Time Correlations in Backscattering Radar Reflectivity Measurements from Cirrus Clouds

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Introduction

The state variables of the atmosphere exhibit correlations at various spatial and temporal scales. These correlations are crucial for understanding short- and long-term trends in climate. Cirrus clouds are important phenomena in the troposphere affecting climate. To improve future parameterization of cirrus clouds in climate models, we must understand the cloud properties and how they change within the cloud. We consider fluctuations of cloud radar signals obtained at isodepths within cirrus clouds (Ivanova et al. 2003)

The radiative properties of ice particles are important ingredients of the parameterization algorithms (Heymsfield and Platt 1984; McFarquhar and Heymsfield 1997; Zurovac-Jevtic 1999) used in radiative transfer schemes for cirrus clouds in climate models. The question is still open as to how cirrus radiative transfer properties might be predicted given their roughly known microphysical characterization (Smith and Del Genio 2001). Therefore, it is essential that correlations between the structure of cirrus clouds and the radiative properties be better understood.

Backscattered signals received at the radar receiver antenna are known to depend on the ice mass content and on the particle size distribution (Atlas et al. 1995}. Ice particles can induce modifications in the radar signals which lead to fluctuations in the (1) backscattering cross section, (2) Doppler velocity, and (3) Doppler spectral width. The motivation for our study is to identify properties of the inner structure of the cirrus clouds through a statistical analysis of the fluctuations of such measured signals. This is a first step toward including these statistics in parameterization schemes of cirrus clouds in large-scale climate models.

We analyze data collected with a millimeter wave cloud radar that operates at 34.86 ~GHz during 2 consecutive days, i.e., January 26 and 27, 1997 (Figure 1) at the Southern Great Plains (SGP) site of the Atmospheric Radiation Measurements (ARM) Program. We focus on three quantities from cloud radar signals:

- Backscattering cross section η
- Doppler velocity $\langle v \rangle$
- Doppler spectral width σ^2.

In order to study the internal structure of cloud properties we cut the cloud thickness into isodepths, identifying the cloud as being between its top and its bottom layer, i.e., at which the signal level is above -45dB. We study the time series of the three sets of measurements at certain isodepths (relative to the thickness h of the cloud), i.e., top, 0.75h, 0.5 h, 0.25 h, and bottom.

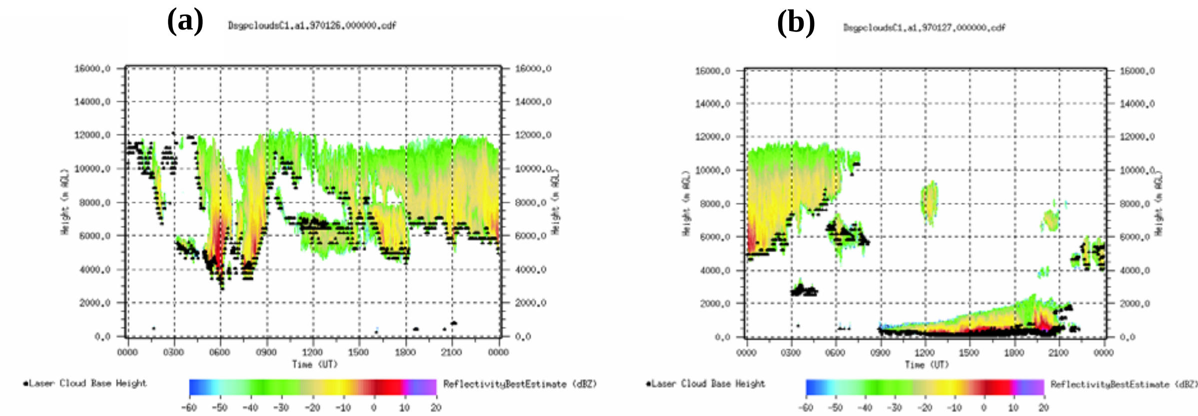

Figure 1. Radar reflectivity observations on January 26 and 27, 1997, at the SGP site.

The isodepths of the cloud observations in Figure 1a, b are plotted in Figure 2. We study the signals of the backscattering cross section η, Doppler velocity <v> and Doppler spectral width σ^2 measured at these isodepths and plotted in Figure 3a-c.

