Stochastic Approach to Study Cirrus Structure Using ARM Millimeter Wavelength Radar Observations

K. Ivanova, Pennsylvania State University **T.P. Ackerman**, University of Washington

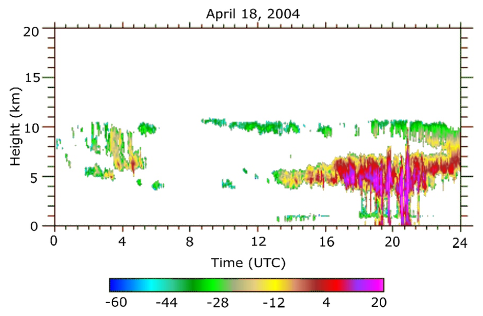
Motivation

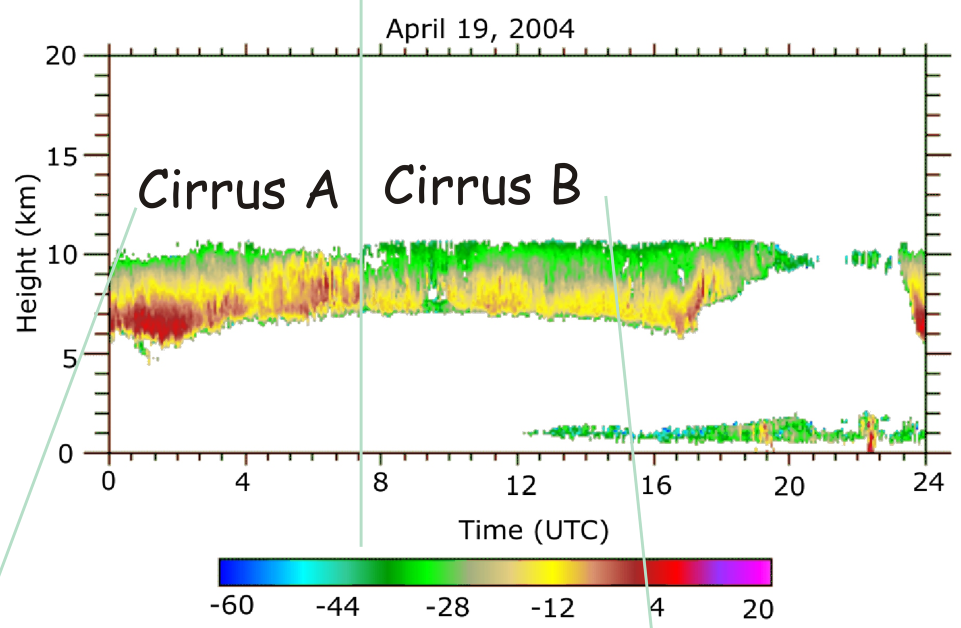
Knowledge of the local dynamical properties within cirrus and the radiative response due to these properties is still lacking.

The interactions between the synoptic conditions in which cirrus form and maintain, and the small-scale of individual generating cells are still not quantitatively understood.

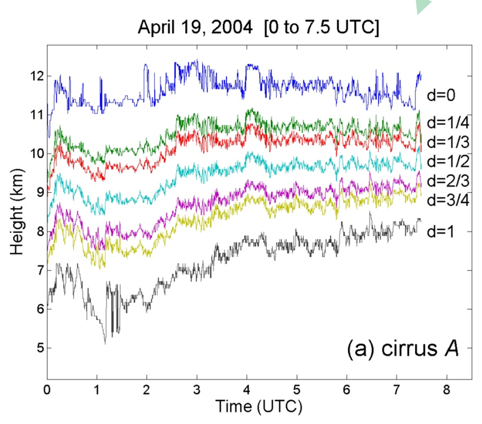
Observations:

