Lagrangian studies of ice nucleation and growth in mixed-phase stratiform clouds

Fan Yang¹, Mikhail Ovchinnikov², Raymond A. Shaw¹

¹Atmospheric Sciences Program & Dept. of Physics, Michigan Technological University
²Pacific Northwest National Laboratory

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

Question 1: Where do all the ice nuclei come from?
Question 2: How do the ice crystals get so big?
**Objective:** How simple can it be and still capture the essential physics?

1. Steady ice nucleation rate throughout cloud: \( n'_i = \phi n_w/\tau \)

2. Quasi-steady growth, with ice crystals falling out of an updraft only as fast as they can grow by vapor deposition:

3. Steady state: rate of ice crystal precipitation equal to rate of crystal nucleation

Using \( IW'C = n_i m_i \) simple model predicts

\[
IW'C = \frac{G' n_i^{5/2}}{n_i^{3/2}}
\]

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

Note: 5/2 power law between ice mass and ice number… with prefactor depending on ice nucleation rate

*For more details, see: Yang, Ovchinnikov, and Shaw, GRL, 40, 3756-3760 (2013)*
IWC versus ice number for ISDAC observations…

For more details, see: Yang, Ovchinnikov, and Shaw, GRL, 40, 3756-3760 (2013)
Questions leading to a Lagrangian view…

Questions about the 2.5 power law:

Is the volumetric, steady ice nucleation rate really necessary? (e.g., what if ice nuclei are introduced from the cloud top or from the surface?)

Is the idealized, 1D concept of quasi-steady growth in an updraft observed in a fully 3D simulation? (related question… can the quasi-steady growth explain the presence of very large ice crystals that cannot form in a thin layer cloud without vertical velocities?)
Trajectories...
Maximum velocity: $u_0 = v_0 = 2\text{ m/s}$

Time independent

$$u = u_0 \sin \left( \frac{2\pi x}{L} \right) \cos \left( \frac{2\pi y}{H} \right)$$

$$v = -v_0 \cos \left( \frac{2\pi x}{L} \right) \sin \left( \frac{2\pi y}{H} \right)$$

2D, time independent velocity field...

Inspired by Maxey and Corrsin (1986) and by Shipway and Hill (2012)
Trajectories...

- $z=750m$

- $z=700m$

- $z=650m$
Lagrangian trajectories: quasi-steady growth...
Lagrangian trajectories: recycled particles...
Trajectories in \((r, z)\) coordinates...

Quasi-steady growth

Vertical wind speed (m/s)
Trajectories in \((r, z)\) coordinates...

- Quasi-steady growth
- Recycled growth

Vertical wind speed (m/s)
\((r, z)\) trajectories in the LES...

Shaded area:
Supercooled liquid cloud

Vertical wind speed (m/s)
A simple model including stochastic ice nucleation and ice growth

- **Quasi-steady** scenario in which crystals fall from the cloud only as fast as they can grow by deposition
- Power-law relationship between ice mass and number with **slope 2.5**
- Ice mass—ice number curve depends on the **nucleation rate**

Interpretation of model results and observations:

- LES with **IN source within liquid cloud** shows the predicted power law
- Ice crystals originating at **cloud top** or **cloud base** do not show the 2.5 power law
- Lagrangian tracks show surprising number of **long lifetime ice crystals**
- Idealized 2D cellular flow field allows us to study idealized trajectories
- Lagrangian trajectories show **quasi-steady growth**
- Lagrangian trajectories also show importance of **“recycled” ice crystals**
- LES trajectories show similar signatures for trajectories

*For more details, see: Yang, Ovchinnikov, and Shaw, GRL, 40, 3756-3760 (2013)*