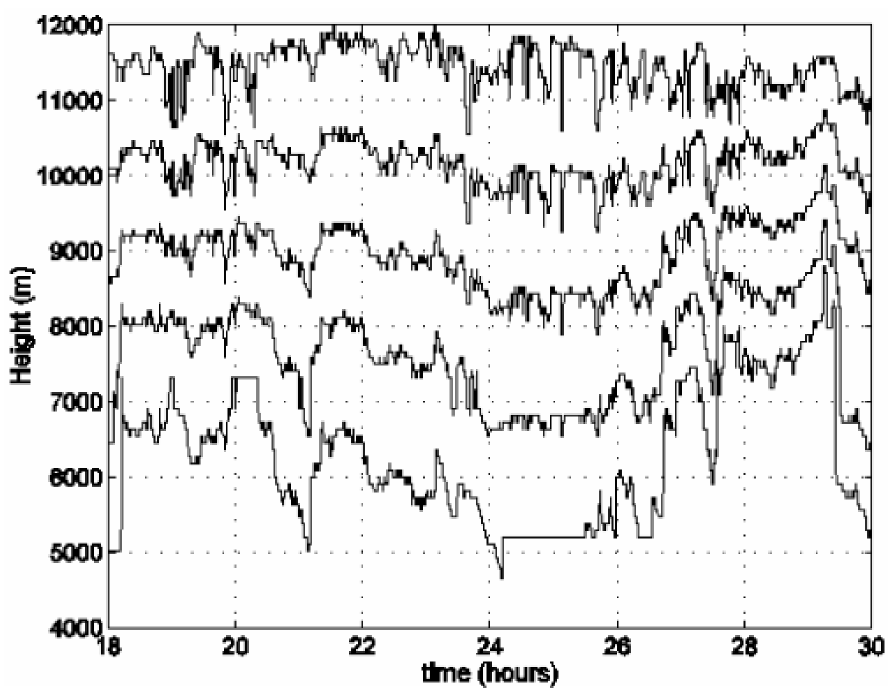

Figure 2. Altitudes of the isodepths at top, 0.75h, 0.5 h, 0.25 h, and bottom of cloud in Figure 1a, b.

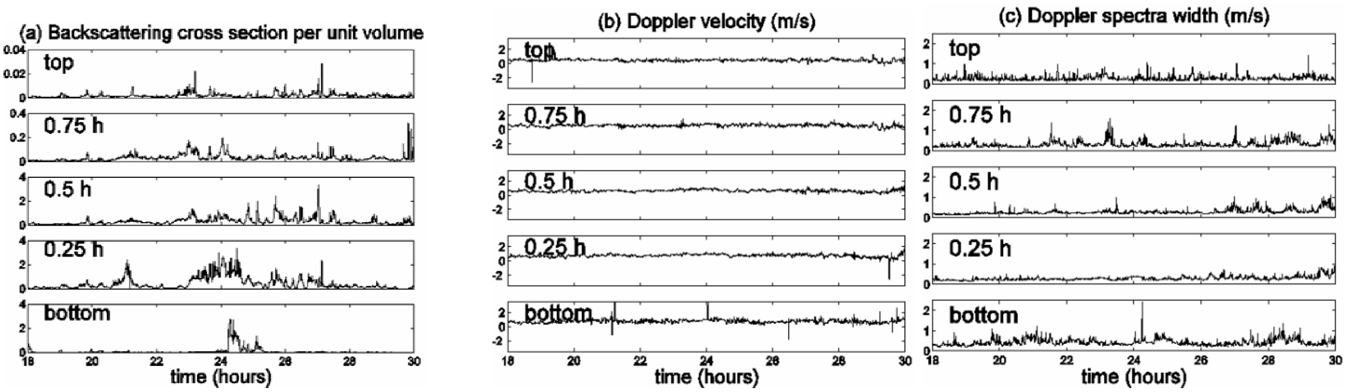

Figure 3. (a) Backscattering cross section per unit volume at different relative heights to the thickness h of the cirrus cloud as measured on January 26 and 27, 1997, at the SGP site of ARM (data in Figure 1a, b). (b) Doppler velocity (m/s). (c) Doppler spectral width (m/s).

