Characterization of Mixed-Phase Clouds During Mixed-Phase Arctic Cloud Experiment from Satellite, Ground-Based, and In-Situ Data

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Introduction

Stratiform clouds containing mainly liquid at their tops with increasing amounts of ice deep inside the cloud commonly occur over the Arctic. The ice crystals usually grow large enough to fall from the cloud as frozen precipitation. These clouds are important to consider in both climate and numerical weather prediction models. However, the mechanisms that support the formation, maintenance, and dissipation of these mixed-phase clouds are still poorly understood. Moreover, the definition of a mixed-phase cloud varied depending on the spatial and temporal resolution of the sampling instrument. With the well-instrumented Atmospheric Radiation Measurement Program North Slope of Alaska site at Barrow, the Mixed-Phase Arctic Cloud Experiment (M-PACE; Harrington and Verlinde [2004]; Verlinde et al. [2006]) conducted during Fall 2004, and frequent *Terra* and *Aqua* Moderate-Resolution

Imaging Spectroradiometer (MODIS) overpasses, it is possible to characterize mixed-phase clouds using data from the different sensors. In this study, MODIS cloud property retrievals, surface-based multi-sensor (SMS) cloud property retrievals, and in-situ cloud data taken onboard the University of North Dakota Citation (CIT) aircraft are used to gain a better understanding of Arctic mixed-phase clouds. Both macro and microphysical cloud properties examined in this study coincide with M-PACE, which took place from 27 September – 27 October 2004 over northern Alaska and the adjacent Arctic Ocean. The mixed clouds considered here are those occurring primarily as low-level stratus clouds trapped under the persistent Arctic inversion. These types of clouds occur frequently in the Arctic, especially during the spring and fall seasons (Shupe et al. 2006). Clouds having a relative liquid (RLIQ) amount in the 10-90% range fit the definition of having a mixed phase. The mixture can occur as loosely-stratified single-phase layers or as pockets of ice crystals surrounded by liquid droplets.

Data

Terra and *Aqua* MODIS cloud phase and liquid cloud property retrievals from 5-12 October 2004 from each overpass that imaged northern Alaska and the surrounding area are utilized. This pixel-level dataset has a spatial resolution of 3 km. The cloud phase data are averaged over a 0.5° x 0.5° latitude-longitude grid from 60-80°N and 130-180°W. For the frequency distributions at Barrow, the satellite data are averaged into a 10-km radius circular region. Additionally, the pixel-level data were matched to the CIT flight track for the 23:40 Universal Time Coordinates (UTC), 12 October *Aqua* image. Minnis et al. (1995, 2005) and Spangenberg et al. (2006) provide details on the methods used to retrieve the MODIS cloud property data used in this study.

For the surface cloud property retrievals, cloud phase is determined using data from the millimeter-wave cloud radar (MMCR), microwave radiometer, and radiosonde temperature and moisture profiles at Barrow (Shupe et al. 2005, 2006). Additionally, the surface-based liquid water path (LWP) data are derived from the microwave radiometer while the ice water path (IWP) and effective ice particle diameter (De) are determined using an MMCR regression retrieval technique (Shupe et al. 2005). The water paths are used to estimate the ratio of liquid water to ice in mixed-phase clouds. The MMCR-based optical depth (τ) is given for the sum of the liquid and ice components of mixed clouds. Data from the Barrow National Weather Service Automated Surface Observing System were checked to determine if any significant weather tends to occur with mixed cloud systems.

For Citation in-situ data, the liquid water content (LWC) and total water content, which are needed to compute the relative percentage of liquid water in mixed phase clouds, were obtained from the King and cloud spectrometer and impactor probes, respectively. The ice water content is the difference between total water content and LWC. The forward scattering spectrometer probe provided the liquid droplet diameter (Dliq) while the 1D cloud probe provided the ice particle diameter (Dice). Instantaneous CIT data were time averaged into approximate 15-second bins for the analysis, which is equivalent to five data samples.

