The Statistical Formulations of Cloud Inhomegeneity Parameters Over the Southern Great Plains

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Introduction

Lack of data on cloud variability is one of the main reasons most current climate models consider clouds as plane-parallel, horizontally homogeneous combinations of cloudy and clear portions defined by cloud fraction. Accounting for cloud inhomogeneity should significantly increase the accuracy of calculations of radiative properties. Unique information on cloud internal variability can be obtained using data from the Atmospheric Radiation Measurement (ARM) observational platforms, in particular cloud reflectivity data from the Millimeter Wave Cloud Radar (MMCR).

In this study, we explore the possibility of using MMCR reflectivity for obtaining cloud sub-grid-scale inhomogeneity and a statistical characterization of cloud internal structure within stratocumulus layers. Cloud inhomogeneity is described based on probability distribution functions (PDFs) and a spectral analysis including wavenumber spectra and its dominant scales. We also used a scale-invariance (scaling) analysis that has been widely utilized over the last few decades to study turbulent flows, including atmospheric turbulence (see e.g., Davis et al. 1996).

Description of Statistical Approaches

The PDFs provide sub-grid information on cloud parameters and have been shown to be an important part of cloud physics and radiative parameterizations in meso- and large-scale models (Sundqvist 1993; Randall 1995; Pincus and Klein 2000). Spectral and scale-invariance analysis provide additional tools to characterize cloud internal structure for developing improved cloud parameterizations which, in turn, result in better formulation of cloud radiative properties. These analyses locate the dominant wave-numbers and determine the upper and lower scales that bound scale-invariant regimes of the flow. The regimes can be stationary or nonstationary; the scaling analysis allows differentiating between them, measuring degrees of nonstationarity and determining the transition from one regime to the other. The scale breaks, which separate different scale-invariant regimes, are important indicators of the change in the dominant physical processes governing the system evolution (Lovejoy et al. 1993; Davis et al. 1996).

By combining spectral and scale-invariance analysis we can classify atmospheric datasets within the scale-invariant range scale as stationary or nonstationary. Stationarity is fundamental for obtaining meaningful spatial statistics and indicates the minimal length and resolution of datasets needed to obtain reliable statistics. Many commonly used statistical procedures produce ambiguous or even meaningless results for nonstationary datasets (Davis et al. 1996).

Description of Cases

We compared statistical properties of two cloud systems, representing a low- and mid-level stratocumulus cloud layer observed over the ARM Southern Great Plains (SGP) Site on December 2, 2000, and May 16, 2000, respectively. In addition to the MMCR reflectivity field (resolution 10 s), we used the Advanced Very High Resolution Radiometer (AVHRR) satellite reflectance field (resolution 1 km) for low-level stratocumulus to compare dominant scales of variability and scaling features for radar reflectivity and satellite reflectance data. We also used large-eddy simulation (LES) models initialized by the Atlantic Stratocumulus Transition Experiment (ASTEX) 1992 data in order to deduce correlations and to find possible links between the characteristic radar reflectivity spatial variability scale and corresponding variability scales of other cloud prognostic variables.

The first case represents a low stratocumulus cloud system developed behind a strong cold front, moving from the north, which passed through the SGP site around 0500 Universal Time Coordinates (UTC) on December 1, 2000. During December 1-2, this front resulted in approximate 8°C drop in temperature, an 18 mb pressure rise, and a wind shift from the south to the north-northwest. The low stratus layer had an average thickness of about 500 m (Figure 1a) and was capped by a strong inversion at 1200-1300 m with a temperature jump of 7°-13°C. The average wind velocity was about 7 m/s. The rather small values of radar reflectivity Z (Figure 2a) show a maximum of less than -10 dBZ within the layer, which indicates the absence of any significant drizzle. Therefore, the variability of Z more than likely reflects the inhomogeneous nature of surface fluxes and convective organization rather than drizzle patchiness. For this case, the PDFs are of the same width in the upper and lower layer of the cloud (Figure 3a).

