Karlsruhe Institute of Technology

The interplay of vertical velocity, ice microphysics, and radiative heating

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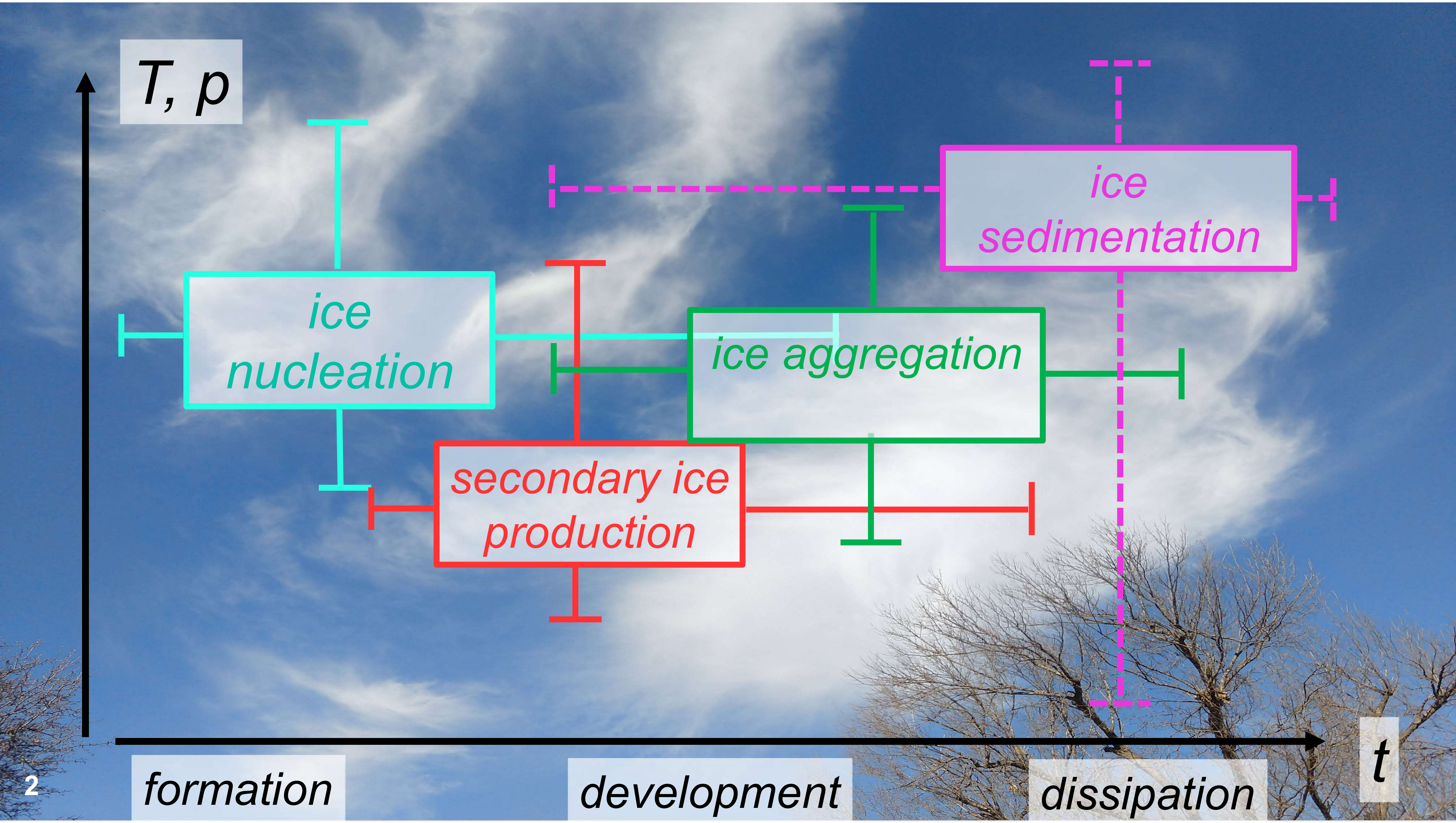


T, p

ice nucleation

secondary ice production

ice aggregation

ice sedimentation

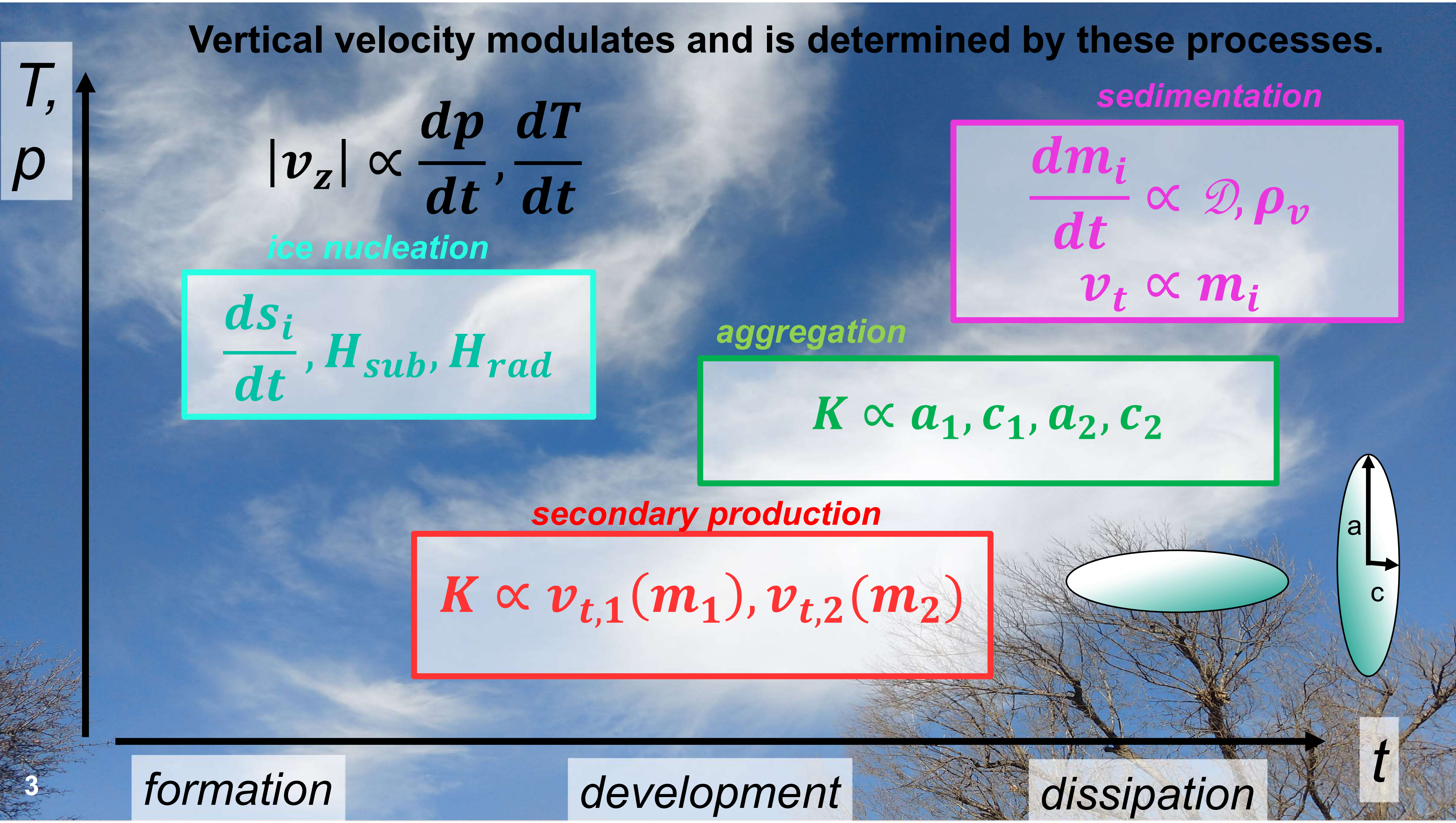
t

formation

development

dissipation

Vertical velocity modulates and is determined by these processes.



$$|v_z| \propto \frac{dp}{dt}, \frac{dT}{dt}$$

ice nucleation

$$\frac{ds_i}{dt}, H_{sub}, H_{rad}$$

sedimentation

$$\frac{dm_i}{dt} \propto \mathscr{D}, \rho_v$$

$$v_t \propto m_i$$

aggregation

$$K \propto a_1, c_1, a_2, c_2$$

secondary production

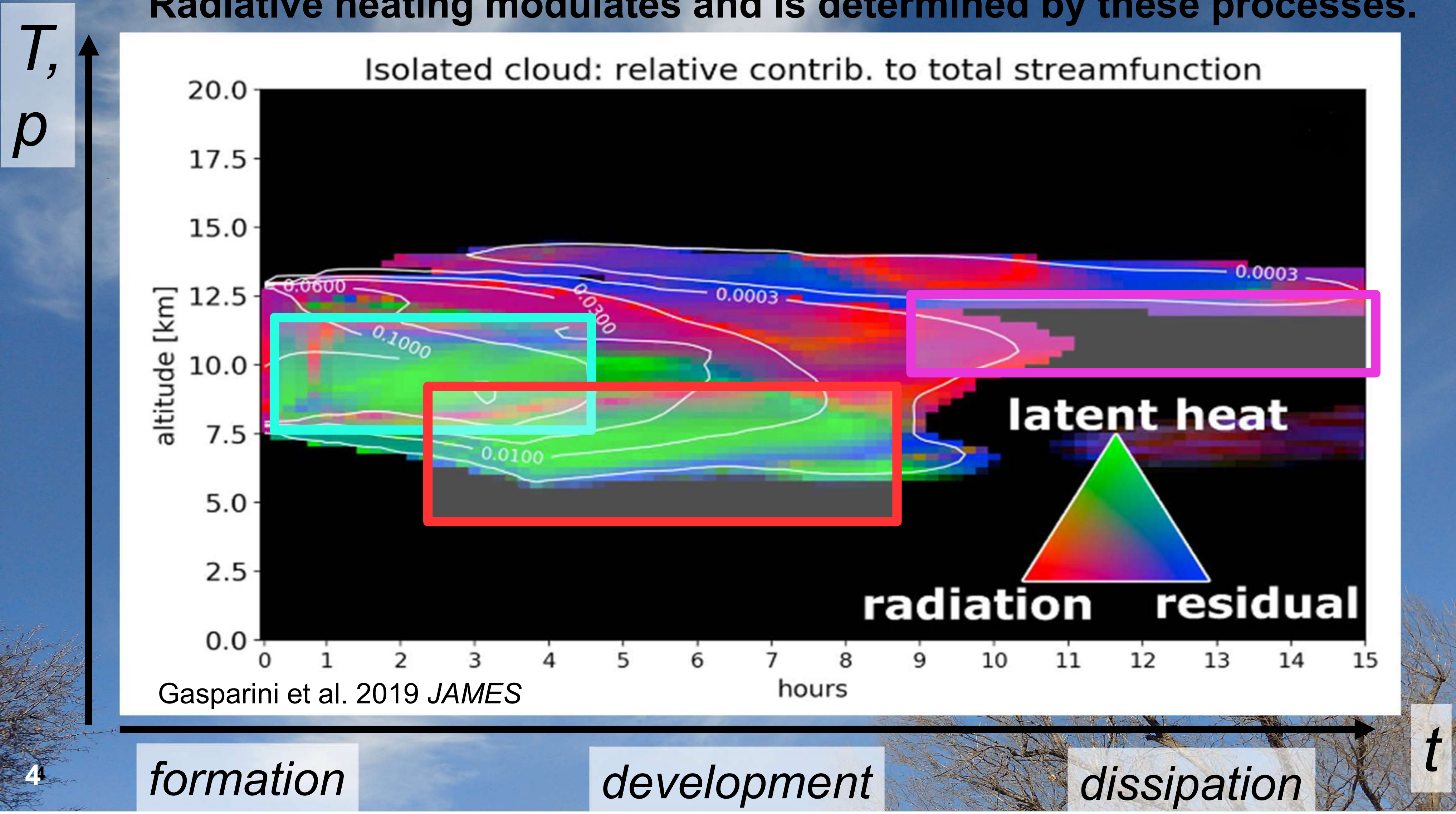
$$K \propto v_{t,1}(m_1), v_{t,2}(m_2)$$

formation

development

dissipation

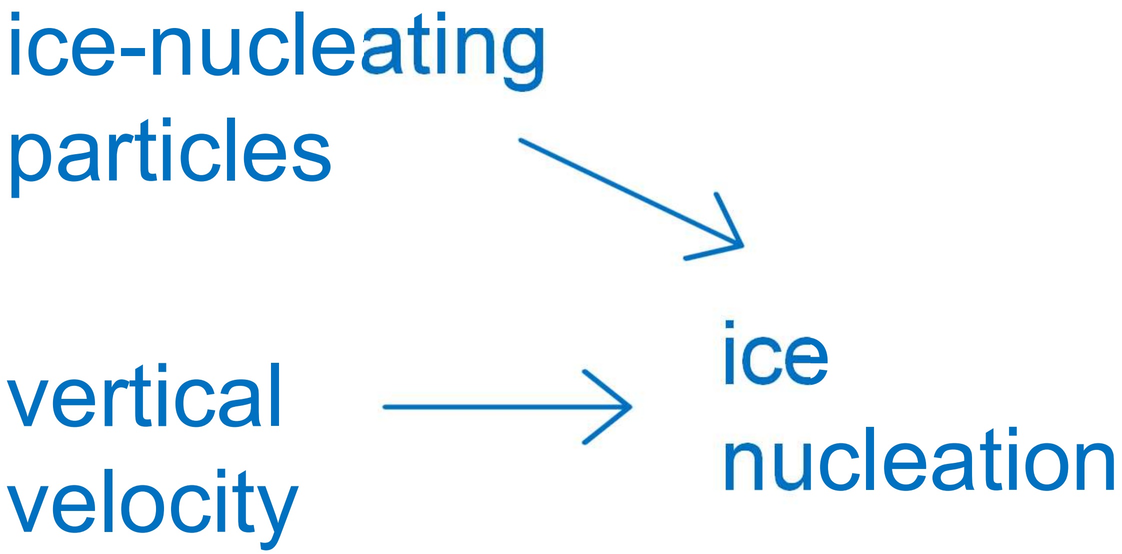
Radiative heating modulates and is determined by these processes.



