

Contrasting Properties of Single-Layer and Multi-Layer Arctic Stratus Sampled During the Mixed-Phase Cloud Experiment

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Introduction

The microphysical properties of both single-layer and multi-layer Arctic boundary layer stratus sampled during Mixed-Phase Cloud Experiment (M-PACE) are studied. In situ measurements are used to determine how cloud properties, such as phase, size distribution and shape of cloud particles, vary as a function of normalized cloud altitude (Z_n) for single-layer stratus. Microphysical properties of single-layer and multi-layer stratus are then contrasted. This contrast may be helpful for evaluating the performance of cloud resolving models and for determining whether models can simulate the difference in cloud properties between single-layer and multi-layer status.

Single-Layer Arctic Boundary Layer Stratus

From 9 to 12 October 2004, a continuous single-layer Arctic boundary layer status, located under a sharp temperature inversion, persisted over the entire M-PACE domain. Thirty-six spiral ascents and descents over Barrow and Oliktok Point, together with 17 ramped flight legs between Barrow and Oliktok Point, were executed to characterize the vertical variability in the single-layer stratus. Figure 1

shows size distributions measured over Oliktok Point within this single-layer arctic stratus on 10 October when the Pacific Northwest National Laboratory Remote Sensing Laboratory lidar detected cloud base at 900 m and a strong liquid layer near cloud top at 1400 m. At this time, the cloud radar indicated the occurrence of large ice crystals in the liquid cloud layer and precipitating ice crystals beneath. The growth of the supercooled water droplets within the liquid cloud layer is seen by the increase of the modal diameter of the forward-scattering spectrometer probe (FSSP) size distributions with height. Drizzle drops with sizes above 20 μm are seen in both the FSSP and one-dimensional cloud probe (1DC) size distributions near cloud top. In general, greater numbers of large ice crystals are seen near cloud base and precipitating beneath cloud, but ice occurs throughout and even at the top of the cloud.

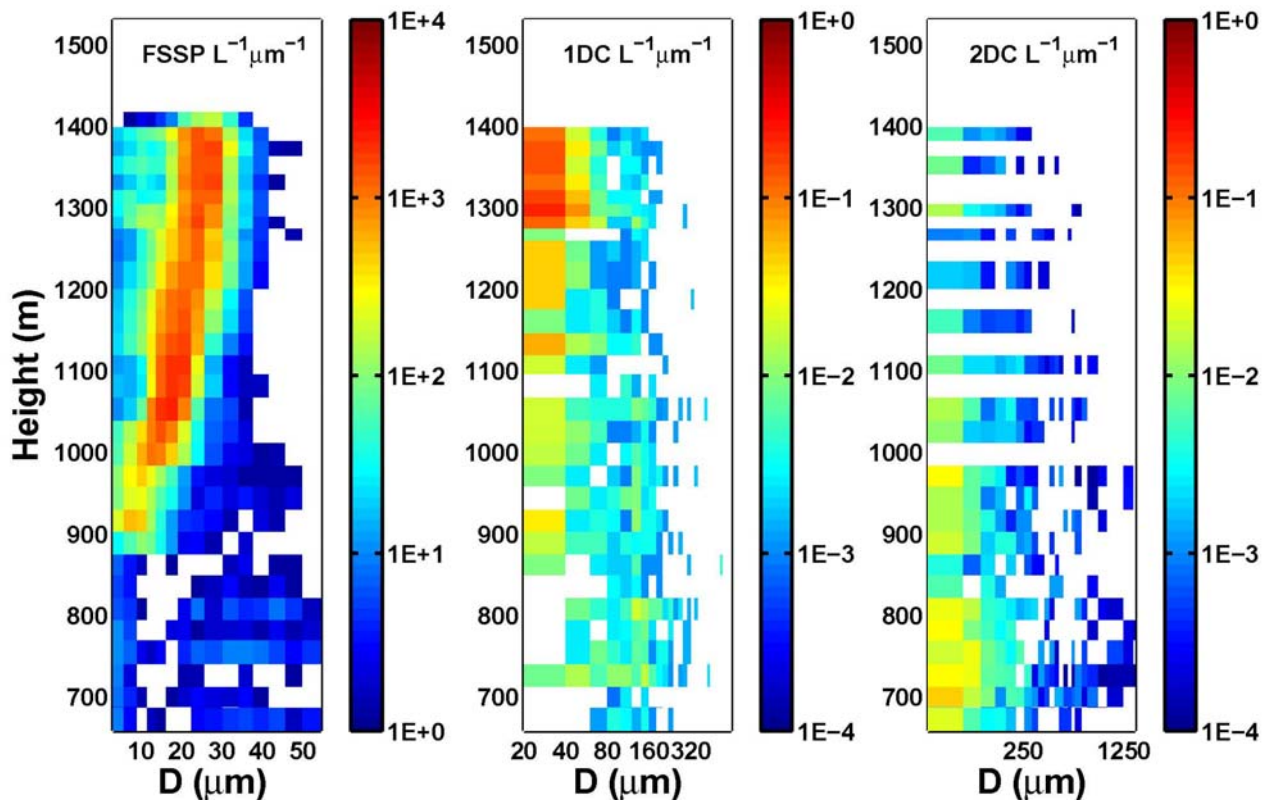


Figure 1. Vertical profile of size distributions for a single-layer stratus cloud, sampled from 2140 to 2147 Universal Time Coordinates (UTC) on 10 Oct.

