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ARM CLIMATE RESEARCH FACILITY

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Abstract

This document describes a new Atmospheric Radiation Measurement (ARM) data set, the ARM Cloud Retrieval Ensemble Data Set (ACRED), which is created by assembling nine existing ground-based cloud retrievals of ARM measurements from different cloud retrieval algorithms. The current version of ACRED includes an hourly average of nine ground-based retrievals with vertical resolution of 45 m for 512 layers. The techniques used for the nine cloud retrievals are briefly described in this document. This document also outlines the ACRED data availability, variables, and the nine retrieval products. Technical details about the generation of ACRED, such as the methods used for time average and vertical re-grid, are also provided.

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1.0 Overview

The ARM Cloud Retrieval Ensemble Data Set (ACRED) is a multi-year ensemble cloud microphysical property data set created by assembling existing cloud retrievals for ARM measurements, which are based on varying cloud retrieval algorithms. Currently, ACRED contains the cloud microphysical properties from nine ground-based cloud retrieval products at five ARM permanent research sites. One purpose of developing such an ensemble data set is to provide a rough estimate of the uncertainties in current ARM-retrieved cloud microphysical properties for climate model evaluation and development. ACRED is also a useful data set that can be used to understand the nature of the uncertainties that are closely associated with the retrieval techniques.

The data are currently available for the five ARM Climate Research Facility sites: SGP.C1 (Lamont, OK), NSA.C1 (Barrow, AK), TWP.C1 (Manus Island, PNG), TWP.C2 (Nauru), and TWP.C3 (Darwin, AU) for the period when these data are available. For each site, ACRED contains three to six retrieval products.

The data are stored in a similar format as the ARM Climate Modeling Best Estimate (CMBE) data set, to facilitate the use of the cloud property data by climate modelers. ACRED contains hourly averaged cloud properties and has 512 vertical layers with a resolution of 45 m.

2.0 Data Availability

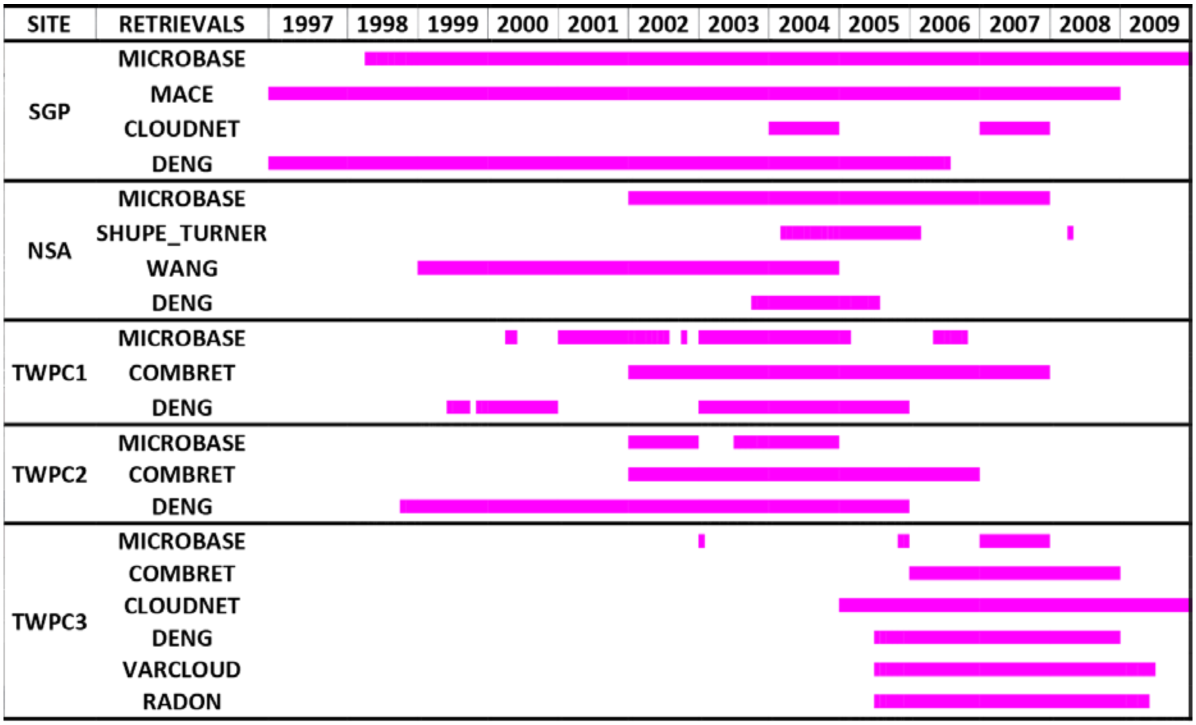
Table 1 lists the periods when ARM ground-based retrieval data are available. Currently, ACRED is available for the period between 1997 and 2009. A total of nine ground-based cloud retrieval products are contained in ACRED, with three to six retrieval products at each site. The retrieval algorithms for these cloud products are described in Section 3.

ACRED includes a series of 3D (varies with time, height, and retrieval method) and 2D (varies with time and retrieval method) variables for cloud properties. Every variable contains three kinds of quantities, which are the time means, standard deviations, and quality control (QC) flags. The major cloud properties in ACRED are the cloud liquid effective radius, liquid water content, vertically integrated liquid water path, cloud ice effective radius, ice water content, and vertically integrated ice water path. Some products also contain quantities such as cloud fraction, total column cloud fraction, cloud liquid optical depth, and ice optical depth at solar wavelength, which are also included in ACRED.

In summary, ACRED mainly contains the time mean, standard deviation and QC for variables of:

- Cloud liquid effective radius (r_e), liquid water content (LWC), and liquid water path (LWP)
- Cloud ice effective radius (r_e), ice water content (IWC) and ice water path (IWP)
- Cloud liquid optical depth (τ_l) and ice optical depth (τ_i) at solar wavelength
- Cloud fraction and cloud total column fraction

Table 1. Current data availability for nine ground-based retrievals at five ARM permanent research sites.



3.0 ACRED Retrieval Products

Currently, ACRED contains nine ground-based cloud retrieval products, as shown in Table 2.

- MICROBASE
  - MICROBASE is ARM's baseline cloud retrieval product, produced by a team led by Dr. Michael Jensen at Brookhaven National Laboratory. The product contains retrieved cloud properties for all types of clouds and for all conditions over the five ARM sites. MICROBASE is based on a simple empirical parameterization method. In principle, MICROBASE is an empirical estimate rather than a physically based retrieval. For liquid clouds, the algorithms in Liao and Sassen (1994) and Frisch et al. (1995) are used for the retrieval of LWC and r_e, respectively. For ice clouds, the algorithms in Liu and Illingworth (2001) and Ivanova et al. (2001) are used for the retrieval of IWC and r_e, respectively. For mixed-phase clouds, liquid and ice are separated based on cloud temperature and then retrieved using above methods.

Table 2. Nine ARM ground-based cloud retrieval products along with their contact information and references.

