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OVERVIEW OF THE MIXED-PHASE ARCTIC CLOUD EXPERIMENT (M-PACE)

Johannes Verlinde*, J. Y. Harrington*, G. M. McFarquhar, J. H. Mather, D. Turner, B. Zak, M. R. Poellot, T. Tooman, A. J. Prenni, G. Kok, E. Eloranta, A. Fridlind, C. Bahrmann, K. Sassen, P. J. DeMott, A. J. Heymsfield

*The Pennsylvania State University, University Park, PA 16803

1. Introduction

The DOE-ARM funded Mixed-Phase Arctic Cloud Experiment (M-PACE) was conducted on the North Slope of Alaska (NSA) October 2004. The experimental domain (Fig. 1) simulated a single column modeling grid-box. The DOE-ARM NSA site at Barrow was supplemented with the High Spectral Resolution Lidar (HSRL) from the University of Wisconsin and the University of Alaska Fairbanks depolarization lidar. The Pacific Northwest National Laboratory (PNNL) Atmospheric Remote Sensing Laboratory (PARSL) was deployed at Oliktok Point, supplemented with a rapid scan AERI from the University of Wisconsin. Radiosonde launches were conducted from the four surface sites.

Figure 1: The M-PACE experimental domain

Two instrumented aircraft participated in the experiment: the University of North Dakota Citation served as an in situ platform, while the piloted Scaled Composites Proteus, sponsored by the DOE-ARM UAV program served as a remote sensing aircraft flying above the cloud decks.

2. Weather Description

The North Slope of Alaska was under, essentially, three different synoptic regimes during MPACE. The first regime, between Sept 24 and Oct. 4, was unsettled. The north slope was affected by a small low pressure center (~990 hPa) with a large high pressure system northwest of the Alaskan coast over the Arctic Ocean. The first two case days, Sept 29 and 30, occurred in the heart of this weather regime. On Sept. 27, the low pressure center tracked west out of northern Canada stalling to the south of Barrow with deep clouds. Oliktok and Toolik were clear as these regions were in the dry slot. On Sept 28, the stalled low began to track back eastward bringing with it our first shot of low level mixed-phase clouds.

After the 4th of Oct., the synoptic regime changed considerably with high pressure building in over the pack ice to the northeast of the Alaska coast that dominated the synoptic regime until the 15th. Initially (Oct 4 - 8), flow associated with the high pressure system came out of the east-northeast with considerable fetch along the Arctic Ocean before impinging on the Alaska coast. This was the source of the cloudiness experienced during the flight operation days of Oct. 5 and 6. By Oct 8, temperatures over the pack ice had dropped considerably reaching ~ -20 C (Fig. 2) with a strengthening of the high. The flow that reached the Alaska coast now came directly from the pack ice (Fig. 2) and, along with it, boundary layer roll clouds (Fig. 3). These rolls likely produced periodic

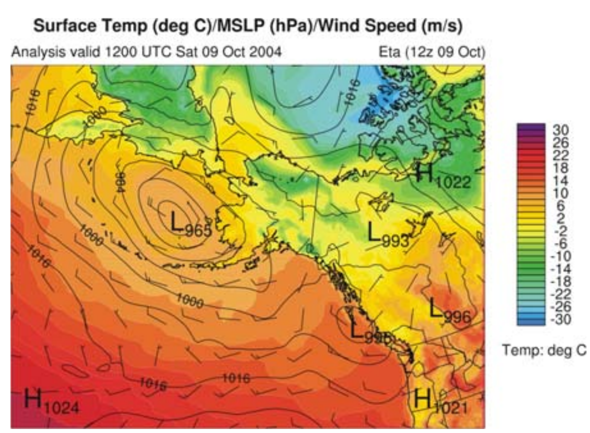

Figure 2: ETA analysis for 1200 UTC Saturday 09 October 2004. Shown are temperatures (shaded), mean sea level pressure (contoured) and windbarbs.

