# The Effect of Precipitation on Variability of Low Stratiform Clouds Over ARM SGP Site

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## Introduction

Continental low stratiform clouds cover the sky about 23% of the time during the fall, winter, and spring months and play a significant role in the Earth' radiation budget. Information about cloud structure and variability is crucial in determining areal averages of cloud radiative and microphysical properties such as over numerical weather prediction (NWP) or Global Climate Model grid cells. Neglecting this variability can lead to substantial underestimates of microphysical process rates (see Pincus and Klein 2000, for example).

The Atmospheric Radiation Measurement (ARM) Program operates a millimeter wave cloud radar (MMCR) at the Southern Great Plains (SGP) Cloud and Radiation Test-Bed (CART) site that provides a unique opportunity to obtain long periods of continuous observations to address issues of cloud system variability. In this paper we analyze two winter seasons of low stratiform clouds observed by the SGP MMCR. The variability of clouds is addressed in terms of probability distribution functions and statistical moments of radar reflectivity. Measures of variability include probability distribution functions (PDFs) of radar-measured quantities, cloud frequency of occurrence, and duration analyzed separately for non- and precipitating low clouds.

Previous studies of boundary layer clouds imply that it is reasonable to assume that variability characteristics might be different between precipitating and non-precipitating clouds. The radar data can be generally categorized into these two divisions by either the behavior of the Doppler velocity field or, as we do, by using an accepted reflectivity threshold.

A significant fraction of the low altitude stratiform clouds observed by the SGP MMCR are cloud-topped boundary layers similar to cloud systems frequently observed over the ocean. Other low clouds are associated with synoptic disturbances such as fronts or the passages of short-wave troughs. Anecdotal evidence suggests that, over the SGP site, these cloud systems occur under different dynamic conditions, in particular the sign of the synoptic-scale vertical velocity. Because of differences in the cloud dynamical forcing, we would expect the variability characteristics between boundary layer clouds and all other low clouds be different.

These results show most importantly that significant differences exist between the variability of precipitating and non-precipitating clouds. A thorough treatment of subgrid variability for a GLOBAL CLIMATE MODEL should take these characteristics into account.

## Description of the Data

Two years of winter season data were considered, December-February 1997-1998 and January-March of 2001. In total, 953 hours of overcast (clouds lasting for an hour or more with cloud cover more than 0.9) low stratiform clouds observed over the ARM SGP site were analyzed.

Each data sample was a continuous time series of radar reflectivity corresponding to a specific cloudy non-precipitating or precipitating segment. Cases with the overlapping upper layer clouds were also included, except for periods when precipitation from the upper clouds contaminated the lower layers. The analysis considered radar reflectivity only within the central one-third portion of the cloud with respect to height.

Cloud segments were subjectively divided into two distinct categories: boundary layer stratocumulus with tops below 1.5 km and a typical depth of several hundred meters, and low altitude stratiform clouds with bases below 2 km and a typical depth of up to a couple of kilometers.

By subjective analysis and using as a threshold the radar reflectivity value of -17 dBZ, each cloud category was further partitioned into sub-sets of precipitating and non- precipitating cloud segments. This enabled us to address variability in the context of the presence or absence of precipitation. Due to some limitations of this analysis, only cloud segments with durations more than 8 minutes (which corresponds to a frozen-turbulence length scale of ~5 km, assuming a 10 $ms^{-1}$ advection velocity) were considered in presented results.