Products	Contact PIs	Affiliations	Sites	Clouds	References
MICROBASE	Mike Jensen; Maureen Dunn	Brookhaven National Laboratory	SGP, NSA, TWP	Liquid	Liao and Sassen 1994; Frisch et al. 1995
				Ice	Liu & Illingworth 2001; Ivanova et al. 2001
				Mixed	All above
MACE	Gerald (Jay) Mace	University of Utah	SGP	Boundary Stratus	Dong et al. 1998 (Layer Average); Dong and Mace 2001 (Vertical Profile)
				Other Liquid	Frisch et al. 1998
				Cirrus	Mace et al. 1998 (Layer Average); Mace et al. 2002 (Vertical Profile)
				Other Ice	Liu and Illingworth 2001
CLOUDNET	Robin Hogan; Ewan O'Connor	University of Reading	SGP, TWP.C3	Liquid part	-
				Ice part	Hogan et al. 2006
DENG	Min Deng	University of Wyoming	SGP, NSA, TWP	Cirrus	Deng and Mace 2006
SHUPE_ TURNER	Matthew Shupe; David Turner	University of Colorado, NOAA National Severe Storms Laboratory	NSA	Liquid only	Frisch et al. 1995; Turner et al. 2007; Turner 2007
				Liquid in thin mixed	Turner 2005, 2007; Turner et al. 2007
				Ice part	Shupe et al. 2005
WANG	Zhien Wang	University of Wyoming	NSA	Mixed	Wang et al. 2004; Wang and Sassen 2002
COMBRET	Jenifer Comstock	Pacific Northwest National Laboratory	TWP	Liquid part	Same as MICROBASE
				Ice (radar & lidar)	Wang and Sassen 2002
				Ice (radar or lidar)	Hogan et al. 2006; -
				Drizzle, rain	-
RADON	Alain Protat Julien Delanoë	CAWCR, LAMOS; LATMOS	TWPC3	Ice	Delanoë et al. 2007
VARCLOUD	Alain Protat Julien Delanoë	CAWCR, LAMOS; LATMOS	TWPC3	Ice	Delanoë and Hogan 2008

CAWCR indicates "The Centre for Australian Weather and Climate Research."
LATMOS indicates "The Laboratoire Atmosphère, Milieux, Observations Spatiales."

- MACE
  - The MACE cloud retrieval data is provided by Professor Jay Mace of the University of Utah. It is currently available for all types of clouds at SGP. The product is derived from a combination of eight different sources, which include six different retrieval techniques and two other empirical fittings. It differs from MICROBASE in that most of the retrieval techniques used by MACE are more physically based. It uses the algorithms described in Mace et al. (1998 and 2002) for cirrus clouds and Dong et al. (1998) and Dong and Mace (2001) for stratus clouds. Empirical parameterization methods described in Frisch et al. (1998) and Liu and Illingworth (2000) are used to derive LWC and IWC for clouds other than cirrus and stratus.
- CLOUDNET
  - The CLOUDNET cloud products, provided by Professor Robin Hogan of University of Reading, include the LWC and IWC for all kinds of clouds and are available at SGP and TWPC3 sites. The CLOUDNET data have been used in evaluating numerical weather forecast models in Europe through the Cloudnet project supported by the European Commission. CLOUDNET uses an empirical parameterization method to derive cloud LWC and IWC (Hogan et al. 2006). Major features include the use of profiles of temperature and pressure to make LWC follow a quasi-adiabatic profile, and the parameterization of IWC as a function of both temperature and radar reflectivity.
- DENG
  - The DENG cloud retrieval data are the ice cloud properties over the five ARM sites provided by Dr. Min Deng of the University of Wyoming. DENG retrievals are obtained from a physically based forward approach developed by Deng and Mace (2006). This forward approach is based on the first three moments of radar measurements, and it is only applied to cirrus clouds.
- SHUPE_TURNER
  - SHUPE_TURNER cloud products, provided by Dr. Matthew Shupe of the University of Colorado and Dr. David Turner of the NOAA National Severe Storms Laboratory, include all types of cloud properties at NSA.C1 site. SHUPE_TURNER uses an advanced cloud phase classification method developed by Shupe (2007). SHUPE_TURNER retrievals consist of four retrieval techniques, including both physically based methods and empirical parameterization methods. The retrieval method described by Turner (2005) is used for cloud liquid properties in thin clouds. The method described by Frisch et al. (1995) is used for pure liquid cloud properties. The method described by Shupe et al. (2005) is used for cloud ice properties.
- WANG
  - The WANG cloud product is for mixed-phase cloud properties. It is provided by Professor Zhien Wang of the University of Wyoming and is available for the NSA site. WANG retrieval products are based on the forward approach developed by Wang et al. (2004), a physically based method, in which ice part is retrieved using the retrieval method shown in Wang and Sassen (2002). This forward approach makes use of both radar and lidar measurements.

- COMBRET
  - The COMBRET cloud product is provided by Dr. Jennifer Comstock of Pacific Northwest National Lab. The product includes all types of cloud properties at the 3 TWP sites. Different from others, COMBRET retrievals distinguish the clouds and precipitation, and retrieve their properties. The retrieval method shown in Wang and Sassen (2002) is used for ice clouds when lidar and radar data are available, fitting approaches (including Hogan et al. 2006) are used for ice clouds when only lidar or radar data is available; the same retrieval techniques as MICROBASE are used for cloud liquid properties; a parameterization method is used for precipitation.
- VARCLOUD
  - VARCLOUD is a cloud retrieval product for ice cloud properties, provided by Dr. Alain Protat of the Centre for Australian Weather and Climate Research (CAWCR) and the Laboratoire Atmosphère, Milieux, Observations Spatiales (LATMOS) in France. It is currently available for the TWP.C3 site. VARCLOUD derives the ice cloud properties using a variational scheme described by Delanoë and Hogan (2008). It retrieves the cloud properties by matching the simulations from forward models to the measurements from radar, lidar, and infrared radiometer. It can obtain cloud properties for regions of the cloud detected by both radar and lidar and regions detected by just one of these two instruments.
- RADON
  - RADON is also a cloud retrieval product for ice cloud properties, provided by Dr. Alain Protat of CAWCR and LATMOS. It is currently only available for the TWP.C3 site. It differs from VARCLOUD by using a radar-only method (radar reflectivity and Doppler velocity) that was developed by Delanoë et al. (2006). This method first derives the ice particle vertical velocity, density, and ice crystal habit based on the relationship between Doppler velocity and radar reflectivity, and then obtains the particle size from vertical velocity and particle numbers from radar reflectivity and particle size.

The techniques used by these retrieval products are described in Section 5.

4.0 Details of ACRED Data Process

- ACRED Hourly Cloud Properties
  - ACRED includes the hourly averaged cloud properties with a vertical resolution of 45 m. The original retrieval products with finer time resolutions and different vertical resolutions need to be converted to the ACRED resolution using time average and vertical re-grid. The ACRED hourly average is the average of in-cloud properties. The standard deviation of cloud properties in ACRED is calculated as the standard deviation of the original cloud properties that are used for hourly average, for which the calculation method is simple and not described here. Note that -9999 is set for any variable when there are no retrievals.

4.1 Effective Radius and Cloud Fraction

Step 1: vertical re-grid. At a given ACRED vertical height, cloud r_e (either liquid or ice) and cloud fraction are set to the value at the height closest from original retrieval products. Here is the algorithm:

```
IF abs(H_orig[closest_layer]-H) ≤ max(Δ_H_orig, Δ_H)/2.0 then
  r_e=r_e_orig[closest_layer]
Else
  r_e = -9999.
```

Step 2: hourly average. For each layer, when positive effective radii from original retrievals are available, they are averaged; when only zero values for effective radius from original retrievals are available, the hourly average is set to zero; when no valid values from original retrievals exist, the hourly average is set to -9999. For cloud fraction, the non-negative cloud fractions from original retrievals are averaged to get the hourly averaged cloud fraction. Here is the process algorithm for effective radius:

```
k=where(r_e_orig > 0, count)
j=where(r_e_orig == 0, count2)
IF (count > 0) then
      r_e=mean(r_e_orig[k])
      fraction=count/totalnum
      ELSE IF (count2 > 0) then
         r_e=0
         fraction=count2/totalnum
    ELSE
         r_e=-9999
         fraction=0
ENDIF
```

Here, fraction is the number fraction of valid data, and totalnum is the total numbers of data within one hour, which is 1 hour/time resolution.