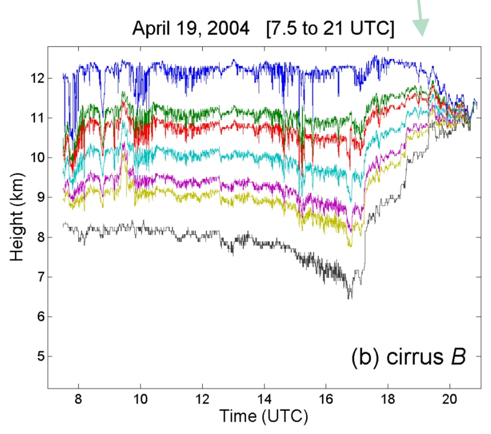
MMCR measurements at ARM SGP site



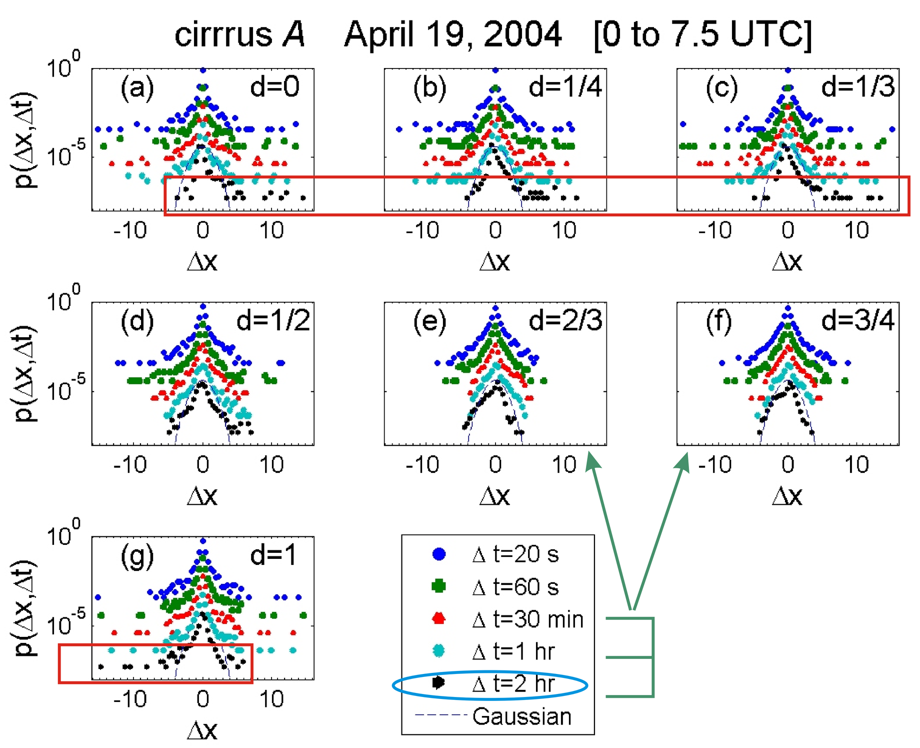


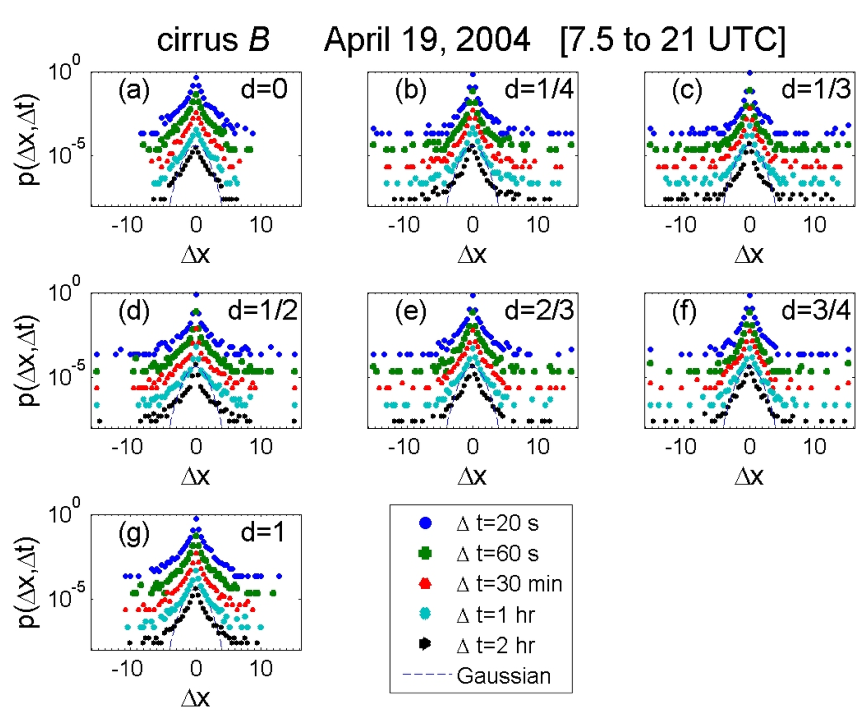
Consider time series of radar reflectivity at depth d into cloud relative to cloud top





Probability distribution functions (pdfs) of reflectivities for various delay times Δt





We find that 2hr scale (~100 km) cirrus A

The pdfs are time-dependent and non-Gaussian for both cirrus A&B.

