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Effects of small-scale variability and turbulent fluctuations on phase partitioning in mixed-phase adiabatic cloud parcels

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Mixed-Phase clouds: A 3 phase system

- Contain both supercooled droplets and ice crystals
- Occur at all latitutes from the poles to the tropics
- Are stable systems that last for days or even weeks

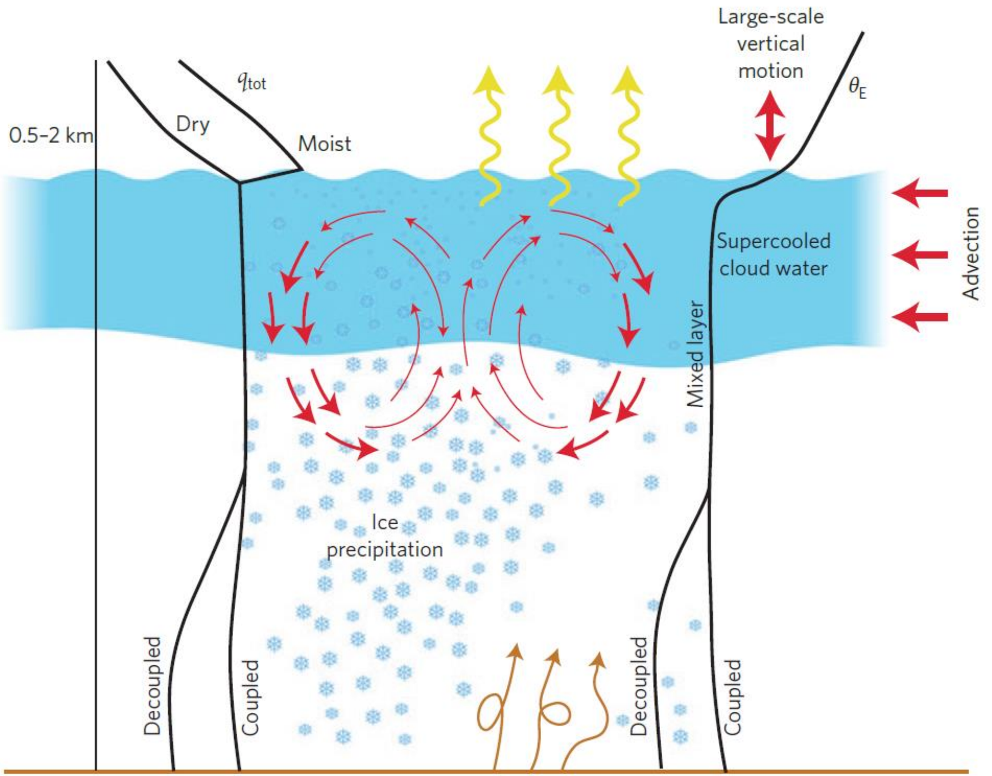


Figure from Morrison et al. 2011

A complex web of interactions

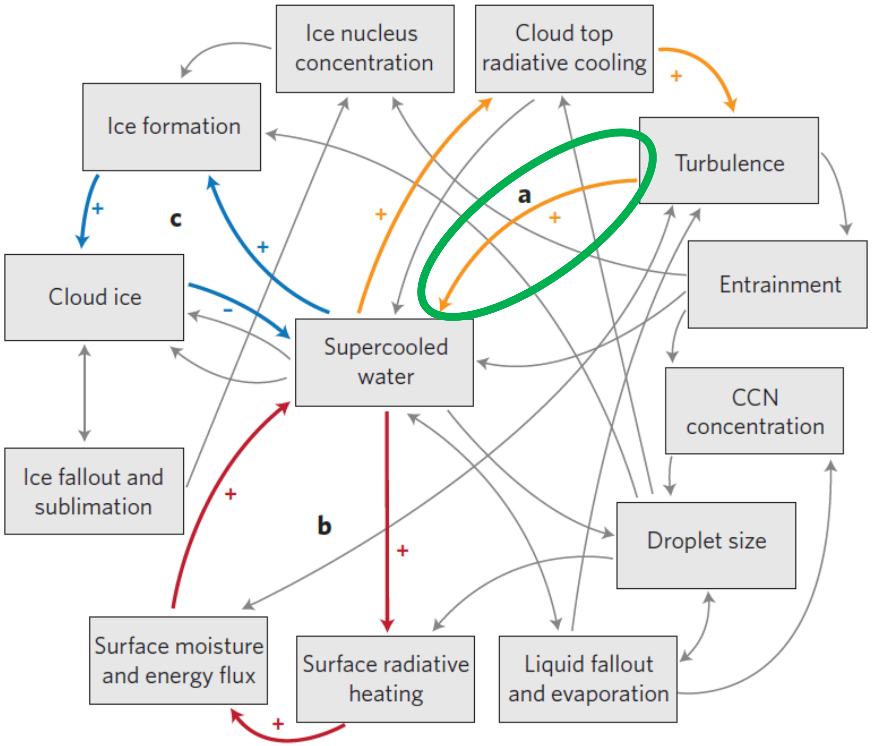
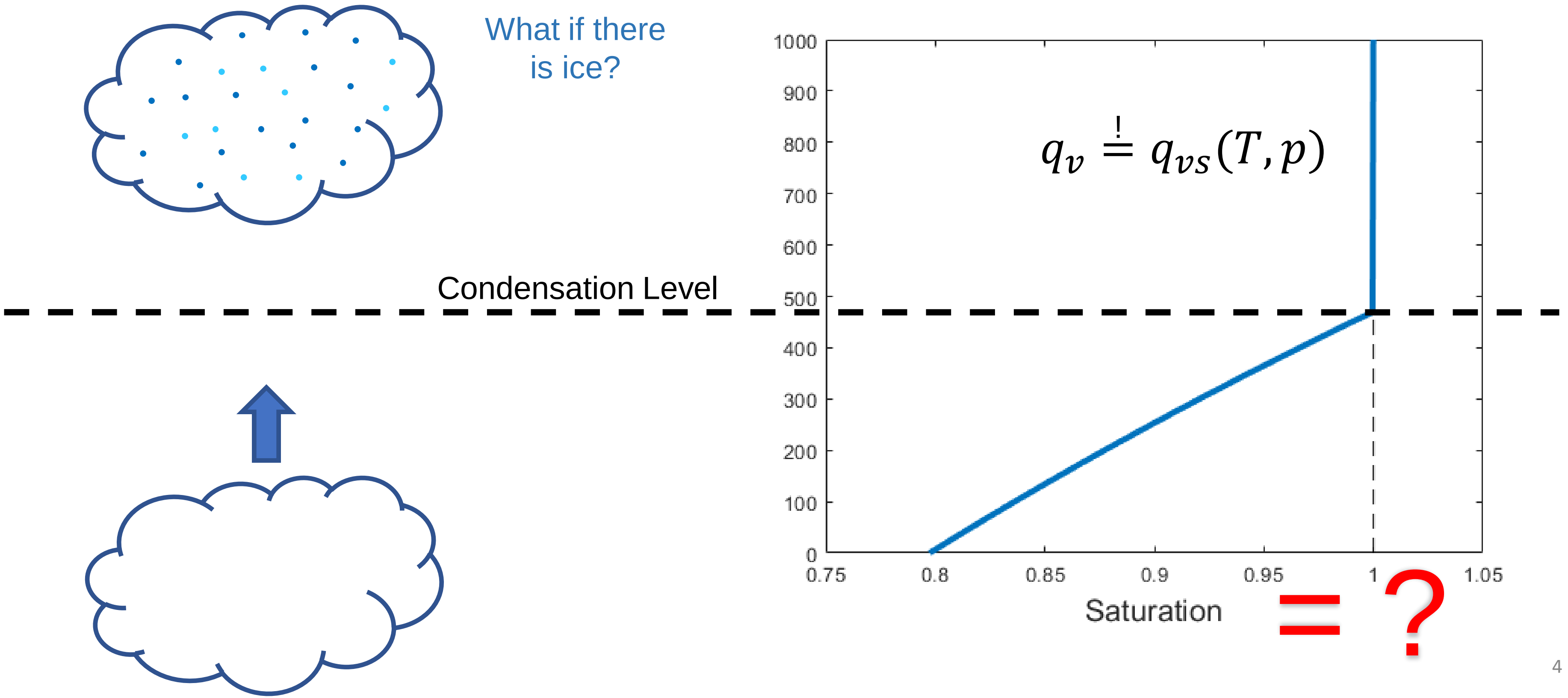