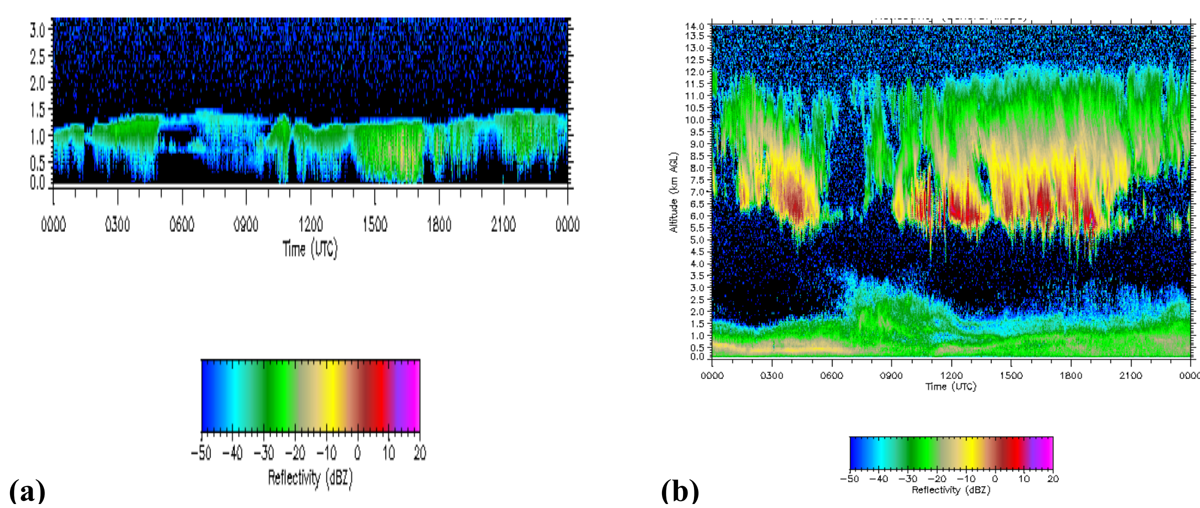

Figure 1. MMCR radar reflectivity data for December 2, 2000, and May 16, 2000.

The second case represents an altostratocumulus cloud system that developed slightly ahead of a warm front and lasted for 1½ days. The front moving from the south passed Oklahoma on May 16-17, 2000, producing showers on the second day. This case represents a powerful cloud system spanning heights from 5.5 to about 11 km (Figure 1b). The mean wind velocity at the middle level is around 25 m/s. The maximum radar reflectivities of about 10 dBZ are located near the cloud base (Figure 2b), indicating accumulation of drizzle drops, but the drizzle is not large enough to reach the ground.

Plots of PDFs at cloud base show broader distributions of PDFs compared to cloud top (Figure 3b). Near cloud top, the PDFs are more uniform reflecting a more homogeneous field of cloud reflectivity and, consequently, cloud albedo and other radiative parameters. The latter are defined mostly by cloud parameters in the upper third of the cloud system.

