Minimalist model of ice microphysics in mixed-phase stratiform clouds

F. Yang[1], M. Ovchinnikov[2], R. A. Shaw[1]

[1]Atmospheric Sciences Program, Michigan Technological University

[2]Pacific Northwest National Laboratory

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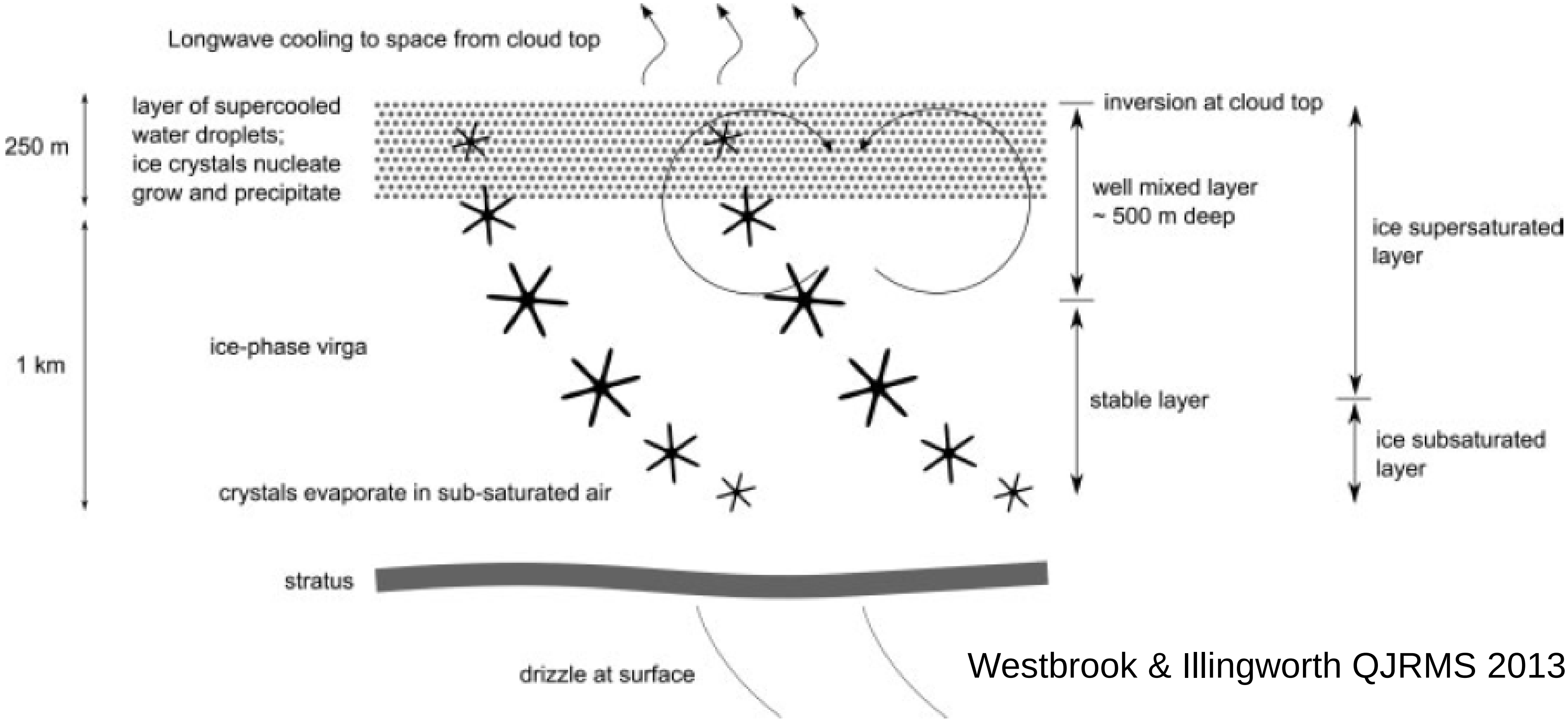
Mixed-phase stratiform clouds…



Westbrook & Illingworth QJRMS 2013

Arctic stratus & altocumulus clouds tend to be thin, long-lived, weakly precipitating ice, and radiatively important…

Question: Where do all the ice nuclei come from?!

