Sensitivity of Tropical Anvils to Ice Aggregation

Jennie Bukowski[1], Stephen Saleeby[1], Randy Chase[1,2], Derek Posselt[3], Brenda Dolan[1], Leah Grant[1], Gabrielle Leung[1], Peter Marinescu[1], Kristen Rasmussen[1], Itinderjot Singh[1], Rachel Storer[4], and Susan van den Heever[1]

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[1]Colorado State University - Department of Atmospheric Science
[2]Cooperative Institute for Research in the Atmosphere
[3]NASA Jet Propulsion Laboratory; California Institute of Technology
[4]University of California – Los Angeles; NASA Jet Propulsion Laboratory

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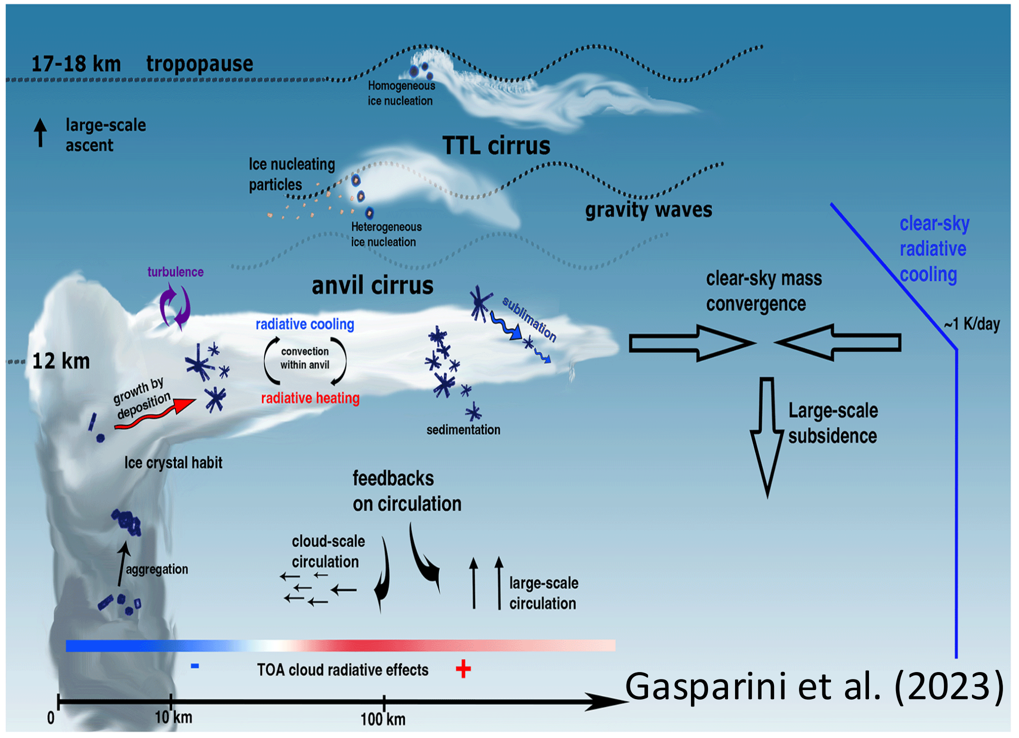
Storm Anvils Modulate Radiation

INVESTIGATION OF CONVECTIVE UPDRAFTS

Physical Processes within Storm Anvils

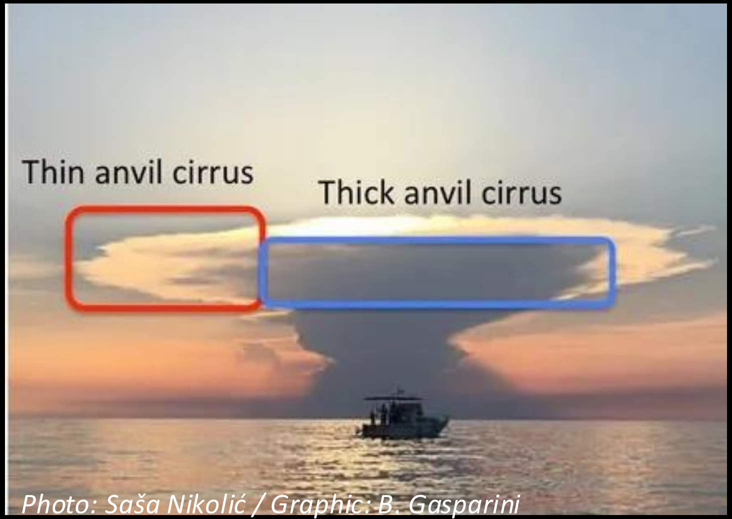


Gasparini et al. (2023)

- Macrophysical and microphysical properties of storm anvils affect cloud-radiative forcing and feedbacks
- Macrophysical anvil properties
  - Anvil extent, height, thickness, lifetime, albedo
- Microphysical anvil properties
  - Ice number, size, mass, shape/habit, fall speeds

Storm Anvils Modulate Radiation

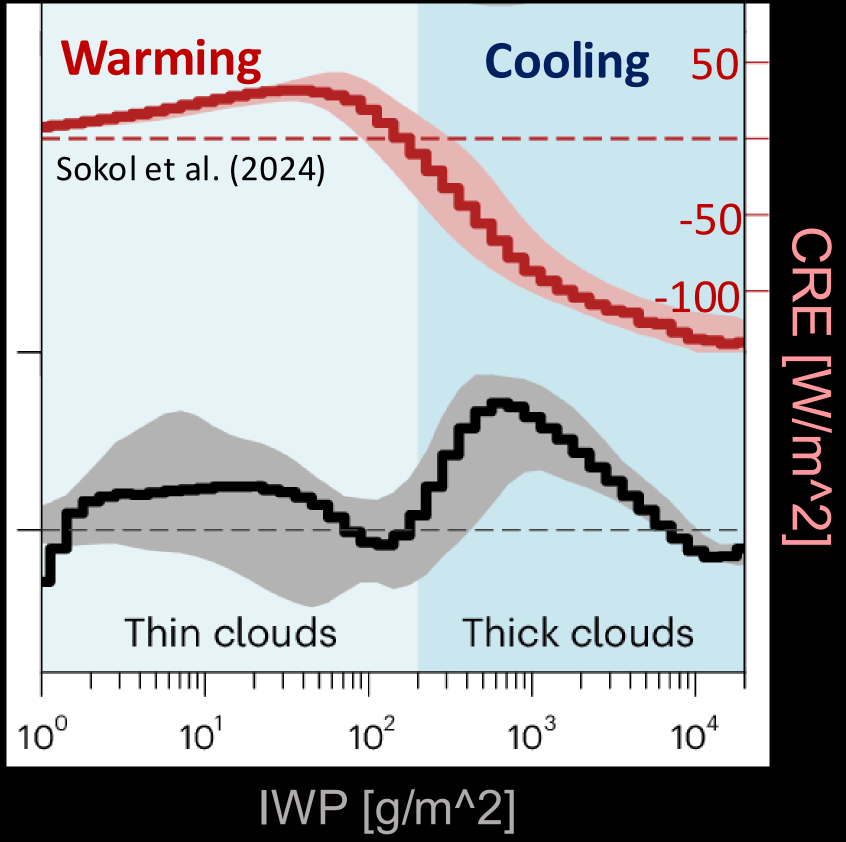
- Anvils affect cloud-radiative forcing and feedbacks
- Thin and thick anvils have opposite radiative impacts (warming / cooling)[1]



Thickness:

Depth of anvil layer
Optical thickness
IWP

Cloud Radiative Effect

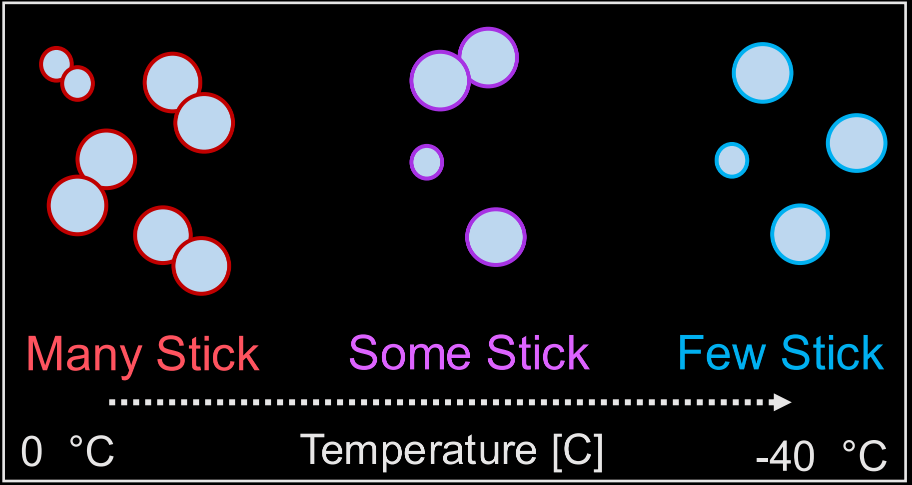


[1]Hartmann and Berry (2017)

