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

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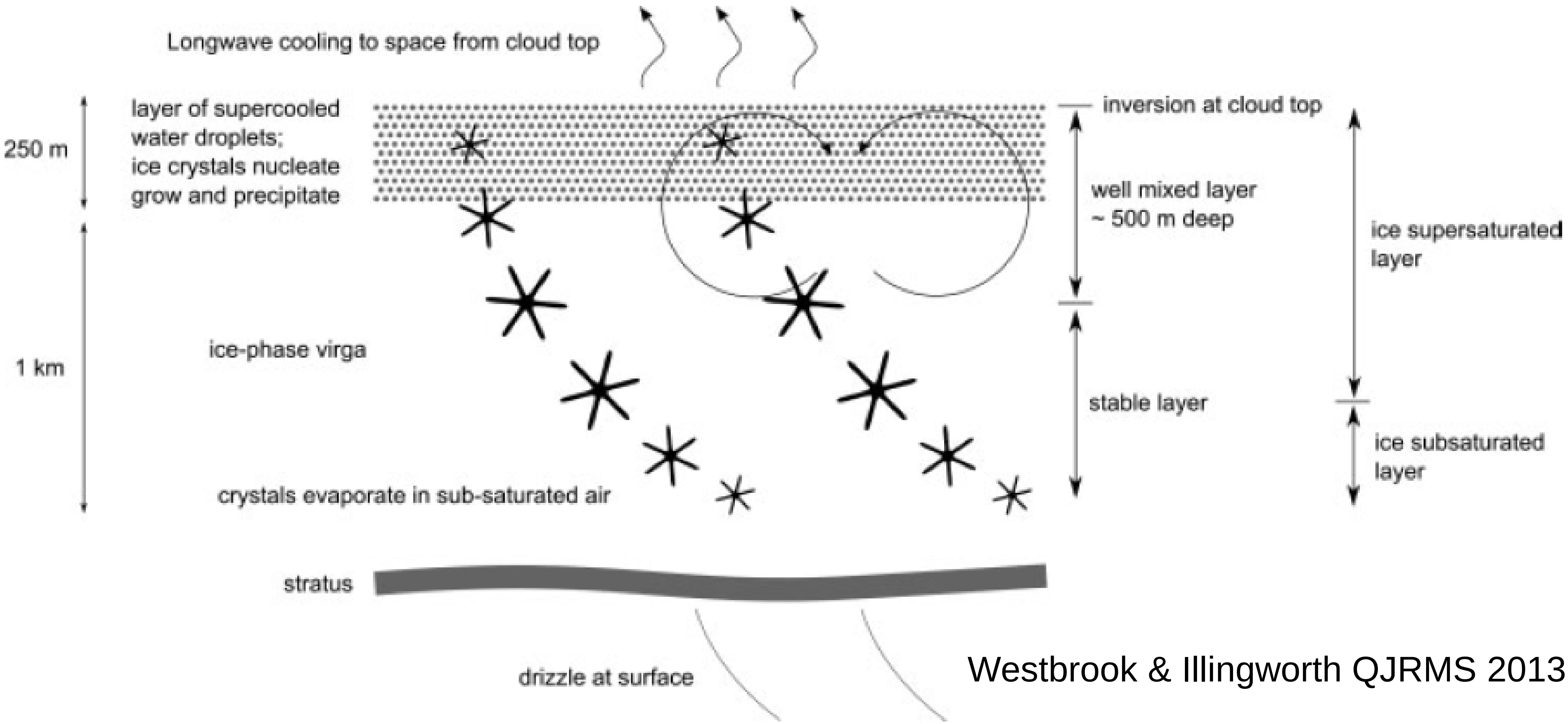
Acknowledgements: DOE ASR

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 1: Where do all the ice nuclei come from?

Question 2: How do the ice crystals get so big?

Simple model of ice nucleation and growth…

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: $v = \frac{h}{2r_i}\frac{dr_i}{dt}$
3. Steady state: rate of ice crystal precipitation equal to rate of crystal nucleation

