How Much Does Ice Microphysics Matter for Simulating Cirrus Clouds?

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Introduction

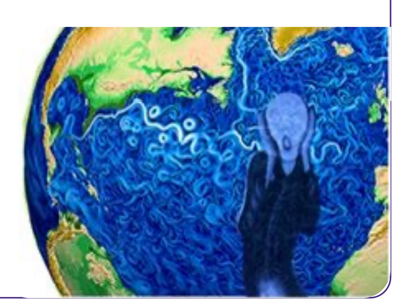
While computational resources have improved and allowed models to run at kilometer-scale resolutions on global domains, microphysics remain a major challenge. There are both difficulties in representing complex subgrid processes in parameterizations and gaps in knowledge about process rates. The sensitivity simulations doubling/halving process rates for small ice shown here are well within the range of uncertainty. We also implement a more physical ice nucleation scheme including hetero- and homogeneous freezing.[1] Other sensitivity simulations include the addition of mean ascent for a more realistic Tropical Tropopause Layer (TTL) structure.

Model

DP-SCREAM: Doubly Periodic Simple Cloud-Resolving E3SM Atmosphere Model in radiative-convective equilibrium[2,3]

- Domain: 108 km x 108 km (doubly periodic boundary)
- Vertical resolution: 127 levs; 233 m in the TTL
- Simulations length: 100 days (last 30 used in analysis)
- Microphysics: Predicted Particle Properties (P3)[4]

Notes: SCREAM performs well in the GSRM version against other DYAMOND models, but tends to simulate popcorn convection.



Sensitivity Study Set-up

To answer the question "How much does microphysics matter for cirrus clouds?", we perform a sensitivity study on sedimentation rate and vapor deposition rate. We run these simulations by adding a factor of 2 or ½ to the process rate for all ice and small ice mass only (see Figure 6). We also test different ice nucleation schemes and including large scale ascent. The runs are described in the Table below. We summarize the sensitivity of each run by looking at the TOA radiative fluxes shown in Figure 1.

Name	Description
Default	Default settings for P3 in DP-SCREAM
Half dep	Vapor deposition is scaled by half for all/small ice mass
2x dep	Vapor deposition is scaled by 2x for all/small ice mass
Half sed	Sedimentation of ice is scaled by half for all/small ice mass
2x sed	Sedimentation rate of ice is scaled by 2x for all/small ice mass
New ice nuc	Ice nucleation is updated to LP2005[1]
LS ascent	Mean slow ascent is prescribed using a mean profile of omega (from w)
SST304K	+4K SST prescribed (304K across domain)
SST296K	-4K SST prescribed to see if results are linear
1 km grid	Reduce the horizontal resolution from 3km to 1km