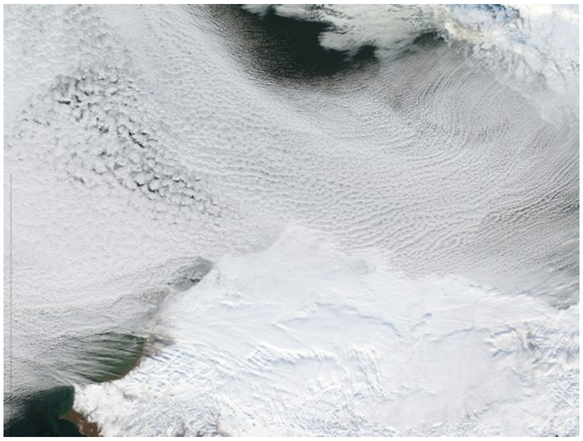

Figure 3: MODIS visible image of the Arctic Ocean and Northern Alaska on 09 October 2004

oscillations in cloud depth observed at Barrow and Oliktok. This regime was the main driver of cloudiness during the Oct 8-10 and Oct 12 case days.

After the 15th of Oct, the high pressure over the pack ice slowly moved towards the southeast. With the block removed, strong low pressure centers (~950 hPa) that were forming near Kamchatka and propagating north through the Bering could now affect the north slope. Eventually, a low propagated into the northwestern portion of the Chukchi Sea producing southerly flow for much of the NSA (Fig. 4). This kept much of the eastern NSA under partially cloudy, or even clear, skies. However, frontal systems spawned by the low strongly affected the NSA west of a line between Barrow and Oliktok.

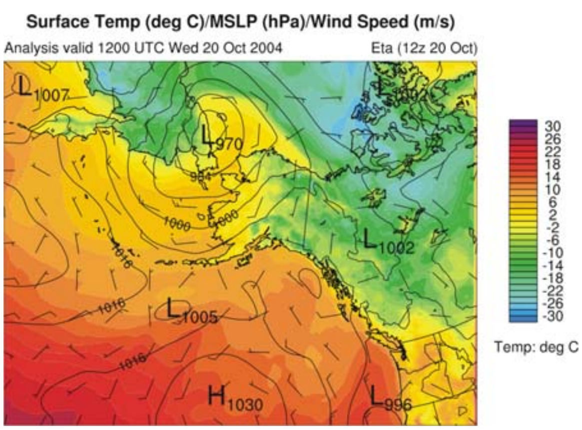

Figure 4: ETA analysis for 1200 UTC Wednesday 20 October 2004. Shown are temperatures (shaded), mean sea level pressure (contoured) and wind (barbs).

This produced deeper clouds near Barrow and plenty of high cirrus. This synoptic regime occurred throughout the remainder of the experiment.

3. Missions

The Citation flew 13 and the Proteus 5 missions in support of M-PACE. Summaries of the conditions for all flights are provided in Table 1. In total 11 missions were dedicated to characterize mixed-phase cloud microphysics and 2 flights for cirrus. Ice freezing nuclei (IN) concentrations were measured on all October flights. Two flights were dedicated to documenting the cloud characteristics in close proximity to the location where IN concentrations were measured. Cloud top temperatures ranged from -6 to -30 ^oC for the St/Sc cases sampled. Droplet concentrations were generally low, but two cases exhibited concentrations in the 100's cm^{-3}. Liquid water contents varied between ~.1 to 1 g m^{-3}. All these clouds had ice precipitation.

Table 1: Summary of M-PACE aircraft operations. All data are preliminary and may change with future quality control. Proteus flights are indicated with *, satellite coordination with &.

Date	Category	T_{min}(C)	FSSP (cm^{-3})
09/29	BL St	-15	70-90
09/30	Multi-layer St	-15.5	20-70
10/05	Multi-layer St	-6	100-400
10/06	Multi-layer St	-17	25-50
10/08*&	Multi-layer St	-11	20-30
10/09a*	BL St	-16	50-100
10/09b	BL St	-15	300-500
10/10*&	BL St	-17	20-40
10/12*&	BL St	-15	40-60
10/17*&	Ci	-57	50 L^{-1} 2DC
10/18	Ci	-55	20 L^{-1} 2DC
10/20	Aerosol/Sc	-13.5	10-30
10/21	Aerosol/Sc	-23/-30	15