To visualize data from these 53 vertical profiles simultaneously, bulk measures of the cloud properties in the single layer clouds are plotted as a function of Z_n , where Z_n varies from 1.0 at cloud top to 0.0 at cloud base. Each blue or red dot in Figures 2 and 3 represents a 10-second averaged bulk quantity measured at the Z_n for a single spiral. A clear trend of increasing liquid fraction with increasing Z_n is seen with the cloud being almost entirely liquid at cloud top. This suggests that parameterizations for liquid water fraction in large-scale models that are functions of only temperature may not adequately

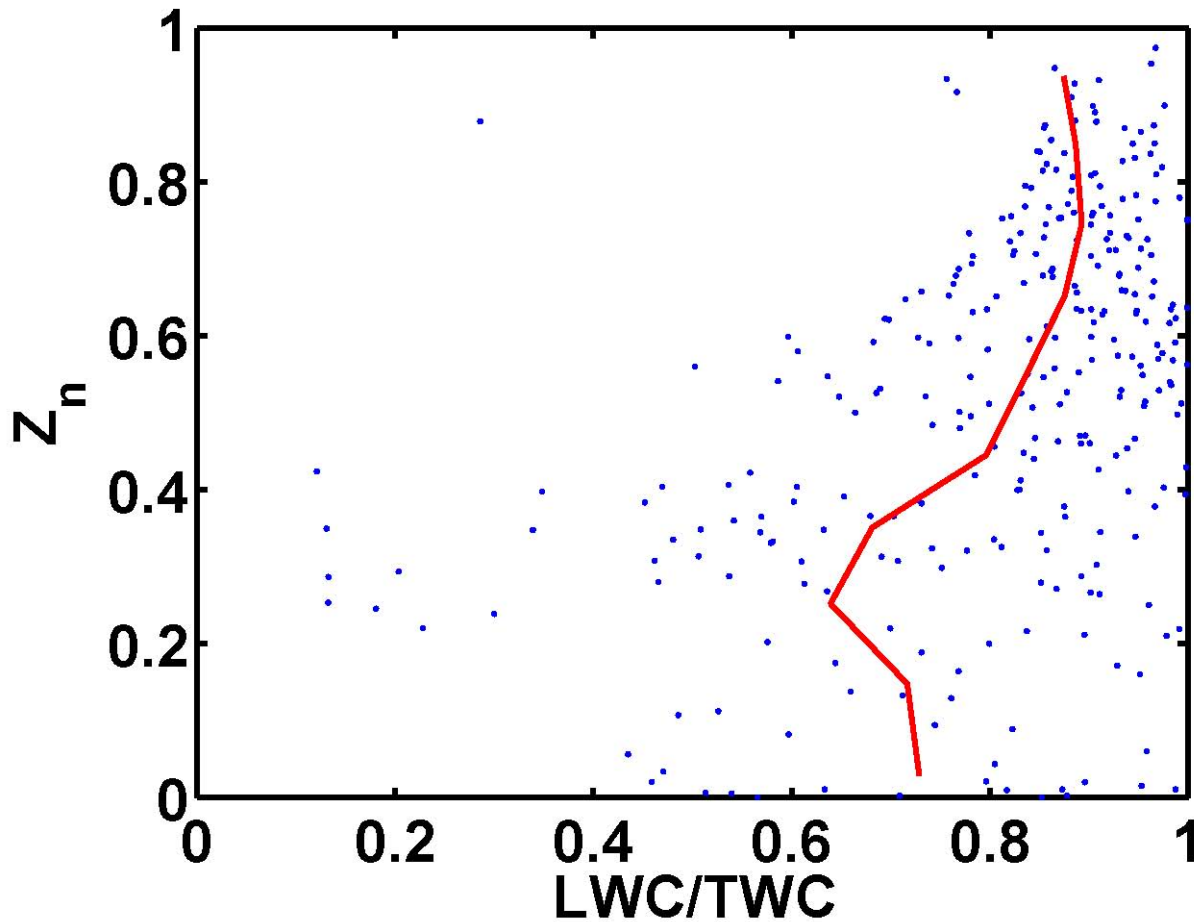


Figure 2. Vertical variation of liquid water content (LWC)/Total water content (TWC) as a function of Z_n .

represent the behavior of arctic mixed-phase clouds since the liquid fraction is highly sensitive to the position within the cloud. The water droplet effective radius increases with height due to condensational growth and the eventual production of drizzle by collision-coalescence near cloud top. However, the ice crystal effective radius defined following Fu (1996) shows little systematic change with Z_n .

