Large eddy simulation of aerosol perturbation in mixed-phase clouds: Dependence on environmental conditions

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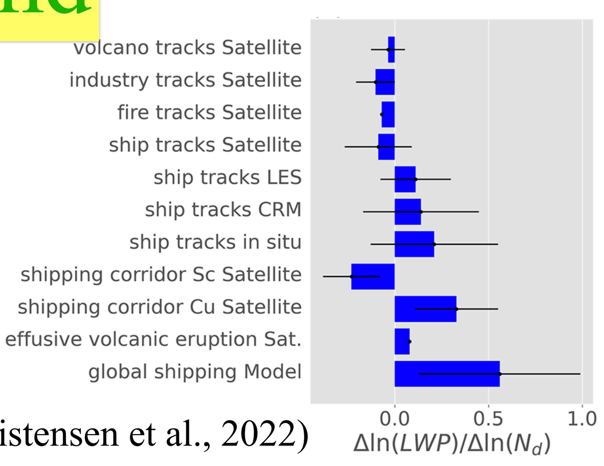
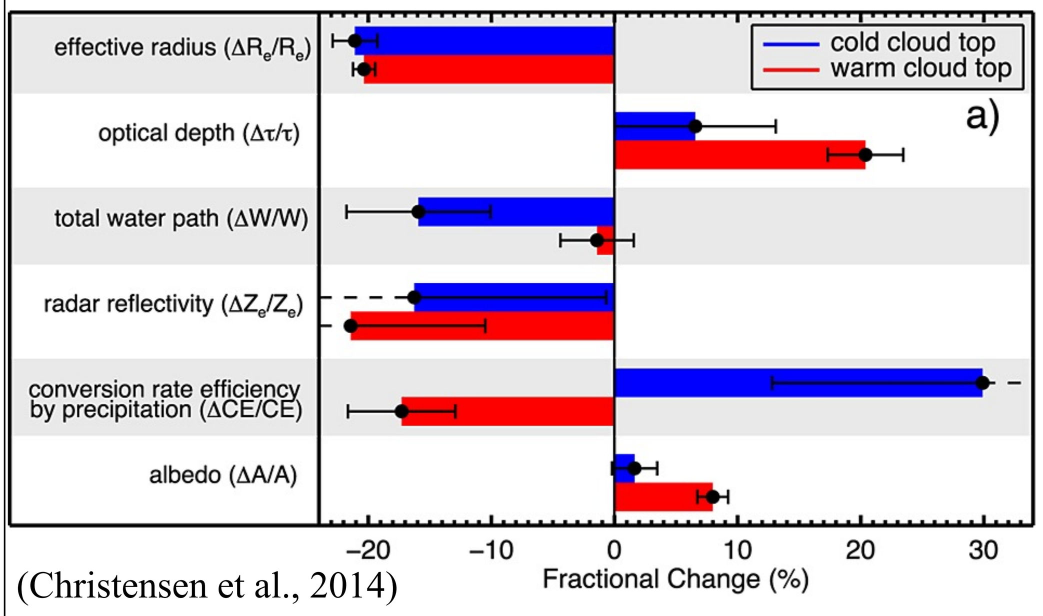
1. Background

Aerosol-polluted tracks such as ship tracks are natural phenomena where emitted aerosols perturb radiative properties of clouds.
It has been shown that responses of warm clouds to aerosol perturbations depend on their environmental conditions (right figure).



(Christensen et al., 2022)



(Christensen et al., 2014)

A previous observational study and a simulation study (Kravitz et al., 2014) indicate that cloud albedo responses in mixed-phase clouds are weaker than in warm clouds (left figure). **However, their cases are still limited.**

