P1.24 Scale dependence of variability in continental stratiform clouds

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1. INTRODUCTION

Internal variability of stratiform clouds is manifested on scales ranging from the grid sizes of cloud resolving models to those of general circulation models, and accurately representing cloud system variability is one of the most important aspects in improving model predictions. Understanding cloud variability on different scales will aid in developing and improving subgrid-scale cloud parameterizations. Information about variability is also crucial for retrievals of microphysical parameters from observations of volume averaged reflectivity, since neglecting variability can lead to substantial biases in the estimation of retrieved microphysical variables.

The Atmospheric Radiation Measurement Program (ARM) operates a Millimeter Wave Cloud Radar (MMCR) at the ARM Climate Research Facility over the Southern Great Plains (ACRF SGP) that provides a unique opportunity to obtain continuous observations in order to address issues of cloud variability. These data contain information on spatial and/or temporal correlations in cloudiness, enabling scale-by-scale (scaling) analyses over a range of hundreds of meters to hundreds of kilometers. The objective of this study is to explore the scale dependence of radar reflectivity for clouds over the ACRF SGP site. Special emphasis is placed on boundary layer clouds and the effect of drizzle.

We search for answers to the following questions: 1) What is the scale for long-range correlations (integral scale) in reflectivity beyond which reflectivity fields can be considered uncorrelated, and what is the effect of drizzle on this integral scale? This question is addressed by analyzing the scale dependence of cloud variability within the range of ~2-200 km. 2) Can radar reflectivity variability serve as a proxy for variability of other cloud microphysical parameters which are directly predicted by numerical models? For this purpose we compare the major scaling parameters of radar reflectivity variability with similar parameters determined from previous studies using in-situ and remote sensing data sets.

2. DATABASE AND APPROACH

We analyzed more than 1100 hours of radar reflectivity observations of overcast warm low stratiform clouds over the ACRF SGP site during two winter seasons (December-February 1997-1998 and January-March of 2001) and the month of the March 2000 IOP. The database consists of time series of radar reflectivity measured every 10 s within the middle portion of the cloud. Cases of overlapping clouds were also included, except for periods when precipitation from them contaminated the lower layer cloud.

Clouds were divided into two categories: boundary layer (BL) stratocumulus with tops below 1.5 km and a depth of several hundred meters, and low altitude (LA) stratiform clouds with cloud top greater than 1.5 km and with a depth of 1-3 km. Precipitation significantly affects cloud dynamics, thermodynamics, and structure of boundary layer, and therefore, the variability of cloud parameters. To address this issue, BL and LA categories were further discriminated into drizzling and non-drizzling categories. Drizzling clouds are defined by the presence of drizzle *within* the cloud layer.

Observations as well as our modeling results suggest a -17 dBZ value of reflectivity Z as an approximate threshold for such discrimination (which, according to our LES simulations, corresponds to the 24 μm drop size threshold). The term 'drizzle' is used to account for the liquid water content in the tail of cloud drop spectra (drop radius > 24 μm).

Scale dependence of variability is investigated by resampling the data into segments of different time (space) length in a scale range from 5 min (~3 km) to 6 hrs (~216 km), in 5 min (~3 km) increments (assuming the "frozen turbulence" hypothesis with an advection velocity of ~10 m s^{-1}). Standard deviation of reflectivity σ is used as a measure of cloud variability in one- and two-point statistical analysis.

3. SCALE DEPENDENCE OF VARIABILITY

Figure 1 shows scale dependence of the mean standard deviation of reflectivity for BL and LA

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clouds. It can be seen that all cloud categories are accurately approximated by the logarithmic curves $<\sigma> = a + b \ln (x+c)$ with correlation coefficient larger than 0.9 (Table 1). The BL non-precipitating clouds approach the nearly saturated regime at time scales of about 3-4 hrs (~140 km). The LA non-precipitating cloud category seem to approach the saturation regime at about 3-4 hrs as well, however, this conclusion may be affected by the relatively small data set in this category.