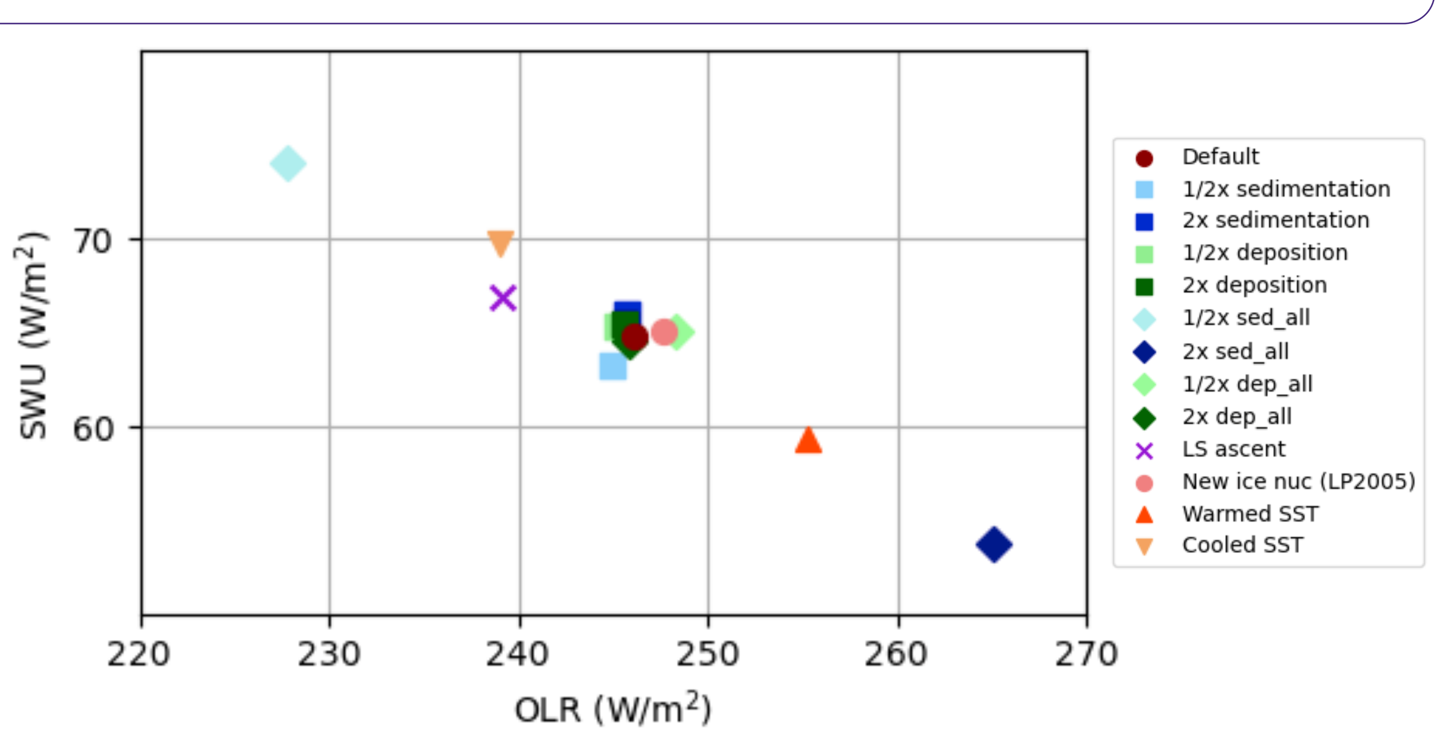


Fig. 1: Mean OLR vs SW upward radiation in W/m2 are plotted for the last 30 days of each simulation. The "small ice" sensitivity runs (squares) cluster around the default (circle). The "all ice" runs (diamonds) show a larger sensitivity to sedimentation (blue) than deposition (green). A run was done with a mean ascent prescribed to represent the BDC (purple X). The warmed and cooled SST runs are ±4K respectively (triangles) from the default 300K SST across the domain.