Using $IWC = n_i m_i$ simple model predicts

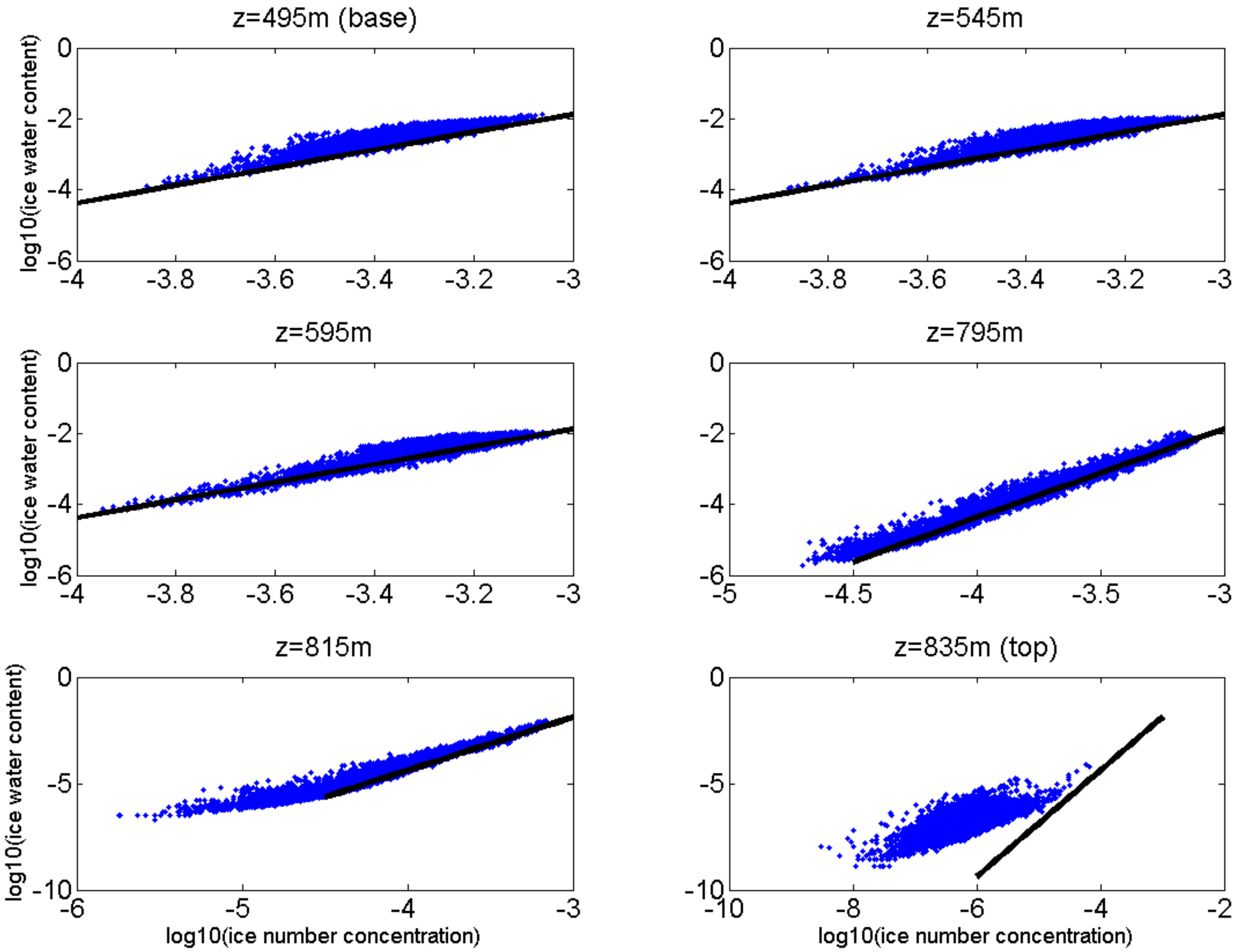
$$IWC = \frac{G' n_i^{5/2}}{n_i'^{3/2}}$$

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

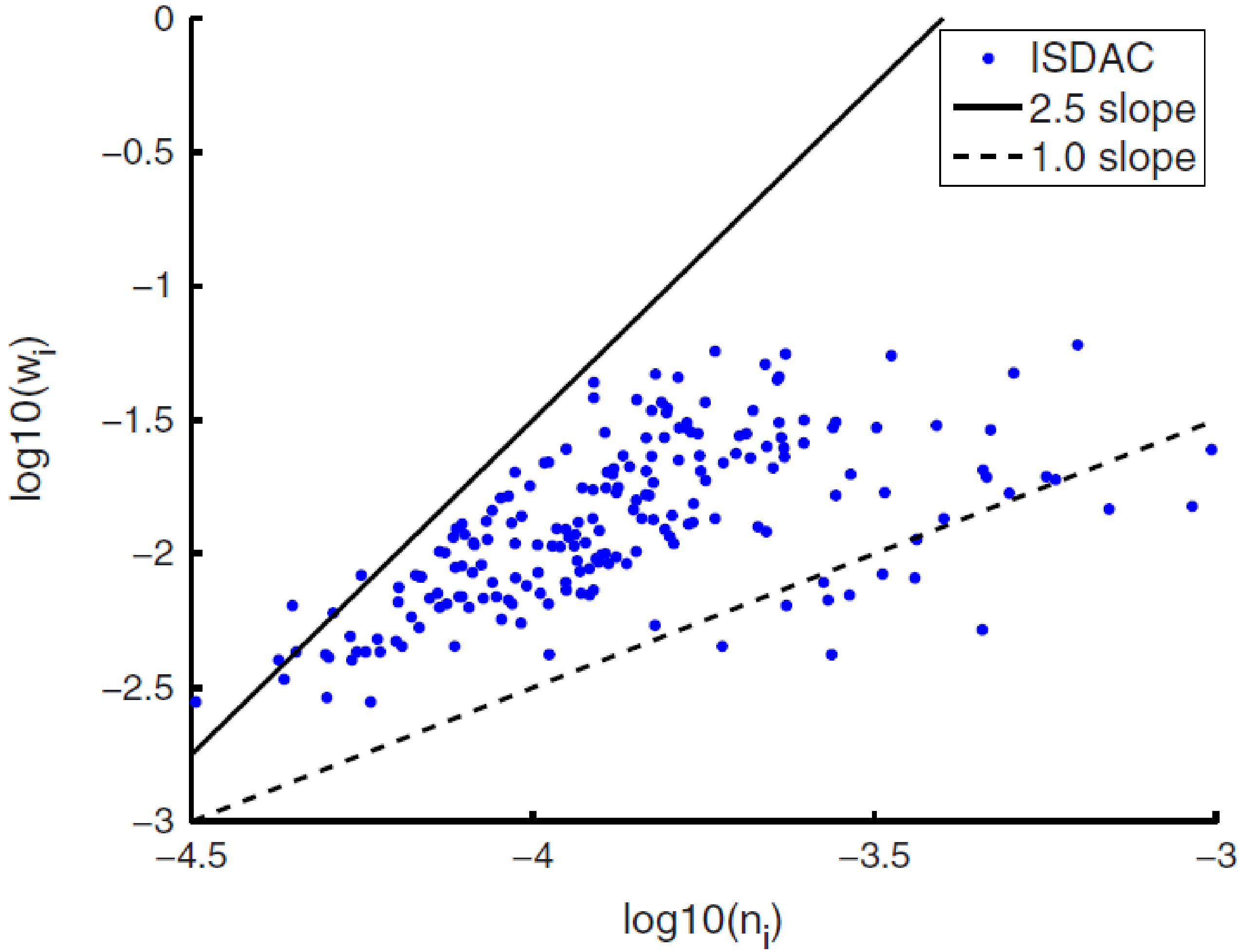
Note: 5/2 power law between ice mass and ice number…
with prefactor depending on ice nucleation rate