## Results

Table 1 shows a breakdown of the cloud segment statistics for boundary layer and low altitude stratiform cloud segments. A total of 531 hours of boundary layer stratiform cloud was observed over 338 segments. The mean and median segment durations of precipitating and non-precipitating boundary layer clouds are comparable. However, because the number of precipitating segments is about 2.4 times less, their total duration is about only one third of the non-precipitating clouds. Of those precipitating,

**Table 1**. Statistics on number and duration of segments.

| **Cloud Type** | **Presence of Precipitation** | **Number of Cloud Segments** | **Cloud Segment Duration [h]** | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | **All segments** | **Mean** | **σ** | **Median** | **90% Cumulative** | **Max.** |
| **Boundary Layer Stratocumulus** | **No** | 239 (71%) | 394.3 (74%) | 1.6 | 2.0 | 0.8 | 4.6 | 11.2 |
| | **Yes** | 99 (29%) | 137.2 (26%) | 1.4 | 2.3 | 0.6 | 3.2 | 17.2 |
| **Low Altitude Stratiform** | **No** | 179 (53%) | 187.8 (44%) | 1.1 | 1.4 | 0.5 | 2.6 | 8.1 |
| | **Yes** | 161 (47%) | 235.2 (56%) | 1.5 | 1.9 | 0.7 | 3.5 | 11.4 |

about half are very lightly drizzling (Z<-14dBZ; not shown in Table 1). Most (90%) of the segments have length (life span) smaller than 3.2 h and 4.6 h in precipitating and non-precipitating cases, respectively while the average life span of the segment is 1.4 h and 1.6 h, respectively. Non-precipitating segments tend to last longer.

A total of 423 h of low altitude clouds were observed over 330 segments. On the contrary, when low altitude clouds occur they tend to precipitate longer than clouds in the boundary layer category.

Their precipitating segments tend to last significantly longer. Mean and median duration of precipitating low altitude segments is about 40% larger than non-precipitating resulting in about 25% larger their total duration, notwithstanding their smaller numbers (47% to 53%, respectively).

Figure 1 shows that the boundary layer stratiform clouds show a more intermittent, patchy structure relative to the low altitude category, indicated by the prevalence of segments with duration less than 1 hour (space scale ~30 km). We speculate that this result may be an indication that dynamic mechanisms governing the formation of cloud drop spectra (and thus, reflectivity) in these clouds are of smaller scales in the boundary layer category when compared to low altitude stratiform clouds. For the latter category, precipitating clouds in particular tend to be associated with longer segment lengths.