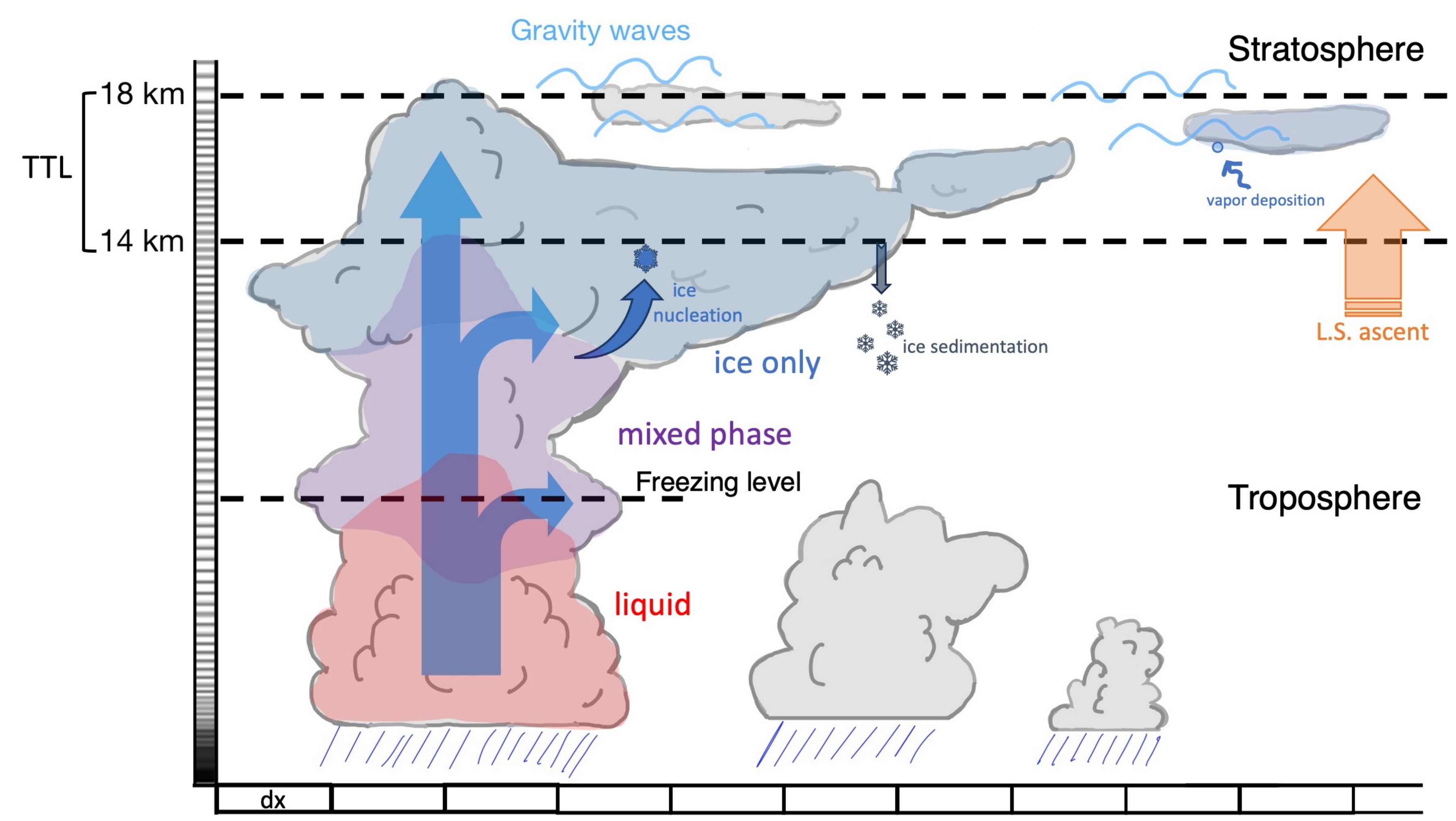


Figure 2: Schematic of the structure of an idealized tropical anvil cloud penetrating the Tropical Tropopause Layer (TTL). We illustrate some of the key ice processes occurring at the subgrid scale of the cloud including ice nucleation, sedimentation, and vapor deposition. Other significant features in the schematic are the convective updrafts and different levels of outflow, the convectively-generated gravity waves which may help to form TTL cirrus clouds away from convection and the presence of large scale (L.S.) ascent, which peaks at the base of the TTL. The blue shading in the cloud indicates the ice phase is present there, purple for the mixed phase layer of the cloud, and red for the liquid portion of the cloud.

