Impacts of Ice Nucleation and Wegener-Bergeron-Findeisen Process on Mixed-Phase Cloud Partitioning with NCAR CAM5

Xiaohong Liu[1], Meng Zhang[1], Yong Wang[1,2], Damao Zhang[1], and Zhien Wang[1]
[1]University of Wyoming [2]Center of Earth System Science (CESS), Tsinghua University, China

Introduction

- ➢ Mixed-phase clouds are one of the key components in the climate system, and are vital to global energy and hydrologic cycles;
- ➢ There are large uncertainties in the model simulations of phase partitioning (liquid versus ice water) in mixed-phase clouds, due to unknowns of e.g., microphysical processes, impact of convective clouds through detrainment, and impacts of large-scale dynamics;
- ➢ Cloud microphysical properties vary greatly in time and space. Satellite observations are valuable for providing insights into the discrepancies in model simulations of mixed-phase clouds.

Data and methodology

- **M-PACE case**: ARSCL clouds, ground-based retrievals of liquid water path (LWP) (Turner et al. 2007; Wang 2007), ice water path (IWP) (Wang 2007), and aircraft measured cloud microphysics.
- **Ground-based multi-year multi-sensor retrievals** of stratiform mixed-phase cloud microphysics from cloud radar, MWR, lidar, temperature at NSA site.
- **A-Train satellite data**: Single-layer clouds with cloud top temperature between -40 and 0 °C. CloudSat 2B-CLDCLASS-LIDAR product, MODIS LWP product (only for water and mixed-phase clouds), and integration of IWC (using temperature-depended Z_e-LWC relationship (Hogan et al. 2006)) from CPR radar detected cloud base to top.
- **SLF** (supercooled liquid fraction) calculation:

$$SLF = \frac{LWP}{LWP + IWP}$$

CAM5 Model

Two-moment stratiform microphysics

- Prognostic "*cloud mass*" and "*cloud droplet number*" (Γ-function size distributions) (Morrison and Gettelman 2008)
- Diagnostic "precipitation mass" and "precipitation droplet number"
- Droplet activation and ice nucleation link to aerosols (Liu et al. 2012)
- Other microphysics processes: evaporation of cloud droplets and vapor deposition on ice crystals (Wegener-Bergeron-Findeisen (WBF) process), autoconversion, accretion, sedimentation, sublimation, melting, etc.

Default mixed-phase ice nucleation scheme

- Deposition nucleation, immersion and condensation freezing in mixed-phase clouds follows Meyers et al. (1992)
- Contact freezing of cloud droplets by coarse mode dust is represented based on Young (1974).

New ice nucleation scheme

- **Soccer ball model** for immersion/condensation nucleation with mean (46°) & standard deviation (0.01), number of surface site (0.3) derived from fitting to observations of natural dust (DeMott et al. 2011).

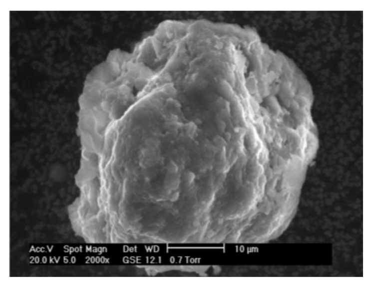
$$p(\theta) = \frac{1}{\sqrt{2\pi}\sigma_\theta} \exp\left(-\frac{(\theta-\mu_\theta)^2}{2\sigma_\theta^2}\right)$$

$$\begin{aligned} P_{unfr}(T,\mu_\theta,\sigma_\theta,t) &= \int_0^\pi p(\theta)\exp(-j_{het}(T,\theta)s_{site}t)\,d\theta \\ &+ \int_{-\infty}^0 p(\theta)\exp(-j_{het}(T,\theta=0)s_{site}t)\,d\theta \\ &+ \int_\pi^\infty p(\theta)\exp(-j_{het}(T,\theta=\pi)s_{site}t)\,d\theta \end{aligned}$$

$$P_{fr}(T,\mu_\theta,\sigma_\theta,n_{site},t) = 1-(P_{unfr}(T,\mu_\theta,\sigma_\theta,t))^{n_{site}}$$

$$j_{het} = \frac{A' r_N^2}{\sqrt{f}} \exp\left(\frac{-\Delta g^\# - f\Delta g_g^o}{kT}\right)$$