Anvil Microphysics
Ice Self-Aggregation at Low Temperatures

- Microphysical properties of anvil ice affects cloud-radiative forcing and feedbacks
  - Many unknowns in ice processes
- Uncertainty on the efficiency of ice self-aggregation
  - How efficiently ice sticks together
- **Ice crystal aggregation decreases as temperature decreases**

Ice Aggregation-Temperature Relationship



Aggregation Mechanisms

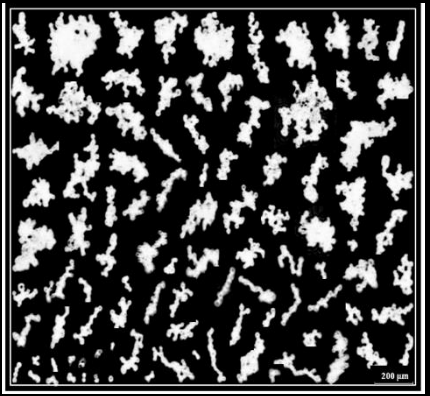
Adhesion	**Sintering**
Interlocking	**Electrical**

Evidence of Ice Aggregation at Low Temperatures

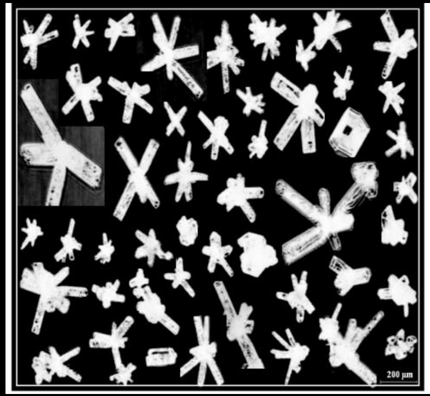
- Ice crystal aggregation decreases as temperature decreases
  - What is the temperature limit where aggregation stops?
- In-situ evidence of ice aggregation at/below -40 ◦C

Aircraft Observations

J.-F. Gayet et al. (2012)

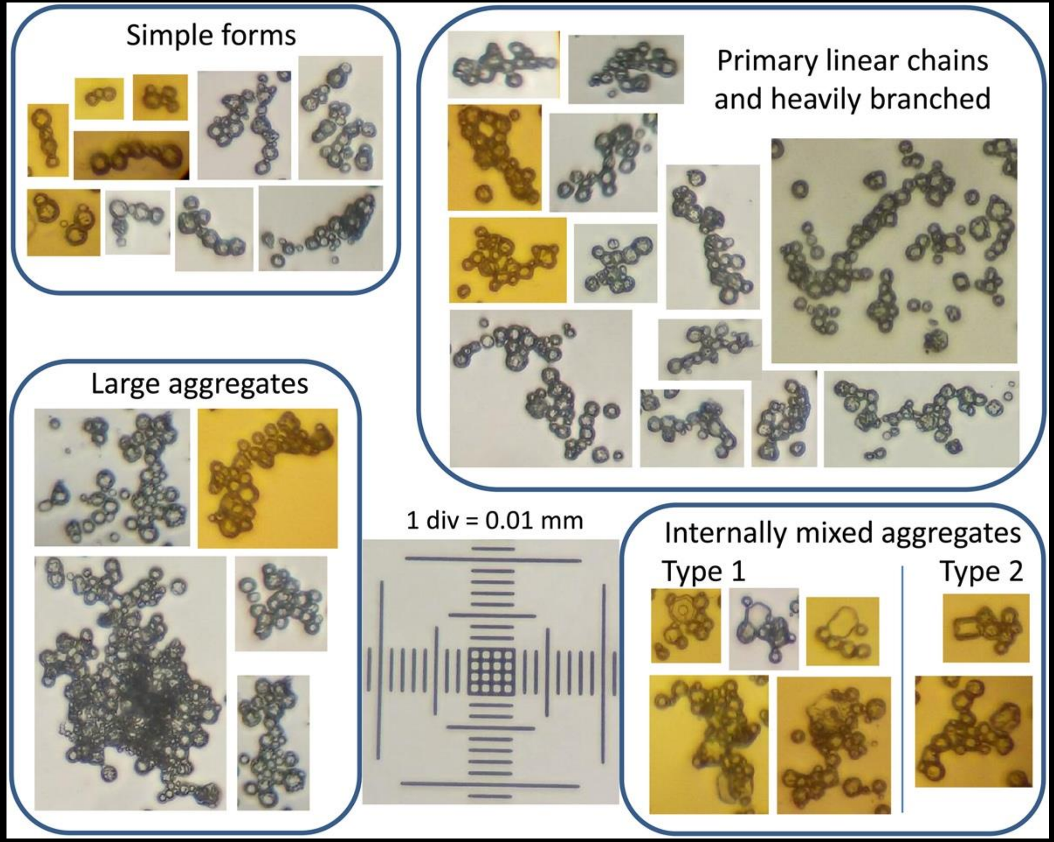


top of overshooting cell
(T = −58 ◦C)



cirrus
(T = −45 ◦C)

Lab-Grown Ice Aggregates: T = −(43 ± 1)°C

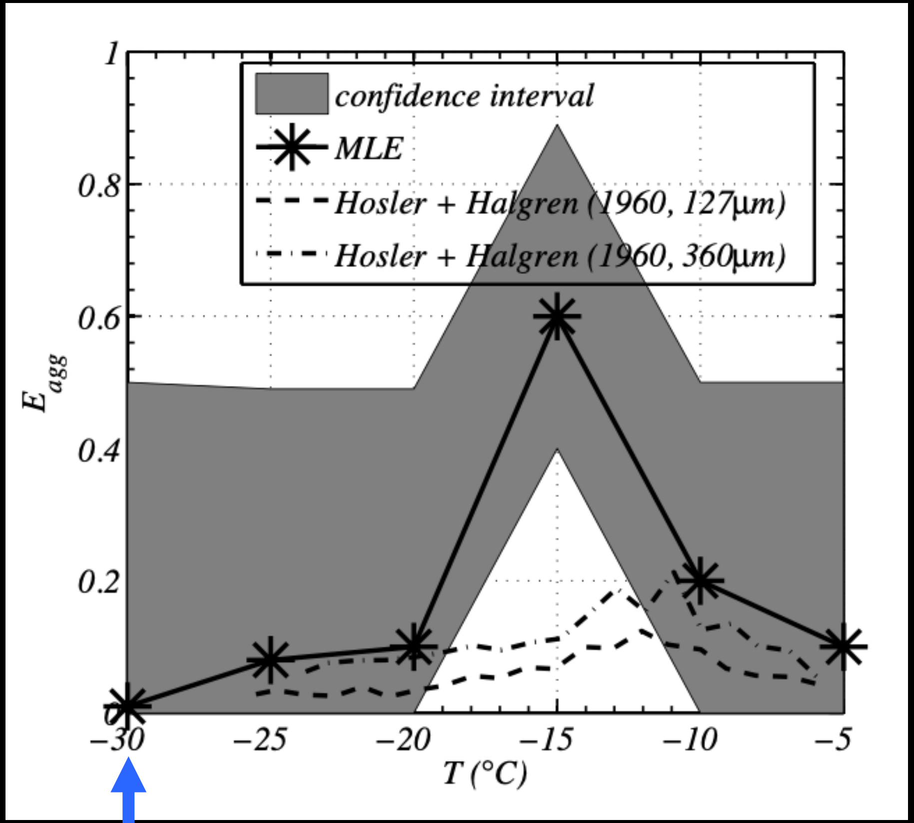


Pedernera & Ávila (2018)

Ice Aggregation Rates are Difficult to Measure

- Ice crystal aggregation decreases as temperature decreases
- **Aggregation process rates are difficult to measure** and depend on complex environmental factors
- Two approaches for representation in models
  - Don't consider T α E_{agg}
  - Parameterize into a simple T α E_{agg} relationship
- Large spread in E_{agg} based on observations

Aggregation-Temperature Parameterization



T < -30°C ??