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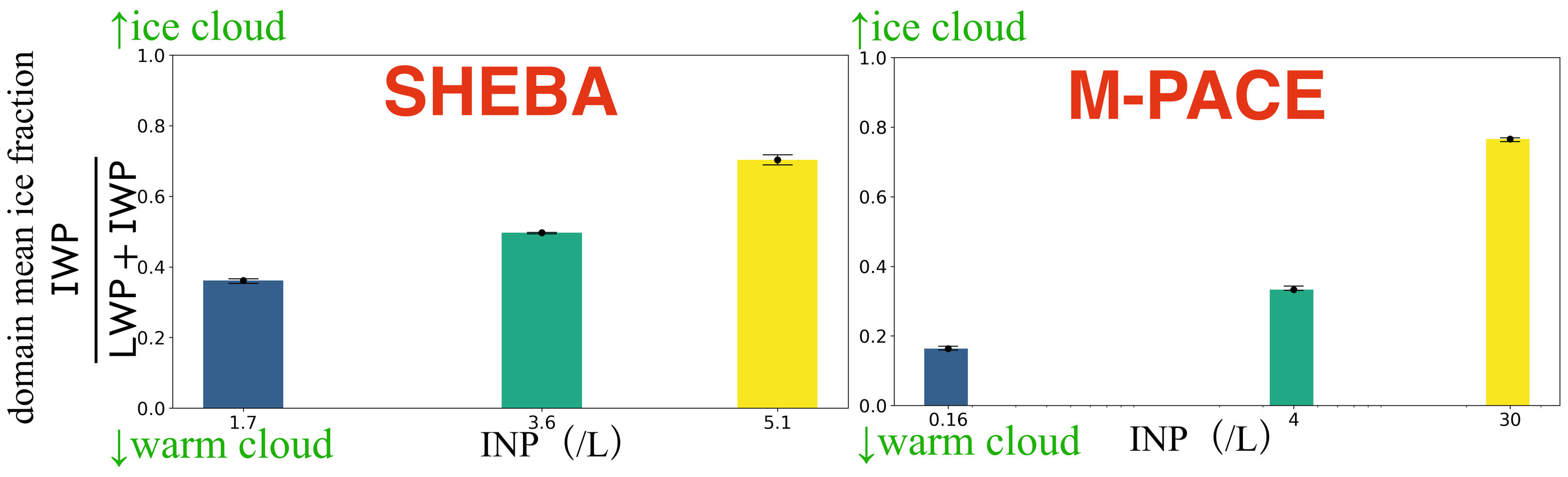
2. Objectives

- What are microphysical processes that causes the differences between the responses of observed mixed-phase clouds and warm ones to ship emissions?
- How do environmental conditions influence the responses of mixed-phase clouds to aerosol perturbations through microphysical processes?



- Large eddy simulations of ship tracks are performed with multiple background concentrations of ice nucleating particles to simulate various cloud phase partitioning (liquid versus ice) and under two observation-based environmental conditions marked by the difference in the surface condition (sea surface and ice surface).

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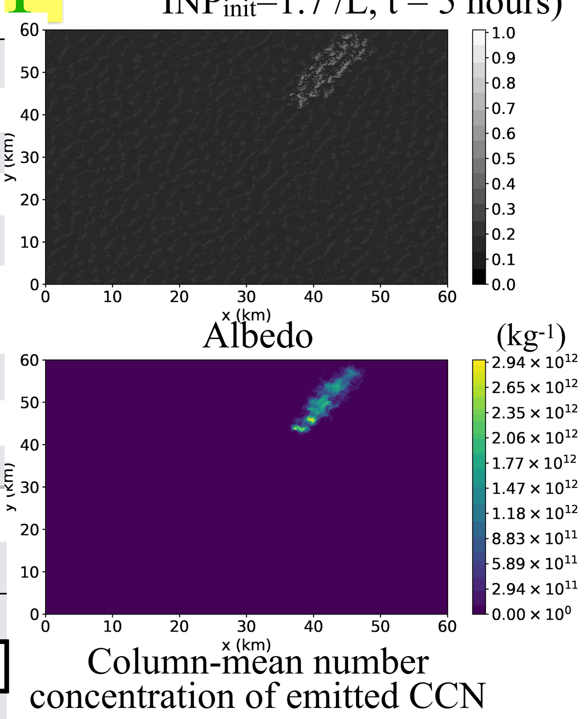
3. Model setup

campaign		SHEBA	M-PACE
surface condition		**sea ice**	**open ocean**
Horizontal domain size		60 km (grid emission) / 3.24 km(domain)	
Vertical domain size		1.2 km	2.4 km
Δz		15 m	20 m
Time step		0.24 s	
Cloud microphysics		SN14 (6-class double-moment bulk) (Seiki and Nakajima, 2014)	
Background CCN (fixed)		351.8 /cm³	74 /cm³
Lateral boundary		double periodic	
CCN emission		**on / off**	
Δx, Δy	Simulation period	Background INP (fixed); INP_{init} SHEBA	Background INP (fixed); INP_{init} M-PACE
20 m	8 hours		0.16 /L (emission OFF only)
30 m	8/12 hours	1.7 /L	**0.16, 4, 30 /L**
50 m	12 hours	**1.7, 3.6, 5.1 /L**	0.16 /L
300 m	20 hours	0.0017, 1.7, 3.6, 5.1 /L	0.16, 4, 6, 10, 30 /L