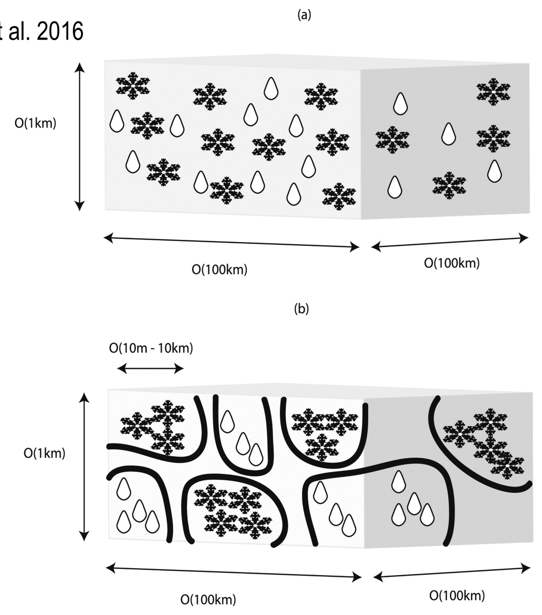
Niedermeier et al. (2014)



High resolution scanning electron microscope image of an individual image of an individual mineral dust particle from Dakar-1 source. (Kulkarni et al. 2010)

Wegener-Bergeron-Findeisen Process

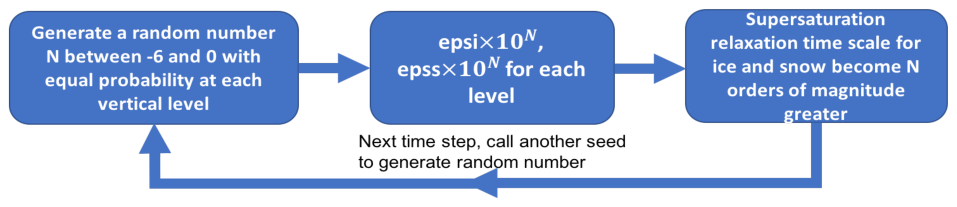
Tan et al. 2016



(a) Homogeneous mixing of liquid and ice
- Mixing zone volume: (100) km x (100) x km x (1) km = (10^{13}) m^3 in the typical GCM grid box.

(b) Heterogeneous mixing of liquid and ice (pocket structure) (Korolev et al. 2003)
- Pockets extend to (10^2) m in extreme case.
- (1^0) m as the mixing zone.
- Mixing zone volume: (10^3) m x (10^3) m x (10) m = (10^7) m^3.

- The supersaturation relaxation time scale for ice deposition is given by $\tau_i = (\text{epsi})^{-1}$ for ice.
- τ_i determine local in-cloud deposition rate of water vapor onto cloud ice through $A = \frac{q_v^* - q_{vi}^*}{\Gamma_p \tau_i}$
- Apply a random number to simulate randomly distributed sub-grid pocket structures of pure liquid and pure ice.

