

ON THE PATCHINESS OF RADAR ECHOES IN MARINE STRATUS

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1. STRATUS OBSERVATIONS

Observations of marine stratus were made with an airborne radar of 3 mm wavelength off the coast of Oregon in September 1995. The radar was mounted on the Wyoming King Air aircraft which also carried sensors for in situ measurements of air motions and of hydrometeors. The radar provided reflectivity and vertical velocity measurements.

The observed clouds were unbroken and fairly homogeneous over the roughly 50 km domains of the flights. The vertical profiles of the liquid water content were close to adiabatic and drizzle was falling from the clouds at rates of about 0.1 mm h^{-1} . Maximum drizzle drop sizes were near $300 \mu\text{m}$ diameter.

A detailed description of the cloud characteristics will appear in Vali et al., 1998 (V98) probably shortly after this conference paper. Clouds on three consecutive days were described. Cloud depths ranged from 220 m to 340 m. The temperature gradient in all cases was $-5 \text{ }^\circ\text{C km}^{-1}$. Findings of specific relevance to this paper may be summarized as follows: (i) Horizontal averages of reflectivity decreased with height above cloud base but even at cloud top had values only 5 to 10 dBZ below the cloud base values. This is consistent with the in situ probe data showing drizzle drops present throughout the cloud volumes, although at reduced concentrations and with smaller sizes near cloud top. (ii) Reflectivities, expressed in dBZ, are approximately normally distributed at any given altitude. One standard deviation widths of the distributions are 4 to 8 dBZ, i.e. comparable to the decrease from cloud base to cloud top. (iii) From the in situ data it could be deduced that the reflectivity is dominated by drizzle drops ($> 50 \mu\text{m}$ diameter) in all but the upper 1/3 of the clouds ($\phi > 0.66$, where ϕ is the distance from cloud base upward as a fraction of the total cloud layer thickness). (iv) The observed vertical velocities (positive upward) were negatively correlated with reflectivity at and near cloud bases, but reversed sign for $\phi > 0.3$. Together with other evidence, this finding was interpreted as evidence for the upward transport of drizzle drops. (v) Regions of higher reflectivity exhibited trail-like appearance in vertical sections through the cloud. There was a hint of cellular structure of the echoes. In horizontal sections through the cloud (constant altitude surfaces) the echoes have highly irregular shapes.

In this paper, we present the results of further analyses concerning the sizes and shapes of the

echoes in horizontal planes. This information gives additional bases for envisaging and modeling the vertical transport and evolution of drizzle in these clouds.

2. ECHO SPACING AND PATCHINESS.

An example of the observed echo structures is shown in Fig. 1 (opposite page). The top panel is a vertical section through the cloud. Cloud base was at 580 m and cloud top was at 920 m. The two lower panels show constant altitude images at 750 m ($\phi=0.5$) and at 625 m ($\phi=0.13$).

Fourier analyses of the reflectivity fields indicate that they have no strong periodicities. The spectra are relatively smooth and extend from the minimum resolved scales to the sizes of the domains. Slight peaks are detectable; for example, the two constant altitude images shown in Fig. 1. indicate preferred spacings of 2 km and 1.5 km for the two altitudes, both at an angle of about 52° with respect to the flight direction. Preferred spacings in the range 1 to 2 km are also found in other samples. Generally, the spacing is somewhat larger for higher altitudes in the clouds. Strong peaks in the power spectra were detected only in one low altitude image that is dominated by precipitation streaks produced by wind shear.

A somewhat different picture results from an analysis of the patchiness of the echoes. We define 'patches' as the areas where the reflectivity exceeds a certain threshold. Sequences of threshold values are examined, starting a few dBZ below the maxima found in given images. Figure 2 shows the echo patches corresponding to the constant altitude images in Fig. 1, with 4 dBZ threshold for the 750 m image and 5 dBZ for the 625 m level.

The dominant features of the patches such as those in Fig. 2 are that they are quite irregular in shape and that they occur in a large range of sizes. The largest sizes increase as the reflectivity threshold is lowered. The total area of the patches increases as the reflectivity threshold is lowered; a factor 10 increase is found for 3 to 3.5 dBZ lowering of the threshold.

