Climate impacts of convective cloud microphysics in NCAR CAM5

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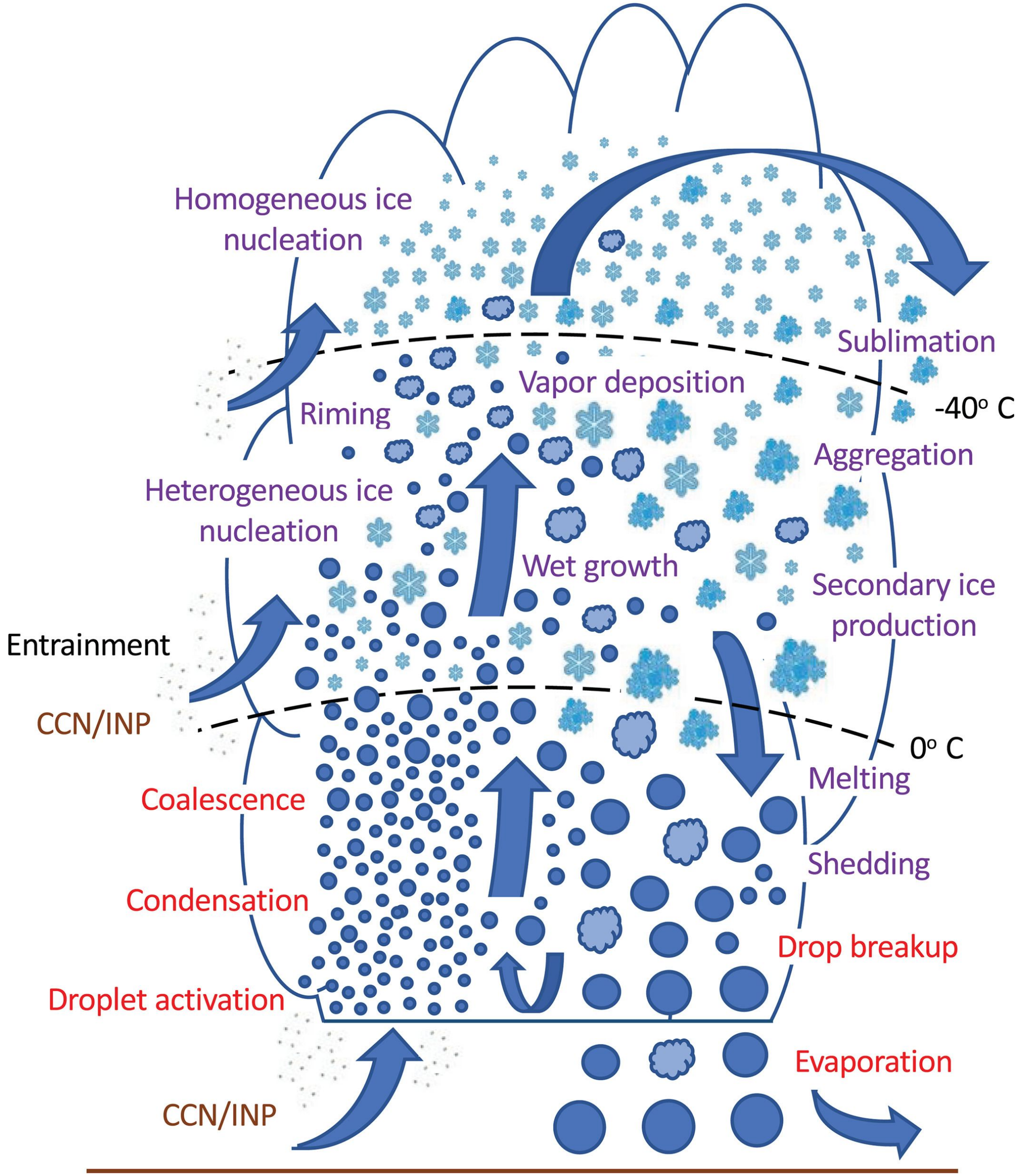
Motivation & Objective



- In GCMs, the convective clouds need to be parameterized due to the coarse resolution