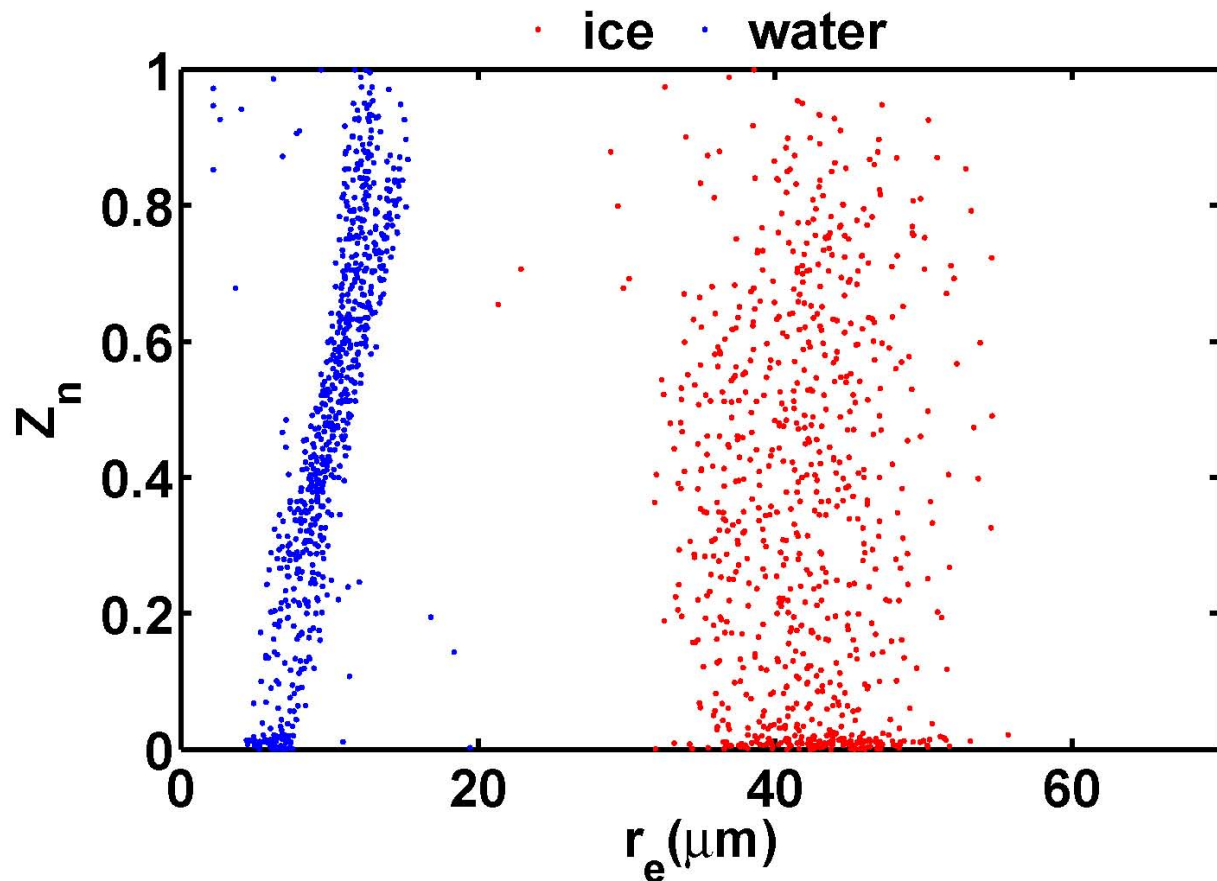


Figure 3. As in Figure 2, except for vertical variation of water droplet and ice crystal effective radius (r_e).

Multi-Layer Arctic Boundary Layer Stratus

In addition to the single-layer arctic status, examples of multi-layer mixed-phase clouds were observed during M-PACE. These clouds were observed during flights in the early part of the field campaign on 5, 6, and 8 October as listed in Table 1. Figure 4 shows an example of the more complex variation of size distributions with altitude for these multi-layer clouds. Even though there is evidence of increase in the FSSP modal diameter with height in individual cloud layers and some evidence of drizzle drops with diameters greater than $20 \mu\text{m}$ at the top of these layers, it is more difficult to define a Z_n for representing the trends in these multi-layer cases.