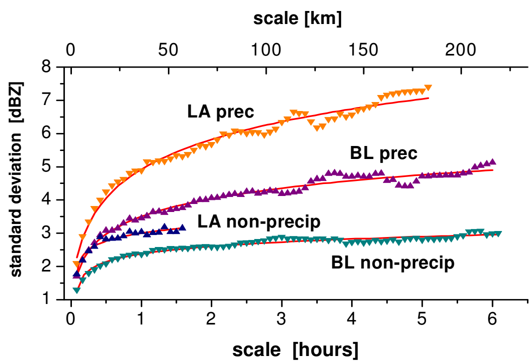


Fig. 1. Dependence of variability (defined as an ensemble-averaged standard deviation) on subsample length for boundary layer (BL) and low altitude (LA) clouds, separated into non-precipitating (non-precip) and precipitating (prec) categories. Red lines show best fit curves.

On the contrary, variability for precipitating LA and BL cloud categories continues to increase over the full scale range up to 6 hours (~200 km), indicating that mesoscale or synoptic forcings exceeding this scale can be an important factor contributing to the variability of cloud structure. This result may imply that liquid water content fields associated with non-precipitating reflectivity fields become roughly uncorrelated in scale beyond the ~100-150 km range. Correlations for precipitating, high reflectivity fields, which are related to precipitation flux, exist beyond the ~200 km scale. The presence of long time-scale correlations for high reflectivity fields implies that single-point histograms for those fields will have significant variability within the cloud layer, indicating that the use of spatial averages in the approximation of the moments of the probability density function of the reflectivity field will lead to random fluctuations of the estimated moments.

On the contrary, the parameters of probability density function for weak reflectivity fields or liquid water content can be reasonably well estimated at scales exceeding integral scale of 100-150 km. Precipitating clouds demonstrate on average a much greater variability and scale dependence relative to non-precipitating clouds (exemplified by larger coefficients *a* and *b* in Table 1); these effects are especially pronounced for the LA cloud category. However, our data do not preclude the possibility of the converse, namely, that the physical processes that favor greater variability may also enhance drizzle production. Undoubtedly drizzle and variability are interdependent.

Table 1. Parameters of the logarithmic fit for BL and LA clouds.

Cloud type	a	b	c	R^2
Boundary layer Non-precip	2.40 ± 0.01	-0.31 ± 0.01	-0.06 ± 0.008	0.95
Boundary layer Precipitating	3.47 ± 0.05	-0.79 ± 0.03	0.03 ± 0.03	0.97
Low altitude Non-precip	3.02 ± 0.02	-0.31 ± 0.03	-0.07 ± 0.008	0.95
Low altitude Precipitating	4.83 ± 0.08	-1.36 ± 0.06	0.07 ± 0.03	0.98

4. TWO SCALE-INVARIANT REGIMES

Power law behavior (or scaling) of the mean standard deviation of reflectivity is most evident in log-log coordinates (Figs. 2 and 3). All cloud categories demonstrate two distinctive scale-invariant regimes with an intervening scale break between about 10-30 km, depending on cloud category. The presence of a scale break in all categories implies a change in dominant physical processes near this scale.

The first scaling regime spans from the minimum resolving scale (5 min in time or ~3 km in space) to the scale break. The second scaling regime covers scales from the scale break to the maximum resolving scale ~ 200 km (~50 km for the LAnp clouds).

In all cloud categories the first scaling regime has significantly larger scaling exponents compared to the second one, indicating a more significant long-range data correlation below the scale break (Table 2). The largest scale break is for the BL non-precipitating category (~30 km). For these clouds the dominant physical mechanisms that change scale invariance begin acting at the ~30 km scale, while for other cloud types the mesoscale forcing mechanisms start probably on a smaller scale (10-15 km).