Minimalist model…

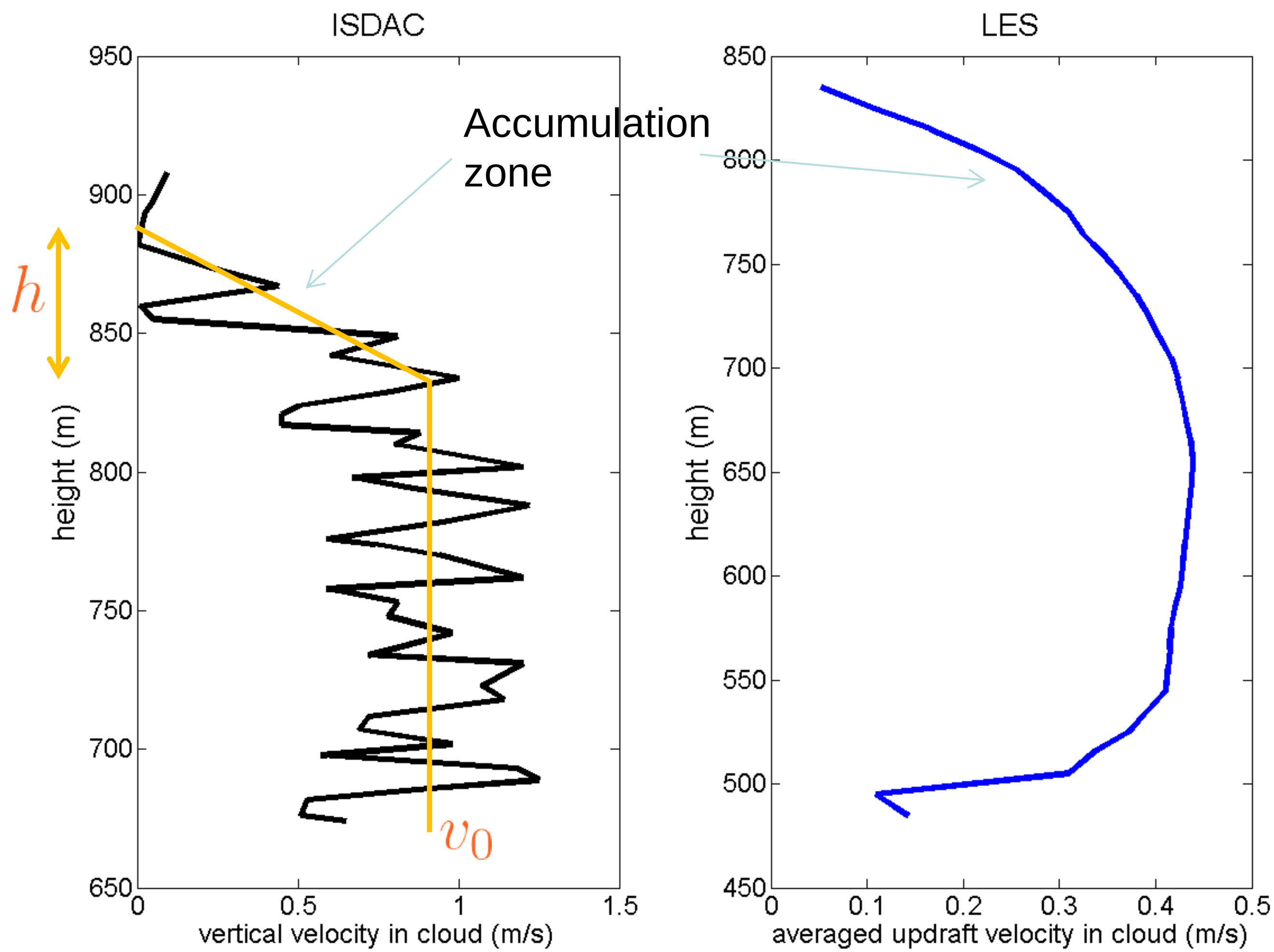
Objective: How simple can it be and still capture the essential physics?

1. Stochastic ice nucleation: $n_i' = \phi n_w / \tau$
2. Ice crystal growth at liquid-water-saturation: $r_i^2 = 2CDs_i t$
3. Ice crystal fall speed in still air: $v_i = br_i^k$

Average ice crystal size at cloud base: $\overline{r_i} \propto h^{1/(k+2)}$

Simple model predicts mean ice size <200 um
Observations show >1000 um
Too Simple!