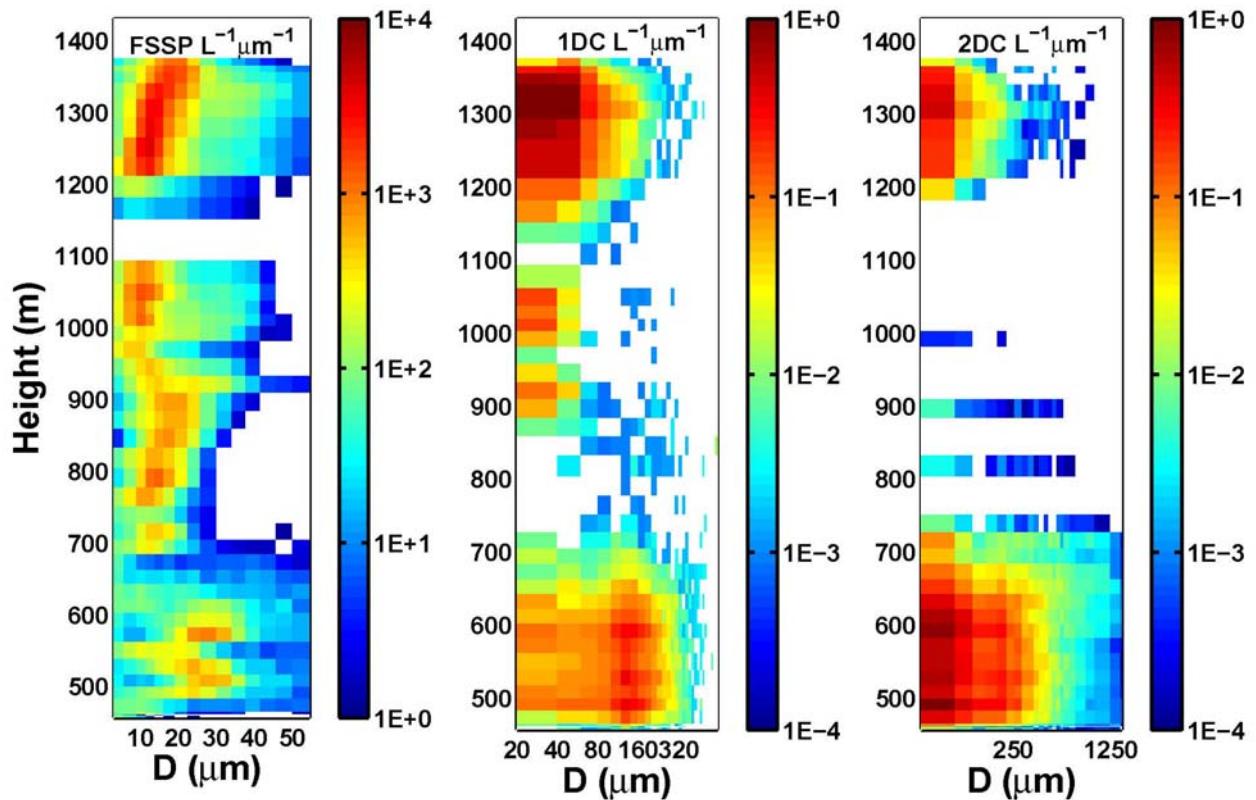


Figure 4. Vertical profile of size distributions for a multi-layer stratus cloud sampled over Barrow from 1950 to 2005 UTC on 5 October.

TABLE 1. Summary of layered nature of boundary layer stratus during M-PACE. Multi-layer clouds dominated during the early stage of the campaign.	
10/05/2004 (18:30-21:40 UTC)	Multi-layer
10/06/2004 (18:22-21:32 UTC)	Multi-layer
10/08/2004 (19:50-22:30 UTC)	Multi-layer
10/09/2004 (20:10-22:50 UTC)	Single layer
10/10/2004 (00:10-03:10 UTC)	Single layer
10/10/2004 (21:20-22:50 UTC)	Single layer
10/12/2004 (23:10-23:59 UTC)	Single layer

The phase (liquid, ice, or mixed) of each 10-second average size distribution was identified following Cober et al. (2001) and McFarquhar and Cober (2004). Periods with supercooled water were first identified using the Rosemount icing detector. Inspection of cloud particle imager (CPI), two-dimensional cloud probe (2DC) and high volume precipitation spectrometer images identified periods with non-spherical particles and hence, the presence of ice. Examination of the FSSP size distributions

helped determine whether significant amounts of ice were present because FSSP size distributions typically exhibit sharp peaks between 10 and 20 μm when supercooled droplets dominate the total water content, but exhibit a flat signal when ice dominates the total water content. A phase identification scheme combining information from these techniques helped unambiguously identify the phase for each 10-second time period. This scheme is applied to all the 10-second time periods of single layer clouds and multi layer clouds. Figure 5 shows the difference of phase occurrence frequency between single-layer and multi-layer stratus. More mixed-phase periods are seen in single-layer stratus than in multi-layer clouds. Ice clouds dominate the multi-layer stratus possibly because of the seeding process caused by ice falling from above.

