

# CloudSat Project

A NASA Earth System Science Pathfinder Mission

## **Level 2B Radar-only Cloud Water Content (2B-CWC-RO) Process Description and Interface Control Document**

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# 1 Introduction

The CloudSat Radar-Only Cloud Water Content (2B-CWC-RO) product provides estimates of vertical profiles of cloud liquid and ice water content, effective radius, and related quantities for each radar profile measured by CloudSat’s Cloud Profiling Radar (CPR) which, based on evaluation of the radar profile, appears to contain cloud. This radar-only product uses measured radar reflectivity factor (herein denoted equivalently as “reflectivity”) from the 2B-GEOPROF CloudSat product as the primary remote sensing input. Note that a related product (2B-CWC-RVOD) exists which uses visible optical depth in addition to radar reflectivity factor to constrain estimates of cloud properties.

The estimated properties are obtained from optimal estimation retrievals applied to the profiles of cloud-containing radar bins. Specifically, the optimal estimation algorithms retrieve profiles of cloud size distribution parameters using the reflectivity profile, ancillary meteorological information, and a priori information about cloud microphysical properties, radar scattering properties, and size distribution parameters. The retrieved size distribution parameter profiles and a priori information are used to calculate profiles of water contents and corresponding water paths. The optimal estimation method provides uncertainty estimates for the retrieved size distribution parameters, and these uncertainties are used to estimate uncertainties for the water contents and water paths.

Distinct retrievals are performed for the liquid- and ice-phase portions of cloudy profiles. Liquid and ice phases are distinguished using temperature profiles taken from ECMWF analysis products collocated with each radar profile and contained in the CloudSat ECMWF-AUX product. Temperature thresholds are used to separate portions of the profile which are liquid-only, ice-only, or mixed (liquid and ice). A liquid-phase retrieval is applied to the liquid-only and mixed portions of the profile, assuming all cloud is completely liquid. Next an ice-phase retrieval is applied to the ice-only and mixed portions of the profile, assuming all cloud is completely frozen. These two sets of retrieval results are then combined into a single composite profile. In the mixed portion of the profile, a temperature-based mixing rule is applied to combine the retrieved liquid- and ice-phase properties in a simple way that is reasonably consistent with the input measurements. While this approach results in a mixture of ice and liquid phases over that part of the vertical profile that has the specified temperature range, users should be aware that the retrieval does not attempt to retrieve mixed-phase cloud properties explicitly.

This document describes the algorithms that have been implemented in Release P1\_R05 of the 2B-CWC-RO product. For each radar profile, the algorithms will

- examine the cloud mask in 2B-GEOPROF to determine which bins in the column contain cloud;
- examine the 2B-CLDCLASS product to determine if any cloudy bins have an undetermined or invalid cloud type (indicating a problematic profile);
- assign *a priori* values to the liquid and ice particle size distribution parameters in each cloudy bin based on climatology, temperature, or other criteria;
- using the *a priori* values and radar measurements from 2B-GEOPROF, retrieve liquid and ice particle size distribution parameters for each cloudy bin;
- derive effective radius, water content, and related quantities from the retrieved size distributions for both liquid and ice phases, together with associated uncertainties;
- create a composite profile by using the retrieved ice properties at temperatures colder than  $-20^{\circ}\text{C}$ , the retrieved liquid properties at temperatures warmer than  $0^{\circ}\text{C}$ , and a linear combination of the two in intermediate temperatures; and
- for each of these estimates, calculate covariance matrices and uncertainties.

## 1.1 What’s New: Product Release History

Changes from Release P.R04 to Release P1\_R05 are described here. See Appendix A for a description of changes for earlier releases.

- An error related to the calculation of attenuation in the radar forward model for liquid-phase retrievals has been corrected.
- Ice-phase retrievals are now applied to only the ice-phase and mixed portions of the profile. Similarly, liquid-phase retrievals are now applied only to the liquid-phase and mixed portions of the profile. Previously, the ice-phase and liquid-phase retrievals were each applied to the full profile (ice-phase, liquid-phase and mixed portions), and this could lead to the forward model overestimating attenuation in the mixed and liquid-phase portions of the profile.

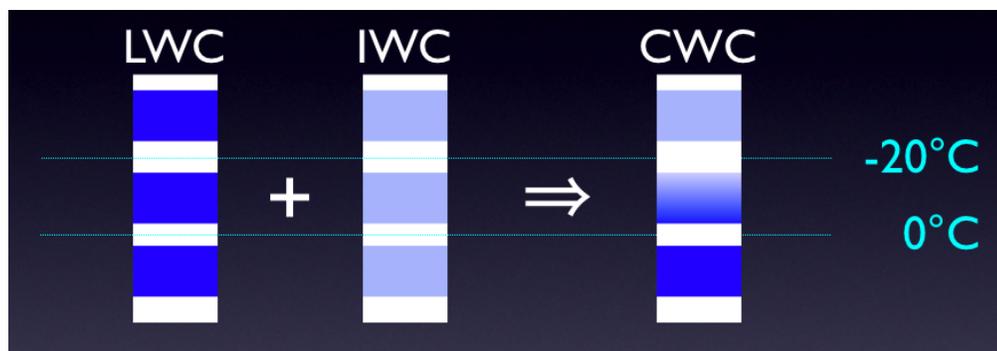


Figure 1: The CWC composite profile is built by combining the retrieved ice and liquid water profiles, according to temperature.

- Variables that provide the number of profiles (as counts and as fractions of the total number of profiles in the granule) that contain one, two, three, and more than three different cloud types as evaluated from 2B-CLDCLASS data are no longer included in the product output.
- An error in the flagging of profiles likely to contain precipitation (profiles with radar reflectivities larger than -15 dBZe) has been corrected.
- Corrections were made to properly store diagnostic values for ice number concentration and to properly calculate particle size distribution width parameter uncertainties.
- The model-measurement uncertainties used in the optimal estimation algorithms were improved and made more realistic. The radar minimum detectable signal value that is now available from 2B-GEOPROF (sem\_MDSignal) is used to calculate uncertainties in observed reflectivity and an uncertainty of 2 dBZ is applied to the radar forward model.
- Water contents and water paths are now stored as floating point values instead of as scaled integers. This change is to address user concerns about the limited precision of the data, an issue particularly significant when water contents and paths are small, and to resolve problems with overflow of values that were being stored as 16-bit integers in the previous product version.

## 2 Algorithm Theoretical Basis—Cloud Water Content

The original list of CloudSat standard data products included separate products for liquid water content and ice water content. Because there was no independent means of determining the cloud phase in any given radar resolution bin, the plan was to run the liquid and ice retrievals separately on the entire radar profile, resulting in a set of liquid microphysical parameters for each cloudy bin and a corresponding set of ice microphysical parameters for each cloudy bin. The user would then select which answer would be more appropriate or combine the two in some way. No attempt would be made to partition the measured reflectivity between the liquid and ice phases—each solution would assume the entire radar signal was due to a single phase of water.

As the retrievals were further developed and the time approached for the first post-launch data releases, it became clear that this approach would be overly confusing and would likely result in “double-counting” of the cloud water content: users interpreting each cloudy bin as containing *both* liquid and ice water content. To avoid this confusion, a new combined cloud water content product and algorithm were developed. In this combined algorithm, the liquid and ice retrievals are run separately, and the two resultant profiles are then combined into a composite profile using a simple scheme based on temperature. In this scheme, the portion of the profile colder than  $-20^{\circ}\text{C}$  is deemed pure ice, so the ice retrieval solution applies there. Similarly, the portion of the profile warmer than  $0^{\circ}\text{C}$  is considered pure liquid, so the liquid solution applies there. In between these temperatures, the ice and liquid solutions are scaled linearly with temperature (by adjusting the ice and liquid particle number concentrations) to obtain a profile that smoothly transitions from all ice at  $-20^{\circ}\text{C}$  to all liquid at  $0^{\circ}\text{C}$ .

This scheme gives a very basic partition of the radar measurements into ice and liquid phases. It is important to note that the partition algorithm is applied separately to the ice and liquid phases regardless of whether both retrievals were

successful. For example, if the liquid retrieval fails to converge, the ice water content will still be scaled such that it goes to zero as the temperature increases to 0°C—there is no attempt to map all the reflectivity to the ice phase to compensate for the failure of the liquid retrieval.

The 2B-CWC-RO data product files contain both the composite profiles (which most users will want to use) and the single-phase retrieval profiles (which may be of interest to some investigators). The fields representing the composite profiles have names beginning with `RO_liq_` and `RO_ice_`. Along with the composited results, the product provides a 16-bit status variable, `RO_CWC_status`; individual bits in this variable indicate error conditions in the ice and liquid retrievals and other associated conditions such as large values of the fit parameters or possible precipitation. The output data from the liquid cloud retrieval (hereafter, the liquid-only retrieval) are found in fields with names starting with `LO_RO_` (for “liquid-only” and “radar-only”). Corresponding outputs from the ice cloud retrieval (hereafter, the ice-only retrieval) have names starting with `IO_RO_`. The implementations of the liquid- and ice-only retrievals are described in sections 3 and 4. Details of the product contents are provided in section 7 and Appendix B.

### 3 Algorithm Theoretical Basis—Liquid-only retrieval

The liquid-only retrieval algorithm is an enhanced version of the radar-only method described in Austin and Stephens (2001, AS01). Among other differences, rather than treating the size distribution width and number concentration as fixed forward model parameters as was done in the AS01 radar-only formulation, this enhanced version includes them in the state variables to be retrieved and allows them to vary with height. The liquid-only retrieval is applied only to the liquid-containing portion of the profile (i.e., the portion diagnosed as containing liquid-phase or mixed cloud particles as described in section 2). This section provides condensed descriptions of the forward model and retrieval formulation as implemented in the operational CloudSat algorithm.

#### 3.1 Forward Model and Measurements

The retrieval uses active remote sensing data together with *a priori* data to estimate the parameters of the particle size distribution in each bin containing cloud. Radar measurements provide a vertical profile of radar reflectivity factor that results from cloud particle backscatter; the measured reflectivity values and a cloud mask (indicating the likelihood that a particular radar bin contains cloud) are obtained from 2B-GEOPROF.

##### 3.1.1 Physics of the Forward Model

The forward model developed for the retrieval assumes a lognormal size distribution of cloud droplets:

$$N(r) = \frac{N_T}{\sqrt{2\pi\omega r}} \exp\left[\frac{-\ln^2(r/r_g)}{2\omega^2}\right], \quad (1)$$

where  $N_T$  is the droplet number density,  $r$  is the droplet radius, and  $r_g$ ,  $\omega$ , and  $\sigma_g$  are defined by

$$\begin{aligned} \ln r_g &= \overline{\ln r}, \\ \omega &= \ln \sigma_g, \\ \sigma_g^2 &= \overline{(\ln r - \ln r_g)^2}, \end{aligned}$$

where  $r_g$  is the geometric mean radius,  $\omega$  is the distribution width parameter,  $\sigma_g$  is the geometric standard deviation,  $\ln$  indicates the natural (base  $e$ ) logarithm, and the overbar indicates the arithmetic mean. The distribution in (1) is fully specified by three parameters:  $N_T$ ,  $\omega$ , and  $r_g$ . The liquid water content LWC and the effective radius  $r_e$  are defined in terms of moments of the size distribution:

$$\text{LWC} = \int_0^\infty \rho_w N(r) \frac{4}{3} \pi r^3 dr, \quad (2)$$

$$r_e = \frac{\int_0^\infty N(r) r^3 dr}{\int_0^\infty N(r) r^2 dr}, \quad (3)$$

where  $\rho_w$  is the density of water.

For clouds having negligible drizzle or precipitation, cloud droplets are sufficiently small to be modeled as Rayleigh scatterers at the CloudSat radar wavelength and sufficiently large that their extinction efficiency approaches 2 for visible wavelengths. These assumptions yield the following definitions of radar reflectivity factor  $Z$  and visible extinction coefficient  $\sigma_{\text{ext}}$ :

$$Z = 64 \int_0^{\infty} N(r) r^6 dr, \quad (4)$$

$$\sigma_{\text{ext}} = 2 \int_0^{\infty} N(r) \pi r^2 dr. \quad (5)$$

Using (1) for the size distribution in (2) through (5) gives the following equations for the various cloud properties:

$$\text{LWC} = \frac{4\pi}{3} N_T \rho_w r_g^3 \exp\left(\frac{9}{2}\omega^2\right), \quad (6)$$

$$r_e = r_g \exp\left(\frac{5}{2}\omega^2\right), \quad (7)$$

$$Z = 64 N_T r_g^6 \exp(18\omega^2), \quad (8)$$

$$\sigma_{\text{ext}} = 2\pi N_T r_g^2 \exp(2\omega^2). \quad (9)$$

All of these properties are functions of position in the cloud column; we can therefore write  $\text{LWC}(z)$ ,  $r_e(z)$ ,  $Z(z)$ , and  $\sigma_{\text{ext}}(z)$ .