Vertical velocity profile…



Fall speed of ice crystal in accumulation zone:

$$v_i = br_i(t)^k - \frac{v_0(h-z)}{h}$$

Minimalist model for accumulation zone…

First-order ODE for ice crystal at height *z* above base of accumulation zone

$$\frac{dz}{dt} = b(2CDs_i t)^{k/2} - \frac{v_0(h-z)}{h}$$

Define: $P = v_0/h$ $Q = b(2CDs_i)^{k/2}$

Take $k = 1/2$

$$\frac{dz}{dt} = Qt^{1/4} - P(h-z)$$

$$z = e^{-Pt} \int Qt^{k/2} e^{Pt} dt + ce^{-Pt}$$

Quasi-steady growth in the accumulation zone…

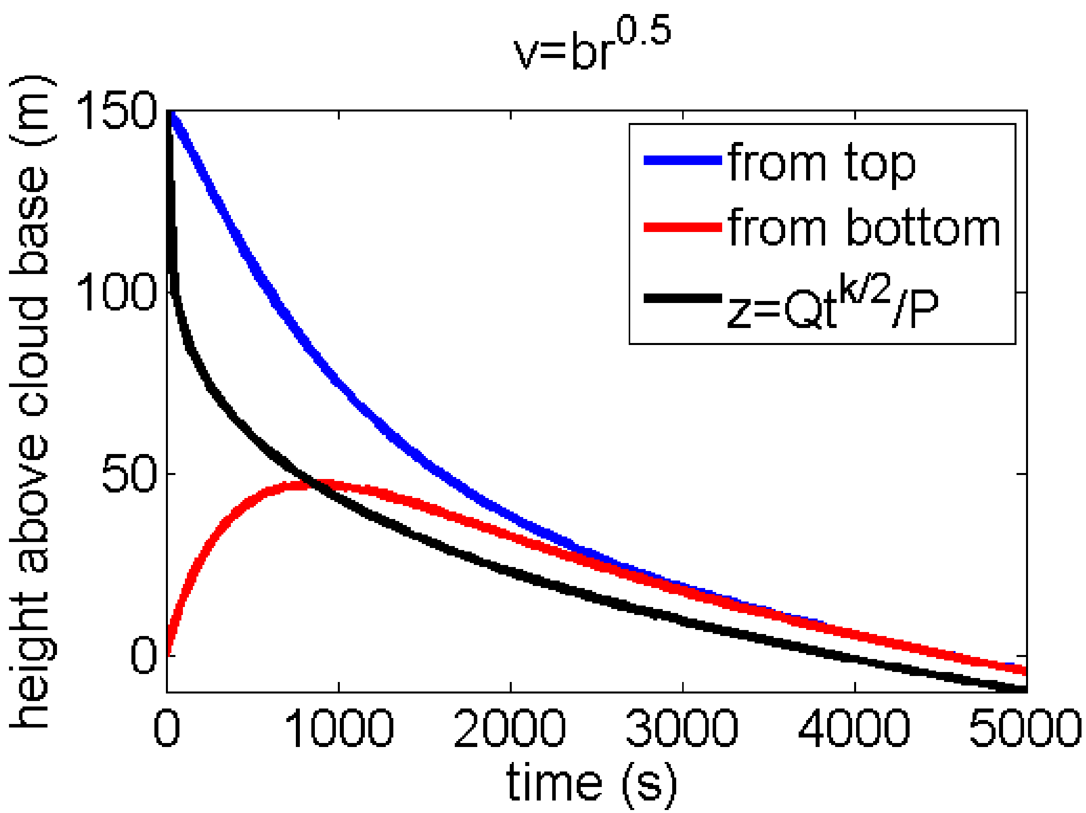
$$\frac{dz}{dt} = Qt^{1/4} - P(h - z)$$

Quasi-steady approximation:

$$P(h - z) = Qt^{1/4}$$

$$\downarrow$$

$$v = \frac{Q}{4Pt^{3/4}} = \frac{Q^4 h}{4v_0^4}$$



Minimalist model predictions for accumulation zone…

In steady state: Rate of ice crystal precipitation equal to rate of crystal nucleation

