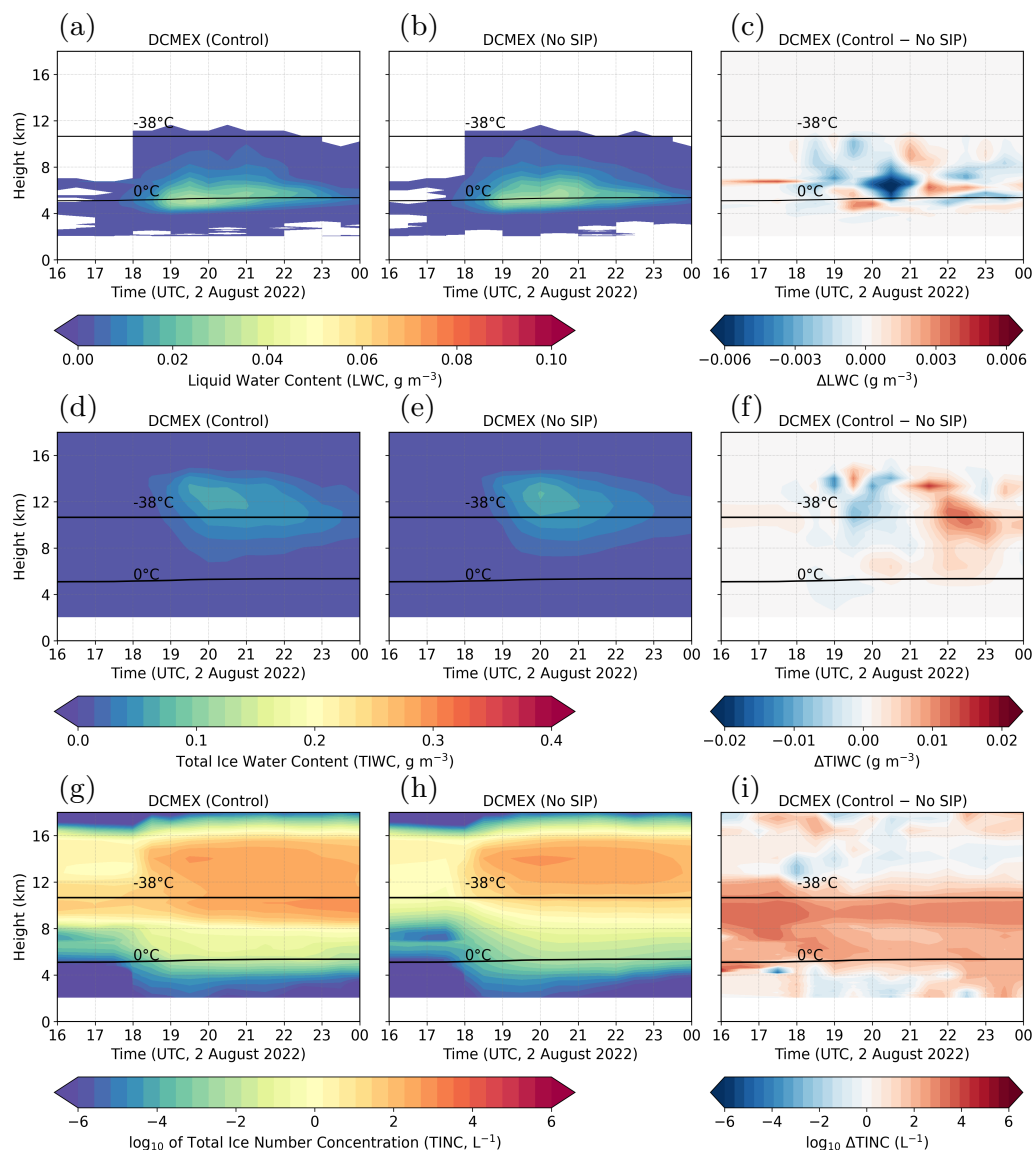


Figure 12. As in Fig. 11, but for DCMEX convection.



In an MCS during MC3E, the exclusion of SIP substantially alters the simulated microphysical structure. The absence of SIP in MC3E predicts over 40% increase in the supercooled liquid mass for extended vertical levels, and period (11 May 12 UTC to 12 May 04 UTC) than with SIP (Fig. 13 (a-c)) whereas the total ice mass decreases by the same factor, especially in the mixed-phase region (Fig. 13 (d-f)). Additionally, in these DCCs, INC extends vertically from near the freezing level to 18 km, with about 3 orders of magnitude less INC in the mixed-phase region without SIP than with it (Fig. 13 (g-i)). Also, the exclusion of SIP from MC3E exhibits reduced vertical spread as well as temporal extent of these clouds. Hence, in these clouds, sustained glaciation facilitated by SIP forms a broad and long-lived anvil structure.