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

IWC versus ice number concentration from LES…



IWC versus ice number for ISDAC observations…



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Questions leading to a Lagrangian view…

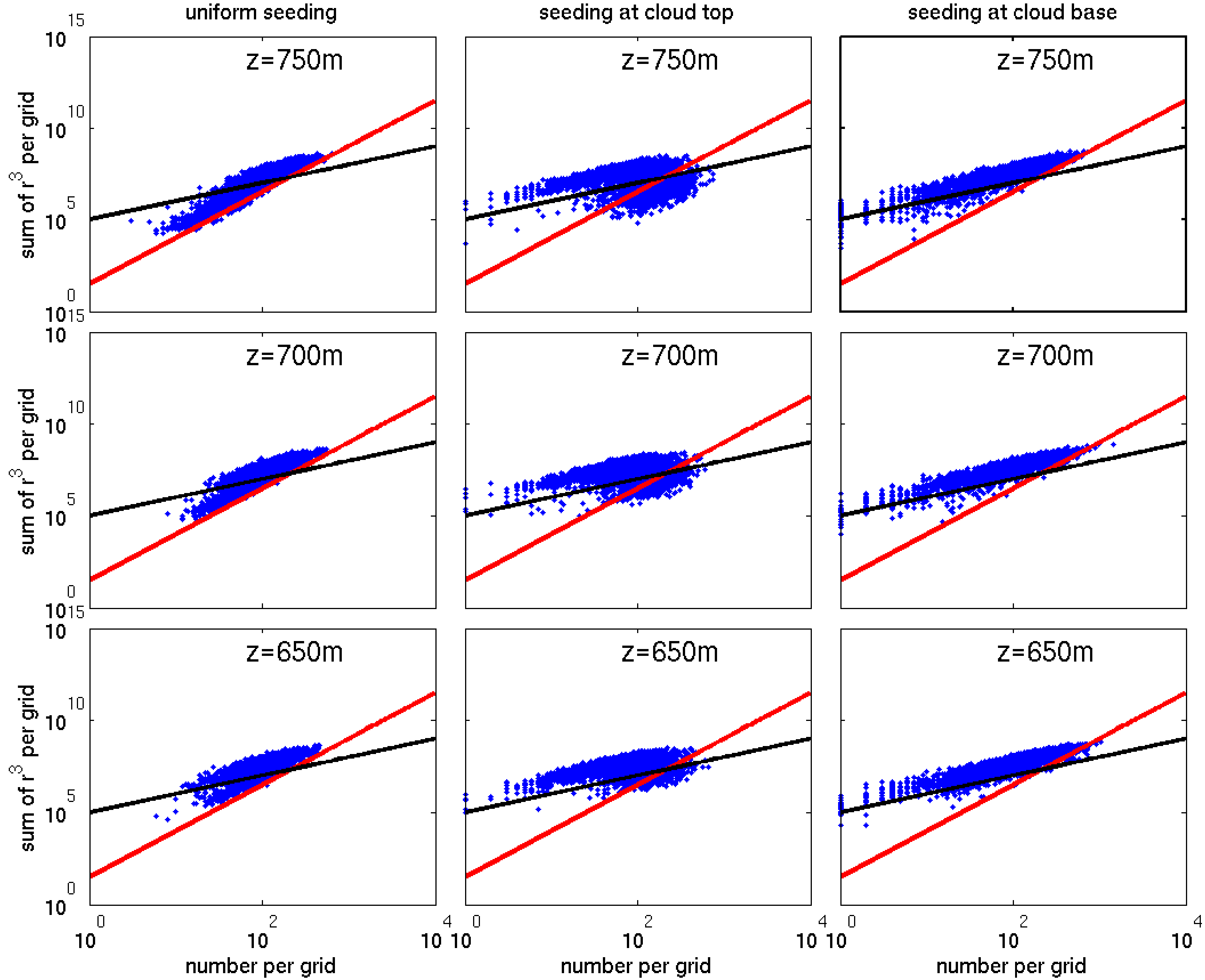
Questions about the 2.5 power law:

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*?)