(SHEBA-based simulation, INP_{init}=1.7 /L, t = 5 hours)



Column-mean number concentration of emitted CCN

- model: SCALE-RM (ver. 5.4.1) (Nishizawa et al., 2015, Sato et al., 2015)
- CCNs are emitted to the lowest grid at the center of the domain for an hour or simultaneously to the whole domain (M-PACE only) as a passive tracer.
- Environmental conditions: M-PACE (Klein et al., 2009) SHEBA (Morrison et al., 2011)

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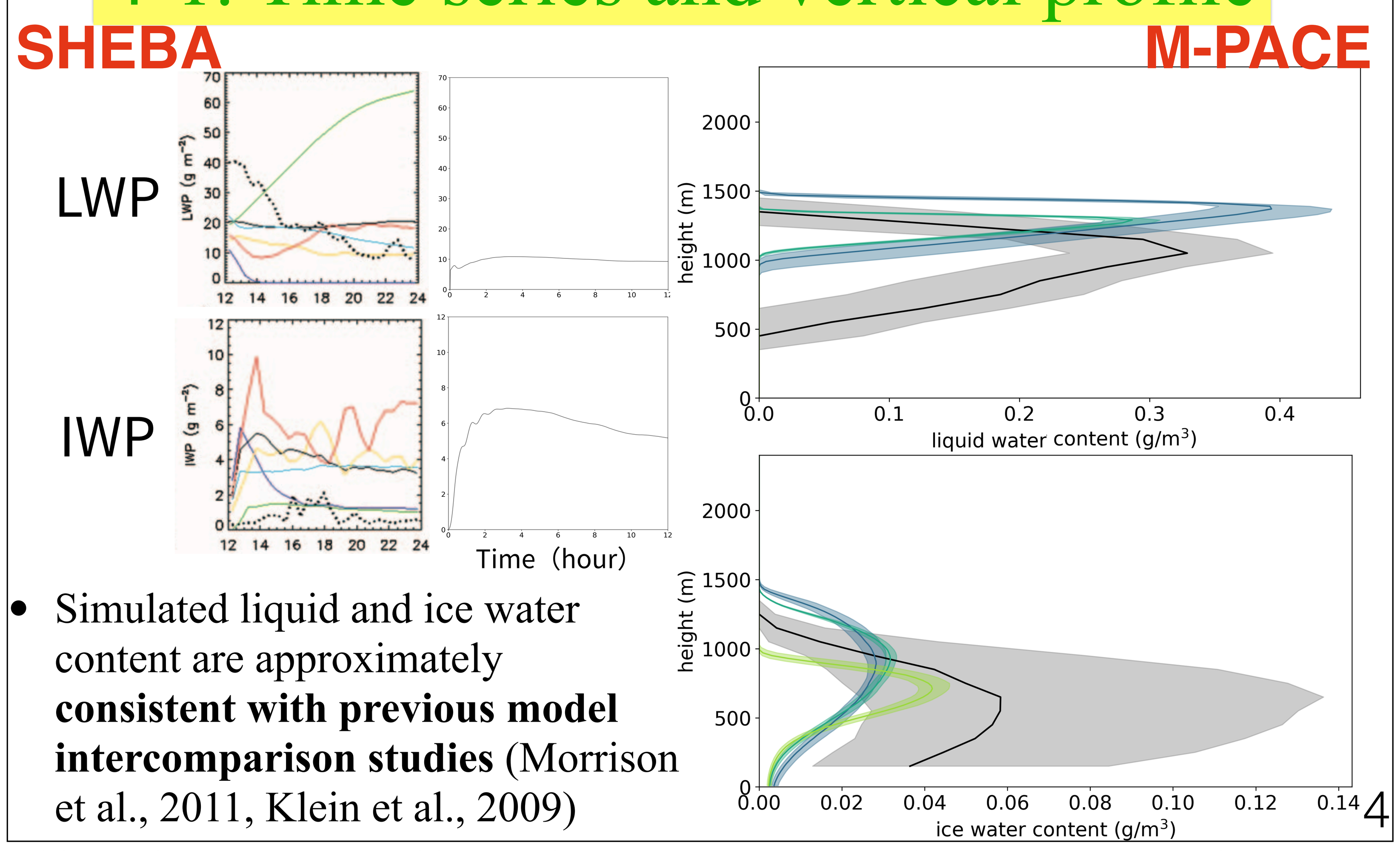
4. Results and Discussion