1. All ice sensitivity

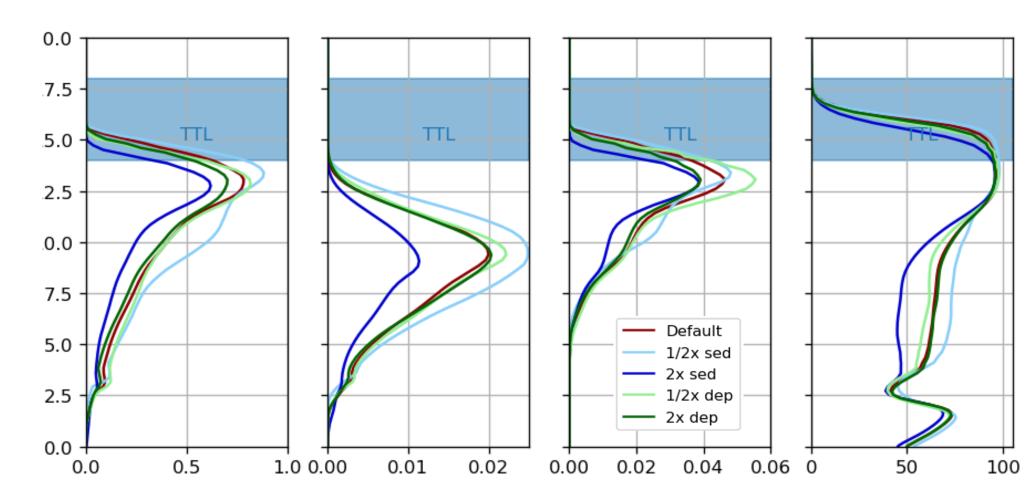


Fig. 3: Mean vertical profiles of cloud fraction, ice water content, ice number concentration, and relative humidity with respect to ice over the last 30 days of the simulation.

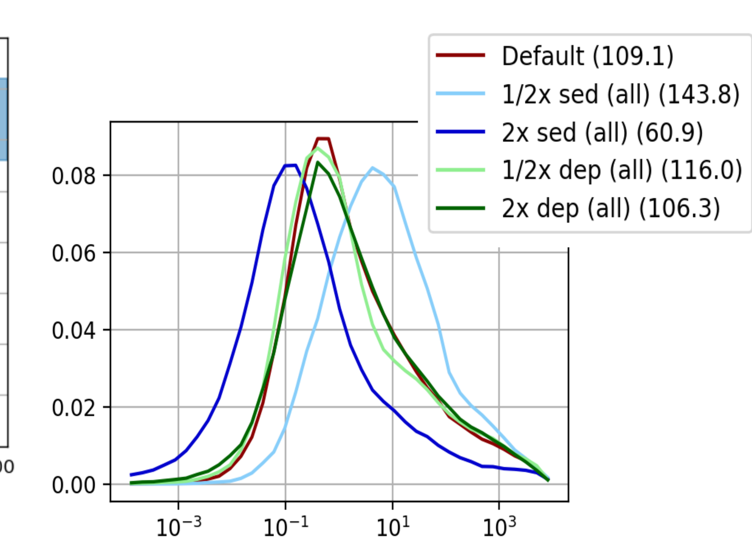
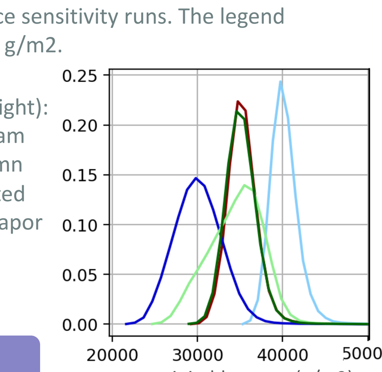


Fig. 4: Histogram of IWP for all ice sensitivity runs. The legend lists the mean values for each in g/m2.

- Clouds are more sensitive to sedimentation
  - Similar results to GCM findings[4,5,6]
  - Main impact on convective clouds
  - Reduce anvil and cirrus clouds as a result

Fig. 5 (right): Histogram of column integrated water vapor



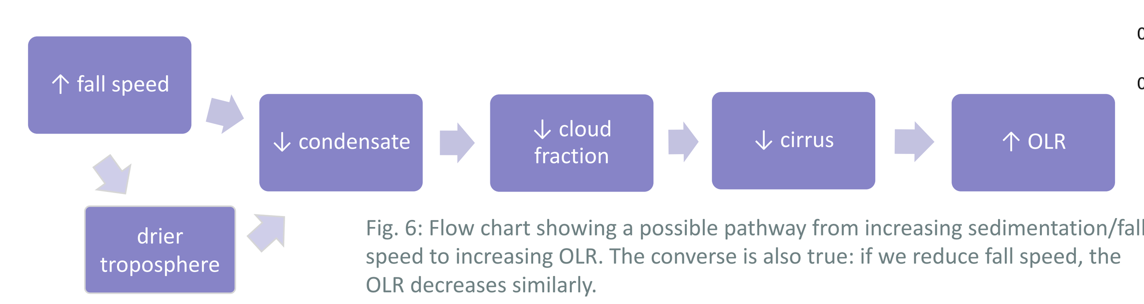


Fig. 6: Flow chart showing a possible pathway from increasing sedimentation/fall speed to increasing OLR. The converse is also true: if we reduce fall speed, the OLR decreases similarly.