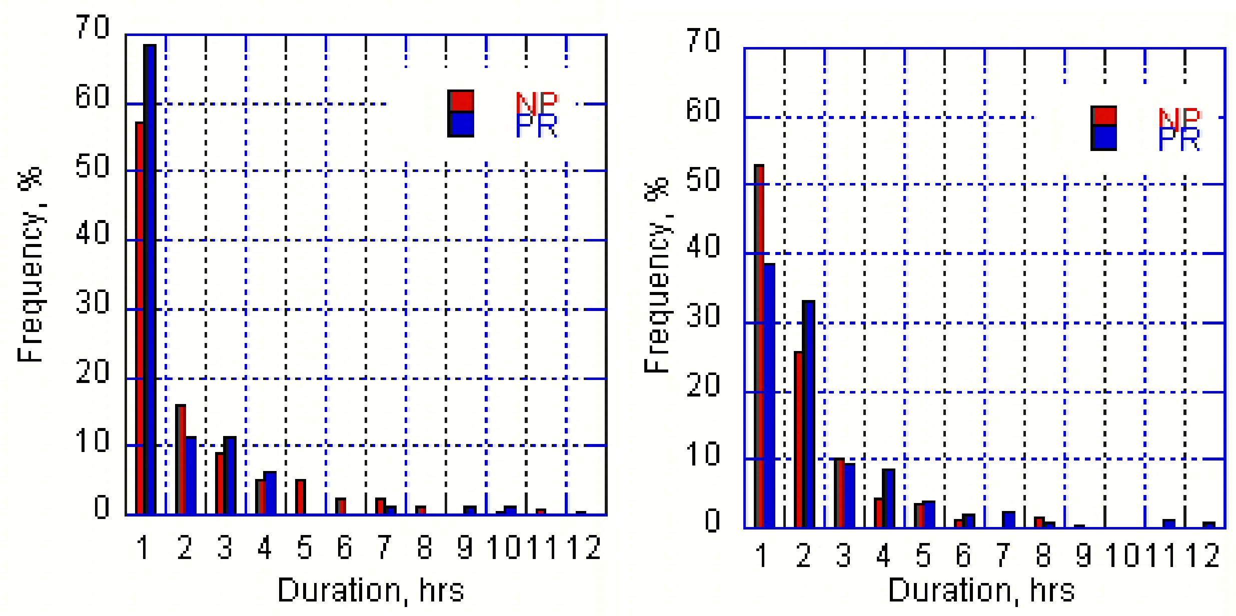

**Figure 1**. (Left) Frequency distribution of precipitating and non-precipitating segment duration for boundary layer and (Right) low altitude stratiform clouds. Red columns denote non-precipitating clouds, and blue columns, precipitating clouds.

Precipitating clouds typically exhibit much greater variability than non-precipitating clouds. This effect is especially pronounced in the low altitude stratiform category. The average ratio of standard deviation to segment mean reflectivity (not shown here) is about 2 and 4 times greater in precipitating clouds compared to non-precipitating for boundary layer and low altitude clouds, respectively. The low altitude category also exhibits greater variability compared to the boundary layer category: the normalized standard deviation (not shown here) is about 30% and 3 times larger for non- and precipitating clouds respectively in low altitude clouds.

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**Figure 2**. Standard deviation of segment reflectivity versus mean for precipitating low altitude clouds.

To characterize cloud system variability we calculated PDFs of reflectivity for each segment and than averaged over all non- and precipitating segments for both cloud types. Figure 3 shows that for the boundary layer stratiform category the average PDFs of reflectivity are quite symmetrical for non-precipitating as well as precipitating clouds and can be well approximated by a two parameter Gamma function of the form

$$P(Z) = \left(\frac{\alpha}{\overline{Z}}\right)^{\alpha} \frac{{q_c}^{\alpha-1}}{\Gamma(\alpha)} e^{-(\frac{\alpha Z}{\overline{Z}})}$$

where $\alpha$ is the shape parameter and $\overline{Z}$ is the distribution mean. Table 2 shows the values of $\overline{Z}$ and $\alpha$ for the approximations. Since the gamma function is defined between $0 \le Z < \infty$, reflectivity needs to be translated so all values are nonzero.