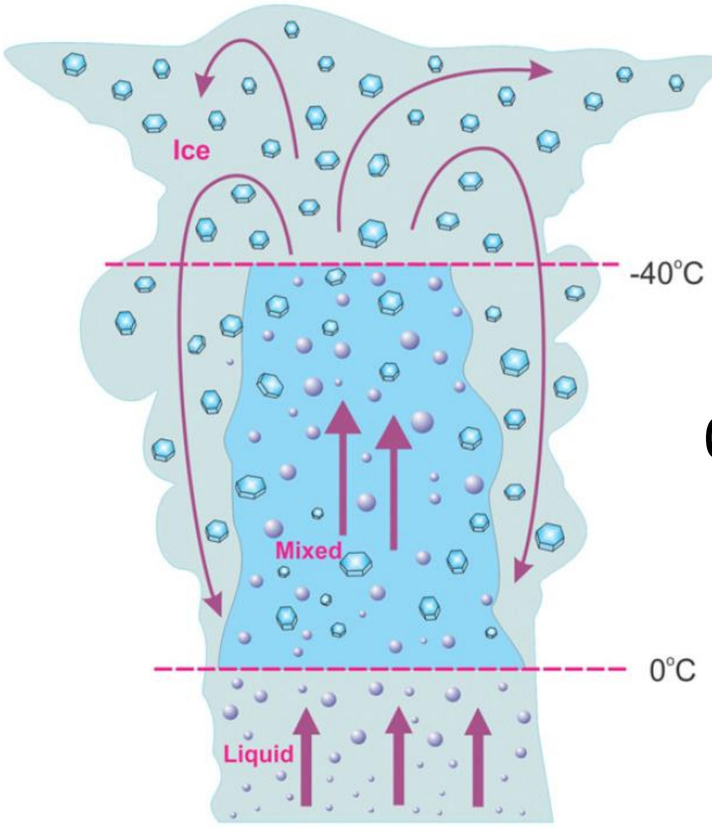
Figure from Morrison et al. 2011

Saturation Adjustment in a warm (ice-free) parcel:
Infinitely fast condensation brings cloudy air to saturation condition.



Liquid water fraction: A parameter to characterize the cloud condensate

$$\varphi = \frac{m_l}{m_c} = \frac{q_l}{q_c} = \frac{q_l}{q_l + q_i}$$



$\varphi = 0$

$0 < \varphi < 1$

$\varphi = 1$

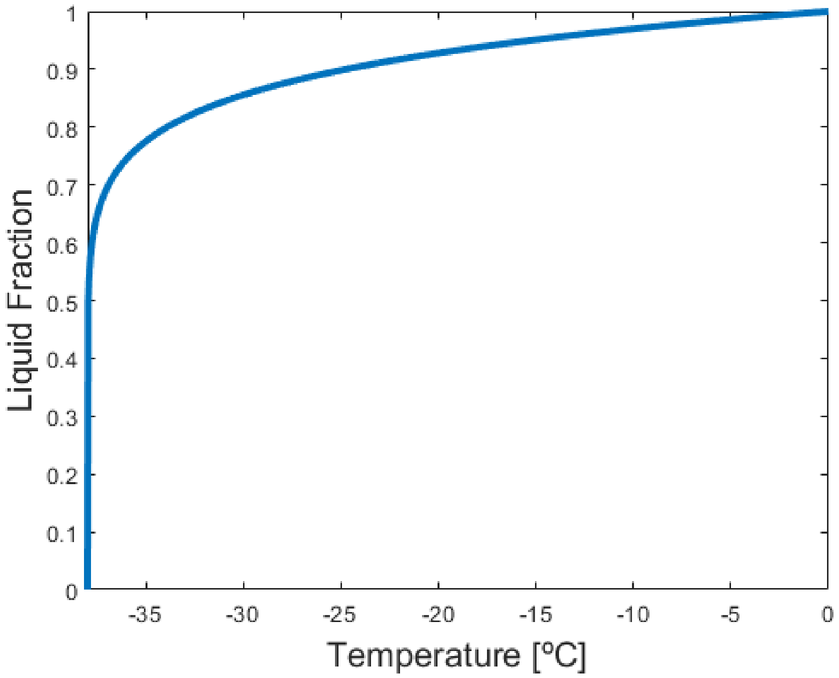
(Korolev et. al. 2017)

Saturation condition in a mixed-phase parcel and Temperature parametrization of liquid water fraction

Saturation Condition:

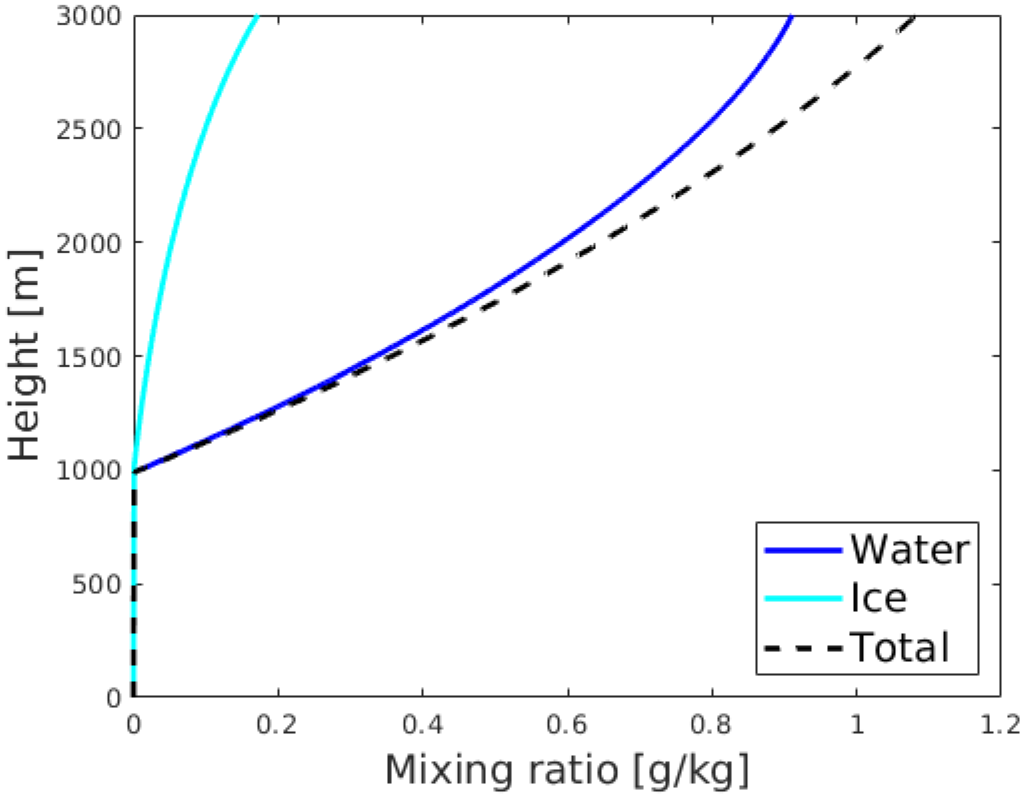
$$q_v \overset{!}{=} \bar{q}_{vs} \equiv \varphi q_{vs,l} + (1 - \varphi) q_{vs,i}$$