The pdfs for delay times Δt=2hr for cirrus A exhibit behavior that is consistent with structure of cirrus based on aircraft in situ measurements [Heymsfield and Miloshevich, 1995], and with results from ground-based Raman lidar studies [Comstock et al., 2004].

The upper 33% of cirrus A shows behavior that is in accordance with what is expected from a region of nucleation with long deposition times as fond in model studies [Khvorostyanov and Sassen, 1998].

The pdfs (Δt=2hr) at the base (d=1) are suggestive of sublimation.

Method of Analysis

It is known that two equations govern the dynamics of a system.

The Fokker-Planck equation for the probability distribution functions

$$\frac{\partial p(x,t)}{\partial t} = \left[-\frac{\partial}{\partial x} D_1(x,t) + \frac{\partial^2}{\partial x^2} D_2(x,t) \right] p(x,t)$$

And the Langevin equation for the state of the system

$$\frac{dx}{dt} = h(x,t) + g(x,t)W(t)$$

All slow, large scale processes — Stochastic approximation to the fast nonlinear processes

Because we infer a stochastic model from discrete empirical data, the Ito calculus is more relevant to describe the dynamics of the system. The Kramers-Moyal expansion of the drift D_1 and diffusion D_2 coefficients is:

$$D_1(x,t) = h(x,t) + \frac{\partial g(x,t)}{\partial x} g(x,t)$$

$$D_2(x,t) = g^2(x,t)$$

The functional dependence of the drift D_1 and diffusion D_2 coefficients can be estimated directly from the moments of conditional probability distribution:

$$D_n(x,t) = \frac{1}{n!} \lim_{\Delta t \to 0} M_n(x,t,\Delta t),$$

$$M_n(x,t,\Delta t) = \frac{1}{\Delta t} \int_{-\infty}^{+\infty} (x' - x)^n p(x', t - \Delta t | x, t) dx'$$, for n=1,2...

Connects the probabilities at larger scales with all smaller, embedded scales

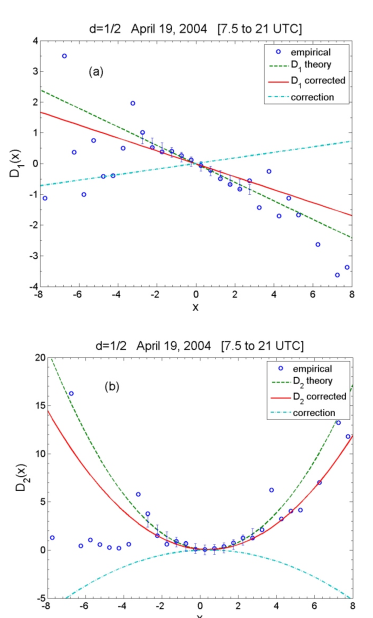
Therefore, the Fokker-Planck equation provides a method for obtaining the drift D_1 and diffusion D_2 coefficients directly from observations.

Effective drift — Deterministic drift — Noise-induced drift

$$D_1^{eff}(x,t) = D_1^{d.d.}(x,t) + D_1^{n.i.}(x,t)$$

$$D_1^{d.d.}(x,t) = h(x,t) \qquad D_1^{n.i.}(x,t) = \frac{\partial g(x,t)}{\partial x} g(x,t)$$

Effective, deterministic, and noise-induced drift



$$\tilde{D}_1^{eff}(x) = a_1 x + a_0$$

$$\tilde{D}_1^{n.i.}(x) = b_2 x + b_1/2$$

$$\tilde{D}_1^{d.d.}(x) = \tilde{D}_1^{eff}(x) - \tilde{D}_1^{n.i.}(x)$$

$$\tilde{D}_1^{d.d.}(x) = h_1 x + h_0$$

$$\tilde{D}_2(x) = b_2 x^2 + b_1 x + b_0$$

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Contact info:
ivanova@psu.edu
ackerman@atmos.washington.edu

We demonstrate that

The time-dependent, non Gaussian pdfs can be produced by a linear system (linear drift D_1) with multiplicative noise (quadratic D_2).

The former is tentatively identified with larger-scale forcing and the latter with in-cloud circulation and turbulence.