Acknowledgments

This work was done on the lands of the Coast Salish peoples, the land which touches the shared waters of all tribes and bands within the Duwamish, Puyallup, Suquamish, Tulalip, and Muckleshoot nations. This conference takes place on the land of the Piscataway and Susquehannock peoples.

Many people have aided my work through conversations but there are a few worth mentioning: Blaž Gasparini for sharing new ice nucleation scheme code and helpful discussions, Hugh Morrison for advice on sensitivity thresholds for small ice, Martina Krämer for advice and her extensive in situ dataset (inspiration for Fig. 11), UW PIRE research group, and everyone who took time to chat about this work and ice microphysics generally.

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Resources

QR code to poster pdf

[1] Liu & Penner, *Meteorologische Zeitschrift* (2005; referred to as LP2005)
[2] Caldwell et al., *JAMES* (2021)
[3] Bogenschutz et al., *JAMES* (2022)
[4] Morrison & Milbrandt, *JAS* (2015)
[5] Sanderson, *J. Climate* (2011)
[6] Lin et al. *JGR: Atmos.* (2021)
[7] Mitchell et al. *GRL* (2008)

2. Small ice sensitivity

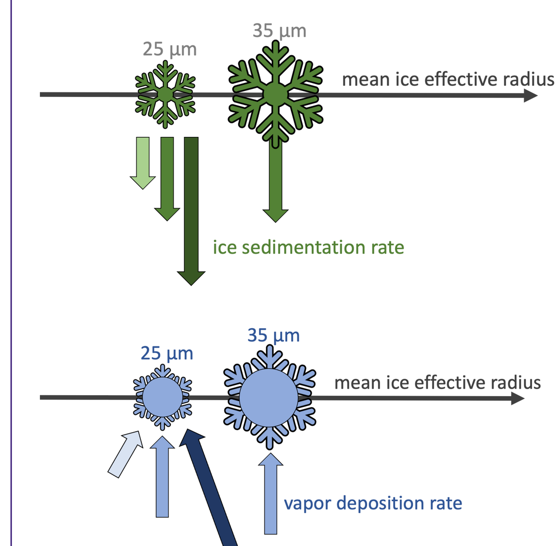

Fig. 7: Schematic of the set up for the small ice sensitivity experiments for sedimentation and deposition.

- Sensitivity for ice with ice effective radius ≤ 25 µm
- Deposition is on par with sedimentation
  - all within 2 W/m^2 of default in Fig. 1
- Model is relatively insensitive to these small changes (but over time and space, it could add up[6])

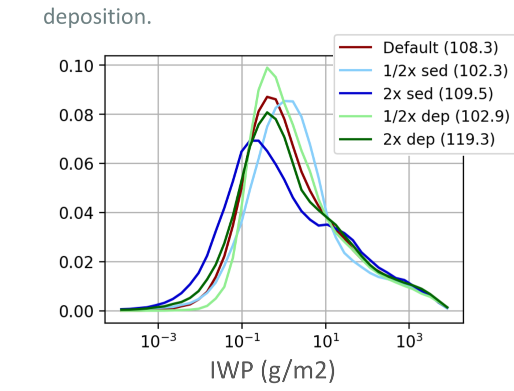

Fig. 8: Histogram of ice water path (logscale). The legend lists mean values of IWP in g/m2.