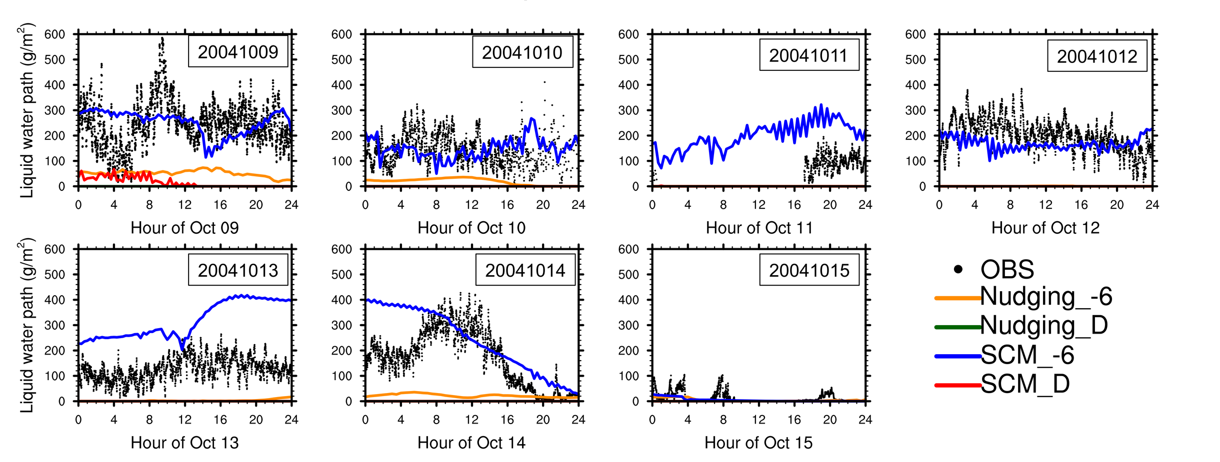


M-PACE Case Study

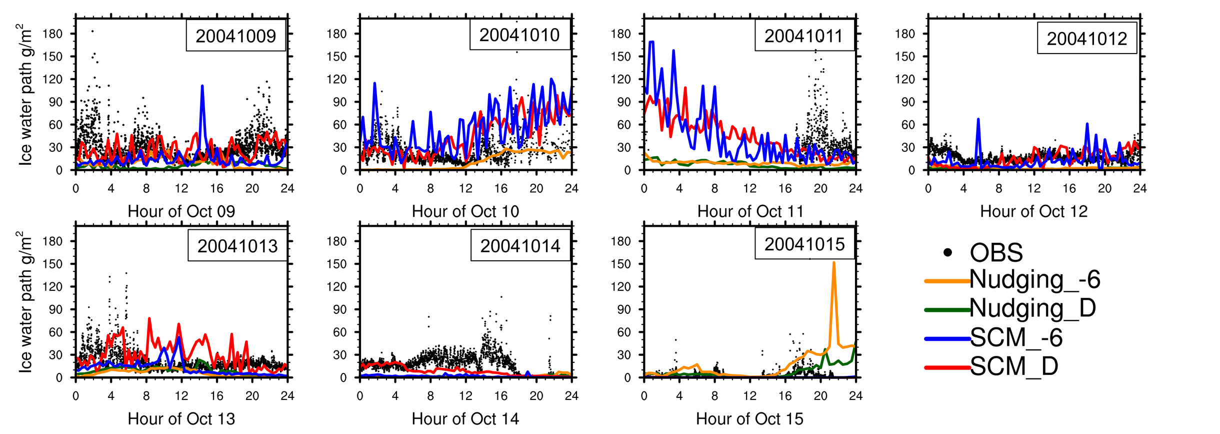
Day-by-day analysis of LWP and IWP in single-layer mixed-phase clouds (October 9-15, 2004)

CAM5 is run in single column mode (**SCM**) and nudging mode (**Nudging**) with homogeneous mixing (SCM_D and Nudging_D) and heterogeneous mixing of liquid/ice (SCM_-6 and Nudging_-6):

Liquid Water Path



Ice Water Path



Supercooled liquid fraction (Oct. 9-12)

