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ARM Thermodynamic Cloud Phase (THERMOCLDPHASE) Value-Added Product Report

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Executive Summary

The U.S. Department of Energy Atmospheric Radiation Measurement (ARM) User Facility's Thermodynamic Cloud Phase (THERMOCLDPHASE) Value-Added Product (VAP) provides vertically resolved thermodynamic cloud phase classifications (Zhang and Levin 2024). This VAP applies the multi-sensor methodology introduced by Shupe (2007) to identify cloud phase at the pixel level as liquid, drizzle, liquid + drizzle, rain, ice, snow, or mixed-phase. In addition, the VAP determines the overall cloud layer phase—classified as liquid, mixed-phase, or ice—based on the fraction of ice-containing pixels within the entire layer.

Acronyms and Abbreviations

AMF	ARM Mobile Facility
ARM	Atmospheric Radiation Measurement
ARSCL	Active Remote Sensing of Clouds Value-Added Product
HSRL	high-spectral-resolution lidar
INTERPSONDE	Interpolated Sonde Value-Added Product
KAZR	Ka-band ARM Zenith Radar
KAZRARSCL	Ka-band ARM Zenith Radar Active Remote Sensing of Clouds
LWP	liquid water path
MDV	mean Doppler velocity
MOSAiC	Multidisciplinary Drifting Observatory for the Study of Arctic Climate
MPL	micropulse lidar
MPLCMASK	Cloud Mask from Micropulse Lidar Value-Added Product
MWR	microwave radiometer
MWRRET	Microwave Radiometer Retrievals Value-Added Product
MWRRETv2	MWR Retrievals with MWRRET Version 2 Value-Added Product
NetCDF	Network Common Data Form
NSA	North Slope of Alaska
QC	quality control
THERMOCLDPHASE	ARM Thermodynamic Cloud Phase Value-Added Product
VAP	value-added product

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1.0 Introduction

Identifying cloud thermodynamic phase is critical for understanding key cloud processes, including ice particle production, precipitation formation, and cloud life cycle evolution. Because ice particles and liquid droplets differ in size, shape, fall velocity, and refractive index, clouds with different thermodynamic structures exhibit significantly different radiative properties. Consequently, cloud phase identification is essential for improving our understanding of cloud radiative properties and the atmospheric radiative budget (de Boer et al. 2011). Moreover, cloud phase identification is often a prerequisite for retrieving cloud properties from remote-sensing measurements, as most retrieval algorithms are designed for specific cloud phases and types (Shupe et al. 2016).

Cloud thermodynamic phase can be classified using remote-sensing measurements. Active sensors such as lidar and radar provide vertically resolved phase information. Lidar backscatter is highly sensitive to small particles with high number concentrations, such as liquid droplets, while lidar depolarization helps identify nonspherical particles like ice crystals. However, lidar signals are rapidly attenuated by cloud droplets. Radar, in contrast, is dominated by signals from larger particles, such as ice crystals, and is generally affected by attenuation only in cases of strong precipitation. Microwave radiometer (MWR) measurements further constrain the presence of liquid layers. Since no single instrument provides sufficient information to characterize the full range of hydrometeors—from small droplets to large ice particles and snow—we use the multi-sensor method developed by Shupe (2007) to classify cloud phase. Similar to the Ka-Band ARM Zenith Radar (KAZR) Active Remote Sensing of Clouds (KAZRARSCL) VAP (Johnson et al. 2022), this approach combines data from the ARM micropulse lidar (MPL) or high-spectral-resolution lidar (HSRL), the KAZR, MWRs, and atmospheric thermodynamic profiles from radiosondes to determine thermodynamic cloud phase.

2.0 Algorithm and Methodology

The cloud thermodynamic phase classification approach developed by Shupe (2007) integrates multiple remote-sensing and radiosonde in situ measurements to identify cloud hydrometeor phases. Specifically, the method combines lidar backscatter intensity (β) and depolarization ratio (δ), radar reflectivity (Z_e), Doppler velocity (V_D), and Doppler spectral width (W_D), along with liquid water path (LWP) from the MWR retrievals VAP (MWRRET) and temperature (T) from radiosondes. By leveraging this multi-sensor synergy, the approach provides a comprehensive basis for distinguishing hydrometeor phases.