4.2 Water Content

The data process algorithm for water content is similar to that for effective radius and cloud fraction, except that we need to keep the LWP/IWP from integrated liquid/ice water content consistent with the original data set after the data process.

Step 1: vertical re-grid. We first convert the water content (like lwc_orig) at each layer into layer water path (like lwp_layer_orig) through lwp_layer_orig=lwc_orig*ΔH_orig, where ΔH_orig is the vertical height step for original cloud products.

Second, we redistribute the original layer lwp to the new (ACRED) vertical grids and calculate the water content at new grids. We use the process for deriving LWC at a new layer n to illustrate the method,

```
        lwc[n]=-9999
    IF ΔH ≤ ΔH_orig then
          layer=where.min(abs(H_orig-H[n]))
          IF abs(H_orig[layer]-H[n]) ≤ ΔH_orig/2 then
          layers=where(abs(H-H_orig[layer]) ≤ ΔH_orig/2)
          lwc[n]=lwp_layer_orig[layer]/n_elements(layers)/ΔH
              ENDIF
         ELSE
           layers=where(abs(H_orig-H[n]) ≤ ΔH/2, count)
            IF count > 0 then
          lwc[n]=total(lwp_layer_orig[layers])/ΔH
            END
      ENDIF
```

where H and ΔH are the height and vertical height step for ACRED data, respectively.

For the algorithm used above, we only consider the conditions when non-negative values of lwp_layer_orig exist.

Third, for a double-check, the lwc at new grids are scaled again by column-integrated LWP from original retrieval products to make sure the new integrated LWP is consistent with the original.

Step 2: hourly average. The algorithm for hourly average of water content is exactly the same as that for effective radius (see Section 4.1).

4.3 Optical Depths

Step 1: vertical re-grid. The vertical re-grid for optical depths (tau) is similar to that for layer water path described in Step 1 of Section 4.2. The following uses the derivation of tau at a new layer n to illustrate the method,

```
        tau[n]=-9999
    IF ΔH ≤ ΔH_orig then
          layer=where.min(abs(H_orig-H[n]))
          IF abs(H_orig[layer]-H[n]) ≤ ΔH_orig/2 then
          layers=where(abs(H-H_orig[layer]) ≤ ΔH_orig/2)
          tau[n]=tau_orig[layer]/n_elements(layers)
              ENDIF
         ELSE
```

```
      layers=where(abs(H_orig-H[n]) ≤ ΔH/2, count)
       IF count > 0 then
    tau[n]=total(tau_orig[layers])
       END
ENDIF
```

Step 2: hourly average. Considering that the cloud transmittance (trans) is proportional to exp(-tau), we first convert tau to trans=exp(-tau). Second, we calculate the hourly average of trans using the same method as that for effective radius (see Section 4.1). Third, the hourly averaged cloud optical depth is calculated as tau=-alog(mean(trans)).

4.4 Water Path

Differing from height-dependent variables (water content, effective radius, cloud fraction), water path is only dependent on time for any retrieval products. We only need to do the hourly average, for which the same average algorithm as that for effective radius (see Section 4.1) is used.

4.5 Retrieval Source

The MACE retrieval product is a combination of several different sources. In order to distinguish them, we pick the flag value for the major source within one hour as the flag value for the retrieval source in ACRED.

- ACRED QC Flag
  - Since the original qc information for the fine time resolution cloud properties will be lost after we do the hourly average and vertical re-grid, we use new qc flags to indicate how many data are valid over the hour time period (number fraction) so users have an idea about how many valid data were used to create the hourly means. Currently we set a qc flag with values of 0, -1, -2, -3 or -4. The means of these qc flags are listed here:
    - qc flag = 0 means that more than 50% of the data are valid over the hour time period
    - qc flag= -1 means more than 30% but less than 50% of the data are valid
    - qc flag= -2 means more than 10% but less than 30% of the data are valid
    - qc flag= -3 means the valid data points are less than 10%
    - qc flag= -4 means missing data point.

5.0 ARM Ground-Based Retrieval Algorithm

This section briefly describes the retrieval techniques used by the nine ARM ground-based retrieval products contained in the ACRED. In general, these retrieval techniques differ from each other in their retrieval fundamental basis, assumptions used, retrieval inputs, and retrieval constraints. Table 3 lists the technique details for these retrieval methods, including the relevant references, the cloud types to which the retrieval algorithms are applied, major assumptions, inputs, and outputs.

Several general equations are usually used by most retrieval techniques, which are

$$\mathrm{LWC} = \frac{4}{3}\pi\rho_L \int_0^\infty N(r) r^3 dr \tag{1}$$

$$\mathrm{IWC} = \frac{4}{3}\pi\rho_i \int_0^\infty N(r) r^3 dr \tag{2}$$

$$r_e = \int_0^\infty N(r) r^3 dr \Big/ \int_0^\infty N(r) r^2 dr \tag{3}$$

$$Z = 2^6 \int_0^\infty N(r) r^6 dr \tag{4}$$

where Z is radar reflectivity, N(r) is the particle number concentration at size r, and ρ_l and ρ_i are the liquid and ice bulk density. Eqs. (1) and (2) are the widely used relationships between cloud LWC/IWC and r; Eqs. (3) and (4) are the definitions of cloud r_e and radar Z. Although Eq. (3) is used by most cloud retrievals, we need to mention that the cloud ice general effective radius in WANG and COMBRET are defined in a different way [Wang and Sassen 2002].

Three kinds of particle size distributions (PSDs) are often assumed,

$$N(\ln r) = \frac{N}{\sigma_x\sqrt{2\pi}} \exp(-(\ln r - \ln r_0)^2 / 2\sigma_x{}^2) \tag{5}$$

$$N(r) = N_x \exp(\alpha)(\frac{r}{r_0})\exp(-\frac{r\alpha}{r_0}) \tag{6}$$

$$N(r) = N_0 \exp(-\lambda r) \tag{7}$$

where r_0 is modal radius, N is the total number concentration (number per volume), N_x and N_0 are the number concentration at the functional maximum (number per volume per unit length), σ_x is the spectral width of the distribution, and α and λ are parameters. Eqs. (5), (6), and (7) are for log-normal, (modified) gamma, and exponential PSDs, respectively.

Radiative transfer models, like the discrete ordinate radiative transfer (DISORT) model and line-by-line radiative transfer model (LBLRTM), are often used by surface radiation-based cloud retrieval algorithms. The microwave radiometer (MWR) LWP, particularly the retrieval of MWR LWP determined by Turner et al. (2007) and Turner (2007) using the Microwave Radiometer Retrievals value-added product (VAP), are widely used for the LWC retrievals as an input or constraint by most retrieval techniques.

For ice cloud retrieval, the power law relationships between particle terminal velocity (V), particle mass (M), and particle maximum length (L) are also frequently used by many retrieval algorithms, which are

$$V = aL^b \tag{8}$$

$$M = mL^n \tag{9}$$

where a, b, m, and n are coefficients dependent on the particle habit.

5.1 MICROBASE

The retrieval techniques used in MICROBASE vary with cloud phases, which are determined using cloud temperature. The cloud phase is set as liquid, ice, and mixed for the temperature range of $T \geq 0^oC$, $T \leq -16^oC$, and $-16^oC < T < 0^oC$, respectively. The retrieval techniques for the three phases of clouds, which are all empirical parameterization methods, are described here.

5.1.1 Liquid Clouds

The parameterization methods developed by Liao and Sassen (1994) and Frisch et al. (1995) are used for the retrieval of LWC and liquid r_e, respectively. The parameterization equations are

$$Z = \frac{3.6}{N_d} LWC^{1.8} \tag{10}$$

$$r_e = r_0 \exp(2.5\sigma_x^2) \tag{11}$$

$$r_0 = \left(\frac{3LWC}{4\pi\rho N \exp(9\sigma_x^2 / 2)} \right)^{1/3} \tag{12}$$

where σ_x is set a value of 0.35 and N is set as a reference number of 100 cm^{-3} in Eq. (10) for LWC calculation and assumed as 200 cm^{-3} in Eq. (12) for r_e derivation. Note that the integrated reflectivity has been scaled to make LWC agree with MWR LWP.