The frequency distributions of patch sizes, expressed as the logarithm of the number vs. the logarithm of the square root of the patch area, can be well described by power law functions with exponents, ϵ , in the range -4 to -2.5 . When normalized by the fraction of the total area that is covered by patches then

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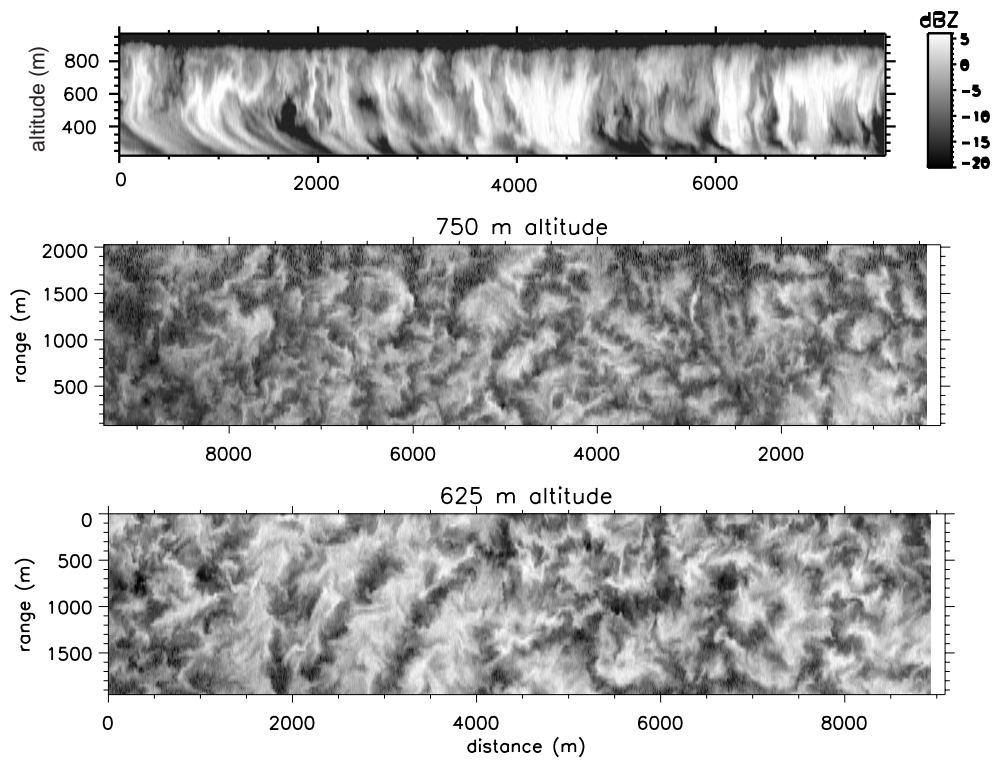


Figure 1. Upper panel shows a vertical section of radar reflectivity observed in marine stratus on 16 September 1995, while the aircraft carrying the radar was flying at about 150 m altitude with the radar pointed upward. The two lower panels are constant altitude images at 750 m and at 625 m obtained with the radar beam pointing to the right of the aircraft. The three images are not simultaneous but are from the same cloud region.

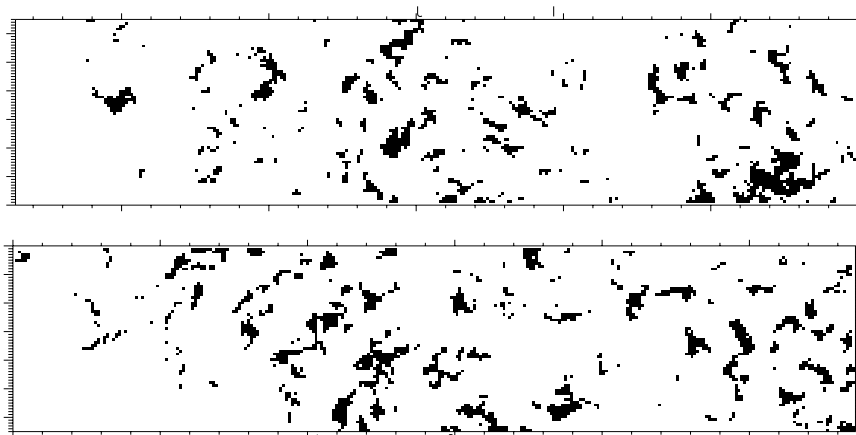


Figure 2. Constant altitude images from Fig. 1 converted to binary fields with areas exceeding 4 dBZ for the upper panel and 5 dBZ for the lower panel shown in black.