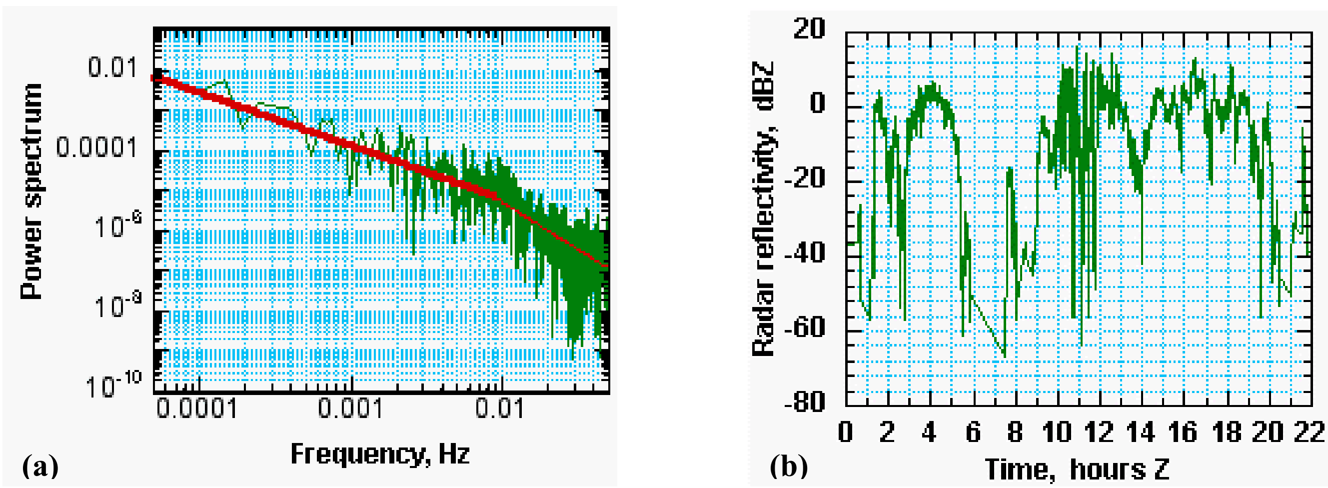

Figure 2. (a) MMCR radar reflectivity time series for December 2, 2000, at height 750 m and (b) for May 16, 2000, at height 6.5 km. Time resolution is 10 s.

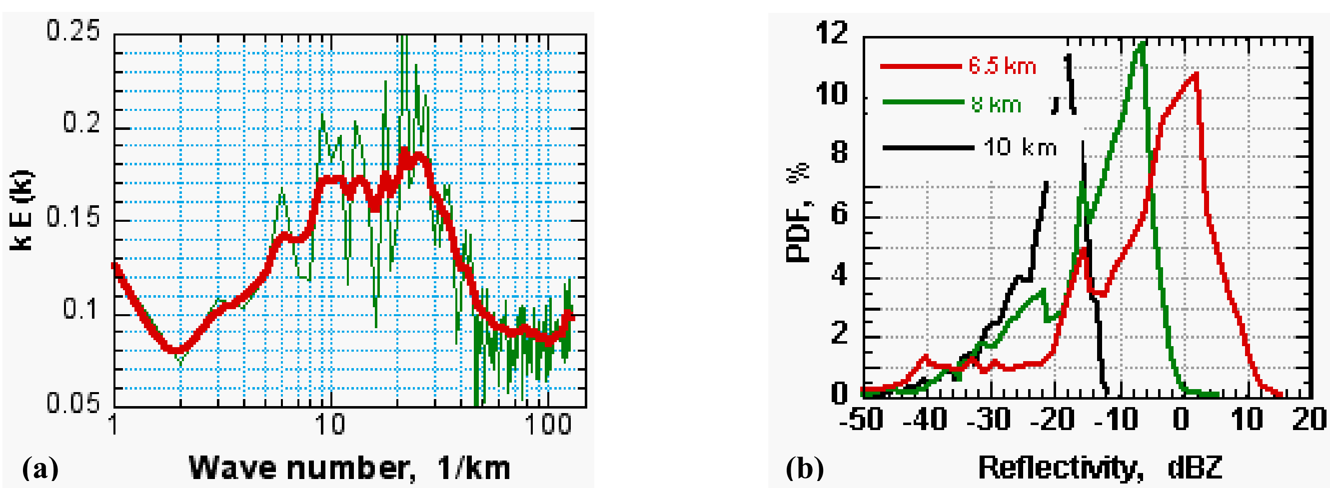

Figure 3. (a) PDF of radar reflectivity (calculated for the whole time series) at different levels in the cloud for the December 2, 2000, and (b) May 16, 2000, cases.