The classification scheme assigns each vertical volume to one of several cloud phase categories: liquid, drizzle, liquid + drizzle (liq_driz), rain, ice, snow, mixed-phase (mixed), or unknown. The liq_driz class represents cases with liquid cloud and drizzle in the same volume, whereas the drizzle class indicates drizzle that has fallen below the cloud. This classification captures the diversity of hydrometeor types typically observed in mixed-phase and evolving cloud systems, and enhances the robustness of phase identification compared to single-instrument approaches. Detailed descriptions of each cloud phase category, including their defining characteristics and criteria, are provided in Table 1. An "unknown" label is assigned in cases when the thermodynamic phase of the hydrometeor cannot be identified due to missing input data sets or when the determined thermodynamic cloud phase is inconsistent with our understanding of cloud structures and physics based on past studies. The VAP also includes a "clear" classification when no hydrometeors are present.

Table 1. Cloud hydrometeor phase type classes (Table 1 in Shupe 2007).

Class	Description
Ice	Only cloud ice particles
Snow	Only snow particles (defined based on a reflectivity threshold which is related to particle size)
Mixed-phase	Cloud liquid droplets and cloud ice particles in the same volume
Liquid	Only cloud liquid droplets
Liquid+drizzle	Cloud liquid droplets and drizzle drops in the same volume
Drizzle	Only drizzle drops (defined based on a reflectivity threshold which is related to drop size)
Rain	Only rain drops (defined based on a Doppler velocity threshold which is related to drop size)

Detailed descriptions of the multi-sensor cloud phase classification method are provided in Shupe (2007). In brief, the approach applies a sequence of decision steps, implemented in consecutive order, to determine the most likely hydrometeor phase within a given atmospheric volume. These steps are summarized in Table 2.

Table 2. General steps to the classification process (Table 2 in Shupe 2007).

Step	Application	Details
1. Lidar mask	Lidar-viewed pixels	Figure 2a provides liquid, ice, aerosol classes
2. Modify lidar mask w/radar	Lidar-viewed pixels	Add mixed-phase, drizzle, snow classes
3. Precip mask w/radar and T	All pixels	$Z_e > 5$ dBZ & $T < 0°C$ = snow $Z_e > 5$ dBZ & $T > 0°C$ = rain $V_D > 2.5$ m/s & $T > 0°C$ = rain
4. Complete mask	Pixels not viewed by lidar	Figure 2, including lidar occultation layer classification
5. Absolute T rules	All pixels	$T < -40°C$ = ice $T > 0°C$ = [liquid, drizzle, rain]
6. LWP constraint	All columns of pixels	If LWP ≤ 0 g/m^2, then liquid pixels to ice If LWP $> 25^a$ g/m^2, then find liquid layer
7. Homogenize	All pixels	7×7 surrounding pixel box a)>35 clear pixels in box: pixel = clear b)>7 pixels of given type in box: no change c)≤7 pixels of given type in box: change to dominant type d) Additional rules

The method relies on threshold values of β, δ, Z_e, V_D, W_D, LWP, and T. These thresholds, illustrated in Figure 1, define the conditions under which a cloud volume is classified as liquid, drizzle, liq_driz, rain, ice, snow, or mixed-phase. By integrating these diverse measurements, the multi-sensor approach enhances the robustness of phase identification. It is noted that while Shupe (2007) used lidar β and δ measurements to distinguish between clear and cloudy pixels as shown in Figure 1a, the THERMOCLDPHASE VAP directly applies the phase classification algorithm to cloudy pixels identified by the ARM Active Remote Sensing of Clouds (ARSCL) VAP (https://www.arm.gov/data/science-data-products/vaps/arscl; Clothiaux et al. 2001). The ARSCL VAP uses combined data from active remote sensors, including radars and lidars, to provide reliable determination of hydrometeor height distributions.

The THERMOCLDPHASE VAP outputs cloud phase classifications with a temporal resolution of 30 seconds and a vertical resolution of 30 meters.