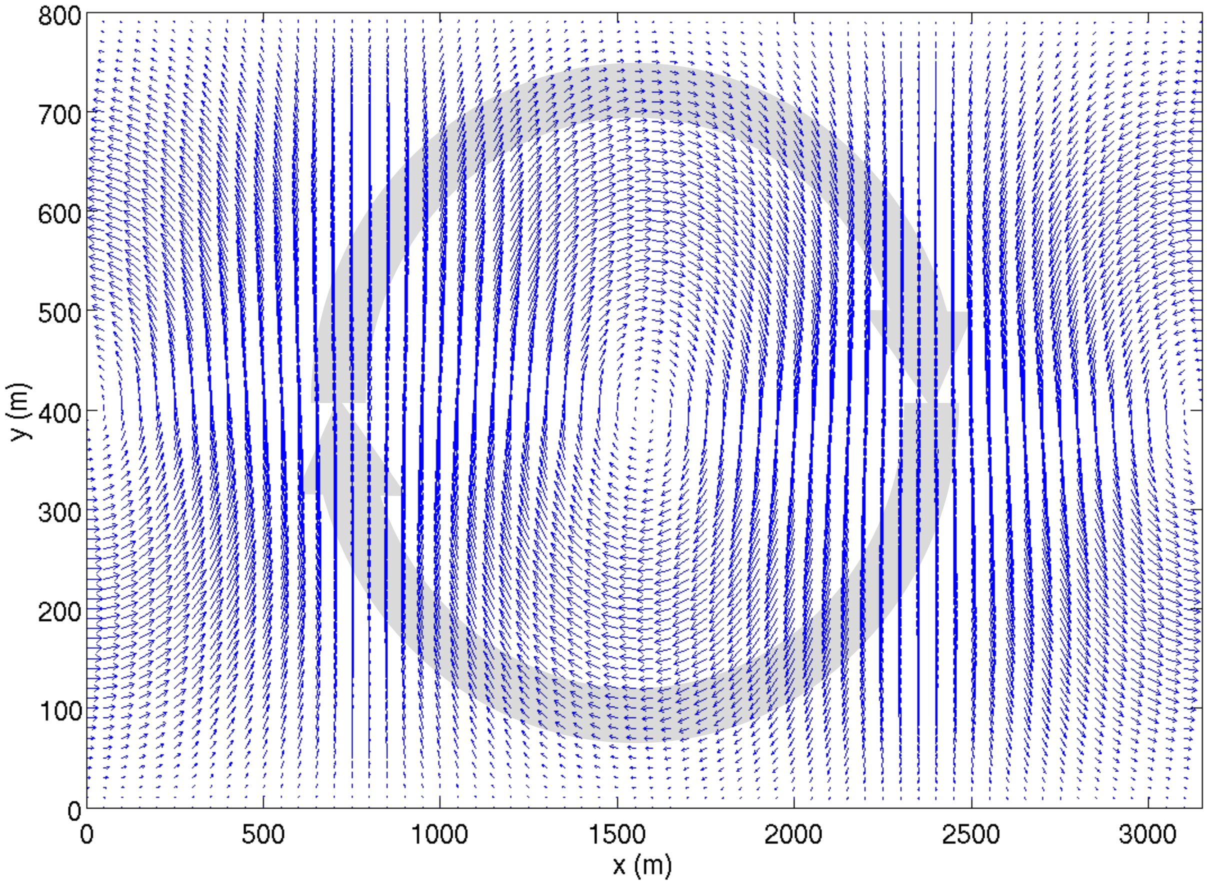


uniform seeding
seeding at cloud top
seeding at cloud base
z=750m
z=700m
z=650m
sum of r³ per grid
number per grid