Retrieval of Dominant Scales of Inhomogeneity and Scale Breaks

We analyzed radar reflectivity power spectra for the December 2, 2000, case from 0.0 to 5.5 UTC at the 750 m height and for May 16, 2000 case from 12.0 to 21.0 UTC at the 6.5 km height. Figure 4 shows the spectra in log-linear coordinates for variables $kE(k)$ *vs log* k, where k is the frequency and $E(k)$ is the radar reflectivity power spectrum. In these coordinates, the area under the curve is proportional to the spectrum energy in the corresponding frequency interval and a local maximum of a curve can be interpreted as a dominant contribution to the power spectrum. The spectra were obtained using raw data and are shown here as examples of information on dominant scales of inhomogeneity in the radar reflectivity field. For interpretation of the results in spatial scale, we can convert time frequency k into spatial scale l by assuming the Taylor hypothesis and using observed December 2 and May 16 mean wind velocities of 7 m/s and 25 m/s, respectively.

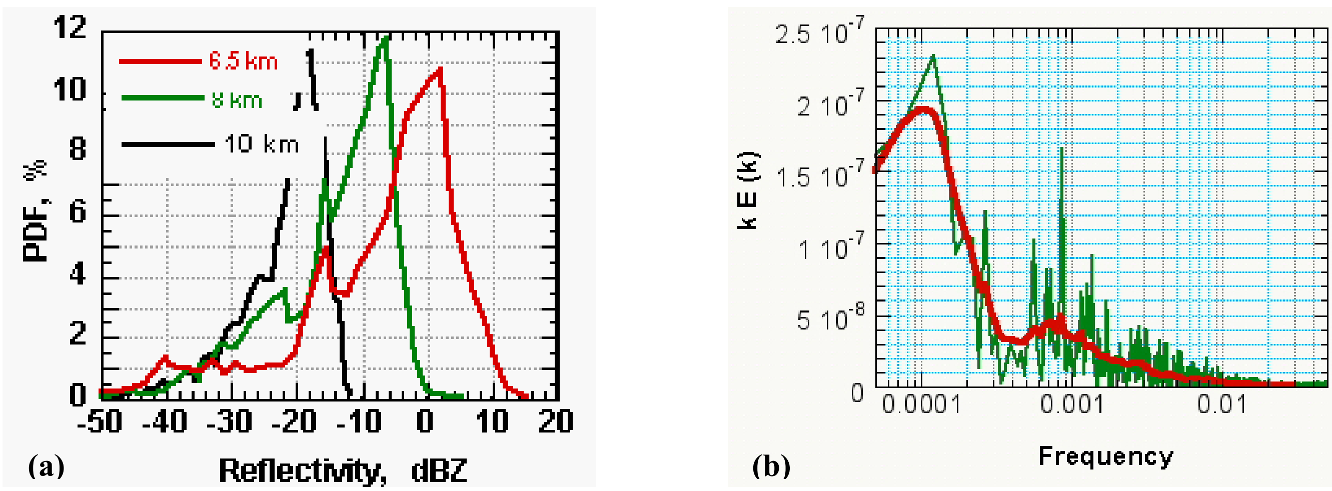

Figure 4. (a) Radar reflectivity power spectra (green line) for the December 2, 2000, case and (b) for the May 16, 2000, case. Smoothed curve is shown in red.

December 2, 2000, Case

Figure 4a shows that on December 2 the major contributions to the spectrum variance come from frequency/spatial ranges $k \sim (5.8 \div 10) \times 10^{-3}$ Hz ($l \sim 0.7 \div 1.2$ km), $k \sim (1.4 \div 2.3) \times 10^{-3}$ Hz ($l \sim 3.0 \div 4.8$ km), $k \sim (7.4 \div 8) \times 10^{-4}$ Hz ($l \sim 8.7 \div 9.5$ km), $k \sim (2.9 \div 3.9) \times 10^{-4}$ Hz ($l \sim 18 \div 24$ km), and around $k \sim 1.5 \times 10^{-4}$ Hz ($l \sim 48$ km). The first maximum at $l \sim 0.7 \div 1.2$ km appears to be directly related to the depths of the boundary and cloud layers. The second rather wide-scale range, $l \sim 3.0 \div 4.8$ km with several local sub-peaks, could be related to the dominant sizes of eddies-convective cells, typical for stratocumulus cloud layers, which also could be related to characteristic "eddy turnover scale." The largest scale, 48 km, is about 12-13 times that of the "eddy turnover scale" (about 2 hours), which is often used in simulation runs as a minimal necessary time for simulation to reach a stationary regime (Stull 1988). Figure 5a indicates a spectrum flattening at $l > 48$ km; thus, the nonstationary regime for scales larger then 46 km seems to become stationary.