4. Preliminary results 10/10/04

The 10th was characterized by low-level north-easterly flow off the pack ice over the ocean to the NSA. Persistent low-level clouds under a sharp inversion were observed for the entire period, with no other cloud overhead (Fig. 5). A combined Proteus/Citation experiment was planned over Oliktok Point to coincide with a close TERRA overpass. Figure 6 presents the PARSL lidar/radar measurements for 30 minutes centered on the time of the aircraft spiral. It reveals a cloud top (from the radar) increasing from about 1200m to 1300m through the period, while the lidar show a liquid cloud base at ~900 m (approximately the top of the 0

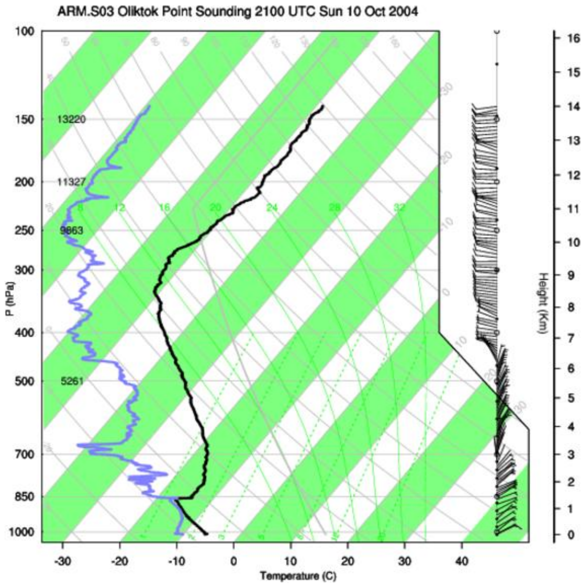

Figure 5: Radiosonde released from Oliktok Point 30 minutes prior to the aircraft observations overhead.

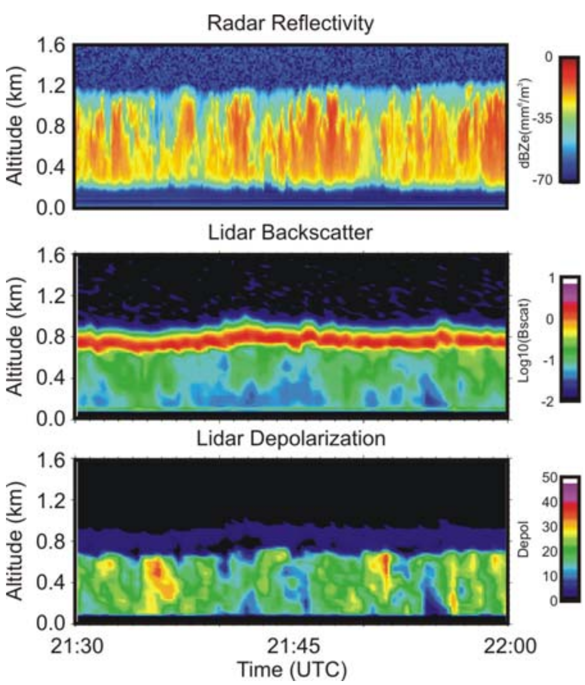

Figure 6: PARSL radar reflectivity (top), lidar back-scatter (middle) and depolarization (bottom). All data are preliminary and may change with future quality control.

valued depolarization ratio layer. The radar image suggests that pockets of ice and/or drizzle (higher reflectivities) were present throughout the cloud layer, while the higher depolarization values below cloud indicate ice precipitation.

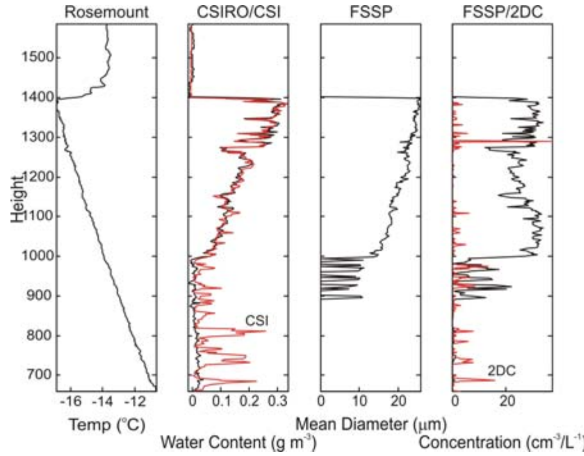

Figure 7: In situ measurements from the Citation from a single spiral at 21:45 UTC over Oliktok Point. The red lines are the CSI total water content and the 2DC concentrations. All data are preliminary and may change with future quality control.