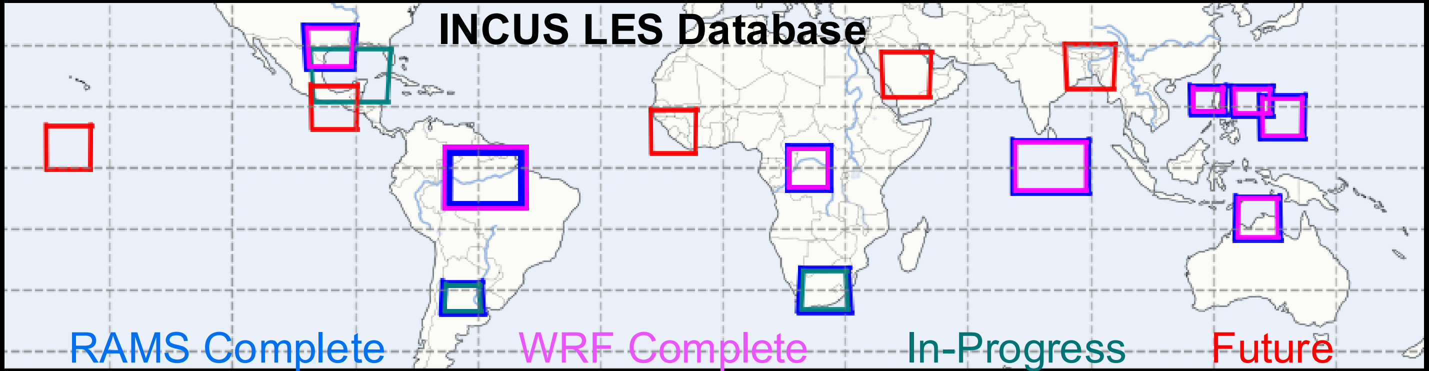
Connolly et al. (2012)

Science Question

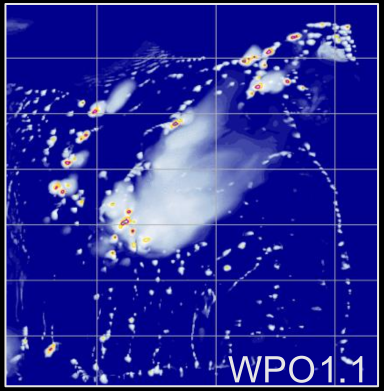
How do ice aggregation rates at low temperatures affect tropical anvil properties and cloud radiative feedbacks?

Methodology – LES Modeling

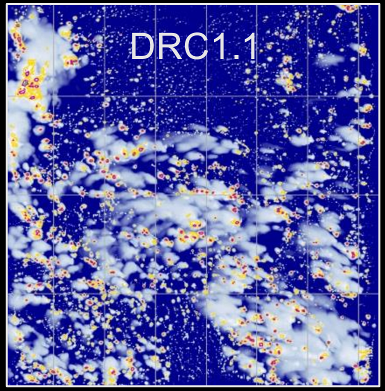
- Mini-Ensemble of 5 Regional Atmospheric Modeling System[1] (RAMS) simulations from the INCUS LES Database
  - Case studies of (sub)tropical convection
    - Diverse environments & storm morphologies
  - 3 nested grids (dx,dy = **1.6 km**, 400m, 100m)
    - 230 vertical levels



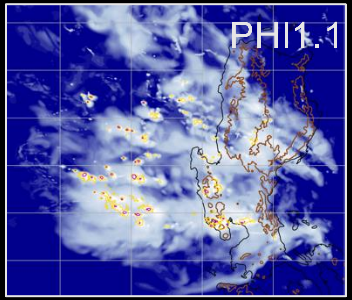
Isolated Maritime



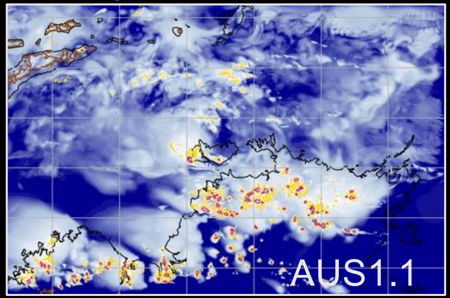
Scattered Continental



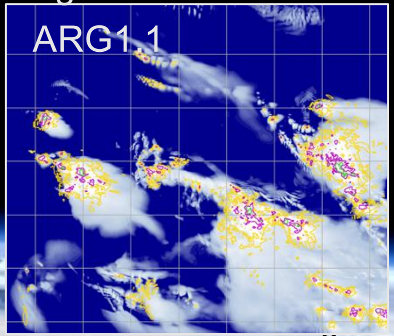
Organized Maritime



Organized Maritime



Organized Continental



[1]*Cotton et al., 2003; Saleeby and van den Heever, 2013*

Methodology – LES Modeling

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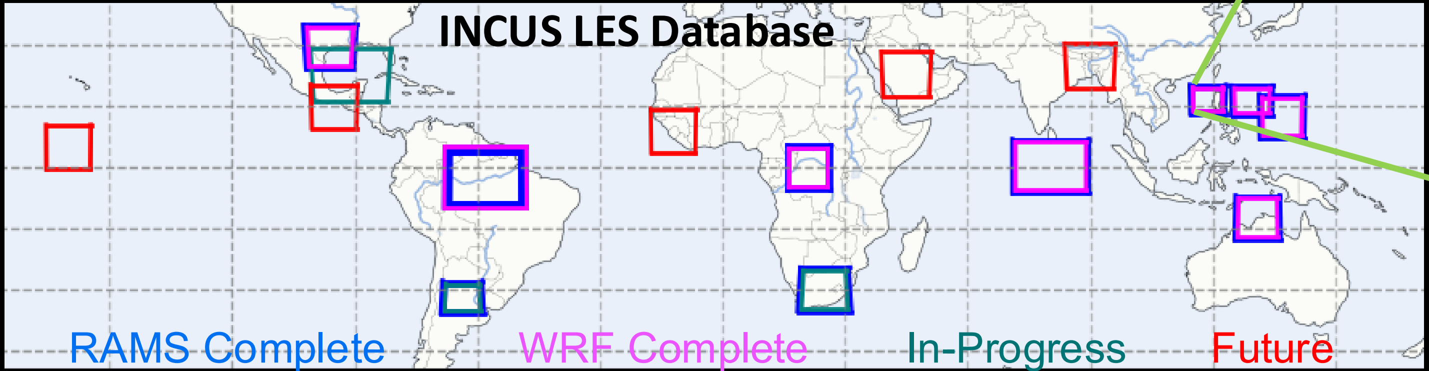
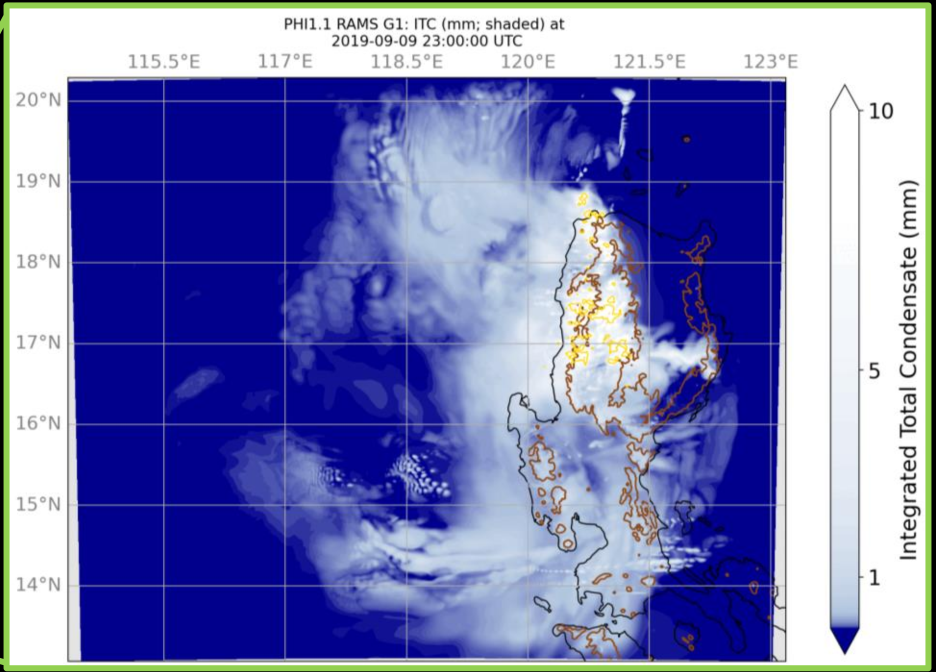
  - Case studies of (sub)tropical convection
    - Diverse environments & storm morphologies
  - 3 nested grids (dx,dy = **1.6 km**, 400m, 100m)
  - RAMS double-moment microphysics
    - Split into discrete hydrometeor species