Results

The primary type of mixed-phase cloud found to occur in the Arctic is stratus topped with liquid water with progressively higher amounts of ice as cloud base is approached. Another, far less common type of mixed cloud, extends from the boundary layer to the mid-troposphere and can have an ice-dominated top. Although there are different kinds of mixed clouds with more than one way to define them, low-level stratus clouds containing mixtures of ice and supercooled liquid water over scales of one up to a few kilometers in horizontal extent are considered here. While the CIT data have a much higher spatial resolution, the 1-3 km scale is appropriate for the satellite and surface-based sensors. Mixed clouds will generally be located within 3 km of the surface, cover expansive areas of the Arctic Ocean, and are observed to last at Barrow for up to a few days at a time. Barrow Automated Surface Observing System data show nearly a continuous fall of light snow with occasional fog in association with mixed cloud systems. Quantitatively, a cloud composed of between 10 and 90% liquid water compared to ice content is considered to be one with a mixed phase. Examination of the SMS phase at the MODIS overpass times during M-PACE revealed that mixed clouds occurred in 65% of the overcast conditions with ice clouds being found 32% of the time and pure liquid clouds only occurred in 3% of the 271 cases. These results correspond to single-layer clouds or to the upper-most layer for multilayered clouds.

A map of the mean satellite-derived mixed-phase cloud amount in the 5-12 October timeframe during M-PACE is shown in Figure 1. The mixed clouds were identified using the methods of Spangenberg et al. (2006). To have valid data, a given 0.5° gridbox must have been imaged by MODIS at least 25% of the time. The all-sky conditions in Figure 1a show that mixed clouds are prevalent over 70% of the time along the northern Alaska coastline with markedly lower amounts south of the Brooks Mountain Range. The corresponding cloudy-sky mixed amount is in Figure 1b. For much of the domain, excluding interior Alaska, almost every time a cloud was present it was mixed from the perspective of the MODIS instrument. Note how most of the mixed clouds occur over the ocean or adjacent coastal areas, suggesting that these cloud form and maintain themselves more often in marine environments. Over the southern areas of the domain, examination of individual images shows that high cirrus and low-level liquid clouds were the dominant varieties. A time sequence of mixed-phase clouds over Barrow identified from the surface multi-sensor retrievals of Shupe et al. (2005) is shown in Figure 2. To be consistent with the satellite data, the time sequence is valid for the phase of the upper-most cloud deck. Mixed clouds fitting the definition of RLIQ amount from 10-90% are in orange while red indicates times where the cloud could be considered to have either all ice or all liquid water. Julian days 279-286 correspond to the mean spatial distribution maps that were shown in Figure 1. Mixed clouds are found to dominate over the other types at Barrow, especially from days 280-290, with more ice clouds observed in the last 10 days. For most days having mixed clouds, the RLIQ definition is satisfied. For those days where it isn’t, there tends to be more non-mixed clouds indicating that phase transitions existed, which acted to complicate the retrievals.