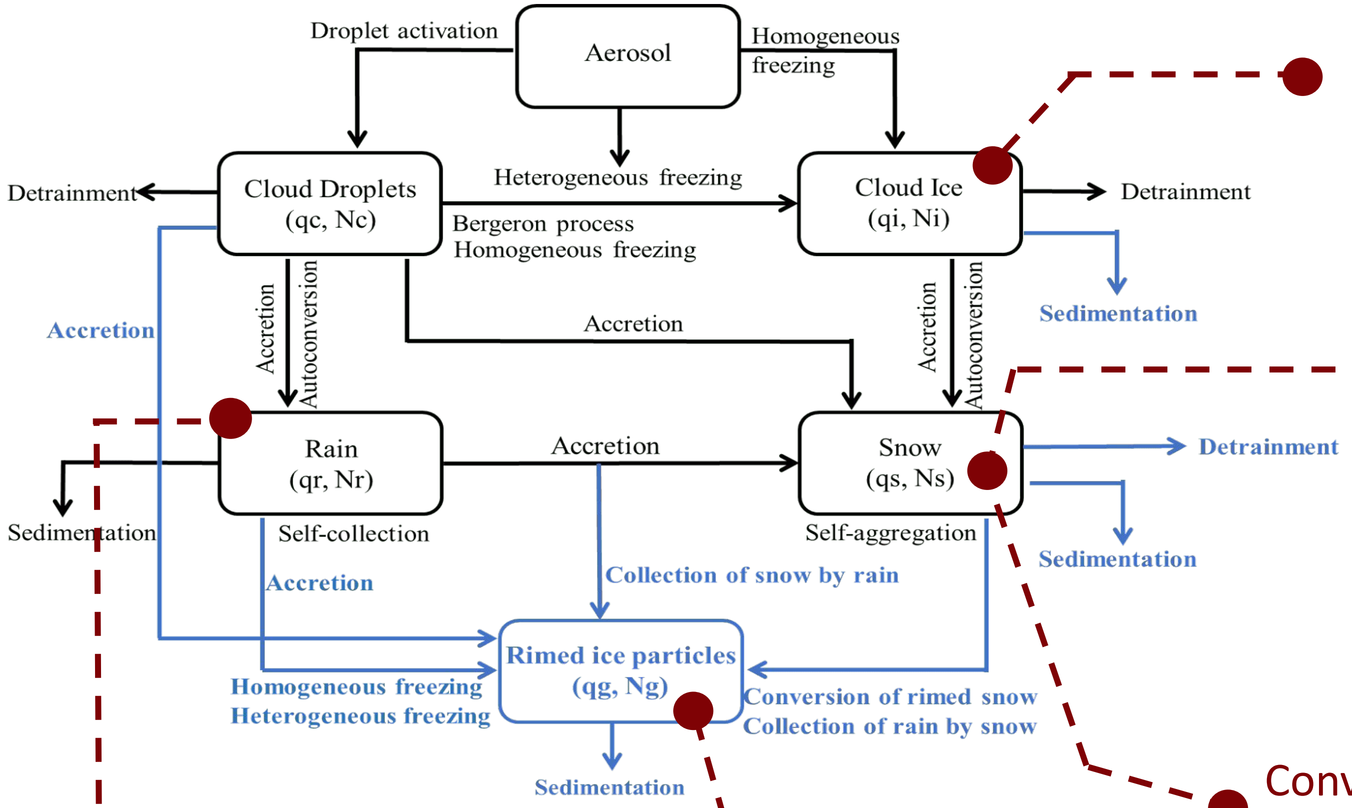
- The convective microphysical processes are usually oversimplified or neglected, hampering our ability to faithfully represent convective clouds in GCMs

- One general issue of existing convective cloud microphysics schemes is that the representations of cloud microphysical process rates are mostly adopted from stratiform cloud microphysics schemes

- The objective of this study is to evaluate and improve the convective cloud microphysics scheme for global climate models, including the CAM

Morrison et al., 2020

Improved Convective Cloud Microphysics



Cloud ice is allowed to fall, based on the *Davis (X)-Reynolds (Re)* number parameterization
Func(ice and air flow properties)

The original snow terminal velocity ($V_t = \alpha D^{\beta}$) is replaced by a physically-based terminal velocity scheme (Elasesser et al., 2017)
Func(IWC, pressure, temperature)