Gasparini et al. 2019 *JAMES*

formation *development* *dissipation*

PART 1

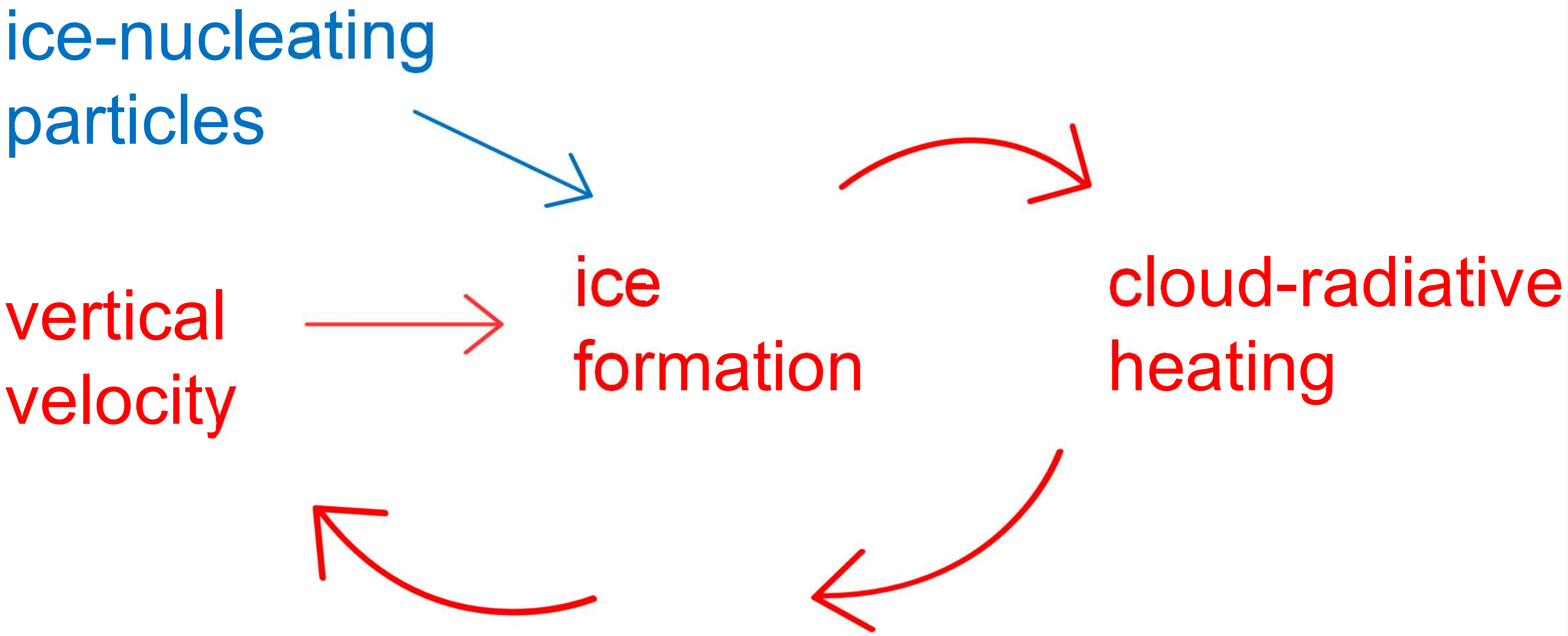


ice-nucleating particles

vertical velocity

ice nucleation

PART 1 **PART 2**



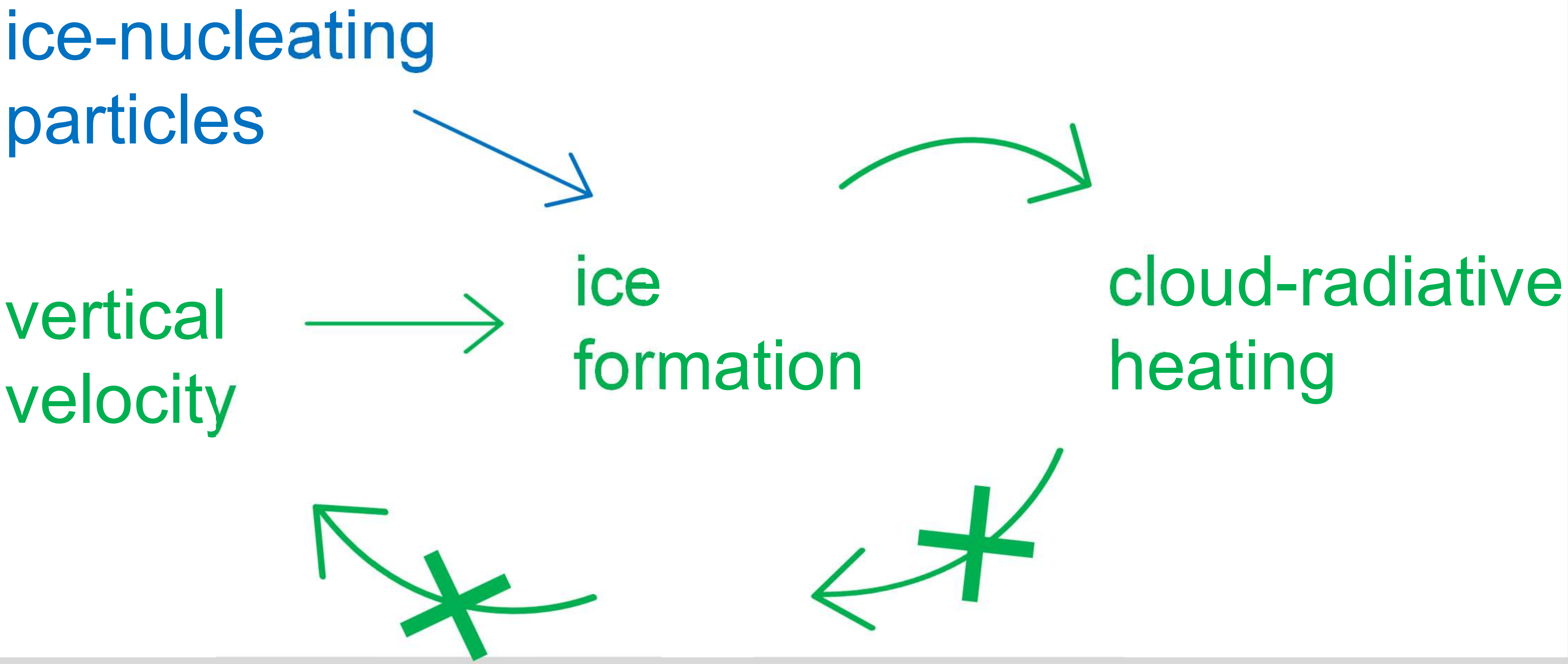
ice-nucleating particles

vertical velocity

ice formation

cloud-radiative heating

PART 1 **PART 2** **PART 3**



ice-nucleating particles

vertical velocity

ice formation

cloud-radiative heating

PART 1

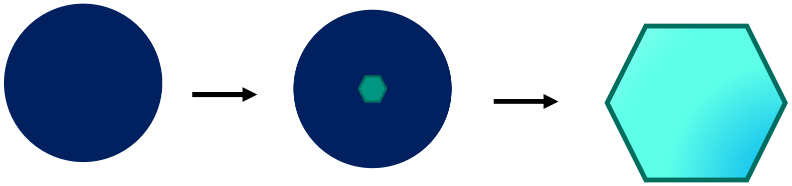
ice-nucleating particles

vertical velocity

ice formation

How do we represent ice formation in the atmosphere?

How do we represent ice formation in the atmosphere?



Homogeneous nucleation

Heterogeneous nucleation

Supersaturation is key ....

$J(s_i)$

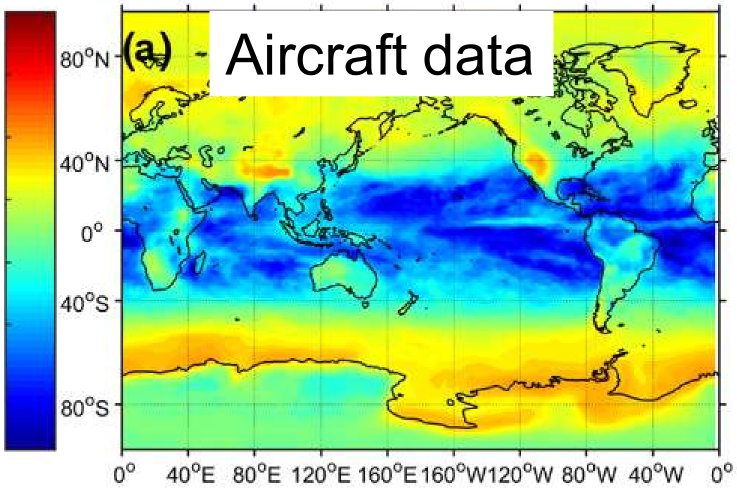
$$\frac{ds_i}{dt} = \text{source from expansion cooling} - \text{sink to ice crystal growth}$$

$$N_i = f(v_z,\ T,\ N_{\mathrm{Sulf}},\ N_{\mathrm{BC}},\ N_{\mathrm{Dust}},\ N_{\mathrm{Org}})$$

Ice crystal numbers vary dramatically in formulations from different sources.

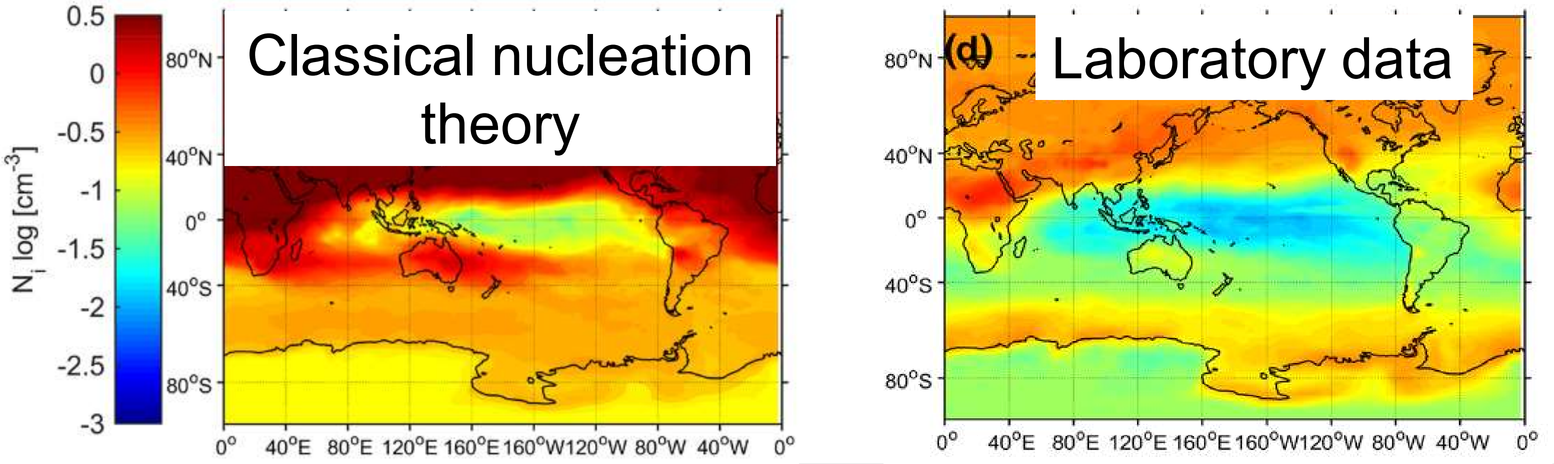
more ice crystals per volume air

less ice crystals per volume air



Aircraft data

Annual average from the Community Atmosphere Model 5.0 at the 232-hPa level



Classical nucleation theory

Laboratory data

Sullivan et al. (2015) *ACP*

How can we better understand these differences?

How can we better understand these ice crystal number differences *in a computationally efficient and interpretable manner?*

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$$N_i = f(\underbrace{v_z,\ T,\ N_{\mathrm{Sulf}},\ N_{\mathrm{BC}},\ N_{\mathrm{Dust}},\ N_{\mathrm{Org}}}_{\text{Automatic differentiation}})$$

$$\left(N_i, \frac{\partial N_i}{\partial v_z}, \frac{\partial N_i}{\partial T}, \frac{\partial N_i}{\partial N_{\mathrm{Sulf}}}, \frac{\partial N_i}{\partial N_{\mathrm{BC}}}, \frac{\partial N_i}{\partial N_{\mathrm{Dust}}}, \frac{\partial N_i}{\partial N_{\mathrm{Org}}}\right) =$$

$$f(v_z,\ T,\ N_{\mathrm{Sulf}},\ N_{\mathrm{BC}},\ N_{\mathrm{Dust}},\ N_{\mathrm{Org}})$$

We can use sensitivities to define ‘attribution metrics’.

$$\xi_{x_j}^{(N_i)} = \frac{\overset{\text{sensitivity}}{\boxed{\overline{(\partial N_i/\partial x_j)}^2}}\,\overset{\text{input variance}}{\boxed{\sigma_{x_j}^2}}}{\sum_{j=1}^{J} \overline{(\partial N_i/\partial x_j)}^2 \sigma_{x_j}^2}$$

0 % - x_j is not linked to temporal variability in N_i

100 % - all temporal variability in N_i is linked to x_j

x_j

grid cells colored by input with largest attribution

🟨 Vertical velocity

v_z

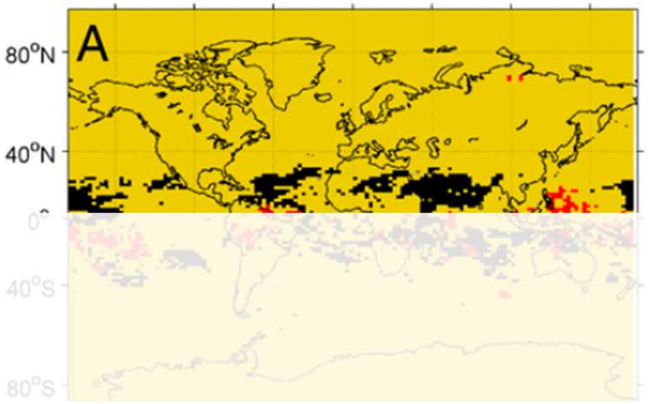
🟥 Sulfate particles

N_{Sulf}

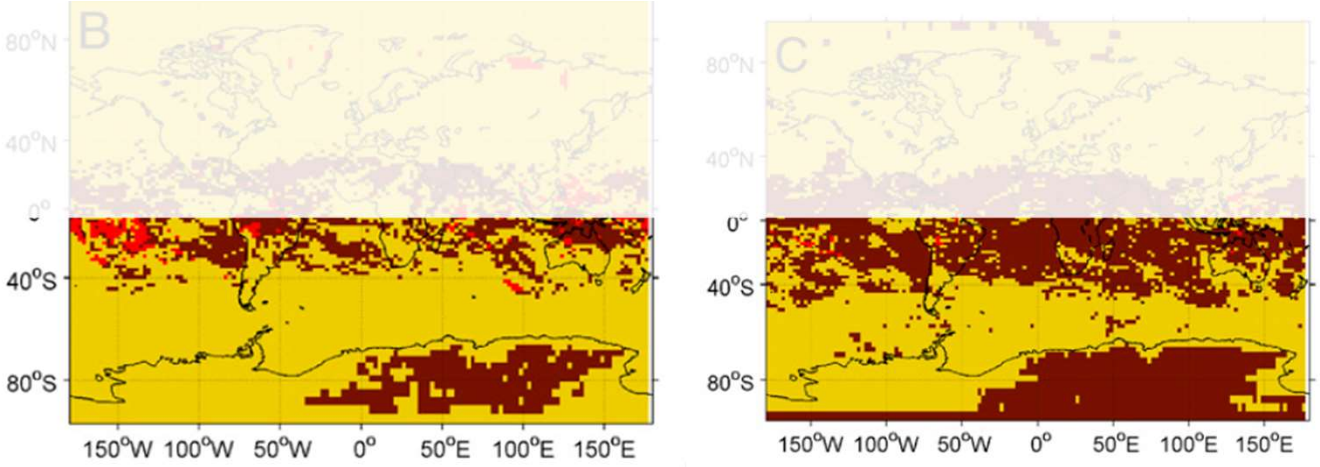
N_{Dust}

▨ Large dust

N_{Dust}



Variability in vertical velocities is crucial to represent ice nucleation.