$$\varphi(T) = \left(\frac{T - T_c}{T_w - T_c} \right)^n$$



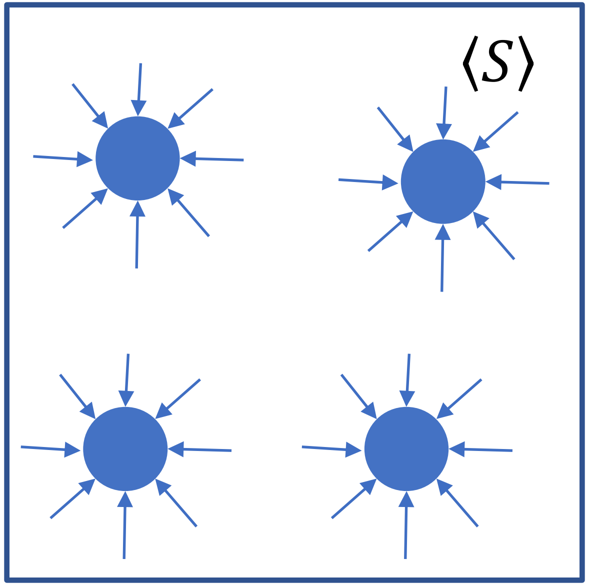
(Kaul et al. 2015)

Mixed-phase Saturation Adjustment: Rising Adiabatic Parcel



! Issue:
No condensation dynamics
(i.e. time evolution)

Improving the condensation model: Introducing droplet growth dynamics



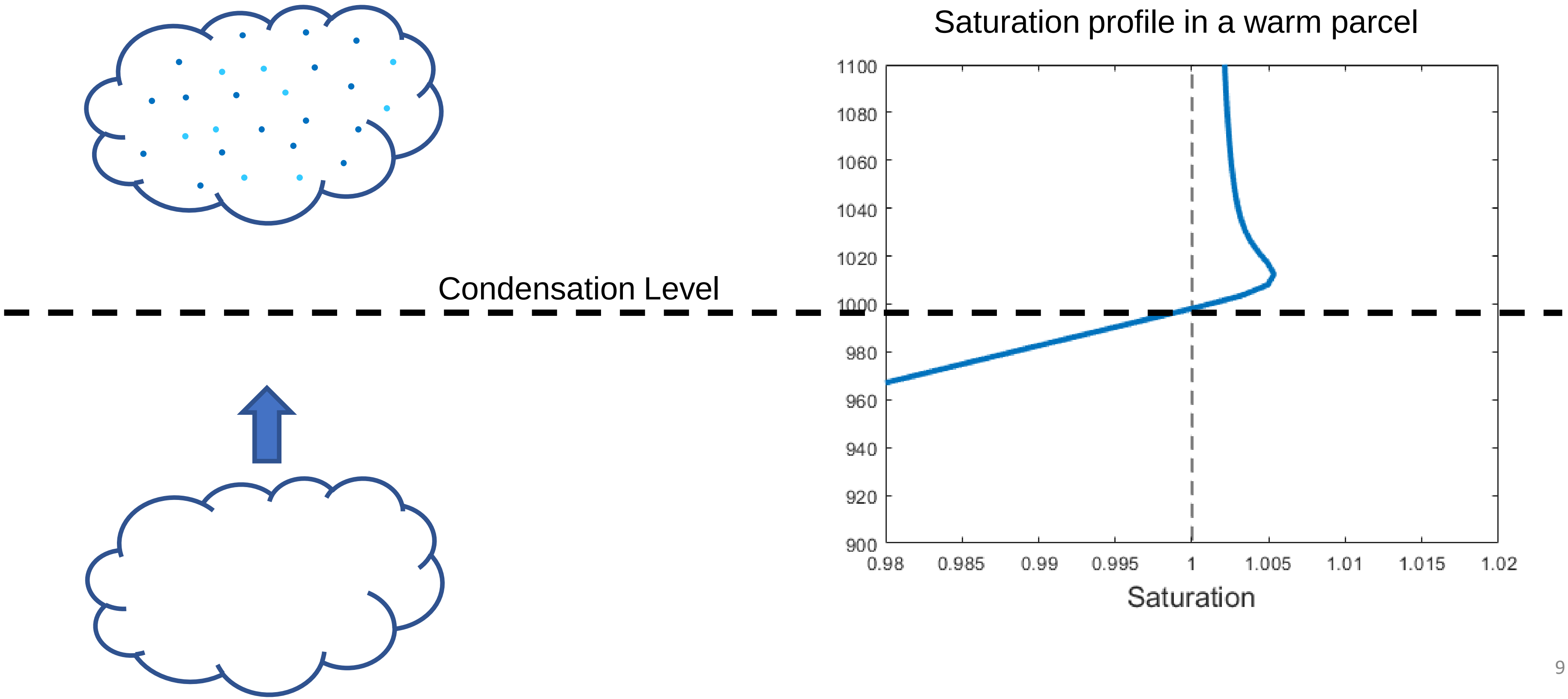
$$\frac{dr_k}{dt} = \frac{1}{r_k} D \left[\langle S \rangle - \frac{A}{r_k} + \frac{B}{r_k^3} \right]$$

$\langle S \rangle$: *Mean Supersaturation*

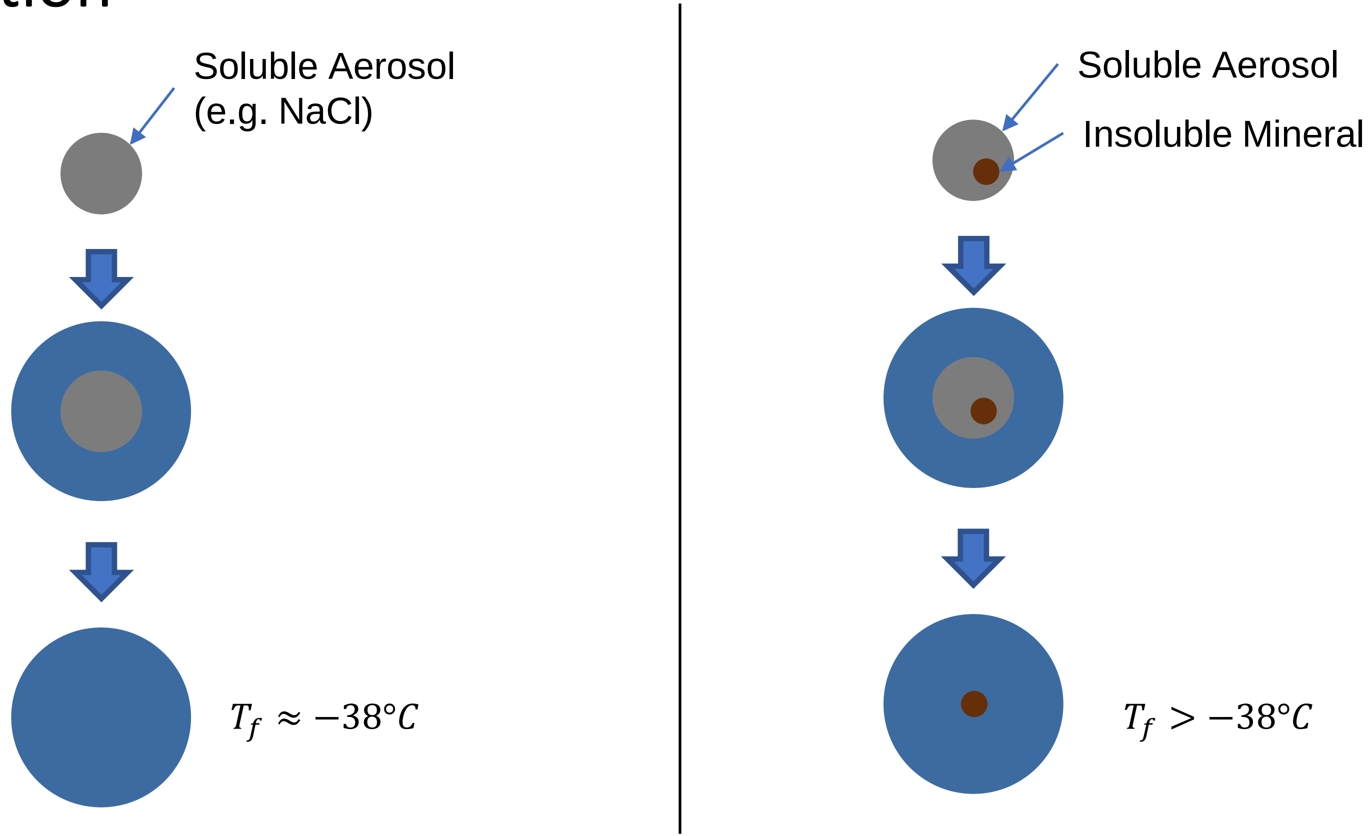
$\frac{A}{r_k}$: *Surface tension effect*