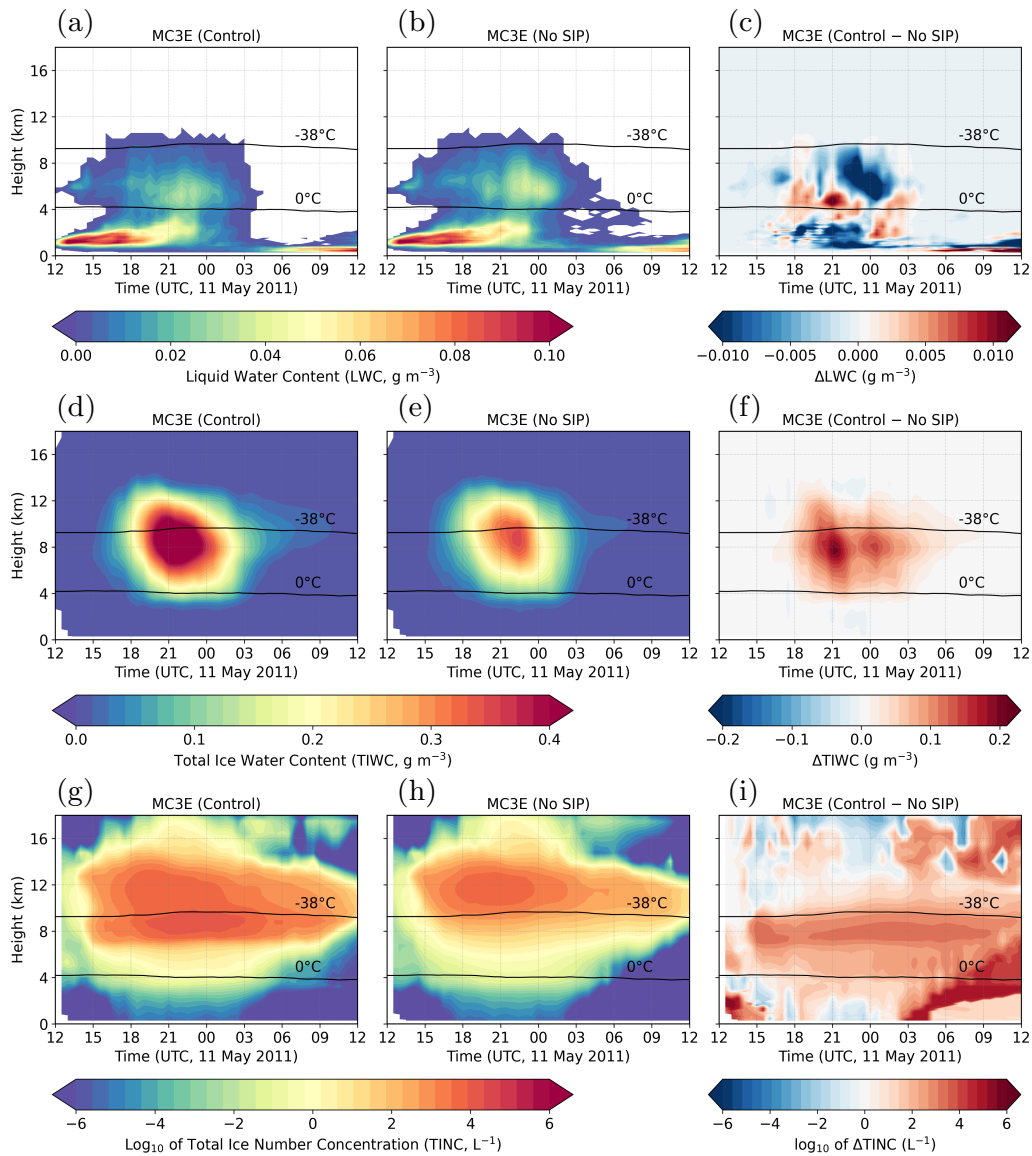


Figure 13. As in Fig. 11, but for MC3E convection.



415 In these marine DCCs of ORCESTRA, the absence of SIP predicts over 20% more supercooled liquid above 5 km, while a 10% increase is seen below it (Fig. 14 (a-c)).

In contrast, excluding SIP predicts a significant change in the distribution and magnitude of the total IWC (Fig. 14 (d-f)) and INC (Fig. 14 (g-i)). In the absence of SIP, at the mixed-phase levels, the total IWC is about 50% lower, mainly due to the reduced depositional growth of ice particles, than in the control run. Also, excluding SIP reduces INC by a factor of 10^2 - 10^3 .

420 Moreover, the presence of SIP sustains the overall ice mass over time and altitude in the control run, which would otherwise rapidly diminish after the convective peak (3-9 UTC). This is because, when present, SIP allows for continuous multiplication of ice via various processes throughout the life cycle of this marine convection, which sustains overall IWC and INC through depositional growth.

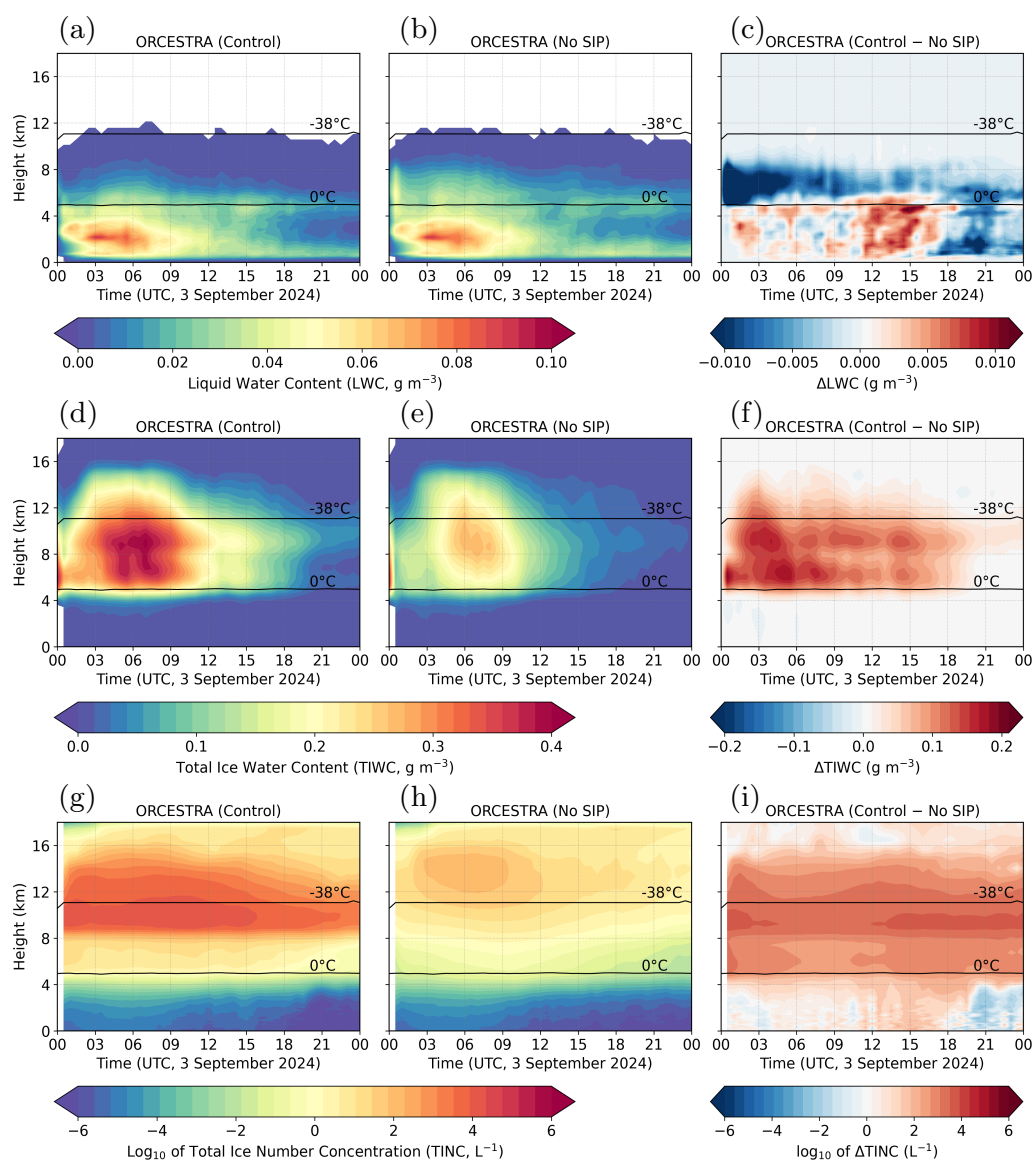


Figure 14. As in Fig. 11, but for ORCESTRa convection.



In summary, SIP significantly impacts the microphysical evolution of the simulated DCCs by promoting upper-level glaciation, which extends cloud lifetime and enhances both temporal longevity and spatial structure. In all simulated DCCs, excluding SIP leads to a 20% reduction in ice mass, a corresponding increase in liquid mass, and a more than tenfold decrease in ice particle numbers. This effect is most pronounced in MC3E, with up to 50% decrease (increase) in ice (liquid) mass without SIP than with it. These microphysical changes are hypothesized to influence the macrophysical and dynamical properties of these DCCs, as discussed in the following sections.

3.4 Impact of SIP on surface precipitation

In this section, the impact of SIP on the accumulated surface precipitation is discussed for the simulated DCCs.

Figure 15 illustrates domain-averaged surface accumulated precipitation in the control runs (black bars) of the simulated DCCs. It is reported that the amount of precipitation differs greatly among these clouds, with ORCESTRA representing intense tropical marine convection and producing the highest (42 mm) precipitation. In addition, MC3E forms about 6 mm surface precipitation, while CAIPEEX and DCMEX show more suppressed convective (< 4 mm) conditions.