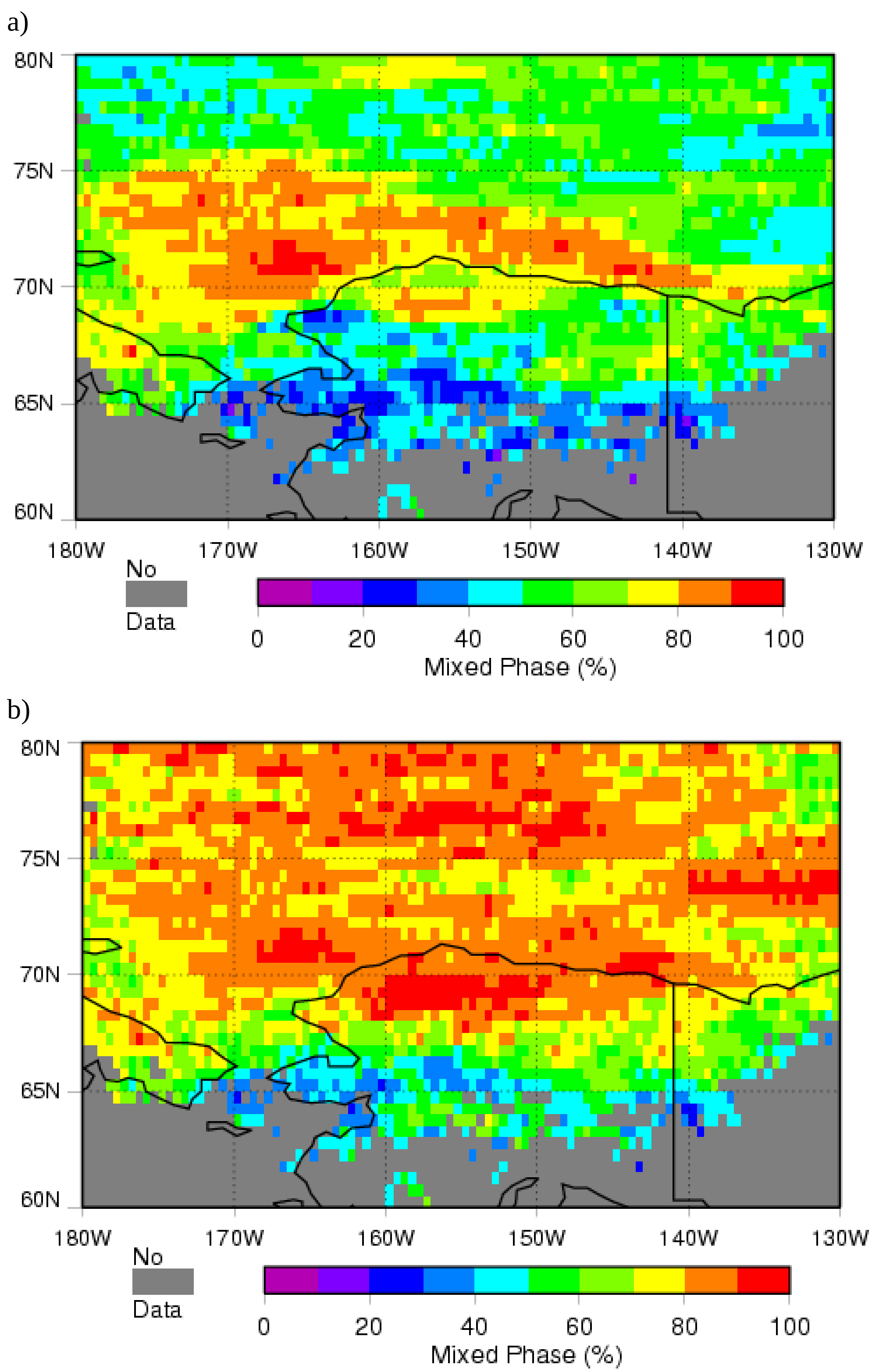

Figure 1. Mean satellite-derived mixed phase cloud amounts for 5 – 12 October 2004. All-sky shown in (a) and cloudy-sky only shown in (b).

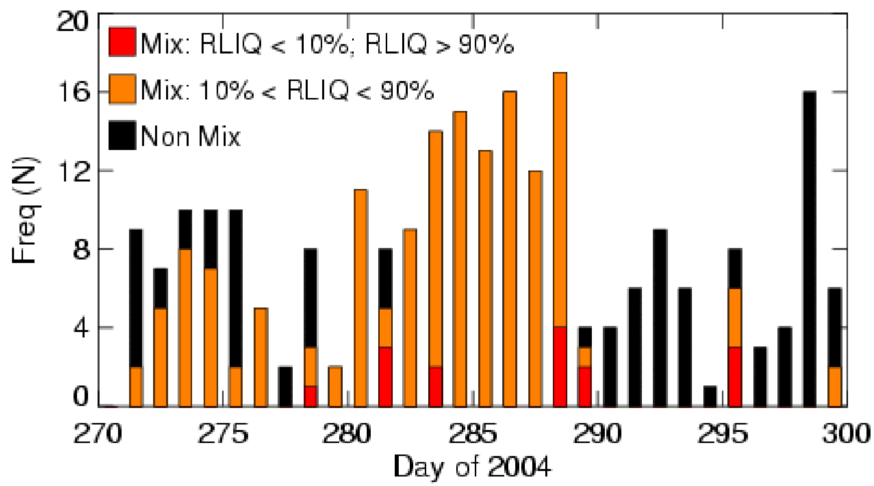

Figure 2. SMS mixed-phase cloud frequency over Barrow during M-PACE.