$\frac{B}{r_k^3}$: *Solute effect*

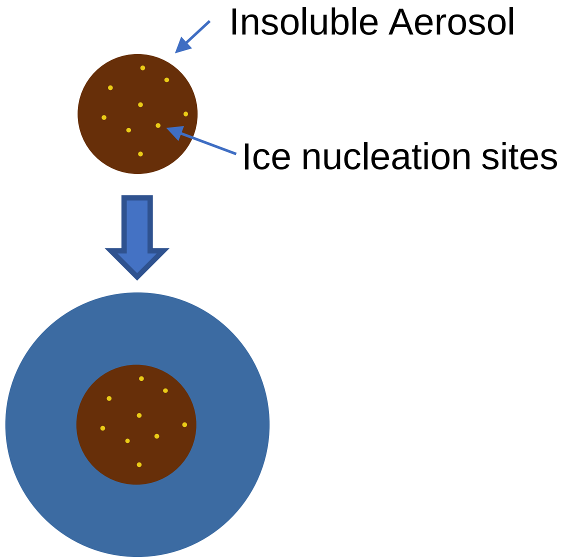
Super-droplet Model: Condensation is driven by supersaturation.



Immersion Freezing: Homogeneous and Heterogeneous Nucleation



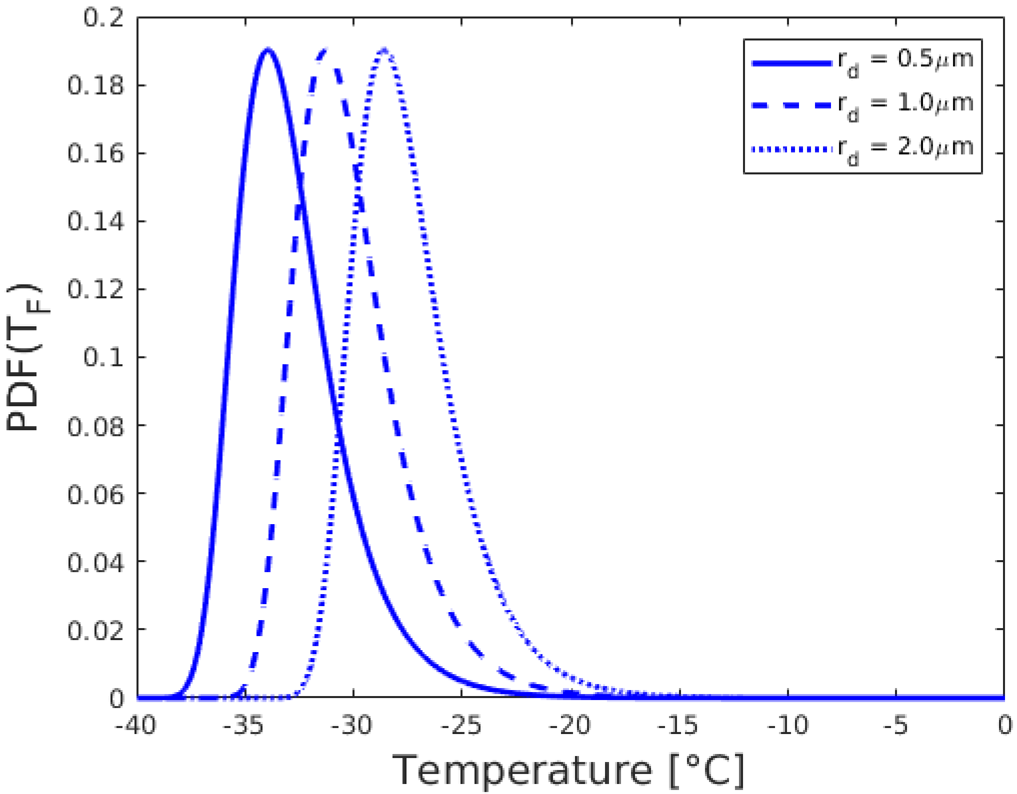
Heterogeneous Freezing Temperature Distribution



Freezing Occurs when:

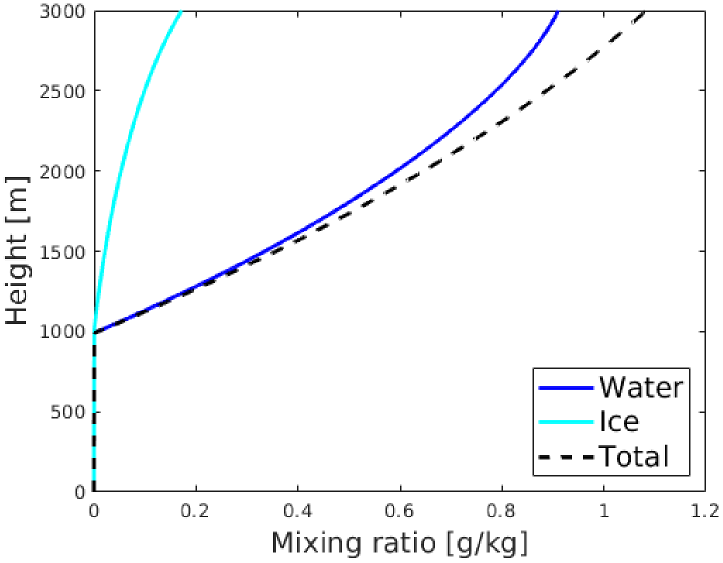
1) $r > r_d$
2) $S > 1$
3) $T_k < T_f$

(Shima et. al. 2020)