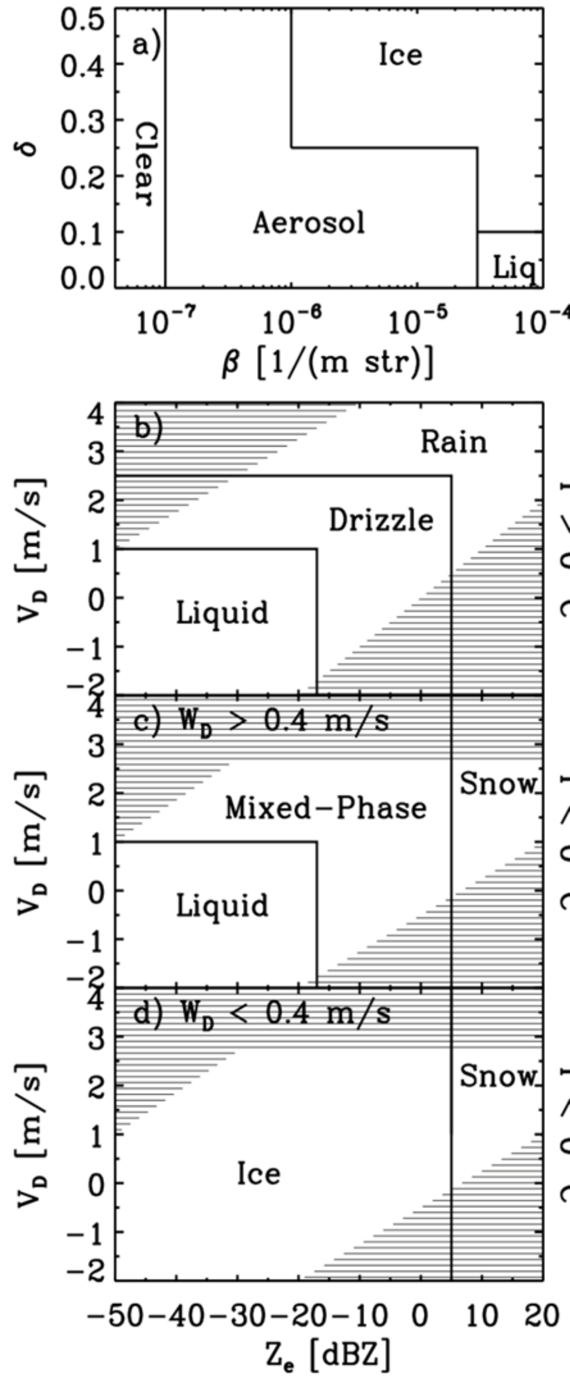

Figure 1. Cloud phase classification diagrams (Figure 2 in Shupe 2007). All radar panels contain shading in regions that do not often occur.

Shupe (2007) used HSRL-derived β and δ measurements to distinguish between liquid and ice-phase hydrometeors. The HSRL is an advanced lidar system capable of providing absolutely calibrated β, which is directly related to particle concentration and size. However, HSRL systems are expensive, and ARM currently operates only three units, deployed at a limited number of fixed sites or during ARM Mobile Facility (AMF) field campaigns. In contrast, the MPL provides only relative backscatter intensity, but it can still differentiate liquid and ice-phase hydrometeors by analyzing the strength of the vertical gradient in the backscattered signal (Wang and Sassen 2001). To enable broader implementation of the THERMOCLDPHASE VAP across more ARM sites, we incorporate cloud phase classification using both HSRL and MPL data. The resulting classifications are labeled as "cloud_phase_hsrl" and "cloud_phase_mplgr," respectively. If HSRL data are not available at a given site or during an AMF deployment, the output will not have the related cloud phase classifications from the HSRL.

To enable more direct comparisons with model outputs, the THERMOCLDPHASE VAP also classifies an entire cloud system within a vertical column as liquid, mixed-phase, or ice. A cloud system is defined as a vertically continuous set of cloudy volumes that interact through microphysical processes; there can be multiple cloud systems within the same vertical column. Specifically, a liquid cloud layer contains only liquid water, such as cloud droplets and drizzle, throughout the vertical extent; a mixed-phase cloud layer includes both liquid and ice water in the vertical column; and an ice cloud layer consists exclusively of ice-phase hydrometeors, such as ice crystals and snow.