Philippines - Organized Maritime

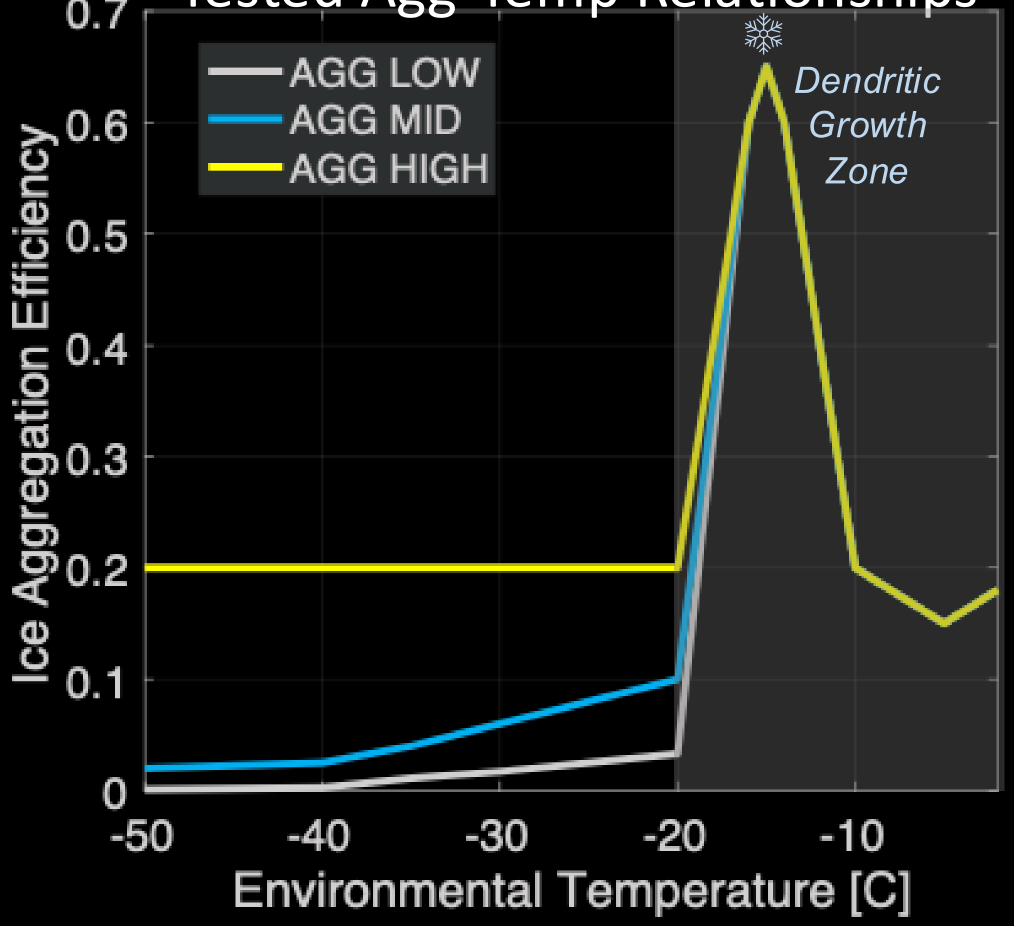


[1] *Cotton et al., 2003; Saleeby and van den Heever, 2013*

Methodology – LES Modeling

- Mini-Ensemble of 5 RAMS simulations
  - Perturb ice aggregation efficiencies (E_{agg}) for -20 ≥ T ≥ -50 ◦C

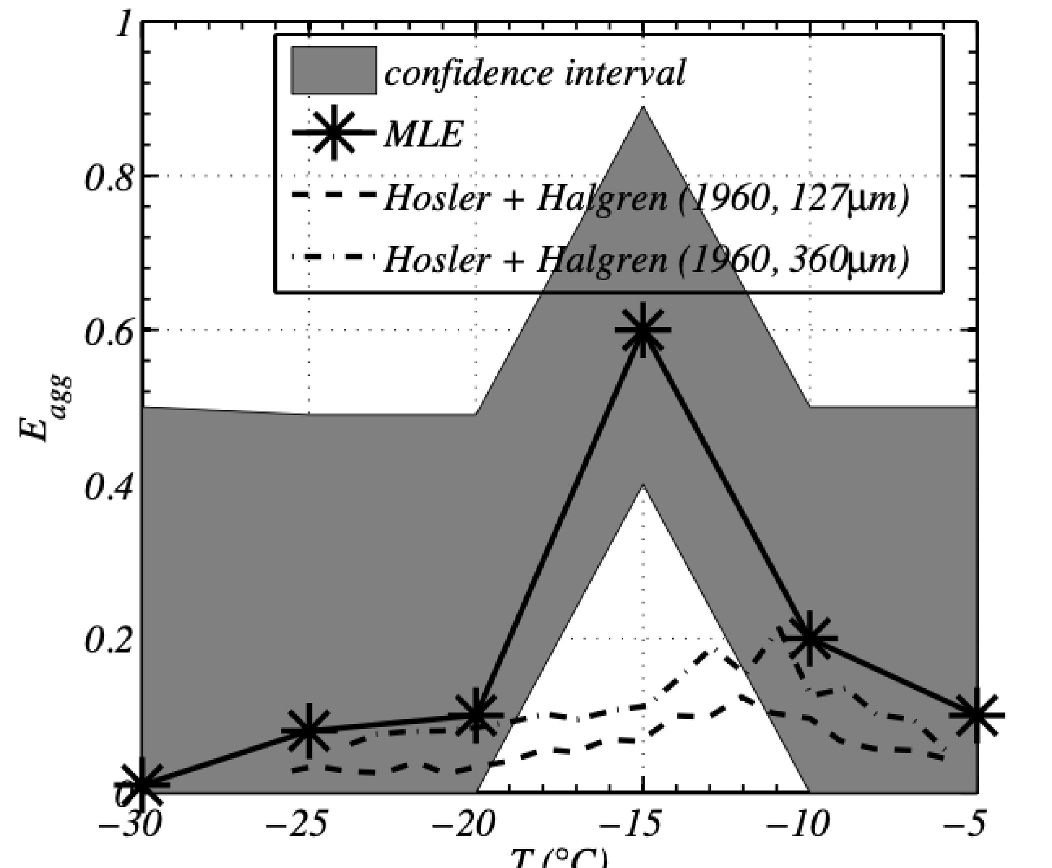
Tested Agg-Temp Relationships



[1]Connolly et al. (2012); Mitchell et al. (2006); Phillips et al. (2015)

Methodology – LES Modeling

- Mini-Ensemble of 5 RAMS simulations
  - Perturb ice aggregation efficiencies (E_{agg}) for -20 ≥ T ≥ -50 ◦C
    - Within the uncertainty range from observations[1]

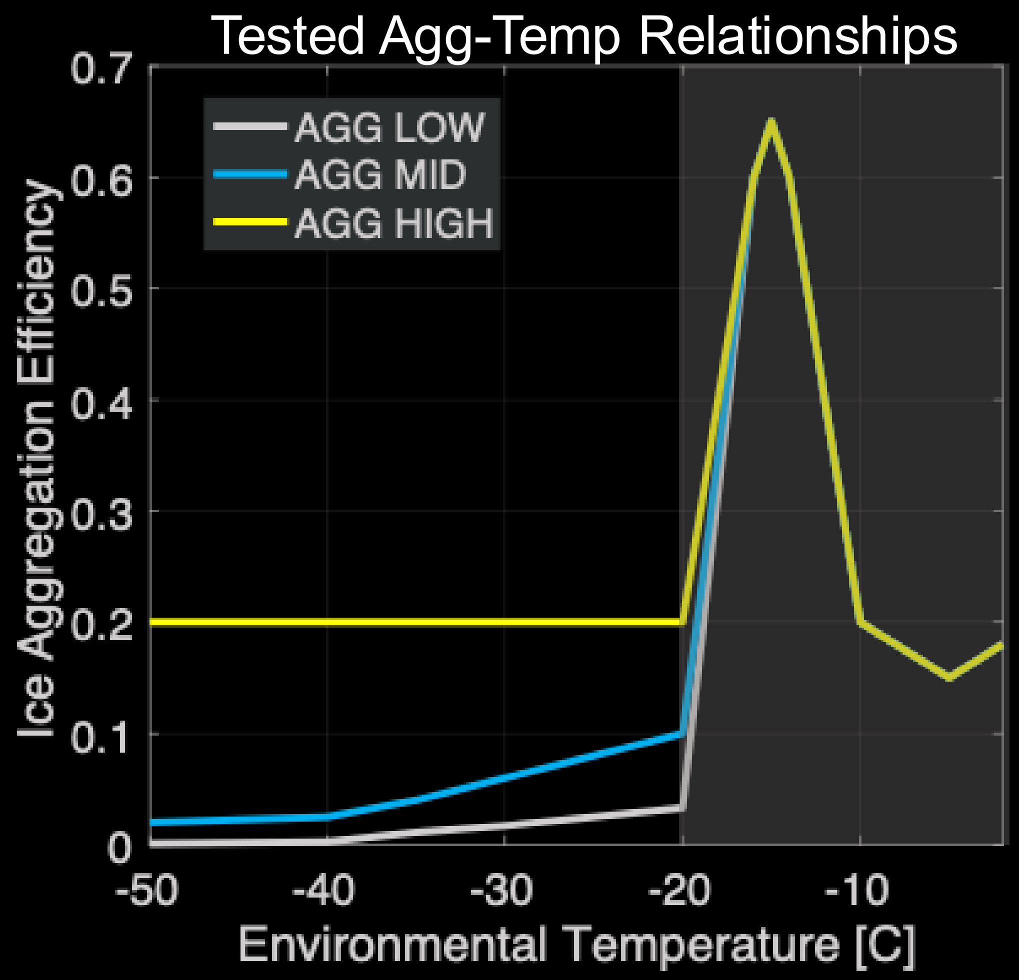


Connolly et al. (2012)

[1]*Connolly et al. (2012); Mitchell et al. (2006); Phillips et al. (2015)*

Methodology – LES Modeling

- Mini-Ensemble of 5 RAMS simulations
  - Perturb ice aggregation efficiencies (E_{agg}) for -20 ≥ T ≥ -50 ◦C
    - Within the uncertainty range from observations[1]
  - All ice-ice collision species perturbed
    - Pristine ice, snow, aggregates, graupel, hail