Convective snow is allowed to detrain and feed large-scale cloud scheme

Constrain warm rain formation in convective clouds

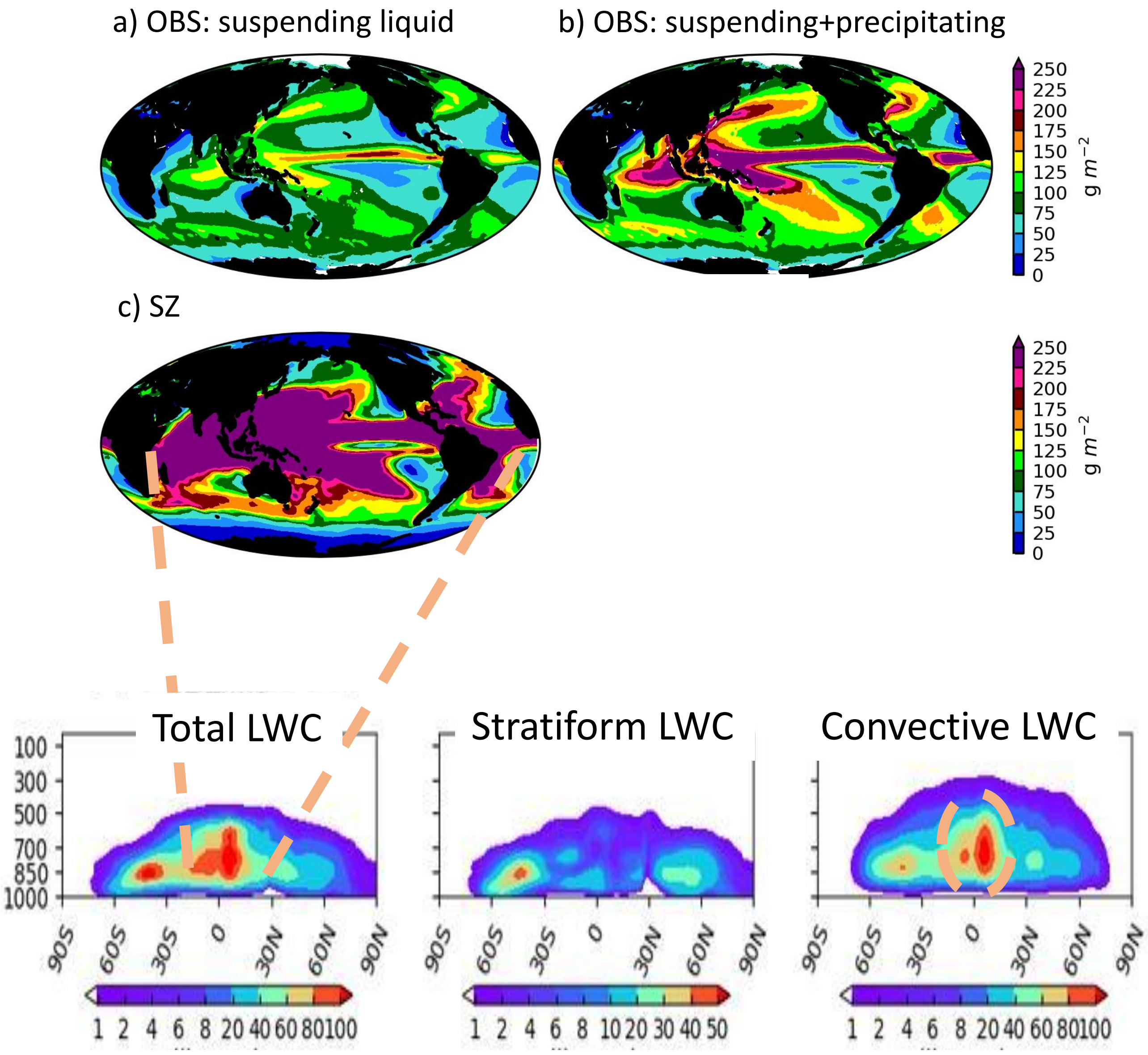
A graupel category is added with a set of graupel microphysics

Lin et al., 2021, 2023
Song and Zhang, 2011

Experiment Setup

	Experiment	Description
1	ZM	The default CAM5.3 model; convection processes are described by the Zhang and McFarlane (1995, ZM) convection scheme by default.
2	SZ	CAM5.3 model with the SZ11 convective microphysics scheme embedded in the saturated updrafts in the ZM scheme; default convective snow terminal velocity is used, with suspended cloud ice crystals, and without considering graupel hydrometeors. Only cloud liquid and cloud ice are allowed to be detrained.
3	SZaftu	Same as the SZ experiment except that coefficients in parameterizations of warm-rain initiation and generation processes (autoconversion and accretion) are adjusted.
4	XReICE_EL17	Same as the SZaftu experiment except the XReICE scheme is used for cloud ice terminal velocity; Elsaesser et al. (2017) parameterization is used for convective snow terminal velocity.
5	XReICE_EL17_rime	Same as the XReICE_EL17 experiment, but with the addition of riming processes and graupel hydrometeors.
6	Conv_snow_detr	Same as the XReICE_EL17_rime experiment, but with convective snow detrainment implemented.