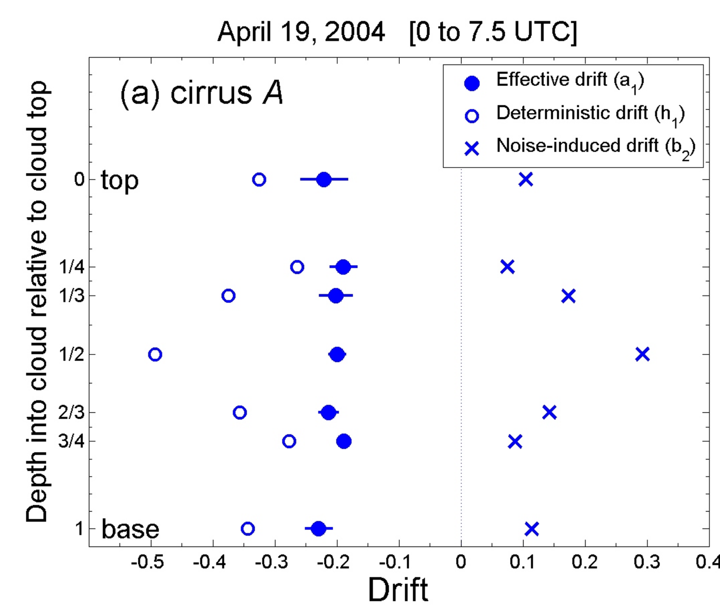
Obtained quadratic dependence of D_2 leads to the existence of noise-induced drift term.

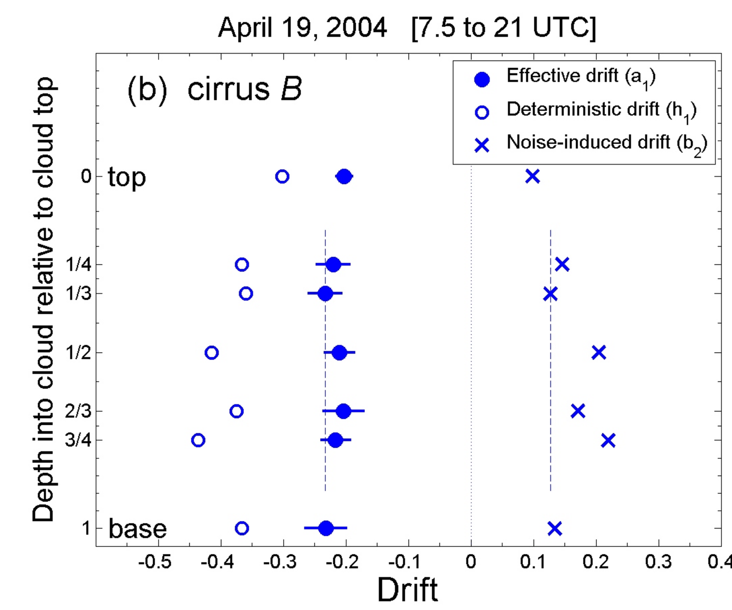
The noise-induced drift presents the stochasticity in the dynamics of the system, the influence of the small-scale noise on the slow, large-scale deterministic processes.

We find that at the scale of the generating cells

The effective drift has larger values at the top and the base because it is in a closer contact with the large-scale conditions.

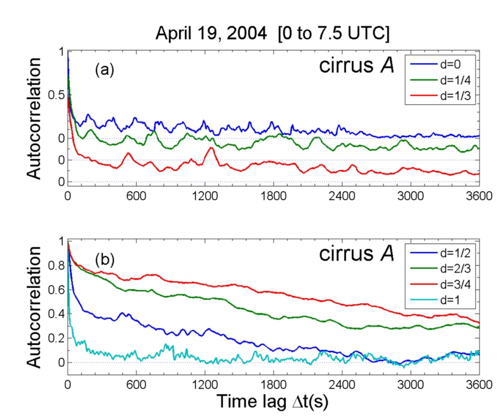
The larger values of the noise-induced drift obtained for the middle 50% of both cirrus A and B are in accordance with what is expected from the ice crystal growth and deposition region.

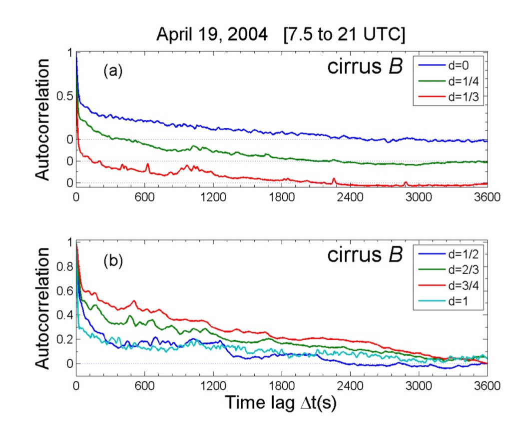




We find correlations with period ω_1=200s at the top and with period ω_2=600s at the upper 33% of cirrus A. These scales are suggestive of phenomena that occur on larger scales simultaneously with the processes that are taking place in the generating cells.

We find no periodicity in cirrus B.





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