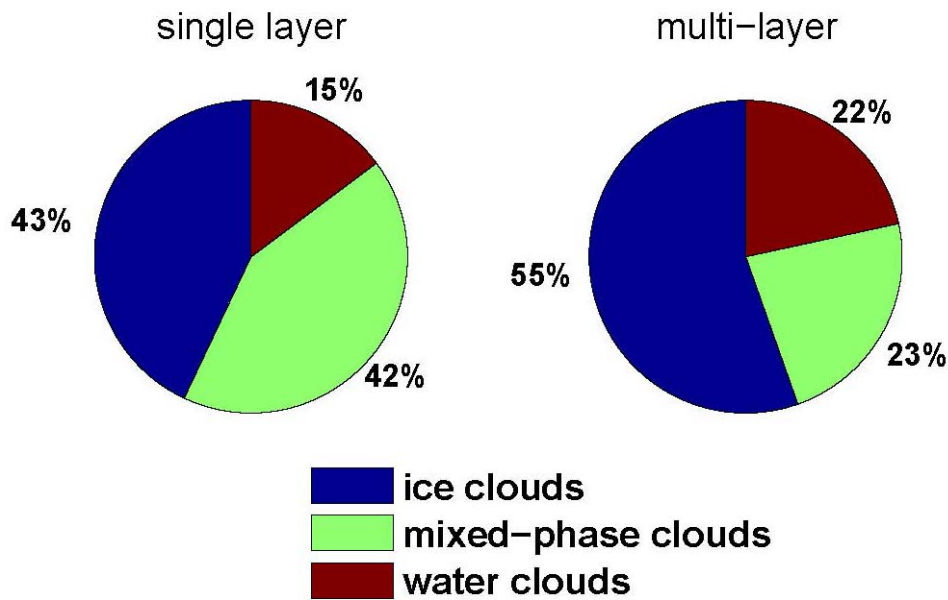


Figure 5. Phase occurrence frequency distribution of single layer and multi-layer stratus.

For 10 second periods when both water and ice were present in single-layer and multi-layer stratus, the frequency distribution of LWC/TWC is shown in Figure 6. Here, LWC is estimated by the King probe and TWC is estimated by the counterflow virtual impactor probe. When mixed-phase time periods occur, multi-layer clouds have more cases with greater contributions from ice than single-layer clouds.

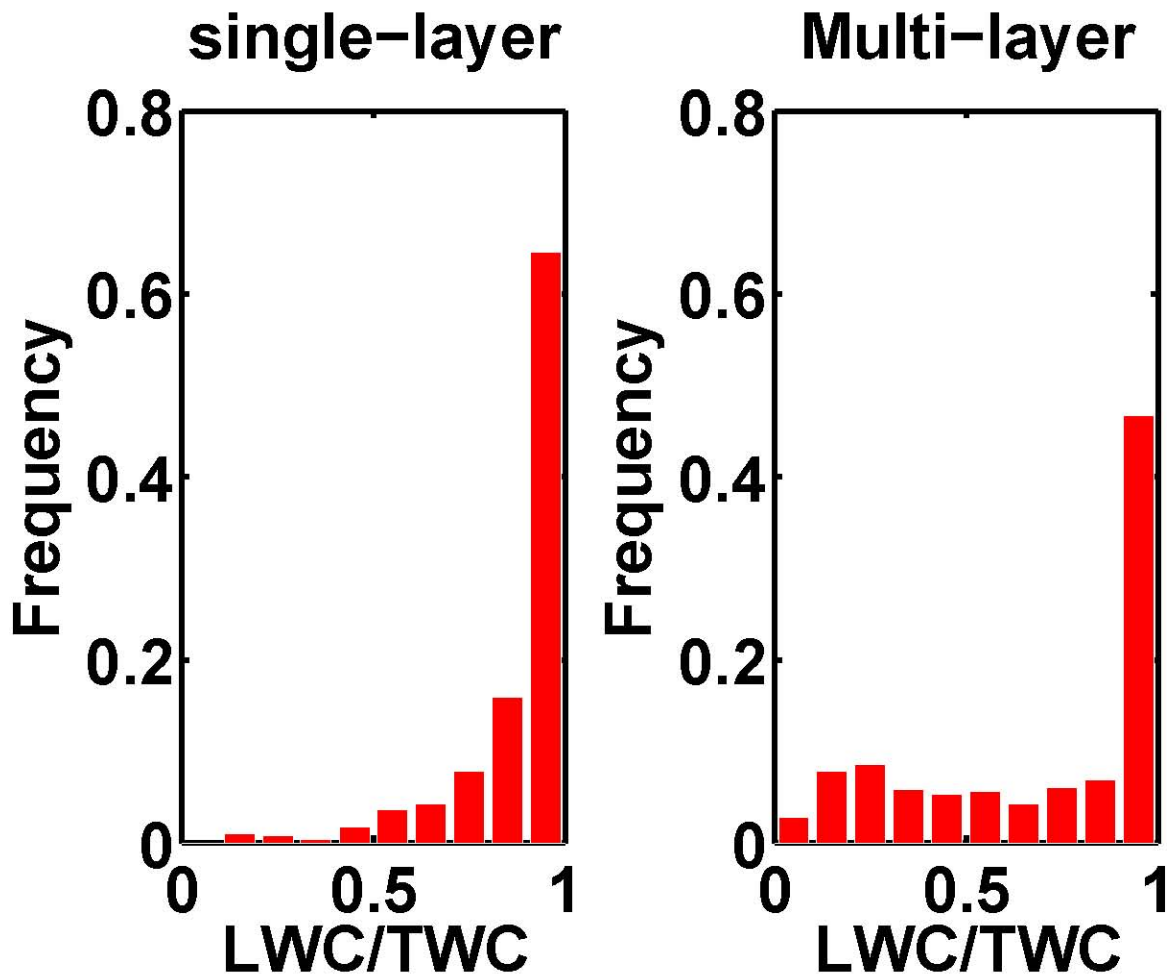


Figure 6. Normalized frequency distribution of LWC/TWC for mixed-phase clouds in single-layer and multi-layer stratus.