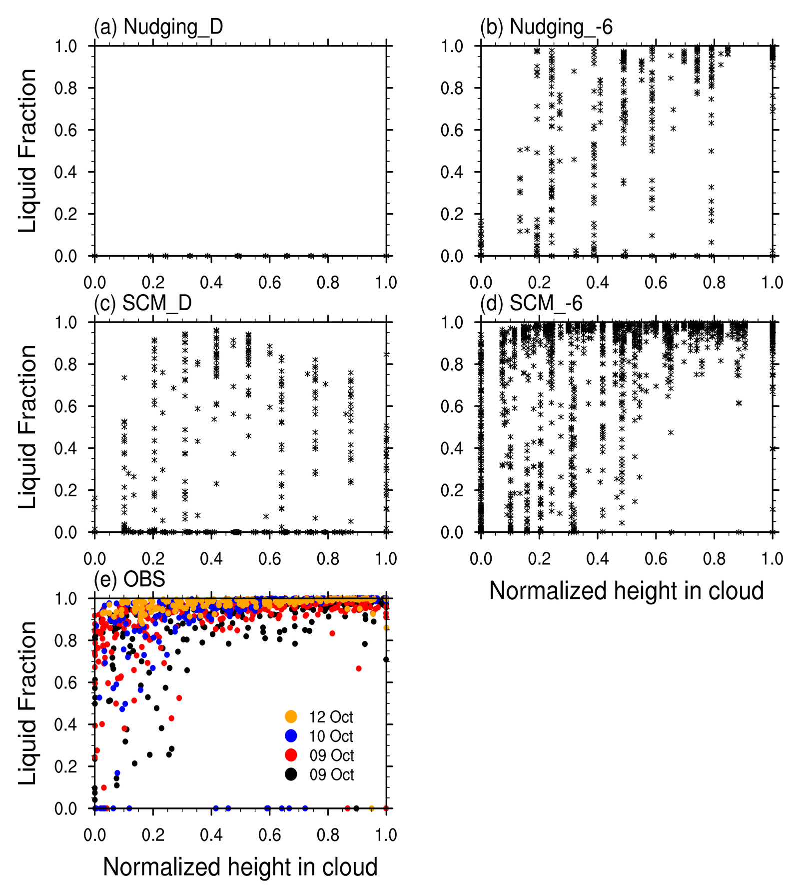


Figure. Liquid fraction as a function of normalized cloud height: from SCM_D, SCM_-6 and Nudging_D, Nudging_-6 simulations in comparison with aircraft observations

Phase partitioning: model vs. observation

Three model simulations: **CTL** (control), **ICE** (new ice nucleation) and **NUG** (nudged winds and temperature). CTL significantly underestimates SLF in all seasons, especially in Southern Hemisphere (SH). ICE improves SLF. NUG slightly improves the SLF in SH while degrades the SLF in Northern Hemisphere (NH).

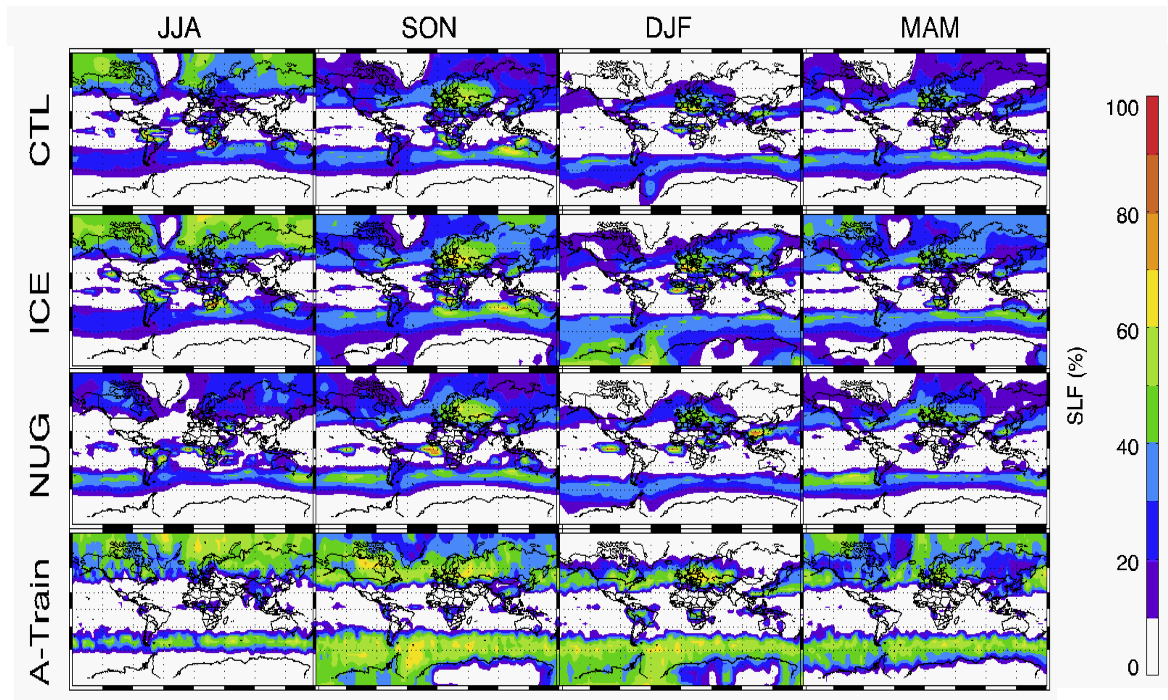


Figure. The global distributions of SLF for four seasons in different simulations as well as the A-Train observations.