Warm Rain Initiation and Formation Biased Too Weak?



○ □Satellite-synergy LWP climatology (MAC-LWP product: include cloud liquid; MAC-TLWP: include cloud liquid and rain, Elsaesser et al., 2017)

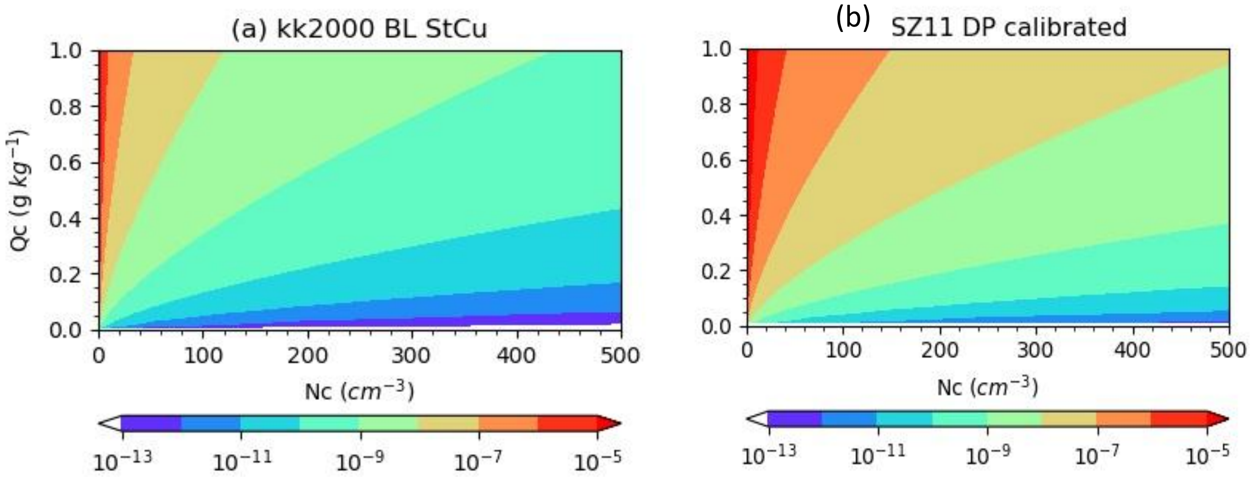
○ □SZ experiment (CAM5.3+default SZ11) produces too much liquid

○ ↓The excessive liquid in the tropics is mainly contributed by convective clouds, resulting in substantially underestimated net TOA SW flux

	FLNT	FSNT
CERES-EBAF	240.37	241.28
SZ	233.13	226.82 ⚠

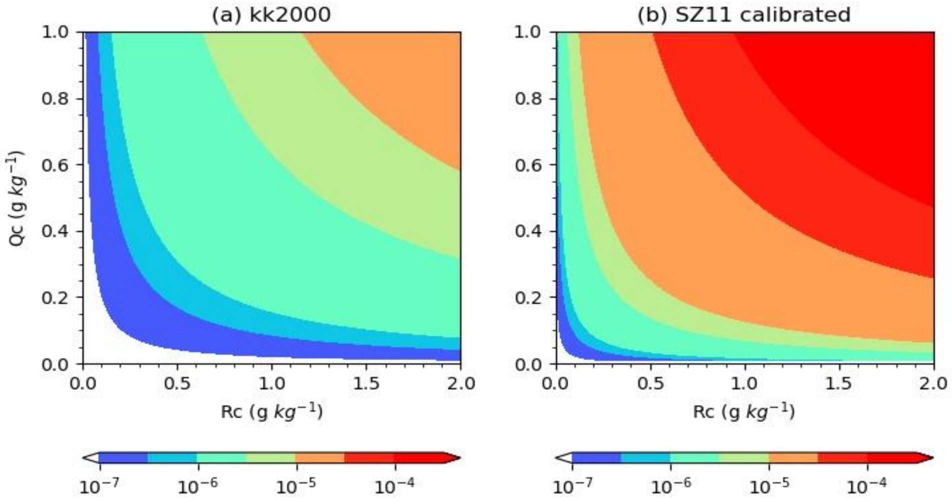
Warm Rain Initiation and Formation Biased Too Weak? Calibrating…