$$n_i \overline{v_i} = n_i' h \qquad IWC = n_i m_i$$

$$IWC = \frac{G' n_i^{5/2}}{n_i'^{3/2}}$$

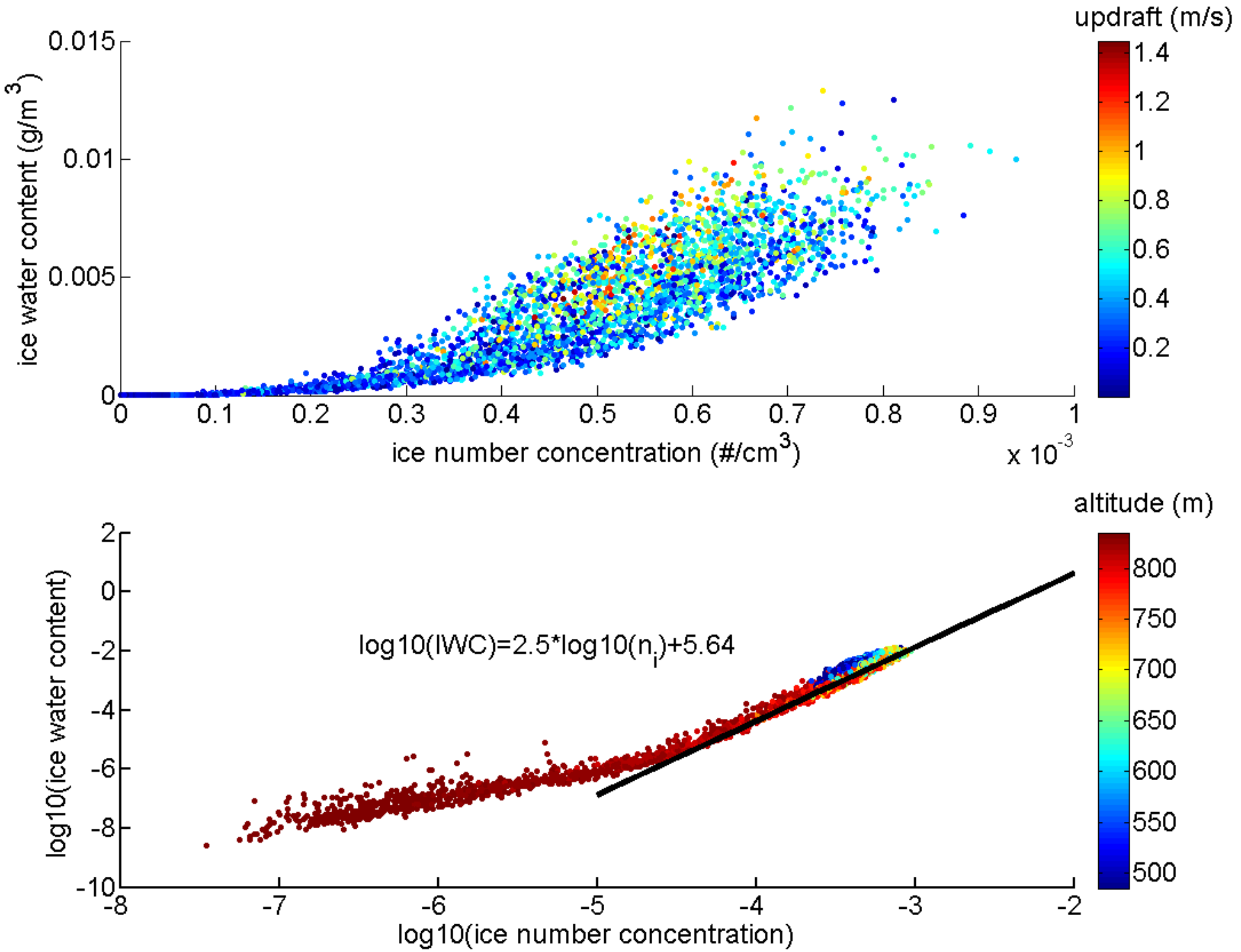
with $G' = \frac{1}{6}\pi \rho_i (2CDs_i)^{\frac{3}{2}}$