Furthermore, in these DCCs, the impact of excluding SIP on the simulated surface precipitation is shown in Fig. 15 (gray bars). In short-lived, weakly precipitating ($< 1 \text{ mm h}^{-1}$) DCCs of CAIPEEX (Patade et al., 2025) and DCMEX (Huihui et al., 2025), excluding SIP causes a negligible change in the surface precipitation, due to relatively weaker SIP activity. In contrast, in long-lived MCSs of MC3E and ORCESTRA, the exclusion of SIP reduces the surface precipitation by 1-5%, mainly due to reduced ice-crystal growth via deposition and riming (Fig. S3 in the supplement).

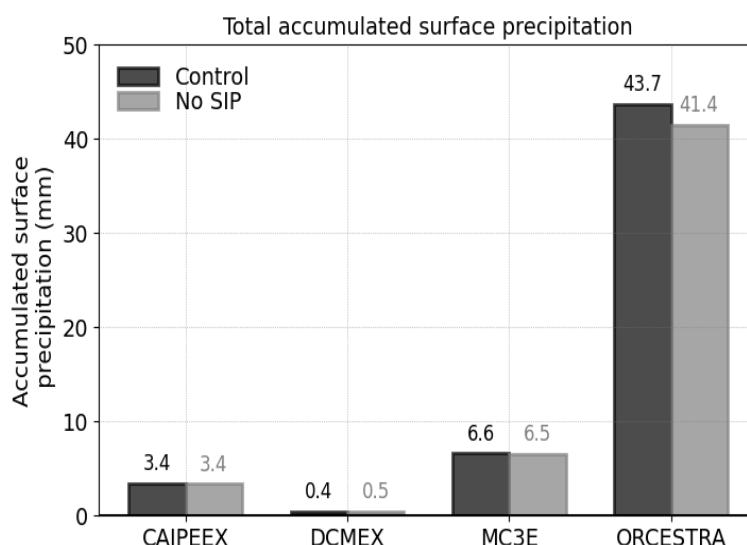


Figure 15. Total accumulated surface precipitation from the control (black bars) and No SIP (gray bars) simulations of CAIPEEX, DCMEX, MC3E, and ORCESTRA clouds.



3.5 Impact of SIP on cloud dynamics

This section discusses dynamical properties, such as latent heating, CRH, mean vertical velocity, and cloud top altitude, from the control simulations of the DCCs. In addition, the sensitivity of these dynamical properties to SIP in the simulated DCCs is analyzed.

445 Figure 16 (left panel) illustrates the evolution of latent heating in the control runs of the simulated storm. The contour lines in Fig. 16 represent key microphysical processes contributing to total latent heating: condensation or evaporation (solid black line), vapor deposition (dashed black line), riming of cloud-liquid and rain (solid gray line), and evaporation and melting of precipitating hydrometeors (dash-dotted black line). This temporal evolution of latent heating reflects the life cycle of simulated DCCs, from initiation and growth to dissipation (Sec. 1), characterized by strong latent heating and cooling, respectively.

450 The simulated latent heating reveals strong variability in intensity and vertical extent across the simulated clouds. As convection intensifies in the control runs of CAIPEEX (between 7 and 11 UTC, Fig. 16a) and DCMEX (between 17 and 20 UTC, Fig. 16d), a pronounced heating core develops between 1-12 km, peaking at 30 K d^{-1} (in CAIPEEX) and 20 K d^{-1} (in DCMEX). In these DCCs, this heating is primarily driven by the heat release in droplet activation (1-2 km, not shown here), condensation (2-12 km), and depositional growth of ice-crystals (9-12 km), and further supported by riming at mid-levels.

455 After 12 UTC in CAIPEEX and 20 UTC in DCMEX, the heating weakens and contracts, and regions of cooling, driven by evaporation and melting, become more prominent, reaching up to -10 K d^{-1} below the freezing level.

Similarly, in its control run (Fig. 16g), MC3E convection exhibits vertically extensive and persistent latent heating, peaking at 40 K d^{-1} above 7 km between 18-23 UTC on 11 May 2011. During its developing phase (15-17 UTC), heating extends from the surface to 10 km, chiefly from nucleation and condensation (up to 8 K d^{-1}). In its mature phase (17-23 UTC), the heating

460 further strengthens to 50 K d^{-1} at 7 km, driven by condensation in the lower troposphere, and riming and deposition aloft (Fig. 16g). Notably, the anvil region ($> 10 \text{ km}$) shows sustained heating from the depositional growth of ice-crystals. After 23 UTC, as the system transitions to a stratiform regime, upper tropospheric heating weakens and spreads horizontally due to reduced deposition, while cooling due to evaporation and melting intensifies below the freezing level, indicating downdrafts and weakening convection.

465 In contrast, among the simulated DCCs, marine convection of ORCESTRA exhibits the strongest ($> 50 \text{ K d}^{-1}$, Fig. 16j) and most sustained diabatic heating. This is chiefly because, in such marine clouds, higher moisture facilitates condensation, which causes up to 80 K d^{-1} heat release at 3 km, between 3-8 UTC. Above the 6 km level, depositional growth of ice crystals dominates overall diabatic heating, with a sustained peak of 80 K d^{-1} between 4-8 UTC. In the mixed-phase region of ORCESTRA, riming (8 K d^{-1}) contributes up to 10% to total latent heating.

470 In the marine convection of ORCESTRA, abundant moisture below cloud base limits cooling due to evaporation and melting, as a shallow subsaturated layer allows precipitation to fall into already humid air. Consequently, evaporation and melting produce weaker cooling than in drier continental environments (Fig. 16 (a-i)). This likely weakens downdrafts and favors



ascending convective turrets, enhancing vertical transport of heat and moisture. Overall, the presence of extra moisture in these marine DCCs boosts latent heating and enables a more vertically extensive, organized convective system.

475 The level of peak latent heating also differs between continental and marine DCCs. In the investigated continental cases, mean diabatic heating peaks at colder temperatures ($< -38^{\circ}\text{C}$) compared to the marine case (ORCESTR), where it peaks at significantly warmer temperatures ($< -20^{\circ}\text{C}$) (supplementary Fig. S3). This difference is primarily due to contrasting micro-physical processes driven by aerosol conditions. Continental DCCs, characterized by higher aerosol loading, form numerous small droplets that remain supercooled at colder ($< -38^{\circ}\text{C}$) levels, where they freeze homogeneously and subsequently grow
480 by vapor deposition. Conversely, marine DCCs with lower aerosol concentrations and higher moisture availability produce fewer, larger droplets that promote glaciation via enhanced collision-coalescence and subsequent raindrop/drizzle freezing. The growth of these frozen hydrometeors through riming and vapor deposition causes latent heating to peak at relatively warmer subzero levels (-20°C).

Figure 16 (b, e, h, k) shows diabatic heating profiles from No SIP runs of the simulated DCCs. In the mixed-phase regions of
485 continental DCCs, the exclusion of SIP reduces latent heating, mainly during the early growth phase, by over 10% in CAIPEEX and DCMEX, and up to 50% in MC3E. Notably, in these regions, latent heating from deposition is weaker than the cooling from sublimation, both with and without SIP (supplementary Figs. S2 (a-f)), especially during the mature and decay phases (Figs. 16 (a-i)). However, without SIP, sublimation is more pronounced due to fewer ice particles, which reduces the surface area available for vapor deposition, than with SIP. Additionally, at these levels, the absence of SIP increases diabatic heating
490 from condensation by 10% compared to with SIP, as more moisture remains available to condense into supercooled liquid (Figs. 16 (b, e, h)). Also, in continental DCCs, excluding SIP has little effect on latent heat release during riming.