After applying the phase identification scheme to all 10-second time periods, size distributions for the time periods with the same phase (ice, mixed-phase and water) are averaged and summarized in Figure 7. FSSP distributions of mixed-phase single-layer clouds are more peaked than FSSP distributions of mixed-phase multi-layer clouds. Since a peaked FSSP distribution is a strong indicator of the presence of supercooled water, this again suggests that there were greater fractions of supercooled water in the single-layer stratus.

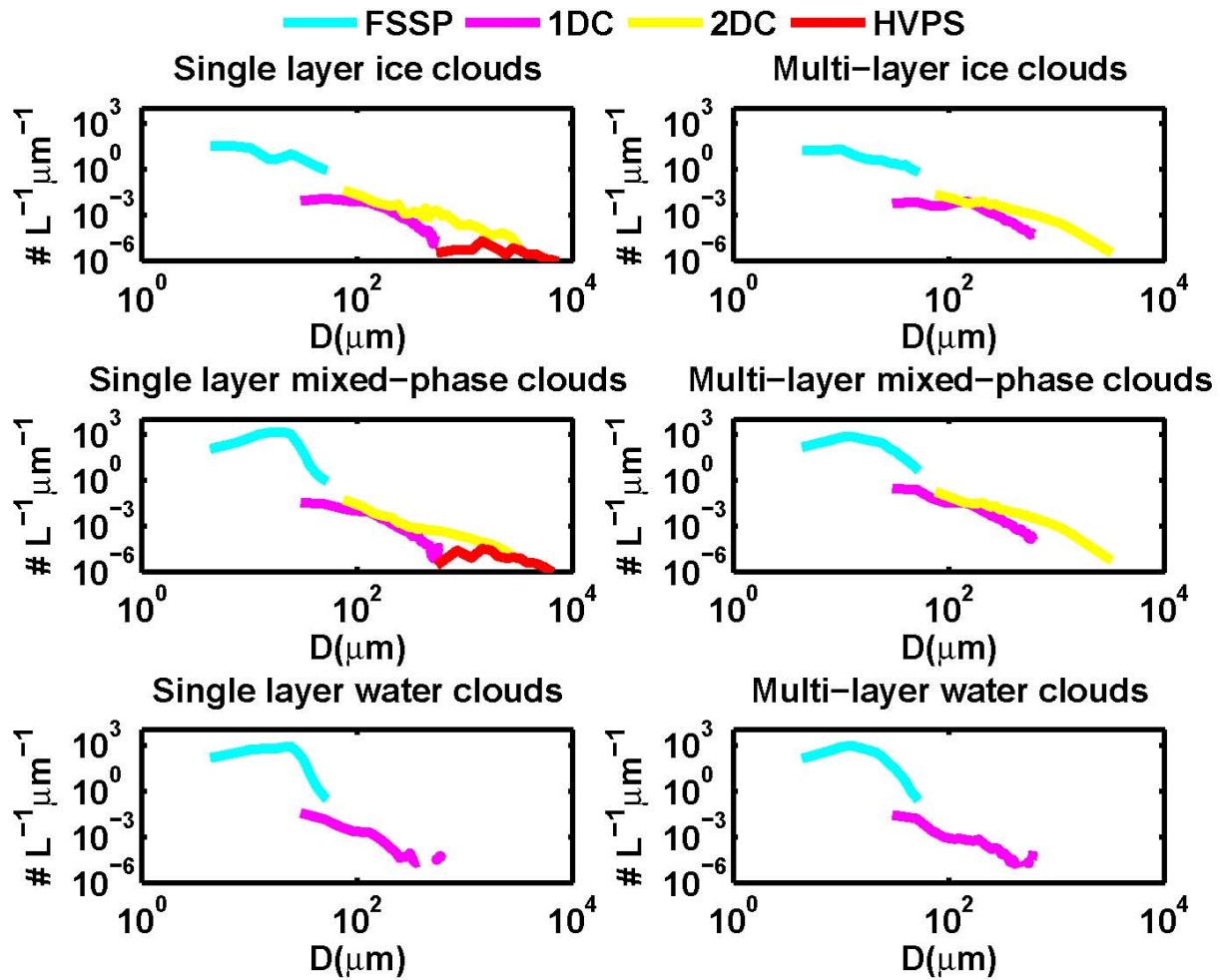


Figure 7. FSSP, 1DC, 2DC and high volume precipitation spectrometer size distributions for ice, mixed-phase and water clouds in single-layer and multi-layer stratus.