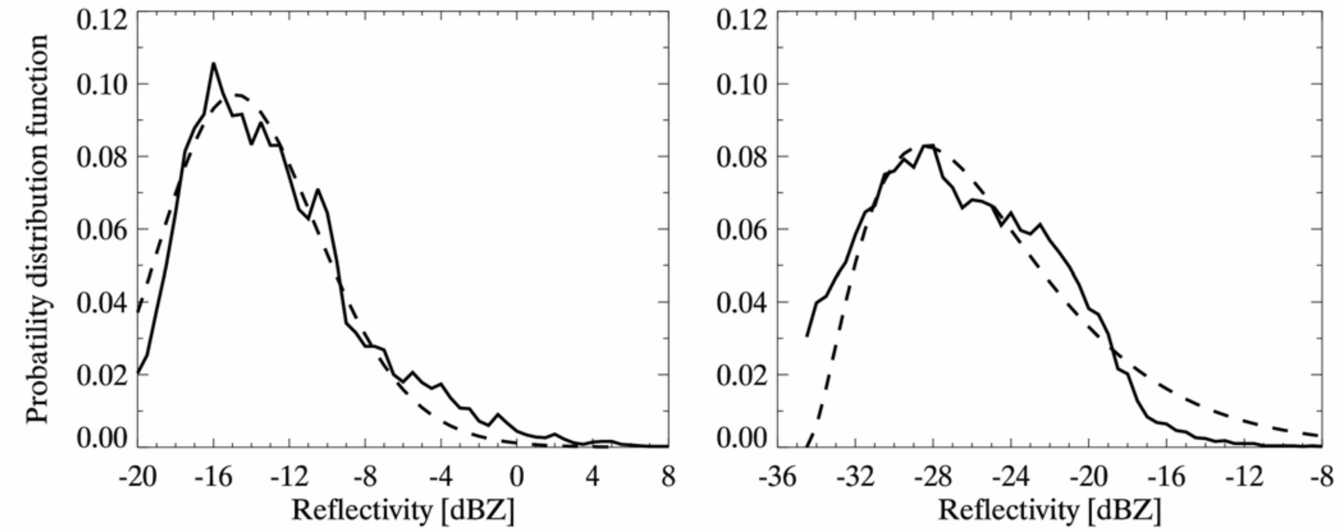

**Figure 3**. DF of reflectivity, averaged over all segments, for non-precipitating (left) and precipitating (right) boundary layer stratocumulus. Dashed lines are gamma fits to the data.

**Table 2**. Gamma distribution parameters used to approximate reflectivity PDFs.

| Category | $\overline{Z}$ | $\alpha$ |
|---|---|---|
| BL Non-Precipitation | -25.0 | 2.7 |
| BL Precipitation | -14.0 | 24 |
| LA Non-Precipitation | Beta function | |
| LA Precipitation | -13.0 | 13 |

PDFs of reflectivity for low altitude stratiform clouds demonstrate different character related to difference in cloud driving forcing mechanisms. The PDF of the non-precipitating category (see Figure 4) is in fact negatively skewed. Satisfactory fit is obtained by Beta function of the form

$$P(\widetilde{Z}) = Z^{\alpha-1}(1-\widetilde{Z})^{\beta-1}\frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}$$

where $\alpha = 2.3$ and $\beta = 1.75$. $\widetilde{Z}$ is the reflectivity that has been translated and scaled such that $0 \le \widetilde{Z} \le 1$.

Low altitude stratiform clouds have significantly higher reflectivities than boundary layer clouds, which might imply greater precipitation rates. The right tails of the distributions in Figures 3 and 4 show that among precipitating low stratiform clouds about 26% are drizzling heavily (Z>0 dBZ) relative to boundary layer stratocumulus where only 2% fall into this category. The small relative amount of strongly drizzling boundary layer clouds seems physically plausible, given that the higher CCN load in continental air precludes the efficient formation of large drizzle drops.

Figure 5 shows PDFs of liquid water content for non-precipitating clouds obtained using radar data and the technique of Frisch et al. (1995). Mean values of LWC are 0.25 g $m^{-3}$ and 0.3 g $m^{-3}$ with median values 0.21 and 0.26 for boundary layer and low altitude categories, respectively. Boundary layer and low altitude clouds have markedly different PDFs of LWC reflecting presence of significant differences between the physical mechanisms driving the cloud system variability.

The LWC retrievals coincide with what is surmised about the dynamic mechanisms driving the two categories. The larger values of LWC in the low altitude category arise from synoptic or mesoscale ascent—strong mechanical forcing that is able to produce significant condensation. The more Gaussian boundary layer LWC curve is indicative of a typical cloud-topped boundary layer, where small-scale updrafts and downdrafts impose a degree of symmetry on the circulation and hence on the microphysical variables.