The ARSCL VAP identifies up to 10 distinct cloud layers within a vertical atmospheric profile. For each identified cloud layer, THERMOCLDPHASE determines its thermodynamic phase based on the fraction of pixels classified as ice-containing (including ice, mixed-phase, or snow) within that layer (denoted as frc_{ice}). Following a threshold-based approach similar to that used in in situ aircraft studies (Wang et al. 2024), the classification criteria are: Liquid: $frc_{ice} < 0.1$; Mixed-phase: $0.1 \leq frc_{ice} \leq 0.9$; Ice: $frc_{ice} > 0.9$. This approach provides a consistent framework for evaluating cloud phase characteristics across remote-sensing retrievals and model simulations.

Uncertainties in the cloud phase classification method primarily arise from the threshold values applied to β, δ, Z_e, V_D, W_D, LWP, and T for distinguishing different cloud phases. These thresholds were established through extensive analysis of long-term observational data sets and are grounded in a comprehensive understanding of cloud properties and measurement characteristics in the Arctic. Additional uncertainty arises from the uncertainties of the individual input parameters.

The THERMOCLDPHASE VAP is initially applied to multiple remote-sensing observations at arctic sites or AMF deployments in the middle and high latitudes. In the future when we extend the VAP to low-latitude sites, we will need to review these thresholds and update them according to the local cloud climatology. This cloud phase classification method may have challenges for deep convective clouds when both lidar and radar signals are fully attenuated.

3.0 Input Data

The required input data sets include 30smplcmask1zwang.c1 from the Cloud Mask from Micropulse Lidar VAP (MPLCMASK; Flynn et al. 2020) and/or hsrl.a1 from the ingested HSRL data (Bambha et al. 2025), which provides lidar backscatter intensity and/or β and δ; arsclkazr1kollias.c0 or arsclkazrcloudsat.c1 from the KAZRARSCL VAP (Johnson et al. 2022), which provides Z_e, V_D, and W_D; and interpolatedsonde.c1 from the Interpolated Sonde VAP (INTERPSONDE; Fairless et al. 2011), which provides temperature profiles. For AMF deployments on ships, such as during the Multidisciplinary

Drifting Observatory for the Study of Arctic Climate (MOSAiC) field campaign, navbe.c1 is also required to provide geolocation information (e.g., latitude, longitude, and altitude). THERMOCLDPHASE is processed daily. If any required input data set is not available for the entire day, the THERMOCLDPHASE VAP does not produce an output data set. If any required input variables are flagged as "missing_value," then a quality control (QC) flag is assigned, and the affected pixels are classified as unknown. In addition, mwrret1liljcloud.c2 from MWRRET VAP (Gaustad et al. 2011) or mwrret2turn.c1 from the MWR Retrievals with MWRRET Version 2 VAP (MWRRETv2; Zhang et al. 2020) may optionally be used to provide liquid water path (LWP) data, which helps constrain cloud phase classifications. If these LWP data sets are unavailable, a QC flag is assigned to indicate that no LWP constraint was applied.

Variables retrieved from the input datastreams and used by the VAP are listed in Table 3.

Table 3. Input variables used by the THERMOCLDPHASE VAP.

Variable name	Description and notes
mpl_backscatter	MPL total attenuated backscatter, background subtracted, overlap, energy and dead-time corrected
mpl_linear_depol_ratio	MPL linear depolarization ratio
cloud_layer_base_height	base height of hydrometeor layers for up to 10 layers, based on combined radar and MPL observations
cloud_layer_top_height	top height of hydrometeor layers for up to 10 layers, based on combined radar and MPL observations
mean_doppler_velocity	ARSCL mean Doppler velocity; contains data from best radar operating mode
reflectivity_best_estimate	best-estimate reflectivity; contains data from best radar operating mode
spectral_width	ARSCL spectral width; contains data from best radar operating mode
hsrl_beta_a_backscatter	HSRL particulate backscatter cross section per unit volume
hsrl_depol	HSRL particulate depolarization ratio
temp	temperature profiles from the Interpolated Sonde VAP (INTERPSONDE)
mwrret1liljclou_be_lwp	liquid water path best-estimate value

4.0 Output Data

The THERMOCLDPHASE VAP produces a single daily file named XXXthermocldphase.YY.c1.YYYYMMDD.HHMMSS.nc where XXX is the site code, YY is the facility code, and YYYYMMDD.HHMMSS is the date and time. Output variables unique to the THERMOCLDPHASE VAP are shown below in Table 4. The rest of the variables are passed through from the input data files.