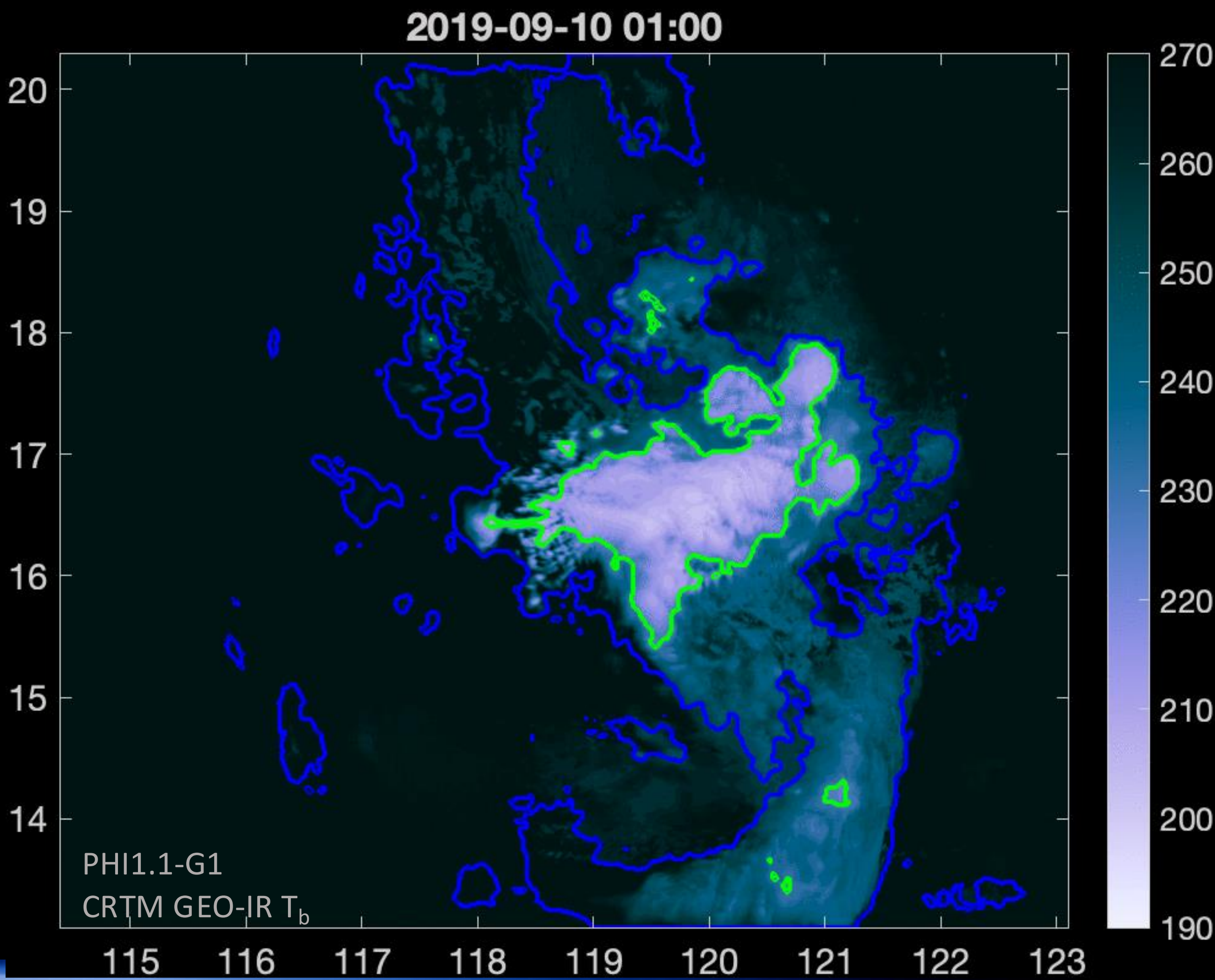
[1] *Connolly et al. (2012); Mitchell et al. (2006); Phillips et al. (2015)*

Methodology – Tracking Thick vs Thin Anvils

- Mini-Ensemble of 5 RAMS simulations
  - Perturb ice aggregation efficiencies (E_{agg}) for -20 ≥ T ≥ -50 ◦C
  - Run CRTM and track anvils in the simulations using T_b
    - Use T_b channel difference image processing approach (Jones et al., 2023) to separate and track **thin** and **thick** anvils
  - Domain average over last 6 hours

Thick Anvil Extent

Thin Anvil Extent



[1]Connolly et al. (2012); Mitchell et al. (2006); Phillips et al. (2015)

Ice Aggregation Affects Anvil Area

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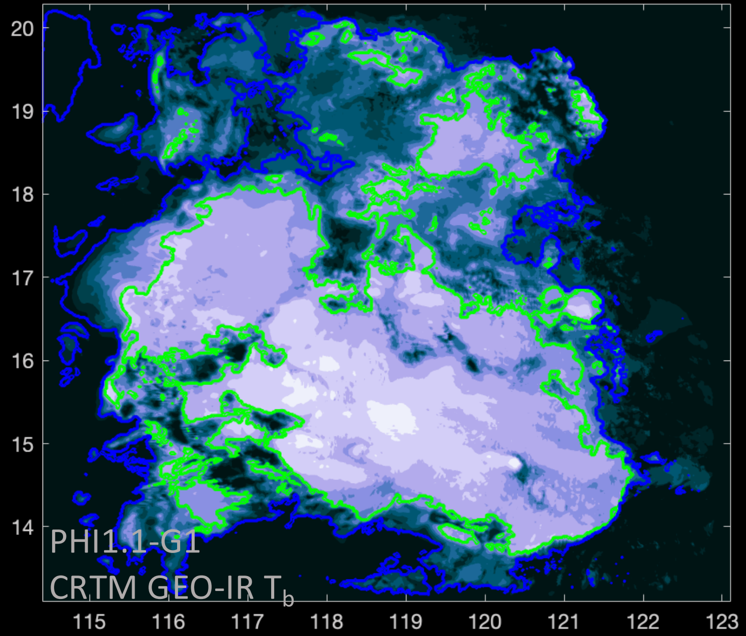
High aggregation → more ice sticks together

Thick Anvil / Thin Anvil

AGG PROCESS LOW

AGG PROCESS MID

AGG PROCESS HIGH



Mean T_b = 257 [K]

Optically opaque thick clouds

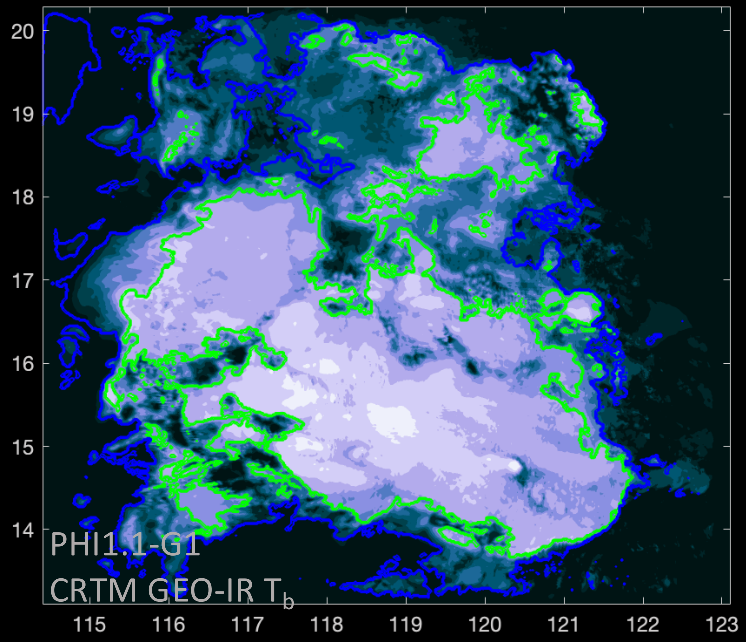
OLR dominated by cloud top temp.

Ice Aggregation Affects Anvil Area

High aggregation → more ice sticks together

Thick Anvil / Thin Anvil

AGG PROCESS LOW

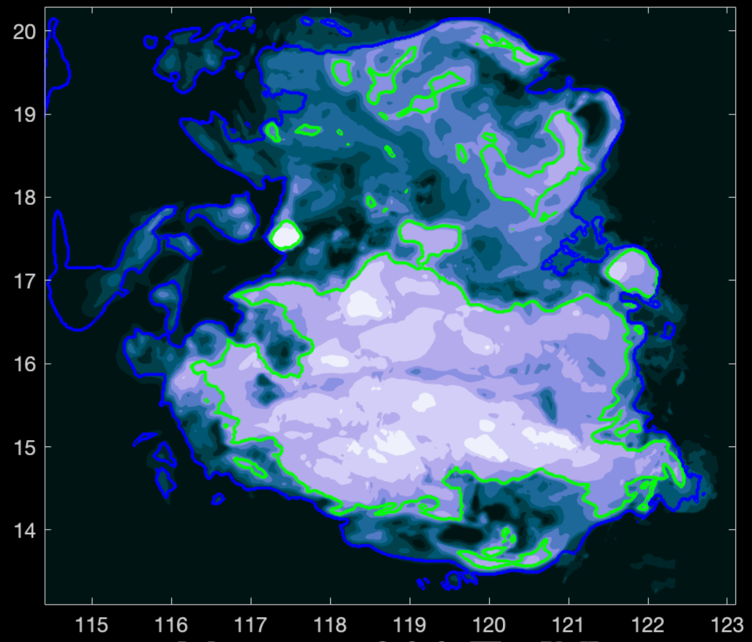


Mean T_b = 257 [K]

Optically opaque thick clouds

OLR dominated by cloud top temp.