Note: 5/2 power law (compare to linear relation expected for mixing or dilution)

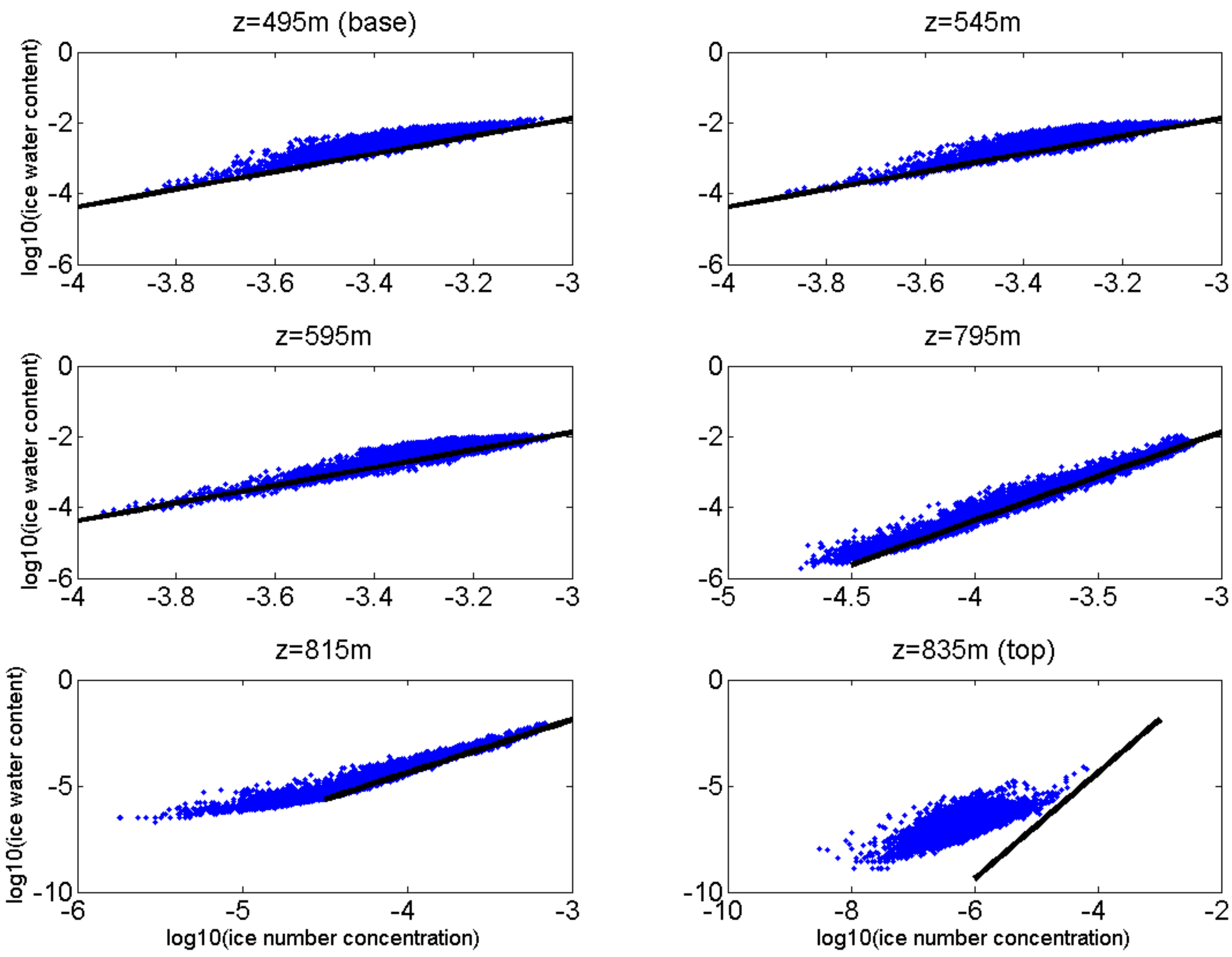
Test with an LES cloud model:
Implement stochastic ice nucleation
proportional to number of cloud droplets