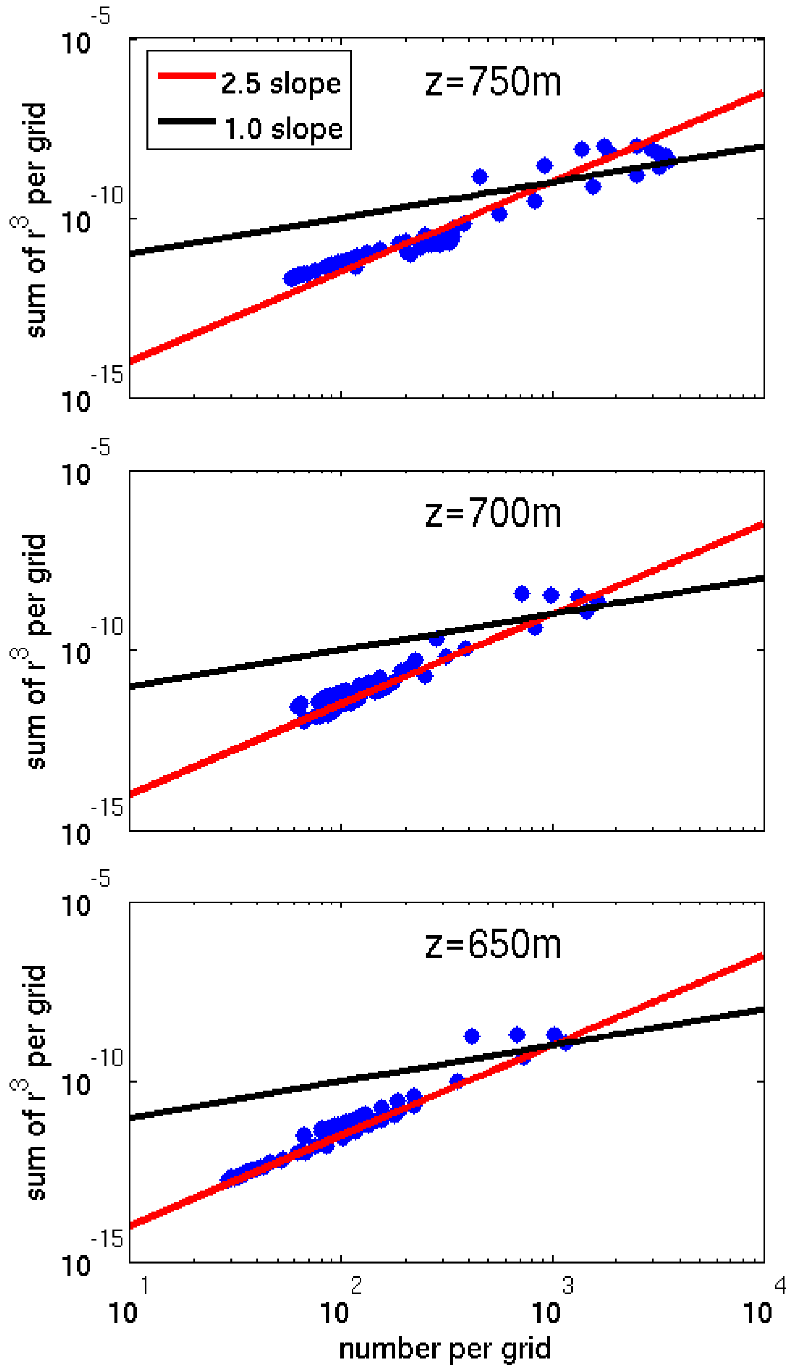
2D, time independent velocity field…

Maximum velocity: u_0=v_0=2m/s
Time independent

$$u = u_0 \sin(2\pi x/L)\cos(2\pi y/H)$$
$$v = -v_0 \cos(2\pi x/L)\sin(2\pi y/H)$$

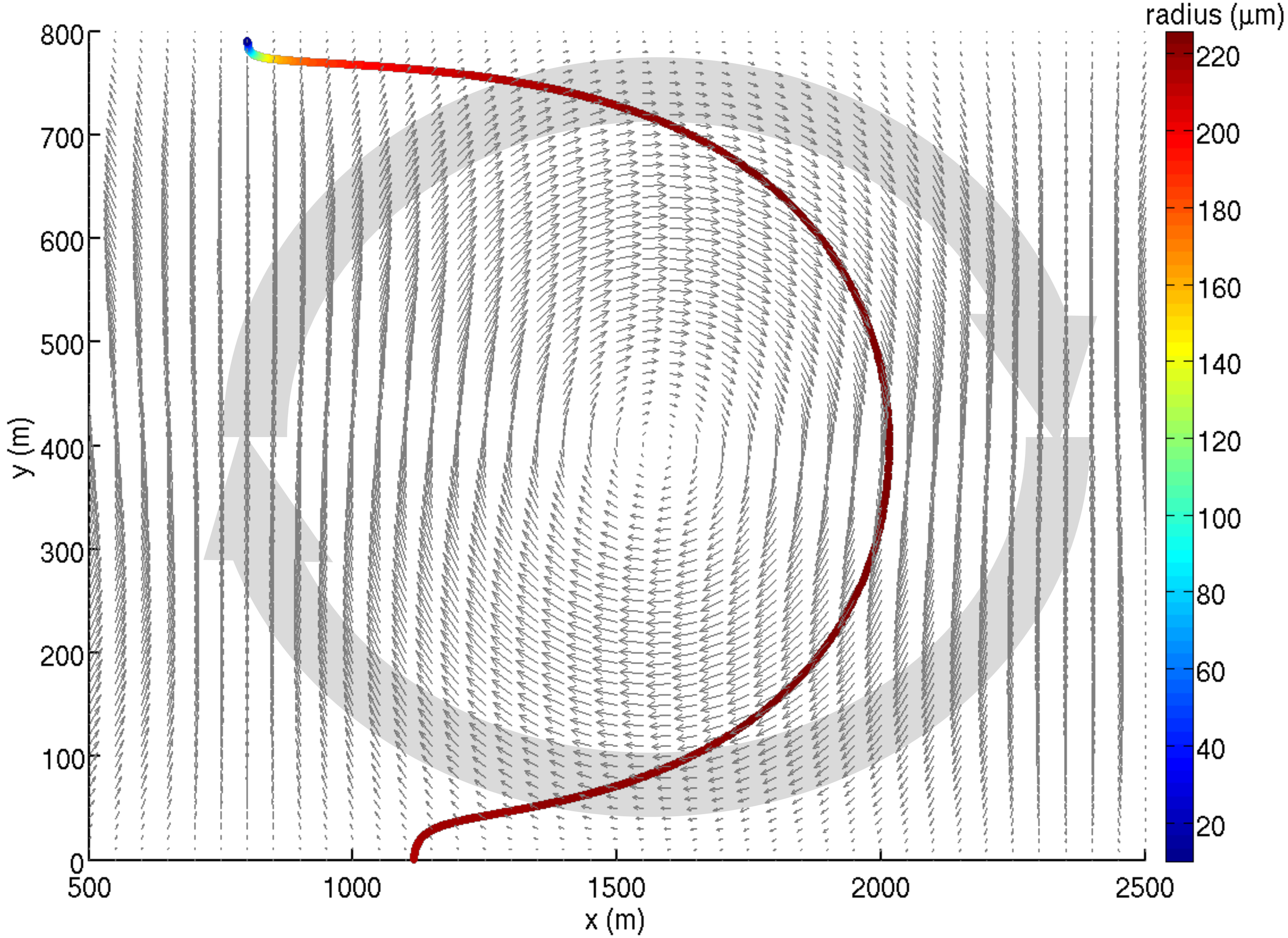


Inspired by Maxey and Corrsin (1986) and by Shipway and Hill (2012)