The visible optical depth  $\tau$  is calculated by integrating the visible extinction coefficient through the cloud column:

$$\tau = \int_{z_{\text{base}}}^{z_{\text{top}}} \sigma_{\text{ext}}(z) dz, \quad (10)$$

where  $z_{\text{base}}$  and  $z_{\text{top}}$  are the cloud base and top, respectively. Equations (6) through (10) express the intrinsic properties of the cloud as functions of the parameters of the assumed drop size distribution; they form the basis of the retrieval. LWC and  $r_e$  are the quantities we seek to retrieve, and values of  $Z$  are related to our measurements. We may also specify LWP, the columnar liquid water content or liquid water path,

$$\text{LWP} = \int_{z_{\text{base}}}^{z_{\text{top}}} \text{LWC}(z) dz. \quad (11)$$

The scattered energy received by the radar from particles at a given range will be attenuated in both directions by cloud particles between that range and the radar receiver. (It will also experience gaseous attenuation, primarily by water vapor; this attenuation is provided as a separate variable in the 2B-GEOPROF product and is therefore not considered here.) The measured reflectivity factor  $Z'$  will be reduced from the intrinsic reflectivity factor  $Z$  according to the following expression:

$$Z'(z) = Z(z) \exp\left[-2 \int_{\text{path}} \sigma_{\text{abs}}(z') dz'\right], \quad (12)$$

where the path integral is over the portion of the cloud between  $z$  and the radar. The absorption coefficient at the radar frequency  $\sigma_{\text{abs}}$  is given by

$$\sigma_{\text{abs}}(z) = \int_0^{\infty} N(r, z) C_{\text{abs}}(r) dr, \quad (13)$$

where  $N(r, z)$  is the particle size distribution at  $z$  and  $C_{\text{abs}}$  is the absorption cross section as a function of particle radius  $r$ . (Scattering effects are much smaller than absorption effects at the radar wavelength, so we approximate the attenuation as being purely due to absorption.)

Assuming the cloud droplets are approximately spherical, we may use Mie theory to obtain an expression for  $C_{\text{abs}}$ :

$$C_{\text{abs}} = \frac{8\pi^2 r^3}{\lambda} \text{Im}\{-K\}, \quad (14)$$

where  $\lambda$  is the radar wavelength and  $K$  is given by

$$K = \frac{m^2 - 1}{m^2 + 2}, \quad (15)$$

where  $m$  is the complex index of refraction of the droplet material (water) at the radar frequency and ambient temperature. Using the lognormal distribution in (1), the absorption coefficient in (13) becomes

$$\sigma_{\text{abs}} = \frac{8\pi^2 N_T}{\lambda} \text{Im}\{-K\} r_g^3 \exp\left(\frac{9}{2}\omega^2\right), \quad (16)$$

where the  $z$  dependence is suppressed for clarity.

Assuming that a lognormal distribution is appropriate, the cloud microphysics are fully described by specification of the three lognormal distribution parameters  $N_T(z)$ ,  $\omega(z)$ , and  $r_g(z)$ . Liquid water content and effective radius may then be obtained through (6) and (7). Because the measured data are limited to a single radar reflectivity factor  $Z'$  for each radar resolution bin, we rely on *a priori* data to constrain the retrieval where the measurements cannot, allowing the retrieved solution to be consistent with the measurements without imposing fixed values of, for example, particle number concentration through the cloud column. The optimal estimation technique employed in this retrieval is described in section 3.2.

### 3.1.2 Departures From the Lognormal Distribution

The retrieval assumes a lognormal distribution of liquid cloud droplets, as given in (1). Departures from this distribution will degrade the accuracy of the retrieval. One source of departure from this analytic distribution is the presence of drizzle or rain within the cloud. The retrieval examines the input reflectivity profile and assumes drizzle or rain is present if  $Z' \geq -15$  dBZ anywhere in the profile. This high-reflectivity condition is indicated in the output by setting a flag in the status variable, but the algorithm is still run as normal, producing output values unless the solution fails to converge to acceptable values. The flag serves as an indicator that the solution is likely unreliable due to a violation of the lognormal distribution assumption. In practice, the presence of significant precipitation causes the retrieval to fail to converge, resulting in an error condition.

### 3.1.3 Mixed phase and multi-layered clouds

As noted earlier, the liquid-only retrieval is applied only to the liquid-containing portion of the profile. Because CloudSat has no coincident measurements to determine the particle phase in a given radar bin, a simple partition scheme is employed to create a composite ice/liquid profile. The partition scheme is described in section 2.

## 3.2 Retrieval Algorithm

The liquid-only retrieval uses an approach described by Rodgers (1976, 1990, 2000) and Marks and Rodgers (1993), where a vector of measured quantities  $\mathbf{y}$  (here, radar reflectivities) is related to a state vector of unknowns  $\mathbf{x}$  (geometric mean radii, number density, and distribution width parameter) by the forward model  $\mathbf{F}$ :

$$\mathbf{y} = \mathbf{F}(\mathbf{x}) + \epsilon, \quad (17)$$

where  $\epsilon$  represents combined forward model and measurement uncertainties. Rodgers (1976) described an optimal-estimation technique in which *a priori* profiles are used as virtual measurements, serving as a constraint on the retrieval. An *a priori* profile  $\mathbf{x}_a$  is specified based on likely or statistical values of the state vector elements, together with an *a priori* covariance matrix  $\mathbf{S}_a$  representing the variability or uncertainty of this profile and the covariance between various profile elements.

The retrieval algorithm obtains the optimal solution by minimizing a cost function  $\Phi$  that represents a weighted sum of the measurement vector-forward model difference and the state vector-*a priori* difference:

$$\Phi = (\mathbf{x} - \mathbf{x}_a)^T \mathbf{S}_a^{-1} (\mathbf{x} - \mathbf{x}_a) + [\mathbf{y} - \mathbf{F}(\mathbf{x})]^T \mathbf{S}_\epsilon^{-1} [\mathbf{y} - \mathbf{F}(\mathbf{x})]. \quad (18)$$

where  $\mathbf{S}_\epsilon$  is the covariance matrix representing the uncertainties  $\epsilon$ . The solution  $\hat{\mathbf{x}}$  which minimizes the cost function is obtained by Newtonian iteration using successive estimates of the  $\mathbf{x}$  vector and the  $\mathbf{K}$  matrix ( $\mathbf{K} = \partial\mathbf{F}/\partial\mathbf{x}$ ). These quantities are also used to provide information on convergence, the quality of the solution, and the amounts and sources of retrieval uncertainty. The various input and output quantities are described here.

### 3.2.1 State and Measurement Vectors

The state vector  $\mathbf{x}$  is the vector of unknown cloud parameters to be retrieved. For a cloud reflectivity profile consisting of  $p$  cloudy bins, the state vector will have  $n = 3p$  elements:

$$\mathbf{x} = \begin{bmatrix} r_g(z_1) \\ \vdots \\ r_g(z_p) \\ N_T(z_1) \\ \vdots \\ N_T(z_p) \\ \omega(z_1) \\ \vdots \\ \omega(z_p) \end{bmatrix}, \quad (19)$$

where  $r_g(z_i)$ ,  $N_T(z_i)$ , and  $\omega(z_i)$  are the geometric mean radius, droplet number concentration, and distribution width parameter for height  $z_i$  (we shall often write these as  $r_{g_i}$ , etc.). Here  $z_1$  is the height of the radar resolution bin at cloud base;  $z_p$  is at the top of the cloud profile. Units are selected to keep the numerical values within similar orders of magnitude:  $\mu\text{m}$  for  $r_g$  and  $\text{cm}^{-3}$  for  $N_T$  ( $\omega$  is dimensionless).

The RO measurement vector  $\mathbf{y}$  is composed of  $m = p$  elements for a cloud profile of  $p$  cloudy bins:

$$\mathbf{y} = \begin{bmatrix} Z'_{\text{dB}}(z_1) \\ \vdots \\ Z'_{\text{dB}}(z_p) \end{bmatrix}, \quad (20)$$

where  $Z'_{\text{dB}}(z_i)$  is the measured radar reflectivity factor for height  $z_i$  (often written as  $Z'_{\text{dB}_i}$ ). Reflectivity factor  $Z$  is specified in units of  $\text{mm}^6 \text{m}^{-3}$ . To reduce the large dynamic range of the reflectivity variable and to make the model more linear,  $Z$  has been converted to a logarithmic variable  $Z_{\text{dB}}$  by the transform  $Z_{\text{dB}} = 10 \log Z$ , where  $Z_{\text{dB}}$  has units of dBZ and  $\log$  indicates the base 10 logarithm.

### 3.2.2 Forward Model and Parameters

The forward model  $\mathbf{F}(\mathbf{x})$  relates the state vector  $\mathbf{x}$  to the measurement vector  $\mathbf{y}$ .  $\mathbf{F}$  therefore has the same dimension as  $\mathbf{y}$ :

$$\mathbf{F}(\mathbf{x}) = \begin{bmatrix} Z'_{\text{dB}_{\text{FM}}}(z_1) \\ \vdots \\ Z'_{\text{dB}_{\text{FM}}}(z_p) \end{bmatrix}, \quad (21)$$

where the individual elements are given by the following expressions:

$$\begin{aligned} Z'_{\text{dB}_{\text{FM}}}(z_i) = & 10 \log \left\{ 64 N_T r_{g_i}^6 \exp(18\omega^2) \right. \\ & \times \exp \left[ \frac{-16\pi^2 N_T}{\lambda} \text{Im}\{-K\} \right. \\ & \left. \left. \times \exp \left( \frac{9}{2} \omega^2 \right) \Delta z \sum_{j=i+1}^p r_{g_j}^3 \right] \right\}, \quad i = 1, \dots, p-1 \end{aligned} \quad (22)$$

$$Z'_{\text{dB}_{\text{FM}}}(z_i) = 10 \log [64 N_T r_{g_i}^6 \exp(18\omega^2)], \quad i = p \quad (23)$$

where the symbol  $\Delta z$  represents the physical thickness of a radar range bin. The subscript FM is a reminder that these quantities are calculated from elements of  $\mathbf{x}$  according to the forward model equations (22) and (23), as opposed to the elements of the  $\mathbf{y}$  vector, which are measured quantities. The form of (22) and (23) assumes that the radar is above the cloud looking down; again,  $z_1$  is the lowest bin in the cloud and  $z_p$  is the highest.

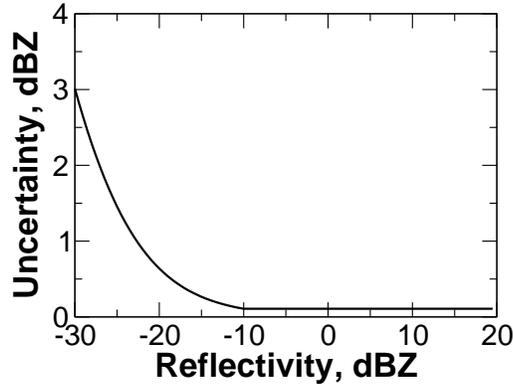


Figure 2: Example of the measurement uncertainty model for the CPR for a minimum detectable signal of -30 dBZ.

### 3.2.3 Forward model and measurement errors

The error covariance matrix  $\mathbf{S}_\epsilon$  describes the uncertainties associated with the model-measurement differences and is composed of two terms:

$$\mathbf{S}_\epsilon = \mathbf{S}_y + \mathbf{S}_F \quad (24)$$

where  $\mathbf{S}_y$  is the covariance matrix describing the measurement uncertainties and  $\mathbf{S}_F$  is the covariance matrix describing forward model uncertainties. For  $\mathbf{S}_y$ , the sources of measurement uncertainty include uncertainty in the absolute radiometric calibration of the radar and measurement noise. Calibration errors, which would result in a bias in the measured reflectivities, are expected to be less than 2 dB based on a prelaunch calibration error budget (Tanelli et al., 2008), but the value of this bias is unknown and is not considered. It is assumed that the measurement errors in distinct radar bins are uncorrelated, giving  $\mathbf{S}_y$  a diagonal form:

$$\mathbf{S}_y = \begin{bmatrix} \sigma_{Z'_{\text{dB}_1}}^2 & 0 & \cdots & 0 \\ 0 & \ddots & 0 & \vdots \\ \vdots & 0 & \ddots & 0 \\ 0 & \cdots & 0 & \sigma_{Z'_{\text{dB}_p}}^2 \end{bmatrix}, \quad (25)$$

where  $\sigma_{Z'_{\text{dB}_i}}$  is the standard deviation of the measured radar reflectivity factor in dBZ.