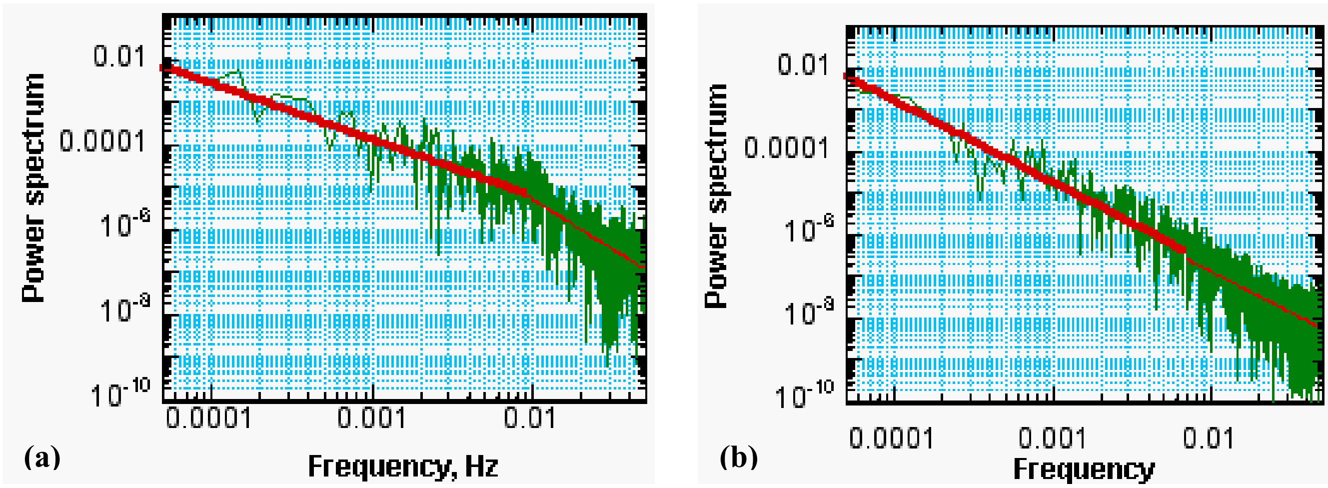

Figure 5. (a) Radar reflectivity power spectra (green line) for the December 2, 2000, case and (b) for the May 16, 2000, case. Approximation by best-fit power function curves is shown in red.

We also performed the Fourier analysis for the AVHRR satellite reflectance field obtained on December 2, 2000. The satellite image covered a 512 × 512 km domain with the spatial resolution of 1 km centered around the SGP site. The two-dimensional (2D) Fourier spectrum was calculated for each of the quarters of the full domain and then averaged. The cold air mass was moving on December 2, 2000, in the north-south direction. Therefore, the 2D reflectance spectrum was considered a function of the north-south component only, keeping the west-east component constant, and the time series of reflectivity was considered as a north-south cross section of the air mass using a translational mean wind speed of 7 m/c. Figure 6 shows local maxima of reflectance energy spectrum centered around the space scales of 3 ÷ 3.9 km, 5.1 ÷ 5.8 km, 7.1 ÷ 9.8 km, and 11.6 ÷ 14.2 km. The largest