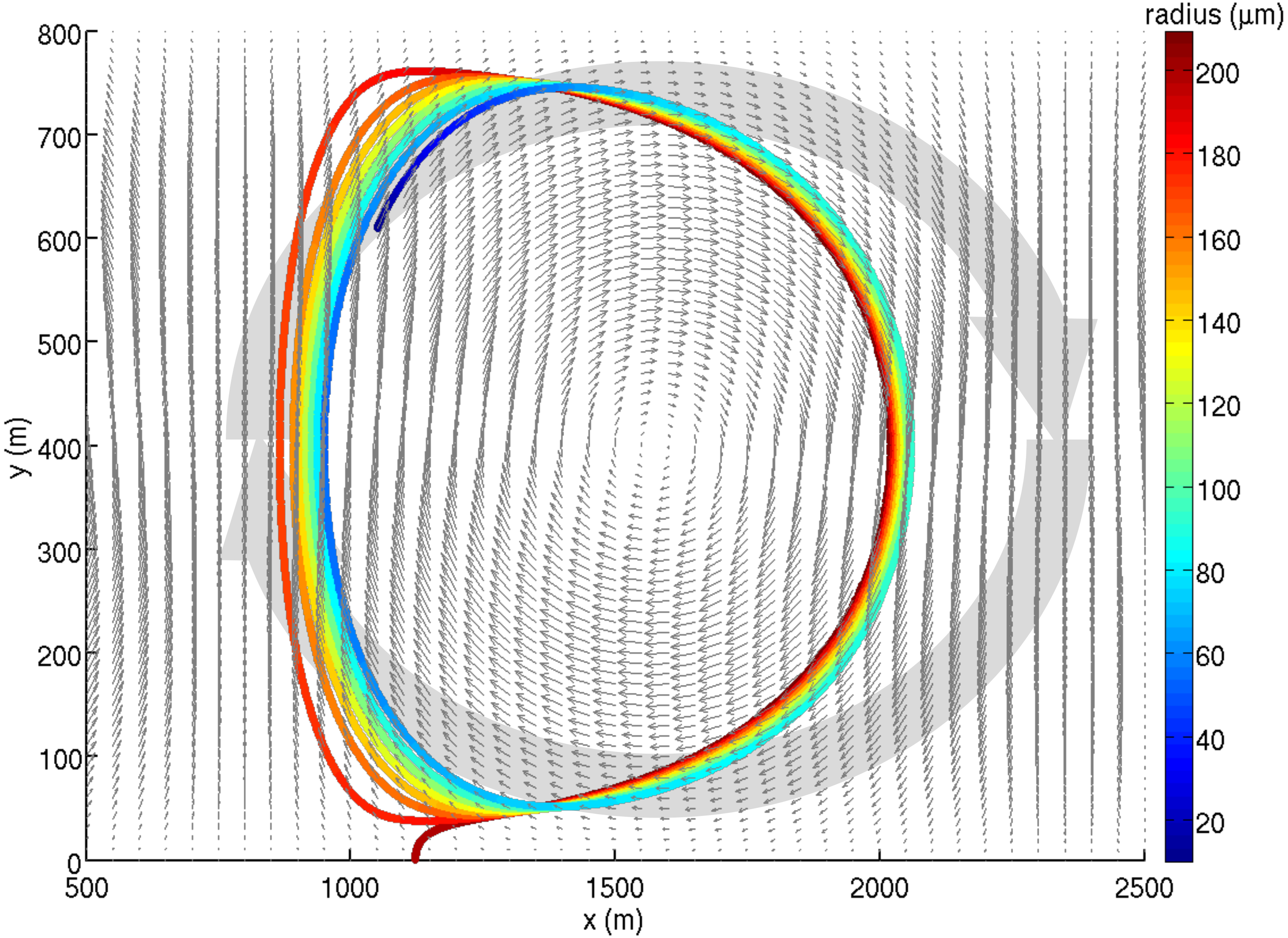


2.5 slope
1.0 slope
z=750m
z=700m
z=650m
sum of r^3 per grid
number per grid
10^{-5}
10^{-10}
10^{-15}
10^{1}
10^{2}
10^{3}
10^{4}