AGG PROCESS MID



Mean = 260 T_b [K]

AGG PROCESS HIGH

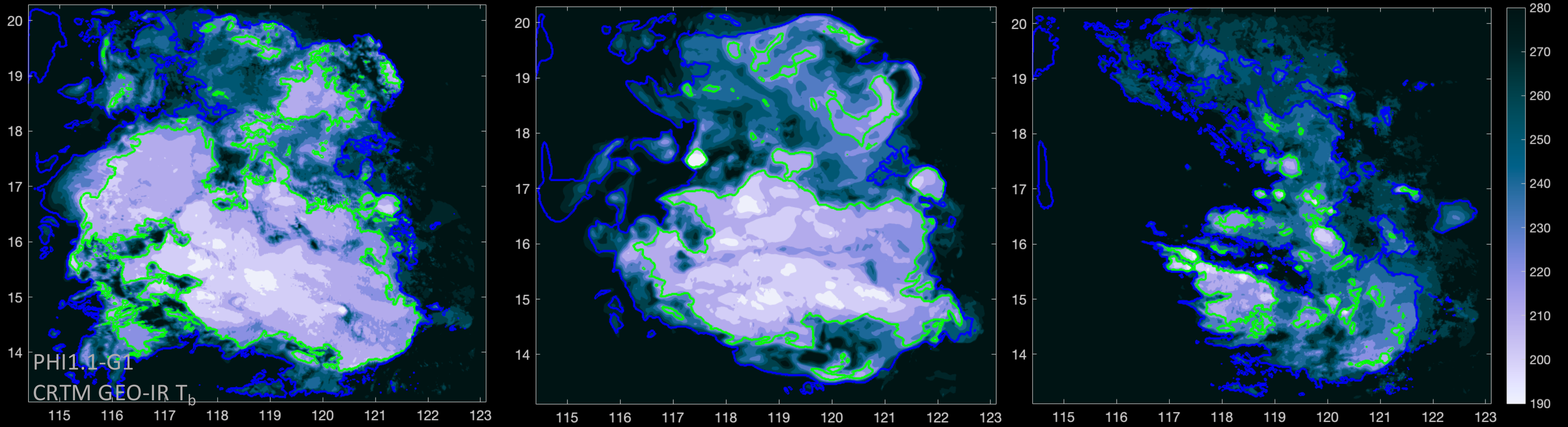
Ice Aggregation Affects Anvil Area

INVESTIGATION OF CONVECTIVE UPDRAFTS

High aggregation → more ice sticks together

Thick Anvil / Thin Anvil

AGG PROCESS LOW | **AGG PROCESS MID** | **AGG PROCESS HIGH**



Mean T_b = 257 [K] | Mean = 260 T_b [K] | Mean T_b = 277 [K]

Optically opaque thick clouds

OLR dominated by cloud top temp.