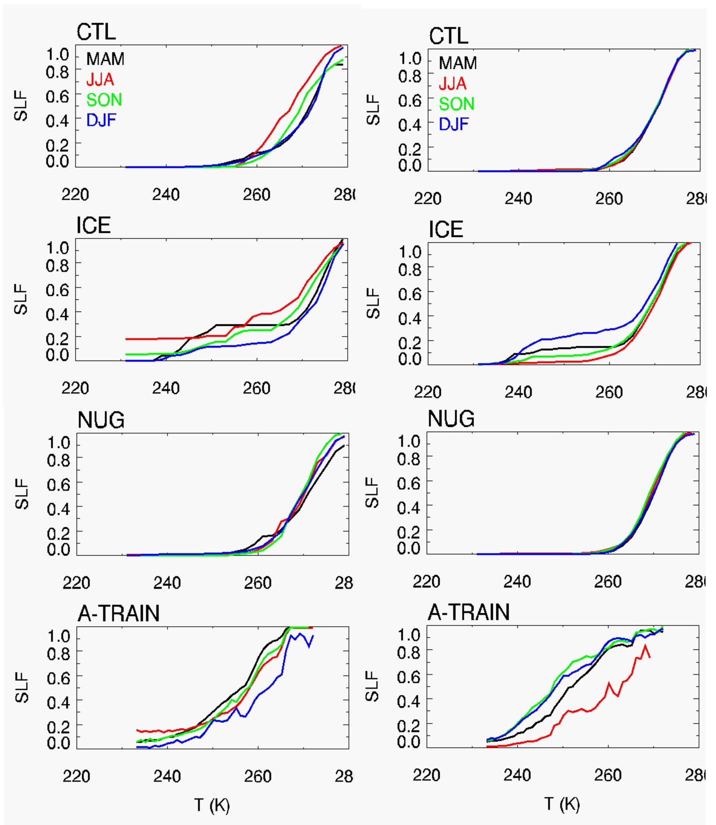


Figure. Temperature-dependent mixed-phase partitioning from model simulations, in comparison with A-Train observations for four seasons in the **60°N-90°N** latitude band (left), and in the **60°S-90°S** latitude band (Right).

Seasonal variation of supercooled liquid fraction at NSA

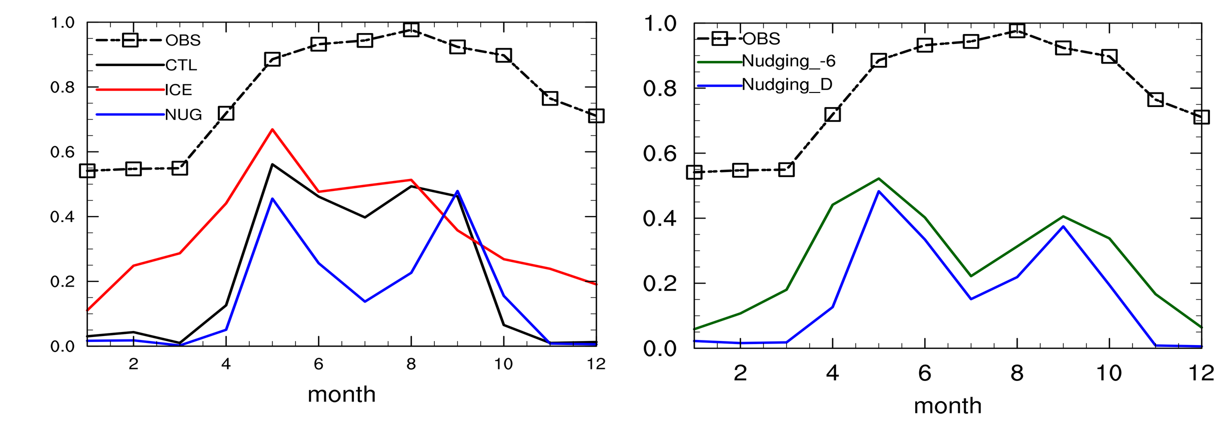


Figure. Seasonal variation of supercooled liquid fraction from model simulations at NSA site, in comparison with ground-based multi-year multi-sensor retrievals

Summary

- Compared to CTL, new ice nucleation parameterization significantly increases model simulated liquid water fraction in mixed-phase clouds at temperatures colder than -20°C, improving comparison with observations in many regions
- However, new ice nucleation parameterization and nudging meteorology do not improve the low biases of SLF in many regions (e.g., Greenland).
- Improving the treatment of WBF process by considering the heterogeneous mixing of liquid and ice enhances the SLF.

Questions: contact xliu6@uwyo.edu