Properties of mixed clouds derived from the SMS retrievals of Shupe et al. (2005, 2006) are considered to be more accurate than the satellite retrievals of Minnis et al. (1995, 2003) and are therefore used as the primary means of characterizing mixed clouds over Barrow. The MODIS effective droplet radius (Re) and cloud radiating temperature at 11 μm (CT11) are used to supplement the SMS retrievals. The cloud property distributions for the full M-PACE time period and a subset from 5-12 October are shown in Figure 3. The SMS retrievals represent 60- minute temporal means centered at the satellite overpass times and are considered only for column mixed amounts above 95%. MODIS CT11 in Figure 3a indicates that mixed clouds sampled during M-PACE ranged from 243-270 K with a maximum frequency occurring near 256 K. There are also a significant number of clouds having CT11 values up to 264 K. Considering the cloud-top height (Ztop; not shown), 70% of the clouds extend up to 2.0 km over Barrow. The remaining 30% of the Ztop values were found from 2.0-5.0 km with a fairly even distribution. Most of the mixed clouds had bases within ~200 m of the surface. Figure 3b shows that mixed clouds have high τ values, peaking from 15-20 with a broad tail toward 60. Practically no mixed clouds were found with $\tau < 5$, indicating that they were dominated by the more optically thick liquid component. Since the SMS particle size retrievals are valid for just the ice phase in mixed clouds, the MODIS retrieval for effective droplet radius (Re) is shown in Figure 3c. Most of the values are evenly distributed in the 6-18 μm range, with fewer than 15% of the values above 18 μm. Since the MODIS instrument sees an integrated effect of the entire cloud, up to 0.5 km below cloud top, the scene will usually be contaminated with ice crystals and/or pockets of drizzle-size drops commonly found near Ztop. Therefore, Re from the satellite retrievals will typically be overestimated compared to in-situ or radar-based retrievals. The De values from the SMS retrievals in Figure 3d show large crystal sizes of 100-125 μm dominating the distribution with a linear dropoff in De toward 70 μm. The LWP and IWP from the SMS retrievals in figures 3e and 3f, respectively, show that mixed clouds tend to have more liquid water with LWP peaking from 100-150 gm^{-2}. The ice component is not insignificant due to the large crystal size and light snow that tends to occur with boundary-layer mixed phase clouds. For the cloud properties considered here, the 5-12 October distributions were similar to those found during the entire M-PACE month.