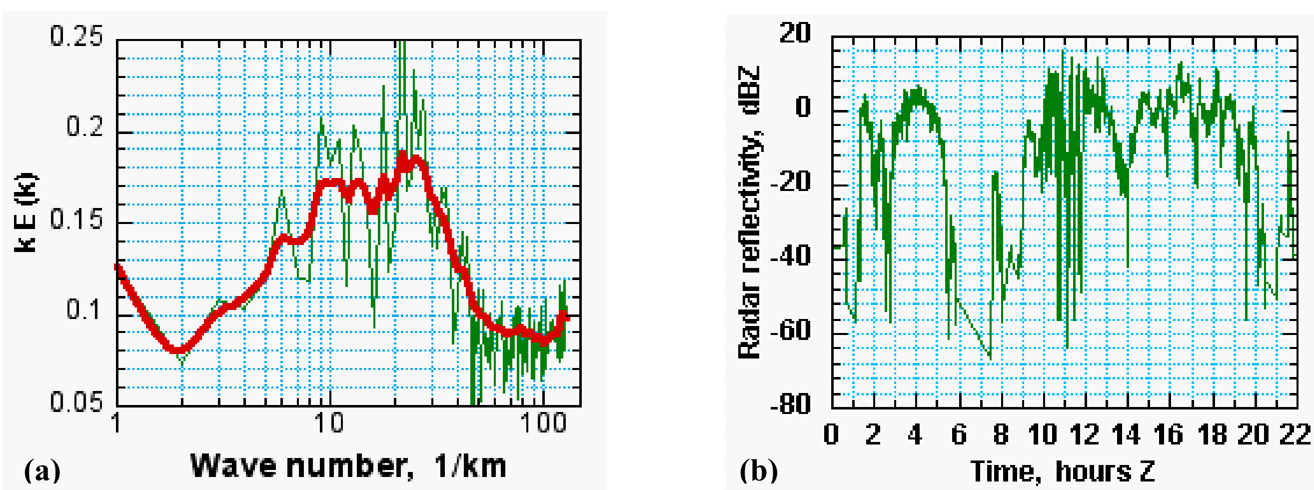

Figure 6. AVHRR reflectance on December 2, 2000. The left and right panels represent *k*E(k)* and *E(k)* (green curve), respectively. Shown in red are a smoothed curve on (a) the left panel and (b) a best-fit power function on the right panel.

contribution into the spectrum variance is around 21.3 km and 42.7 km. As we can see, many dominant scales from cloud radar reflectivity and satellite reflectance fields overlap indicating that cloud albedo and radar reflectivity fields have a similar variability determined by similar physical processes. More studies are needed to come to a conclusion on this fact.

To find scale breaks for both cases we approximated the spectra by best-fit power functions, which are straight lines in log-log coordinates (Figure 5). The slope of the line determines the value of the exponent. The absolute value of the exponent in both cases are greater than 1, which means that the reflectivity series in both cases are nonstationary over a wide range of middle scales except for very large and small scales where additional analysis is needed. For the December 2 case, there is an apparent scale break around 1.2 km. The reflectivity field on scales larger than the scale break is only slightly nonstationary (the absolute value of exponent is ~1.2), while on scales smaller than the scale break it is quite nonstationary (the absolute value of exponent is ~2.2). The power spectrum exponent for reflectance data is ~ 1.2 and there are no scale breaks, which coincides with the results for reflectivity data on scales larger than ~1.2 km and means that the reflectance field, too, is only slightly nonstationary (remember that reflectance field resolution is 1 km; it therefore does not resolve scales of 1.2 km or less).

For the altostratocumulus cloud system of May 16, the scale break is not that obvious: the absolute value of exponents do not differ much and are ~1.8 and ~2.0 for large- and small-scale portions of the spectrum, respectively. Thus, in this case, the reflectivity field is nonstationary; almost all are of the same degree over the whole scale range with slightly increased nonstationarity at smaller scales.