Sullivan et al. (2016) *PNAS*

We can use sensitivities to define ‘attribution metrics’.

sensitivity

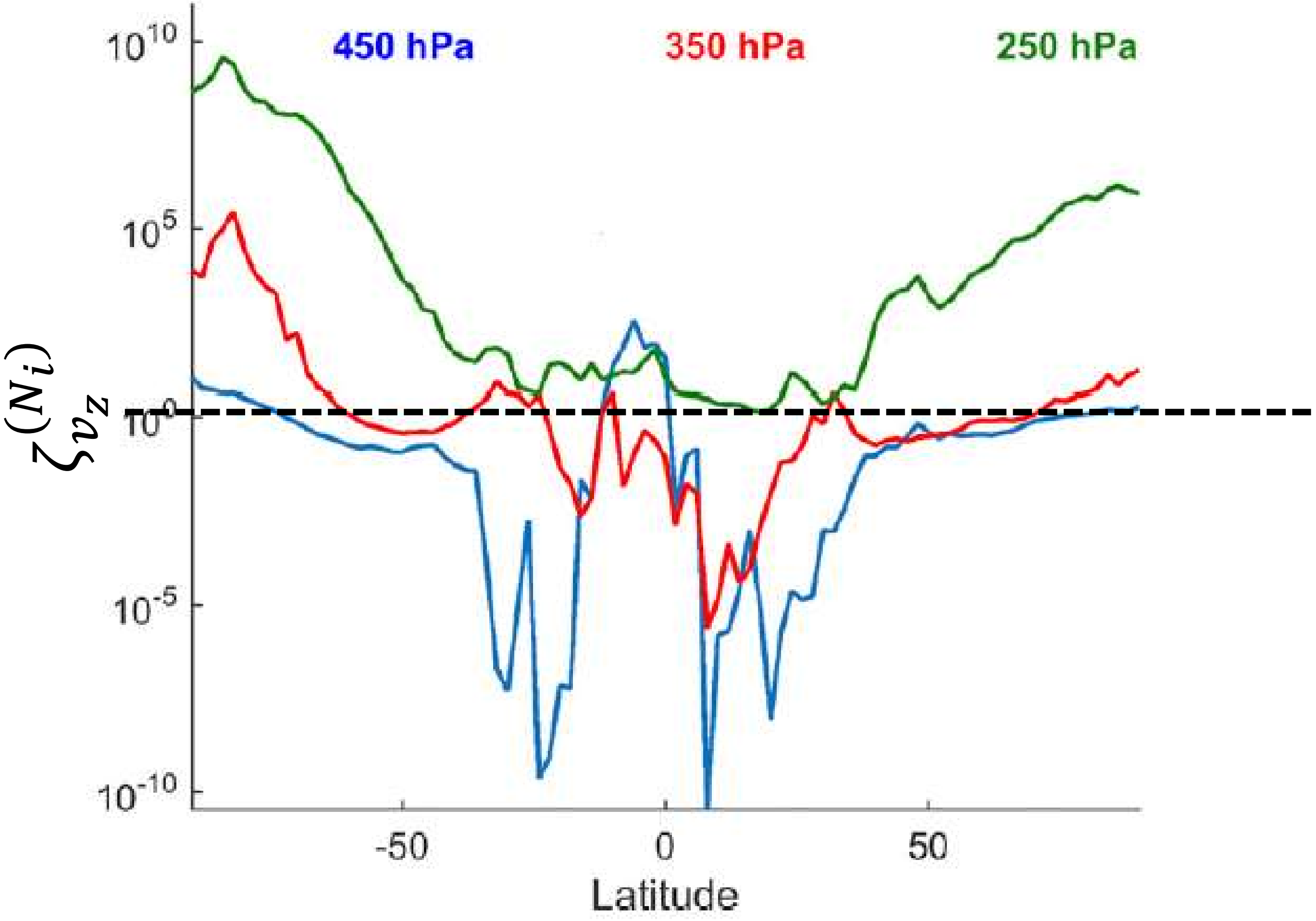
$$\zeta_{x_j}^{(N_i)} = \frac{\boxed{(\overline{\partial N_i/\partial x_j})^2}}{\boxed{\sigma_{x_j}^2}} \frac{\overline{x_j}^4}{\overline{N_i}^2}$$

input variance

<< 1 – fluctuations in x_j are large

>> 1 – any fluctuations in x_j are amplified

>> 1 – large sensitivity to v_z



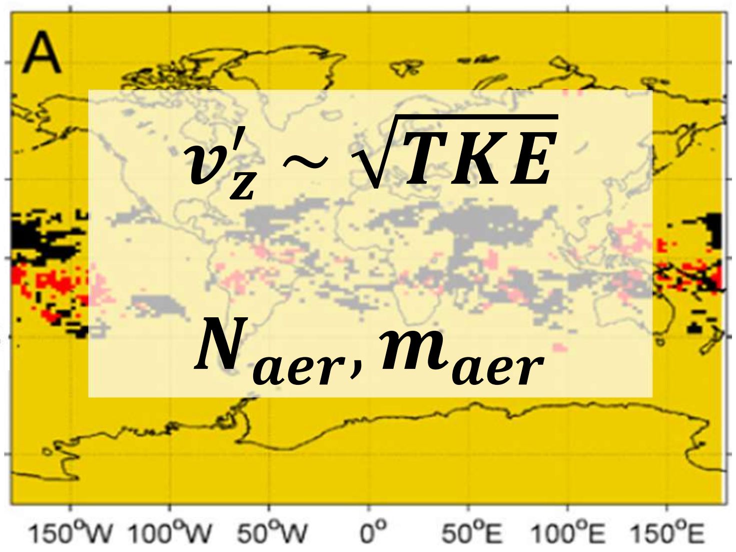
At higher latitudes and altitudes, sensitivity to vertical velocity causes its large attribution.

At lower latitudes and altitudes, variance in vertical velocity cause its large attribution.

<< 1 – large fluctuations in v_z

Subgrid-scale variability in v_z and aerosol module alter model attributions.

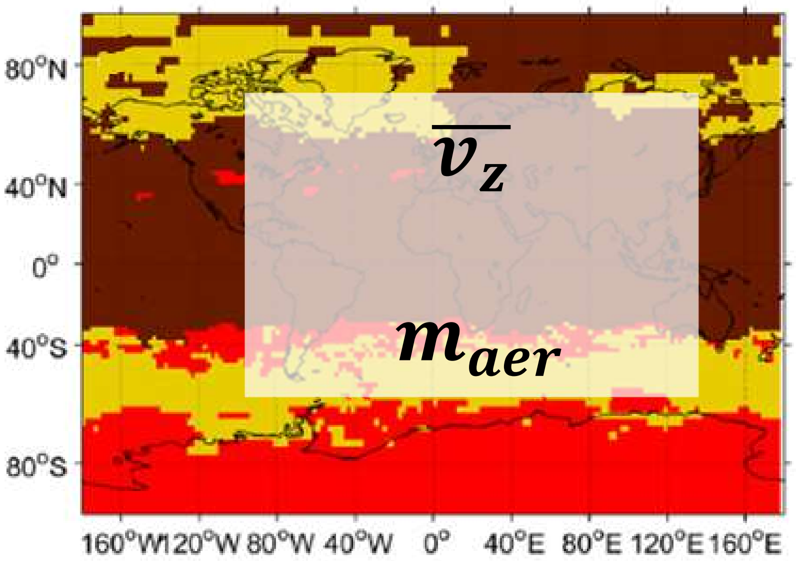
- 🟨 Vertical velocity v_z
- 🟥 Sulfate particles N_{Sulf}
- 🟫 Small dust particles N_{Dust}
- ⬛ Large dust N_{Dust}



$$v'_z \sim \sqrt{TKE}$$

$$N_{aer}, m_{aer}$$

Community Atmosphere Model 5.0

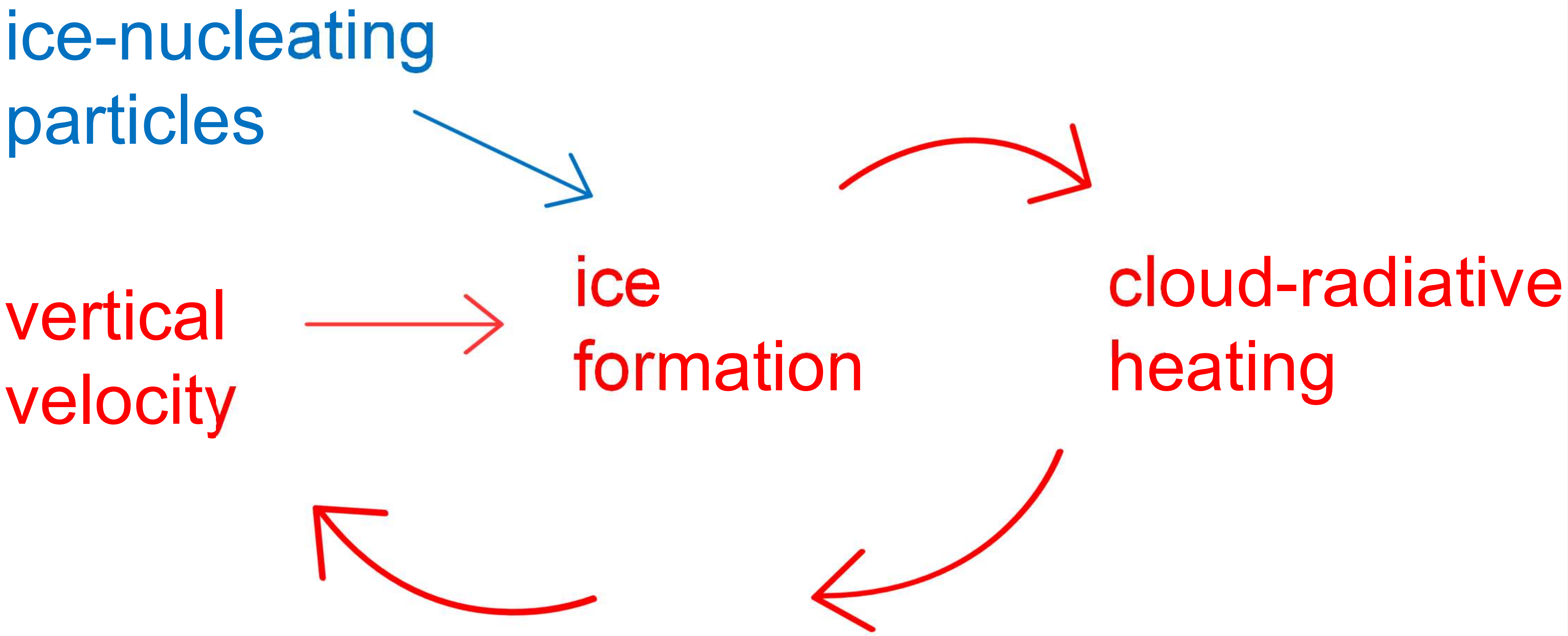


$$\overline{v_z}$$

$$m_{aer}$$

Goddard Earth-Observing Model

PART 1 **PART 2**



ice-nucleating particles

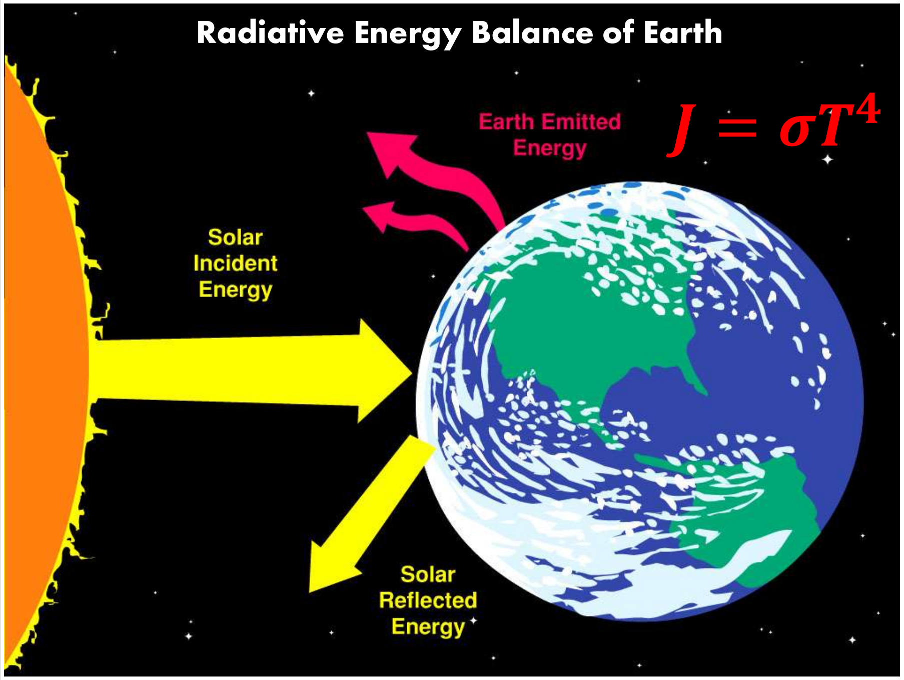
vertical velocity

ice formation

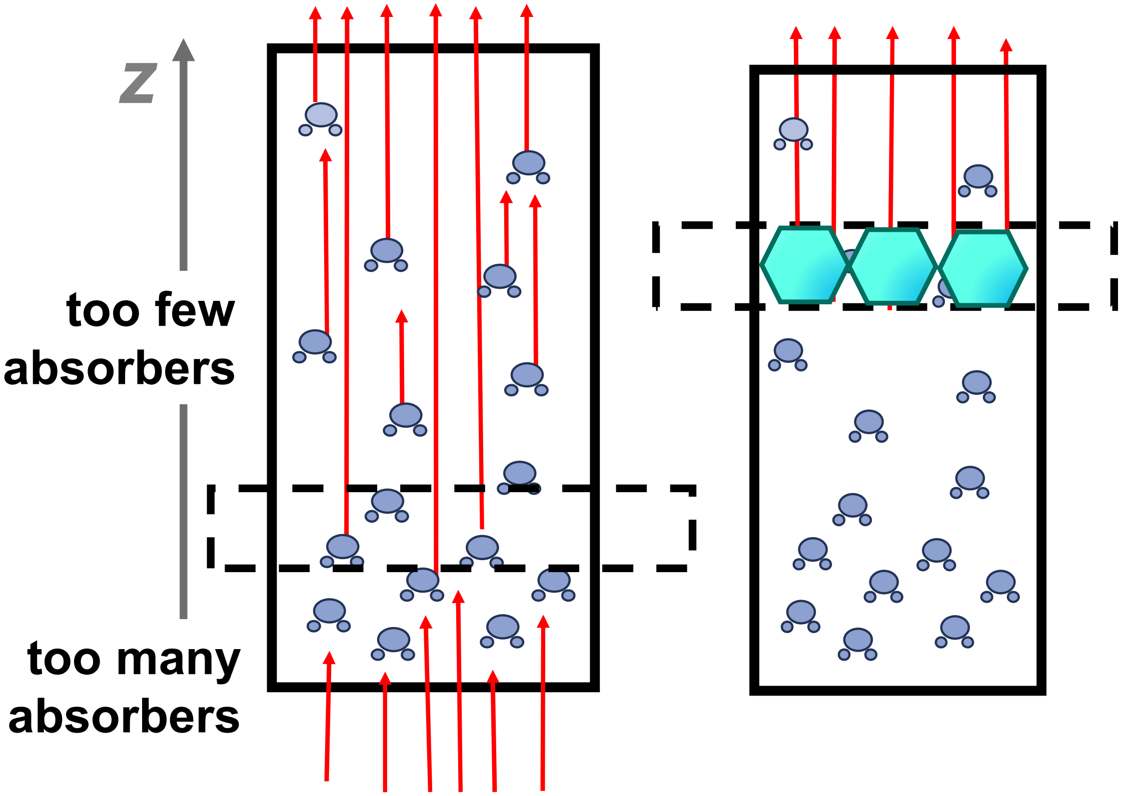
cloud-radiative heating

Ice cloud emits less radiation than clear sky.

less emitted infrared radiation



$J = \sigma T^4$

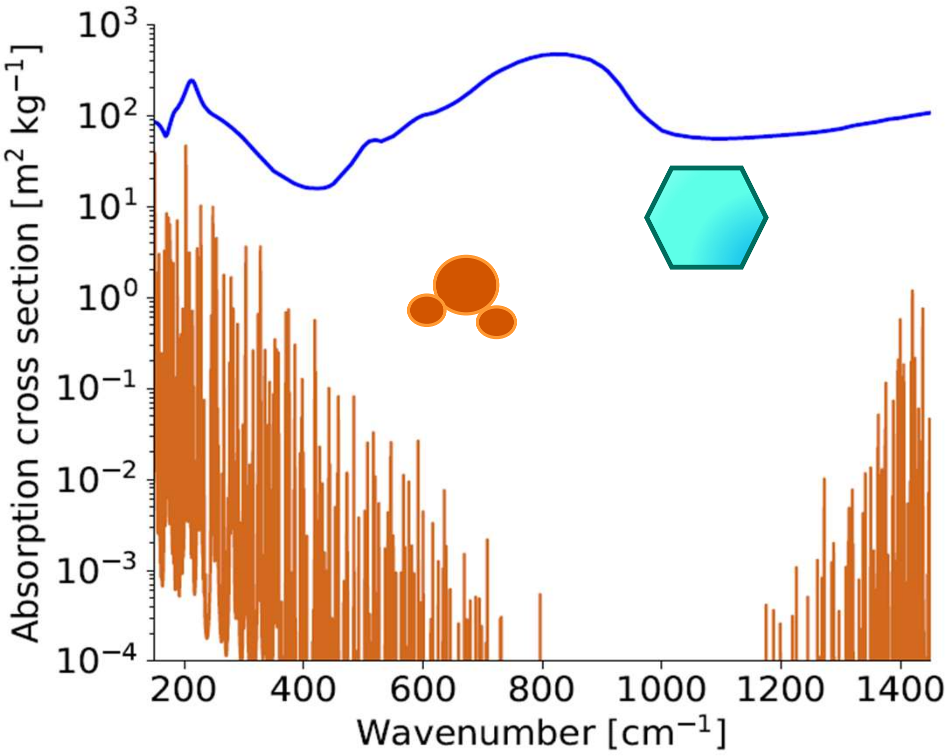


too few absorbers

too many absorbers

Column schematics adapted from N. Jeevanjee

Ice cloud absorbs more radiation than clear sky.