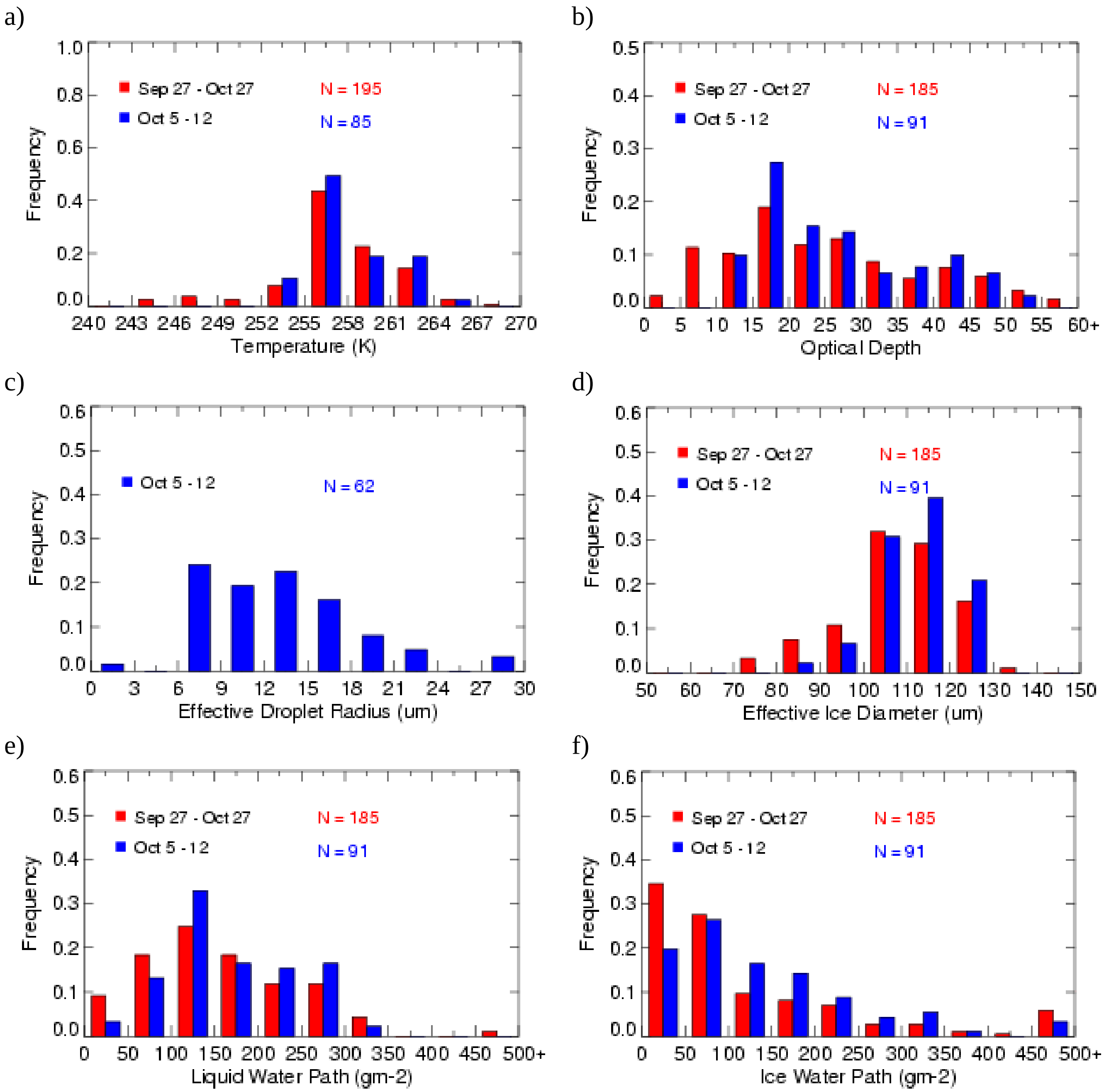

Figure 3. Cloud property distributions during M-PACE. (a) MODIS CT11, (b) SMS τ, (c) MODIS Re, (d) SMS De, (e) SMS LWP, and (f) SMS IWP.

Analysis of a case study during 12 October 2004 was accomplished using in-situ CIT data combined with MODIS satellite imagery and cloud retrievals. To reduce noise inherent in the MODIS imagery, the 6.7 and 7.3 μm channels are first filtered using a 2-dimensional fast-Fourier transform technique then smoothed using 7 x 7 pixel means. The other channels are smoothed using 3 x 3 pixel means. Cloud identification in the MODIS imagery was carried out using the methods of Trepte et al. (2002) with phase discrimination provided by Spangenberg et al. (2006). The Terra-MODIS satellite imagery, including cloud phase, is shown in Figure 4. An extensive, uniform, single-layer mixed-phase cloud system occurred during this case over northern Alaska and the surrounding Arctic Ocean with large streams of cirrus to the south over interior Alaska and Yukon Province. This can be seen by comparing the 11 μm BT (T11) image in Figure 4a with the phase image in Figure 4d. The brightness temperature difference between the MODIS 8.5 μm and 11 μm channels (T85-11) in Figure 4b shows a rather uniform area of values from –0.5 to –1.5 K in association with the mixed clouds. This information, combined with the relatively low brightness temperature difference between the MODIS 7.3 and 7.6 water vapor channels (T73-67), indicates that the mixed clouds are fairly well separated from their pure liquid counterparts. In the far western part of the domain, some supercooled liquid clouds are seen in areas where T85-11 is low and T73-67 is high. The slight increase in T85-11 over the Arctic Ocean towards 0.0 K in the northeastern part of the domain suggests that the cloud top is found in an area where the T lapse rate is becoming more negative and/or more signal from the frozen surface below is reaching the satellite. It does not necessarily indicate that more ice exists at cloud top. In fact, T11 (Figure 4a) and T73-67 (Figure 4c) show no decrease in this area, a condition that would be indicative of a higher cloud with more ice across its top. The small amount of ice phase cloud showing up in the far northwestern part of the domain is at the leading edge of a band of cirrus clouds passing by to the north of that area, somewhat apparent in 1-km resolution, expanded MODIS imagery.