Below freezing levels in these continental DCCs, excluding SIP leads to a small (5%) increase in overall latent heating, mainly due to enhanced evaporation and melting of precipitation compared to with SIP. In contrast, at -40°C in these continental clouds, excluding SIP increases total latent heating by up to 10%, mainly due to enhanced vapor deposition (Fig. 16,
495 Fig. S3 (a-f) in the supplement). This is mainly because, without SIP, homogeneously formed ice crystals tend to grow larger and more efficiently via vapor deposition, releasing more latent heat than with SIP.

In contrast, in the developing and mature phases (0-9 UTC) of ORCESTR marine DCCs (Fig. 16 (j, k)), excluding SIP results in up to 15% lower latent heating (Fig. 16l) compared to the control run, chiefly in the mixed-phase region. This decrease is due to a 70% reduction in depositional growth of ice particles, as fewer INC form without SIP (Figs. 16l, supplementary
500 Fig. S3 (g, h)). However, at these levels, latent heating from condensation doubles when SIP is excluded, as more moisture is available instead of being consumed by ice-crystal growth.

In ORCESTR, excluding SIP increases supercooled liquid availability above 7 km (Fig. 14a), enhancing ice growth via riming and resulting in about 20% more diabatic heating. Also, below the freezing level in this marine convection, the exclusion of SIP causes little change ($\pm 1\%$) in total latent heating, as evaporation of precipitating hydrometeors is minimal in the
505 saturated environment.

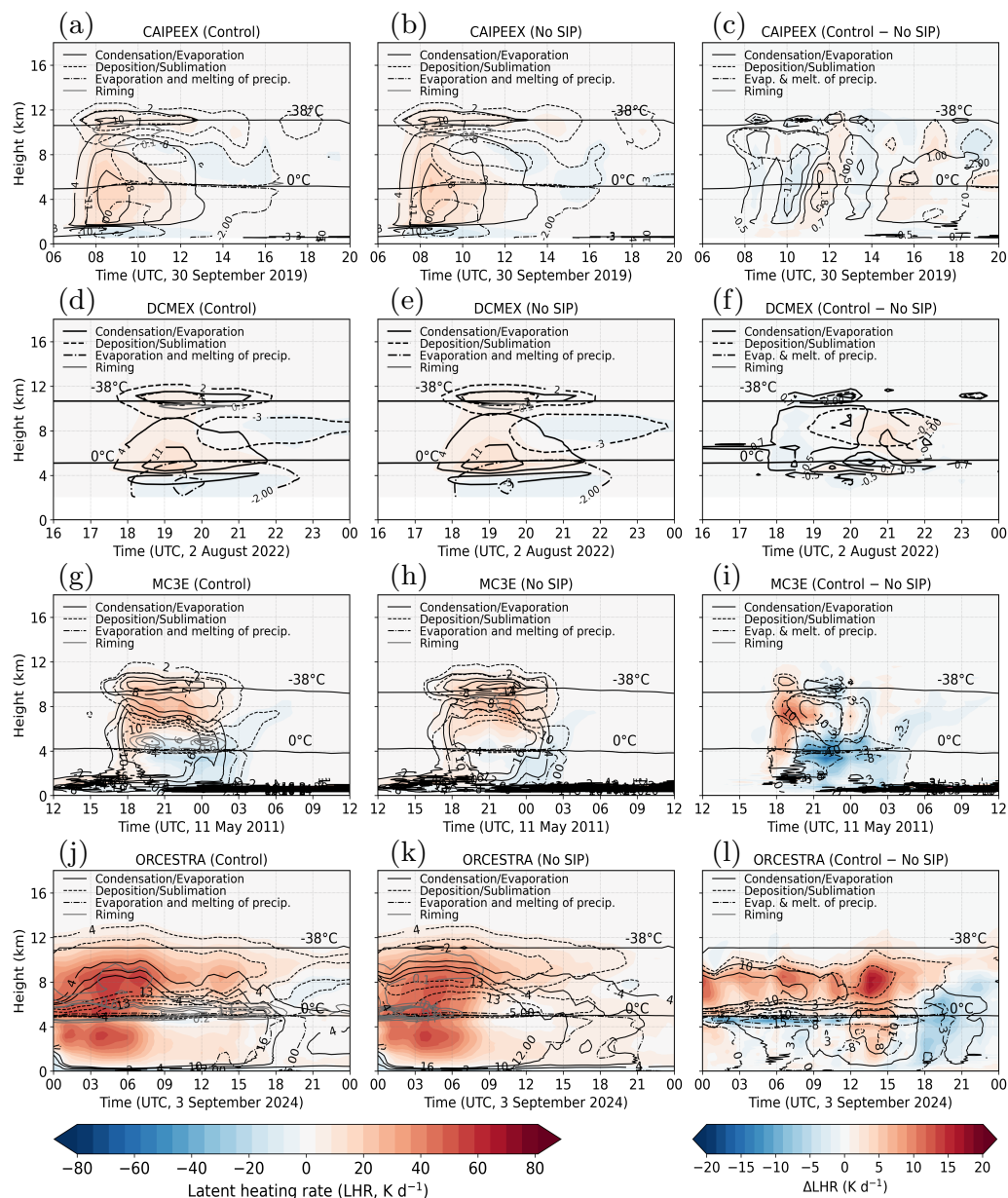


Figure 16. Domain averaged time-height profiles of the total latent heating in the (a) control, and (b) No SIP simulations of the CAIPEEX clouds. Also, the change in latent heating from the exclusion of SIP (Control minus No SIP) for the CAIPEEX case is shown in (c). The contour lines in (a, b, c) show the contribution to the latent heating from major microphysical processes, such as condensation/evaporation (positive/negative values shown in solid black lines), deposition/sublimation (positive/negative values shown in dashed black lines), riming (dashed-dot black lines), and evaporation and melting of precipitation (solid gray lines). In (c), only major processes, such as Condensation/Evaporation, Deposition/Sublimation, and Evaporation and melting of precipitation, are shown. The other processes, such as rain freezing, homogeneous and heterogeneous nucleation, are not shown as they contribute little ($< 2\%$) to the overall latent heating. The same information is shown for the simulated (d, e, f) DCMEX, (g, h, i) MC3E, and (j, k, l) ORCESTRA clouds in their control and No SIP runs.



Figure 17 illustrates the vertical profiles of mean CRH from the control runs (solid black line) of DCCs. The maximum CRH reaches up to 3 K d^{-1} at -40°C in the continental DCCs (CAIPEEX, DCMEX, MC3E), and at -20°C in the marine case (ORCESTR), coinciding with the respective peaks in latent heating (supplementary Fig. S3) due to the contrasting microphysical processes described above.

510 The impact of SIP on CRH is assessed in Fig. 17 by comparing the control simulation with the No SIP run (solid gray line). It is reported that, in the mixed-phase region (0 to -38°C), excluding SIP reduces CRH by up to 20% in continental DCCs and 40% in marine DCCs. This reduction is primarily attributed to lower INC (Figs. 11-14) at these levels in the absence of SIP, which weakens CRH through reduced (to up to 20%) depositional growth of ice particles.