Table 4. Output variables from the THERMOCLDPHASE VAP.

cloud_phase_hsrl	Thermodynamic cloud phase determined from HSRL lidar extinction coefficient method
qc_cloud_phase_hsrl	Bit-packed quality check for cloud_phase_hsrl. Bit 1: Value is equal to missing_value; bit 2: Temperature data are not available; bit 3: Liquid water path data are not available
cloud_phase_layer_hsrl	Thermodynamic phase of the cloud layer determined from HSRL lidar extinction coefficient method
cloud_phase_mplgr	Thermodynamic cloud phase determined from MPL lidar intensity gradient method
qc_cloud_phase_mplgr	Bit-packed quality check for cloud_phase_mplgr. Bit 1: Value is equal to missing_value; bit 2: Temperature data are not available; bit 3: Liquid water path data are not available
cloud_phase_layer_mplgr	Thermodynamic phase of the cloud layer determined from MPL lidar intensity gradient method

5.0 Examples

Figure 2 presents an example of multi-sensor remote-sensing observations used as input for the THERMOCLDPHASE VAP for May 11, 2018, at the ARM NSA atmospheric observatory. Figure 3 provides detailed thermodynamic cloud phase classifications for the same day. Specifically, Figure 3a displays cloud phase classifications derived using HSRL data, while Figure 3b illustrates the corresponding cloud layer phase classifications. For comparison, Figure 3c shows classifications using MPL data. Overall, the classifications based on HSRL and MPL data exhibit strong agreement, with only minor differences.

To validate the VAP implementation, Figure 3d compares our results with the original multi-sensor method from Shupe (2007). The agreement is generally very good. However, our implementation identifies slightly more snow pixels. This difference likely arises because we applied the radar reflectivity offset correction recommended by Kollias et al. (2019), which suggests that the KAZR at the NSA site requires an offset adjustment of approximately 4 dBZ.