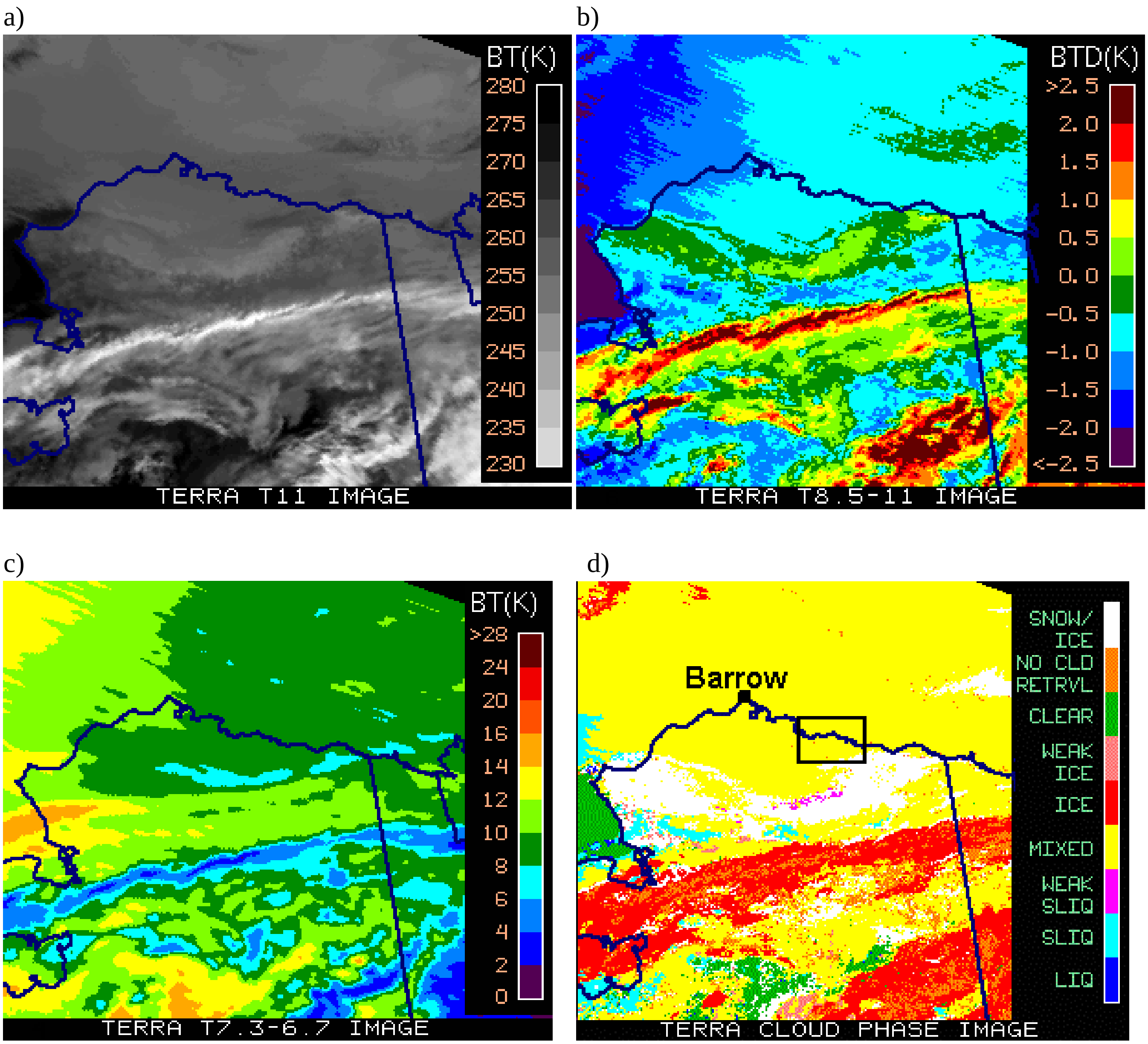

Figure 4. Terra MODIS satellite imagery valid for 21:45 UTC 12 October 2004. (a) T11, (b) T85-11, (c) T73-67, and (d) cloud phase. Supercooled liquid in phase colorbar is for supercooled liquid.