The noise characteristics of the CPR vary with signal strength. For reflectivities above -10 dBZ, one standard deviation of noise as a fraction of the mean signal is about -16 dB, while for reflectivities below -10 dBZ, noise is an increasing fraction of signal, reaching 0 dB (noise power = signal power) at the minimum detectable signal (R. Austin, personal communication, 4 November 2008). Figure 2 indicates the approximate uncertainties as a function of observed reflectivity and based on one standard deviation of noise at the minimum detectable signal. For the CPR, minimum detectable signal may vary with radar operating parameters and is recorded in the 2B-GEOPROF variable `sem.MDSignal`. The algorithm adjusts the uncertainty model for variations in `sem.MDSignal`.

Forward model uncertainties are taken to be uniform with a constant value of 2 dBZ in each radar bin. Although forward model errors likely contribute to covariances between the reflectivity uncertainties in distinct radar bins, such covariances are ignored, giving  $\mathbf{S}_F$  a simple diagonal form. Omitting such covariances, which are not well known, avoids introducing potentially spurious constraints on the retrieval and is expected to lead to conservative estimates for uncertainties in the retrieved state (e.g., L'Ecuyer et al., 2006).

### 3.2.4 A Priori Data and Covariance

*A priori* data for the retrieval are selected based on collections of microphysical measurements of related cloud types. Reference values for each of these categories are obtained from a database of cloud microphysical parameters (e.g., Miles et al. 2000). The selected values for each radar profile are included in the product output. The *a priori* vector  $\mathbf{x}_a$  is specified

as follows:

$$\mathbf{x}_a = \begin{bmatrix} r_{ga}(z_1) \\ \vdots \\ r_{ga}(z_p) \\ N_{Ta}(z_1) \\ \vdots \\ N_{Ta}(z_p) \\ \omega_a(z_1) \\ \vdots \\ \omega_a(z_p) \end{bmatrix}. \quad (26)$$

We also specify an *a priori* error covariance matrix  $\mathbf{S}_a$ :

$$\mathbf{S}_a = \begin{bmatrix} \sigma_{r_{ga_1}}^2 & 0 & \cdots & 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & \ddots & 0 & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & 0 & \sigma_{r_{ga_p}}^2 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & \cdots & 0 & \sigma_{N_{Ta_1}}^2 & 0 & \vdots & \vdots & \vdots & \vdots \\ \vdots & \cdots & \vdots & 0 & \ddots & 0 & \vdots & \vdots & \vdots \\ 0 & \cdots & 0 & \cdots & 0 & \sigma_{N_{Ta_p}}^2 & 0 & \vdots & \vdots \\ 0 & \cdots & 0 & \cdots & \cdots & 0 & \sigma_{\omega_{a_1}}^2 & 0 & \vdots \\ \vdots & \cdots & \vdots & \cdots & \cdots & \cdots & 0 & \ddots & 0 \\ 0 & \cdots & 0 & \cdots & \cdots & \cdots & \cdots & 0 & \sigma_{\omega_{a_p}}^2 \end{bmatrix}. \quad (27)$$

Adjustment of the *a priori* parameters  $\mathbf{x}_a$  and uncertainties  $\mathbf{S}_a$  in future versions may allow customization of the retrieval for different cloud types, generation regimes (e.g., continental or maritime), and geographic areas (tropical, mid-latitude, etc.).

### 3.2.5 Convergence and Quality Control

The state vector  $\hat{\mathbf{x}}$  is obtained by iteration. The *a priori* values  $\mathbf{x}_a$  are used as the initial value of  $\hat{\mathbf{x}}$ . Convergence of the solution is determined using a test with the following form:

$$\Delta\hat{\mathbf{x}}^T \mathbf{S}_x^{-1} \Delta\hat{\mathbf{x}} \ll n, \quad (28)$$

where  $n$  is the dimension of the  $\hat{\mathbf{x}}$  vector, i.e. the number of cloudy radar bins times three. The error covariance matrix  $\mathbf{S}_x$  of the retrieved state vector  $\hat{\mathbf{x}}$  is given by

$$\mathbf{S}_x = (\mathbf{S}_a^{-1} + \mathbf{K}^T \mathbf{S}_y^{-1} \mathbf{K})^{-1}. \quad (29)$$

Elements of the  $\mathbf{S}_x$  matrix give the covariance between elements of the retrieved state vector  $\hat{\mathbf{x}}$ ; diagonal elements of  $\mathbf{S}_x$  are variances in the elements of  $\hat{\mathbf{x}}$  and give a measure of the uncertainty in the retrieval. For this retrieval, we specify the criterion for “much less than” in (28) such that

$$\Delta\hat{\mathbf{x}}^T \mathbf{S}_x^{-1} \Delta\hat{\mathbf{x}} < 0.01n. \quad (30)$$

After the iteration converges, we seek a test that shows the goodness of fit of the retrieved values to the measurements. Using the hypothesis that the fit to the measurements (including the *a priori* virtual measurements) is consistent with the measurement uncertainties (including the *a priori* uncertainties), Marks and Rodgers (1993) used the following  $\chi^2$ :

$$\chi^2 = [\mathbf{y} - \mathbf{F}(\hat{\mathbf{x}})]^T \mathbf{S}_y^{-1} [\mathbf{y} - \mathbf{F}(\hat{\mathbf{x}})] + (\mathbf{x}_a - \hat{\mathbf{x}})^T \mathbf{S}_a^{-1} (\mathbf{x}_a - \hat{\mathbf{x}}). \quad (31)$$

This quantity should follow a  $\chi^2$  distribution with  $m$  degrees of freedom ( $n$  parameters fitted to  $m + n$  measurements, where  $n$  and  $m$  are the dimensions of the  $\hat{\mathbf{x}}$  and  $\mathbf{y}$  vectors, respectively). Marks and Rodgers (1993) noted that a typical value of  $\chi^2$  for a “moderately good retrieval” is  $m$ .

As currently implemented, the retrieval rejects profiles where any element of the  $\hat{\mathbf{x}}$  vector becomes negative during any iteration. (This is infrequent.) Profiles are also rejected if the measured reflectivity factor exceeds a specified maximum level (i.e., it is unphysical) or if the necessary inputs are unavailable.

## 4 Algorithm Theoretical Basis—Ice-only retrieval

The details of the ice-only retrieval algorithm are described in Austin et al. (2009); an earlier version with somewhat different capabilities is described by Benedetti et al. (2003). The ice-only retrieval is applied only to the ice-containing portion of the profile (i.e., the portion diagnosed as containing ice-phase or mixed cloud particles as described in section 2). This section provides condensed descriptions of the forward model and retrieval formulation as implemented in the operational CloudSat algorithm.

### 4.1 Forward Model and Measurements

Like the liquid-only retrieval, this retrieval uses active remote sensing data together with *a priori* data to estimate the parameters of the particle size distribution in each bin containing cloud. Radar measurements provide a vertical profile of radar reflectivity factor that results from cloud backscatter; the measured reflectivity values and a cloud mask (indicating the likelihood that a particular radar bin contains cloud) are obtained from 2B-GEOPROF.

#### 4.1.1 Physics of the Forward Model

The forward model developed for the retrieval assumes a lognormal size distribution of ice crystals:

$$N(D) = \frac{N_T}{\sqrt{2\pi\omega D}} \exp\left[\frac{-\ln^2(D/D_g)}{2\omega^2}\right], \quad (32)$$

where  $N_T$  is the ice particle number concentration,  $D$  is the diameter of an equivalent mass ice sphere,  $D_g$  is the geometric mean diameter, and  $\omega$  is the width parameter. The distribution in (32) is fully specified by three parameters:  $N_T$ ,  $D_g$ , and  $\omega$ . The ice water content (IWC) and the effective radius  $r_e$  are defined in terms of moments of the size distribution:

$$\text{IWC} = \int_0^\infty \rho_i \frac{\pi}{6} N(D) D^3 dD \quad (33)$$

$$r_e = \frac{1}{2} \frac{\int_0^\infty N(D) D^3 dD}{\int_0^\infty N(D) D^2 dD}, \quad (34)$$

where  $\rho_i$  is the density of ice.

For thin ice clouds, the cloud ice particles are sufficiently small to be modeled as Rayleigh scatterers at the CloudSat radar wavelength and sufficiently large that their extinction efficiency approaches 2 for visible wavelengths. Because ice particle attenuation is generally small at W-band for typical cloud ice water paths, ice particle attenuation effects are neglected. These assumptions yield the following definitions of radar reflectivity factor  $Z$  and visible extinction coefficient  $\sigma_{\text{ext}}$ :

$$Z_{\text{Ray}} = \int_0^\infty N(D) D^6 dD \quad (35)$$

$$\sigma_{\text{ext}} = 2 \int_0^\infty N(D) \frac{\pi}{4} D^2 dD \quad (36)$$

Using (32) for the size distribution in (33) through (36) gives the following equations for the various cloud properties:

$$\text{IWC} = \rho_i \frac{\pi}{6} N_T D_g^3 \exp\left(\frac{9}{2}\omega^2\right) 10^{-3} \quad (37)$$

$$r_e = \frac{1}{2} D_g \exp\left(\frac{5}{2}\omega^2\right) 10^3 \quad (38)$$

$$\sigma_{\text{ext}} = \frac{\pi}{2} N_T D_g^2 \exp(2\omega^2) 10^{-3} \quad (39)$$

$$Z_{\text{Ray}} = N_T D_g^6 \exp(18\omega^2), \quad (40)$$

All of these properties are functions of position in the cloud column; we can therefore write  $\text{IWC}(z)$ ,  $r_e(z)$ ,  $\sigma_{\text{ext}}(z)$ , and  $Z_{\text{Ray}}(z)$ .

The visible optical depth  $\tau$  is calculated by integrating the visible extinction coefficient through the cloud column:

$$\tau = \int_{z_{\text{base}}}^{z_{\text{top}}} \sigma_{\text{ext}}(z) dz, \quad (41)$$

where  $z_{\text{base}}$  and  $z_{\text{top}}$  are the cloud base and top, respectively. Equations (37) through (41) express the intrinsic properties of the cloud as functions of the parameters of the assumed particle size distribution; they form the basis of the retrieval. The parameters IWC and  $r_e$  are the quantities we seek to retrieve, and values of  $Z$  are related to our measurements. We may also specify the columnar ice water content or ice water path (IWP),

$$\text{IWP} = \int_{z_{\text{base}}}^{z_{\text{top}}} \text{IWC}(z) dz. \quad (42)$$

The three parameters  $N_T(z)$ ,  $D_g(z)$ , and  $\omega(z)$  fully define the size distribution. Ice water content and effective radius may then be obtained through (37) and (38). Because the measured data are limited to a single radar reflectivity factor  $Z'$  for each radar resolution bin, we rely on *a priori* data to constrain the retrieval where the measurements cannot, allowing the retrieved solution to be consistent with the measurements without imposing fixed values of, for example, particle number concentration through the cloud column. The optimal estimation technique employed in this retrieval is described in section 4.2.