5.1.2 Ice Clouds

The parameterization methods described in Liu and Illingworth (2001) and Ivanova et al. (2001) are used for the retrieval of IWC and ice r_e, respectively. Liu and Illingworth (2000) assumed an exponential particle size distribution and derived the parameters based on limited aircraft measurements for a regression form

$$IWC = aZ_e^b \tag{13}$$

and got the final results of

$$IWC = 0.137Z^{0.643} \qquad at\, 94GHz \tag{14}$$

$$IWC = 0.097 Z^{0.59} \qquad at\, 35\, GHz \tag{15}$$

The parameterization equation for ice r_e in Ivanova et al. (2001) is

$$r_e = (75.3 + 0.5895T)/2 \tag{16}$$

5.1.3 Mixed-phase Clouds

The four empirical parameterization methods described in Sections 5.1.1 and 5.1.2 are used for the mixed-phase clouds retrieval by introducing one variable, ice fraction (f_{ice}), which is defined as

$$f_{ice} = -T/16 \tag{17}$$

The cloud liquid and ice properties are then derived using Eqs. (10)–(12) and Eqs. (15)–(16) based on the separated radar reflectivity Z_{liquid} and Z_{ice}

$$Z_{liquid} = (1 - f_{ice})Z \tag{18}$$

$$Z_{ice} = f_{ice} Z \tag{19}$$

5.2 MACE

MACE cloud products are derived from a combination of eight different sources, which include six different retrieval techniques and two other empirical fittings. Unlike MICROBASE, most of the retrieval techniques used by MACE are more physically based retrievals. It uses the algorithms described in Mace et al. (1998 and 2002) for cirrus clouds, Dong et al. (1998) and Dong and Mace (2001) for stratus clouds, Liu and Illingworth (2000) for other types of ice clouds, and Frisch et al. (1998) for other liquid clouds.

5.2.1 Ice Clouds

5.2.1.1 Layer-averaged Cloud Properties for Thin Cirrus

Mace et al. (1998) retrieved thin cirrus cloud properties by deriving the following major equations with assumptions of modified gamma particle size distribution (α=1), hexagonal particle habit, and horizontal homogeneity,

$$Z = N_x e^{\alpha} D_x{}^7 \frac{(6+\alpha)!}{\alpha^{7+\alpha}} \tag{20}$$

$$IWC = \rho_i \frac{\pi}{6} N_x D_x{}^7 \tag{21}$$

$$N_T = D_x N_x e^{\alpha} \frac{\alpha}{\alpha^{\alpha+1}} \tag{22}$$

$$r_e = \frac{D_x}{2} \frac{(3+\alpha)!}{(2+\alpha)!} \alpha^{\alpha} \tag{23}$$

$$\frac{\ln(1-\varepsilon)}{k_1 \overline{Z_e} \Delta h} = \frac{C_1 k_2^3 D_x^5 + C_2 k_2^2 D_x^4 + C_3 k_2 D_x^3 + C_4 D_x^2 + \frac{C_5}{k_2} D_x + \frac{C_6}{k_2^2}}{D_x^2 (B_0 D_x^3 + \frac{B_1}{k_2} D_x^2 + \frac{B_2}{k_2^2} D_x + \frac{B_3}{k_2^3})} \tag{24}$$

where C, B series are constant coefficients, and k_1 and k_2 are dependent parameters. Mace et al. (1998) use an optimal iteration method to derive Dx based on atmospheric emitted radiance interferometer (AERI) radiation measurements and MOTRAN3 radiance calculation using Eq. (24). Then cloud properties of ice r_e, N, and IWC are derived using Eqs. (20)–(23).

5.2.1.2 Profiles of Cloud Properties for Cirrus

Mace et al. (2002) tried to develop cirrus clouds properties with a forward approach with assumptions of exponential particle size distribution (Eq. 7), bullet rosette ice crystal habit, and horizontal homogeneity. The retrieval idea is to derive the two parameters (N_e and λ_e in Eq. 7) for the exponential PSD using the calculation of first three moments of radar measurements, which are water-equivalent radar reflectivity (Z_e), Doppler velocity ($V^q{}_d$), and its spectral width ($\sigma^q{}_x$). In this process, the method accounts for the air motion and takes use of the power law relationship (Eq. 8 and 9) between particle mass (m), particle terminal velocity, and particle maximum dimension (L). The derived forward equations are

$$Z_e = N_e \gamma \int_0^{\infty} L^{6+k} \exp(-\lambda_e L) dL \tag{25}$$

$$\overline{V}^q{}_d = \frac{a\gamma N_e}{Z_e} \int_0^{\infty} L^{6+k+b} \exp(-\lambda_e L) dL \tag{26}$$

$$\overline{\sigma}^q{}_x = \frac{\gamma N_e}{Z_e} \int_0^{\infty} (aL^b - \overline{V}^q{}_d)^2 \exp(-\lambda_e L) dL \tag{27}$$

where γ and κ are parameters depending on particle backscatter cross-section of an ice crystal, and a and b are coefficients depending on particle habit.

After deriving N_e and λ_e, the cloud properties of ice water content (IWC), number concentration (N), and mass median particle length (L_{MM}) are calculated through

$$IWC = mN_e \int_0^{\infty} L^n \exp(-\lambda_e L) dL \tag{28}$$

$$N = N_e \int_0^{\infty} \exp(-\lambda_e L) dL \tag{29}$$

$$0.5 = \frac{mN_e \int_0^{L_{MM}} L^n \exp(-\lambda_e L) dL}{IWC} \tag{30}$$

5.2.1.3 Ice Water Content for Other Ice Clouds

The parameterization method from Liu and Illingworth (2000) has been described in Section 5.1.2 with Eq. (15).

5.2.2 Liquid Clouds

5.2.2.1 Layer-averaged cloud properties for boundary layer stratus

Dong et al. (1998) derives layer-averaged cloud properties for the boundary layer stratus. For thin stratus, it uses the optimal iteration method based on the shortwave irradiance measurements and δ2-stream radiation calculation. For thick clouds, it uses an empirical parameterization method based on the MWR LWP, transmission ratio γ, and solar zenith angle $\mu_{0.}$ The major assumptions used by Dong et al. (1998) include the log-normal particle size distribution (σ_x=0.35) and horizontal homogeneity. The major equations used by Dong et al. (1998) include

$$\bar{r}_e = r_m \exp(5\sigma_x^2 / 2) \tag{31}$$

$$N = \frac{3LWP}{4\pi\rho_w r_e^3 \Delta Z} \exp(3\sigma_x^2) \tag{32}$$

$$\tau = \frac{3LWP}{2r_e \rho_w} \tag{33}$$

$$\gamma = \frac{F_m(cloudy)}{F_m(clear)} \tag{34}$$

where r_m is a modal radius, ΔZ is the cloud depth and F_m(cloudy) and F_m(clear) are the measured cloud sky and inferred clear-sky downward solar fluxes at the surface, respectively.