4-1. Time series and vertical profile



- Simulated liquid and ice water content are approximately **consistent with previous model intercomparison studies** (Morrison et al., 2011, Klein et al., 2009)

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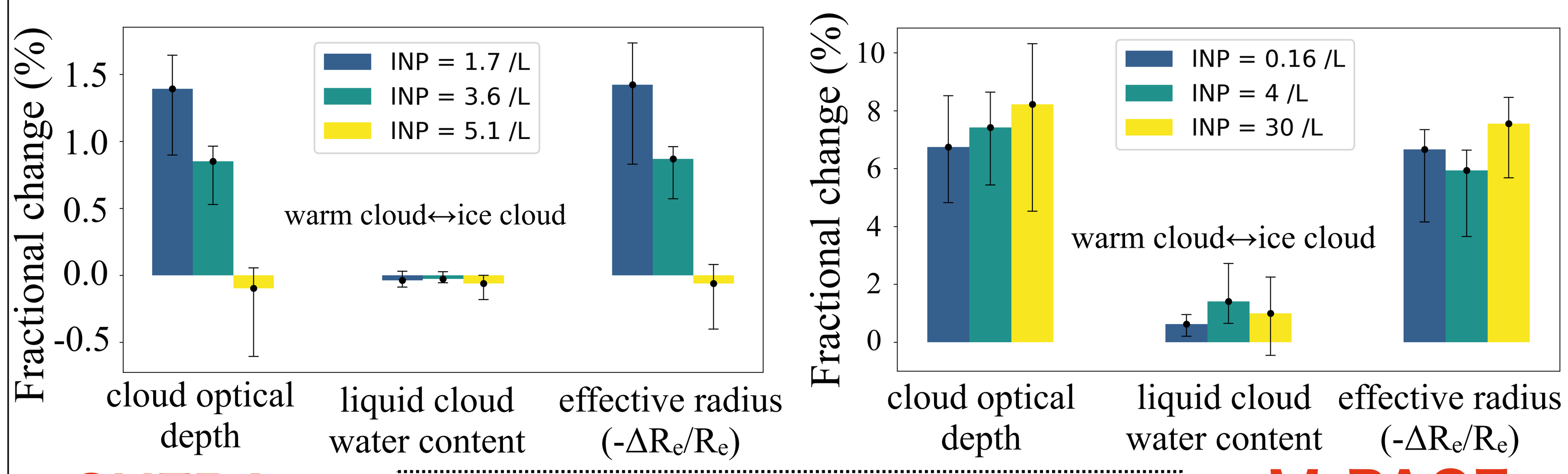
4-2. Fractional change (point source)

- **SHEBA**: The responses of **cloud optical depth** to CCN emission are **smaller** in clouds **with more ice** than those containing less ice, which is **consistent with the previous observational study** (Christensen et al., 2014).
- **M-PACE**: The responses of **cloud optical depth** are **larger** in clouds **with more ice**, which is the **opposite** of the SHEBA cases.
- Both cases: The responses in cloud optical depth are **mainly due to the responses in effective radius**, suggesting the Twomey effect (Twomey, 1974).



$$\tau = \frac{3}{2}\frac{LWP}{\rho_w R_e} \therefore \frac{\Delta\tau}{\tau} = \frac{\Delta LWP}{LWP} - \frac{\Delta R_e}{R_e}$$