#### 4.1.2 Algorithm refinements: correction for Lorenz-Mie effects

At frequencies of radars commonly used for cirrus cloud detection (35 or 94 GHz), the size parameter (the ratio between the diameter of the particle  $D$  and the radar wavelength  $\lambda$ ) remains smaller than unity for crystal sizes up to 100  $\mu\text{m}$  (and even larger for 35 GHz). Therefore, the Rayleigh approximation is almost always satisfied at these frequencies. However, because radar reflectivity in the Rayleigh regime is a function of the *sixth* power of the particle's equivalent mass sphere diameter, the error introduced by use of the Rayleigh approximation on the large crystals that violate the Rayleigh criterion may be significant, even if these coarser particles are few in number. To quantify this error, we performed Lorenz-Mie calculations and parameterized the ratio of the (exact) Lorenz-Mie radar reflectivity to the (approximate) Rayleigh reflectivity in terms of the size distribution parameters. Starting from the most general form of the radar equation, we have

$$\frac{P_r}{P_t} = \frac{\tilde{C}\lambda^2}{R^2} \int n(D)C_b(D)dD, \quad (43)$$

where  $\tilde{C}$  is the generalized radar constant and  $C_b(D)$  is the *backscattering* coefficient. In the Rayleigh limit,  $C_b(D)$  takes the form

$$C_b(D) = \frac{\pi^5}{\lambda^4} |K|^2 D^6, \quad (44)$$

where  $K$  is given by

$$K = \frac{m^2 - 1}{m^2 + 2}, \quad (45)$$

where  $m$  is the complex index of refraction of the particle material (water ice) at the radar frequency and ambient temperature. The dependence on the sixth power of the diameter in the radar reflectivity definition derives from (44).

The Lorenz-Mie theory provides an exact expression for  $C_b$  for homogeneous spheres that can be used instead of (44) to define an equivalent ‘‘Mie’’ radar reflectivity,  $Z_{\text{Mie}}$ . We computed  $Z_{\text{Mie}}$  using a code provided by Bohren and Huffman (1983) and plotted the ratio of  $Z_{\text{Mie}}$  and  $Z_{\text{Ray}}$  as a function of the distribution parameters  $D_g$  and  $\omega$ . At small particle sizes, the ratio is unity, indicating that the Rayleigh approximation is valid. For larger sizes, the two quantities begin to diverge, but the shape of the ratio function is well fitted by the following combination of Gaussian functions:

$$f_{\text{Mie}}(D_g, \omega) = \frac{Z_{\text{Mie}}}{Z_{\text{Ray}}} = A_0 \exp \left[ -\frac{1}{2} \left( \frac{D_g}{A_1} \right)^2 \right] + A_2 \quad (46)$$

where

$$A_0 = a_{01} + a_{02} \exp \left[ -\frac{1}{2} \left( \frac{\omega - 1}{a_{03}} \right)^2 \right] \quad (47)$$

$$A_1 = a_{11}(\omega - 1)^2 + a_{12} \quad (48)$$

$$A_2 = a_{21}(\omega - 1)^2 \quad (49)$$

where  $a_{01}$ ,  $a_{02}$ ,  $a_{03}$ ,  $a_{11}$ ,  $a_{12}$ , and  $a_{21}$  are specific coefficients of the fit. The expression  $f_{\text{Mie}}$  derived to account for the Lorenz-Mie effects has analytical properties and is differentiable, as is the radar forward model of (40). The new forward model can be written as

$$Z = Z_{\text{Ray}} f_{\text{Mie}}(D_g, \omega). \quad (50)$$

#### 4.1.3 Further possible algorithm refinements: correction for density effects

Radar reflectivity is conventionally defined with respect to water  $Z_e$ , even when the radar target is known to be a volume of ice particles. To transform the ice quantities into equivalent radar reflectivity with respect to water, a constant correction factor defined as the ratio of  $K_{ice}$  and  $K$  is introduced, where these constants are proportional to the refractive index. In so doing, an implicit assumption is also made that the density of ice crystals is constant. The refractive index from porous ice particles such as large snow flakes/aggregates is generally considered to be some mixture of ice and air and is thus reduced in value from that of solid ice. Future versions of the retrieval could attempt to treat the effects of porosity by making  $K_{ice}$  a function of density. [Matrosov (1999) discusses this problem in great detail.] In the current version of the algorithm, no density correction is implemented. The equivalent reflectivity factor is thus written

$$Z_e = Z_{\text{Ray}} f_{\text{Mie}}(D_g, \omega) \tilde{K} \quad (51)$$

where  $\tilde{K} = 0.232$  is a fixed correction factor (Stephens 1994).

#### 4.1.4 Departures from the Lognormal Distribution

The retrieval assumes a lognormal distribution of ice particles, as given in (32). Departures from this distribution will degrade the accuracy of the retrieval. One source of departure from this analytic distribution is the presence of large particles within the cloud, which may introduce a bimodality in the particle spectra (e.g., in thick anvil cirrus) and contribute to large reflectivities. Reflectivities greater than  $-15$  dBZ are indicated in the output by setting a flag in the status variable; however, the algorithm is still run as normal, producing output values unless the retrieval fails to converge to acceptable values. The flag serves as an indicator that the solution is likely unreliable due to a violation of the lognormal distribution assumption.

#### 4.1.5 Mixed phase and multi-layered clouds

As noted earlier, the ice-only retrieval algorithm is applied only to the ice-containing portion of the profile. Because CloudSat has no coincident measurements to determine the particle phase in a given radar bin, a simple partition scheme is employed to create a composite ice/liquid profile. The partition scheme is described in section 2.

## 4.2 Retrieval Algorithm

The ice-only retrieval uses the same optimal estimation framework used by the liquid-only retrieval as described in section 3.2. The various input and output quantities are described here; see Austin et al. (2009) and Benedetti et al. (2003) for a more detailed description.

### 4.2.1 State and Measurement Vectors

The state vector  $\mathbf{x}$  is the vector of unknown cloud parameters to be retrieved. To ensure positivity of the retrieved quantities, the retrieval is formulated in logarithmic form for some of the unknowns following Fujita and Satoka (1997). For a cloud reflectivity profile consisting of  $p$  cloudy bins, the state vector will have  $n = 3p$  elements:

$$\mathbf{x} = \begin{bmatrix} \log_{10} D_g(z_1) \\ \vdots \\ \log_{10} D_g(z_p) \\ \log_{10} N_T(z_1) \\ \vdots \\ \log_{10} N_T(z_p) \\ \omega(z_1) \\ \vdots \\ \omega(z_p) \end{bmatrix}, \quad (52)$$

where  $D_g(z_i)$ ,  $N_T(z_i)$ , and  $\omega(z_i)$  are the geometric mean diameter, number concentration, and distribution width parameter for height  $z_i$  (we shall often write these as  $D_{g_i}$ , etc.). Here  $z_1$  is the height of the radar resolution bin at cloud base;  $z_p$  is at the top of the cloud profile. The units of  $D_g$  are mm and the units of  $N_T$  are  $\text{m}^{-3}$ ;  $\omega$  is dimensionless.

The measurement vector  $\mathbf{y}$  is identical in structure to that used in the liquid-only retrieval, composed of  $m = p$  elements for a cloud profile of  $p$  cloudy bins:

$$\mathbf{y} = \begin{bmatrix} Z'_{\text{dB}}(z_1) \\ \vdots \\ Z'_{\text{dB}}(z_p) \end{bmatrix}, \quad (53)$$

where  $Z'_{\text{dB}}(z_i)$  is the measured radar reflectivity for height  $z_i$  (often written as  $Z'_{\text{dB}_i}$ ). Reflectivity is specified in units of  $\text{mm}^6 \text{m}^{-3}$ . To reduce the large dynamic range of the reflectivity variable and to make the model more linear,  $Z$  has been converted to a logarithmic variable  $Z_{\text{dB}}$  by the transform  $Z_{\text{dB}} = 10 \log Z$ , where  $Z_{\text{dB}}$  has units of dBZ and  $\log$  indicates the base 10 logarithm.

#### 4.2.2 Forward Model and Parameters

The forward model  $\mathbf{F}(\mathbf{x})$  relates the state vector  $\mathbf{x}$  to the measurement vector  $\mathbf{y}$ .  $\mathbf{F}$  therefore has the same dimension as  $\mathbf{y}$ :

$$\mathbf{F}(\mathbf{x}) = \begin{bmatrix} Z'_{\text{dB}_{\text{FM}}}(z_1) \\ \vdots \\ Z'_{\text{dB}_{\text{FM}}}(z_p) \end{bmatrix}, \quad (54)$$

where the individual elements are given by the following expression:

$$Z'_{\text{dB}_{\text{FM}}}(z_i) = 10 \log[N_T D_g^6 \exp(18\omega^2) f_{\text{Mie}}(D_g, \omega) \tilde{K}], \quad i = 1, \dots, p \quad (55)$$

where the symbol  $\Delta z$  represents the physical thickness of the radar range bins. The subscript FM is a reminder that these quantities are calculated from elements of  $\mathbf{x}$  according to the forward model equation (55), as opposed to the elements of the  $\mathbf{y}$  vector, which are measured quantities.

#### 4.2.3 Forward model and measurement errors

As was true for the liquid-only retrieval, the error covariance matrix  $\mathbf{S}_e$  describes the uncertainties associated with the model-measurement differences. Measurement uncertainties are formulated the same as was described for the liquid-only retrieval, and forward model uncertainties are set to the same 2 dBZ value. The resulting error covariance matrix is the same as described in section 3.2.3.

#### 4.2.4 A Priori Data and Covariance

*A priori* data values for the ice-only retrieval are selected in two ways. Values of  $D_g$  and  $\omega$  are determined using temperature-based parameterizations constructed from collections of ice particle size distribution measurements from aircraft flights during recent field campaigns (Austin et al., 2009). The values therefore vary through the cloud profile according to the temperature indicated by the CloudSat ECMWF-AUX data product. A different procedure was used to set the *a priori*  $N_T$  value. Rather than using a temperature-based value for this parameter, it was recognized that reflectivity values measured by CloudSat are sometimes very different from those predicted by the *a priori* database, even after taking temperature into account. In these cases, the number concentration parameter seemed the logical parameter to account for most of the difference. It was therefore deemed necessary to find a way to obtain a value of  $N_T$  that would be “closer” in state space to the set of values consistent with a given measurement. This was accomplished by combining (33), (40), and (51) and solving for  $N_T$ . The value of IWC was determined independently from  $Z_e$  using a  $Z$ -IWC relation from Liu and Illingworth (2000). Values of  $N_T$  were obtained for each cloudy bin and then averaged through the profile to obtain a single profile value of  $N_{T_a}$ , which was then used in the retrieval process. Uncertainties in all three parameters were then calculated using the values obtained from the aircraft measurement database.

The *a priori* vector  $\mathbf{x}_a$  for the ice-only retrieval is specified as follows:

$$\mathbf{x}_a = \begin{bmatrix} \log_{10} D_{ga}(z_1) \\ \vdots \\ \log_{10} D_{ga}(z_p) \\ \log_{10} N_{Ta}(z_1) \\ \vdots \\ \log_{10} N_{Ta}(z_p) \\ \omega_a(z_1) \\ \vdots \\ \omega_a(z_p) \end{bmatrix}. \quad (56)$$

We also specify an *a priori* error covariance matrix  $\mathbf{S}_a$ :

$$\mathbf{S}_a = \begin{bmatrix} \sigma_{\log_{10} D_{ga_1}}^2 & 0 & \cdots & 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & \ddots & 0 & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & 0 & \sigma_{\log_{10} D_{ga_p}}^2 & 0 & \cdots & 0 & 0 & \cdots & 0 \\ 0 & \cdots & 0 & \sigma_{\log_{10} N_{Ta_1}}^2 & 0 & \vdots & \vdots & \vdots & \vdots \\ \vdots & \cdots & \vdots & 0 & \ddots & 0 & \vdots & \vdots & \vdots \\ 0 & \cdots & 0 & \cdots & 0 & \sigma_{\log_{10} N_{Ta_p}}^2 & 0 & \vdots & \vdots \\ 0 & \cdots & 0 & \cdots & \cdots & 0 & \sigma_{\omega_{a_1}}^2 & 0 & \vdots \\ \vdots & \cdots & \vdots & \cdots & \cdots & \cdots & 0 & \ddots & 0 \\ 0 & \cdots & 0 & \cdots & \cdots & \cdots & \cdots & 0 & \sigma_{\omega_{a_p}}^2 \end{bmatrix}. \quad (57)$$

#### 4.2.5 Convergence and Quality Control

Convergence criteria for the ice-only retrieval are identical to those used for the liquid-only retrieval (see section 3.2.5). The goodness-of-fit statistic is likewise identical.