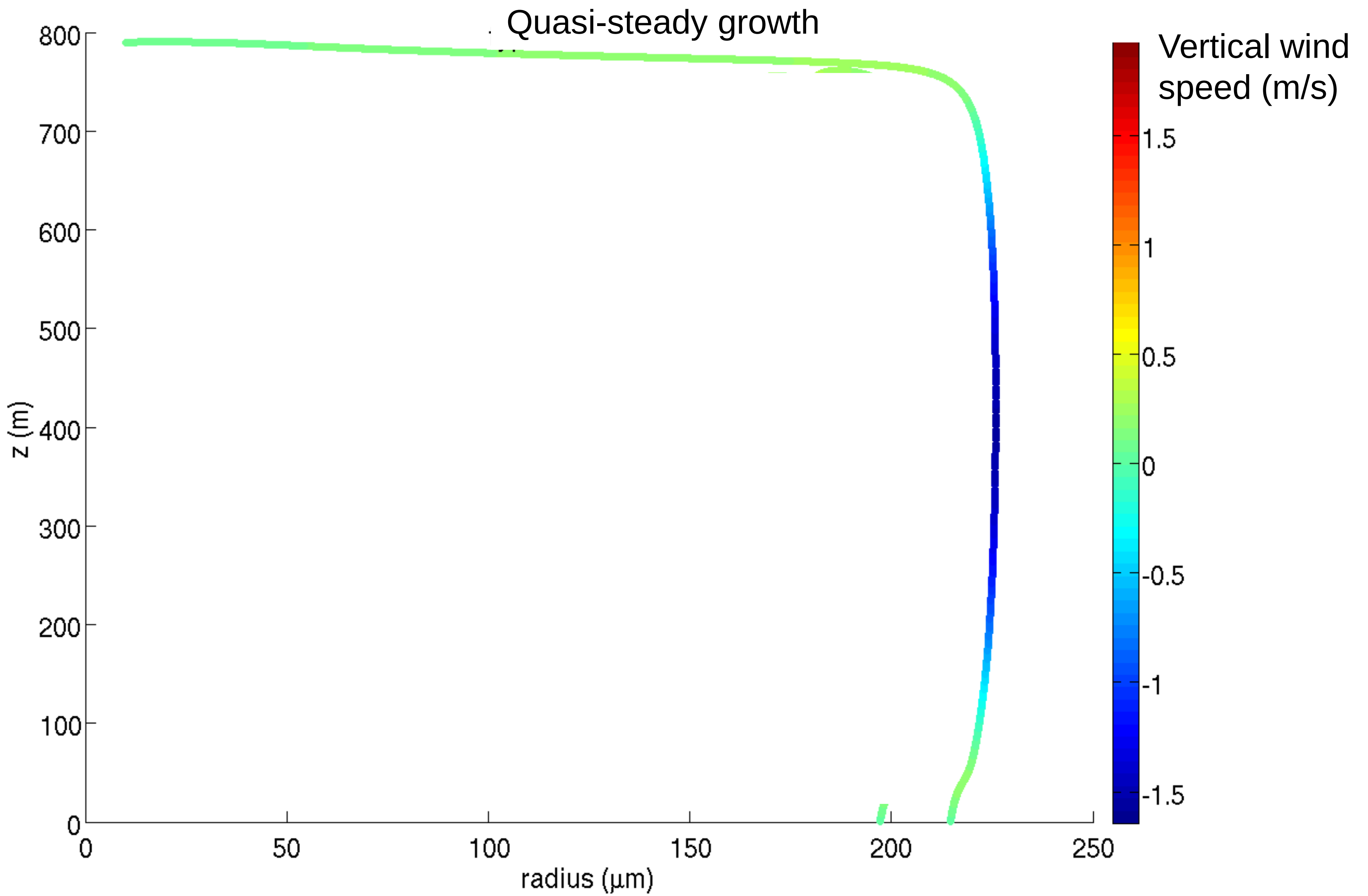
Lagrangian trajectories: quasi-steady growth…



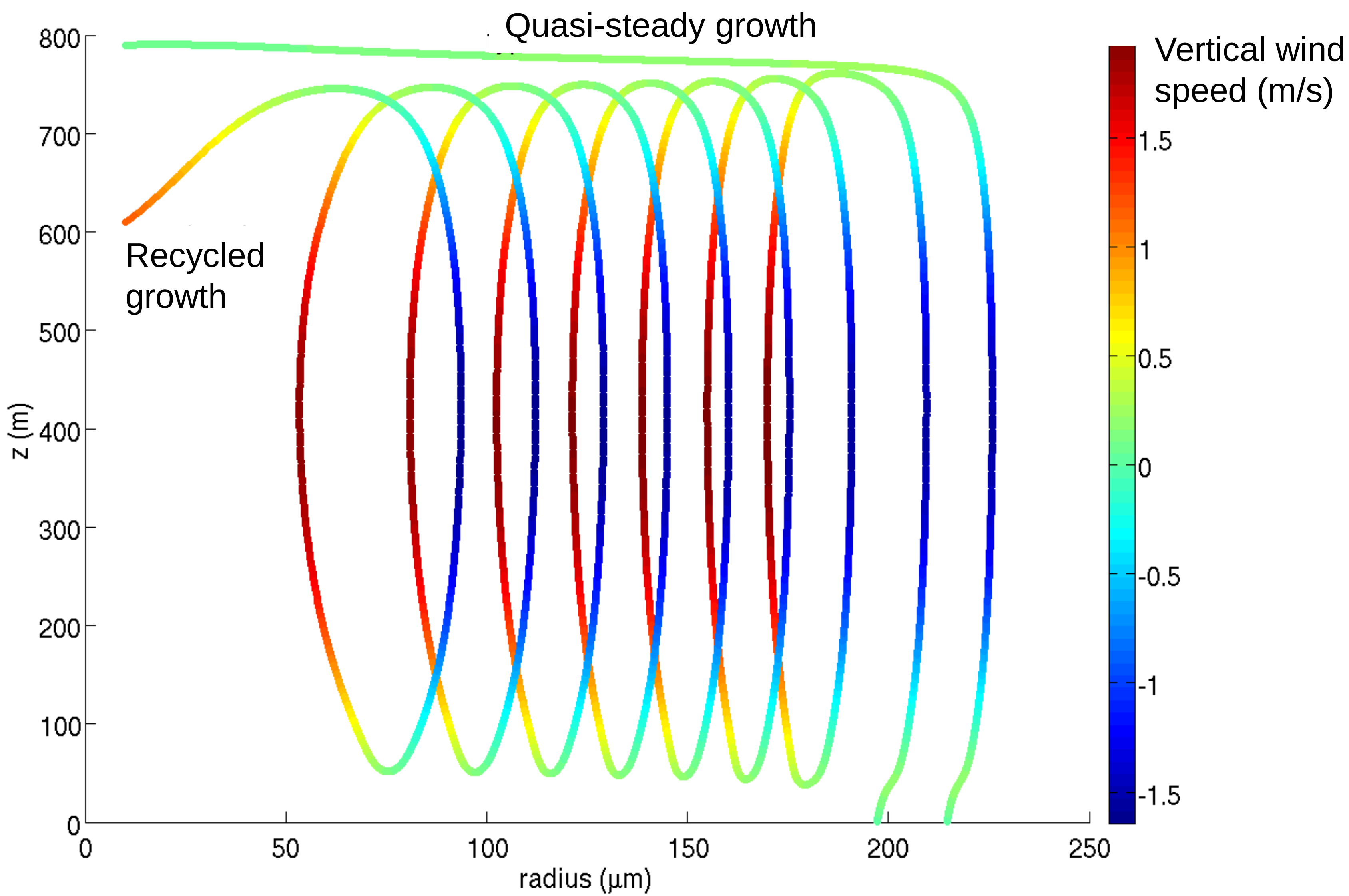
Lagrangian trajectories: recycled particles…