For thin stratus, Dong et al. (1998) derives layer-averaged liquid r_e ($\overline{r_e}$) using an optimal iteration approach whereby $\overline{r_e}$ is adjusted until the δ2-stream model-computed transmission ratio converges, within a specified error, to the measured transmission ratio. For thick clouds, the following parameterization equation is used for the liquid $\overline{r_e}$ calculation

$$\bar{r}_e = -2.07 + 2.49LWP + 10.25\gamma - 0.25\mu_0 + 20.28LWP\gamma - 3.14LWP\mu_0 \quad (35)$$

5.2.2.2 Profiles of Cloud Properties for Boundary-Layer Stratus

For daytime, Dong and Mace (2001) derives the vertical profiles of cloud liquid effective radius ($r_e(h)$) based on the layer-averaged effective radius from Dong et al. (1998) and the assumption of

$\langle r^6 \rangle = k^2 \langle r^3 \rangle^2$, which are

$$r_e(h) = \bar{r}_e \left[\frac{\Delta H}{\Delta h} \frac{Z^{1/2}(h)}{\sum_{base}^{top} Z^{1/2}(h)} \right]^{1/3} \quad (36)$$

For nighttime, Dong and Mace (2001) derives liquid $r_e(h)$ using an empirical parameterization method

$$r_e(h) = \frac{\exp(3.912 - 0.5\sigma_x^2)}{N^{0.167}} \exp(0.0384 dBZ(h)] \quad (37)$$

where the constant values of N and σ_x are used. Other cloud properties are derived with Eqs. (32) and (33). For profiles of LWC, Dong and Mace (2001) derives using MWR LWP through

$$LWC(h) = \frac{LWP}{\Delta h} \frac{Z^{1/2}(h)}{\sum_{base}^{top} Z^{1/2}(h)} \quad (38)$$

5.2.2.3 Liquid Water Content for Other Liquid Clouds

Frisch et al. (1998) use a parameterization method to derive LWC for liquid clouds. It is based on the MWR LWP and cloud radar reflectivity with the assumption of $\langle r^6 \rangle = k^2 \langle r^3 \rangle^2$, which has been used by Dong and Mace (2001) and shown in Eq. (38).

5.3 CLOUDNET

5.3.1 Liquid Water Content

Profiles of temperature and pressure from the European Centre for Medium-Range Weather Forecast (ECMWF) were used to estimate the theoretically adiabatic LWC for each cloud. The adiabatic liquid water content is then scaled so that its integral matches the retrieved MWR LWP. Therefore, the CLOUDNET LWC follows a quasi-adiabatic profile. If the liquid layer is detected by the lidar only, and the adiabatic-integrated LWC is less than that measured by the MWR, the cloud top is extended until the adiabatic integrated LWC agrees with the value measured by the MWR.

5.3.2 Ice Water Content

CLOUDNET uses an empirical parameterization method developed by Hogan et al. (2006) for IWC calculation. The parameterization method developed by Hogan et al. (2006) is an advance to that developed by Liu and Illingworth (2000) described in Section 5.1.2 (Eq. 13). The IWC in Hogan et al. (2006) is dependent on both radar reflectivity and temperature in a form of

$$\log_{10}(IWC) = (0.000242)ZT + 0.0699Z - 0.0186T - 1.63 \qquad at\,35\,GHz \tag{39}$$

$$\log_{10}(IWC) = (0.000580)ZT + 0.0923Z - (0.00706)T - 0.992 \qquad at\,94\,GHz \tag{40}$$

where radar reflectivity (Z) and temperature (T) are in units of dBZ and degree C. By adding the temperature dependency, the IWC from Hogan et al. (2006) varies more smoothly.

5.4 DENG

DENG retrievals are also physically based, but particularly developed for cirrus clouds (Deng and Mace 2006). Deng and Mace (2006) uses the millimeter-wavelength cloud radar (MMCR) Doppler spectrum to derive the two parameters (N_0 and λ in Eq. 7) for an assumed exponential particle size distribution.

Deng and Mace (2006) determine that the MMCR measurements, water-equivalent radar reflectivity (Z_e), Doppler velocity (V_d) and spectral width (σ_d) are dependent on N_0, λ and the other two variables of the mean air vertical velocity (Wm) and the standard deviation of the vertical motion (W_σ), in a form of

$$Z_e = f(\lambda, N_0) \tag{41}$$

$$V_d = f(\lambda, W_m) \tag{42}$$

$$\sigma_d = f(\lambda, W_\sigma) \tag{43}$$

In order to obtain the four unknown variables from three limited equations, Wσ is considered as a parameter obtained using the following equation

$$W_\sigma = a_w \sigma_d^{b_w} \frac{|Z_e|}{\max(|Z_e|)} \tag{44}$$

where a_w and b_w are constants.

Besides the exponential particle size distribution assumption, Deng and Mace (2006) have also used the power law relationships described in Eqs. (8) and (9). For ice crystal habit, DENG assumes hexagonal columns.

5.5 SHUPE_TURNER

SHUPE_TURNER determines the cloud phases using an advanced cloud phase classification method developed by Shupe (2007). SHUPE_TURNER derives cloud liquid r_e using an AERI-based retrieval method for optically thin (optical depth<6) clouds (Turner 2005), a parameterization method (Frisch et al. 1995) for other liquid-only clouds, and a value of 8 um for optically thick, multiphase cloud scenes that cannot be retrieved. A radar reflectivity-based parameterization method (Frisch et al. 1995) is used to derive the LWC for liquid-only clouds, in which the number concentration has been adjusted to make integrated LWC match the MWRRET LWP. For clouds for which this parameterization method does not work, the LWC is derived using an adiabatic calculation scaled by the MWRRET LWP. For ice cloud properties, SHUPE_TURNER derives ice r_e using the AERI-based retrieval method for optically thin clouds and using the radar reflectivity-based parameterization method [Shupe et al. 2005] for other clouds. IWC is obtained using a radar reflectivity-based empirical parameterization method (Shupe et al. 2005).

5.5.1 Cloud Liquid and Ice Properties in Thin Mixed-Phase Clouds

Turner (2005) developed a retrieval algorithm for the mixed-phase clouds (MIXCRA) with optical depths less than 6, which retrieves the cloud optical depths of liquid (τ_l) and ice (τ_i), ice fraction, liquid r_e ($r_{e,w}$), and ice r_e ($r_{e,i}$). Note that only cloud liquid and ice r_e are included in the SHUPE_TURNER cloud product. Turner (2005) derives these cloud properties by minimizing the difference in cloud emissivity spectrum between model (LBLRTM and DISORT) simulation and AERI radiation-based observation. The optimal retrieval formulation is

$$X^{n+1} = X_a + (S_a^{-1} + K^T S_e^{-1} K)^{-1} \{K^T S_e^{-1} [Y - F(X^n) + K(X^n - X_a)]\} \tag{45}$$

where X is state vector (τ_w, τ_i, $r_{e,w}$, and $r_{e,i}$), K is the sensitivity of the emissivity spectrum to the state vector determined by LBLRTM and DISORT, and Y is the measurements of cloud emissivity spectrum. The meanings of other variables and details of X and K are described in Turner (2005).

5.5.2 Cloud Liquid Properties in Pure Liquid Clouds

Frisch et al. (1995) derives the cloud liquid r_e for liquid properties in pure liquid clouds that Turner (2005) cannot apply and derives the cloud LWC for liquid-only clouds using a radar reflectivity-based empirical parameterization method with a log-normal particle size distribution assumption

$$LWC = 0.30 \rho Z^{1/2} N^{1/2} \tag{46}$$

$$r_e = r_0 \exp(2.5\sigma_x^2) \tag{47}$$

$$r_0 = \left(\frac{3LWC}{4\pi\rho N \exp(9\sigma_x^2 / 2)} \right)^{1/3} \tag{48}$$

where σ_x is often set a value between 0.30 and 0.45 and N can be adjusted to fit the radiometer measurements of the total integrated liquid water.

5.5.3 Cloud Ice Properties

Shupe et al. (2005) derives the IWC for all ice clouds and ice particle characteristic size (median volume diameter D_0) for clouds that Turner (2005) cannot apply using an empirical parameterization method similar to that used by Matrosov (1999)

$$IWC = aZ_e^b \tag{49}$$

$$D_0 = 143a^{-0.53} Z_e^{0.53(1-b)} \tag{50}$$

where b=0.63 and a is a time-dependent parameter.