the size distributions converge to a single function. An example is shown in Fig. 3 for the two images of Figs. 1 and 2. In each panel distributions for various reflectivity thresholds are plotted. Differences between the curves for the two altitudes are evident but are small. Similar differences are found when comparing distributions from

different days. Thus, the results shown in Fig 3. appear to hold a substantial degree of generality. An alternate way of expressing the similarities in size distributions is that the slopes ϵ for different data sets are principally determined by the fraction of the total area covered by patches. The mean value of ϵ for 5% total patch area is

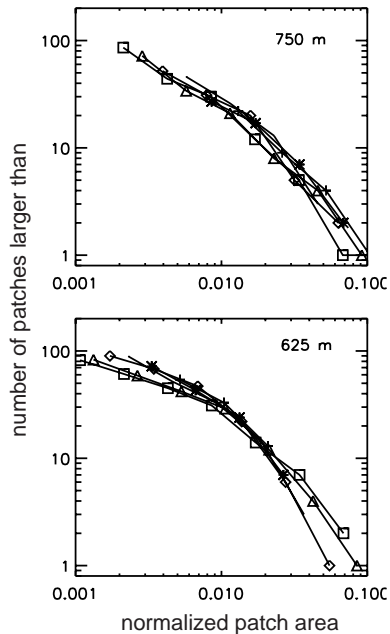


Figure 3. Frequency distributions of patches of different sizes. Patch size is normalized to the total area of patches for the given reflectivity threshold. Reflectivity thresholds for 750 m were 3 to 6 dBZ and for 625 m they were 4 to 7 dBZ at 0.5 dBZ intervals.

-4.2, while for 20% coverage the mean ϵ is -3.2 for all images examined and for all reflectivity thresholds. A linear dependence of the slope on area coverage describes the data well.

In terms of the areas covered by patches of different sizes, the distributions for different reflectivity thresholds also converge to single curves similarly to the pattern shown in Fig. 3.

3. PERIMETER FRACTALS

For given reflectivity thresholds, such as those in Fig. 2, plots between patch perimeter and the square root of the patch area show strong correlations. The slope of the line defined by these points yields the perimeter fractal dimension of the set of patches (Cahalan and Joseph, 1989). Minimum patch sizes of 10 pixels are used for this analysis.

For all the cases examined the perimeter fractal dimensions are 1.5 ± 0.1 . No trends are evident in this parameter with respect to either reflectivity threshold or altitude in the cloud.

4. DISCUSSION

The results here presented reinforce and to some extent quantify the conclusions arrived at in V98.

It was shown in V98 that the reflectivity patterns are primarily due to variations in the concentrations and

sizes of drizzle drops. This claim is supported, among others, by the fact that the variability in reflectivity due to cloud droplets is considerably less than the observed variation. Hence, the patches of high reflectivities can be viewed as regions of above average drizzle concentrations.

The simplest deduction from the findings here presented is that there is a substantial degree of randomness in the formation and distribution of drizzle in stratus. There is no evidence for the existence of organized 'cells' or similar structures. The size distributions with large negative exponents were largely unexpected.

The appearance of the patterns in Fig. 2 is reminiscent of those that arise in computer simulations of clustering (e.g. Family et al., 1985). The fractal dimension of 1.5 is also close to the value of ~ 1.4 that was obtained for the cluster models.

Another demonstration of the random element in the patch patterns is that very similar results are obtained for a field of random points smoothed by 7 to 11 pixels. Such smoothed random number fields yielded size distributions with the same shapes ($\epsilon \approx -4$ to -2.5) and with the same perimeter fractals as the cloud data.

Furthermore, it is important to note that there are no qualitative differences in patch shapes and in their size distributions from different altitudes within the clouds. The observed decreases in reflectivities with increasing height are reflected as decreases in the fraction of area occupied by regions exceeding given reflectivity thresholds, but not in changes in ϵ , nor in different perimeter fractal dimensions.

Small patches contribute the major part of the total area of high reflectivity at all altitudes. For stagnant air this would mean that the majority of the drizzle flux is in small patches, but that interpretation is invalidated by the comparable magnitudes of vertical air velocities and particle fall velocities. In light of the reversal in the reflectivity vs. vertical velocity (air velocity plus particle velocity) correlation with height, it is thus clear that a fuller understanding of these issues will require that the correlation be examined as a function of echo dimensions.

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