IWC versus ice number concentration…

$$IWC = \frac{G' n_i^{5/2}}{n_i'^{3/2}}$$

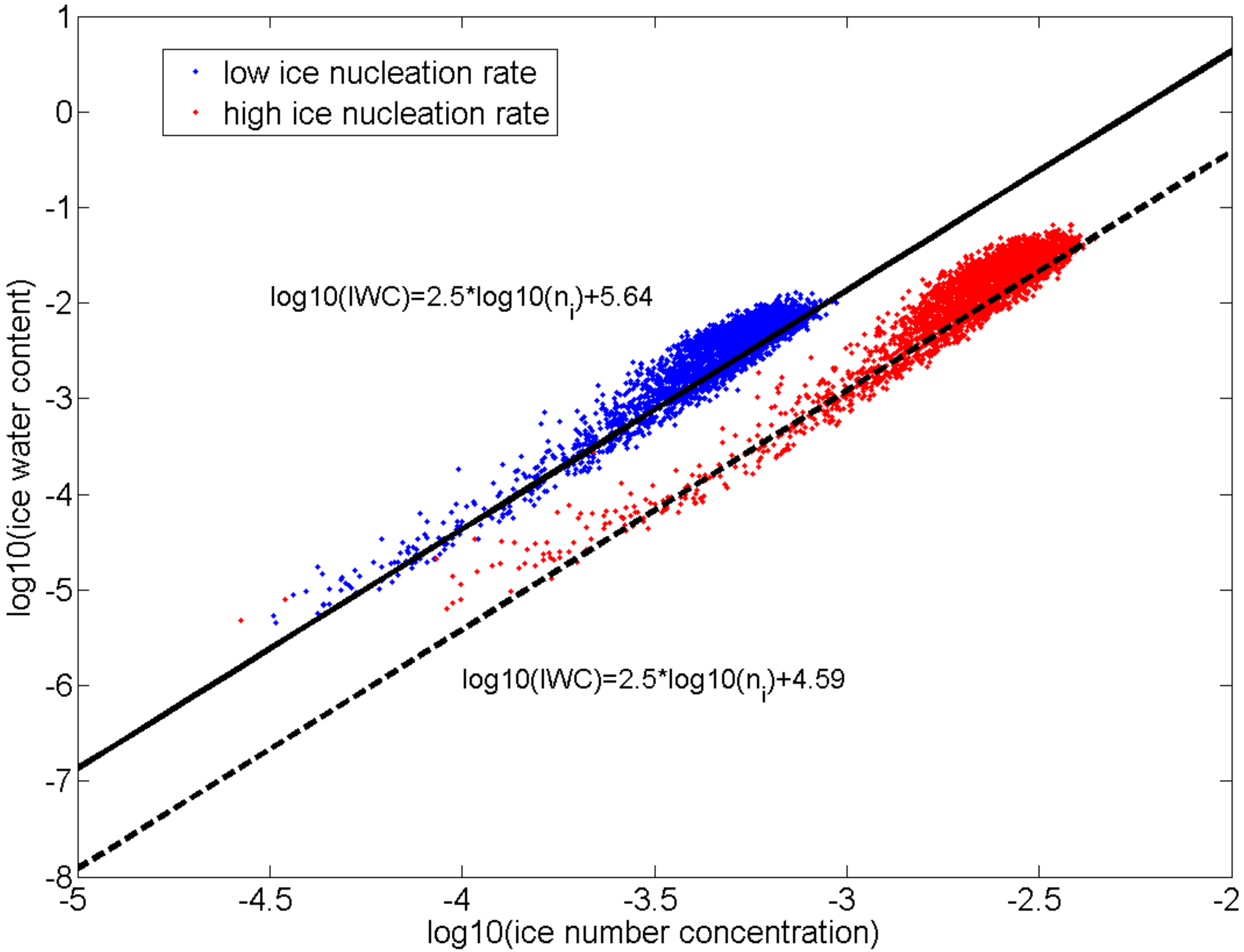


2.5 power law throughout cloud…

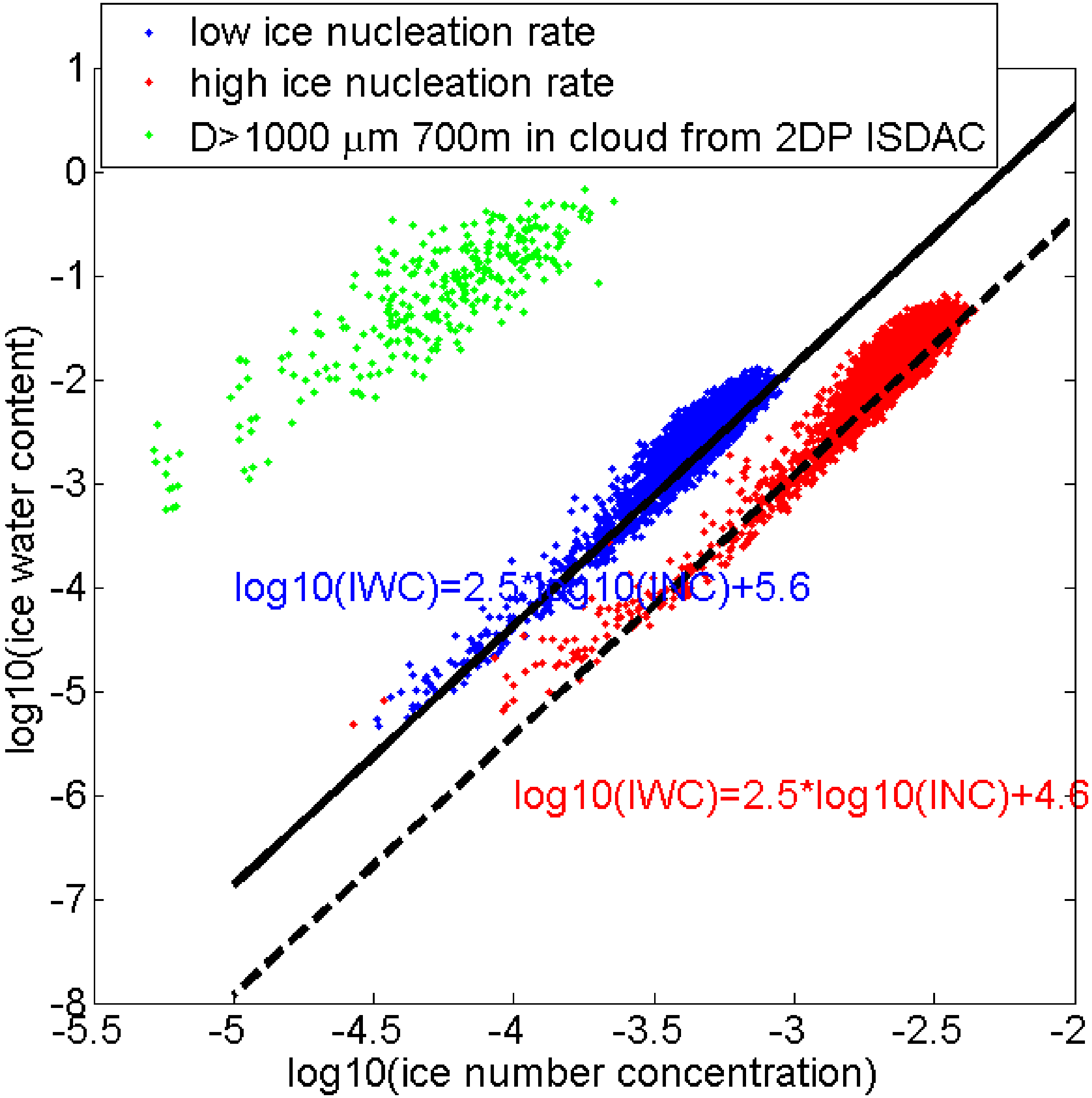


Dependence on ice nucleation rate…

$$IWC = \frac{G' n_i^{5/2}}{n_i'^{3/2}}$$



ISDAC observations…



Summary…

A simple model including

- Stochastic ice nucleation
- Deposition growth of ice in water saturated cloud
- Ice crystal settling in a linear-velocity “accumulation zone”

Predicts

- Quasi-steady scenario in which crystals falling from cloud are uniform size
- Power-law relationship between ice mass and ice number with slope 2.5
- Ice mass-ice number curve depends on the nucleation rate

Interpretation of model results and observations:

- LES with stochastic ice nucleations shows the predicted power law
- ISDAC observations show some encouragement…