## 5 Algorithm Inputs

Table 1 summarizes all variables used as inputs to the 2B-CWC-RO product algorithm. A number of these, principally related to data quality, geolocation, and radar health, are simply passed through from 2B-GEOPROF into the 2B-CWC-RO product. Of the quantities used directly in the algorithm computations, 2B-GEOPROF provides the principal inputs. The retrievals use the radar reflectivity, the cloud mask, and the gaseous attenuation values from this product. For cases where this input is missing, 2B-CWC-RO will have no output. For 2B-CLDCLASS, various bits in the cloud\_scenario variable are used to detect cloud type and to screen problematic profiles. Future versions of the retrievals may use the indicated cloud type, surface type, and other flags to refine the retrieval algorithm, for example by selecting different *a priori* values according to cloud type. From ECMWF-AUX, which takes ECMWF analysis products and interpolates the variables to the CloudSat data grid, the algorithm uses the temperature profiles. This temperature information is used to assign *a priori* values in the ice-only retrieval, to diagnose the liquid-containing and ice-containing portions of the profile, and also to guide the combination of the separately retrieved ice and liquid cloud properties into the composite profiles.

Table 1: 2B-CWC-RO inputs.

Source	Name	Dimension	Units
2B-GEOPROF	Vertical_binsize	scalar	m
“	TAI_start	scalar	seconds
“	UTC_start	scalar	seconds
“	Pitch_offset	scalar	degrees
“	Roll_offset	scalar	degrees
“	Data_quality	Nray	–
“	Data_status	Nray	–
“	Data_targetID	Nray	–
“	RayStatus_validity	Nray	–
“	Navigation_land_sea_flag	Nray	–
“	Profile_time	Nray	seconds
“	Range_to_intercept	Nray	km
“	Latitude	Nray	degrees
“	Longitude	Nray	degrees
“	sem_MDSignal	Nray	dBZe
“	DEM_elevation	Nray	m
“	SurfaceHeightBin	Nray	–
“	Height	$N_{bin}, N_{ray}$	m
“	CPR_Cloud_mask	$N_{bin}, N_{ray}$	–
“	Gaseous_Attenuation	$N_{bin}, N_{ray}$	dB
“	Radar_Reflectivity	$N_{bin}, N_{ray}$	dBZe
2B-CLDCLASS	cloud_scenario	$N_{bin}, N_{ray}$	–
ECMWF-AUX	Temperature	$N_{bin}, N_{ray}$	K

## 6 Algorithm Summary

The algorithm is implemented in Fortran 90. The following is a pseudocode description of the algorithm implementation:

**start** 2B-LWC-RO

**get** orbit of 2B-GEOPROF data (CPR cloud mask, radar reflectivity)

**get** orbit of 2B-CLDCLASS data (cloud scenario)

**get** orbit of ECMWF-AUX data (temperature)

**for-each** 2B-GEOPROF vertical profile

**convert** bit flags to integer values

**determine** if liquid-only retrieval will be run (known & valid cloud scenario, cloud present,  $Z$  physical)

**if** running liquid-only retrieval

**determine** size of state vector

**assign** *a priori*  $r_g$ ,  $N_T$ , and  $\omega$  values and uncertainties

**set**  $y$  vector (2B-GEOPROF) using condensed profile retaining liquid-phase and mixed cloudy bins only

**set**  $S_a$ ,  $S_a^{-1}$ ,  $S_\epsilon$  matrices

**repeat**

**calculate**  $K$ ,  $D_y$  matrices

**calculate**  $F$  (forward-model) vector

**calculate**  $S_\epsilon^{-1}$ ,  $S_x^{-1}$ ,  $S_x$  matrices

**calculate** new state vector  $\hat{x}$

**if**  $\hat{x}$  goes negative, reject

```

        calculate  $\Delta\hat{x}$ , convergence test
        if more than 15 iterations, reject
    end-repeat until convergetest < 0.01n
    calculate  $r_e$ , LWC, LWP
    calculate  $\chi^2$  and A
    calculate retrieval uncertainties
    calculate output percent uncertainties
    load output variables
else
    ; RO liquid-only retrieval not run
    load output variables with error values and set status flags
end-if (running liquid-only retrieval)
end-for (loop over profiles)
calculate metadata statistics
end 2B-LWC-RO
start 2B-IWC-RO
get orbit of 2B-GEOPROF data (CPR cloud mask, radar reflectivity)
get orbit of 2B-CLDCLASS data (cloud scenario)
get orbit of ECMWF-AUX data (temperature)
for-each 2B-GEOPROF vertical profile
    convert bit flags to integer values
    determine if ice-only retrieval will be run (known & valid cloud scenario, cloud present, Z physical)
    if running ice-only retrieval
        determine size of state vector
        assign a priori  $D_g$ ,  $N_T$ , and  $\omega$  values and uncertainties
        set y vector (2B-GEOPROF) using condensed profile retaining ice-phase and mixed cloudy bins only
        set  $S_a$ ,  $S_a^{-1}$ ,  $S_\epsilon$  matrices
        repeat
            calculate K,  $D_y$  matrices
            calculate F (forward-model) vector
            calculate  $S_\epsilon^{-1}$ ,  $S_x^{-1}$ ,  $S_x$  matrices
            calculate new state vector  $\hat{x}$ 
            calculate  $\Delta\hat{x}$ , convergence test
            if more than 15 iterations, reject
        end-repeat until convergetest < 0.01n
        calculate  $r_e$ , IWC, IWP
        calculate  $\chi^2$  and A
        calculate retrieval uncertainties
        calculate output percent uncertainties
        load output variables
    else
        ; RO ice-only retrieval not run

```

**load** output variables with error values and set status flags  
**end-if** (running ice-only retrieval)  
**end-for** (loop over profiles)  
**calculate** metadata statistics  
**end** 2B-IWC-RO  
**start** 2B-CWC-RO  
**get** orbit of 2B-GEOPROF data  
**get** orbit of 2B-LWC-RO data  
**get** orbit of 2B-IWC-RO data  
**get** orbit of ECMWF-AUX data  
**calculate** ice phase fraction from temperature for all cloudy bins  
**calculate** liquid phase fraction from temperature for all cloudy bins  
**map** liquid properties into composite profiles, scaling properties by liquid phase fraction  
**map** ice properties into composite profiles, scaling properties by ice phase fraction  
**calculate** revised ice and liquid water path from composite profiles  
**copy** error fill values into composite profiles  
**add** error codes for other error conditions  
**set** flags in status variable  
**write** metadata statistics to text file  
**end** 2B-CWC-RO

## 7 Data Product Output Format

The 2B-CWC-RO data product includes swath data and metadata in an HDF-EOS formatted file. Descriptions of output variables are provided in Appendix B. Scale factors used in converting file values into science data values are included in the file as HDF variable attributes. Users are encouraged to read scale factors directly from the file rather than from written documentation because the scale factors may change.

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# Appendices

## A Change history for prior product releases

### A.1 Release P\_R03 to release P\_R04

Changes from release P\_R03 to P\_R04 include:

- The scale factors for several variables in the HDF product granule files have been changed.
- For the liquid water content retrieval and product variables
  - Number concentration and width parameter have been allowed to vary with height.
- For the ice water content retrieval and product variables
  - The assumed size distribution has been changed from modified gamma to lognormal.
  - Number concentration and width parameter have been allowed to vary with height.
  - *A priori* values are now selected based on temperature-.
  - Cloudy bins warmer than +1°C are omitted from the retrieval (because no *a priori* data apply).
  - The parameterization of the  $f_{Mie}$  ratio was changed.
- For the combined water content product variables
  - Profiles of all three size distribution parameters are reported for both ice and liquid.

## B Output variables

### B.1 Compositing retrieval

#### Cloud properties

Name: RO\_ice\_distrib\_width\_param  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units: –

Retrieved ice particle size distribution width parameter,  $\omega$ , obtained for ice-containing radar bins from the ice-only retrieval.

Fill values:

0.0: Clear column (2B-GEOPROF)  
 -3.333: Solution negative (2B-IWC-RO)  
 -4.444: Solution diverged (2B-IWC-RO)  
 -7.777: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 -8.888: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)  
 -9.999: Bad or missing temperature (ECMWF-AUX)

Name: RO\_ice\_distrib\_width\_param\_uncertainty  
 Variable Type: UINT(1)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units: %

Fractional uncertainty in RO\_ice\_distrib\_width\_param, expressed in percent and rounded to the nearest integer. A value of 250 indicates an uncertainty  $\geq 250\%$ .

Fill values:

0: Clear column (2B-GEOPROF)  
 253: Solution negative (2B-IWC-RO)  
 253: Solution diverged (2B-IWC-RO)  
 253: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 254: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)  
 253: Bad or missing temperature (ECMWF-AUX)

Name: RO\_ice\_effective\_radius  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units:  $\mu\text{m}$

Retrieved ice particle size distribution effective radius,  $r_e$ , obtained for ice-containing radar bins from the ice-only retrieval.

Fill values:

0.0: Clear column (2B-GEOPROF)  
 -333.3: Solution negative (2B-IWC-RO)  
 -444.4: Solution diverged (2B-IWC-RO)  
 -777.7: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 -888.8: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)  
 -999.9: Bad or missing temperature (ECMWF-AUX)

Name: RO\_ice\_effective\_radius\_uncertainty  
 Variable Type: UINT(1)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units: %

Fractional uncertainty in RO\_ice\_effective\_radius, expressed in percent and rounded to the nearest integer. A value of 250 indicates an uncertainty  $\geq 250\%$ .

Fill values:

0: Clear column (2B-GEOPROF)  
 253: Solution negative (2B-IWC-RO)  
 253: Solution diverged (2B-IWC-RO)  
 253: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 254: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)  
 253: Bad or missing temperature (ECMWF-AUX)

Name: RO\_ice\_number\_conc  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units:  $L^{-1}$

Retrieved ice particle size distribution number concentration,  $N_T$ , obtained from the ice-phase retrieval and scaled with temperature in radar bins diagnosed as containing mixed ice and liquid.

Fill values:

0.0: Clear column (2B-GEOPROF)  
 -333.3: Solution negative (2B-IWC-RO)  
 -444.4: Solution diverged (2B-IWC-RO)  
 -777.7: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 -888.8: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)  
 -999.9: Bad or missing temperature (ECMWF-AUX)

Name: RO\_ice\_num\_conc\_uncertainty  
 Variable Type: UINT(1)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units: %

Fractional uncertainty in RO\_ice\_number\_conc, expressed in percent and rounded to the nearest integer. A value of 250 indicates an uncertainty  $\geq 250\%$ .

Fill values:

0: Clear column (2B-GEOPROF)  
 253: Solution negative (2B-IWC-RO)  
 253: Solution diverged (2B-IWC-RO)  
 253: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 254: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)  
 253: Bad or missing temperature (ECMWF-AUX)

Name: RO\_ice\_phase\_fraction  
 Variable Type: INT(2)  
 Dimension:  $N_{bin}, N_{ray}$   
 Units: -

Fraction of measured reflectivity assigned to the ice phase using a very simple temperature-based scheme (=1.0 below Temp\_min\_mixph\_K, 0.0 above Temp\_max\_mixph\_K, and varying linearly between these two temperatures). The effective number concentration in a given bin will be given by  $N_T(\text{ice}) * ro\_ipf$  for ice and  $N_T(\text{liq}) * (1-ro\_ipf)$  for liquid. The corresponding IWC and LWC are calculated using the scaled effective number concentrations (see RO\_liq\_water\_content and RO\_ice\_water\_content).

Name: RO\_ice\_water\_content  
 Variable Type: INT(2)  
 Dimension:  $N_{bin}, N_{ray}$   
 Units:  $\text{mg m}^{-3}$

Retrieved ice water content, obtained from the ice-only retrieval and scaled with temperature in the radar bins diagnosed as containing mixed ice and liquid.

Fill values:

0.0: Clear column (2B-GEOPROF)  
 -333.3: Solution negative (2B-IWC-RO)  
 -444.4: Solution diverged (2B-IWC-RO)  
 -777.7: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 -888.8: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)  
 -999.9: Bad or missing temperature (ECMWF-AUX)

Name: RO\_ice\_water\_content\_uncertainty  
 Variable Type: UINT(1)  
 Dimension:  $N_{bin}, N_{ray}$   
 Units: %

Fractional uncertainty in RO\_ice\_water\_content, expressed in percent and rounded to the nearest integer. A value of indicates an uncertainty  $\geq 250\%$ .

Fill values:

0: Clear column (2B-GEOPROF)  
 253: Solution negative (2B-IWC-RO)  
 253: Solution diverged (2B-IWC-RO)  
 253: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 254: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)  
 253: Bad or missing temperature (ECMWF-AUX)

Name: RO\_ice\_water\_path  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{ray}}$   
 Units:  $\text{g m}^{-2}$

Retrieved ice water path obtained from RO\_ice\_water\_content.