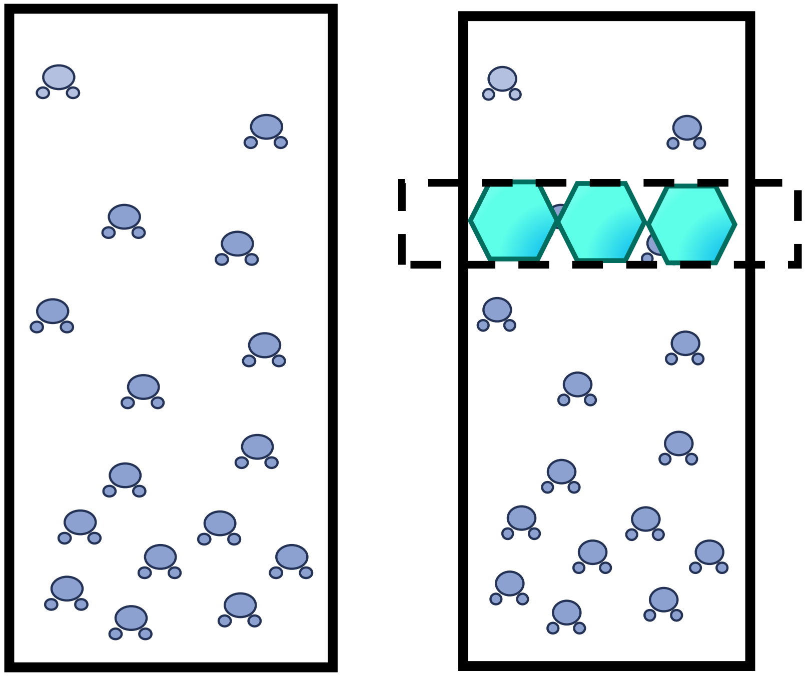


Ice data from Warren and Brandt 2008; wv data from HITRAN.

less emitted infrared radiation

and

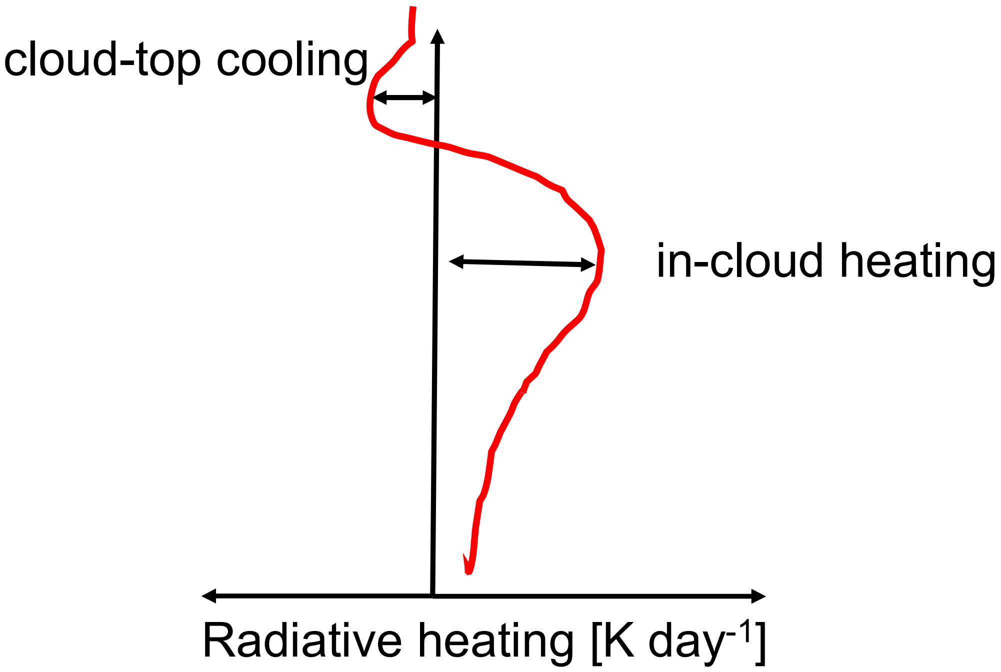
strong atmospheric heating

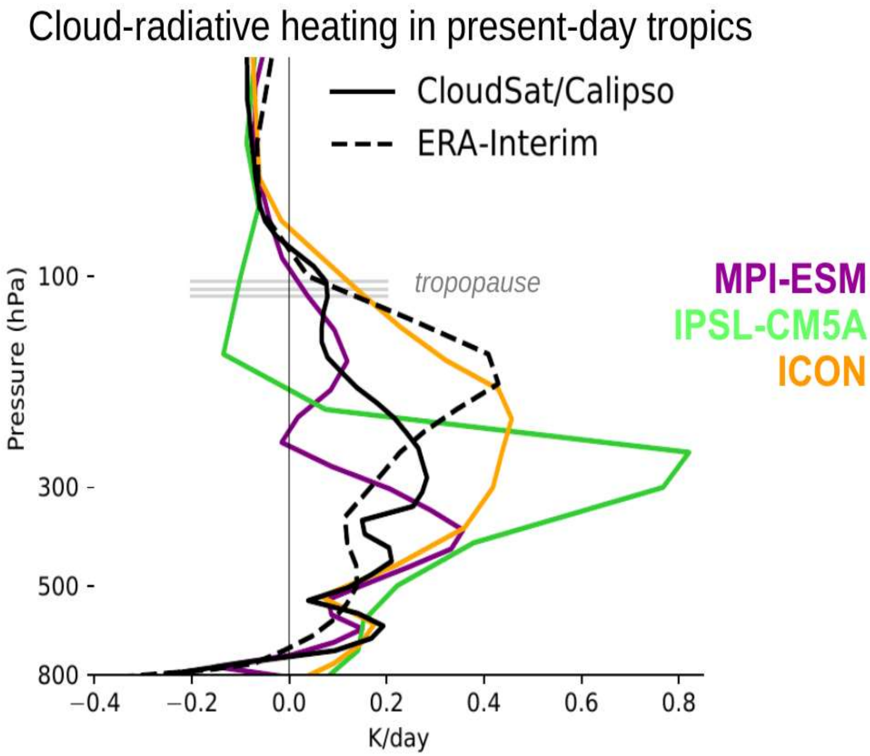


less emitted infrared radiation

and

strong atmospheric heating

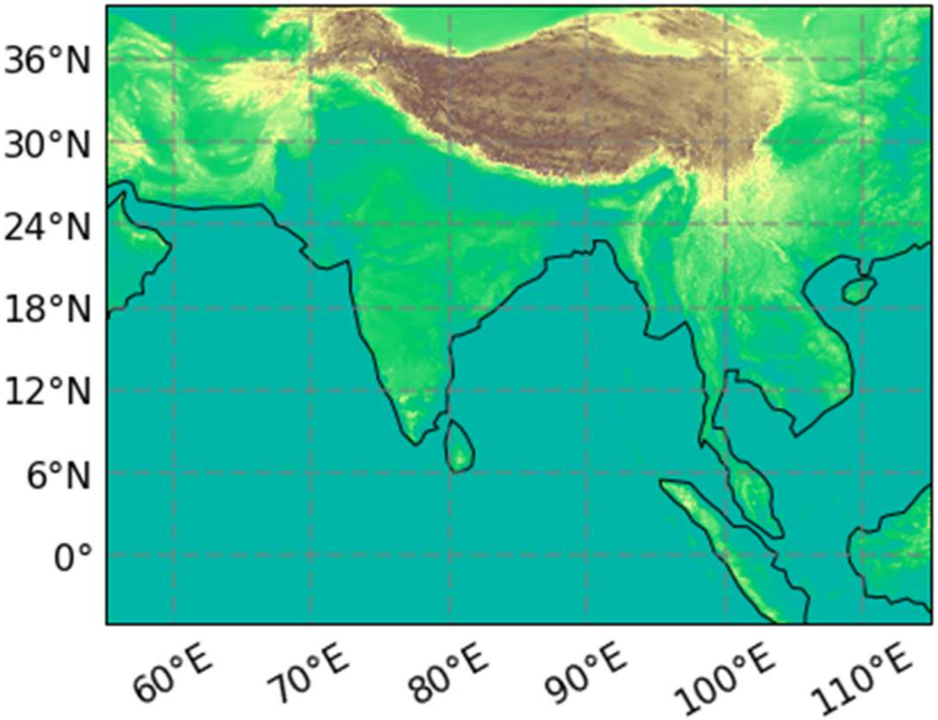



Cloud-radiative heating in present-day tropics

A. Voigt, N. Albern, G. Papavasileiou (2019) *J. Clim.*

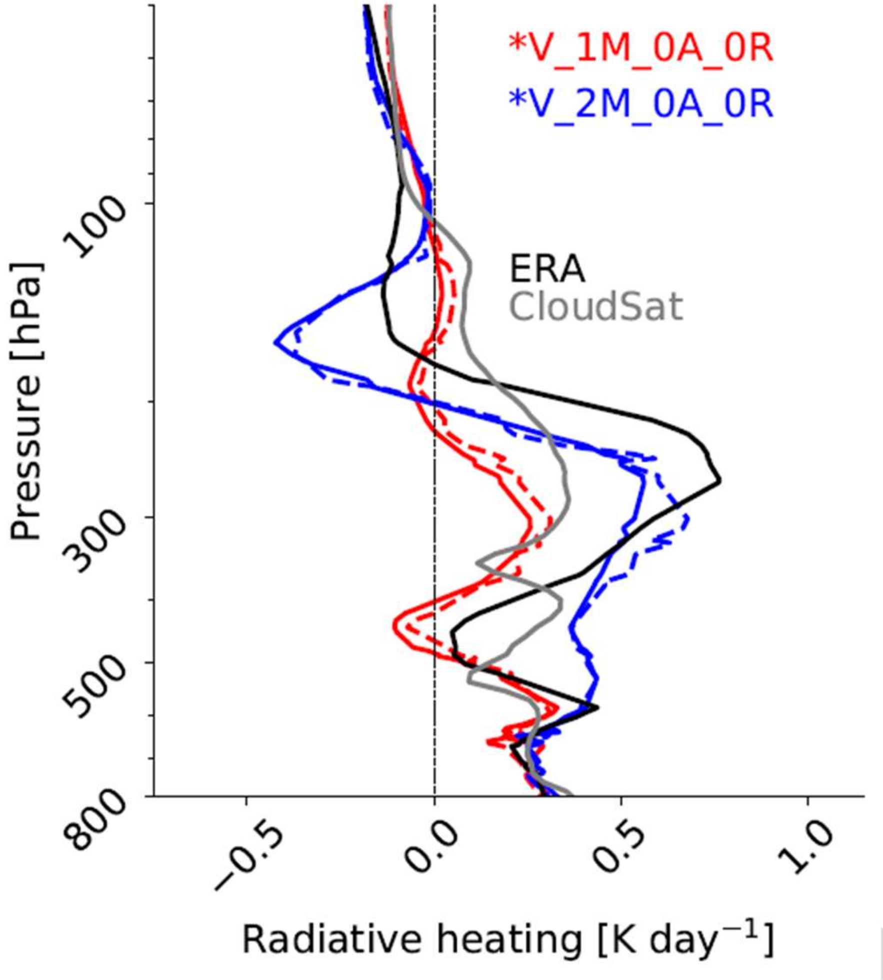
We investigate four microphysical switches in storm-resolving simulations.

M	One-moment or two-moment
V	Default or higher vertical resolution
A	Aerosol dependence or not
R	Consistent size (effective Radius) of ice crystals between microphysics and radiation or not



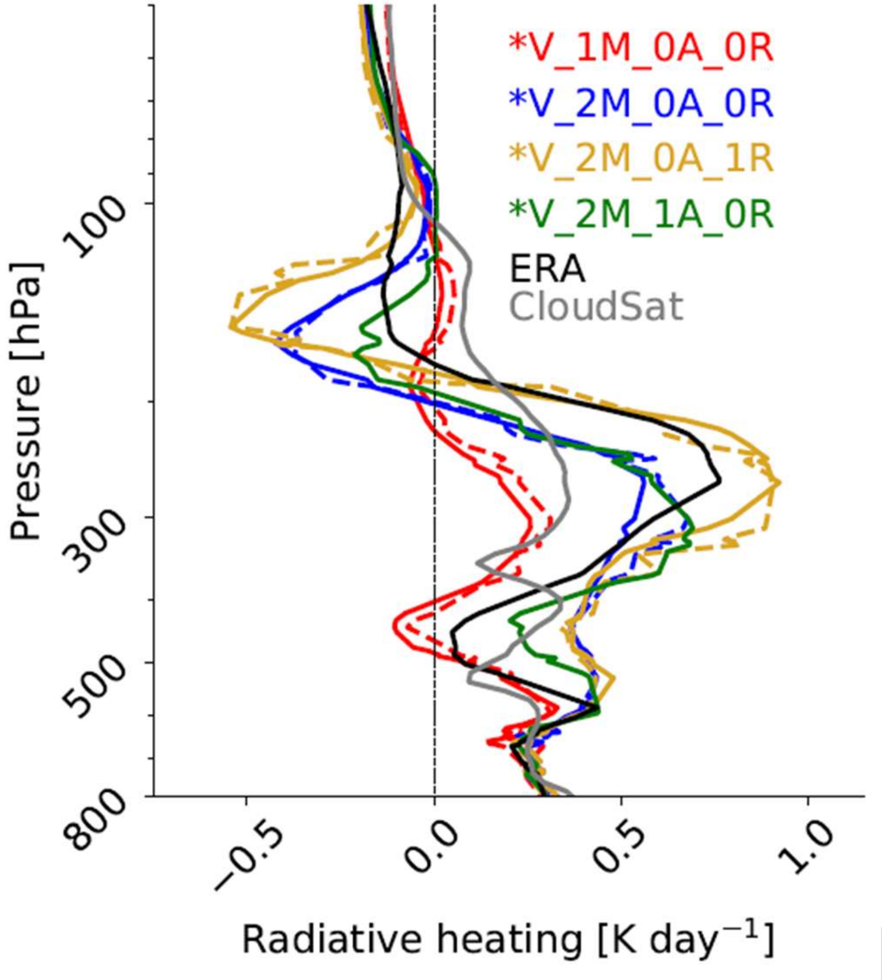
Icosahedral Nonhydrostatic Model, 2.5-km equivalent resolution, 3 days of simulation, 24-second time step