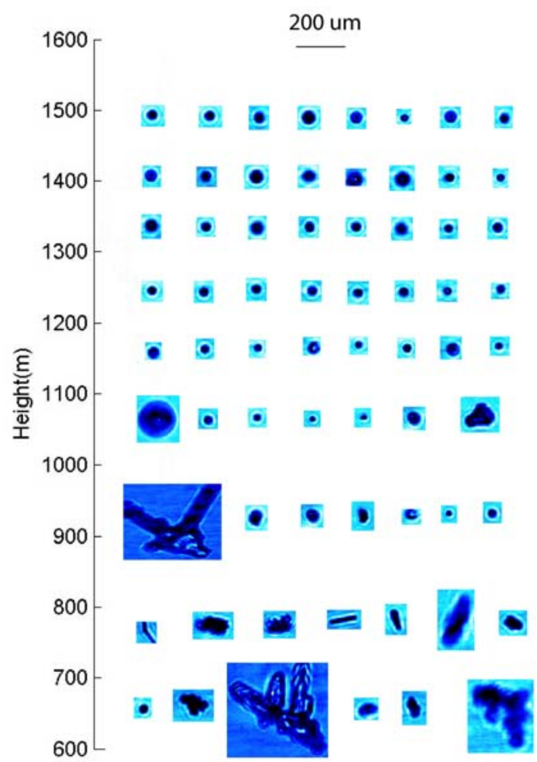

Figure 8: Selected hydrometeor images from the Cloud Particle Imager as a function of height for the 21:45 spiral on October 10.

The in situ measurements from the Citation reveal a similar picture (Fig. 7). It shows cloud base varying between 900 and 1000 m, with cloud top at 1400 m, higher than the radar observed top. The very sharp liquid and thermal inversions suggest that the aircraft exited cloud in one of small convective elements where cloud top may be expected to be slightly higher. The difference between the total water content as measured by the CSI and the liquid water content as measured by the CSIRO King probe is an indication of the ice content in the cloud (the accuracy of which will depend on the calibration of both instruments). Figure 8 shows the frequent occurrence of what is believed to be supercooled cloud droplets near cloud top, with occasional concentrations of larger ice crystals near cloud base. The concentrations measured by the 2DC and HVPS probe (Fig. 9) reveal that the ice mass was concentrated in low concentrations of bigger ice crystals, Examples of these larger ice particles measured by the HVPS are shown in Figure 10. Note that the HVPS detected 1 cm sized particles throughout the depth of the cloud.

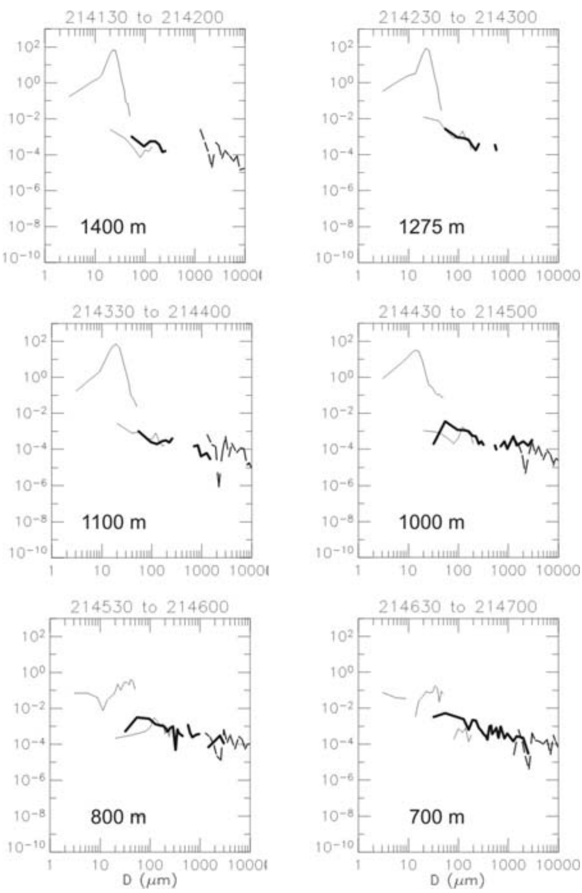

Figure 9: Particle size distributions as a function of height as measured by the FSSP, 1DC, 2DC and HVPS (in order of increasing size). Note the presence of bigger particles throughout the depth of the cloud. All data are preliminary and may change with future quality control.