May 16, 2000, Case

The b panels on Figures 1-5 show similar analysis for the altostratocumulus case on May 16, 2000. The dominant space scales in Figure 4a are 4.7-4.9 km, 5.8-6.1 km, and 7.9-8.6 km. These are most likely related to the changing depth of the cloud layer (see Figure1b). The scales of preference 18 km, 23 km and in the interval (30-50) km, which as a whole accumulated a large amount of energy with peaks on 30.5 km, 36 km, and 45 km, seem to represent characteristic sizes of midsize patches of inhomogeneity probably typical for this type of cloud. The dominant scales of 128 km and, especially, 205 km (both well determined by three and four points of the spectrum, respectively) represent the largest inhomogeneity patches. The maximum on the 205-km scale is 4-10 times larger than any other maximum and represents a characteristic time period on the order of 2 hours. For larger scales (see Figure 5b), the spectrum flattens and appears to fall into the stationary regime. The variability of the radar field for altostratocumulus clouds is much smaller than for the low stratocumulus cloud system: the power spectrum for the latter is 2-10 times greater, depending on the scale, than for middle layer (see Figure 5).

Correlation Between Radar Reflectivity and Other Cloud Parameters

We conducted LES model simulations of a marine stratocumulus case based on ASTEX data to answer the question: What is the correlation between the radar reflectivity and cloud microphysical parameters? Figure 7a shows that the inhomogeneity scales in simulated radar reflectivity fields are directly related to the inhomogeneity scales of some other cloud physical parameters important in radiative transfer models. Model results demonstrate that there is a considerable correlation in variability between the fields of radar reflectivity and liquid water path (LWP), as well as the vertical velocity variance (Figure 7b) fields. This indicates that statistics characterizing variability of MMCR reflectivity might be used to study variability of LWP (Figure 7c), velocity variance, and possibly other cloud parameters.