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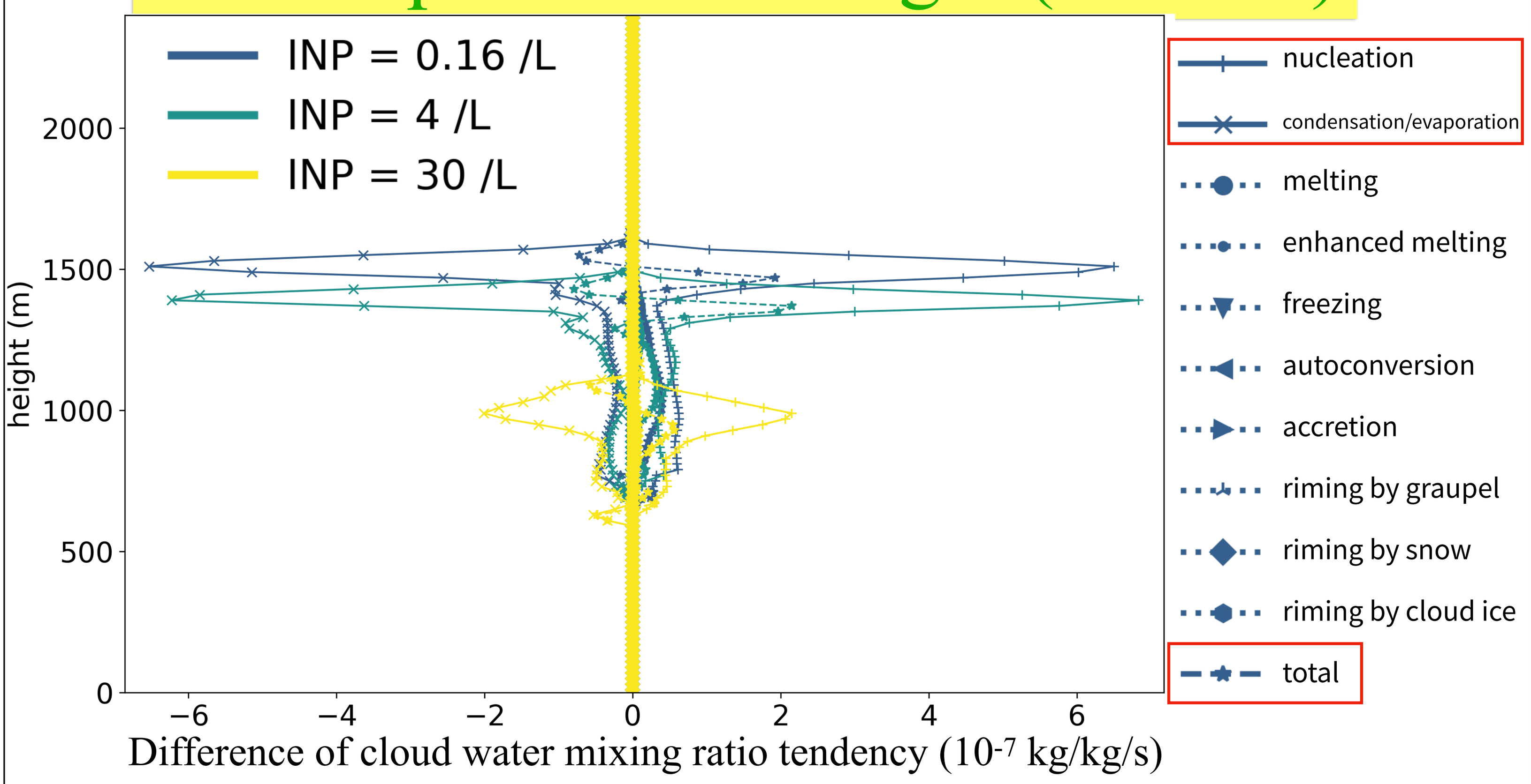
4-3. Liquid water budget (domain)



- In the M-PACE-based cases with CCN emission to the entire domain, increased cloud water due to **nucleation** is largely consumed by **evaporation**.
- **Autoconversion and accretion are not the main sinks of cloud water.**