On scales larger than scale break, long-range correlation still exists up to 180-200 km and even beyond, but it is significantly weaker ($\alpha 2$ significantly smaller than $\alpha 1$ in Table 2) especially in BL non- precipitating clouds. For BLnp clouds we might expect that the scale around 100-150 km can be a reasonable estimate for the integral scale implying that there is no essentially long-range correlation beyond this scale

For other categories the integral scale would be beyond our largest resolvable scale 200 km. LA precipitating category is characterized by largest scaling exponents, demonstrates the highest level of variability and the longest long-range correlation, which continues probably to synoptic scales far larger than those considered here.

Table 2 shows that scale-invariant exponents in the 1st scaling regime are in some instances close to those for inertial-sub range passive scalar fluctuations (0.33). The LA clouds have larger exponents than those for BL clouds. The smaller exponents in the 2nd scaling regime indicate weaker long-range correlations on the meso-β scale. The scale break for non-precipitating BL clouds is much larger than for all other cloud categories, as meso-γ scale and precipitation forcings dominate in the LA and precipitating BL cloud categories.

Scaling parameters of stratiform continental clouds over the ACRF SGP, as well as stratocumulus clouds observed during ASTEX, FIRE, and SOCEX, show some degree of universality; however, differences determined by cloud types, the presence of precipitation, as well as local climatological conditions, result in differences in scaling ranges and scale-invariant exponents. We hypothesize that the differences in scaling parameters are more likely to stem from differences in cloud types and depend less on the particular cloud parameter, be it radar reflectivity, LWC, or saturation excess.

The similarity between parameters in Table 2 is an indication that statistical parameters of radar reflectivity may serve as a proxy for variability of more broadly used cloud parameters. Integrated in-situ observations of cloud parameters complemented by simultaneous radar reflectivity measurements are needed to determine the range of conditions for which this conclusion may hold.

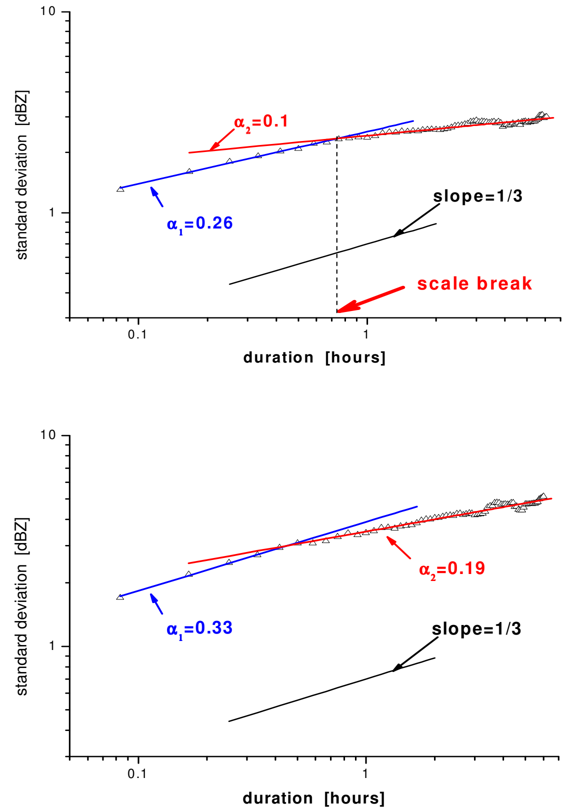
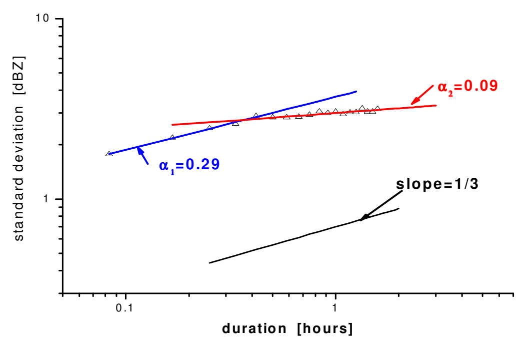


Fig. 2. Scale dependence of ensemble-average standard deviation for boundary layer clouds (top for non-precipitating, and bottom is for precipitating clouds). . The first (second) scaling range is denoted by the blue (red) line. Corresponding power exponents are also shown and summarized in Table 2. The Kolmogorov line (black) is given as a reference.