Fill values:

0.0: Clear column (2B-GEOPROF)  
 -333.3: Solution negative (2B-IWC-RO)  
 -444.4: Solution diverged (2B-IWC-RO)  
 -777.7: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 -888.8: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)  
 -999.9: Bad or missing temperature (ECMWF-AUX)

Name: RO\_ice\_water\_path\_uncertainty  
 Variable Type: UINT(1)  
 Dimension:  $N_{\text{ray}}$   
 Units: %

Fractional uncertainty in RO\_ice\_water\_path, expressed in percent and rounded to the nearest integer. A value of 250 indicates uncertainty  $\geq 250\%$ .

Fill values:

0: Clear column (2B-GEOPROF)  
 253: Solution negative (2B-IWC-RO)  
 253: Solution diverged (2B-IWC-RO)  
 253: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 254: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)  
 253: Bad or missing temperature (ECMWF-AUX)

Name: RO\_liq\_distrib\_width\_param  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units: -

Retrieved liquid particle size distribution width parameter,  $\omega$ , obtained for liquid-containing radar bins from the liquid-only retrieval.

Fill values:

0.0: Clear column (2B-GEOPROF)  
 -3.333: Solution negative (2B-LWC-RO)  
 -4.444: Solution diverged (2B-LWC-RO)  
 -7.777: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 -8.888: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)  
 -9.999: Bad or missing temperature (ECMWF-AUX)

Name: RO\_liq\_distrib\_width\_param\_uncertainty  
 Variable Type: UINT(1)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units: %

Fractional uncertainty in RO\_liq\_distrib\_width\_param, expressed in percent and rounded to the nearest integer. A value of 250 indicates an uncertainty  $\geq 250\%$ .

Fill values:

0: Clear column (2B-GEOPROF)  
 253: Solution negative (2B-LWC-RO)  
 253: Solution diverged (2B-LWC-RO)  
 253: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 254: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)  
 253: Bad or missing temperature (ECMWF-AUX)

Name: RO\_liq\_effective\_radius  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units:  $\mu\text{m}$

Retrieved liquid particle size distribution effective radius  $r_e$ , obtained for liquid-containing radar bins from the liquid-only retrieval.

Fill values:

0.0: Clear column (2B-GEOPROF)  
 -333.3: Solution negative (2B-LWC-RO)  
 -444.4: Solution diverged (2B-LWC-RO)  
 -777.7: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 -888.8: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)  
 -999.9: Bad or missing temperature (ECMWF-AUX)

Name: RO\_liq\_effective\_radius\_uncertainty  
 Variable Type: UINT(1)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units: %

Fractional uncertainty in RO\_liq\_effective\_radius, expressed in percent and rounded to the nearest integer. A value of 250 indicates an uncertainty  $\geq 250\%$ .

Fill values:

0: Clear column (2B-GEOPROF)  
 253: Solution negative (2B-LWC-RO)  
 253: Solution diverged (2B-LWC-RO)  
 253: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 254: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)  
 253: Bad or missing temperature (ECMWF-AUX)

Name: RO\_liq\_number\_conc  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units:  $\text{cm}^{-3}$

Retrieved liquid particle size distribution number concentration  $N_T$ , obtained from the liquid-only retrieval and scaled with temperature in the radar bins diagnosed as containing mixed ice and liquid.

Fill values:

0.0: Clear column (2B-GEOPROF)  
 -333.3: Solution negative (2B-LWC-RO)  
 -444.4: Solution diverged (2B-LWC-RO)  
 -777.7: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 -888.8: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)  
 -999.9: Bad or missing temperature (ECMWF-AUX)

Name: RO\_liq\_num\_conc\_uncertainty  
 Variable Type: UINT(1)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units: %

Fractional uncertainty in RO\_liq\_number\_conc, expressed in percent and rounded to the nearest integer. A value of 250 indicates an uncertainty  $\geq 250\%$ .

Fill values:

0: Clear column (2B-GEOPROF)  
 253: Solution negative (2B-LWC-RO)  
 253: Solution diverged (2B-LWC-RO)  
 253: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 254: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)  
 253: Bad or missing temperature (ECMWF-AUX)

Name: RO\_liq\_water\_content  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units:  $\text{mg m}^{-3}$

Retrieved liquid water content, obtained from the liquid-only retrieval and scaled with temperature in the radar bins diagnosed as containing mixed ice and liquid.

Fill values:

0.0: Clear column (2B-GEOPROF)  
 -3333.0: Solution negative (2B-LWC-RO)  
 -4444.0: Solution diverged (2B-LWC-RO)  
 -7777.0: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 -8888.0: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)  
 -9999.9: Bad or missing temperature (ECMWF-AUX)

Name: RO\_liq\_water\_content\_uncertainty  
 Variable Type: UINT(1)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units: %

Fractional uncertainty in RO\_liq\_water\_content, expressed in percent and rounded to the nearest integer. A value of 250 indicates an uncertainty  $\geq 250\%$ .

Fill values:

0: Clear column (2B-GEOPROF)  
 253: Solution negative (2B-LWC-RO)  
 253: Solution diverged (2B-LWC-RO)  
 253: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 254: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)  
 253: Bad or missing temperature (ECMWF-AUX)

Name: RO\_liq\_water\_path  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{ray}}$   
 Units:  $\text{g m}^{-2}$

Retrieved liquid water path obtained from RO\_liq\_water\_content.

Fill values:

0.0: Clear column (2B-GEOPROF)  
 -3333.0: Solution negative (2B-LWC-RO)  
 -4444.0: Solution diverged (2B-LWC-RO)  
 -7777.0: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 -8888.0: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)  
 -9999.0: Bad or missing temperature (ECMWF-AUX)

Name: RO\_liq\_water\_path\_uncertainty  
 Variable Type: UINT(1)  
 Dimension:  $N_{\text{ray}}$   
 Units: %

Fractional uncertainty in RO\_liq\_water\_path, expressed in percent and rounded to the nearest integer. A value of 250 indicates uncertainty  $\geq 250\%$ .

Fill values:

0: Clear column (2B-GEOPROF)  
 253: Solution negative (2B-LWC-RO)  
 253: Solution diverged (2B-LWC-RO)  
 253: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 254: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)  
 253: Bad or missing temperature (ECMWF-AUX)

### Metadata

Name: RO\_CWC\_status  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{ray}}$   
 Units: -

A two-byte (16-bit) status flag. Various bits indicate errors, convergence, and related information about the combined retrieval. Non-zero values of bits 0, 1, 4, 5, or 6 indicate a partially or wholly aborted retrieval.

0 (LSB): LWC retrieval failed  
 1: IWC retrieval failed  
 2: Possible precipitation ( $Z > -15$  dBZe)  
 3: Combined LWC/IWC (both cloud types present in profile)  
 4: Bad GEOPROF input  
 5: Bad CLDCLASS input  
 6: Bad ECMWF temperature  
 7: Unassigned  
 8: Large  $\chi^2$  in LWC  
 9: Large  $\chi^2$  in IWC  
 10: Clear profile according to GEOPROF  
 11: Unassigned  
 12: Unassigned  
 13: Unassigned  
 14: Unassigned  
 15 (MSB): Unassigned

Name: N\_cloudy\_bins  
 Variable Type: INT(1)  
 Dimension: N<sub>ray</sub>  
 Units: -

Number of bins in the column deemed to contain cloud by 2B-GEOPROF (usually far less than 125). Bins are deemed cloudy if CPR.Cloud\_mask >= Cloud\_mask\_threshold.

Fill values:

0: Clear column (2B-GEOPROF)

-77: Unphysical, bad, or missing reflectivity factor Z' (2B-GEOPROF)

-88: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: N\_clear\_CPR  
 Variable Type: INT(4)  
 Dimension: scalar  
 Units:

Number of profiles containing no cloud, based on 2B-GEOPROF (LO\_RO\_status bit 12 set)

Name: N\_drizzle\_or\_precipitation  
 Variable Type: INT(4)  
 Dimension: scalar  
 Units:

Number of profiles containing possible drizzle or precipitation (LO\_RO\_status bit 15 set), based on radar reflectivity factor threshold of -15 dBZe.

Name: N\_indeterminate\_scenario  
 Variable Type: INT(4)  
 Dimension: scalar  
 Units:

Number of profiles in which the 2B-CLDCLASS cloud scenario is not determined in any cloudy bin (LO\_RO\_status bit 6 set)

Name: N\_invalid\_CLDCLASS  
 Variable Type: INT(4)  
 Dimension: scalar  
 Units:

Number of profiles in which 2B-CLDCLASS has invalid values or is missing (LO\_RO\_status bit 7 set)

Name: N\_invalid\_temperature  
Variable Type: INT(4)  
Dimension: scalar  
Units:

Number of profiles in which ECMWF-AUX temperature has invalid values or is missing (IO\_RO\_status bit 9 set)

Name: N\_low\_confidence\_CLDCLASS  
Variable Type: INT(4)  
Dimension: scalar  
Units:

Number of profiles in which 2B-CLDCLASS cloud classification has low confidence (LO\_RO\_status bit 8 set)

Name: N\_ray\_granule  
Variable Type: INT(4)  
Dimension: scalar  
Units:

Total number of rays (profiles) in granule.

Name: N\_unphys\_missing\_reflectivity  
Variable Type: INT(4)  
Dimension: scalar  
Units:

Number of profiles containing an unphysical or missing value of radar reflectivity (LO\_RO\_status bit 13 set)

Name: PCT\_clear\_CPR  
Variable Type: INT(1)  
Dimension: scalar  
Units:

Fraction of total profiles containing no cloud, expressed as a percentage and rounded to the nearest integer. Normal range: <20%

Name: PCT\_drizzle\_or\_precipitation  
Variable Type: INT(1)  
Dimension: scalar  
Units:

Fraction of total profiles containing possible drizzle or precipitation (based on radar reflectivity factor threshold of -15 dBZe), expressed as a percentage and rounded to the nearest integer. Normal range: <40%

Name: PCT\_indeterminate\_scenario  
 Variable Type: INT(1)  
 Dimension: scalar  
 Units:

Fraction of total profiles in which the 2B-CLDCLASS cloud scenario is not determined in any cloudy bin, expressed as a percentage and rounded to the nearest integer. Normal range: <5%

Name: PCT\_invalid\_CLDCLASS  
 Variable Type: INT(1)  
 Dimension: scalar  
 Units:

Fraction of total profiles in which 2B-CLDCLASS has invalid values or is missing, expressed as a percentage and rounded to the nearest integer. Normal range: <1%

Name: PCT\_invalid\_temperature  
 Variable Type: INT(1)  
 Dimension: scalar  
 Units:

Fraction of total profiles in which ECMWF-AUX temperature has invalid values or is missing, expressed as a percentage and rounded to the nearest integer. Normal range: <1%

Name: PCT\_low\_confidence\_CLDCLASS  
 Variable Type: INT(1)  
 Dimension: scalar  
 Units:

Fraction of total profiles in which 2B-CLDCLASS cloud classification has low confidence, expressed as a percentage and rounded to the nearest integer. Normal range: <10%

## B.2 Ice-only retrieval

### Cloud properties

Name: IO\_RO\_AP\_distrib\_width\_param  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units: -

A priori value of the ice particle size distribution width parameter,  $\omega$ , for the ice-only retrieval.

Fill values:

0.0: Clear column (2B-GEOPROF)

-7.777: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)

-8.888: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: IO\_RO\_AP\_log\_geo\_mean\_diameter  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units:  $\log_{10}(\text{mm})$

A priori value of  $\log_{10}(D_g)$  for the ice-only retrieval, where  $D_g$  is the ice particle size distribution geometric mean diameter.

Fill values:

0.0: Clear column (2B-GEOPROF)

-7.777: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)

-8.888: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: IO\_RO\_AP\_log\_number\_conc  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units:  $\log_{10}(L^{-1})$

A priori value of  $\log_{10}(N_T)$  for the ice-only retrieval, where  $N_T$  is the ice particle size distribution number concentration.

Fill values:

0.0: Clear column (2B-GEOPROF)

-7.777: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)

-8.888: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: IO\_RO\_AP\_sdev\_distrib\_width\_param  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units: -

A priori value of the standard deviation of the ice particle size distribution width parameter,  $\omega$ , for the ice-only retrieval.