In single-layer clouds the LWC/TWC ratio increases with Z_n . As shown in Figure 4, the cloud vertical structure is more complex in multi-layer clouds. It is also more difficult to define either Z_n for each layer within a multi-layer cloud or for representing the entire cloud. Hence, the LWC/TWC ratio is used to represent the variation of cloud properties. The variation of the FSSP, 1DC and 2DC size distributions for single layer and multi layer clouds is illustrated in Figure 8. The increase of the modal diameter of the FSSP size distribution with LWC/TWC is clearer in the single-layer cases than in the multi-layer cases.

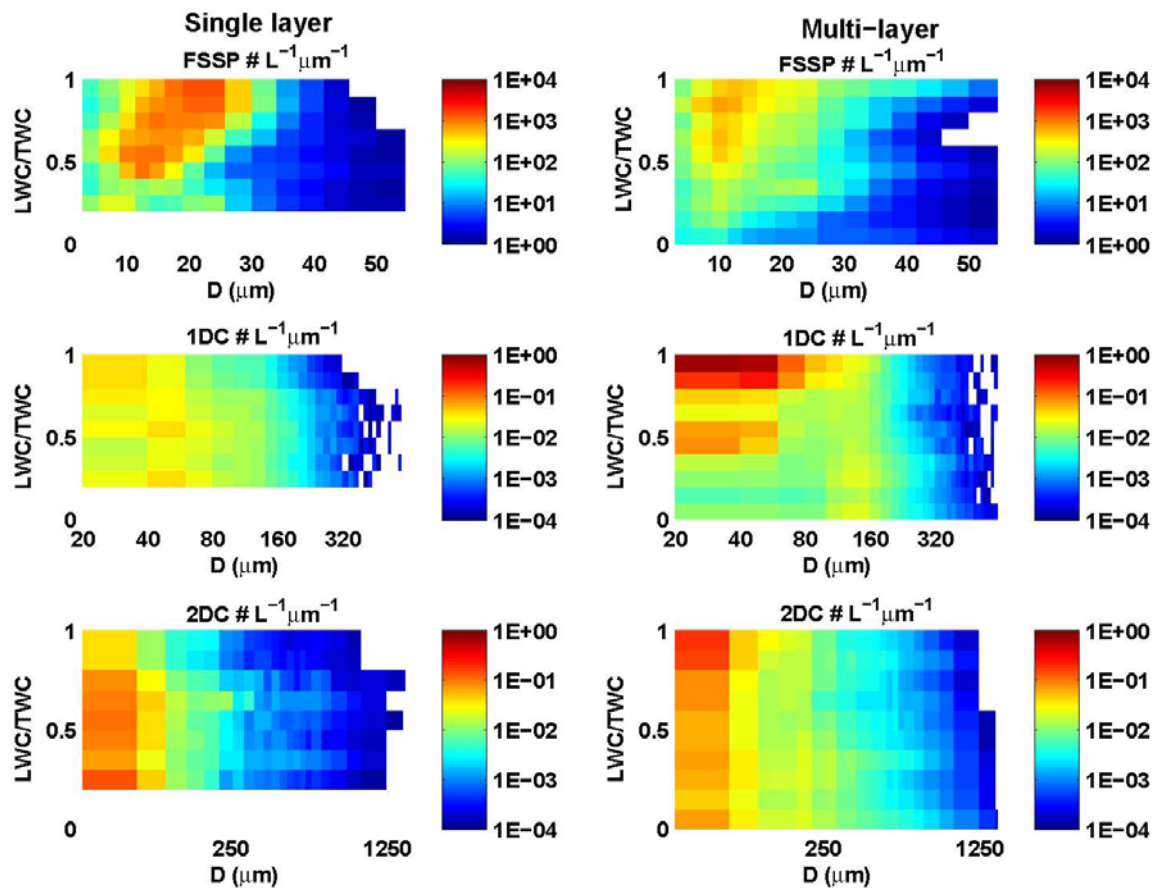


Figure 8. Variation of FSSP, 1DC and 2DC size distributions as a function of LWC/TWC for single-layer and multi-layer clouds.

A habit is assigned to each cloud particle depending on the width/length ratio and roundness ($4 \cdot \text{area} / \pi \cdot \text{length} \cdot \text{length}$) measured by CPI. The habit frequency distributions as a function of the LWC/TWC ratio for different size particles are compared for both single-layer and multi-layer clouds in Figure 9. For $0 < D < 60 \mu\text{m}$, spherical and quasi-spherical particles dominate the total number of particles. The percentage of spherical particles increases with LWC/TWC. More spherical particles are in the single-layer clouds while more quasi-spherical particles are in the multi-layer clouds. These quasi-spherical particles possibly indicate the presence of small ice crystals. For $60 < D < 120 \mu\text{m}$ there are more spheres for multi-layer cases than for single-layer cases. For $D > 120 \mu\text{m}$, there are more needles in multi-layer stratus and more irregular particles in single-layer stratus.