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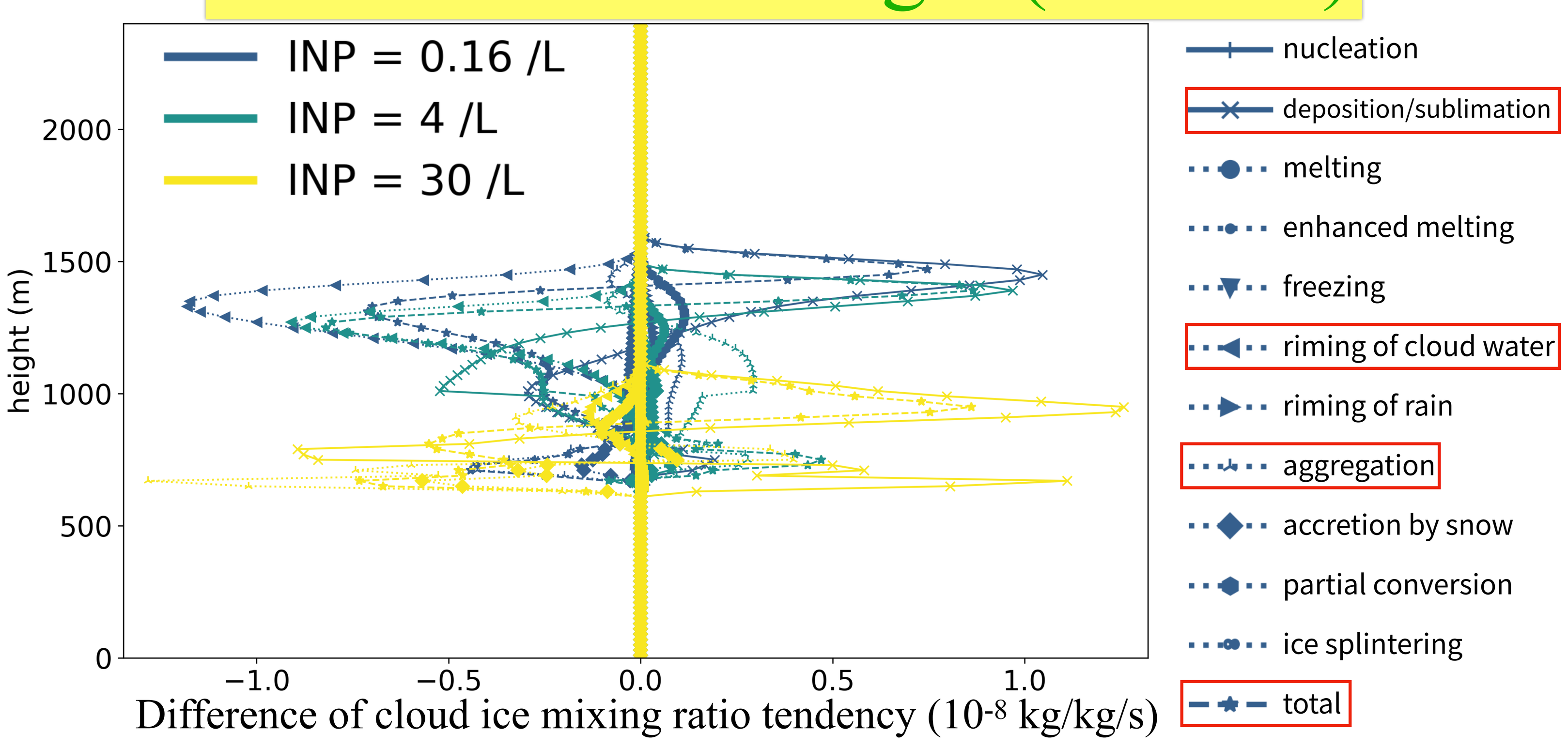
4-4. Ice water budget (domain)



- Decrease in **aggregation**, which increases cloud ice mixing ratio, is smaller than decrease in **riming** of downsized **cloud droplets** due to CCN emission. **Contribution of aggregation to the ice water mass budget is small.**
- These responses indicate that the Twomey effect is stronger than the lifetime effect (Albrecht, 1989).

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5. Summary and Future work

- An LES model is used and aerosols are emitted from a point source or to the entire domain under **two** observation-based **environmental conditions.** Sensitivity experiments are conducted to vary **the number concentration of INPs** to simulate **various cloud phase partitioning** and to **switch on and off CCN emissions**.
  - In this model, whether **responses of cloud albedo** to CCN emission are smaller or larger in clouds with more ice **depends on the environmental condition**.
  - Cloud radiative responses are **mainly caused by the Twomey effect rather than lifetime effect** because **collision-coalescence processes contribute little to the mass budget** in the model.
- Future work is needed to clarify the **model uncertainty** of the contribution of microphysical processes to the responses and to investigate its **dependence on the environmental condition**.

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