We apply the detrended fluctuation analysis (DFA) method (Peng et al. 1994) to characterize the correlations in these signals. The DFA method is suited to accurately quantifying power-law correlations in noisy nonstationary signals with polynomial trends (Peng et al. 1994; Vandewalle and Ausloos 1998; Hu et al. 2001; Chen et al. 2002). The advantage of the DFA method over conventional methods, such as the power spectrum analysis, is that it avoids the spurious detection of apparent long-range correlations that are an artifact of the nonstationarity (related to linear and higher order polynomial trends in the data).

Briefly, the DFA method involves the following steps: (1) the signal time series is integrated, to "mimic"' a random walk after the mean value of the signal is subtracted; (2) the integrated time series y(n) is divided into boxes of equal length τ; (3) in each box, a least squares linear fit to the data, representing the trend in that box, z(n) is calculated; (4) the integrated time series is detrended by subtracting the local trend in each box; (5) the above computation is repeated over all time scales (box sizes τ) to provide a relationship between $F(\tau)$ and the box size τ (i.e., the size of the window of observation). A power law relation between the average root-mean-square fluctuation function $F(\tau)$ and the size of the observation window indicates the presence of so called scaling, i.e., when the fluctuation correlations can be characterized by a scaling exponent α

$$F(\tau) \sim \tau^{\alpha}$$

Fluctuation functions of the three quantities of interest at the five isodepths are calculated and found that they possess two different regimes of scaling, characterized by two scaling exponents α_1 and α_2. Fluctuation functions of the signals at the middle of the cloud are plotted in Figure 4a. To confirm that the found correlations are intrinsic to the signals of interest we create a surrogate data series by shuffling the amplitudes of the signals. It is known (Viswanathan et al. 2002) that the fat tailed distributions are thought to be caused by long-range correlations. Destroying all correlations by shuffling the order of the fluctuations is known to cause the fat tails almost to vanish. We have found that the long-range correlations do vanish in surrogate data as seen from the DFA-functions plotted in Figure 4b for the data with DFA-function in Figure 4a.

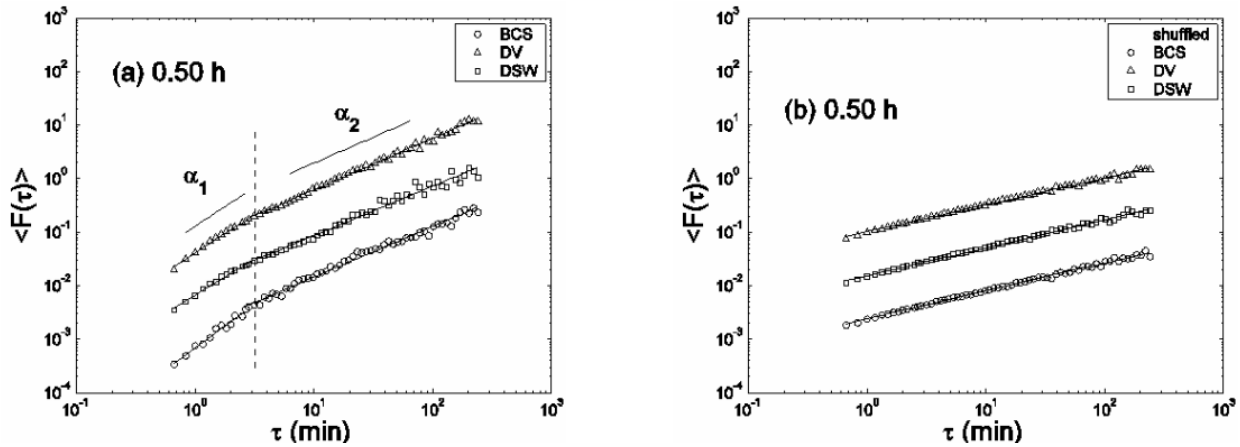

Figure 4. DFA-functions for (a) backscattering cross section (circles), Doppler velocity (triangles) and Doppler spectral width (squares) and (b) same, but shuffled signals, at the middle of the cloud. DFA-functions are displaced for readability. The α-values are plotted in Figure 5.

The specific values of the α_1 and α_2 exponents for all signals of interest are plotted in Figure 5. Clear separation between the α_1 and α_2 values is observed for all signals at all levels in the cloud.