5. CONCLUSIONS

More than 1100 hours of radar reflectivity data of continental low stratiform clouds observed during 7 winter months were analyzed to study cloud system variability, particularly long term correlations and scaling properties present in radar reflectivity fields. The results show that dependence of cloud variability (the mean standard deviation of reflectivity) on scale can be very accurately approximated by a logarithmic function on the scales from 3km to 200 km.

All cloud categories demonstrate two distinctive scale-invariant regimes with the scale break between them at about 10-30 km depending on cloud category. Precipitating clouds in both cloud types have larger scaling exponents than non-precipitating clouds indicating greater variability and its dependence on scale presumably associated with precipitation. These clouds have a smaller scale break probably due to strong γ-mesoscale forcing and internal precipitation processes that have been shown can lead to cloud layer breakup. Similar processes result in an even smaller scale break for LA clouds. However, on scales larger than the scale break, long-range correlation still exists up to 180-200 km and even beyond, but it is significantly weaker.



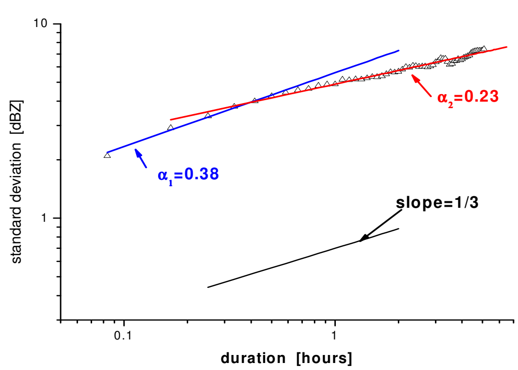


Fig. 3. Scale dependence of ensemble-average standard deviation for low altitude clouds. The notation is the same as on Fig. 2.

For boundary layer non-precipitating clouds our results suggest that the scale around 100-150 km can be a reasonable estimate for the integral scale implying that there is no essentially long-range correlations beyond this scale. For other cloud categories the integral scale would be beyond our largest resolvable scale 200 km. It implies that the use of spatial averages in the approximation of the moments of the single-point probability density function of the high value reflectivity field (related to precipitation flux) will lead to random fluctuations of the estimated moments. On the contrary, the parameters of probability density function for low value reflectivity fields (related to liquid water content) in boundary layer clouds can be reasonably well estimated if the length of averaging is about the integral scale of 100-150 km.

We hypothesize that scaling parameters of radar reflectivity may bear similarity to those of other cloud microphysical parameters, which are directly predicted by numerical models; therefore statistics of reflectivity variability may serve as a proxy for variability of LWC or precipitation flux.

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Table 2. Comparison of scaling parameters for different cloud variables from selected data sets

Cloud type	Parameter	Exponent $\alpha 1$	Exponent $\alpha 2$	Scale break	Max resolvable scale
ASTEX Davis et al. 1996, Marshak et al. 1997	LWC	0.24	n/a	≈ 60 km	≈ 120 km
ASTEX Wood et al. 2002	saturation excess	0.33	n/a	> Lmax	≈ 70 km
FIRE Wood et al. 2002	saturation excess	0.32	n/a	≈ 30 km	≈ 70 km
SOCEX Davis et al. 1999	LWC	0.30	n/a	≈ 5-10 km	≈ 26 km
ACRF SGP BL non-precipitating Kogan et al. 2005	Radar reflectivity	0.26	0.1	≈ 30 km	≈ 200 km
ACRF SGP BL precipitating Kogan et al.2005	Radar reflectivity	0.33	0.19	≈ 20 km	≈ 200 km
ACRF SGP LA non-precipitating Kogan et al.2005	Radar reflectivity	0.29	0.09	≈ 15 km	≈ 50 km
ACRF SGP LA precipitating Kogan et al.2005	Radar reflectivity	0.38	0.23	≈ 15 km	≈ 150 km