5.6 WANG

WANG derives the mixed-phase cloud properties using a physically based method developed by Wang et al. (2004), in which the ice part is retrieved using the method from Wang and Sassen (2002). The basic retrieval idea is that the mixed-phase clouds are treated as two connected cloud layers, where the top is a water-dominated liquid cloud and the bottom is an ice cloud.

5.6.1 Ice Part

Profiles of IWC and ice r_e are retrieved using the lidar extinction coefficient (σ) and the water equivalent radar reflectivity (Z_e) through

$$\sigma = IWC\left(a_0 + \frac{a_1}{D_{ge}}\right) \tag{51}$$

$$Z_e = C' \frac{IWC}{\rho_i} D_{ge}^b \tag{52}$$

where a_0, a_1 are coefficients dependent on wavelength, C' and b are parameters dependent on size range, and $\rho i=0.92$ g cm^{-3}. Two major assumptions have been applied in this technique: the random oriented hexagon with given aspect ratio D/L (D and L are the width and length of ice crystal) and the modified gamma size distribution. Note that the size D_{ge} in WANG (also COMBRET) is a generalized effective diameter defined differently from Eq. (3), which is

$$D_{ge} = \frac{\int_{L_{\min}}^{L_{\max}} DDLN(L)dL}{\int_{L_{\min}}^{L_{\max}} (DL + \frac{\sqrt{3}}{4} D^2) N(L) dL} \quad (53)$$

where N(L) is the ice crystal size distribution and L_{min} and L_{max} are the minimum and maximum lengths of ice crystals.

In ACRED, we have converted D_{ge} into r_e using the following simple equation (Fu 1996)

$$r_e = D_{ge} * 0.6495 \quad (54)$$

5.6.2 Liquid Part

After knowing the ice properties, an optimal iteration method is used to determine the cloud liquid properties by minimizing the function F, defined as

$$F = \sum_{i=1}^{12} [\frac{I'(\lambda_i)}{I(\lambda_i)} - 1]^2 \quad (55)$$

where $I(\lambda_i)$ and $I'(\lambda_i)$ are the measured and calculated downward radiance at wavelength λ_i, respectively. Twelve wavelengths between 8 and 13 um are used by Wang et al. (2004), and the DISORT model is used for calculating radiance as a function of τ_w, $r_{e,w}$, cloud base temperature, and known ice properties. Note that τ_w is parameterized based on $r_{e,w}$ and LWP.

Similar to CLOUDNET, LWC in WANG is derived using an adiabatic calculation between cloud liquid base and top scaled by the MWRRET LWP.

5.7 COMBRET

COMBRET includes the properties of clouds, drizzle, and rain, which are classified based on the phase determination method developed by Shupe (2007) with the parameters tuned for tropical clouds. COMBRET defines each height-time bin as having radar, lidar, or both signal detection and then applies the corresponding retrieval algorithms. For cloud ice properties, the retrieval method developed by Wang and Sassen (2002) is used when both lidar and radar signals are available; a fitting approach developed by Hogan et al. (2006) is used when only radar signal is available; another fitting approach is used when only lidar signal is available. For cloud liquid properties, the same retrieval algorithms as MICROBASE are adopted. For drizzle and rain, COMBRET uses a radar reflectivity-based parameterization method.

5.7.1 Clouds

The MICROBASE liquid cloud retrieval algorithms, the radar-based fitting approach developed by Hogan et al. (2006), and the radar-lidar method developed by Wang and Sassen (2002), have been described in Sections 2, 3.2 and 6.1. Here we describe the fitting approach used for the ice clouds when only lidar signal is available, which is

$$IWC/\sigma = f(T) \tag{56}$$

where σ is the lidar extinction coefficient. The tuned parameterizations in Eq. (39) (Hogan et al. 2006) and Eq. (56) are determined using daily fit (when the daily sample points number is more than 1500) or climatology fit (when the daily sample points number is less than 1500) based on the ice cloud retrievals when both radar and lidar measurements are available. After knowing IWC, the general effective radius D_{ge} is then calculated through

$$D_{ge} = \frac{2.3IWC}{\rho_i \sigma} \tag{57}$$

As in WANG, D_{ge} in COMBRET has also been converted r_e in ACRED.

5.7.2 Drizzle and Rain

COMSTCOK uses a radar reflectivity-based parameterization method to derive the properties of drizzle and rain. First, rain rate (R) is computed using

$$R = (\frac{Z}{a})^{1/b} \tag{58}$$

where a=12.4 and b=1.18 for both rain and drizzle. The algorithm can really only retrieve the rain rate in light rain or drizzle (i.e., stratiform precipitation). Second, assuming a Marshall-Palmer type distribution, it calculates the size distribution of rain/drizzle through

$$N(r) = N_0 \exp(-kr) \tag{59}$$

where $k = 41.0R^{-0.21}$, N_0=0.8 cm^{-4}. Third, LWC and r_e are calculated using Eqs. (1) and (3).

5.8 VARCLOUD

VARCLOUD derives the ice cloud properties using a variational method based on the combination of measurements from radar, lidar, and infrared radiometer (Delanoe and Hogan 2008). This algorithm retrieves ice cloud properties (visible extinction, IWC, and effective radius) seamlessly between regions of the cloud detected by both radar and lidar, and regions detected by just one of these two instruments. The retrieval technique uses the optimal estimation framework to iteratively minimize the difference between the forward-modeled observations and real observations. It includes a rigorous treatment of measurements and forward model errors. At each step, forward-modeled radar reflectivity and lidar-attenuated backscatter are computed using the forward model and the state vector containing extinction, extinction-to-backscatter ratio, and number concentration.

Once the convergence is achieved, the optimal state vector is converted to IWC and ice r_e using look-up tables. The forward model assumes a microphysical model describing the shape of the particle size distribution using the normalized approach [Delanoë et al. 2005]. The mass-size relationship, used to derive the look-up table linking ice cloud properties to measurements parameters, follows a power law proposed by Brown and Francis (1995) for spherical aggregates. The lidar forward model accounts for multiple scattering and attenuation using the model of Hogan (2006). Extinction-to-backscatter ratio is retrieved with a vertically constant assumption. Following we give a brief summary about the retrieval technique described in Delanoe and Hogan (2008).

First, a state vector, including the visible extinction coefficient (α_v), the extinction-to-backscatter ratio (S), and a number concentration-related variable (N_0'), is used to generate a look-up table. Note $N_0^{'} = N_0^{*} / \alpha_v^{0.6}$, where N_0* is the total number concentration. With this look-up table, three forward approaches are run to get the simulations for observation matching variables.

Second, three forward models are used to generate the simulation results. For the radar forward approach, the radar reflectivity is first calculated from the look-up table, and then it is converted to the radar resolution. For the lidar forward approach, the equivalent area size is first calculated from the look-up table, and then the lidar extinction coefficient is derived using a fast multiple scattering model. For the infrared radiometer forward approach, the spectral extinction coefficient is calculated from the look-up table, and then the spectral radiation is obtained with a fast radiance model. Sometimes the extinction coefficients are also integrated to get the optical depth.