515 SIP exclusion exhibits the most pronounced impact on LW CRH (Fig. 17), which decreases by up to 15% (in continental DCCs) and 50% (in marine DCCs) due to reduced absorption of outgoing LW radiation. In continental DCCs, excluding SIP causes minimal change ($< 5\%$) in SW CRH. In contrast, excluding SIP from ORCESTR marine DCCs exhibits enhanced SW radiative warming (from strong cooling to weak warming), primarily due to increased incoming SW radiation through the cloud column. This is because of a significant reduction in INC (by a factor of 10^3 , supplementary Fig. S2(d)), which causes optically thinner mixed-phase clouds and thereby allows more SW radiation to reach and absorb at lower levels.

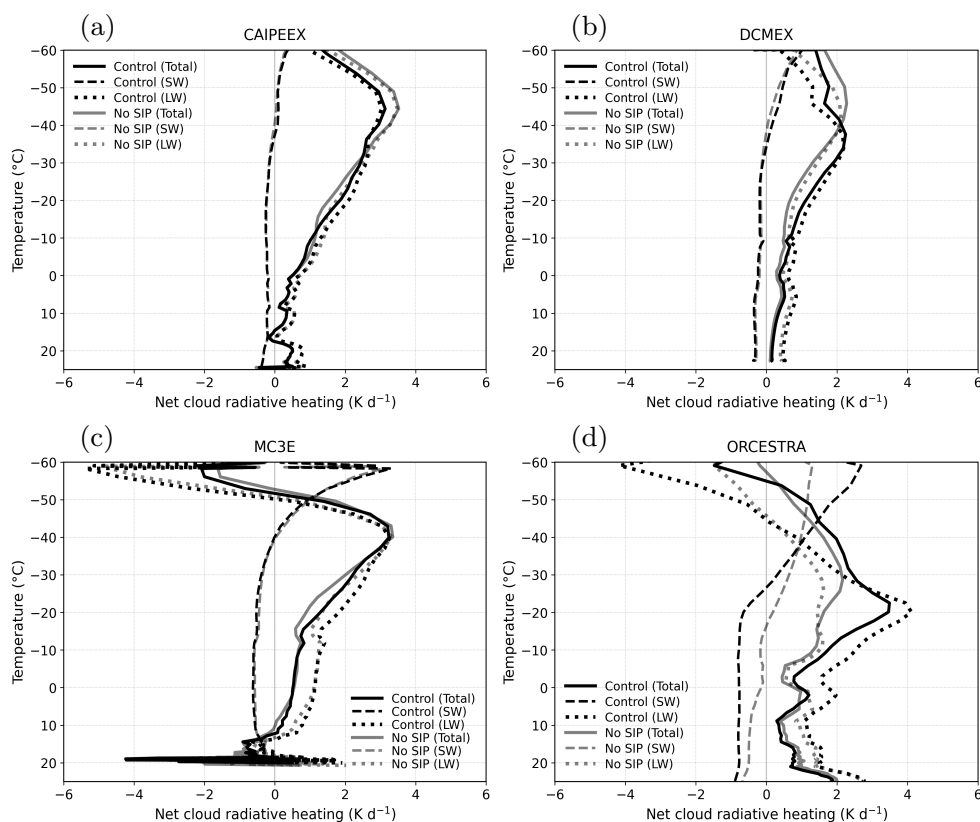


Figure 17. Simulated domain-averaged net cloud radiative heating (CRH, K d^{-1}) from the control (solid black lines) and No SIP (solid gray lines) simulations of (a) CAIPEEX, (b) DCMEX, (c) MC3E, and (d) ORCESTRA clouds. Also shown are the SW (dashed lines) and LW (dotted lines) components of CRH.



520 Excluding SIP in the simulated DCCs causes noticeable changes in the 90th-percentile vertical velocities (Fig. 18), thereby influencing the overall convective strength. In the mixed-phase regions of continental DCCs, excluding SIP weakens vertical motion by about 5-10%, while in the marine convection of ORCESTR, the reduction exceeds 20%. This is explicable in terms of reduced diabatic heating (Figs. 16, 17), which lowers parcel buoyancy in the ‘No SIP’ simulations. Noticeably, below the freezing level in MC3E (Fig. 18a), SIP exclusion causes a little (3%) increase in vertical velocity, due to 20% less diabatic cooling there (Fig. S3 (b, f) in the supplement).

Thus, above the freezing level, all simulated DCCs show weaker updrafts when SIP is excluded, primarily because reduced diabatic heating through diminished microphysical processes (Fig. 16). Similar changes appear in the maximum updraft and downdraft magnitudes (Fig. S4 in the supplement).

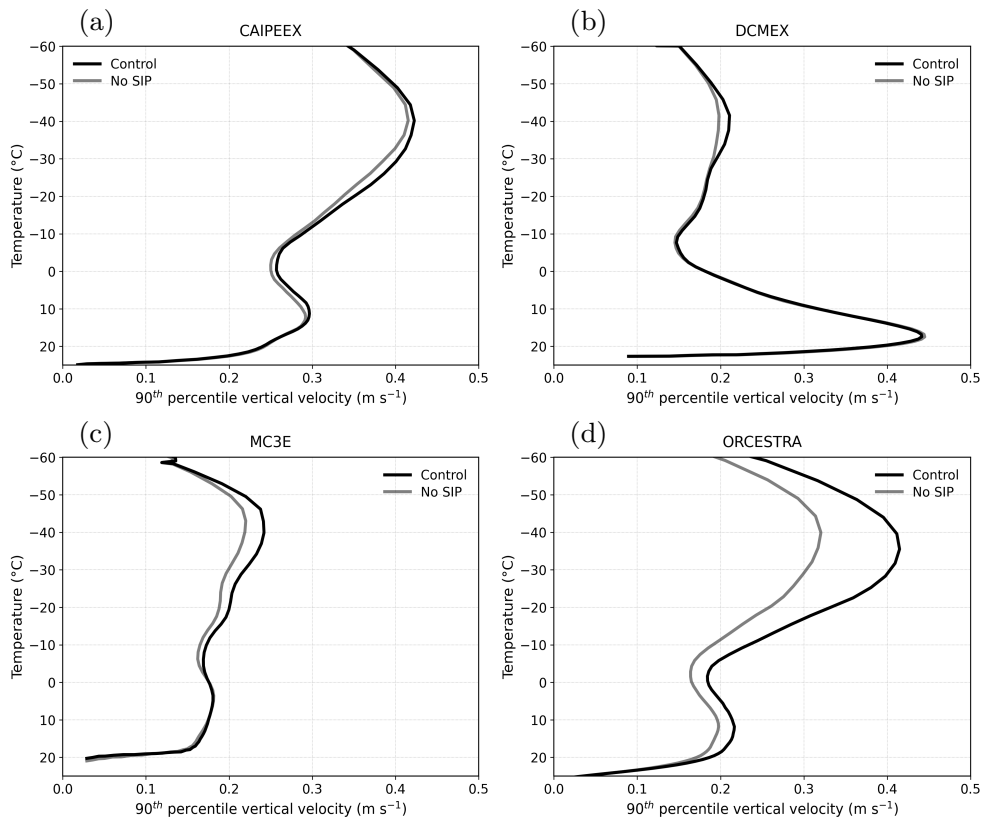


Figure 18. Domain-averaged profiles of the vertical velocity during convective periods from the control (black lines) and No SIP (gray lines) of the DCCs during (a) CAIPEEX, (b) DCMEX, (c) MC3E, and (d) ORCESTR.