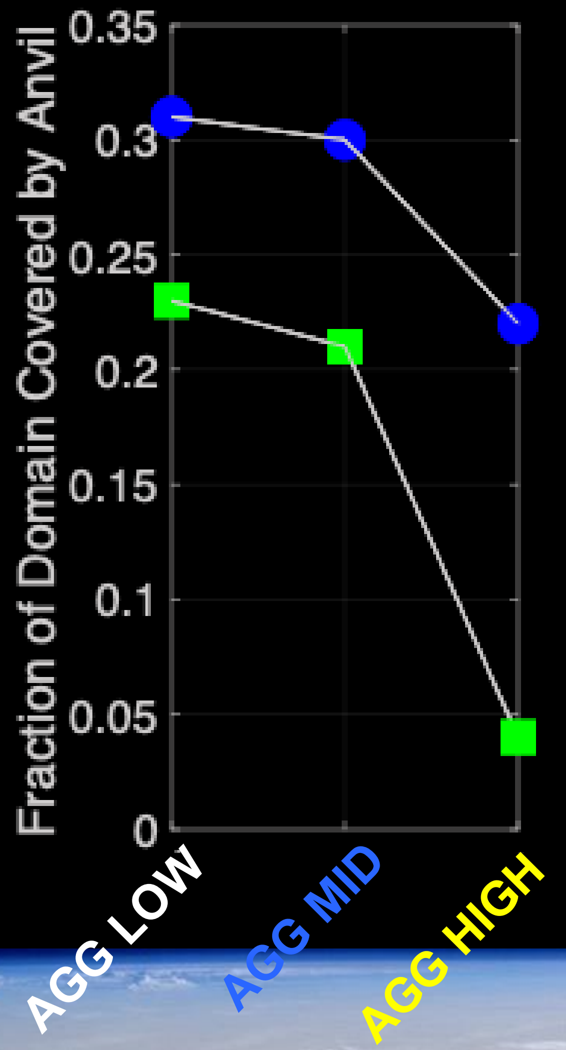
Optically thin clouds

OLR mixed signal of clouds+surface

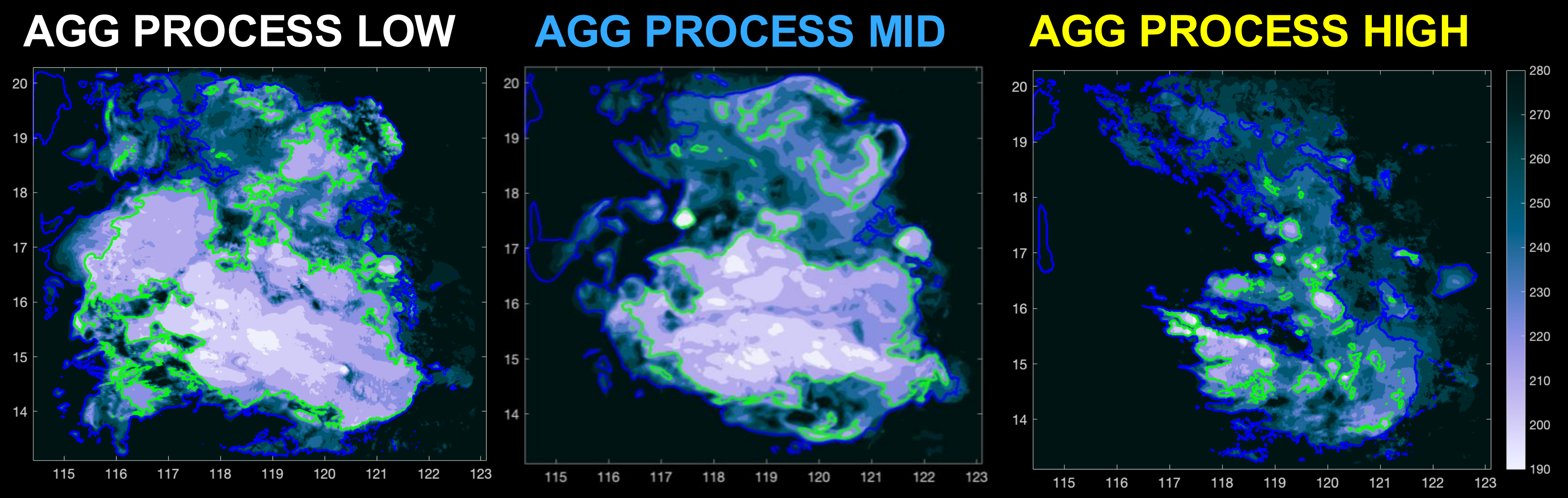
Ice Aggregation Impacts Anvil Thickness

INVESTIGATION OF CONVECTIVE UPDRAFTS

Change in Domain Anvil Fraction



Thick Anvil / Thin Anvil



Thick anvil extent is <u>highly sensitive</u> to ice aggregation

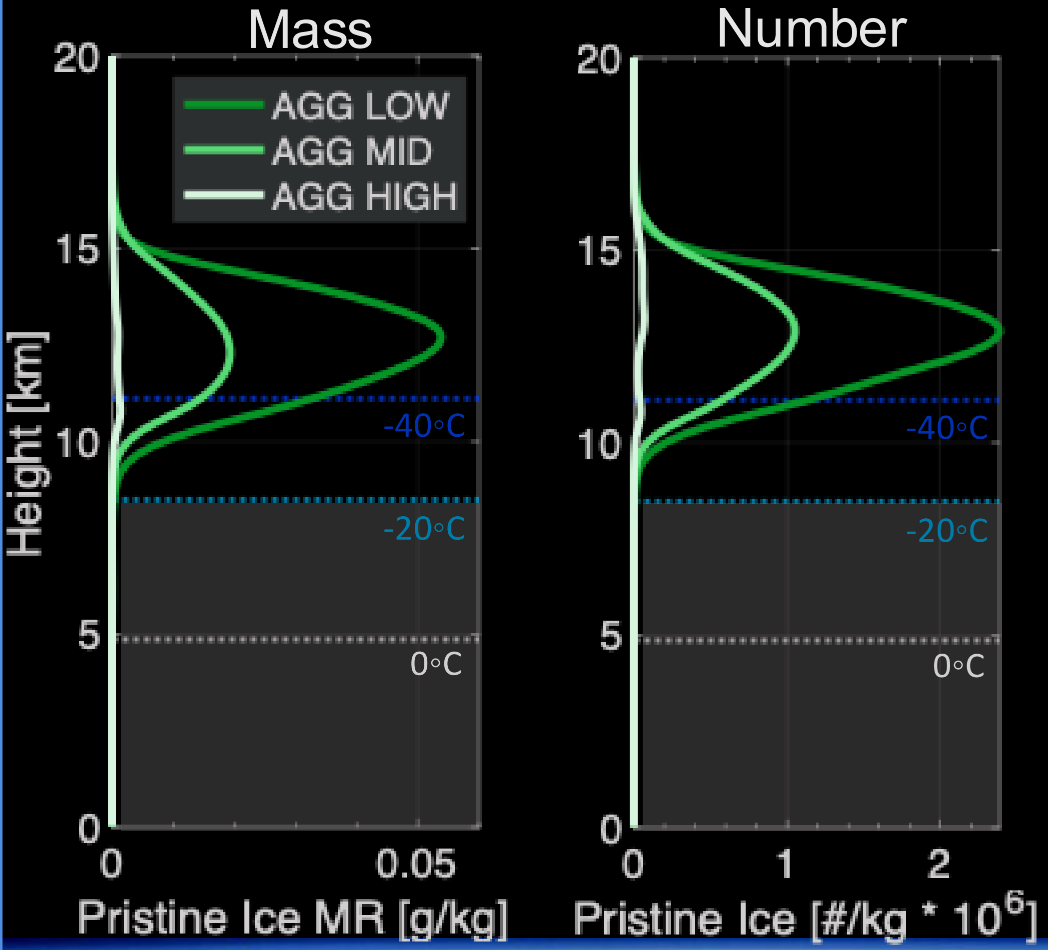
Thin anvil extent is <u>less sensitive</u> to ice aggregation

Difference between thick and thin extent increases as aggregation increases

Ice Aggregation Alters Microphysics

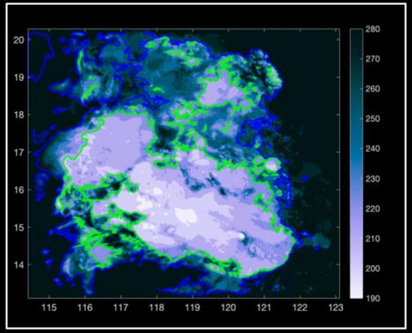
INVESTIGATION OF CONVECTIVE UPDRAFTS

Change in Pristine Ice



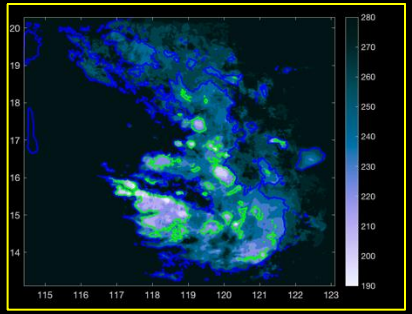
High aggregation → more ice sticks together

AGG PROCESS LOW



LOTS of small ice

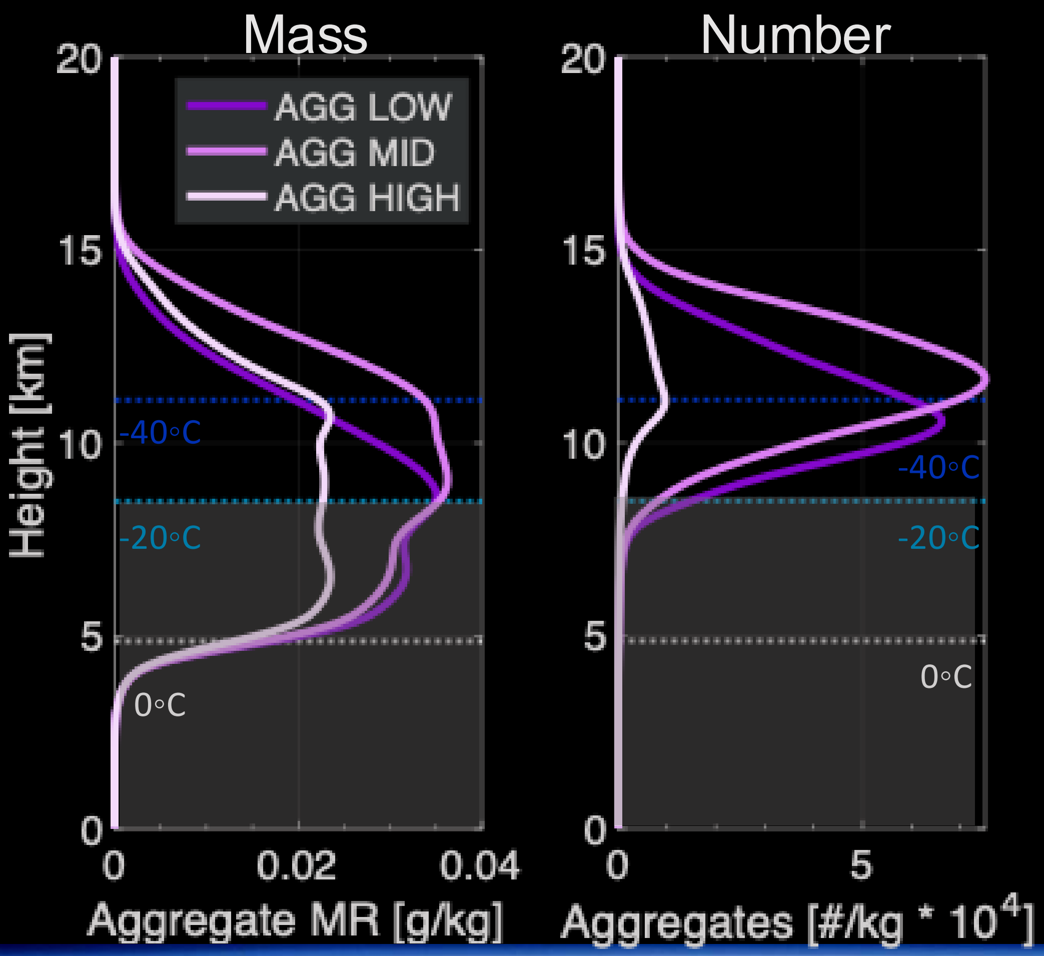
AGG PROCESS HIGH



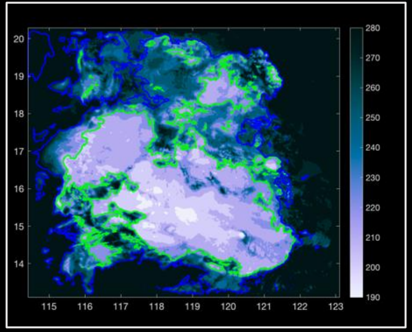
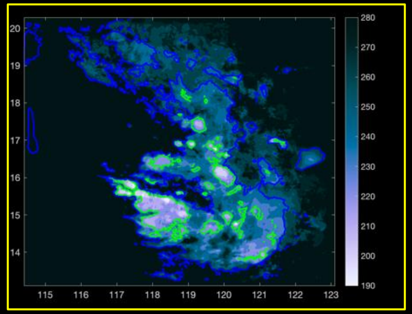
FEW pristine ice

Ice Aggregation Alters Microphysics

Change in Aggregates



High aggregation → more ice sticks together

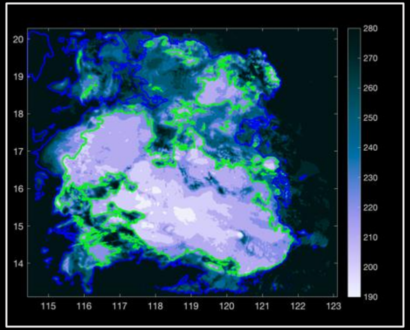
AGG PROCESS LOW	AGG PROCESS HIGH
	
LOTS of small ice	FEW pristine ice
Particles grow, but not large enough to fall out	Aggregates are (too) large, fall out (too) quickly
INCREASED lifetime	DECREASED lifetime