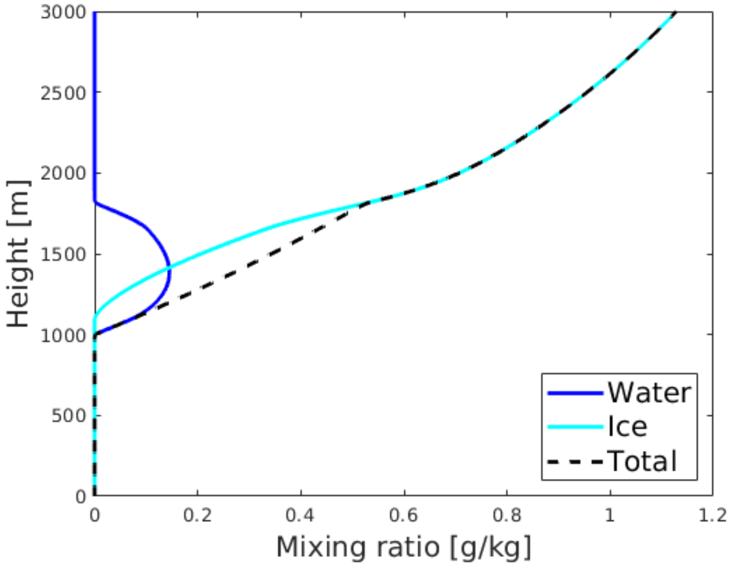


Comparison between bulk and particle-based models demonstrates ice-water instability

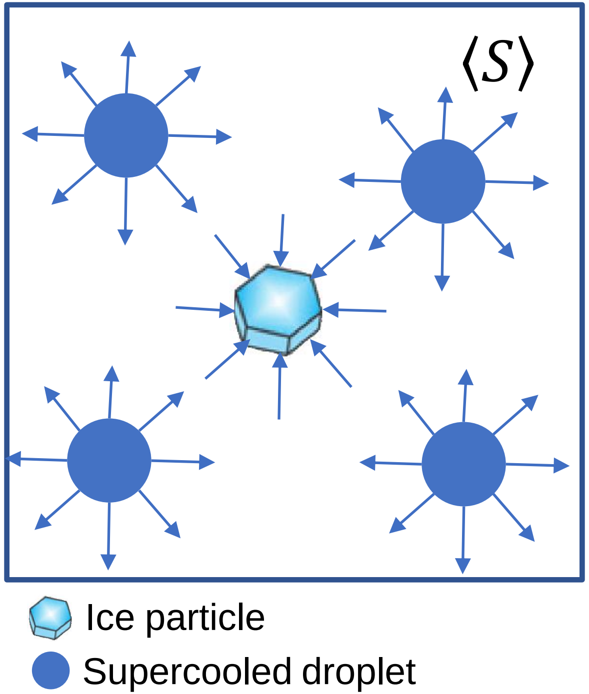
Saturation Adjustment

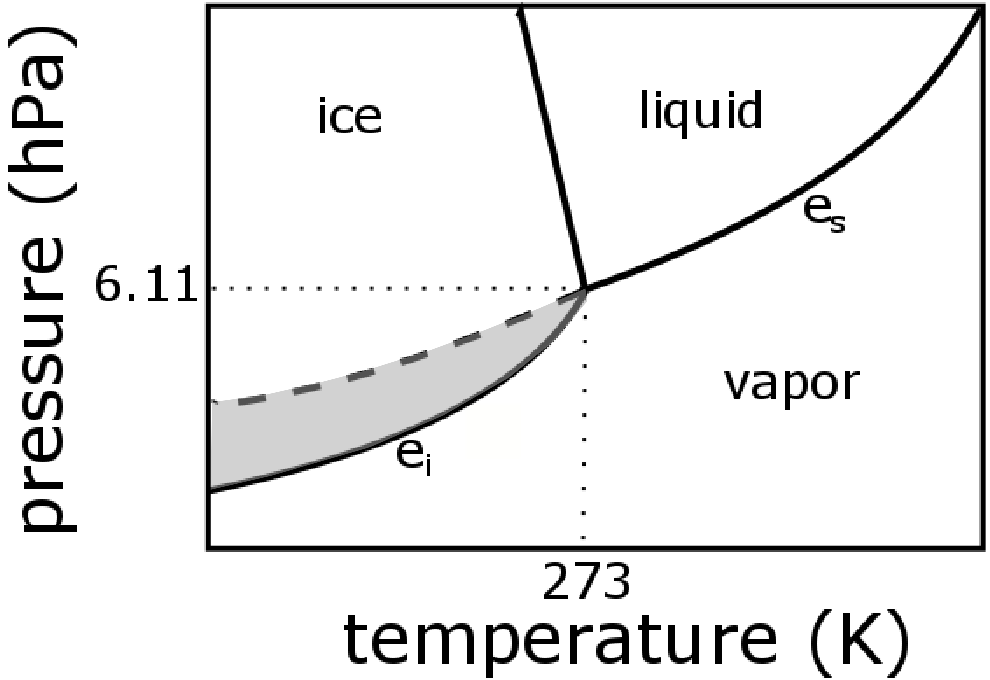


Super-droplets

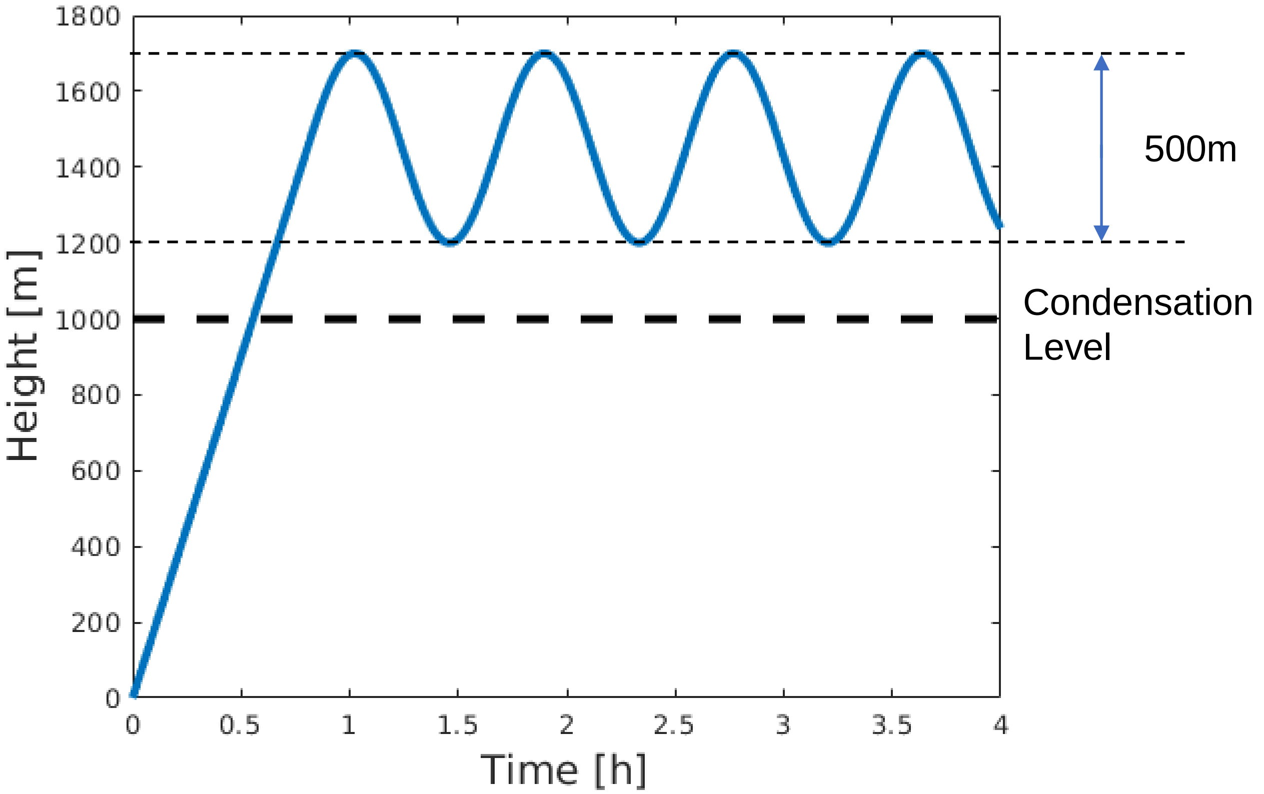


The Wegener-Bergeron-Findeisen Mechanism:
A condenstation instability in mixed-phase clouds