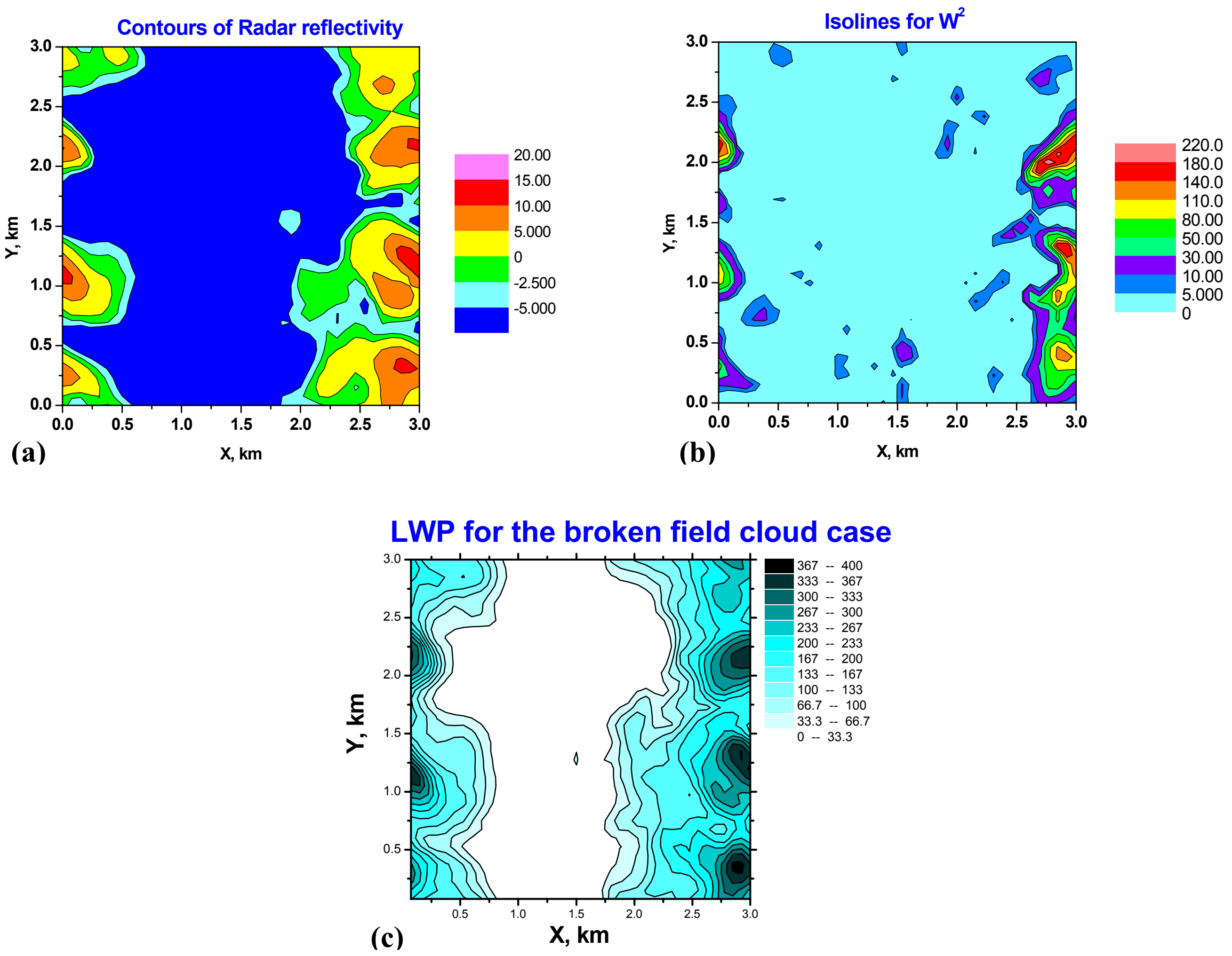

Figure 7. Contour plots of radar reflectivity, vertical velocity variance, and LWP in a LES simulation of a broken stratocumulus cloud field initialized used ASTEX 1992 data.

Conclusions

Cloud variability on a wide range of scales has a significant influence on calculation of cloud radiative properties and improving meso- and large-scale model prediction. In this study, we have investigated various approaches to characterize cloud variability, using as an example low stratocumulus clouds and altostratocumulus clouds observed over the ARM SGP site on December 2, 2000, and May 16, 2000, respectively. A mix of observations, including MMCR reflectivity, satellite reflectance, and large-scale meteorological conditions, were used. Several approaches based on PDF, spectral, and scaling analysis proved to be useful for characterization of cloud variability.

The analysis of MMCR data shows a very high level of variability in the low stratocumulus case, which is 2-10 times larger than in the altostratocumulus case. This magnitude difference is most likely due to the influence of surface fluxes and contributions from small-scale turbulence typical for boundary layer (BL). The scaling analysis shows that MMCR radar reflectivity and satellite reflectance fields are statistically scale-invariant and quite nonstationary in both cases over the whole scale range (~0.1-100 km, ~1.2-400 km for low and middle layer, respectively). The degree of nonstationarity is slightly higher for the low stratocumulus compared to the middle stratocumulus, which can be explained by the higher level of variability. In the low stratocumulus case there is an apparent scale break somewhere around ~1.2 km in the reflectivity field, which appears to be related to the inversion level height. The presence of this break suggests that over the ranges of spatial scales smaller than 1.2 km the physical processes that govern this cloud system are different than at larger scales. The reflectance field shows no scale break, apparently because of coarser resolution of satellite data. Our results do not show any obvious scale break in the reflectivity field for the altocumulus case. Thus, in this case the same physical processes dominate the whole range of spatial scales.

An important finding of this limited study is that most ranges of dominant scales for reflectivity and reflectance fields overlapped, as well; both fields show about the same degree of nonstationarity. The LES simulations demonstrate similar scales of inhomogeneity within reflectivity, LWP, and vertical velocity variance fields. If confirmed in statistically significant numbers of other cases, this would allow studying cloud inhomogeneity of reflectance and other cloud parameters using fine resolution MMCR data.

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