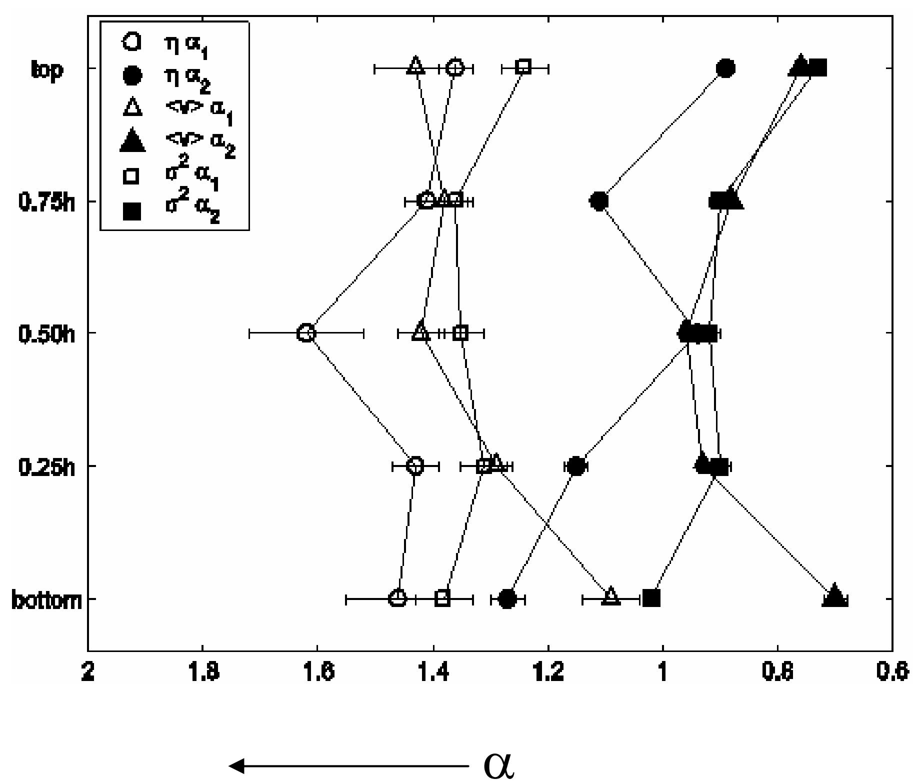

Figure 5. Values of α_1 (open symbols) and α_2 (solid symbols) exponents representing the scaling properties of the DFA-functions for backscattering cross section (circles), Doppler velocity (triangles) and Doppler spectral width (squares) at the top, 0.75h, 0.5h, 0.25h and bottom of the cloud.

DFA-functions for all three series (the backscattering cross section η, the Doppler velocity <v>, and the Doppler spectral width σ^2) exhibit scaling with a crossover at about 4 min. Different scaling behavior occurs in all three series between the top of the cloud and the bulk of the cloud, and as height increases from the bottom, especially for long time scales. Signal fluctuations at short time ranges are uncorrelated, α_1 ~1.5 thus, suggesting a birth-and-death (nucleation) process. Scaling behavior at long time ranges changes to a 1/f process, α_2 ~1, suggesting propagation effects in the cirrus cloud at long time scales, similar to growth and percolation features.

Conclusions

In conclusion, the time dependence characteristics of physical quantities in cirrus clouds have been obtained. The backscattering cross section η, the Doppler velocity <v>, and the Doppler spectral width σ^2 correspond to the physical coefficients in the Navier-Stokes equations, describing the bulk modulus, viscosity, and thermal conductivity of the flow. In all cases, power-law time correlations exist with a crossover between regimes at about 3 to 5 min. Short time range correlations of radar back scattering cross section are uncorrelated, i.e., are Brownian-like; at time lags longer than about ~3 to ~5 min correlations are of the 1/f noise type. We also find that different types of scaling properties distinguish the top and the bottom layers from the interior of the clouds. This can be understood to be due to different mechanisms on the boundaries and in the bulk of the cloud, depending on the time scales. The data analysis leads to a consistent physical picture on the inner non equilibrium structure, i.e., ice crystal nucleation and growth.

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