Auto-conversion process rate



↑ The process rate of the autoconversion of cloud liquid water to rain is described by the formulation developed by Khairoutdinov and Kogan (2000, hereafter KK2000) as $P_{auto}^{qc} = \gamma_{auto} 1350 q_c^{2.47} Nc^{-1.79}$

Accretion process rate

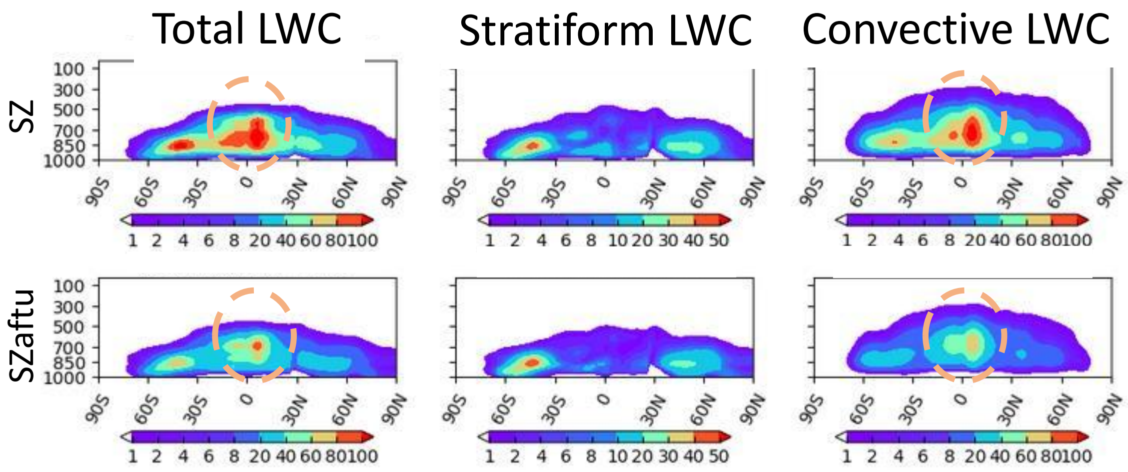


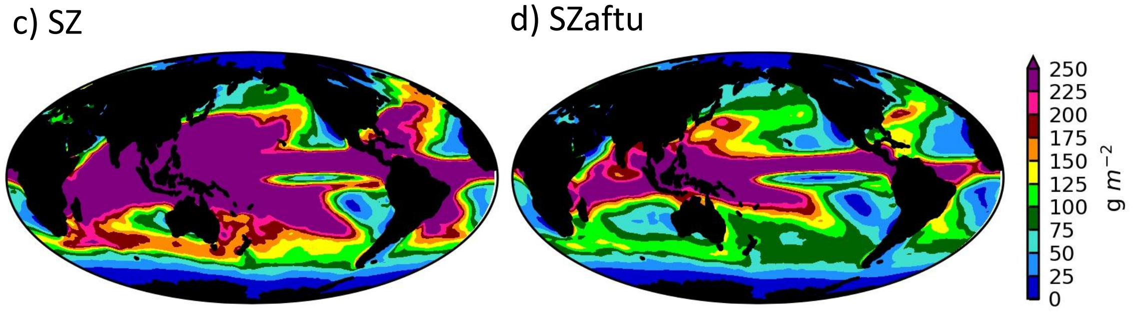
↑The process rate of the accretion of cloud liquid water by rain is parameterized by KK2000 as $P_{accr}^{qc} = \gamma_{accr} 67 q_c^{1.15} q_r^{1.15}$