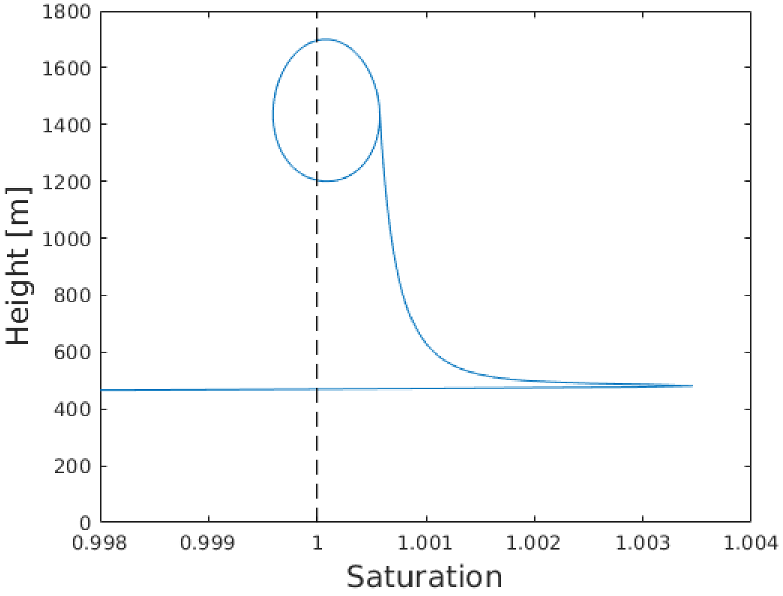


Oscillating Adiabatic Parcel: A framework to assess microphysical models

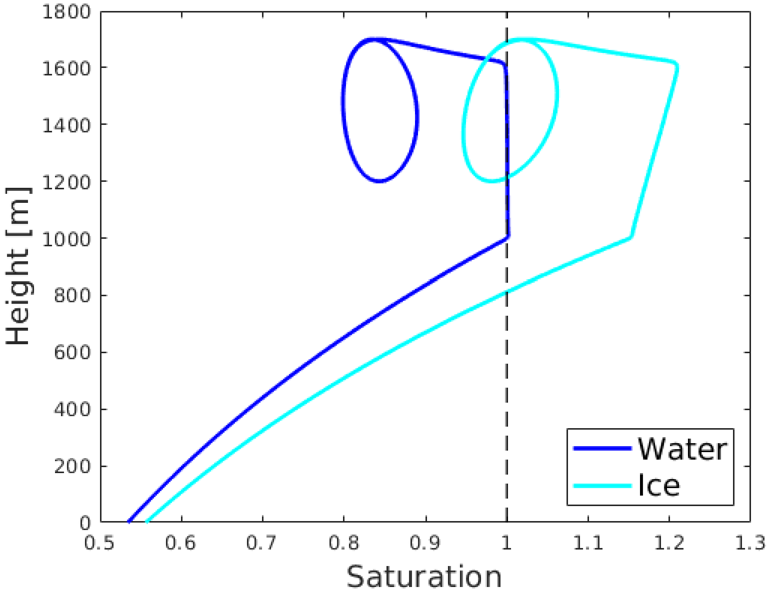


Liquid and Ice saturations in oscillating homogeneous air parcels

Warm parcel



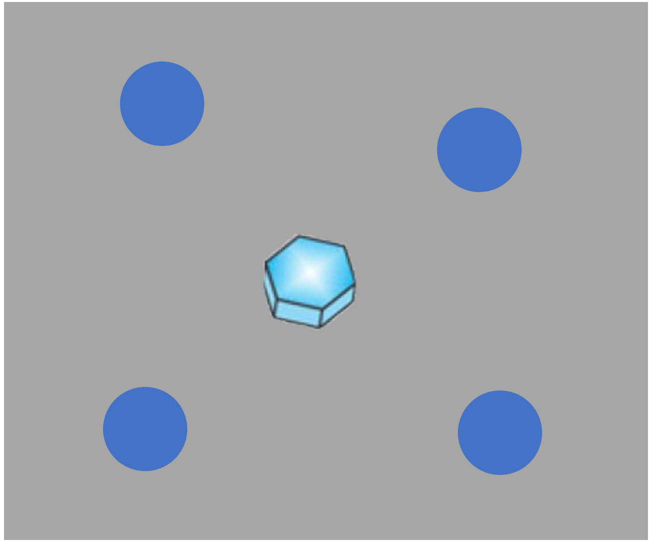
Mixed-phase parcel



! Issue:
All droplets are subject to the same average saturation $\langle S \rangle$.

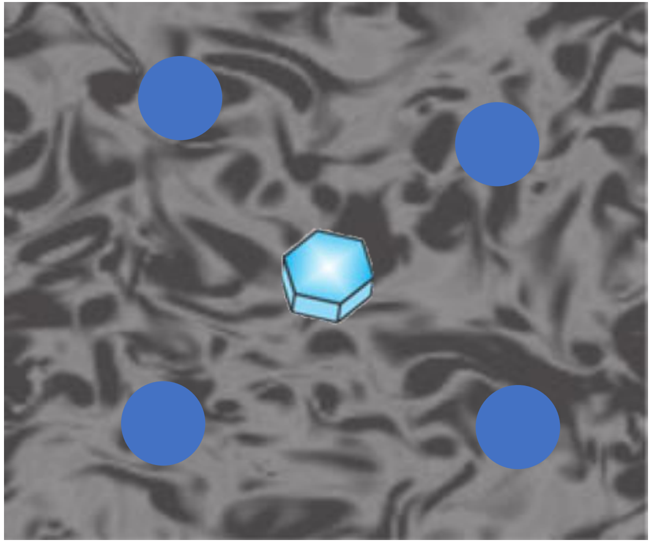
Introducing Small Scale Variability

Homogeneous parcel



$$\tau_{mix} = 0$$

Stochastic parcel



$$\tau_{mix} \sim \left(\frac{L^2}{\varepsilon}\right)^{1/3}$$

Additional Superdroplet Attributes

Homogeneous Parcel

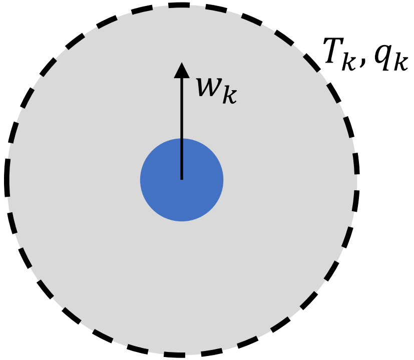
$$\boldsymbol{a} = \{r, r_d, r_d^{insol}, T_f\}$$

r : Droplet radius
r_d : Dry radius (amount of solute)
r_d^{insol} : Insoluble dry radius
T_f : Freezing temperature

Stochastic Parcel

$$\boldsymbol{a} = \{r, r_d, r_d^{insol}, T_f, T_k, q_k, w_k\}$$

T_k : Local temperature
q_k : Local vapor mixing ratio
w_k : Local vertical velocity



Model Equations

Homogeneous Parcel

$$\frac{d\langle q\rangle}{dt} = -\langle C\rangle - \langle D\rangle$$

$$\frac{d\langle T\rangle}{dt} = \frac{L_v}{c_p}\langle C\rangle + \frac{L_s}{c_p}\langle D\rangle + \frac{L_f}{c_p}\langle F\rangle - \frac{c_p}{g}\langle w\rangle$$