The CIT flight on 12 October occurred a couple of hours after the *Terra* image in Figure 4 was taken. Consequently, CIT in-situ cloud data are matched with cloud data taken from an *Aqua* overpass at 23:40 UTC. The results are summarized in Figure 5 with the area where the aircraft flew being denoted by the box in Figure 4d. The MODIS cloud height retrievals in Figure 5a indicate a low-level cloud along the northern coastline of Alaska occurred between 0 and 2.5 km above the surface with a depth of ~1 km. The MODIS phase retrieval shows an entirely mixed-phase cloud with the in-situ CIT data showing mostly mixed phase and some areas of plain supercooled liquid. The CIT altitude is somewhat offset below the MODIS boundaries, a good indication that the satellite (slightly) overestimated the height of the cloud. The corresponding particle size data is shown in Figure 5b. Since the satellite senses an integrated scene at the tops of mixed clouds, its effective Dliq value is found between the CIT liquid and ice particle size, near 38 μm, although (expectedly) closer to the liquid. For this case, the CIT Dliq occurred between 10 and 24 μm while the CIT Dice occurred between 70 and 105 μm. The CIT water path values were computed by multiplying the in-situ LWC and ice water content by the cloud depth taken from the MODIS retrievals. These water paths are valid for a small segment of the cloud in terms of the water concentration; they are not valid for mean concentrations over the entire cloud depth. The resulting water paths from the CIT, along with the corresponding MODIS-retrieved LWP, are shown in Figure 5c. The liquid component dominates the ice, with wide fluctuations in CIT LWP ranging from 50-400+ gm^{-2}. The fluctuations are primarily the result of the varying CIT altitude (compare figures 5a and 5c), with the higher LWP derived from higher LWC near Ztop. The CIT IWP typically rises no higher than 75 gm^{-2}. The MODIS LWP retrievals are found between the CIT water paths, from 75-160 gm^{-2}. They are much less variable, at least in part because the satellite senses a relatively large area only across Ztop.