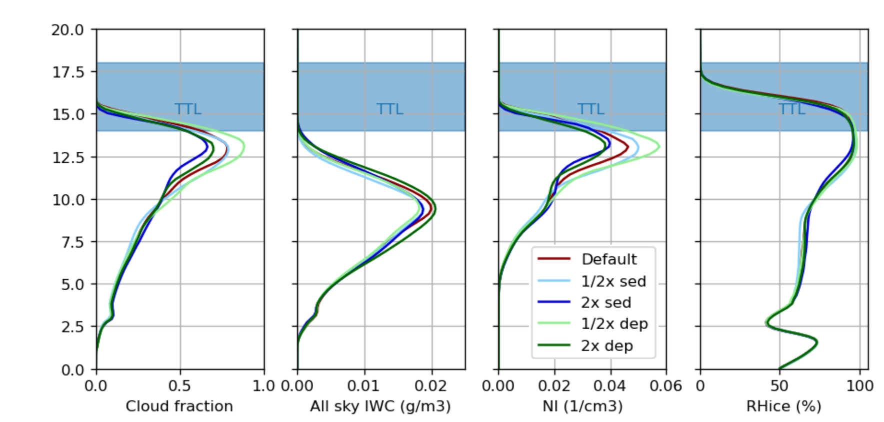

Fig. 9: Mean vertical profiles of cloud fraction, ice water content, ice crystal number concentration, and relative humidity with respect to ice from the last 30 simulated days for the default (gray), +/- 4K SST (red/blue).

3. Mean vertical ascent

- BDC approximated by small mean vertical ascent is prescribed (peaks at 14 km).

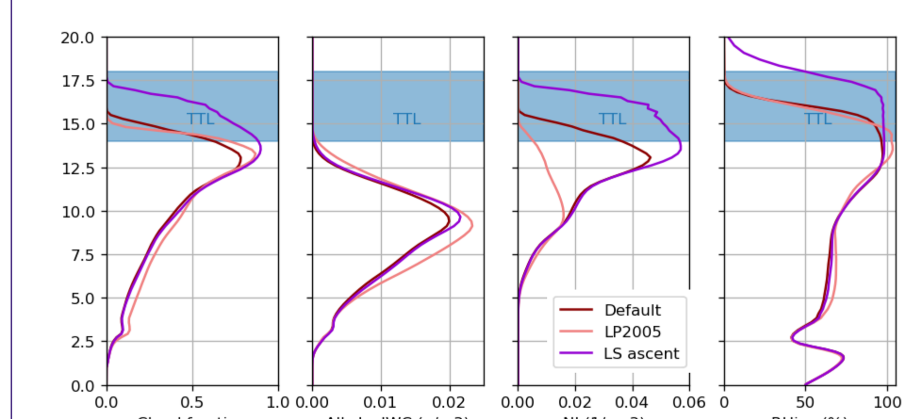

Fig. 10: Mean vertical profiles of cloud fraction, ice water content, ice crystal number concentration, and relative humidity with respect to ice from the last 30 simulated days for the default (dark red), new ice nucleation following Liu & Penner (2005; pink), and large-scale ascent (purple).

TTL cirrus cloud fraction is highly sensitive to mean vertical ascent (these are optically thin but still have a small impact of TOA radiation).

Main Take-aways

1. Convective clouds are highly sensitive to sedimentation.
2. Anvil and cirrus clouds are impacted by changes in small ice but small effect on TOA radiation.
3. Cirrus clouds are highly sensitive to the presence of large-scale ascent and ice nucleation scheme.

Next Steps

1. Run on a larger domain (tropical western pacific channel)
2. Run at 1 km horizontal resolution
3. Explore more of the differences between ice nucleation schemes (See Fig. 11)
4. Add tracers for time since convection and nucleation

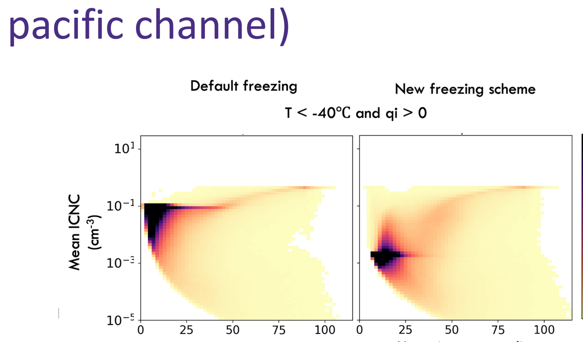

Fig. 11: Joint histogram of ice crystal number concentration vs ice mass radius for different ice nucleation schemes.