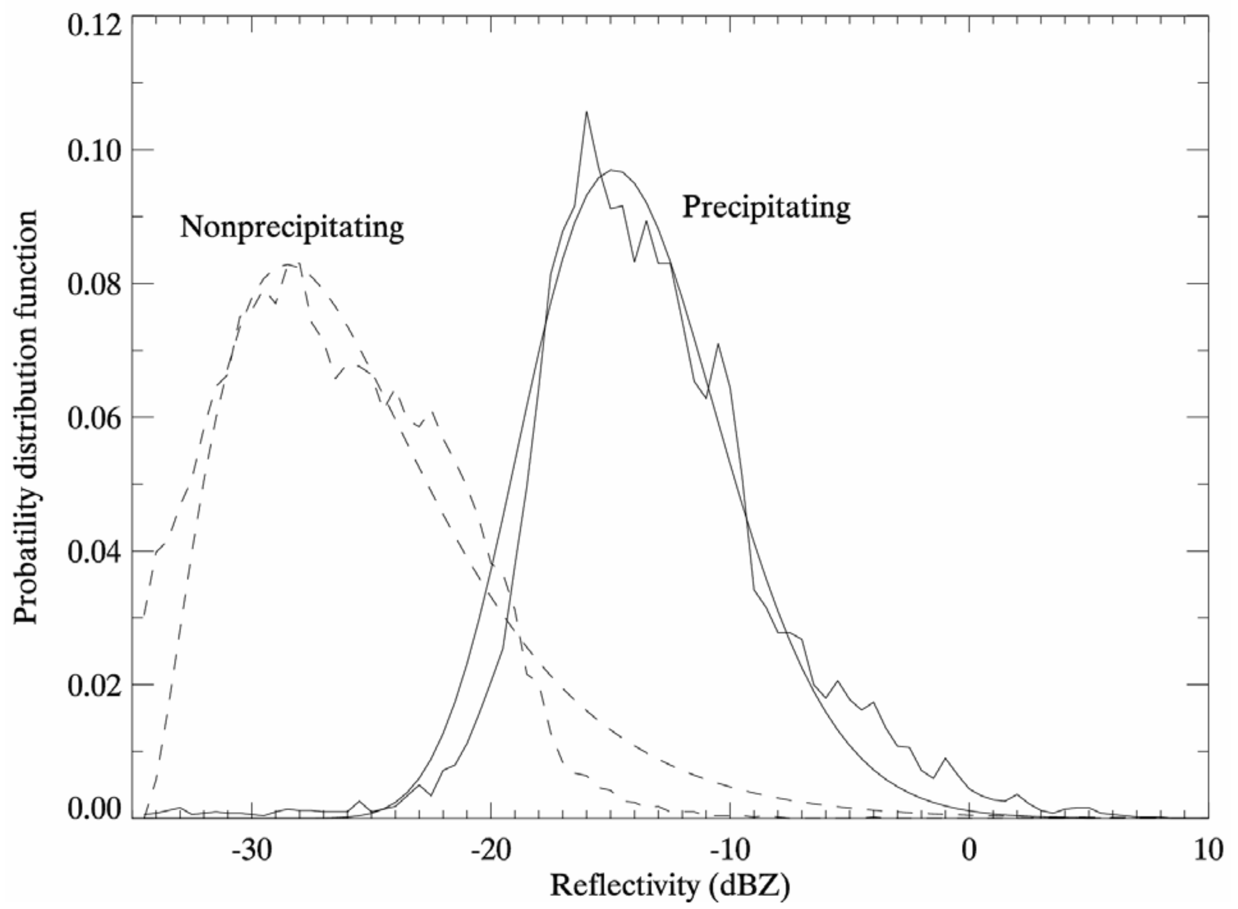

**Figure 4**. PDF of reflectivity, averaged over all segments, for precipitating and non-precipitating low altitude clouds. Smooth lines are gamma and Beta function fit to the data.

## Summary

We analyzed 953 hours of overcast low stratiform cloud layers observed over the ARM SGP site during two winter seasons. Our analysis shows distinct differences between PDFs of precipitating and non-precipitating cloud systems as well as between PDFs of two low stratiform cloud categories:

1. The total duration of all precipitating boundary layer clouds is only 1/3 that of non-precipitating boundary layer clouds. On the contrary, all precipitating low altitude clouds have about 25% greater total duration than non-precipitating.

2. Precipitating clouds typically exhibit much greater variability than non-precipitating clouds. This effect is especially pronounced in the low altitude stratiform category. Variability of low altitude clouds is greater (3 times for precipitating clouds) than of boundary layer clouds.