M – microphysics **V** – vert res **R** – ice crystal size **A** - aerosol

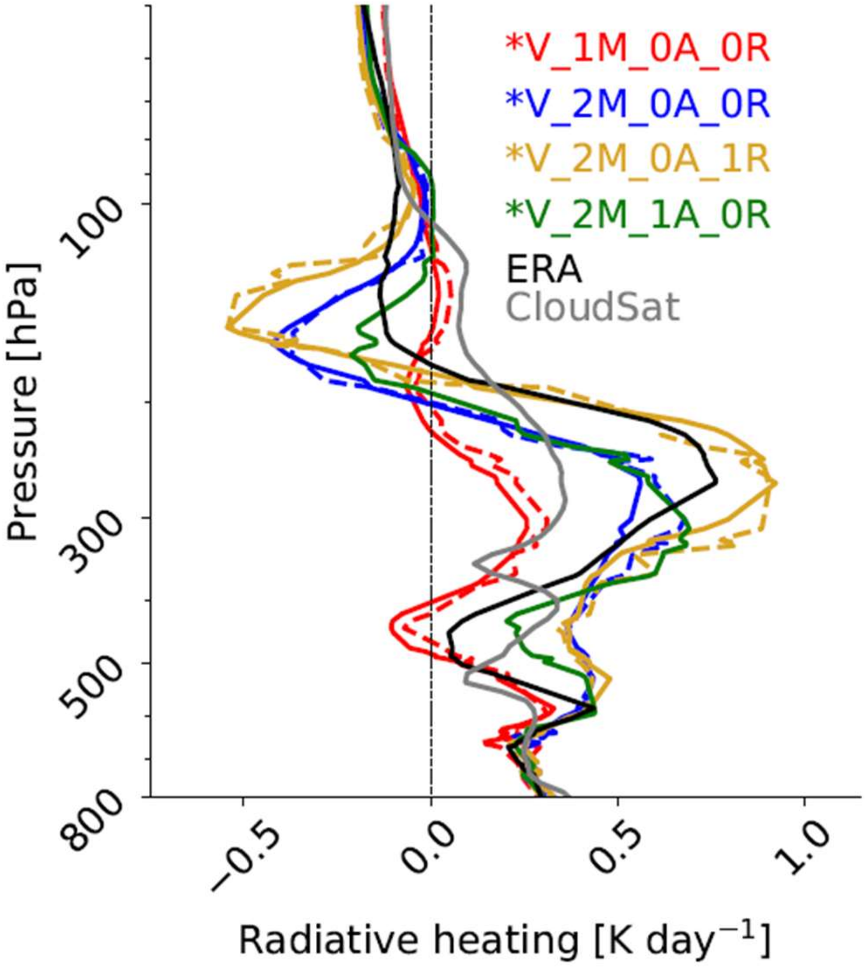


- **Reanalysis and satellite profiles do not agree.**
- **Vertical resolution has little impact.**
- **In-cloud heating is almost 2 times larger from 1M → 2M.**
- **Cloud-top cooling is almost 10 times larger.**

M – microphysics **V** – vert res **R** – ice crystal size **A** - aerosol



- **Heating-cooling dipole increases by a factor of 2 with consistent ice crystal size.**
- **Heating-cooling dipole decreases above 200 hPa and below 400 hPa with aerosol dependence.**

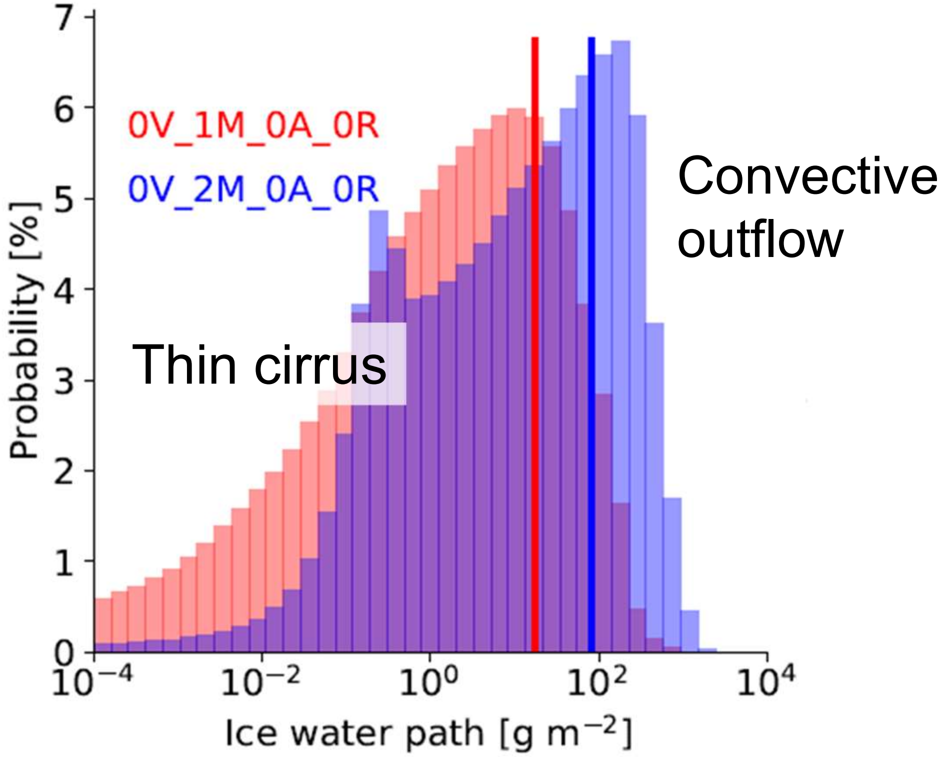


- ***We can kind of generate whatever we want with ice microphysics switches...***

- Cloud-top cooling is almost 10 times larger.
- Heating-cooling dipole increases by a factor of 2 with consistent ice crystal size.
- Heating-cooling dipole de an aerosol dependence.

… but we can also understand why.

In-cloud heating is almost 2 times larger from 1M → 2M.



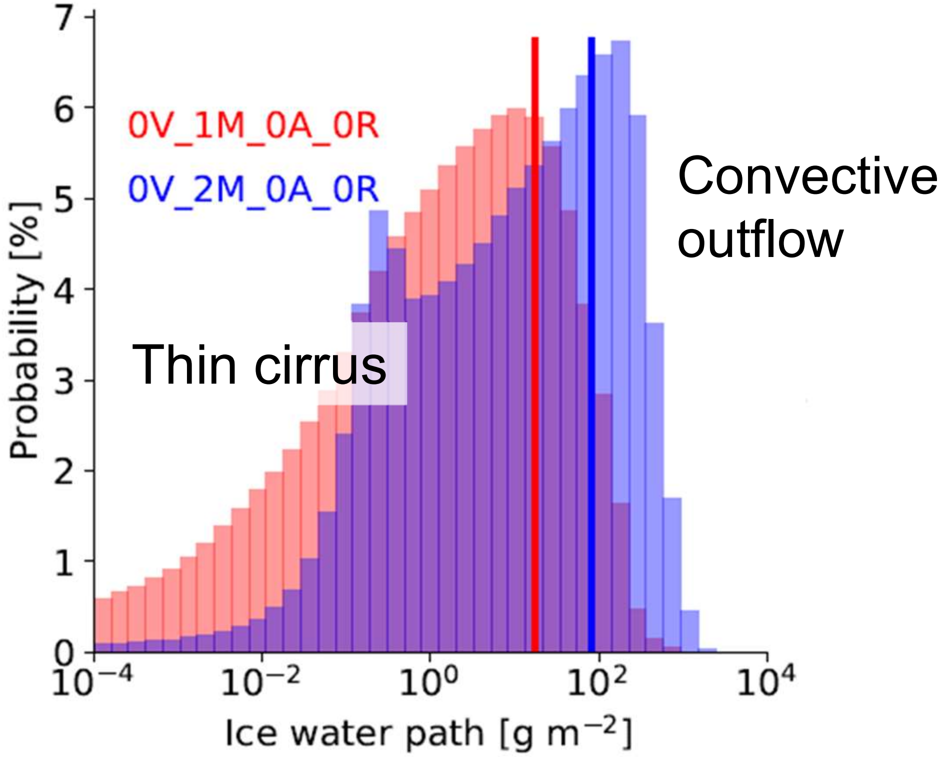
Unimodal versus bimodal IWP distribution

$$\frac{H_{2M}}{H_{1M}} \sim \frac{1 - \exp[-\kappa_{i,2M} \int \rho_{i,2M} dz']}{1 - \exp[-\kappa_{i,1M} \int \rho_{i,1M} dz']}$$

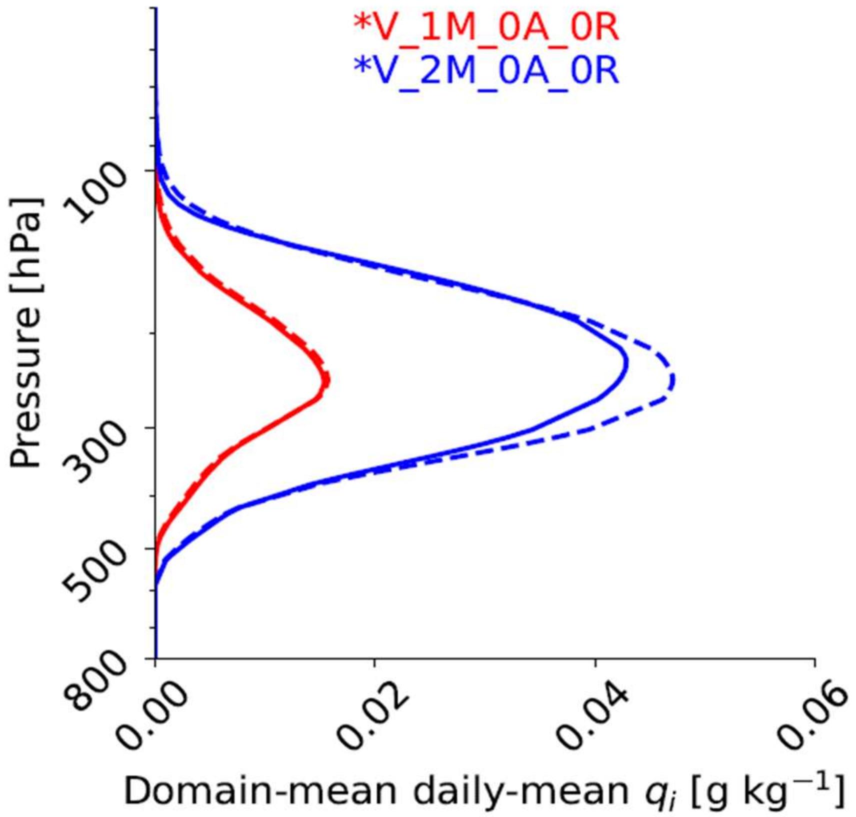
$$\sim \frac{1 - \exp[-100\ \mathrm{m}^2\ \mathrm{kg}^{-1} \cdot 0.08\ \mathrm{kg\ m}^{-2}]}{1 - \exp[-100\ \mathrm{m}^2\ \mathrm{kg}^{-1} \cdot 0.008\ \mathrm{kg\ m}^{-2}]}$$

$$\sim 2$$

In-cloud heating is almost 2 times larger from 1M → 2M.

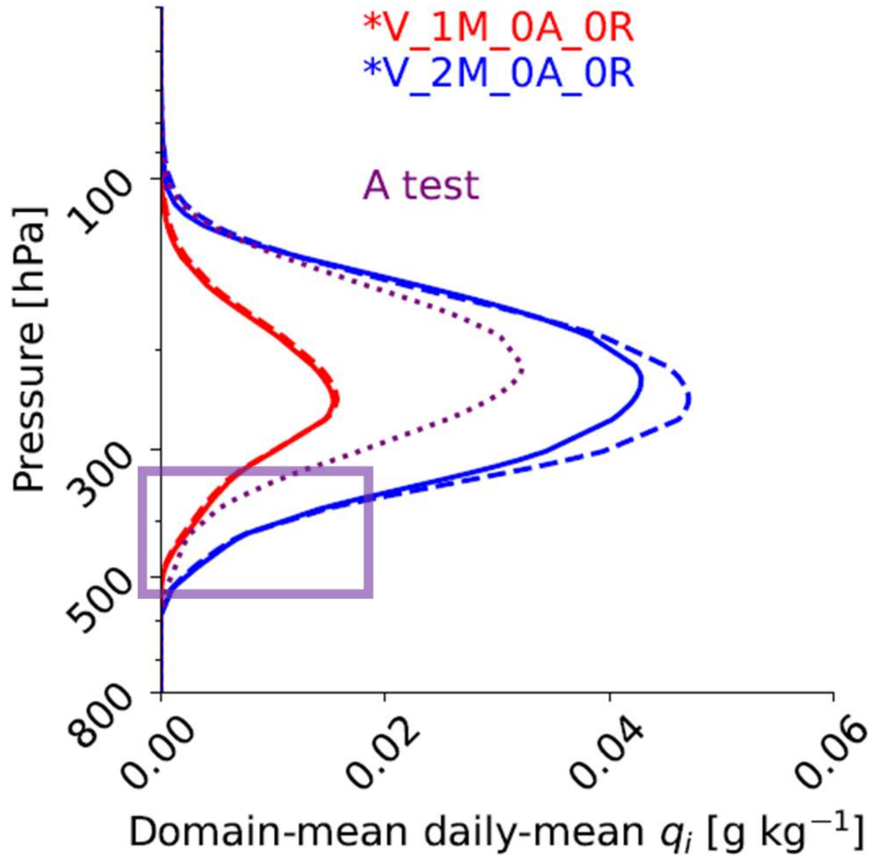


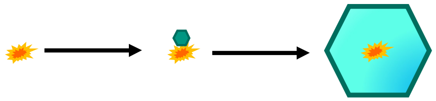
Unimodal versus bimodal IWP distribution



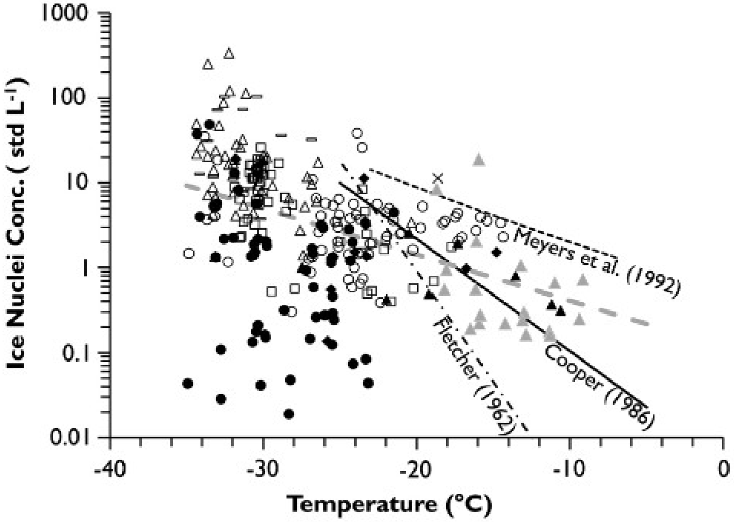
2M generates >4 times more ice *and* over a greater depth.