The impact of SIP on the cloud top height (CTH) in the simulated DCCs is shown in Fig. 19. The CTH at each grid cell is defined as the highest level where total water content exceeds 0.001 g m^{-3} . Overall, excluding SIP decreases the CTH by about 0.5-1 km in continental DCCs, with a slight increase in CAIPEEX DCCs in their mature stage. This decrease is 2-3 km in ORCESTRA marine convection. This is due to reduced latent heat release, which weakens buoyancy and limits the vertical development of these DCCs when SIP is absent. This effect is more pronounced in ORCESTRA convection, where cloud growth is more sensitive to latent heating and ice-crystal processes, as noted in Figs. 19 (j-l). Without SIP, the suppression of ice-crystal processes weakens convective intensity, leading to shallower cloud tops. These findings are in contrast to a modeling study by Grzegorzczak et al. (2025), who reported stronger latent heating and a 1.5 km higher cloud top when SIP was excluded in simulated DCCs.

In summary, in the simulated DCCs, the exclusion of SIP significantly reduces diabatic (latent and radiative) heating, which weakens the strength of convection through decreased vertical motion. This reduction is primarily driven by suppressed ice-crystal processes, such as depositional growth and riming, which lowers latent heat release and CRH. In such DCCs, SIP results in enhanced absorption of outgoing LW radiation, increasing net CRH by over 20%. With SIP, the increase in latent heat release increases the CTH by 5-30%, both in continental and marine DCCs.

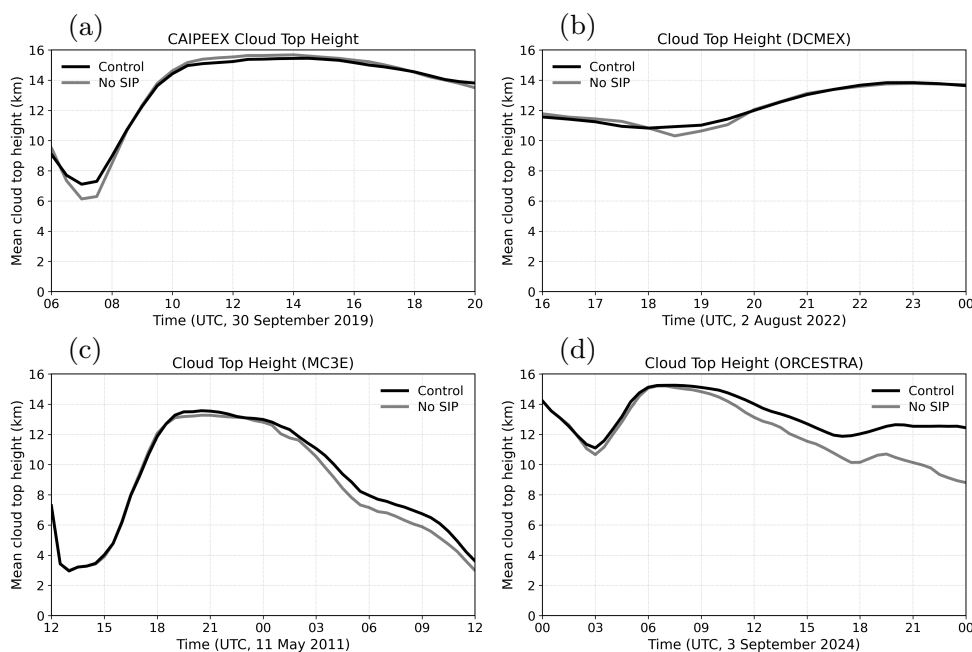


Figure 19. Time series of the cloud top height in the control (black lines) and No SIP (gray lines) simulations of (a) CAIPEEX, (b) DCMEX, (c) MC3E, and (d) ORCESTRA DCCs. The same information is shown for (c, d) DCMEX, (e, f) MC3E, and (g, h) ORCESTRA clouds. The cloud top height at each grid cell is defined as the highest level where total water content exceeds 10^{-3} g m^{-3} .



3.6 Comparison of SIP parameterizations for raindrop shattering

In the control runs (Table 3), SIP during fragmentation in RDF is represented using the SUL18 parameterization. To assess the impact of the choice of SIP parameterization of RDF fragmentation on the simulated cloud properties, these convective cases are simulated with the PHIL18 scheme (Sec. 2.2.1, PHIL18 run) and compared with their corresponding control (SUL18) runs.

Figure 20 shows the domain-averaged total INC simulated in the control (black line), PHIL18 (black line), and No SIP (grey line) runs. Between 0 and -10°C levels in all simulated DCCs (Fig. 20 (a, d, g, j)), both SUL18 and PHIL18 schemes predict about 1.5 times higher mean INC than SUL18.

This difference is because PHIL18 forms secondary ice splinters during both immersion freezing of raindrops and collisions between raindrops and ice particles. In comparison, SUL18 only considers SIP during immersion freezing of raindrops.

Moreover, in the mixed-phase region of these DCCs, the additional INC in PHIL18 enhances depositional growth (not shown) and results in 2-10% more diabatic heating than the control run (Fig. 20 (h, k)). This enhanced diabatic heating with PHIL18 boosts buoyancy, which leads to an increase in vertical motion compared to SUL18 (not shown here).

In summary, the choice of the RDF SIP scheme has a moderate impact on the simulated properties in these DCCs.