The prevalence of liquid as opposed to ice condensate can be understood from the ice nuclei (IN) measurements made with the Colorado State University continuous flow diffusion chamber (CFDC) during MPACE. These measurements were focused on the aerosol particles feeding into cloud systems and their ability to activate ice formation at

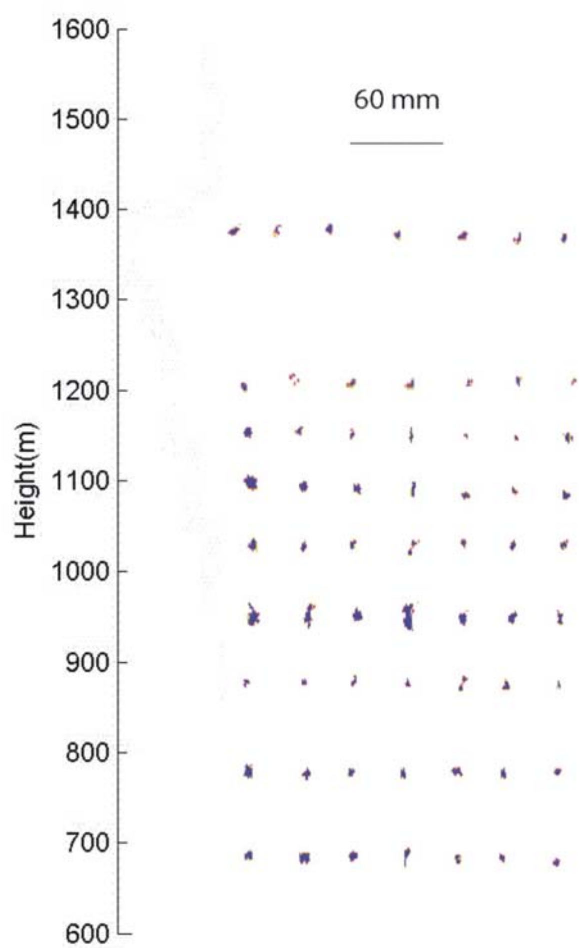

Figure 10: High Volume Particle Sample images as a function of height on October 10.

relevant temperatures and humidities. IN data were collected throughout October, and preliminary results are summarized in Figure 11. In this figure, each data point represents average IN concentrations for a particular flight leg, with flight legs spanning 4-31 min. Measurements taken below water saturation represent deposition nucleation, while measurements above water saturation represent the sum of deposition and condensation freezing. All of the data suggest low average IN concentrations during the study period. However, relatively high concentrations, up to 63 per liter, were observed over shorter periods of time, indicating a potential local source. Also shown in the figure are measurements taken when the aircraft was primarily in cloud. Interestingly, these values do not differ drastically from measurements taken out of cloud; however, in cloud measurements may suffer from artifacts resulting from cloud particle collisions with the inlet.

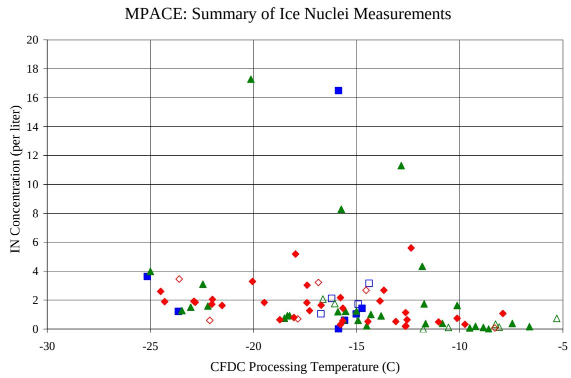

Figure 11: Ice nuclei concentration as a function of CFDC processing temperature. Data are presented for measurements taken in clear air and above cloud top (diamonds), in cloud (triangles), and below cloud base (squares). Data are shown for measurements taken above (filled) and below (open) water saturation. All data are preliminary and may change with future quality control.