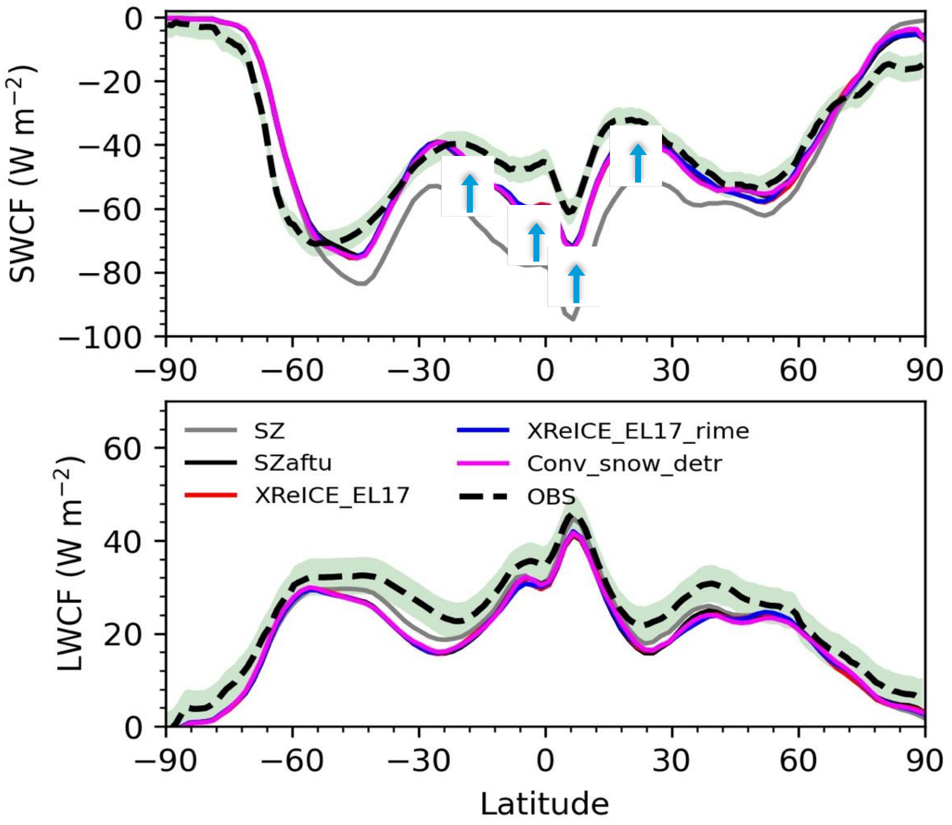
We modified the warm-rain initiation and generation processes (i.e., auto-conversion and accretion) guided by satellite estimates of cloud liquid water path (LWP) climatology and CERES-EBAF TOA radiation budget.

- The KK2000 parameterizations of auto-conversion and accretion were originally developed for marine stratocumulus clouds and failed to reflect the fast auto-conversion and accretion rates in deep convective clouds with strong updrafts and large liquid condensate mass (Khvorostyanov and Curry, 2014).
- Meanwhile, the SZ experiment shows unrealistically high LWP at mid- and low latitude regions, which supports the hypothesis that liquid water in convective clouds is not efficiently converted into precipitation.