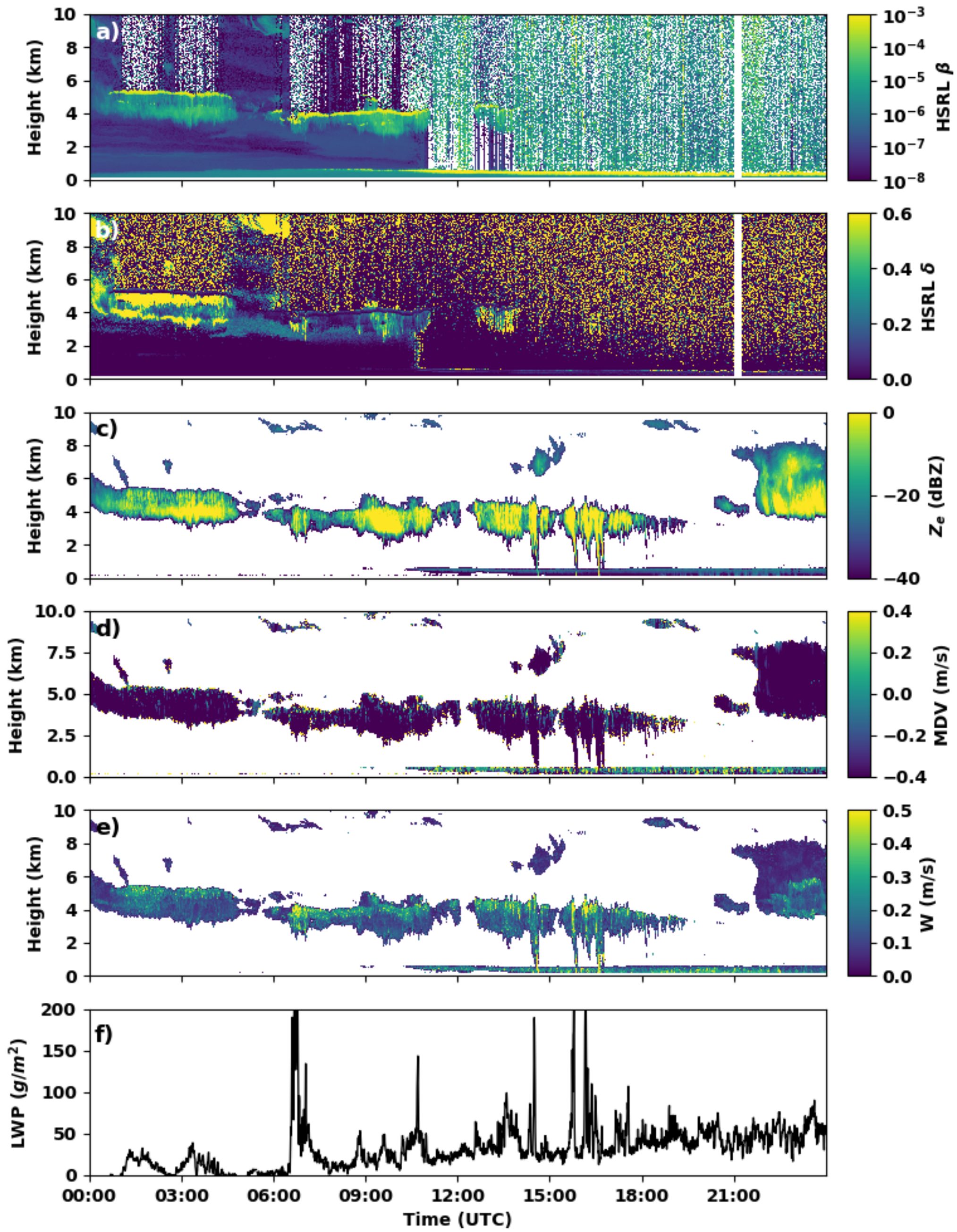

Figure 2. An example of multi-sensor remote-sensing measurements of clouds on May 11, 2018, at the ARM North Slope of Alaska (NSA) site. Panels from top to bottom are: a) HSRL backscatter coefficient (HSRL β); b) HSRL depolarization ratio (HSRL δ); c) KAZR radar equivalent reflectivity factor (Ze); d) KAZR mean Doppler velocity (MDV); e) KAZR Doppler spectral width (W); f) LWP from the MWRRET VAP.