- Water phase transitions
- Adiabatic Cooling

Stochastic Parcel

$$\frac{dq_k}{dt} = -\frac{q_k - \langle q\rangle}{\tau} - c_k - d_k$$

$$\frac{dT_k}{dt} = -\frac{T_k - \langle T\rangle}{\tau} + \frac{L_v}{c_p}c_k + \frac{L_s}{c_p}d_k + \frac{L_f}{c_p}f_k - \frac{c_p}{g}w_k$$

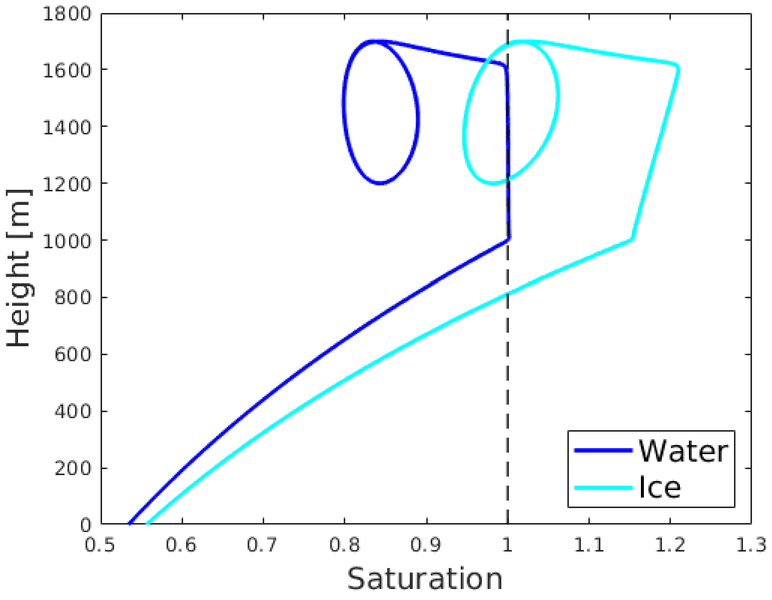
$$\frac{dw_k}{dt} = -\frac{w_k - \langle w\rangle}{\tau} + \sqrt{\frac{2\sigma^2}{\tau}}dW_k$$

- Water phase transitions
- Adiabatic Cooling
- Relaxation due to turbulent mixing
- Stochastic velocity fluctuations

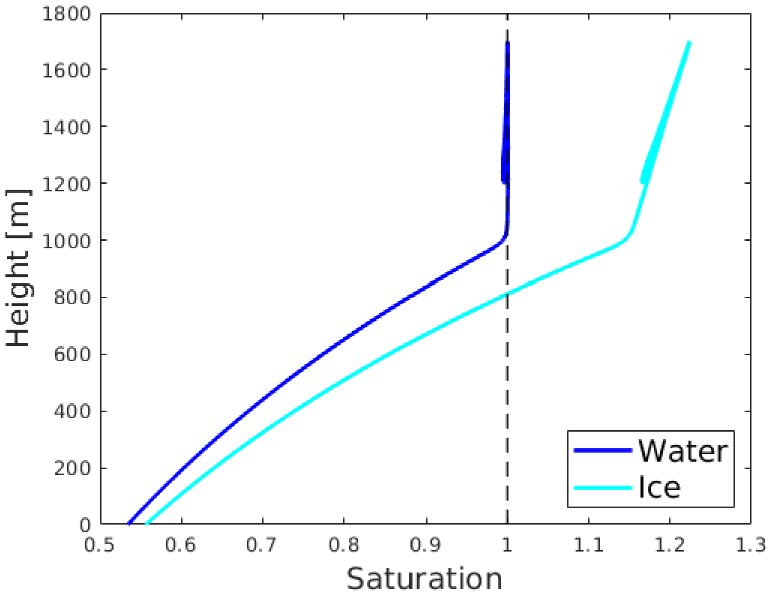
$$Homogeneous = \langle Stochastic\rangle$$