Why does 2M generate >4 times more ice? *low*





$$C_{\mathrm{INP}} = A\exp\left[-B(T-T_{min})^{C}\right]$$



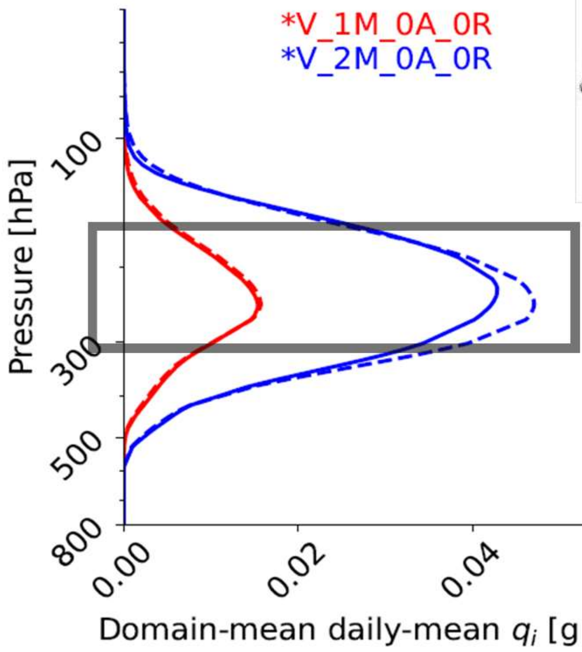
T_{min} = 237 K
A = 2.969 x 10^4 m$^{-3$}

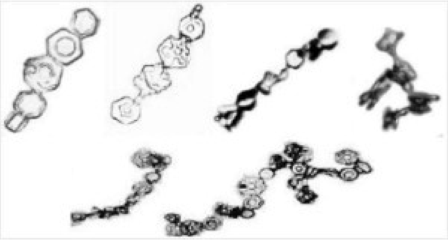
T_{min} = 237 K
A = 1.0 x 10^2 m^{-3}

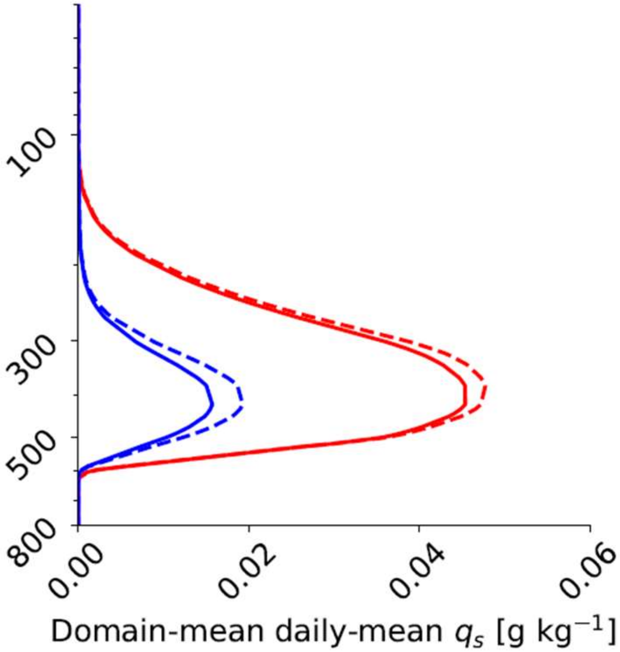
Parameters from Hande et al. 2015 *ACP* & Doms et al. 2005

Fig from DeMott et al. 2010 *PNAS*

Why does 2M generate >4 times more ice? *middle*







$$\frac{\partial m_a}{\partial t} \propto e_{ab} N_a m_b \mathrm{G}_1(\delta_a, \delta_b, \theta_a, \theta_b)$$

$$\frac{\partial m_b}{\partial t} = -\frac{\partial m_a}{\partial t}$$

$$\frac{\partial N_a}{\partial t} \propto -e_{ab} N_a N_b \mathrm{G}_2(\delta_a, \delta_b, \theta_a, \theta_b)$$

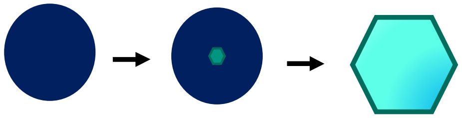
$$S_{au} = C(q_i - q_{i,0})$$

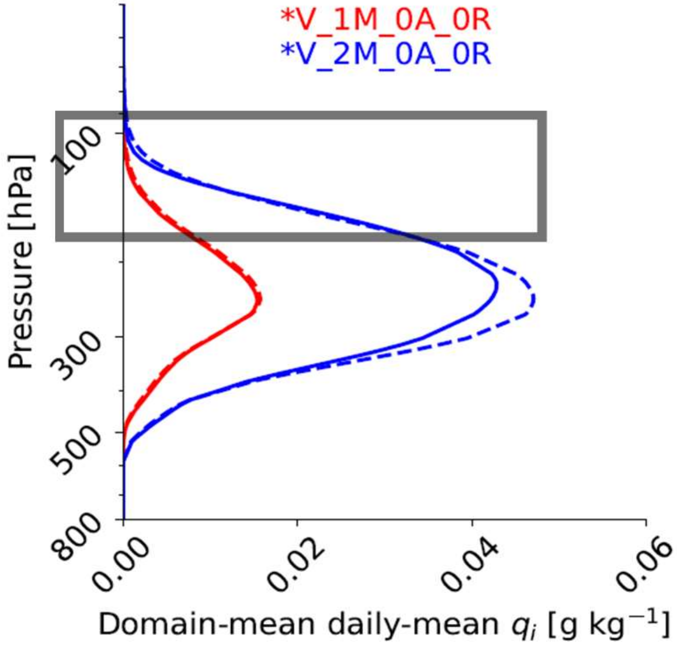
$C = 10^3$ s^{-1}

ice-to-snow conversion processes:

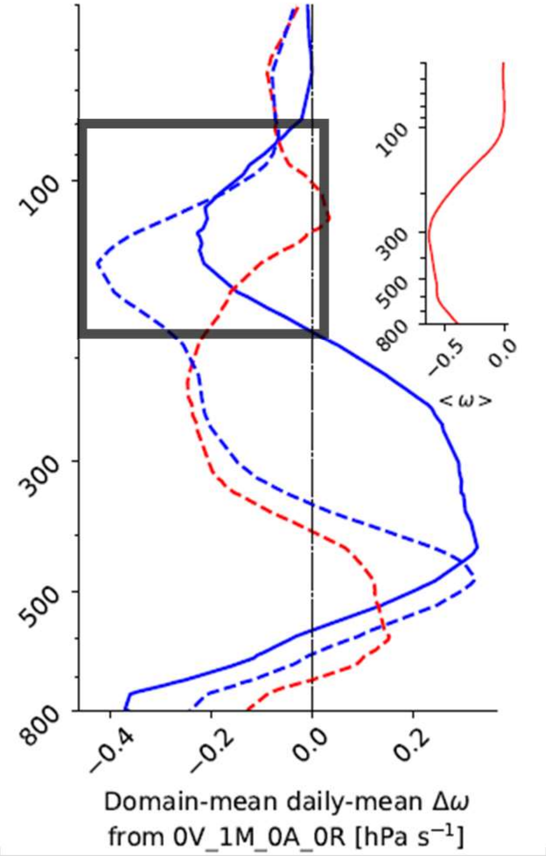
- **i + i = s (aggregation, ice autoconversion)**
- s + c = i (riming)
- i + s = s (aggregation)

Why does 2M generate >4 times more ice? *high*



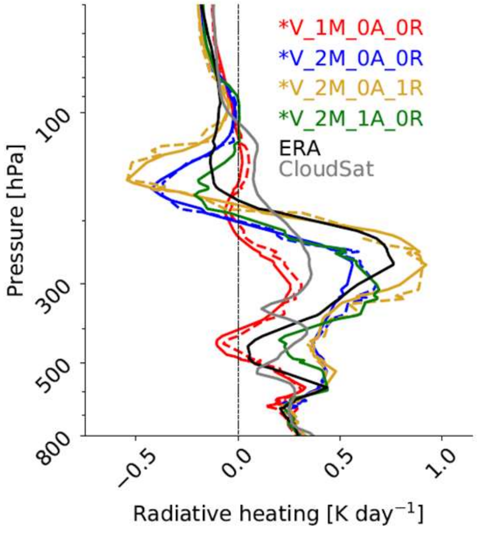


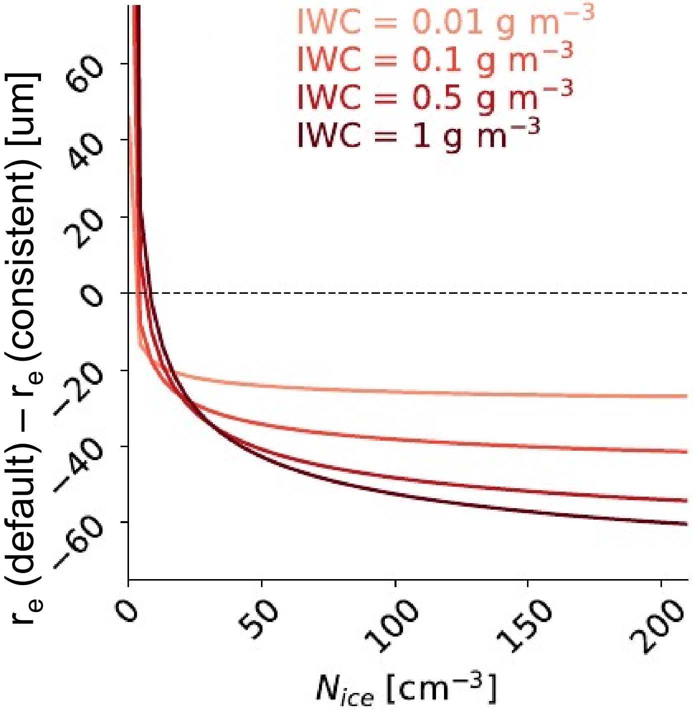
2 times larger UT mean vertical velocity in 2M

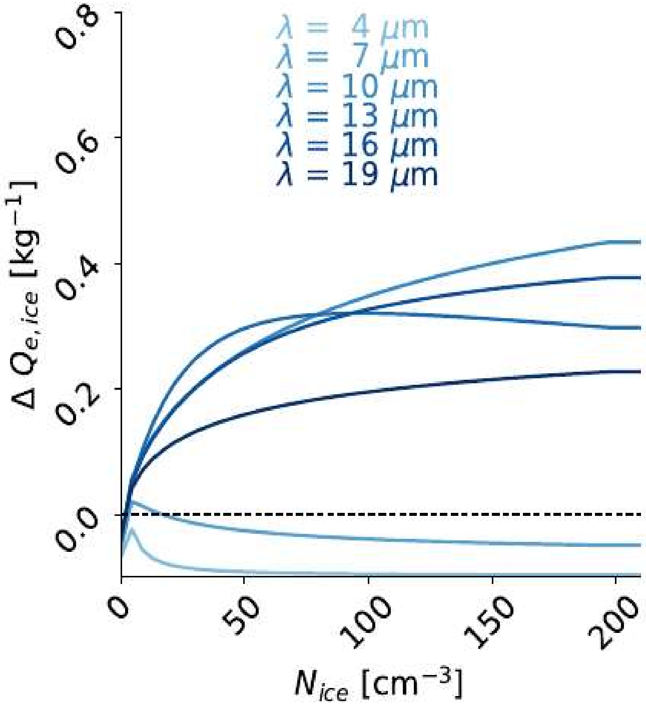


And what about the ice crystal effective radius?

$$\kappa_{i,1R} \sim Q_i \qquad H_{1R} \sim 1 - \exp\left[-\kappa_{i,1R} \int \rho_{i,1R}\, dz'\right]$$

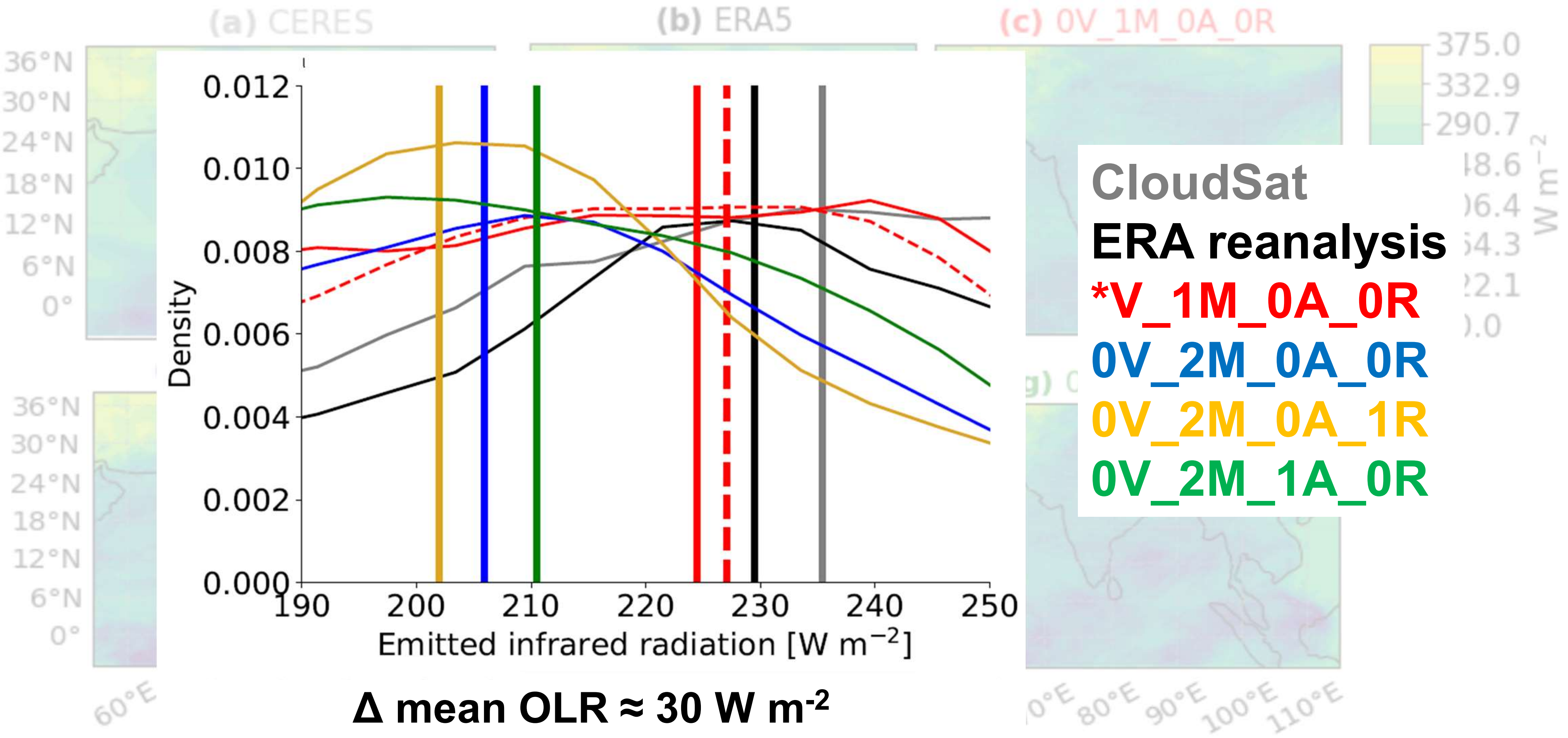






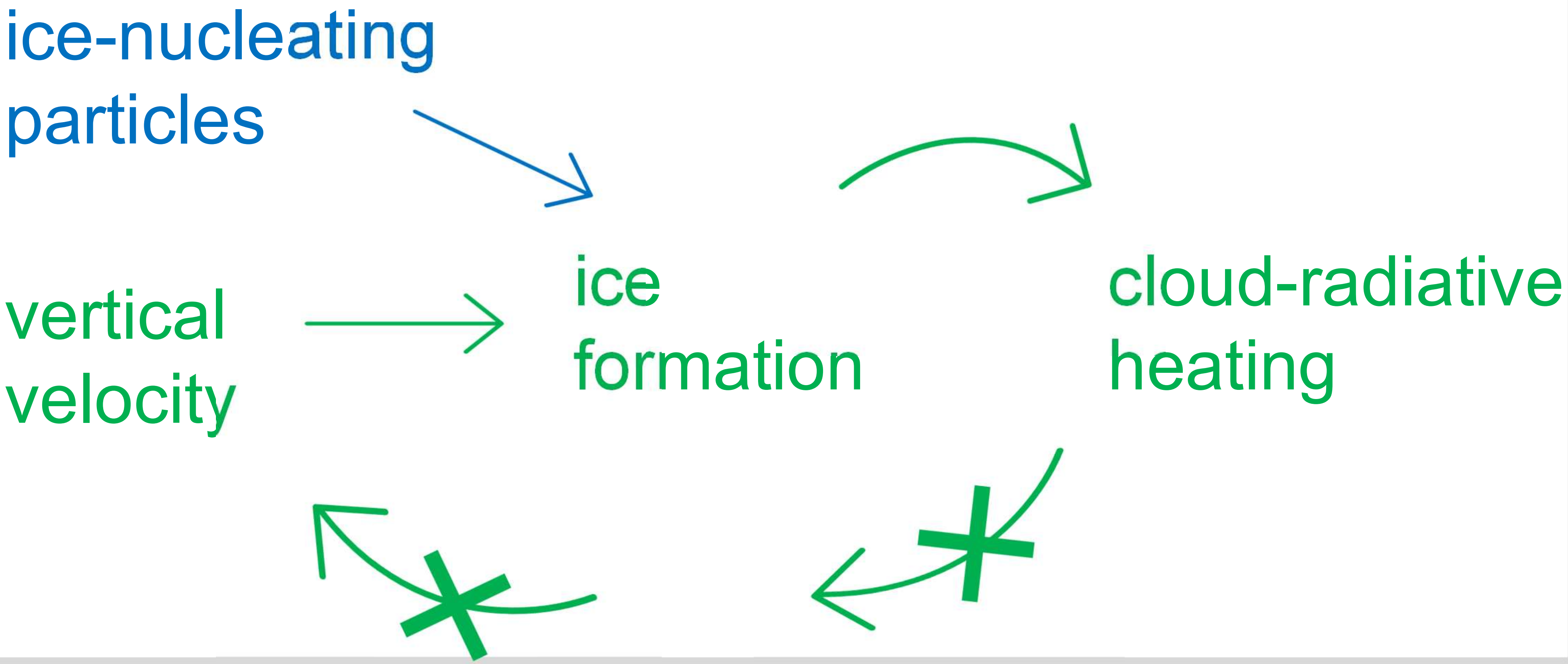
Here, increased extinction efficiency in the infrared window is key.