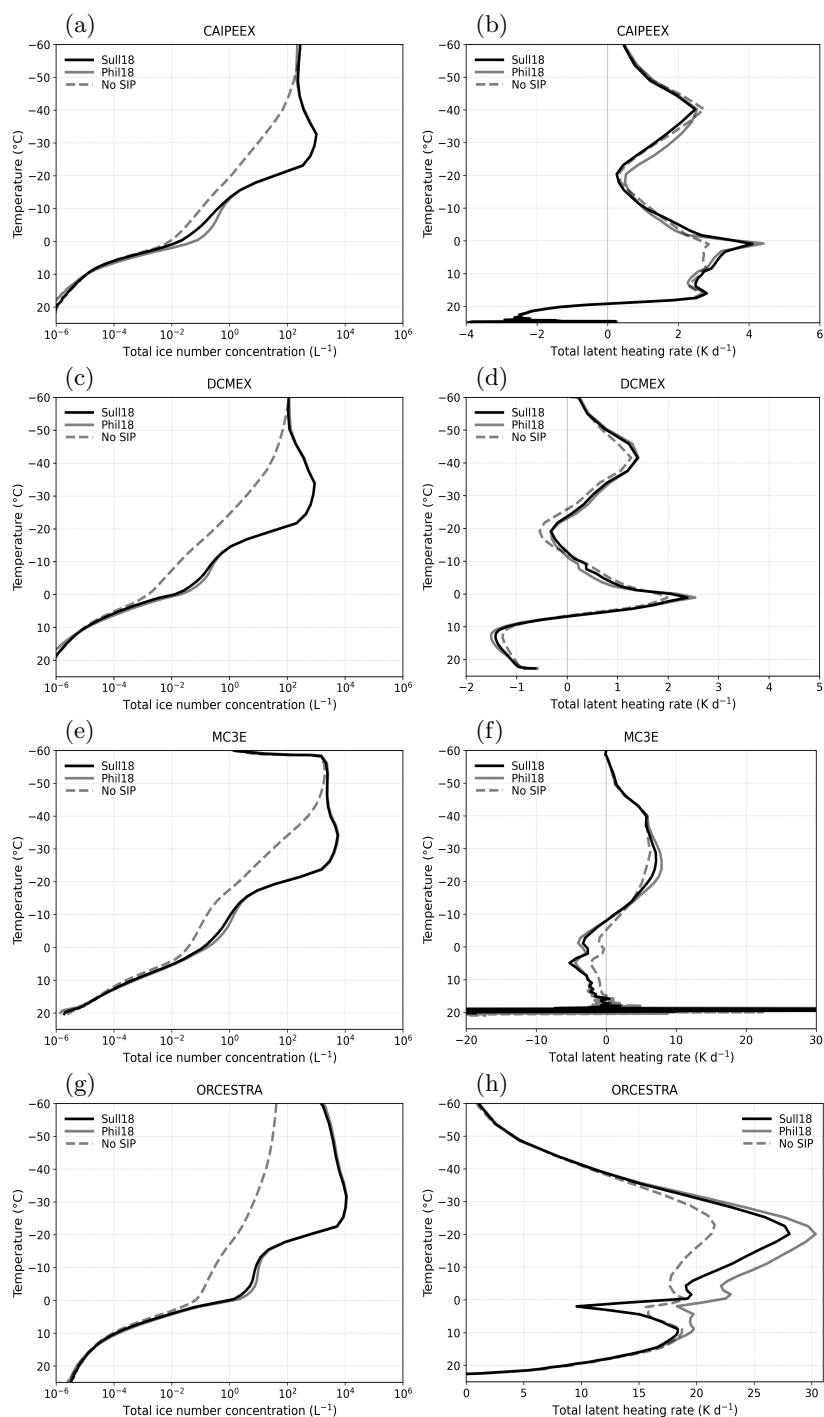


Figure 20. Profiles of the means of the domain-averaged total ice number concentrations from the control (which include Sul18 RDF, solid black lines), Phil18 RDF (solid gray lines), and No SIP (dashed gray lines) runs in the (a) CAIPEEX, (c) DCMEX, (e) MC3E, and (g) ORCESTRA clouds. Also, the domain-averaged (b, d, f, h) latent heating rate in the control ('Sul18 RDF'), PHIL18 RDF, and No SIP runs are shown for these simulated clouds.



4 Summary and conclusions

This study assesses the impact of SIP on the microphysics and dynamics of DCCs by simulating four contrasting cloud cases with the ICON model. These include three aircraft-observed continental cases, observed in (i) CAIPEEX over India on 30 September 2019, (ii) DCMEX over New Mexico on 2 August 2022, (iii) MC3E over Oklahoma on 11 May 2011, and (iv) marine convection on 3 September 2024 during ORCESTRA over the tropical Atlantic region, observed by the EarthCARE satellite. For all simulated DCCs, the simulated microphysical properties (LWC, CDNC, IWC, INC) and radar reflectivity are adequately validated against coincident observations. Additionally, a new SIP treatment for RDF, proposed by PHIL18, is implemented in ICON and compared to the existing scheme of SUL18.

In the simulated DCCs, SIP from IIC accounts for over 90% of secondary ice, dominating overall INC in their mixed-phase regions (Fig. 10). In addition, the HM process contributes to over 30% in the lower mixed-phase region, while RDF and SBF contribute less than 2% to total secondary ice. Two factors may explain this minimal contribution of SBF to total INC in these DCCs: parameterization uncertainties in the Deshmukh et al. (2022) formulation, or the physical limitation that most fragments from SBF evaporate before reaching supersaturated regions where fragment growth can occur (Korolev and Leisner, 2020).

The findings of the present study are;

1. In the simulated continental DCCs of CAIPEEX, DCMEX, and MC3E, the impact of SIP on microphysical properties varies in the range of simulated clouds. In their mixed-phase regions, without SIP, the supercooled liquid mass increases by 30–60% due to enhanced condensation of vapor. In contrast, in a relatively saturated environment of marine DCCs of ORCESTRA, excluding SIP causes little (10%) increase in supercooled liquid at subzero levels. Also, in the mixed-phase region of these DCCs, the absence of SIP causes a decrease in the IWC (INC) by 10–30% ($10\text{--}10^3 \text{ L}^{-1}$) compared to with SIP.
2. Furthermore, the sensitivity of the surface precipitation to SIP is simulated to depend closely on the convective intensity and longevity. In continental DCCs of CAIPEEX, DCMEX, prohibiting SIP predicts no significant change in the accumulated surface precipitation, whereas it decreases by about 4% in more vigorous, long-lived continental MC3E and marine ORCESTRA convection.
3. In the simulated DCCs, excluding SIP reduces total latent heating by 10–20%, consistent with Qu et al. (2022) and Grzegorzczuk et al. (2025), with the magnitude depending on convection intensity and duration. The reduction arises primarily from weakened ice-crystal growth by vapor deposition, leading to suppressed depositional heating and enhanced sublimational cooling in the mixed-phase region. These effects are modest (20%) in short-lived, weakly precipitating systems (CAIPEEX, DCMEX) but can reach up to 50% in sustained, moderately to strongly precipitating DCCs (MC3E, ORCESTRA). At the mixed-phase levels, enhanced vapor condensation partly offsets the cooling, indicating that the absence of SIP inhibits ice-phase processes and promotes the warm-rain pathway.



4. Excluding SIP from the simulated DCCs causes about a 15-40% decrease in the net CRH, mainly through LW CRH (20-50% decrease without SIP). This can be attributed to reduced absorption of outgoing LW radiation due to fewer ice particle mass and number in the absence of SIP.

5. In these DCCs, reduced CRH (by 15-40%) and latent heat release (by 10-20%) without SIP decreases buoyancy and leads to shallower cloud tops (up to 1-3 km) than with SIP. This contrasts with Grzegorzczuk et al. (2025), who reported shallower cloud top in the presence of SIP due to enhanced latent heating in an idealized simulation. This reduced buoyancy without SIP also lowers the mean vertical velocity by about 10%, indicating lower convective vigor than with SIP. Collectively, these findings highlight that excluding SIP suppresses convective intensity and leads to significantly shallower cloud development.

6. In all simulated DCCs, both SUL18 and PHIL18 schemes of SIP through RDF predict similar INC and dynamical properties. Therefore, a simpler scheme by SUL18 for SIP in RDF can be used in numerical models to simulate the observed IWC and INC and associated radiative and dynamical properties.

7. This study further confirms the negligible impact of SIP in SBF on overall INC in a range of simulated DCCs, consistent with the findings of Waman et al. (2022) and Yang et al. (2024).