Too Strong SW Cloud Forcing Is Reduced



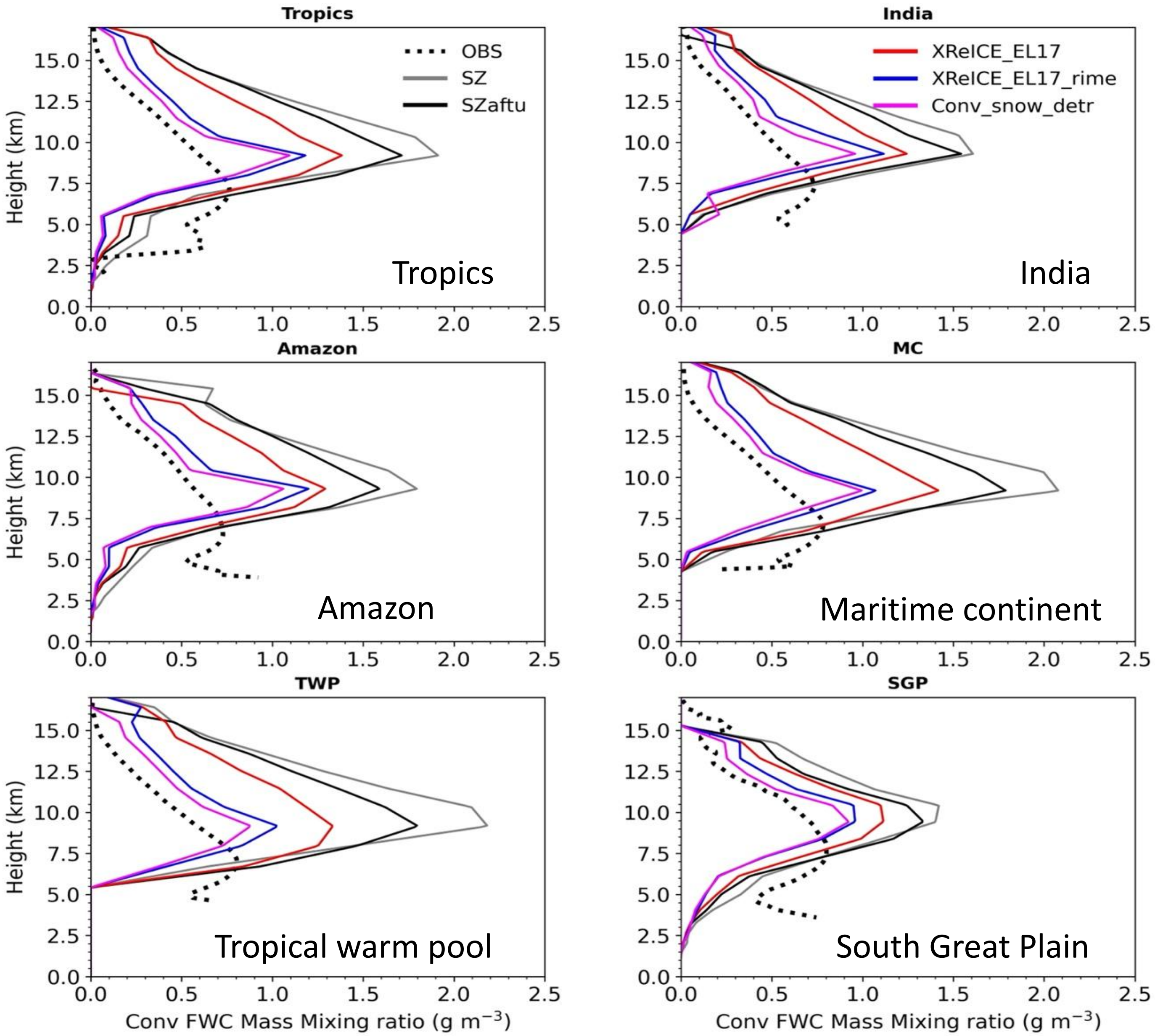




	FLNT	FSNT
CERES-EBAF	240.37	241.28
SZ	233.13	226.82 ⚠
SZaftu	235.40	237.90

- Compared to CAM5.3 with the default convective microphysics, the too strong cloud shortwave radiative forcing due primarily to excessive convective cloud liquid is largely ameliorated over the tropics and midlatitude after rain initiation and generation rate is enhanced, in better agreement with the CERES-EBAF estimates.

IWC Profiles against Satellite Estimates

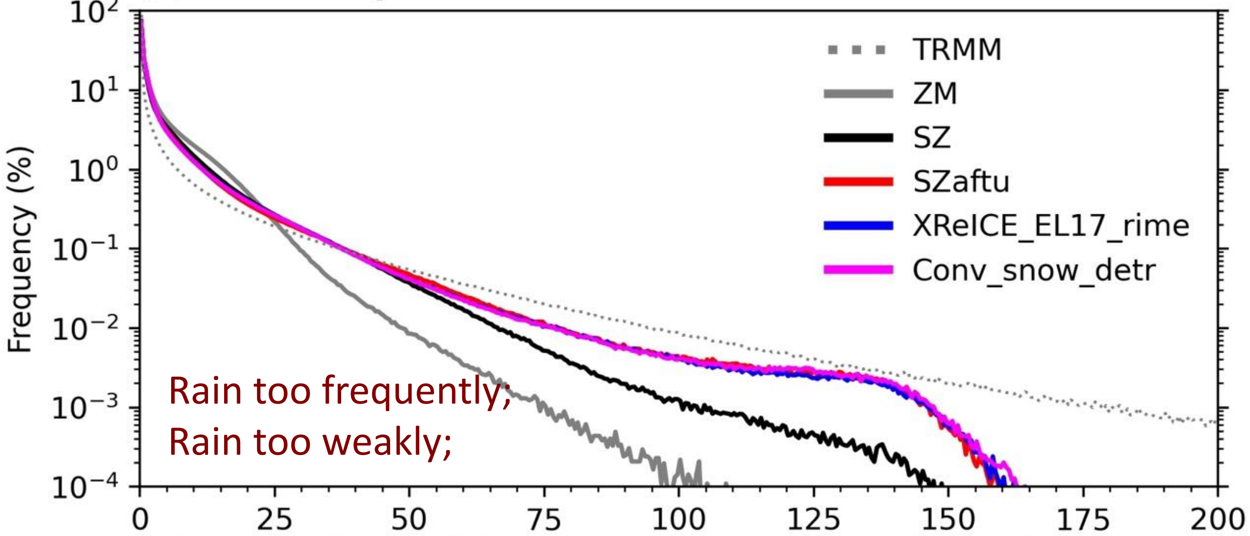


- vertical profiles of convective IWC

When evaluated against the CloudSat-CALIPSO estimates, the overestimation of convective ice mass is alleviated with the improved convective ice microphysics, among which adding graupel microphysics and the accompanying increase in hydrometeor fall speed play the most important role