Fields of outgoing longwave radiation also change dramatically.



Δ mean OLR ≈ 30 W m^{-2}

PART 1 **PART 2** **PART 3**



ice-nucleating particles

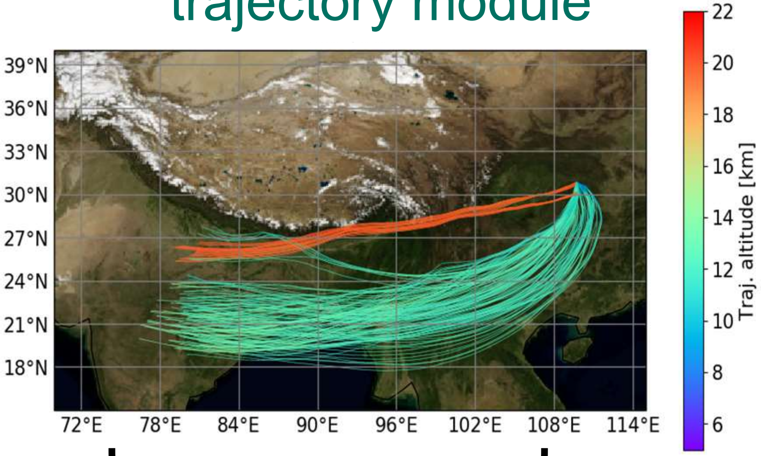
vertical velocity

ice formation

cloud-radiative heating

Dynamics is fixed along Lagrangian trajectories.

LAGRANTO-based trajectory module



CLaMS-ICE box model

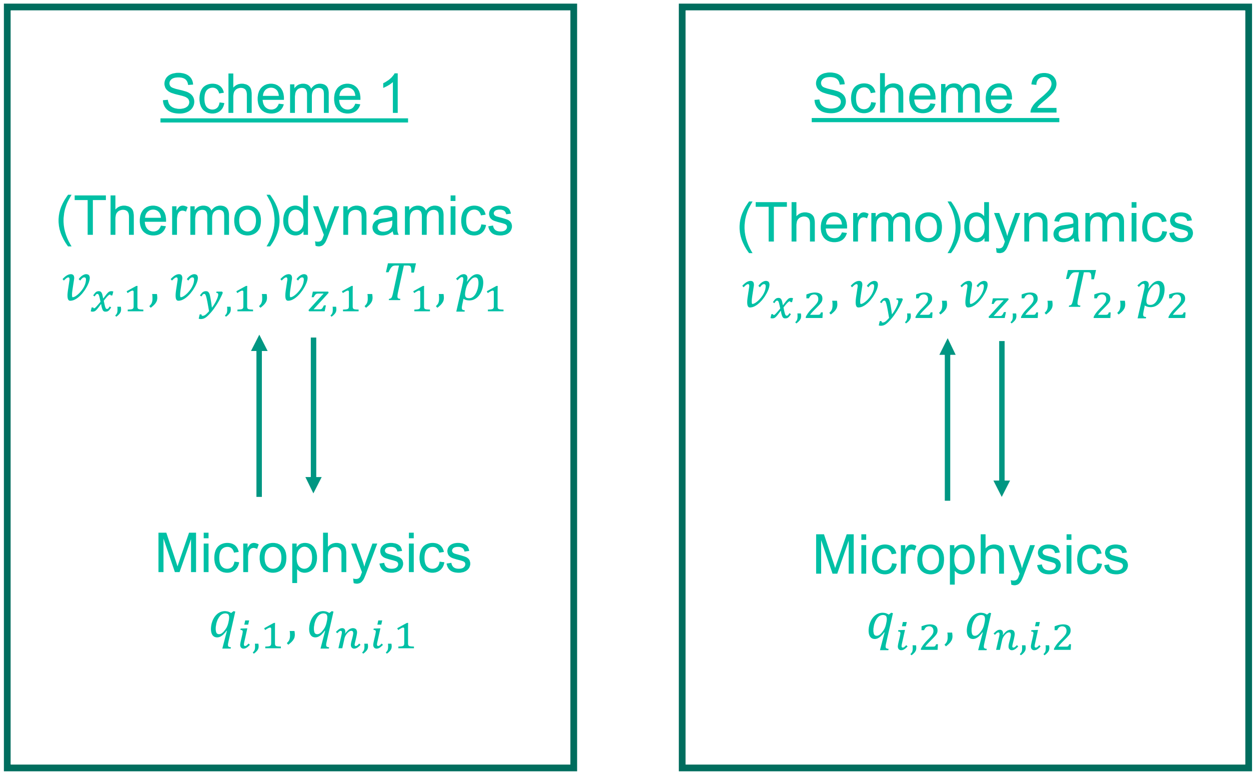
Offline radiative transfer code

```
CALL rrtm_interface(                                          &
     & current_date  ,horizontal mesh    , vertical levels    ,&
     & land fraction ,solar zenith angle ,                    ,&
     & diffuse and direct visible and near-IR albedos         ,&
     & land emissivity  ,full and half pressure levels        ,&
     & full and half temperature levels     ,vapor mixing ratio ,&
     & liquid mixing ratio   ,ice mixing ratio                ,&
     & cloud droplet number concentration  ,ice crystal number ,&
     & cloud fraction      ,trace gas concentrations          ,&
     & aerosol concentrations                                 ,&
     & longwave and shortwave net and clear-sky fluxes         )
```

Tunable microphysics

Dynamics is fixed along Lagrangian trajectories

in a variant of microphysical piggybacking.



Scheme 1

(Thermo)dynamics

$v_{x,1}, v_{y,1}, v_{z,1}, T_1, p_1$

Microphysics

$q_{i,1}, q_{n,i,1}$

Scheme 2

(Thermo)dynamics

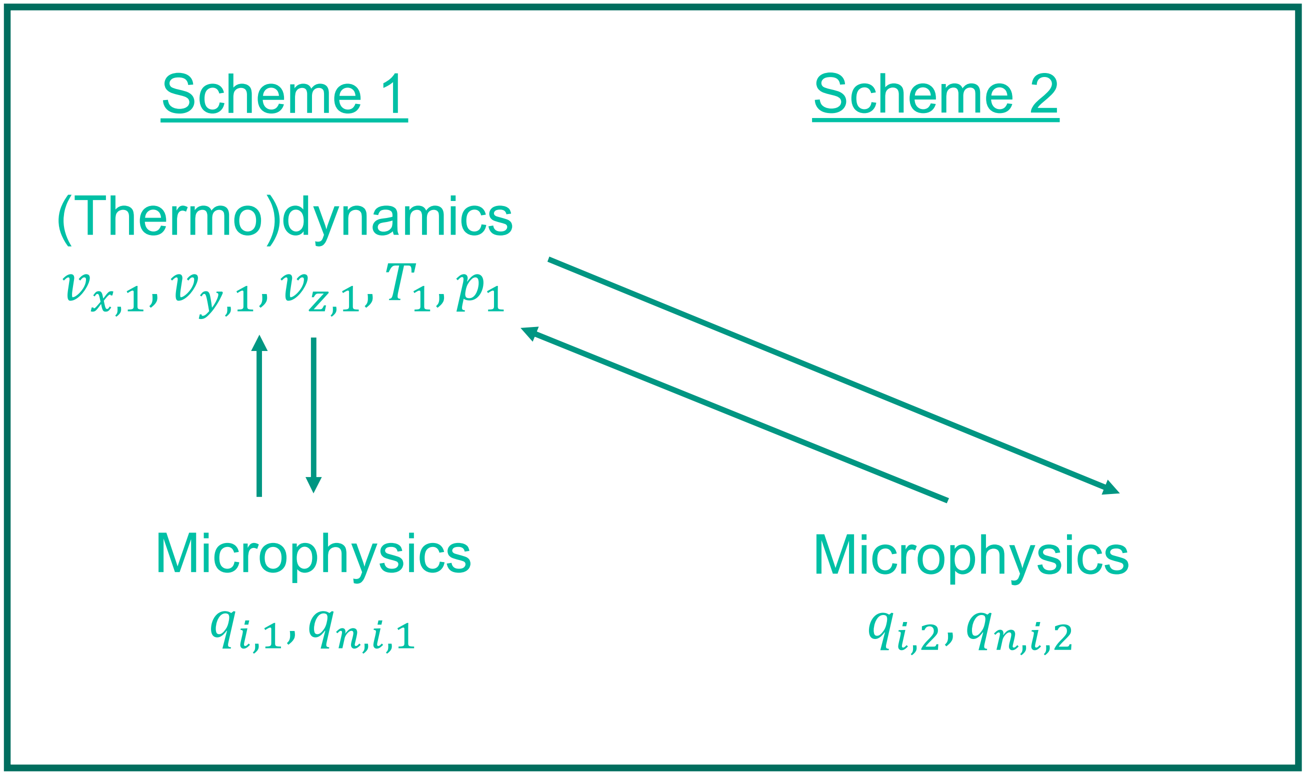
$v_{x,2}, v_{y,2}, v_{z,2}, T_2, p_2$

Microphysics

$q_{i,2}, q_{n,i,2}$

Dynamics is fixed along Lagrangian trajectories

in a variant of microphysical piggybacking.



Scheme 1

Scheme 2

(Thermo)dynamics

$v_{x,1}, v_{y,1}, v_{z,1}, T_1, p_1$

Microphysics

$q_{i,1}, q_{n,i,1}$

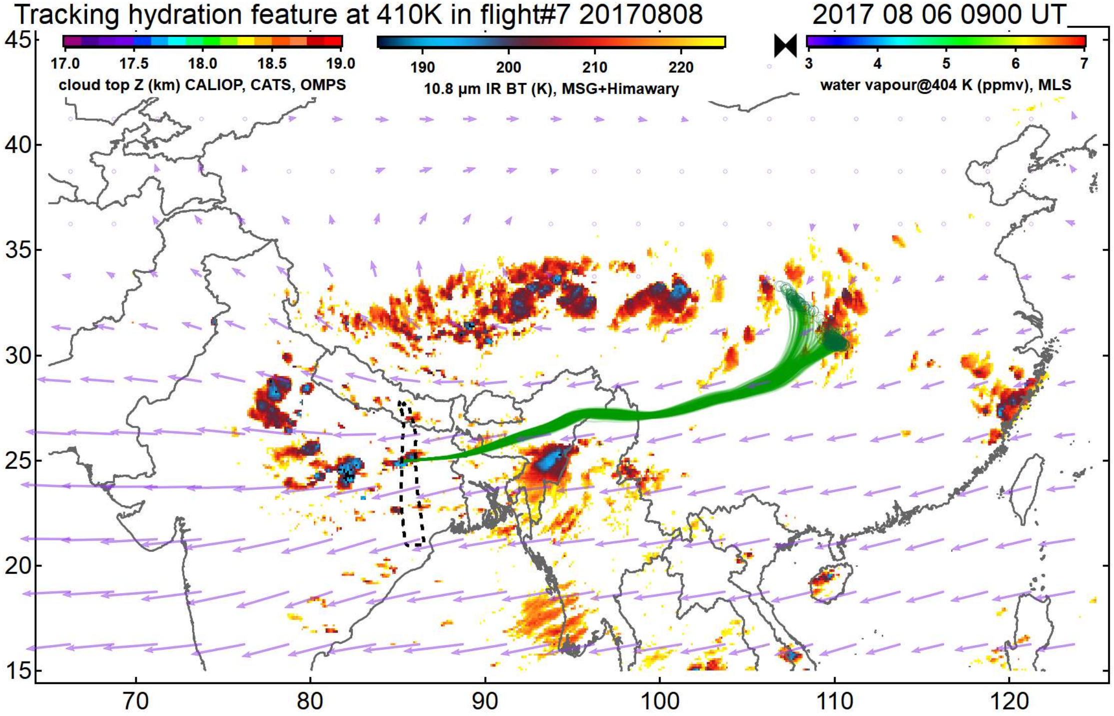
Microphysics

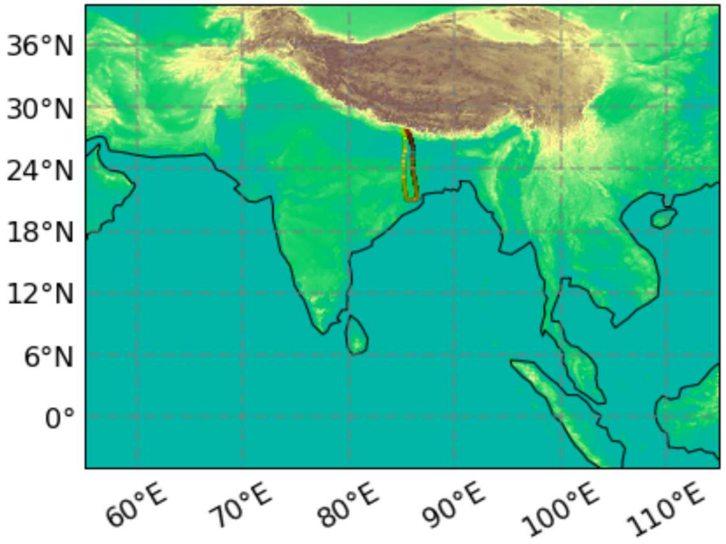
$q_{i,2}, q_{n,i,2}$

Images from W. W. Grabowski *Untangling microphysical impacts on deep convection applying a novel modeling methodology*

Lagrangian trajectories are initiated in the Sichuan Basin.

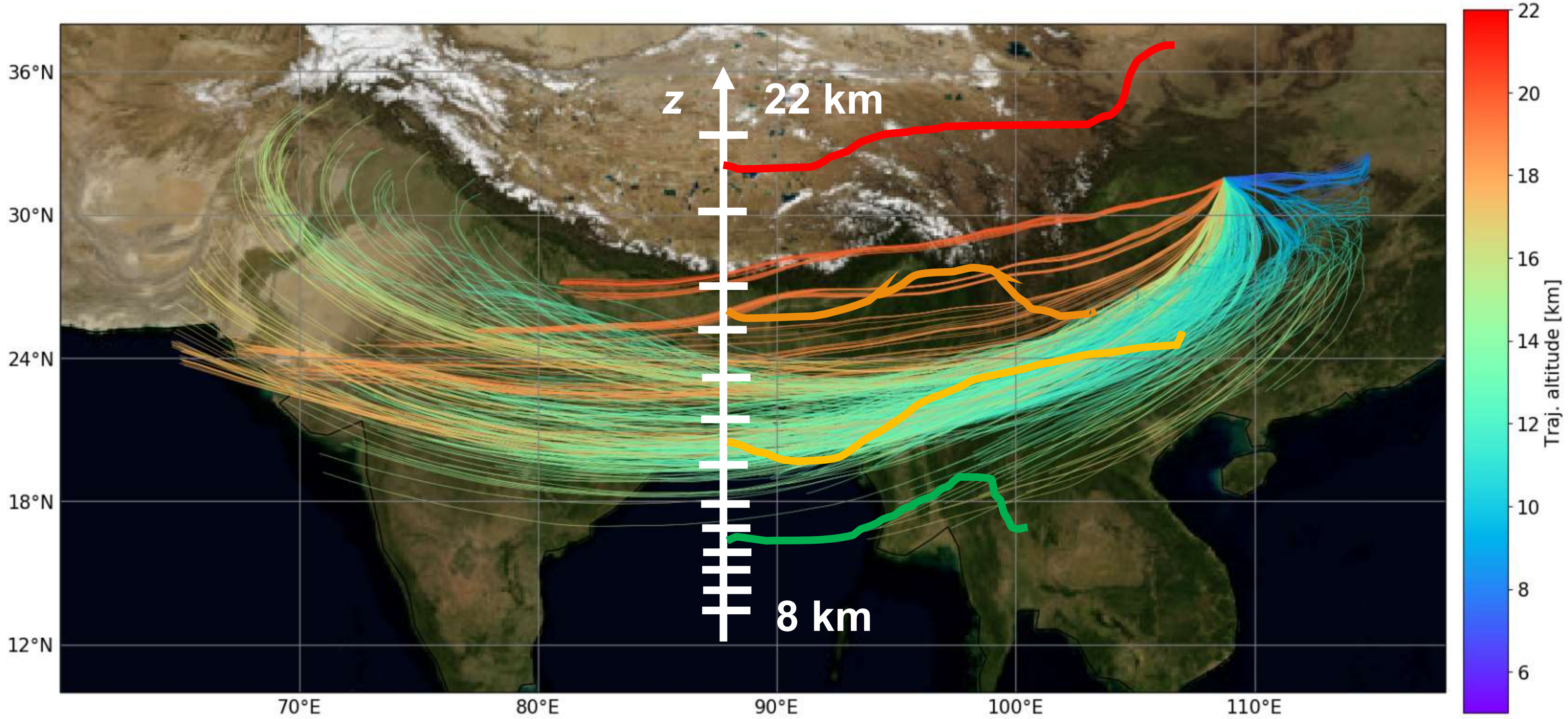
Upper-level moisture during Flight 7 was tracked to convective overshooting in the Sichuan basin.