To conclude, this study reveals that SIP impact varies greatly among DCCs in different environmental conditions and convective strengths. By constraining SIP effects across four DCCs under different environments (from continental to marine), this study demonstrates that the magnitude of SIP influence on microphysics, dynamics, and diabatic properties systematically scales with convective evolution, intensity, and longevity, ranging from negligible effects in weak, short-lived systems to pronounced impacts in vigorous, long-lived DCCs. The exclusion of SIP leads to a substantial decrease in both temporal and vertical extent of convection in the MC3E and ORCESTRA clouds, chiefly due to reduced glaciation in their mixed-phase regions, as also reported by Qu et al. (2022). This study also found that, in the simulated DCCs, without SIP, the reduction in latent heating and CRH decreases buoyancy and mean vertical velocity at subzero levels, resulting in shallower cloud tops in sustained convection. This comprehensive assessment across diverse convective regimes establishes that SIP fundamentally controls the intensity, longevity, and radiative properties of sustained deep convection.

This study further confirms the critical role of various SIP processes in numerical models to accurately simulate the observed INC in natural DCCs (Fig. S2). It should be noted that uncertainties remain in existing SIP schemes (Seidel et al., 2024; Korolev and Leisner, 2020), which can significantly limit their accuracy and efficiency. These uncertainties are primarily from factors such as variability in cloud conditions, irregular particle habits in natural clouds, the nonlinear nature of microphysical processes, and various model assumptions and simplifications. Consequently, these challenges may hinder the realistic representation of these processes in numerical models, which underscores the need for additional observational and experimental studies to increase their fidelity.



Appendix A: Acronyms

Table A1: List of acronyms

Acronym	Full Form
CDP	Cloud Droplet Probe
CIP	Cloud Imaging Probe
PIP	Precipitation Imaging Probe
2DS	2-Dimensional Stereo probe
HVPS-3	High Volume Precipitation Spectrometer-version 3
CPR	Cloud Profiling Radar
NASA	National Aeronautics and Space Administration
JAXA	Japan Aerospace Exploration Agency
EarthCARE	European Space Agency and JAXA Cloud Aerosol Radiation Explorer
MPI-M	Max Planck Institute for Meteorology
DKRZ	Deutsches Klimarechenzentrum
NWP	Numerical Weather Prediction
DE	Dimensionless Energy
CKE	Collision Kinetic Energy
LBC	Lateral Boundary Conditions
ECMWF	European Center for Medium-range Weather Weather Forecasts
ERA5	Fifth generation atmospheric reanalysis from the ECMWF
LWC	Liquid Water Content
CDNC	Cloud Droplet Number Concentration
IWC	Ice Water Content
INC	Ice Number Concentration
CAIPEEX	Cloud-Aerosol Interaction and Precipitation Experiment
DCMEX	Deep Convective Microphysics Experiment
MC3E	Midlatitude Continental Convective Clouds Experiment
ORCESTRA	Organized Convection and EarthCARE Studies
ICON	ICOsahedral Nohydrostatic
SIP	Secondary Ice Production
HM	Hallett-Mossop
RDF	Raindrop Freezing Fragmentation

Continued on next page



Table A1 – *Continued from previous page*

Acronym	Full Form
IIC	Fragmentation in Ice-Ice Collision
SBF	Fragmentation in Sublimation of dendritic snow and graupel
SUL18	Sullivan et al. (2018)
PHIL18	Phillips et al. (2018)
LW	Longwave
SW	Shortwave
CRH	Cloud Radiative Heating
DCCs	Deep Convective Clouds
AP	Aerosol Particle
INP	Ice Nucleating Particle
CCN	Cloud Condensation Nuclei



Table A2. List of symbols and parameters

Symbol	Description	Unit
D	Diameter of freezing drizzle/raindrop	mm
RH_i	Relative Humidity over ice	%
S_i	Saturation ratio with respect to ice	–
N_{sec}	Number of secondary ice fragments	–
T	Temperature	K (except where marked as °C)
N_{hm}	3.5×10^8	fragments per kg
q_{rime}	Rimed ice mass mixing ratio	kg kg ⁻¹
$\Xi_{RDF}, \zeta, \beta_{RDF}, \eta$	D dependent polynomials from PHIL18	–
Ω	T dependent polynomial from PHIL18	–
N_S, N_B	Number of small and big fragments in RDF mode 1 by PHIL18	–
T_0	Value of T at maximum of Lorentzian for N_{sec}	°C
$T_{B,0}$	Value of T at maximum of Lorentzian of N_B	°C
ζ_B, η_B	D dependent polynomials for N_B	–
DE	Dimensionless Energy	–
DE_{crit}	Critical DE	–
K_0	Collision Kinetic Energy	kg m ⁻²
m, m_i	Mean masses of raindrop and colliding ice particle	kg
v, v_i	Mean velocities of raindrop and colliding ice particle	m s ⁻¹
c_w	Specific heat capacity of liquid water	4200 J K ⁻¹ kg ⁻¹
L_f	Specific latent heat of freezing	3.3×10^5 J kg ⁻¹
$f(T)$	Frozen fraction at end of (stage 1) freezing; $f(T) = -c_w T / L_f$	–
C	Asperity-fragility coefficient	J ⁻¹
α	Surface area (equivalent spherical) of smaller particle	m ²
$A(M)$	Number density of breakable asperities in region of contact	m ⁻²
n_{branch}	Number density of branches on smaller particles	m ⁻²
b_1	Fraction of surface of smaller particle in region of impact	–
γ	Empirical parameters (Deshmukh et al., 2022)	–
β_{SBF}	Empirical parameters (Deshmukh et al., 2022)	m ^{-0.5} s ⁻¹
d	Crystal diameter	m
v', v^*	Onset transition factors for dendritic snow and graupel (Deshmukh et al., 2022)	–
Ξ_{SBF}	Emission factor (Deshmukh et al., 2022)	–
ρ_r	Bulk density of rimed particle	kg m ⁻³
ρ_{D0}	Density of a rimed particle by Dong et al. (1994)	kg m ⁻³
f_v	Ventilation coefficient for vapor diffusion	–



Code availability. The present study used the October 2024 release of the ICON model, which is available at: <https://gitlab.dkrz.de/icon/icon-model.git>. The raw simulation outputs will be archived on the high-performance storage system at the DKRZ. The post-processing codes can be accessed: https://github.com/Deepak-Waman/ACP_SIP_DYNAMICS_2025.git. The post-processed data will be made available on KIT-Open.

Data availability. The aircraft/radar data for the CAIPEEX case is available on request. The EarthCARE data for ORCESTRa is available at <https://gportal.jaxa.jp/gpr/user/regist1?lang=en>. The DCMEX data can be accessed through <https://data.ceda.ac.uk/badc/dcmex/data>, and MC3E at <https://www.earthdata.nasa.gov/data/projects/mc3e/data-access-tools>. The Radiosonde data for the simulated cases is obtained from <https://weather.uwyo.edu/upperair/sounding.shtml>.

Author contributions. DW and CH conceptualized the study. DW, JM, and GW implemented the SIP processes in ICON. BK and CB were involved in the ICON setup and experiment design, and BK further offered guidance for the analysis of the simulations. SP, SS, and TP made the observational data for CAIPEEX available, while DF and AB provided data for DCMEX. RF offered guidance on the EarthCARE data. DW conducted the simulations and analysis, and wrote the manuscript with input from all co-authors. CH supervised the project and secured funding.

Competing interests. The authors declare that they have no conflict of interests.

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