Third, an optimal estimation formulation is used to achieve the optimal state vectors for the clouds based on forward calculations and observations. The cost function is

$$2J = \sum_{i=1}^{q} \frac{(\ln Z_i - \ln Z_i^{'})^2}{\sigma^2_{\ln Z_i}} + \sum_{i=1}^{p} \frac{(\ln \beta_i - \ln \beta_i^{'})^2}{\sigma^2_{\ln \beta_i}} + \frac{(\delta_\gamma - \delta_\gamma^{'})^2}{\sigma^2_{\delta_\gamma}} + \frac{(I_\lambda - I_\lambda^{'})^2}{\sigma^2_{I_\lambda}} + \frac{(\Delta I - \Delta I^{'})^2}{\sigma^2_{\Delta I}} + \sum_{i=1}^{n+m+1} \frac{(x_i - x_i^a)^2}{\sigma^2_{a,i}} \quad (60)$$

where δ is visible optical depth, I is radiation, λ is spectral wavelength, and x is state vector. The first five elements on the right-hand side of Eq. (60) represent the deviation of the observations lnZ, lnβ, I_λ, ΔI, and δ_γ, from the values predicted by the forward model lnZ', lnβ', I_λ', ΔI', and δ_γ', with the root-mean-squared (RMS) observational errors.

5.9 RADON

RADON uses the radar measurements of radar reflectivity and Doppler velocity to characterize ice cloud properties (Delanoe and Hogan 2008). This radar-only method relies on the concept of scaling the ice particle size distribution, which is

$$N(D_{eq}) = N_0^* F(\frac{D_{eq}}{D_m}) \quad (61)$$

where $N(D_{eq})$ is the PSD, $F(D_{eq}/D_m)$ is the normalized PSD, D_{eq} is the "equivalent melted" diameter (which is the diameter the ice particle would have if it was a spherical water particle of the same mass), and N_0^* (m^{-4}) is the intercept parameter of the PSD proportional to IWC/D_m^4. The volume-weighted diameter D_m is the ratio of the fourth to the third moment of the PSD.

With this size distribution, the relationship between radar reflectivity and particle size and the relationship between particle terminal velocity and particle size are used to derive the cloud properties. In detail, RADON first derives the ice particle terminal fall velocity from Doppler velocity using a statistical method; second, the ice particle density and particle habit are derived based on the relationship between ice terminal velocity and radar reflectivity; third, particle volume weighted diameter (D_m) is retrieved from the vertical velocity using

$$V_t = gD_m^l \quad (62)$$

where (g, l) are related to the retrieved ice density and particle habit; fourth, the intercept parameter N_0^* is derived from the radar reflectivity, which is related to particle size through (Mie scattering),

$$Z_e = \frac{\lambda^4}{|K_W|^2 \pi^5} 10^{18} \int N(D)\sigma_{bsc}(\rho, D, \lambda) dD \, (mm^6 m^{-3}) \quad (63)$$

$$N_0^* = \frac{|K_W|^2 \pi^5 10^{-18}}{\lambda^4} Z_e I(D_m)^{-1} \, (m^{-4}) \quad (64)$$

$$I(D_m) = \int F(\frac{D}{D_m}) \sigma_{bsc} dD \quad (65)$$

where D_m is in meters and I(Dm) is an integral function that depends on the ice particle density and the mean volume-weighted diameter.

Finally, IWC and ice r_e can be derived through

$$IWC = \frac{N_0^* \pi \rho_W D_m}{4^4} \, (g\, cm^{-3}) \quad (66)$$

$$r_e = \frac{3(IWC)}{2\rho_i \alpha} 10^6 \, (\mu m) \quad (67)$$

In summary:

- MICROBASE is based on the simple empirical parameterization methods (EPM).
- MACE is a physically based cloud retrieval product.

- CLOUDNET derives the cloud liquid and ice water content using empirical equations based on both the radar reflectivity and temperature, making IWC vary smoothly, and derives the LWC by scaling the MWR LWP with the adiabatic gradient determined from profiles of temperature and pressure.
- SHUPE_TURNER uses an advanced cloud phase classification method developed by Shupe (2007), and the retrieval techniques include both physically based methods and empirical retrieval methods.
- Both WANG and DENG use physically based retrieval algorithms, particularly developed for mixed-phase clouds and cirrus clouds, respectively.
- COMBRET retrievals distinguish clouds and precipitation and then derive their properties using a series of parameterization methods.
- VARCLOUD derives ice cloud properties using an optimal minimization method based on several forward approaches with measurements from radar, lidar, and radiometer.
- RADON obtains ice cloud properties using a radar-only method with uniqueness in the derived ice density and particle habit.

Table 3. Retrieval algorithms (assumptions, retrieval ideas, and inputs) for nine ARM cloud products. The meanings of the symbols and abbreviations can be found from the algorithm references.

Product	Clouds	Assumptions		Theory-Based Functions/Models/parameters	Major Inputs	Method
		PSD	Habit			
MICROBASE	Liquid	Log-normal (σ=0.35)	spherical	LWC=F(Z, LWP); re=F(Z, LWC); N~100cm^{-3} (r_e); N~200cm^{-3} (LWC)	Z	EPM
	Ice	Exponential	Planar polycrystal	IWC=F(Z_e); re=F(T)	Z_e, T	EPM
	Mixed	See above	See above	f_{ice}=-T/16; Z_{liquid}=(1-f_{ice})*Z; Z_{ice}=f_{ice}*Z	Z, T	EPM
MACE	Boundary stratus (layer)	log-normal (σ=0.35)	Spherical	Thick: r_{e_layer}=F(LWP, γ, μ0); Thin: δ-2 stream model	LWP, γ, μ0	EPM; optimal
	Boundary stratus (profile)	Log-normal	Spherical	LWC=F(LWP, Z); day: r_e=F(r_{e_layer}, Z); night: r_e=F(Z)	LWP, Z	Forward
	Other Liquid	-	spherical	LWC=F(LWP, Z); $\langle r^6\rangle=\langle r^3\rangle^2$	LWP, Z	Forward
	Cirrus (layer)	Modified Gamma (α=1)	hexagonal	MODTRAN3 model (optical thin)	Z_e, I	Optimal
	Cirrus (Profile)	Exponential	Bullet Rosette	Z_e=F(L, n(L)); V_d=F(L, n(L), V(L)); σ_d^2=F(L, n(L), V(L))	Z_e, V_d	Forward
	Other Ice	Exponential	-	IWC = aZ_e^b , a, b are constants	Z_e	EPM
CLOUDNET	Liquid part	-	-	LWC from LWP-scale with adiabatic gradient	T, P; LWP	Forward
	Ice part	Gamma	-	IWC=F(Z_e, T)	T, P; Z_e	EPM
DENG	Ice	Exponential	hexagonal	Z_e=F(λ, N_0); V_d=F(λ, W_m); σ_d=F(λ, W_σ); W_σ=F(σ_d, Z_e);	Z_e, V_d, σ_d σ_d	Optimal
SHUPE_ TURNER	Pure liquid clouds	Log-normal	Spherical	r_e=F(Z, N) with adjusted N; LWC=F(Z)	Z, LWP	Forward
	Liquid & ice in optical thin clouds	Gamma	Any	Liquid and ice re: AERI based LWC: adiabatic gradient scaled by LWP; IWC=aZ_e^b	I; LWP	Optimal
	Ice in other clouds	exponential		IWC=aZ_e^b; r_e=F(Z_e); a=a(time), b=0.63	Z_e	EPM
WANG	Mixed	Modified gamma; log-normal	hexagonal	Ice part: IWC=F(σ_{ext}, r_e); r_e=F(σ_{ext}, Z_e); Liquid part: DISORT;	LWP, I, Z_e, σ_{ext}, T_{cb}	Forward Optimal
COMBRET	Liquid (radar)	Same as MICROBASE, except N=100 cm^{-3}				
	Ice (Z_e & σ_{ext})	Modified Gamma	hexagonal	IWC=F(σ_{ext}, Z_e); r_e=F(σ_{ext}, Z_e);	Z_e, σ_{ext}	EPM
	Ice (Z_e or σ_{ext})	Fitting Gamma	-	IWC=F(Z_e, T); IWC=F(σ_{ext}, T); r_e=F(IWC, Z_e); r_e=F(IWC, σ_{ext})	Z_e, T or σ_{ext}, T	EPM
	Drizzle and Rain	Marshall-Palmer type	-	R=F(Z); N(r)=F(R, r); r_e=volume/area;	Z	EPM
RADON	Ice	Normalized (N_0^*, D_m)	retrieved	ρ_I, V_t and w =f(V_d-Z relationship); IWC=f(Z_e, N_0^*), σ_{ext}=f(Z, N_0^*), D_m=f(V_T), r_e=F(IWC, σ_{ext});	Z_e, V_d	Forward
VARCLOUD	Ice	Normalized (N_0^*, D_m)	spherical aggregates	Radar and lidar forward models. (IR forward model available)	Z_e, σ_{ext}, I, T	Optimal

6.0 Validation of ACRED data

The hourly averaged cloud properties in ACRED have been compared to the original retrieval products for validation. Here we show a couple of examples.