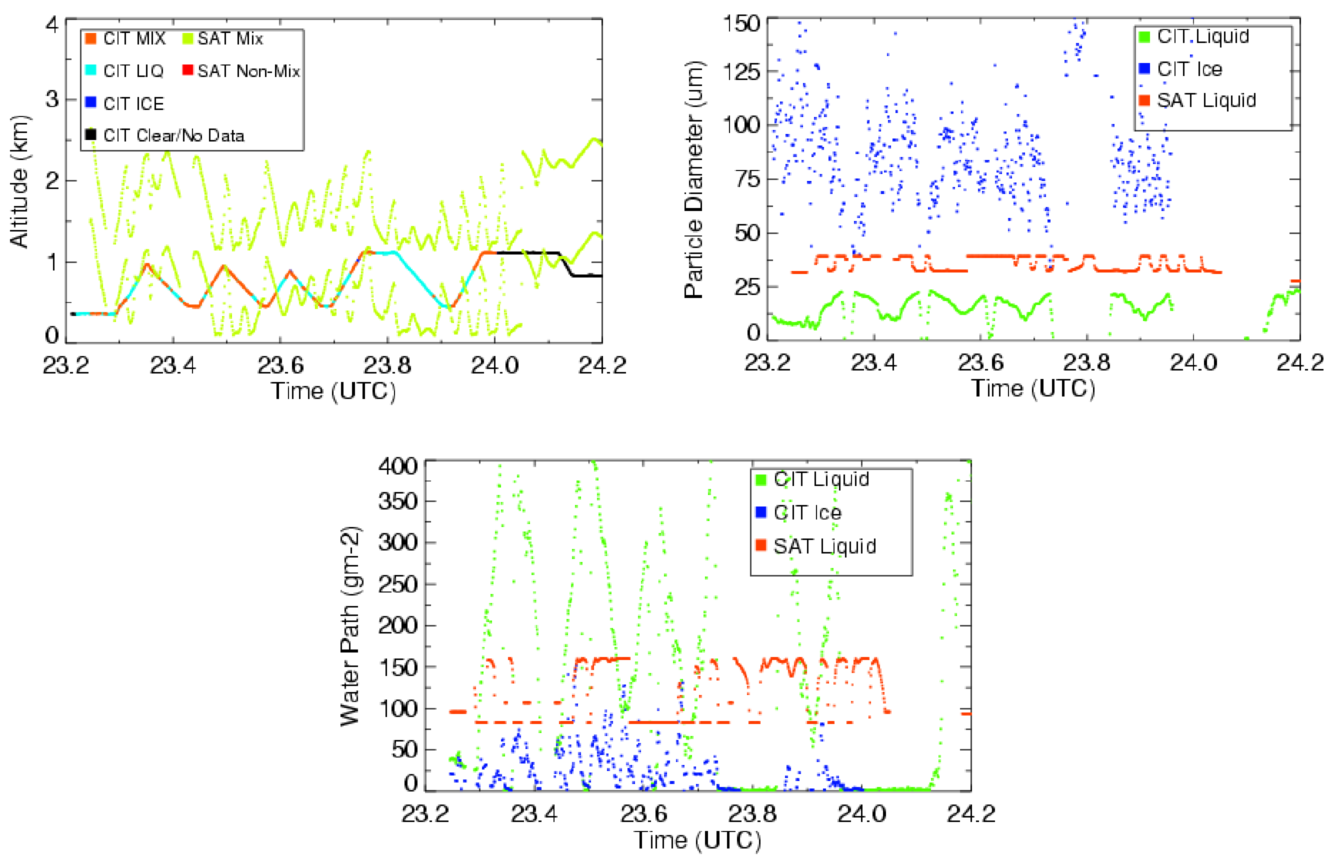

Figure 5. CIT altitude and in-situ cloud measurements with corresponding matched Aqua-MODIS liquid retrievals for the image at 23:40 UTC 12 October 2004. (a) Cloud phase, (b) particle size, and (c) water path.

Summary

In this study, boundary-layer mixed-phase clouds were characterized over the Arctic in the vicinity of Barrow, Alaska during M-PACE using data from satellite, aircraft, and ground-based instruments. These cloud systems will typically have between 10 and 90% of their total water content occurring in the liquid form. The satellite analysis from MODIS showed that mixed-phase clouds occurred up to 90% of the time just off the coast of northern Alaska during the middle of M-PACE. Fewer mixed clouds occurred over interior Alaska, south of 67°N latitude. These clouds were found below the surface-based temperature inversion, as opposed to other kinds of deep mixed clouds occurring mostly in unstable summertime conditions. The National Weather Service automated weather station in Barrow usually reported steady light snow in conjunction with the mixed cloud decks, even for those clouds having thicknesses of just 1.25 km. Cloud tops were normally found from 1-2 km above sea level with cloud temperatures primarily in the 255-265 K range. Droplets with Re of 10-15 μm were found to co-exist with ice crystals having De values in the 80-120 μm range. The LWP (75-300 gm^{-2}) was found to be dominant over the IWP (10-200 gm^{-2}) in the majority of mixed-phase clouds sampled during M-PACE.

Compared to ground-based cloud property retrievals for mixed clouds, satellite retrievals are generally less accurate but are still very useful due to their extensive spatial coverage. It is unlikely that current satellite sensors will be able to measure with great accuracy the amount of liquid water relative to ice in mixed clouds. However, information as to whether the mixed clouds are trapped under an inversion and have large amounts of liquid at their tops or are thicker, cold clouds, with mostly ice at their tops, can probably be gained using the methods of Spangenberg et al. (2006). Also, current satellite cloud retrieval algorithms are normally set up to detect and process the ice and liquid phase only and cannot be tuned to retrieve mixed cloud microphysical properties. Since low-level mixed clouds over the Arctic tend to have liquid at their tops, a realistic droplet size can probably be retrieved, with some downward adjustment needed due to large ice crystal contamination. Also, the current algorithms produce ice crystal diameters that are either too small or non-existent for low-level mixed clouds due to water droplet contamination. It might be possible to develop a parameterization of the ice crystal diameter in liquid-topped mixed-phase clouds in terms of cloud temperature, optical depth, water droplet size, and atmospheric thermal and water vapor structure. Satellite macrophysical cloud property retrievals such as cloud top and base height should be just as good for mixed clouds as for those clouds containing a single phase.

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