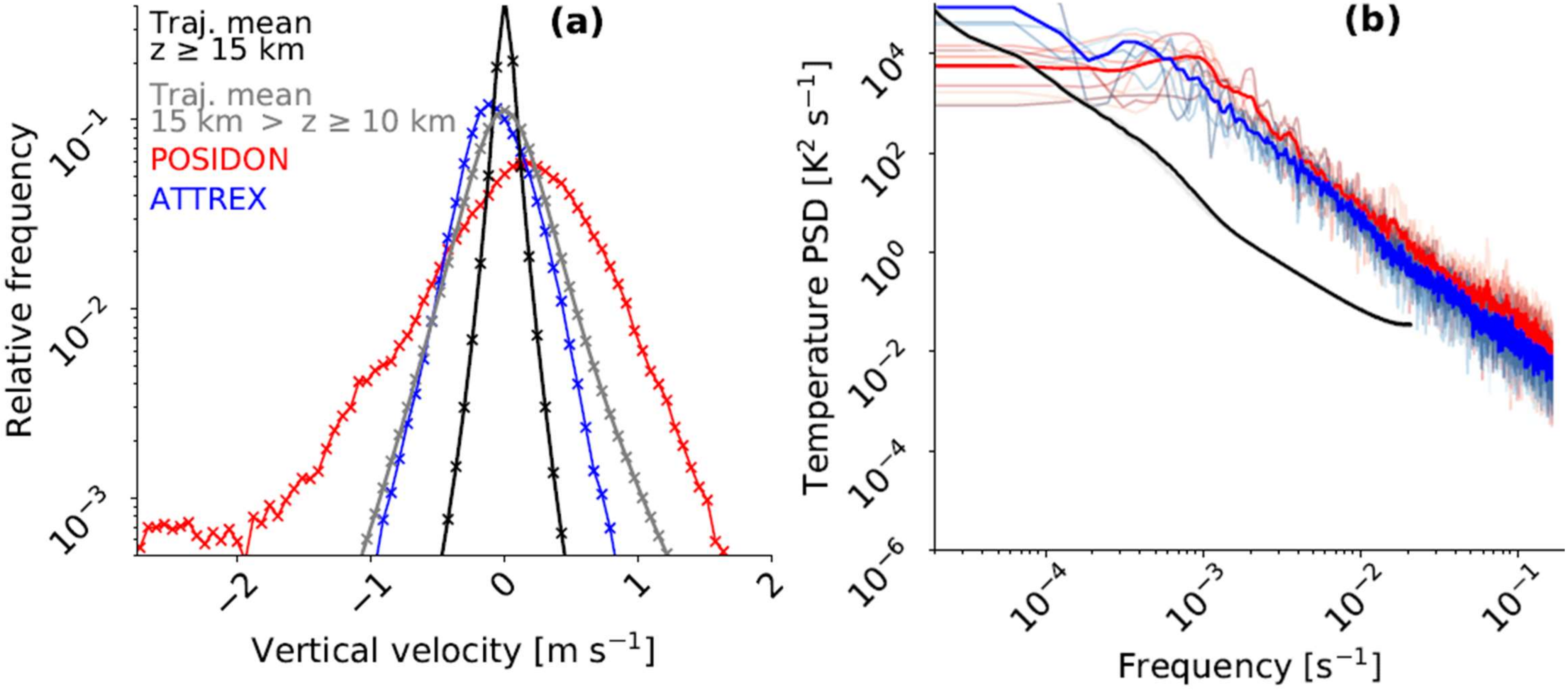


K. O. Lee, T. Dauhut, J. P. Chaboureau, S. Khaykin, M. Krämer, and C. Rolf (2019). *Atmos. Chem. Phys.*
S. Khaykin et al. (2021). *in preparation for Atmos. Chem. Phys.*

Lagrangian trajectories are initiated in the Sichuan Basin.

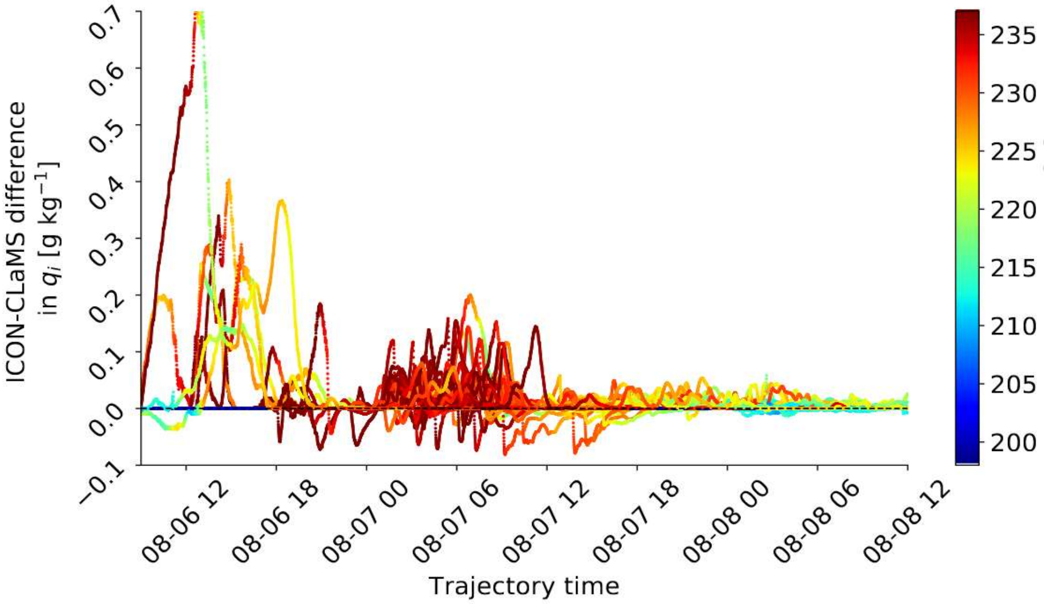


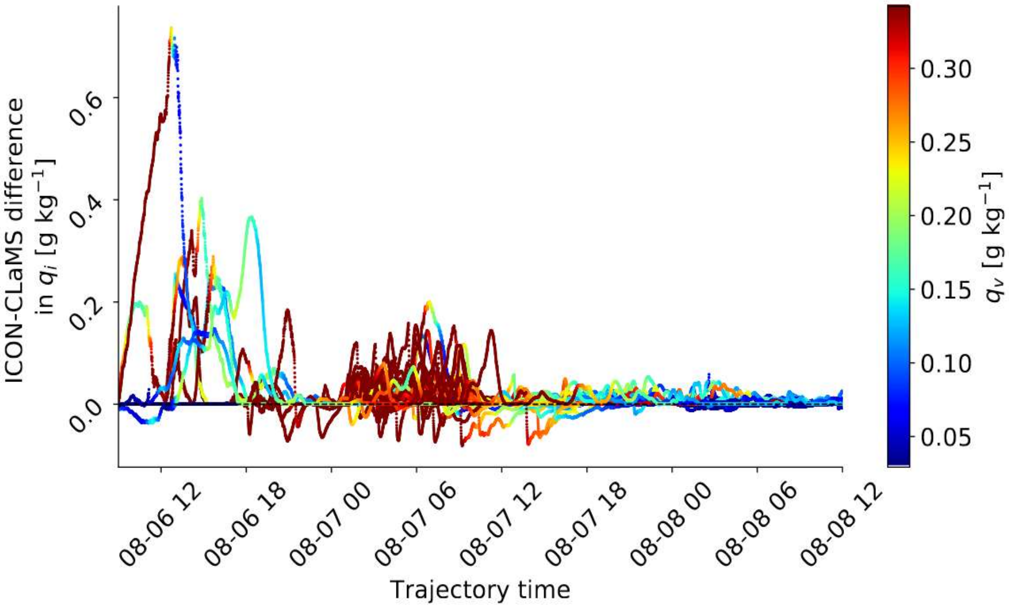
What do the trajectory dynamics look like?



POSIDON and ATTREX data courtesy of Eric Jensen

The ICON 2-mom scheme predicts much more ice than CLaMS…

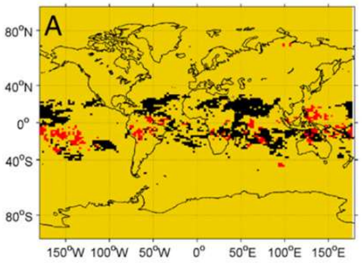




…especially for warmer subzero temperatures and high moisture content.

Summary

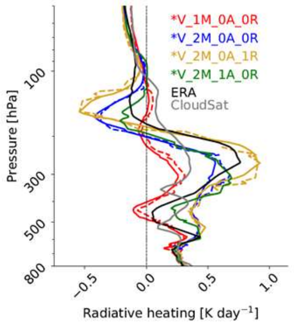
Attribution metrics defined from sensitivites identify vertical velocity variability as a crucial input to ice nucleation.



Different regions are driven by sensitivity versus variance.

Attributions are model framework-dependent.

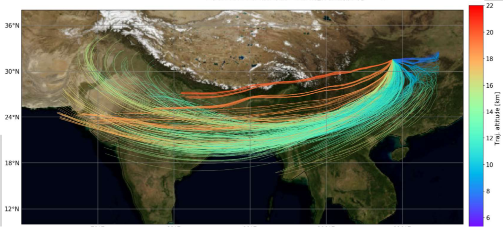
Ice microphysical parameters can change cloud-radiative heating by a factor of 4 and mean OLR by 30 W m^{-2}.



1-mom *versus* 2-mom differences have an“altitudinally-stratified explanation.”

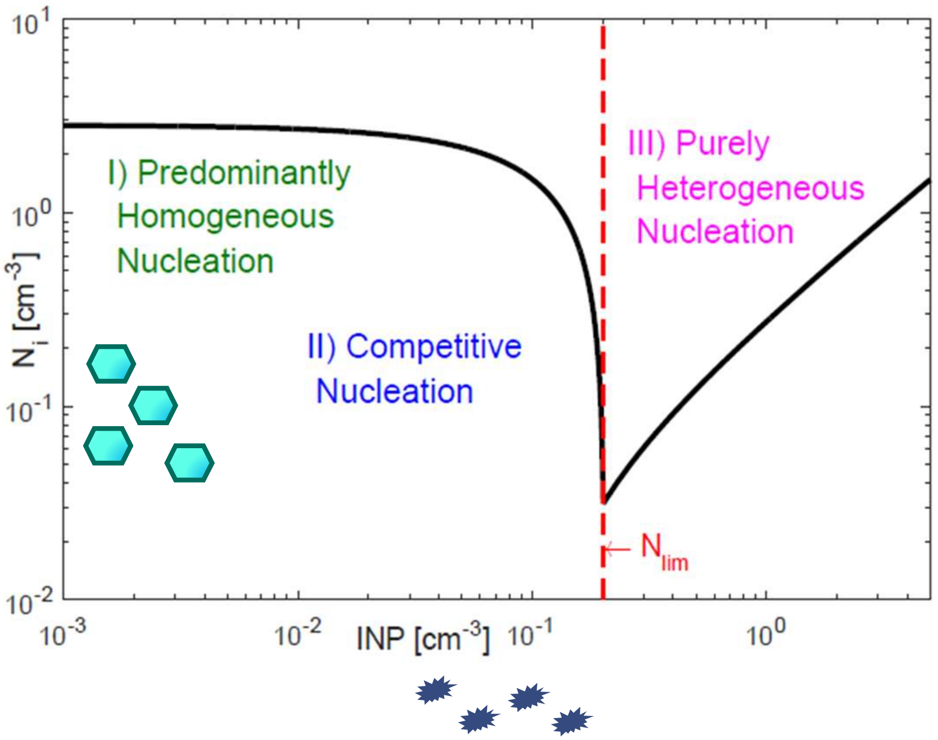
Ice crystal size affects the mass extinction coefficient.

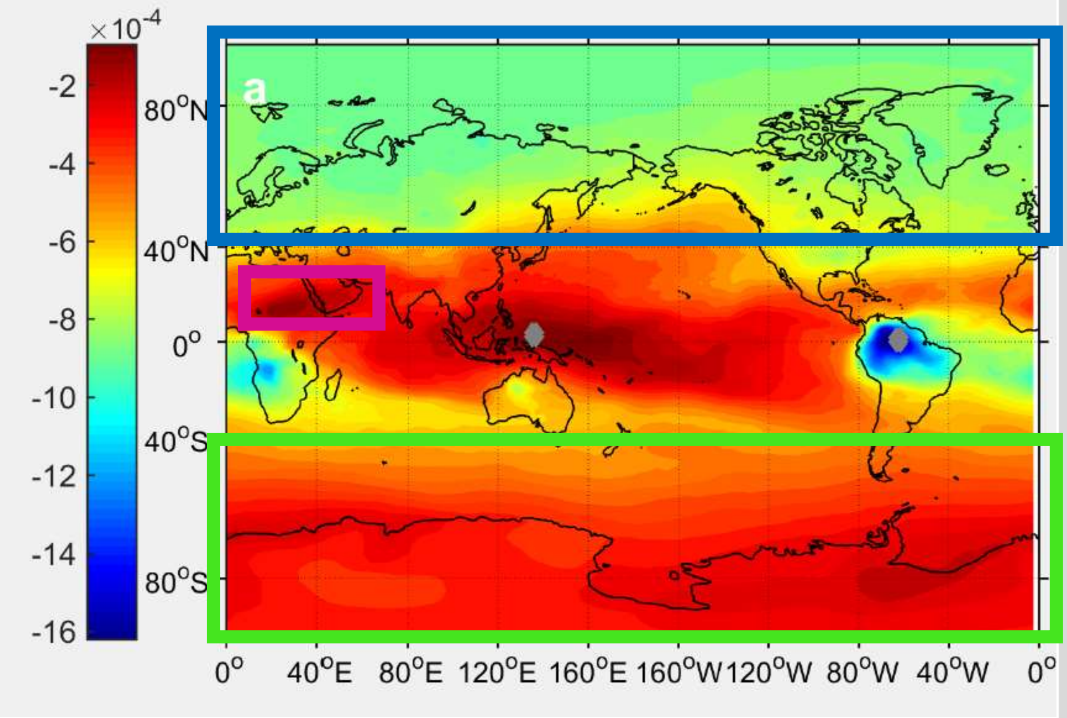
Lagrangian trajectories allow us to isolate the direct impact of microphysics on radiative heating rates.



SUPPLEMENTAL SLIDES

Sensitivities allow us to classify nucleation regime and efficiency.





$$\frac{\partial N_i}{\partial N_{\mathrm{INP}}}$$