Figures 1 and 2 show the comparison of cloud liquid and ice r_e between the hourly averaged ACRED data and the original data in October 2004 at SGP, respectively. Both the liquid and ice r_e in ACRED show exactly the same pattern as those in original cloud retrieval products. Similar results can be obtained for other cloud properties and other sites. These results indicate the effectiveness of the ACRED data processing algorithms.

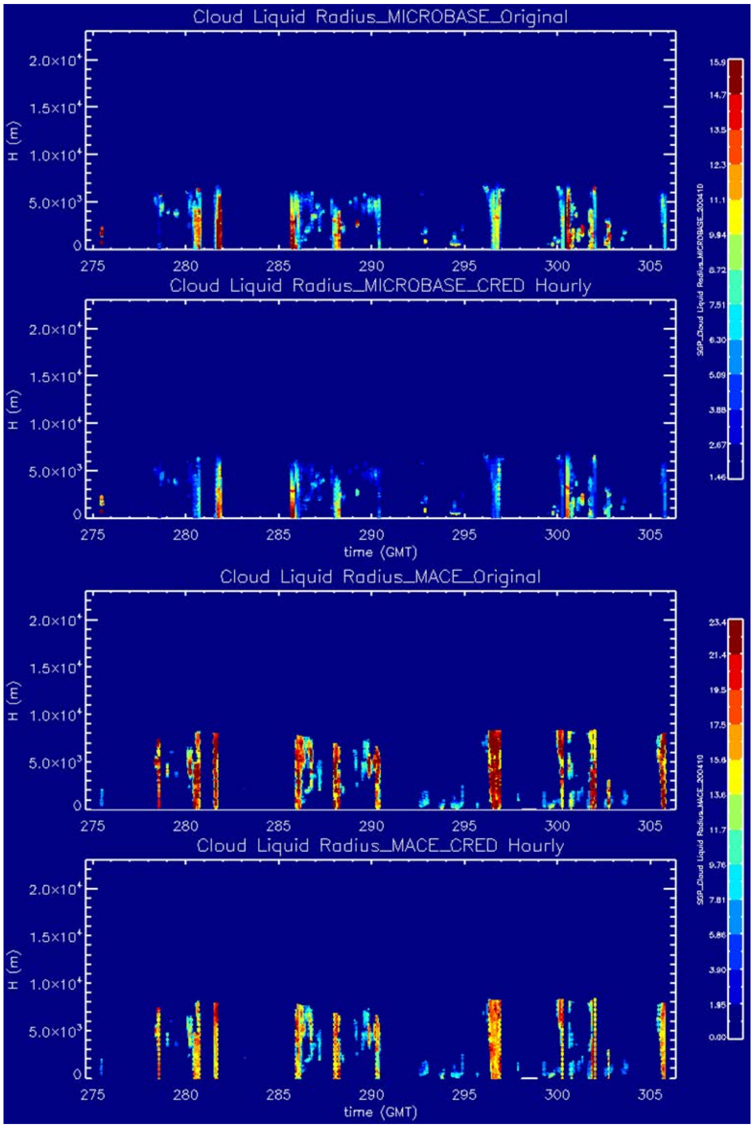


Figure 1. The contour image for cloud liquid effective radius from ACRED and original retrieval products as a function of time and height at SGP in October 2004.

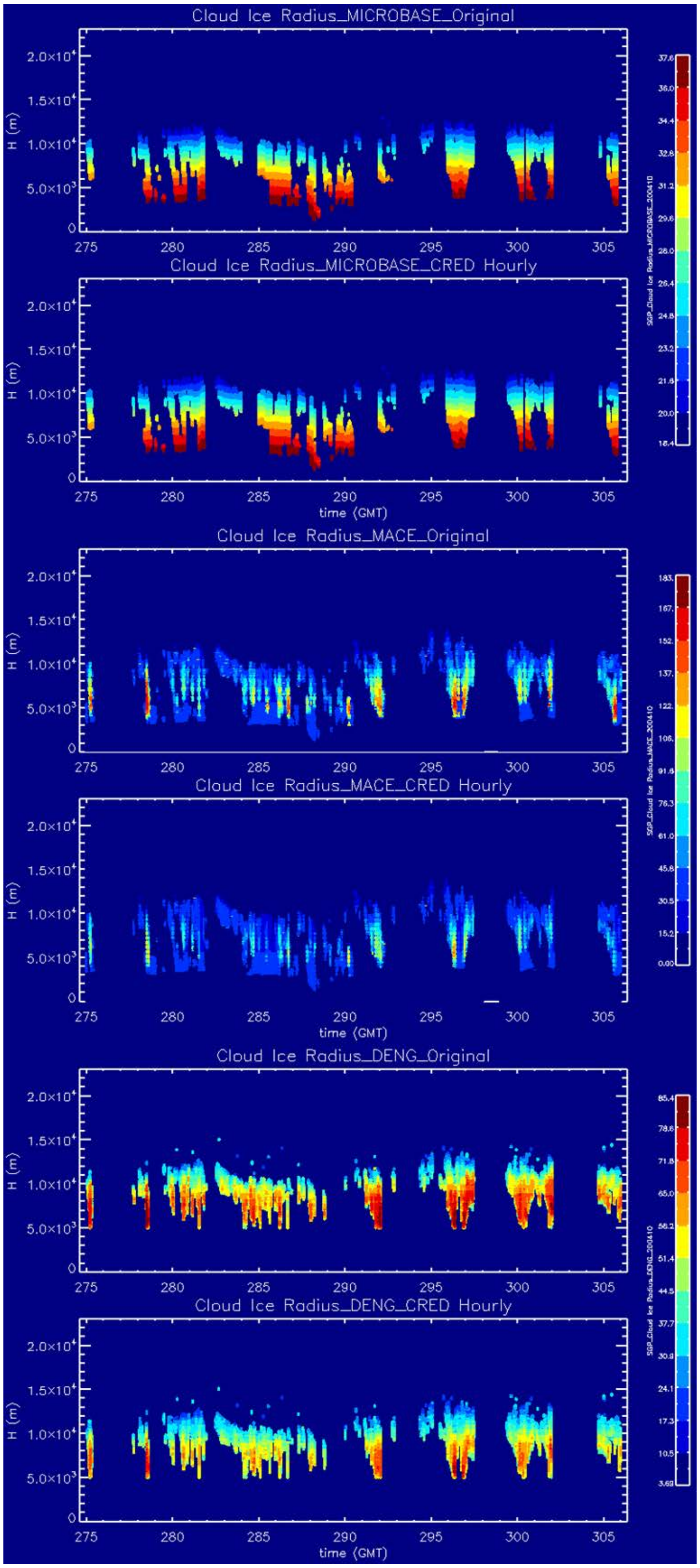


Figure 2. Same as Figure 1, but for cloud ice effective radius.

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