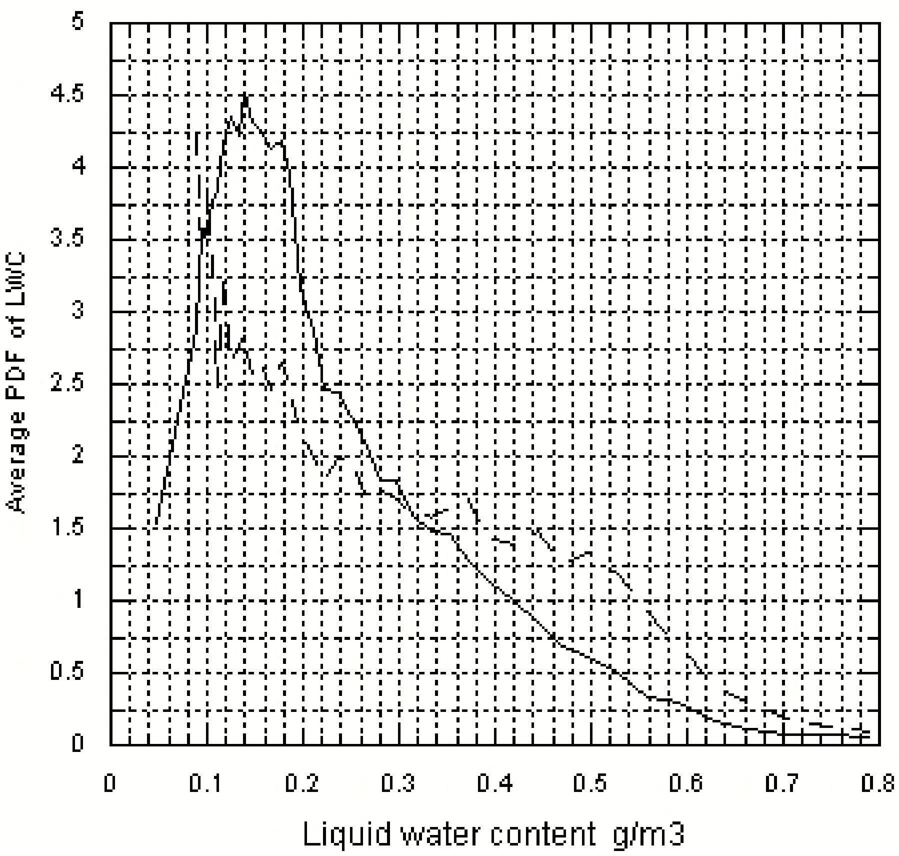

**Figure 5**. PDF of LWC, averaged over all segments, for non-precipitating boundary layer (solid) and low altitude stratiform clouds (dashed).

3. For the boundary layer stratiform category, the PDFs of mean reflectivity are quite symmetrical for precipitating and non-precipitating cloud and in general can be well approximated by a two parameter Gamma function.

4. PDFs of reflectivity for low altitude stratiform clouds demonstrate a different character. The non-precipitating category tends to be negatively skewed because of its shift towards greater reflectivity. PDFs in this category may be reasonably approximated with beta functions.

5. Most of the calculated PDFs can be reasonably approximated using well-known PDFs. This enables the calculation of a process rate or radiative quantity over an NWP or GLOBAL CLIMATE MODEL grid cell by integrating the rate expression over the PDF. This is equivalent to spatial integration of the local quantity over the grid itself. Using well-known PDFs is conducive to obtaining analytic expressions for a process rate integrated over the PDF. The PDFs of the boundary layer and low altitude categories differ substantially, as do precipitating and non-precipitating categories. This implies a need for the development of separate parameterizations to account for subgrid scale variability within these cloud types, as well as some method of "closure" to decide from the resolved model variables which of these PDFs to use.

6. Of the four categories studied, low altitude precipitating clouds would have the most pronounced effect on NWP forecast accuracy. The strong dependence of variability on radar reflectivity shown in Figure 2 allows the formulation of a PDF in terms of only one parameter—radar reflectivity—which may be related to the resolved model variables or predicted by future parameterizations.

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