5. Preliminary results 10/17/05

In addition to the 11 flights dedicated to low-level mixed-phase clouds, 2 cirrus missions were flown. We present preliminary results from one of these cases. The 17th of October was characterized by advection of mid- and upper level cloud advecting of the M-PACE domain from a weak front to the west of Barrow. The soundings at Barrow revealed a deep moist layer between 500 and 250 hPa, separated by a dry layer from a thin moist layer at 650 hPa. Both the Citation and the Proteus sampled this cloud system.

Figure 12 show results from the University of Wisconsin HRSL for the period the aircraft were in the air. This fully calibrated lidar reveals a thick cirrus layer extending from about 5 km up to 10.5 km, with a low optical depth altocumulus layer below. The total optical depth of the entire cloud layer was, on average for the entire period shown, approximately 0.75.

Figure 13 presents the lidar view of the same system, but viewed from above by the Proteus cloud detection lidar. This figure presents the lidar backscatter for the entire flight; the Proteus was over Barrow for the period 21:30 through 23:30 UTC and penetrated the cirrus between approximately 22:30 and 23:30. Note the surface return from the passes over the Brooks Range on the ferry to and from Fairbanks.

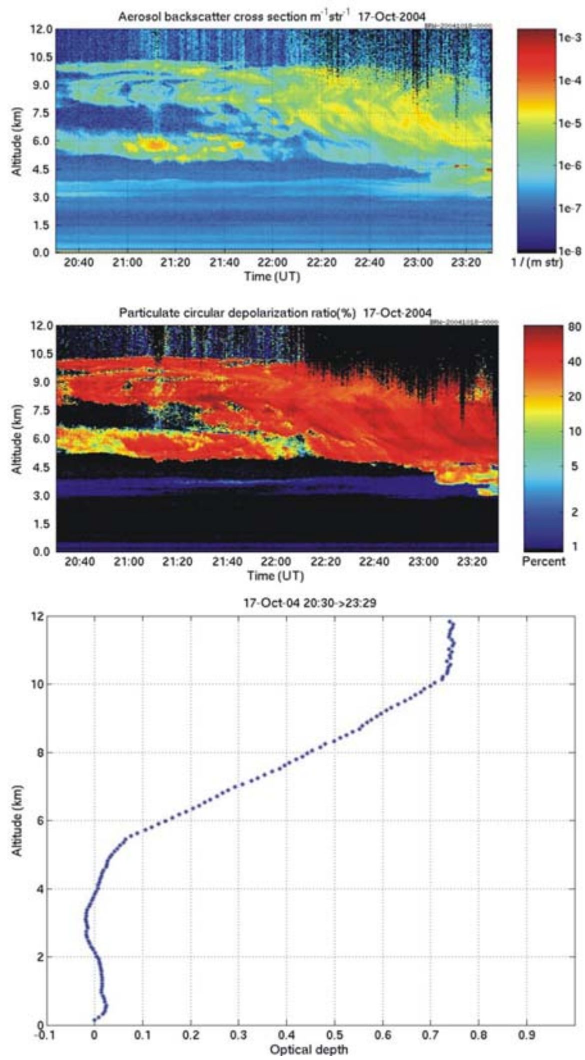

Figure 12: Calibrated aerosol backscatter, particulate depolarization ratio, and mean optical depth from the University of Wisconsin HRSL

Figures 14 and 15 present in situ measurements from the Citation. The Citation did not climb to the top of the uppermost cirrus layer, but did sample the second highest layer completely. Moreover, it descended through the mid-level liquid layer as well. The maximum ice water contents measured by the CSI in this cirrus cloud were 60 mg m^{-3}. Bullet rosettes were the dominant particle habit, with mean crystal sizes increasing from ~100 μm at cloud top to ~200 μm at the base. The ice crystal concentrations varied

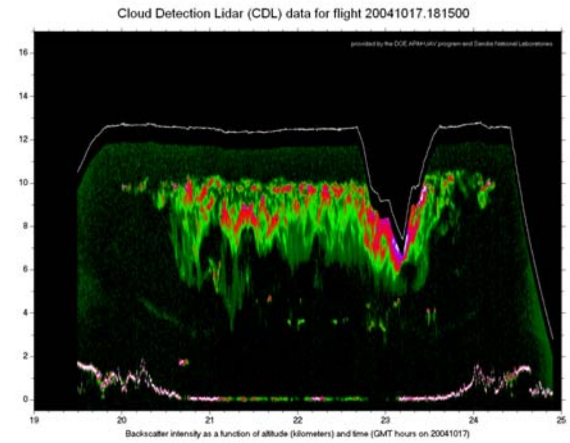

Figure 13: Cloud detection lidar image from the Proteus lidar. Proteus flight altitude in white.