Liquid and Ice saturations in a mixed-phase parcel

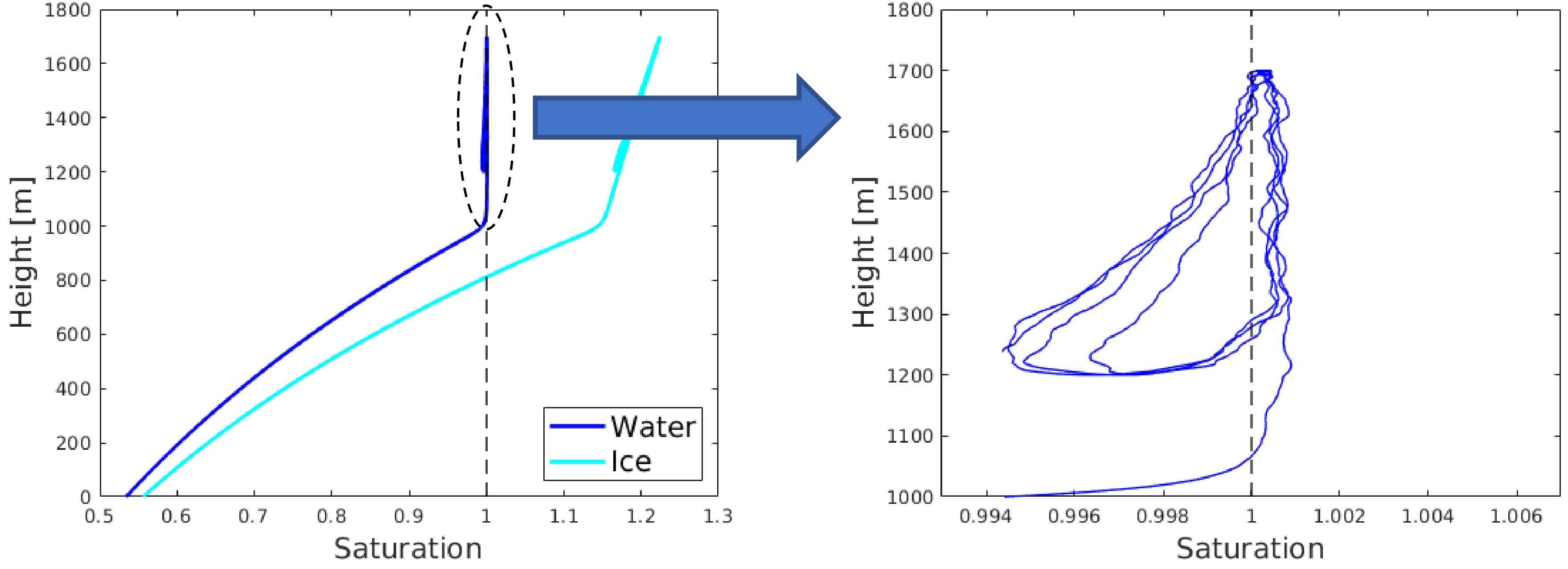
Homogeneous parcel



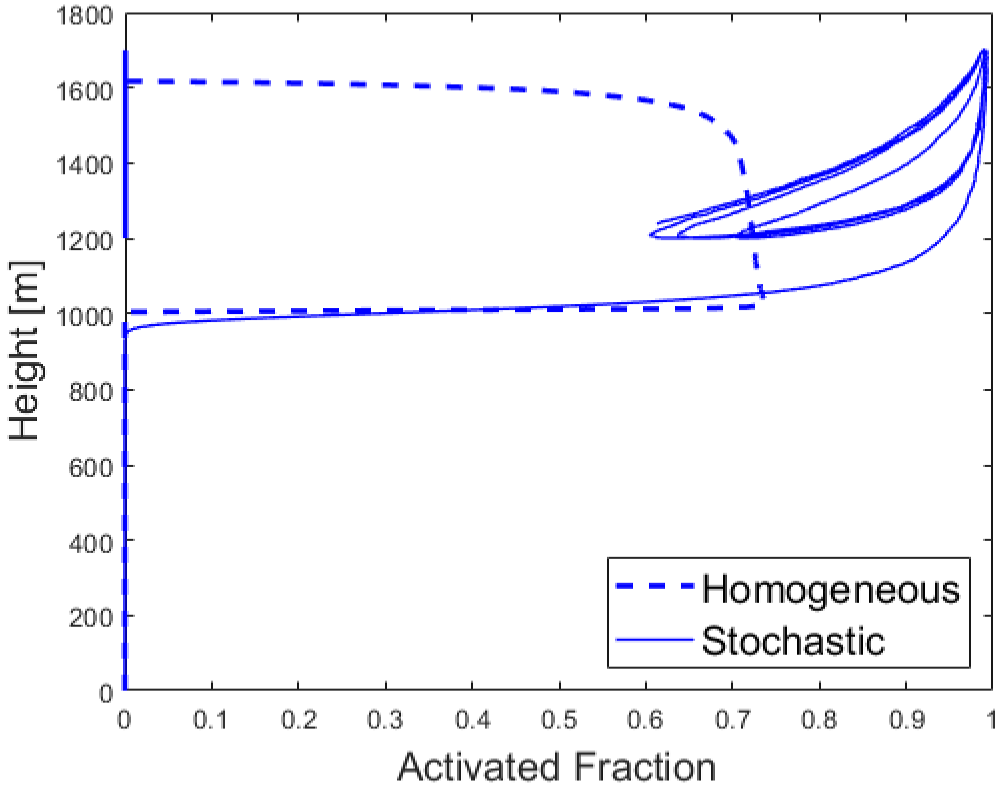
Stochastic parcel



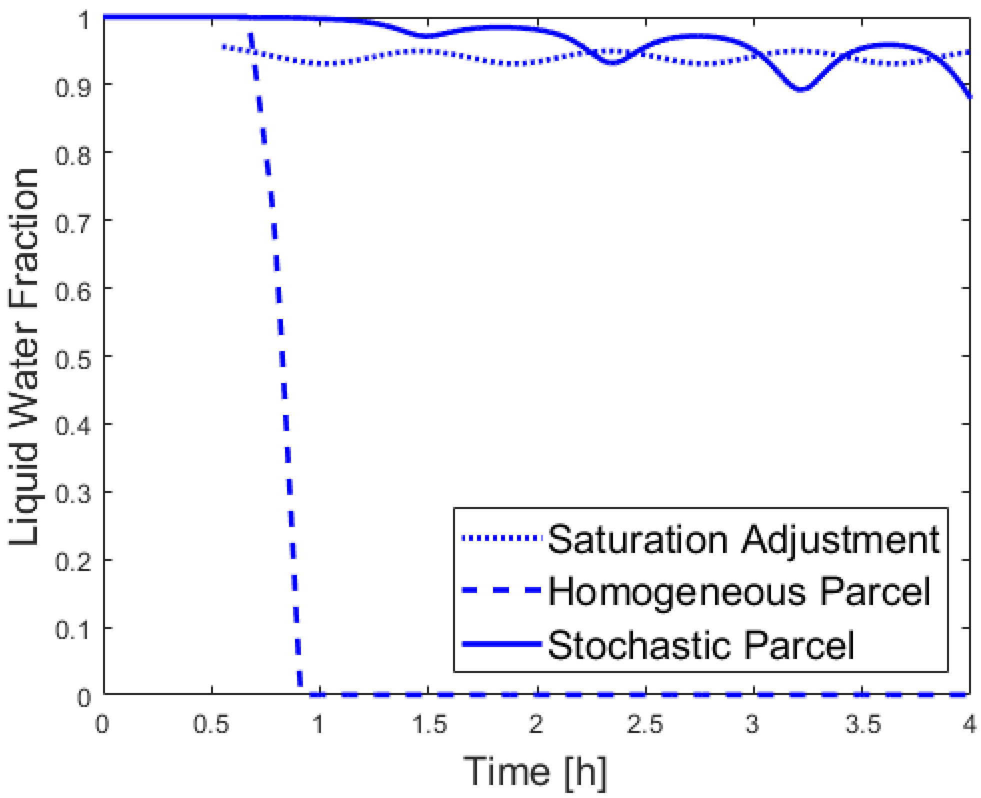
Liquid and Ice saturations for a stochastic mixed-phase parcel



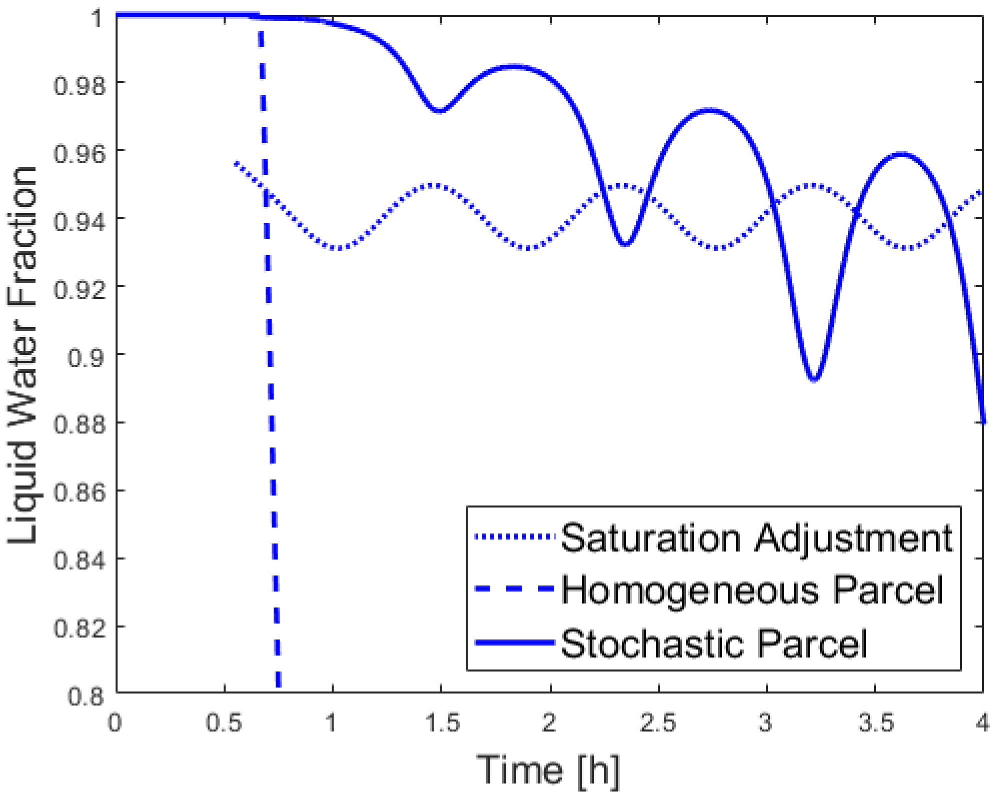
The fraction of ativated droplets is sensitive to the turbulent mixing time scale.



Time Evolution of liquid water fraction for 3 different models



Saturation Adjustment and Stochastic Parcel results for φ are in opposition of phase.



Final Remarks

- Small scale variability in temperature and water vapor density fields have a great impact on the evolution of phase partitioning.

- Small-scale (sub-grid) variability models attempt to reproduce the effect of small-scale turbulence in particle growth with a lower computational cost.

Thank you.