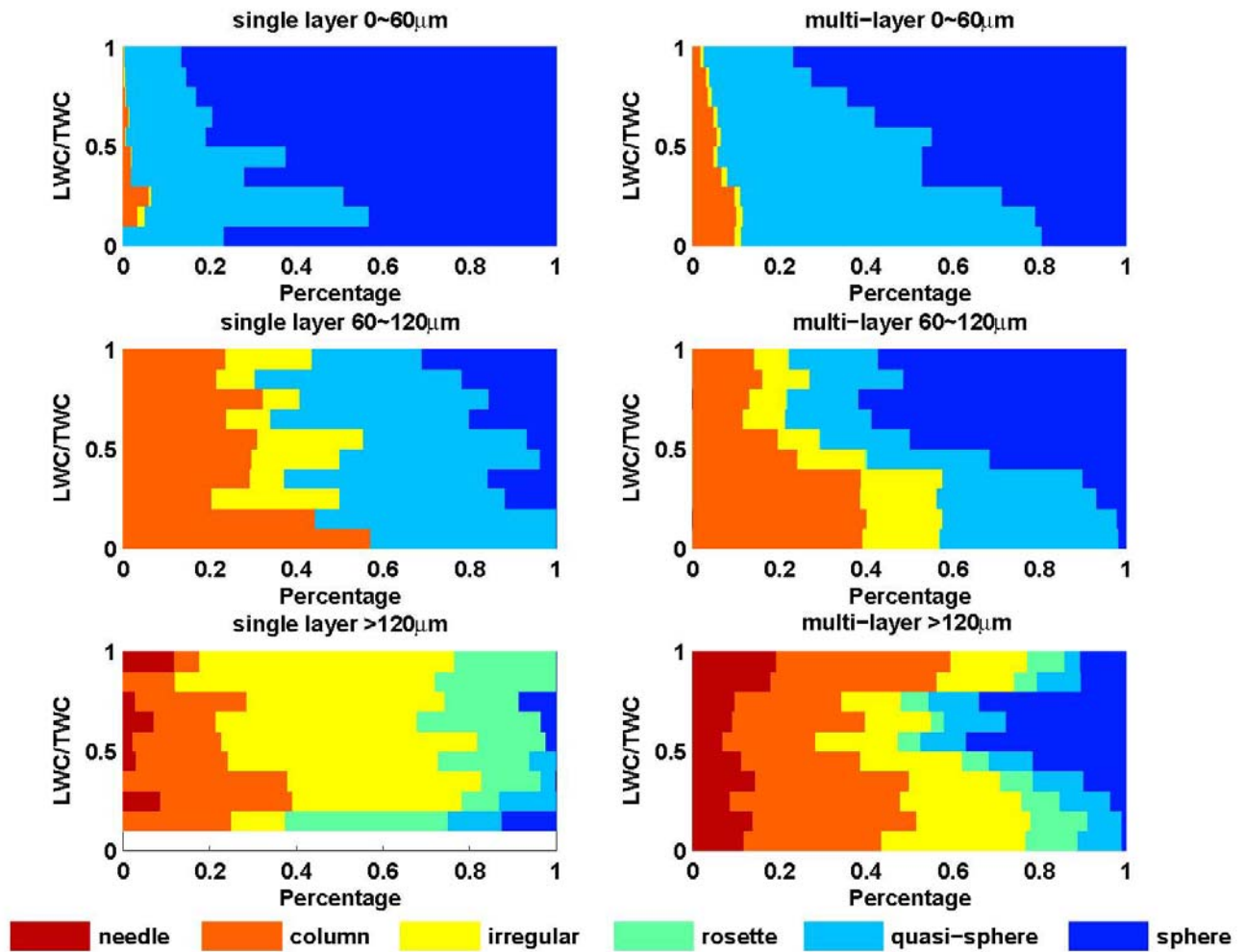


Figure 9. Variation of fraction of different habits as a function of LWC/TWC ratio for single layer and multi-layer boundary layer stratus.

Conclusions

The principle conclusions of this study are as follows:

- 1) During M-PACE a greater fraction of time periods with mixed-phase clouds occurred in the single-layer stratus whereas a greater fraction of time periods with the ice phase clouds occurred in multi-layer stratus.
- 2) For mixed-phase periods, the ice made up a greater fraction of the total water content for the multi-layer clouds compared to the single-layer clouds.

- 3) There is a clear increase in the modal diameter of the FSSP distribution with normalized cloud altitude for the single-layer clouds; although present in individual cloud layers in multi-layer clouds to some degree, it is more difficult to represent this trend as a function of normalized cloud altitude.
- 4) For $0 < D < 60 \mu\text{m}$, spherical and quasi-spherical particles dominate the cloud particles imaged by the CPI for both single-layer and multi-layer status. The percentage of spherical particles increases with LWC/TWC. For $D > 120 \mu\text{m}$, there are more needles in multi-layer stratus and more irregular particles in single-layer stratus.

Acknowledgments

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