Fill values:

0.0: Clear column (2B-GEOPROF)

-7.777: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)

-8.888: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: IO\_RO\_AP\_sdev\_log\_geo\_mean\_diameter  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units:  $\log_{10}(\text{mm})$

A priori value of the standard deviation of  $\log_{10}(D_g)$  for the ice-only retrieval, where  $D_g$  is the ice particle size distribution geometric mean diameter.

Fill values:

0.0: Clear column (2B-GEOPROF)

-7.777: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)

-8.888: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: IO\_RO\_AP\_sdev\_log\_num\_conc  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units:  $\log_{10}(L^{-1})$

A priori value of the standard deviation of  $\log_{10} /; (N_T)$  for the ice-only retrieval, where  $N_T$  is the ice particle size distribution number concentration.

Fill values:

0.0: Clear column (2B-GEOPROF)

-7.777: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)

-8.888: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: IO\_RO\_distrib\_width\_param  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units: -

Retrieved ice particle size distribution width parameter,  $\omega$ , for the ice-only retrieval.

Fill values:

0.0: Clear column (2B-GEOPROF)

-3.333: Solution negative (2B-IWC-RO)

-4.444: Solution diverged (2B-IWC-RO)

-7.777: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)

-8.888: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: IO\_RO\_distrib\_width\_param\_uncertainty  
 Variable Type: UINT(1)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units: %

Fractional uncertainty in the retrieved ice particle size distribution width parameter,  $\omega$ , for the ice-only retrieval. This is expressed in percent and rounded to the nearest integer. A value of 250 indicates an uncertainty  $\geq 250\%$ .

Fill values:

0: Clear column (2B-GEOPROF)

253: Solution negative (2B-IWC-RO)

253: Solution diverged (2B-IWC-RO)

253: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)

254: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: IO\_RO\_effective\_radius  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units:  $\mu\text{m}$

Retrieved effective radius,  $r_e$ , for the ice-only retrieval.

Fill values:

0.0: Clear column (2B-GEOPROF)  
 -333.3: Solution negative (2B-IWC-RO)  
 -444.4: Solution diverged (2B-IWC-RO)  
 -777.7: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 -888.8: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: IO\_RO\_effective\_radius\_uncertainty  
 Variable Type: UINT(1)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units: %

Fractional uncertainty in the retrieved effective radius,  $r_e$ , for the ice-only retrieval. This is expressed in percent and rounded to the nearest integer. A value of 250 indicates an uncertainty  $\geq 250\%$ .

Fill values:

0: Clear column (2B-GEOPROF)  
 253: Solution negative (2B-IWC-RO)  
 253: Solution diverged (2B-IWC-RO)  
 253: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 254: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: IO\_RO\_ice\_water\_content  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units:  $\text{mg m}^{-3}$

Retrieved ice water content for the ice-only retrieval.

Fill values:

0: Clear column (2B-GEOPROF)  
 -3333: Solution negative (2B-IWC-RO)  
 -4444: Solution diverged (2B-IWC-RO)  
 -7777: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 -8888: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: IO\_RO\_ice\_water\_content\_uncertainty  
 Variable Type: UINT(1)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units: %

Fractional uncertainty in the retrieved ice water content for the ice-only retrieval. This is expressed in percent and rounded to the nearest integer. A value of 250 indicates an uncertainty  $\geq 250\%$ .

Fill values:

0: Clear column (2B-GEOPROF)  
 253: Solution negative (2B-IWC-RO)  
 253: Solution diverged (2B-IWC-RO)  
 253: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 254: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: IO\_RO\_ice\_water\_path  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{ray}}$   
 Units:  $\text{g m}^{-2}$

Retrieved value of the ice water path for the ice-only retrieval. Note, this value is specific to the ice-only retrieval and so assumes that clouds in the ice-containing portion of the profile are completely ice. See the documentation for details.

Fill values:

0: Clear column (2B-GEOPROF)  
 -3333: Solution negative (2B-IWC-RO)  
 -4444: Solution diverged (2B-IWC-RO)  
 -7777: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 -8888: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: IO\_RO\_ice\_water\_path\_uncertainty  
 Variable Type: UINT(1)  
 Dimension:  $N_{\text{ray}}$   
 Units: %

Fractional uncertainty in the retrieved ice water path for the ice-only retrieval. This is expressed in percent and rounded to the nearest integer. A value of 250 indicates uncertainty  $\geq 250\%$ .

Fill values:

0: Clear column (2B-GEOPROF)  
 253: Solution negative (2B-IWC-RO)  
 253: Solution diverged (2B-IWC-RO)  
 253: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 254: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: IO\_RO\_log\_number\_conc  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units:  $\log_{10}(L^{-1})$

Retrieved value of ice particle number concentration  $\log_{10}(N_T)$  for the ice-only retrieval.

Fill values:

0.0: Clear column (2B-GEOPROF)

-3.333: Solution negative (2B-IWC-RO)

-4.444: Solution diverged (2B-IWC-RO)

-7.777: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)

-8.888: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: IO\_RO\_log\_num\_conc\_uncertainty  
 Variable Type: UINT(1)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units: %

Fractional uncertainty in the retrieved  $\log_{10}(N_T)$  for the ice-only retrieval. This is expressed in percent and rounded to the nearest integer. A value of 250 indicates an uncertainty  $\geq 250\%$ .

Fill values:

0: Clear column (2B-GEOPROF)

253: Solution negative (2B-IWC-RO)

253: Solution diverged (2B-IWC-RO)

253: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)

254: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: IO\_RO\_norm\_chi\_square  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{ray}}$   
 Units: –

Goodness-of-fit statistic chi-square for the retrieved state vector for the ice-only retrieval, normalized by the number of elements in the measurements vector.

Fill values:

0.0: Clear column (2B-GEOPROF)  
 -33.33: Solution negative (2B-IWC-RO)  
 -44.44: Solution diverged (2B-IWC-RO)  
 -77.77: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 -88.88: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

### Metadata

Name: IO\_RO\_status  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{ray}}$   
 Units: –

A two-byte (16-bit) status flag for the ice-only retrieval. Various bits indicate errors, convergence, and related information about the retrieval. Non-zero values of bits 4, 5, 6, 7, 9, or 13 indicate an aborted retrieval.

Bit assignments table:

0 (LSB): Unassigned  
 1: Unassigned  
 2: Unassigned  
 3: Unassigned  
 4: 1 = RO solution not converged  
 5: 1 = negative width parameter element in state vector  
 6: 1 = cloud scenario not determined in any cloudy bin  
 7: 1 = invalid 2B-CLDCLASS condition (cloud type >8, cloud type <1, latitude type 3, or quality flag 2 or 3) or CLDCLASS missing  
 8: 1 = cloud classification low confidence (2B-CLDCLASS)  
 9: 1 = bad or missing ECMWF-AUX temperature  
 11 & 10: 00 = single cloud type in column (or clear)  
 01 (i.e. bit 10 set) = two cloud types  
 10 (i.e. bit 11 set) = three cloud types  
 11 = more than three cloud types  
 12: 1 = clear column according to 2B-GEOPROF  
 13: 1 = unphysical, bad, or missing radar reflectivity value  
 14: 1 = large value of normalized chi-square  
 15 (MSB): 1 = possible drizzle or precipitation

Name: IO\_RO\_N\_large\_norm\_chisq  
Variable Type: INT(4)  
Dimension: scalar  
Units:

Number of profiles in which RO ice-only solution has large value ( $>3.0$ ) of norm\_chisq (IO\_RO\_status bit 14 set).

Name: IO\_RO\_N\_negative\_x  
Variable Type: INT(4)  
Dimension: scalar  
Units:

Number of profiles in which RO ice-only solution stopped with inappropriate negative values in the state vector,  $x$ . (IO\_RO\_status bit 5 set).

Name: IO\_RO\_N\_not\_converged  
Variable Type: INT(4)  
Dimension: scalar  
Units:

Number of profiles in which RO ice-only solution does not converge (IO\_RO\_status bit 4 set).

Name: IO\_RO\_N\_solution\_found  
Variable Type: INT(4)  
Dimension: scalar  
Units:

Number of profiles with RO ice-only solution found (includes clear and liquid- only profiles); defined by IO\_RO\_status bits 4, 5, 6, 7, & 13 being unset.

Name: IO\_RO\_PCT\_large\_norm\_chisq  
Variable Type: INT(1)  
Dimension: scalar  
Units:

Fraction of total profiles in which RO ice-only solution has large value ( $>3.0$ ) of norm\_chisq, expressed as a percentage and rounded to the nearest integer. Normal range:  $<5\%$

Name: IO\_RO\_PCT\_negative\_x  
Variable Type: INT(1)  
Dimension: scalar  
Units:

Fraction of total profiles in which RO ice-only solution stopped with inappropriate negative values in the state vector,  $x$ , expressed as a percentage and rounded to nearest integer. Normal range:  $<5\%$ .

Name: IO\_RO\_PCT\_not\_converged  
 Variable Type: INT(1)  
 Dimension: scalar  
 Units:

Fraction of total profiles in which RO ice-only solution does not converge, expressed as a percentage and rounded to the nearest integer. Normal range: <3%

Name: IO\_RO\_PCT\_solution\_found  
 Variable Type: INT(1)  
 Dimension: scalar  
 Units:

Fraction of total profiles with RO ice-only solution found (including clear and liquid-only profiles), expressed as a percentage and rounded to the nearest integer. Normal range: >70%

### B.3 Liquid-only retrieval

#### Cloud properties

Name: LO\_RO\_AP\_distrib\_width\_param  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units: –

A priori value of the liquid particle size distribution width parameter,  $\omega$ , for the liquid-only retrieval.

Fill values:

0.0: Clear column (2B-GEOPROF)

-7.777: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)

-8.888: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: LO\_RO\_AP\_geo\_mean\_radius  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units:  $\mu\text{m}$

A priori value of the liquid particle size distribution geometric mean radius,  $r_g$ , for the liquid-only retrieval.

Fill values:

0.0: Clear column (2B-GEOPROF)

-77.77: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)

-88.88: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: LO\_RO\_AP\_number\_conc  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units:  $\text{cm}^{-3}$

A priori value of the liquid particle size distribution number concentration,  $N_T$ , for the liquid-only retrieval.

Fill values:

0.0: Clear column (2B-GEOPROF)

-777.7: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)

-888.8: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: LO\_RO\_AP\_sdev\_distrib\_width\_param  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units: -

A priori value of the standard deviation of the liquid particle size distribution width parameter,  $\omega$ , for the liquid-only retrieval.

Fill values:

0.0: Clear column (2B-GEOPROF)

-7.777: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)

-8.888: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: LO\_RO\_AP\_sdev\_geo\_mean\_radius  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units:  $\mu\text{m}$

A priori value of the standard deviation of the liquid particle size distribution geometric mean radius,  $r_g$ , for the liquid-only retrieval.

Fill values:

0.0: Clear column (2B-GEOPROF)

-77.77: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)

-88.88: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: LO\_RO\_AP\_sdev\_num\_conc  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units:  $\text{cm}^{-3}$

A priori value of the standard deviation of the liquid particle size distribution number concentration,  $N_T$ , for the liquid-only retrieval.

Fill values:

0.0: Clear column (2B-GEOPROF)

-777.7: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)

-888.8: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: LO\_RO\_distrib\_width\_param  
 Variable Type: INT(2)  
 Dimension:  $N_{bin}, N_{ray}$   
 Units: -

Retrieved liquid particle size distribution width parameter,  $\omega$ , for the liquid-only retrieval.

Fill values:

0.0: Clear column (2B-GEOPROF)  
 -3.333: Solution negative (2B-LWC-RO)  
 -4.444: Solution diverged (2B-LWC-RO)  
 -7.777: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 -8.888: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: LO\_RO\_distrib\_width\_param\_uncertainty  
 Variable Type: UINT(1)  
 Dimension:  $N_{bin}, N_{ray}$   
 Units: %

Fractional uncertainty in the retrieved liquid particle size distribution width parameter,  $\omega$ , for the liquid-only retrieval. This is expressed in percent and rounded to the nearest integer. A value of 250 indicates an uncertainty  $\geq 250\%$ .

Fill values:

0: Clear column (2B-GEOPROF)  
 253: Solution negative (2B-LWC-RO)  
 253: Solution diverged (2B-LWC-RO)  
 253: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 254: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: LO\_RO\_effective\_radius  
 Variable Type: INT(2)  
 Dimension:  $N_{bin}, N_{ray}$   
 Units:  $\mu\text{m}$

Retrieved effective radius,  $r_e$ , for the liquid-only retrieval.

