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Theory and observations of ice particle evolution, using Doppler radar

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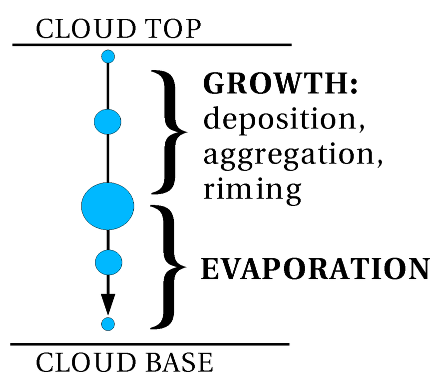
1 Introduction

The growth of ice crystals and snowflakes in ice clouds is a key process both for the development of preciptation, and in terms of the effect that such clouds have on climate.

In this work, Doppler radar is used to study the evolution of ice particles as they sediment through the cloud. The measured Doppler fall speeds are used, together with radar-derived estimates for the cloud top altitude, in order to estimate the time for which the 'average' particle has been falling.

Here, the change in radar reflectivity is used as an indication of the growth and subsequent evaporation of the ice particles, and we study its variation as a function of how long the particles have been falling for.



2 Measuring particle fall time

We calculate a characteristic fall time for ice particles at a height h:

$$\langle t \rangle = \int_h^{h_{top}} \langle v \rangle^{-1} \mathrm{d}h$$

using the Doppler velocity profile $\langle v \rangle$ and the cloud top height h_{top} (estimated from the radar).

The radar wavelength was 8.57mm (35-GHz), so most cirrus particles are in the Rayleigh regime, where the reflectivity Z is the square of the mass m integrated over the particle size distribution $n(m)$:

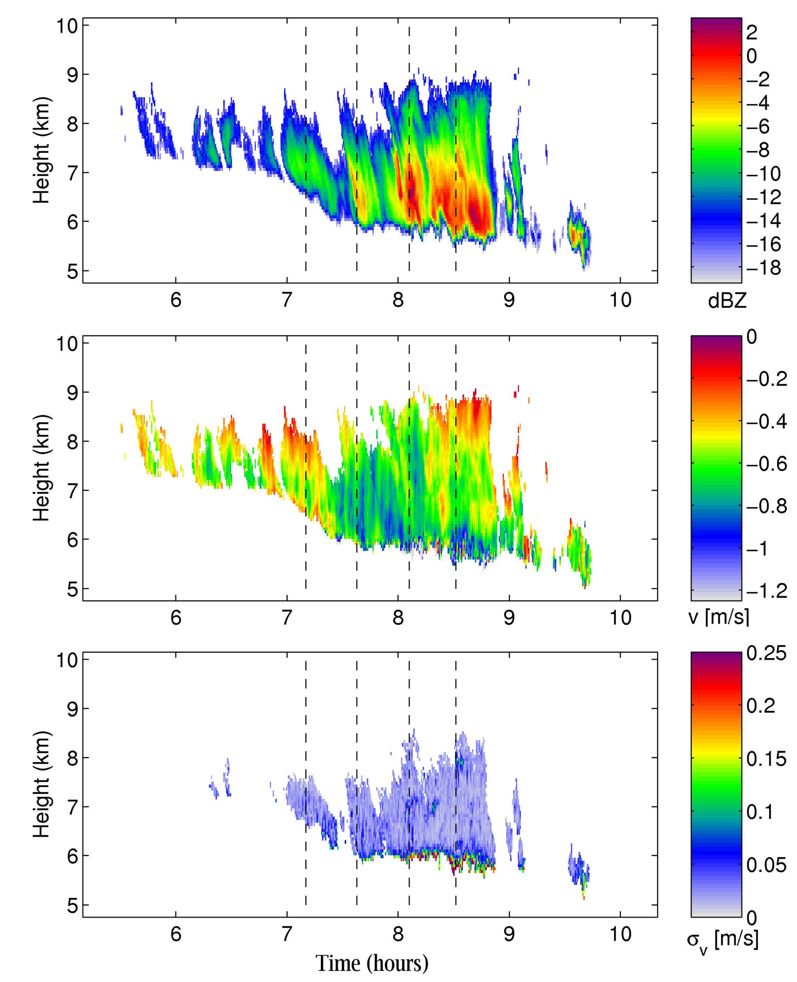
$$Z \propto \int n(m) m^2 \mathrm{d}m \qquad (1)$$

To investigate the evolution of the ice particles we take vertical profiles of cloud and study how Z changes with $\langle t \rangle$.

The variation in the reflectivity Z should be indicative of the changing average particle size, and we have attempted to quantify this (see panel 4).

The key advantage of plotting Z against fall time (rather than altitude) is that $\langle t \rangle$ has a direct physical relationship with the growth, whereas the evolution by altitude is convoluted with the (unknown) vertical air motion of the particles.