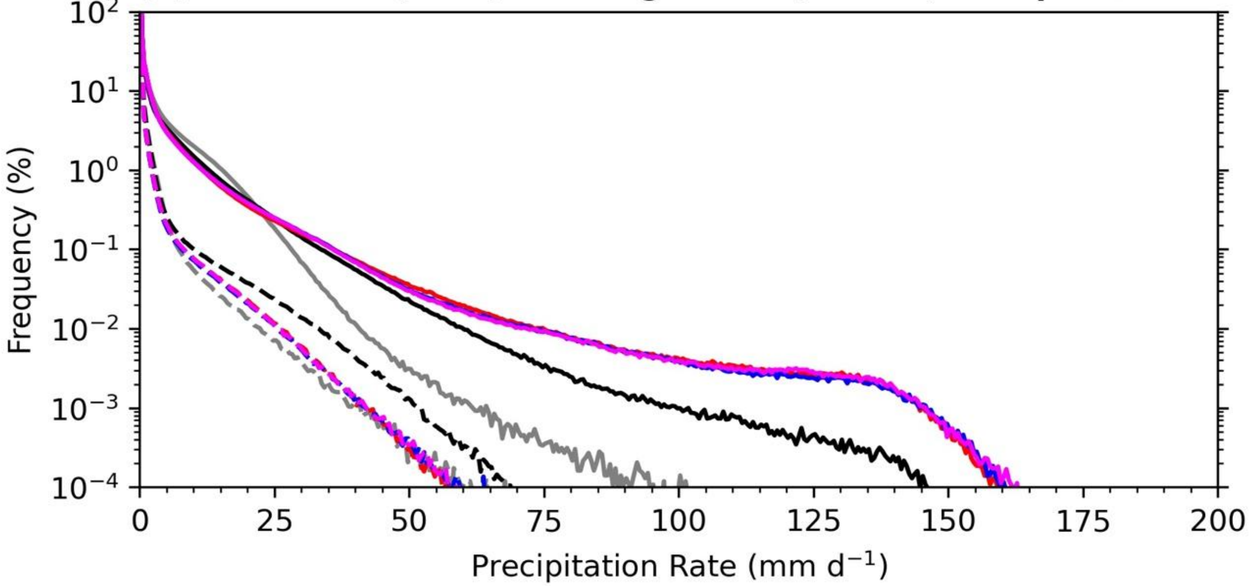
Frequency of Heavy & Light Precipitation

(a) Total Precipitation



Rain too frequently;
Rain too weakly;

(b) Convective (solid) and Large-scale (dashed) Precipitation



- ○ The probability distribution function (PDF) of rainfall intensity is sensitive to warm rain processes in convective clouds
- ○ Enhancement in warm rain production shifts the PDF toward heavier precipitation, which agrees better with the TRMM observations.
- ○ Common biases of overestimating the light rain frequency and underestimating the heavy rain frequency in GCMs are mitigated.

Possible reasons why heavy precipitation is Insensitive to ice microphysics:

- ○ Precipitating hydrometeors (snow and graupel) already dominate the ice-phase condensate.
- ○ Numerical integration limitation: integrating the precipitating hydrometeor budget equation from bottom up along the strong updrafts.

Summary & Conclusions

- We improved the treatments of convective cloud microphysics in the NCAR Community Atmosphere Model version 5.3 (CAM5.3) by (1) implementing new terminal-velocity parameterizations for convective ice and snow particles, (2) adding graupel microphysics, (3) considering convective snow detrainment, and (4) enhancing rain initiation and generation rate in warm clouds.

- Cloud shortwave radiative forcing is improved over both tropics and midlatitude when warm rain formation is constrained by LWP climatology, TOA radiative balance and cloud forcing observations.

- Overestimation of convective IWC is ameliorated by improving the convective ice microphysics, among which adding graupel microphysics and the accompanying increase in hydrometeor fall speed play the most important role.

- Common biases of more light precipitation but less heavy precipitation are alleviated.

- Lin et al., 2021: Improved convective ice microphysics parameterization in the NCAR CAM model, *J. Geophys. Res.*, https://doi.org/10.1029/2020JD034157
- Lin et al., 2023: Climate impacts of convective cloud microphysics in NCAR CAM5, *J. Clim*, *https://doi.org/10.1175/JCLI-D-22-0136.1*

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