Fill values:

0.0: Clear column (2B-GEOPROF)  
 -333.3: Solution negative (2B-LWC-RO)  
 -444.4: Solution diverged (2B-LWC-RO)  
 -777.7: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 -888.8: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: LO\_RO\_effective\_radius\_uncertainty  
 Variable Type: UINT(1)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units: %

Fractional uncertainty in the retrieved effective radius,  $r_e$ , for the liquid-only retrieval. This is expressed in percent and rounded to the nearest integer. A value of 250 indicates an uncertainty  $\geq 250\%$ .

Fill values:

0: Clear column (2B-GEOPROF)  
 253: Solution negative (2B-LWC-RO)  
 253: Solution diverged (2B-LWC-RO)  
 253: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 254: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: LO\_RO\_liquid\_water\_content  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units:  $\text{mg m}^{-3}$

Retrieved liquid water content for the liquid-only retrieval.

Fill values:

0.0: Clear column (2B-GEOPROF)  
 -3333.0: Solution negative (2B-LWC-RO)  
 -4444.0: Solution diverged (2B-LWC-RO)  
 -7777.0: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 -8888.0: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: LO\_RO\_liquid\_water\_content\_uncertainty  
 Variable Type: UINT(1)  
 Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
 Units: %

Fractional uncertainty in the retrieved liquid water content for the liquid-only retrieval. This is expressed in percent and rounded to the nearest integer. A value of 250 indicates an uncertainty  $\geq 250\%$ .

Fill values:

0: Clear column (2B-GEOPROF)  
 253: Solution negative (2B-LWC-RO)  
 253: Solution diverged (2B-LWC-RO)  
 253: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 254: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: LO\_RO\_liquid\_water\_path  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{ray}}$   
 Units:  $\text{g m}^{-2}$

Retrieved value of the liquid water path for the liquid-only retrieval. Note, this value is specific to the liquid-only retrieval and so assumes that clouds in the liquid-containing portion of the profile are completely liquid. See the documentation for details.

Fill values:

0.0: Clear column (2B-GEOPROF)  
 -3333.0: Solution negative (2B-LWC-RO)  
 -4444.0: Solution diverged (2B-LWC-RO)  
 -7777.0: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 -8888.0: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: LO\_RO\_liquid\_water\_path\_uncertainty  
 Variable Type: UINT(1)  
 Dimension:  $N_{\text{ray}}$   
 Units: %

Fractional uncertainty in the retrieved liquid water path for the liquid-only retrieval. This is expressed in percent and rounded to the nearest integer. A value of 250 indicates uncertainty  $\geq 250\%$ .

Fill values:

0: Clear column (2B-GEOPROF)  
 253: Solution negative (2B-LWC-RO)  
 253: Solution diverged (2B-LWC-RO)  
 253: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 254: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: LO\_RO\_norm\_chi\_square  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{ray}}$   
 Units: -

Goodness-of-fit statistic chi-square for the retrieved state vector for the liquid-only retrieval, normalized by the number of elements in the measurements vector.

Fill values:

0.0: Clear column (2B-GEOPROF)  
 -33.33: Solution negative (2B-LWC-RO)  
 -44.44: Solution diverged (2B-LWC-RO)  
 -77.77: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 -88.88: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: LO\_RO\_number\_conc  
Variable Type: INT(2)  
Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
Units:  $\text{cm}^{-3}$

Retrieved value of the liquid particle size distribution number concentration,  $N_T$ , for the liquid-only retrieval.

Fill values:

0.0: Clear column (2B-GEOPROF)

-333.3: Solution negative (2B-LWC-RO)

-444.4: Solution diverged (2B-LWC-RO)

-777.7: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)

-888.8: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: LO\_RO\_num\_conc\_uncertainty  
 Variable Type: UINT(1)  
 Dimension:  $N_{bin}, N_{ray}$   
 Units: %

Fractional uncertainty in the retrieved liquid particle size distribution number concentration,  $N_T$ , for the liquid-only retrieval. This is expressed in percent and rounded to the nearest integer. A value of 250 indicates an uncertainty  $\geq 250\%$ .

Fill values:

0: Clear column (2B-GEOPROF)  
 253: Solution negative (2B-LWC-RO)  
 253: Solution diverged (2B-LWC-RO)  
 253: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)  
 254: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

### Metadata

Name: LO\_RO\_status  
 Variable Type: INT(2)  
 Dimension:  $N_{ray}$   
 Units: -

A two-byte (16-bit) status flag for the liquid-only retrieval. Various bits indicate errors, convergence, and related information about the retrieval. Non-zero values of bits 4, 5, 6, 7, or 13 indicate an aborted retrieval.

Bit assignments table:

0 (LSB): Unassigned  
 1: Unassigned  
 2: Unassigned  
 3: Unassigned  
 4: 1 = RO solution not converged  
 5: 1 = negative element in state vector  
 6: 1 = cloud scenario not determined in any cloudy bin  
 7: 1 = invalid 2B-CLDCLASS condition (cloud type  $>8$ , cloud type  $<1$ , latitude type 3, or quality flag 2 or 3) or CLDCLASS missing  
 8: 1 = cloud classification low confidence (2B-CLDCLASS)  
 9: Unassigned  
 11 & 10: 00 = single cloud type in column (or clear)  
 01 (i.e. bit 10 set) = two cloud types  
 10 (i.e. bit 11 set) = three cloud types  
 11 = more than three cloud types  
 12: 1 = clear column according to 2B-GEOPROF  
 13: 1 = unphysical, bad, or missing radar reflectivity value  
 14: 1 = large value of normalized chi-square  
 15 (MSB): 1 = possible drizzle or precipitation

Name: LO\_RO\_N\_large\_norm\_chisq  
Variable Type: INT(4)  
Dimension: scalar  
Units:

Number of profiles in which RO liquid-only solution has large value ( $>3.0$ ) of norm\_chisq (LO\_RO\_status bit 14 set).

Name: LO\_RO\_N\_negative\_x  
Variable Type: INT(4)  
Dimension: scalar  
Units:

Number of profiles in which RO liquid-only solution stopped with inappropriate negative values in the state vector,  $x$  (LO\_RO\_status bit 5 set).

Name: LO\_RO\_N\_not\_converged  
Variable Type: INT(4)  
Dimension: scalar  
Units:

Number of profiles in which RO liquid-only solution does not converge (LO\_RO\_status bit 4 set).

Name: LO\_RO\_N\_solution\_found  
Variable Type: INT(4)  
Dimension: scalar  
Units:

Number of profiles with RO liquid-only solution found (includes clear profiles); defined by LO\_RO\_status bits 4, 5, 6, 7, & 13 being unset.

Name: LO\_RO\_PCT\_large\_norm\_chisq  
Variable Type: INT(1)  
Dimension: scalar  
Units:

Fraction of total profiles in which RO liquid-only solution has large value ( $>3.0$ ) of norm\_chisq, expressed as a percentage and rounded to the nearest integer. Normal range:  $<5\%$

Name: LO\_RO\_PCT\_negative\_x  
Variable Type: INT(1)  
Dimension: scalar  
Units:

Fraction of total profiles in which RO liquid-only solution stopped with inappropriate negative values in the state vector,  $x$ , expressed as a percentage and rounded to nearest integer. Normal range:  $<1\%$

Name: LO\_RO\_PCT\_not\_converged  
 Variable Type: INT(1)  
 Dimension: scalar  
 Units:

Fraction of total profiles in which RO liquid-only solution does not converge, expressed as a percentage and rounded to nearest integer. Normal range: <3%

Name: LO\_RO\_PCT\_solution\_found  
 Variable Type: INT(1)  
 Dimension: scalar  
 Units:

Fraction of total profiles with RO liquid-only solution found (including clear and cirrus profiles), expressed as a percentage and rounded to nearest integer. Normal range: >70%

#### B.4 Radar health, navigation and geolocation

Name: Data\_quality  
 Variable Type: UINT(1)  
 Dimension:  $N_{\text{ray}}$   
 Units: -

Flags indicating radar data quality. If 0, then data are of good quality. Otherwise, treat as a bit field with 8 flags. See the complete description in the documentation for 1B-CPR.

Name: Data\_status  
 Variable Type: UINT(1)  
 Dimension:  $N_{\text{ray}}$   
 Units: -

This is a bit field that contains radar data status flags. See the complete description in the documentation for 1B-CPR.

Name: Data\_targetID  
 Variable Type: UINT(1)  
 Dimension:  $N_{\text{ray}}$   
 Units: -

The target id indicates the orientation of the spacecraft bus. For normal operations the target ID is 0. See the complete description in the documentation for 1B-CPR.

Name: DEM\_elevation  
 Variable Type: INT(2)  
 Dimension:  $N_{\text{ray}}$   
 Units: meters

Surface elevation in meters above mean sea level. A value of -9999 indicates ocean. A value of 9999 indicates an error in calculation of the elevation.

Name: Height  
Variable Type: INT(2)  
Dimension:  $N_{\text{bin}}, N_{\text{ray}}$   
Units: m

Height of the radar range bins in meters above mean sea level.

Name: Latitude  
Variable Type: REAL(4)  
Dimension:  $N_{\text{ray}}$   
Units: degrees

Spacecraft geodetic latitude.

Name: Longitude  
Variable Type: REAL(4)  
Dimension:  $N_{\text{ray}}$   
Units: degrees

Spacecraft geodetic longitude

Name: Pitch\_offset  
Variable Type: REAL(4)  
Dimension: scalar  
Units: degrees

The pitch angle offset from nadir during normal operations. Pitch up is positive (radar points along the flight track in the direction of motion), down is negative (radar points along the flight track opposite the direction of motion).

Name: Profile\_time  
Variable Type: REAL(4)  
Dimension:  $N_{\text{ray}}$   
Units: seconds

Seconds since the start of the granule for each profile. The first profile is 0.

Name: Range\_to\_intercept  
Variable Type: REAL(4)  
Dimension:  $N_{\text{ray}}$   
Units: km

Range from the spacecraft to the CPR boresight intercept with the geoid.

Name: Roll\_offset  
 Variable Type: REAL(4)  
 Dimension: scalar  
 Units: degrees

The roll angle offset from nadir during normal operations. Positive roll results in the radar pointing to the right of the flight track. Negative roll to the left.

Name: TAI\_start  
 Variable Type: REAL(8)  
 Dimension: scalar  
 Units: seconds

The TAI timestamp for the first profile in the data file. TAI is International Atomic Time: seconds since 00:00:00 Jan 1 1993.

Name: UTC\_start  
 Variable Type: REAL(4)  
 Dimension: scalar  
 Units: seconds

The UTC seconds since 00:00 Z of the first profile in the data file.

Name: Vertical\_binsize  
 Variable Type: REAL(4)  
 Dimension: scalar  
 Units: m

Effective vertical height of the radar range bin.

## B.5 Retrieval configuration

Name: RO\_radar\_uncertainty  
 Variable Type: INT(2)  
 Dimension:  $N_{bin}, N_{ray}$   
 Units: dBZ

Uncertainty in the radar reflectivity factor used in the radar-only liquid-only and ice-only retrievals. The uncertainty is a function of reflectivity and minimum detectable signal.

Fill values:

0.0: Clear column (2B-GEOPROF)

-33.33: Solution negative (2B-LWC-RO)

-44.44: Solution diverged (2B-LWC-RO)

-77.77: Unphysical, bad, or missing reflectivity factor  $Z'$  (2B-GEOPROF)

-88.88: Cloud scenario not determined, invalid class, or class bad/missing (2B-CLDCLASS)

Name: Cloud\_mask\_threshold  
Variable Type: INT(1)  
Dimension: scalar  
Units: -

Value of CPR.Cloud\_mask used as the lower threshold for processing the LWC and IWC (and therefore CWC) retrievals. Bins having CPR.Cloud\_mask  $\geq$  Cloud\_mask\_threshold are considered cloudy.

Name: Temp\_min\_mixph\_K  
Variable Type: REAL(4)  
Dimension: scalar  
Units: K

Minimum temperature for which retrieval allows a mixed-phase solution. Colder temperatures are retrieved as pure ice.

Name: Temp\_max\_mixph\_K  
Variable Type: REAL(4)  
Dimension: scalar  
Units: K

Maximum temperature for which retrieval allows a mixed-phase solution. Warmer temperatures are retrieved as pure liquid.