Trajectories in (r, z) coordinates…

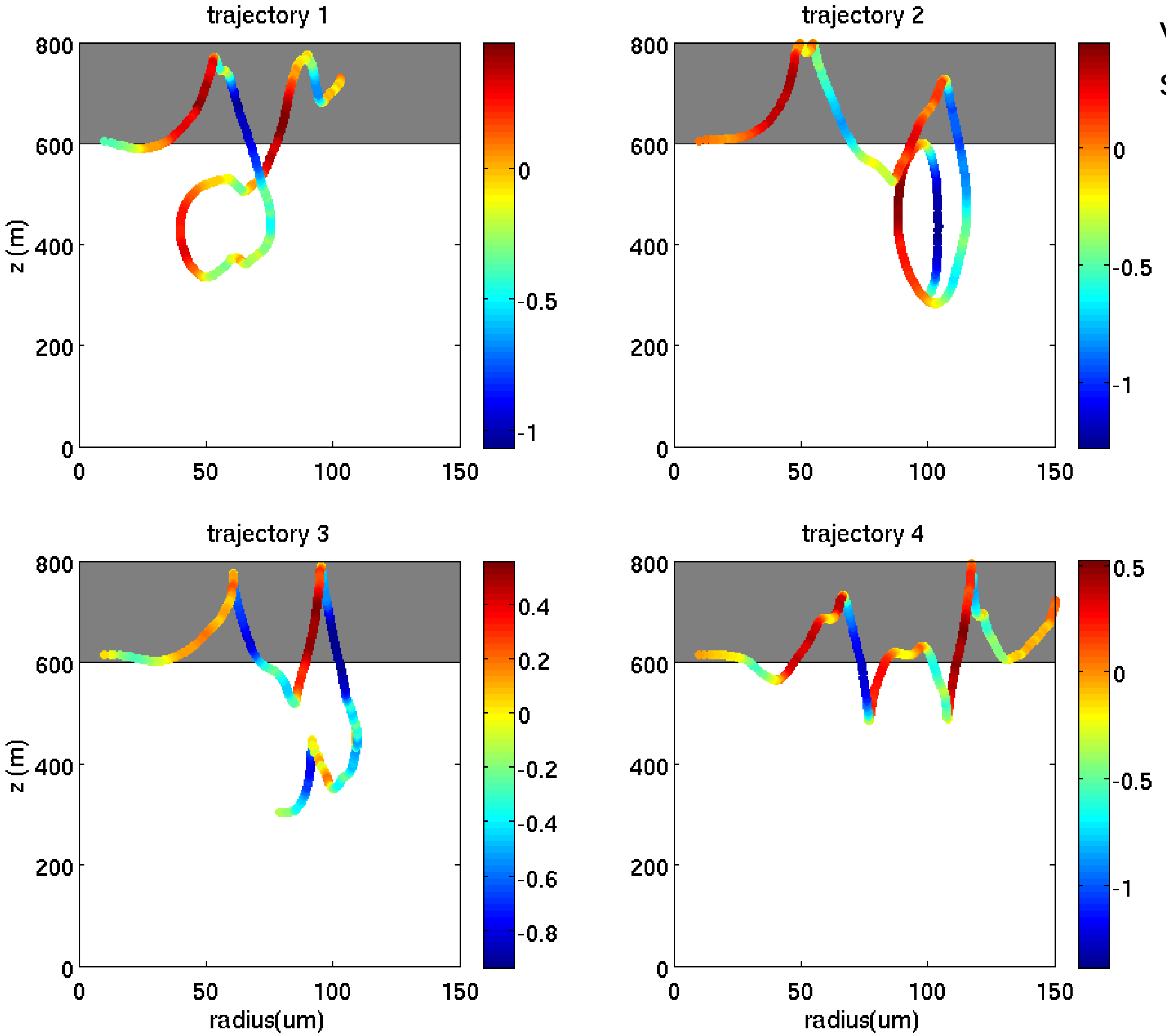


Trajectories in (r, z) coordinates…



(r, z) trajectories in the LES…

Shaded area: Supercooled liquid cloud



Vertical wind speed (m/s)

Summary…

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

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