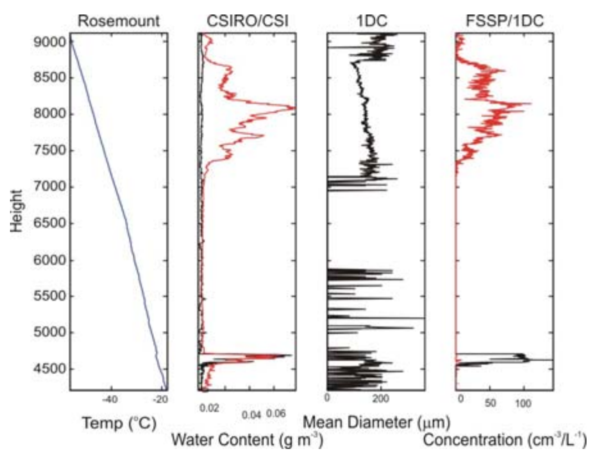

Figure 14: In situ measurements from the Citation from a single spiral at 21:26 UTC over Barrow. The red lines are the CSI total water content and the 1DC concentrations. All data are preliminary and may change with future quality control.

between 30 and 50 L^{-1}. The data collected during the flight on the 18th revealed similar characteristics for the cirrus clouds. These characteristics are similar to what is observed in in situ formed mid-latitude cirrus.

The mid-level cloud (at 4.5 km) sampled by the Citation was predominantly liquid at a temperature of -23 ^{o}C, as was suggested by the observations from the surface lidar, although there were indications of ice particles from the PMS probes. The measured LWC was 60 mg m^{-3} with droplet concentrations of 100 cm^{-3}.

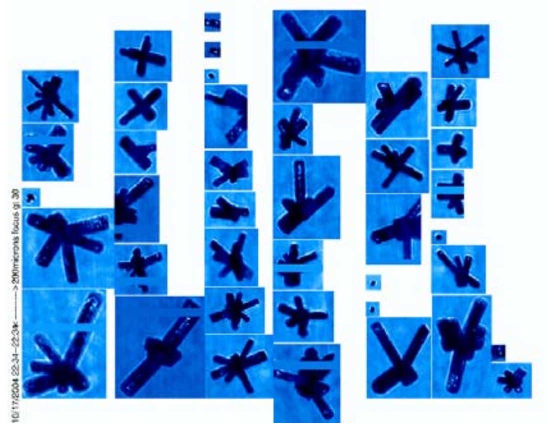

Figure 15: Hydrometeor images from the Cloud Particle Imager from October 17.

6. Radiosonde Intensive Operation Periods

There were two periods of intensive radiosonde releases from all four surface sites in support of single column modeling exercises. During these periods 4 radiosondes were released per day from each site. These periods were from 00 UTC on the 5th of October through 00 UTC on the 9th, and again from 00 UTC on the 14th through 12 UTC on the 22nd.

7. Summary

The Mixed-Phase Arctic Cloud Experiment documented the microphysical characteristics of several types of Arctic mixed-phases clouds. Five Citation research flights were conducted in single layer boundary layer stratus, three of which with coordination with the Proteus above and a fully equipped radiation site below, thus constraining the radiation. Six Citation flights investigated the more common, but more complex, multi-layered mixed phase clouds. In these cases ice precipitation from layers above fall into multiple thin cloud layers below. In all cases the entire cloud structure was documented. These cases are complex with a great degree of horizontal and vertical variability. For two of these case a single layer was isolated and sampled, with emphasis on documenting the ice nucleus concentration above and below cloud. In addition to these mixed-phase clouds, two research flights were conducted in Arctic cirrus clouds.
Acknowledgements: We would like to acknowledge all the people who endured difficult conditions in the field to collect these data.