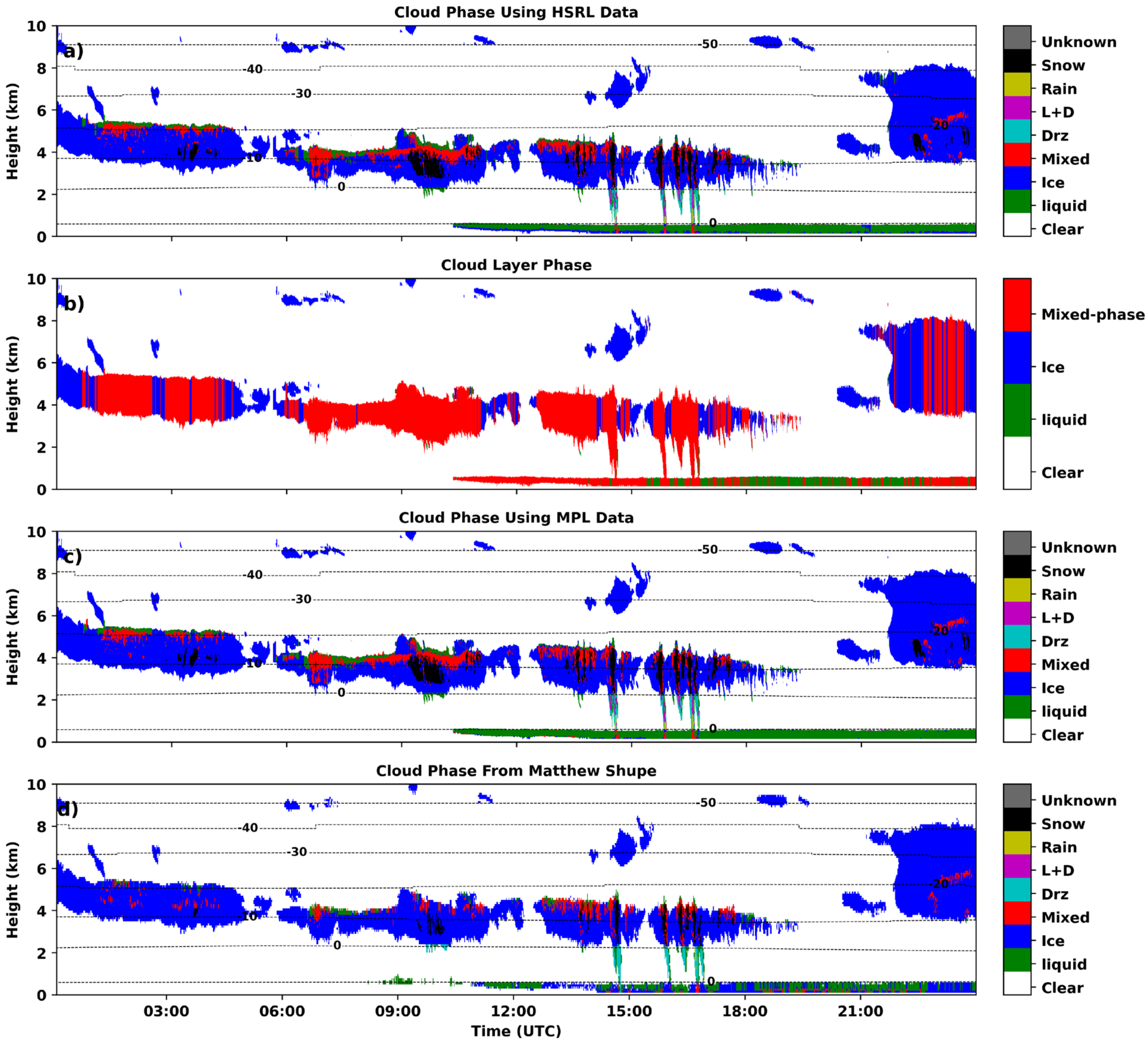

Figure 3. Thermodynamic cloud phase classification from the THERMOCLDPHASE VAP on May 11, 2018, at the ARM NSA site. Panels from top to bottom are: a) cloud phase using HSRL data; b) cloud layer phase using HSRL data; c) cloud phase using MPL data; d) cloud phase from Matthew Shupe.

6.0 Summary

The THERMOCLDPHASE VAP provides vertically resolved thermodynamic cloud phase classifications by integrating multiple ground-based remote-sensing observations and applying the multi-sensor methodology developed by Shupe (2007). At the pixel level, the VAP classifies cloud hydrometeor phases as liquid, drizzle, liquid + drizzle, rain, ice, snow, or mixed-phase. It also determines the overall cloud layer phase—categorized as liquid, mixed-phase, or ice—based on the fraction of ice-containing pixels within each layer.

The multi-sensor approach leverages the complementary strengths of different instruments. Lidar backscatter is highly sensitive to small particles with high number concentrations, such as liquid droplets, while radar reflectivity is dominated by signals from larger particles, such as ice crystals. The VAP uses lidar backscatter data from the HSRL or MPL, radar observations from the ARSCL VAP, temperature profiles from the INTERPSONDE VAP, and LWP from the MWRRET or MWRRETv2 VAP.

The THERMOCLDPHASE VAP outputs pixel-level cloud phase classifications at a temporal resolution of 30 seconds and vertical resolution of 30 meters. It also provides cloud layer phase identification for up to 10 distinct layers per profile. All results are stored in daily Network Common Data Form (netCDF) files for user access and analysis.

The THERMOCLDPHASE VAP serves as a valuable resource for investigating cloud physical processes, including thermodynamic phase transitions and cloud life cycle evolution. It provides detailed, vertically resolved phase information that can be used to evaluate and validate model simulations of cloud thermodynamic properties, improving the representation of mixed-phase and ice processes in atmospheric models. In addition, the data set offers critical input for the development and validation of remote-sensing retrieval algorithms, enhancing the accuracy of derived cloud and precipitation properties.

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