3 Cloud data



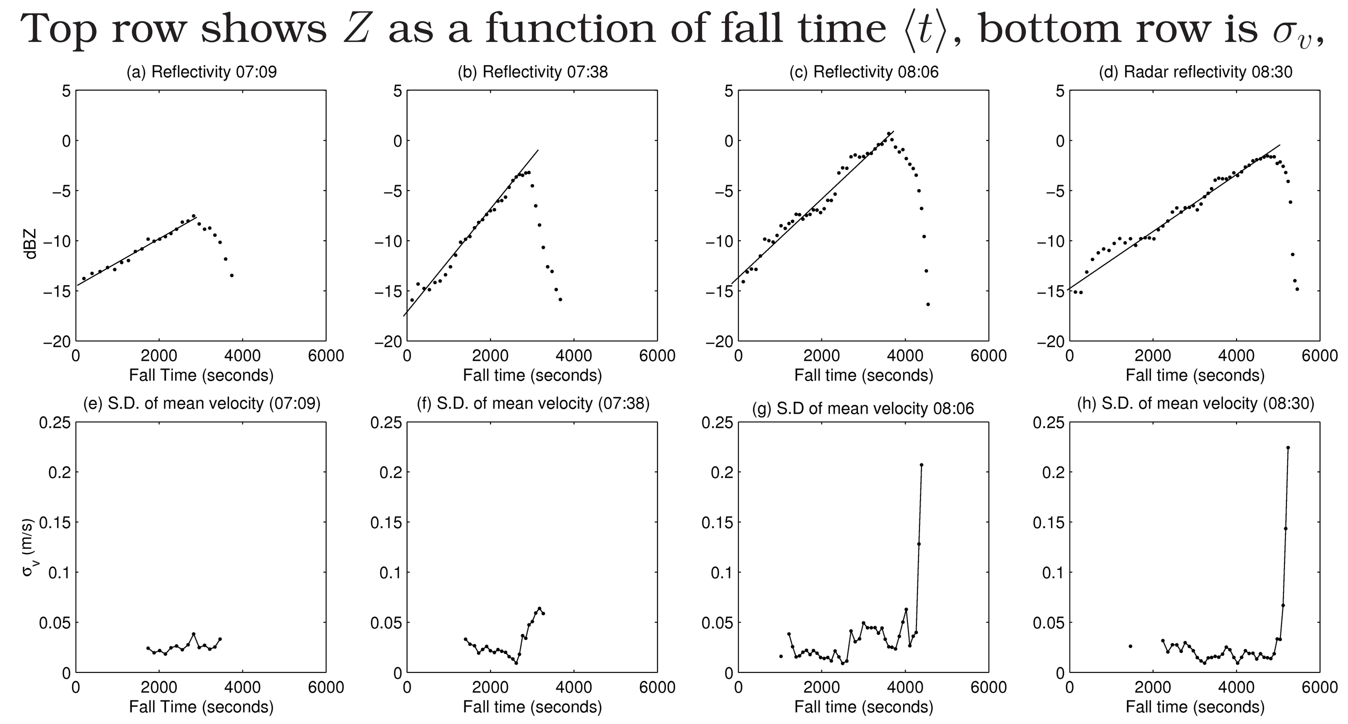
Vertically pointing radar measurements were made of an ice cloud over Chilbolton in the south of England on the 13th May 2004.

The time series is shown left; Z and $\langle v \rangle$ are averaged over 30 second intervals.

σ_v is standard deviation in the 1s doppler velocity over the 30s interval.

Here we analyse four vertical profiles (dashed lines):

Top row shows Z as a function of fall time $\langle t \rangle$, bottom row is σ_v,



All four of the reflectivity profiles show a **clear exponential increase with fall time** for between 2500-5000 seconds, which we attribute to particle growth in the cloud.

At the largest times (near the base of the cloud) there is a sharp fall off in Z. We attribute this to evaporation of the particles, and in at least two of the cases shown above there is a sudden increase in σ_v, indicative of turbulence and evaporation.

We have analysed a number of other case studies in a similar way, and a significant fraction have shown the same exponential growth.

4 Scaling distributions

Observations indicate ice particle size distributions scale 'dynamically': the basic psd shape is always the same, but rescaled as the particles grow larger.

A key result from this idea is that the psd moments are related:

$$Z = \int n(m) m^2 \mathrm{d}m \propto \langle m \rangle^{2-k} \int n(m) m^k \mathrm{d}m$$

where $\langle m \rangle$ is the average particle mass.

We now assume that there is some moment of the distribution k which is conserved through the vertical profile.

For aggregation this is mass flux density $k = 1 + c$ (where $v \propto m^c$)
For deposition or riming it's the total concentration (of ice) $k = 0$.

If this assumption is correct, then Z and $\langle m \rangle$ exist in a power law relationship. From our observations of $Z \sim \exp(\langle t \rangle)$: this means that **the average particle size grows exponentially with fall time**.

5 Indicative of aggregation?

For aggregation the growth depends on the scaling of the collision rate between particles of mass m_i, m_j:

$$\text{Collision rate } (2 \times m_i, 2 \times m_j) = 2^{\lambda} \times \text{Collision rate } (m_i, m_j)$$

There are two physical regimes[a] for the parameter λ:
$\lambda < 1$ where $\langle m \rangle \propto t^{1/(1-\lambda)} \Rightarrow$ power law Z
$\lambda = 1$ where $\langle m \rangle \propto \exp(wt)$, w=constant $\Rightarrow$ **exponential** Z

Recently, a new model of ice crystal aggregation[b] has proposed a feedback between the drag law and the particle geometry, which stabilises the growth at $\lambda = 1$. This theory leads to the prediction that mass $\propto$ diameter^2 in agreement with observations[c]. We suggest that these radar observations of exponential particle growth are further evidence for this theory.

Future directions: theory indicates that the slope of the dBZ-$\langle t \rangle$ plots should provide an estimate for the mass flux density, though need an estimate of the collision efficiency.

New dual wavelength (35 & 94-Ghz) measurements will give a more direct measure of average particle size.

[a] Van Dongen and Ernst (1985) *Phys. Rev. Lett.* **54** 1396
[b] Westbrook, Ball, Field (2004), *Phys. Rev. E* **70** 021403
[c] Brown and Francis (1995), *J. Atmos. & Ocean. Tech.* **12** 410