Ice Aggregation Impacts Cloud-Radiation Interactions

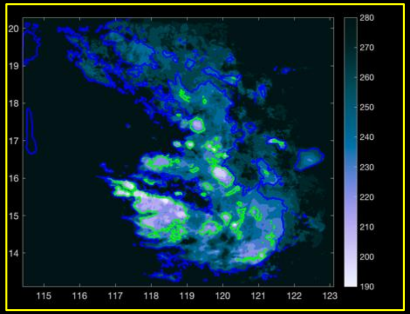
INVESTIGATION OF CONVECTIVE UPDRAFTS

- **AGG PROCESS LOW** has more widespread anvil cover
  - More opportunity for cloud radiative effects

AGG PROCESS LOW



AGG PROCESS HIGH

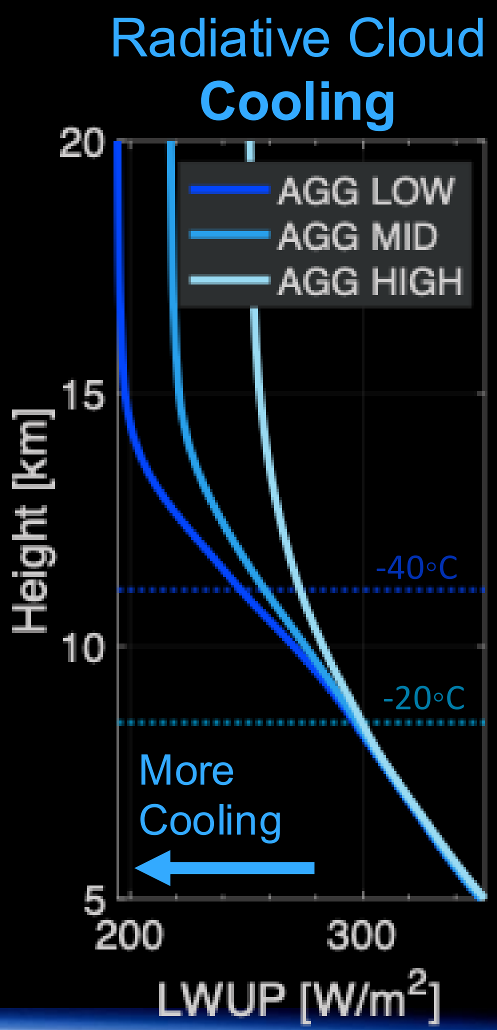


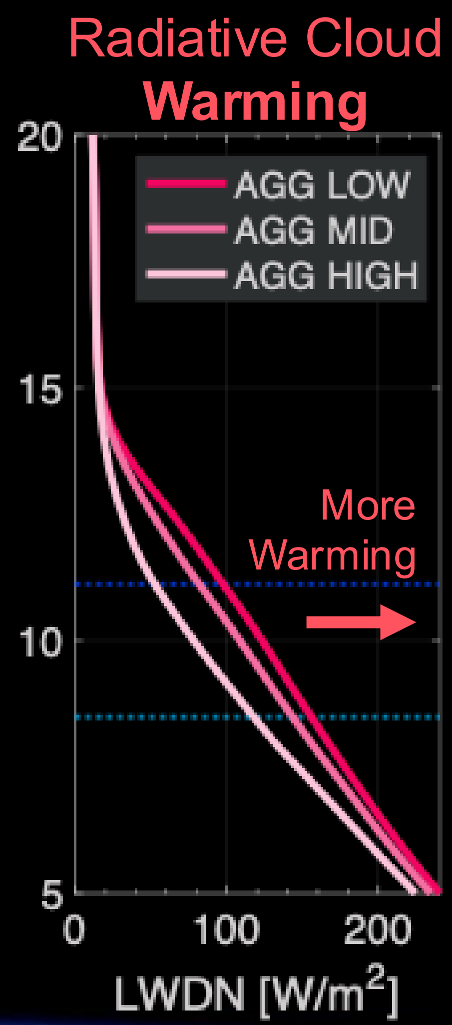
MORE radiative cooling at cloud top

LESS radiative cooling at cloud top

MORE LW cloud emission warming

LESS LW cloud emission warming

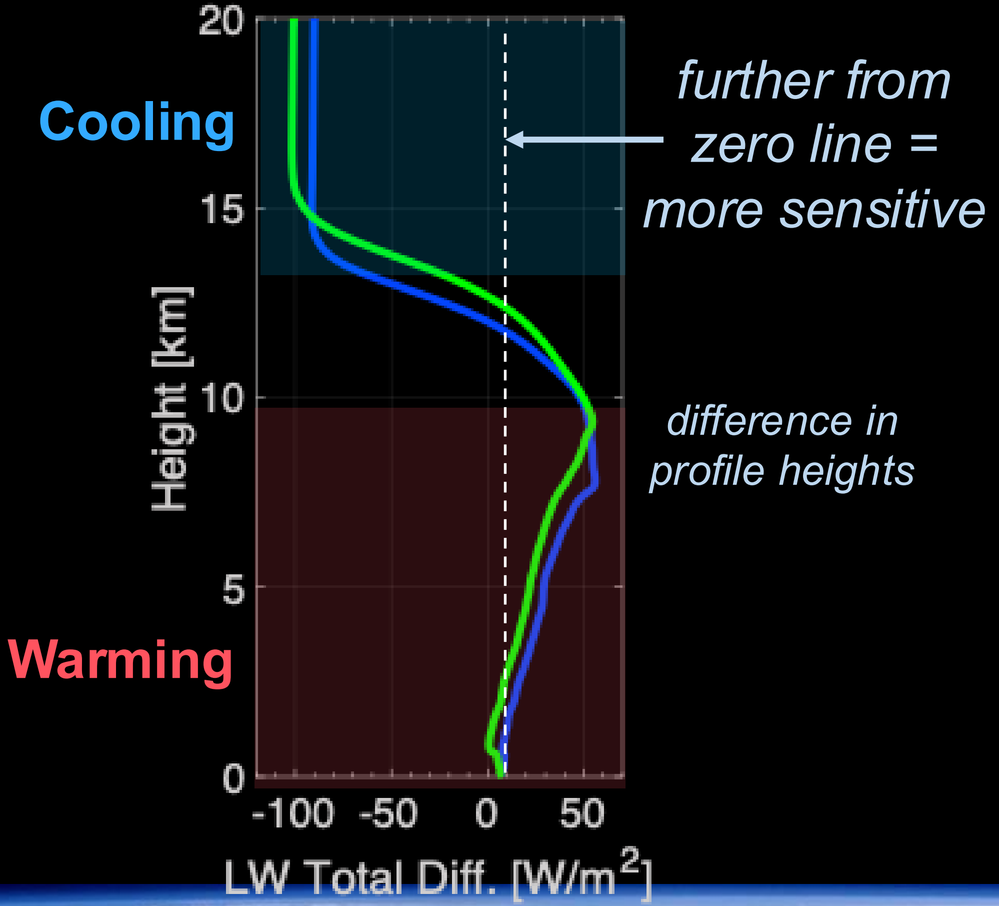




Thin vs Thick Anvil Radiative Effects

Net LW Effect of Increasing AGG Rates

(AGG LOW – AGG HIGH)



For LW Radiative Effects:

Cloud cooling and OLR is more affected by aggregation than cloud warming

Thick anvils are more sensitive to changes in aggregation and contribute most to the sensitivity of cloud cooling

Jennie Bukowski
jbukowsk@colostate.edu

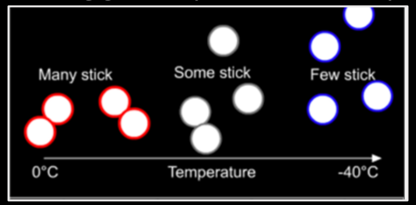
Conclusions

INVESTIGATION OF CONVECTIVE UPDRAFTS

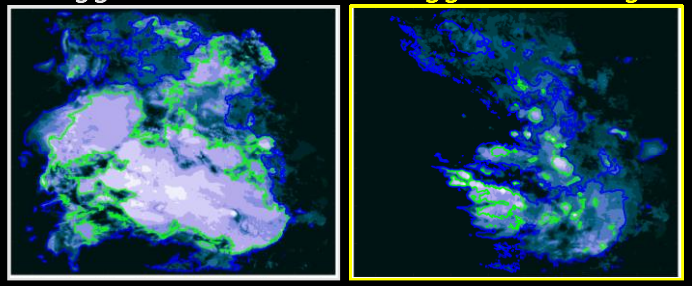
- Ice aggregation processes are complex
  - Uncertainty in parameterizing E_{agg} at T<-20◦C
- Increasing aggregation decreases anvil extent
- Increasing aggregation rates leads to less small ice, more large aggregates
  - Small ice in **AGG PROCESS LOW** too small to fall out
    - Unrealistically large extent and lifetime
  - Large ice in **AGG PROCESS HIGH** falls out too fast
- Aggregation changes cloud radiative budget
  - Increasing aggregation decreases cloud cooling

How can we improve representation and understanding of ice aggregation?

Ice Agg-Temp Relationship



Ice Agg Process Low *Ice Agg Process High*



Ice Agg Impacts on Cloud Radiation