DOE/SC-ARM/TR-139

Cloud Optical Properties from the Multifilter Shadowband Radiometer (MFRSRCLDOD): An ARM Value-Added Product

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DISCLAIMER

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Office of Science, Office of Biological and Environmental Research

Acronyms and Abbreviations

μm	micrometer(s)
AMF	ARM Mobile Facilities
ARM	Atmospheric Radiation Measurement
ARSCL	Active Remote Sensing of Clouds
DOD	Data Object Design
g	gram(s)
GHz	gigahertz
GOES	Geostationary Operational Environmental Satellite
I	measured irradiance
I_0	top-of-atmosphere irradiance
LOS	line of sight
LWP	liquid water path
MFR	Multifilter Radiometer
MFRSR	Multifilter Rotating Shadowband Radiometer
MFRSRCLDOD	Cloud Optical Depth from MFRSR
min	minute(s)
MWR	Microwave Radiometer
MWRLOS	Microwave Water Radiometer: Water Liquid And Vapor Along Line of Sight Path
MWRRET	Microwave Radiometer Retrievals
nm	nanometer(s)
NSA	North Slope of Alaska
s	second(s)
SGP	Southern Great Plains
SURFSPECALB	Surface Spectral Albedo
TWP	Tropical Western Pacific
UTC	Universal Time Coordinates
VAP	Value-Added Product

Contents

Figures

Tables

1.0 Introduction

The microphysical properties of clouds play an important role in studies of global climate change. Observations from satellites and surface-based systems have been used to infer cloud optical depth and effective radius. Min and Harrison (1996) developed an inversion method to infer the optical depth of liquid water clouds from narrow band spectral Multifilter Rotating Shadowband Radiometer (MFRSR) measurements (Harrison et al. 1994). Their retrieval also uses the total liquid water path (LWP) measured by a microwave radiometer (MWR) to obtain the effective radius of the warm cloud droplets. Their results were compared with Geostationary Operational Environmental Satellite (GOES) retrieved values at the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) site (Min and Harrison 1996). Min et al. (2003) also validated the retrieved cloud optical properties against in situ observations, showing that the retrieved cloud effective radius agreed well with the in situ forward scattering spectrometer probe observations. The retrieved cloud optical properties from Min et al. (2003) were used also as inputs to an atmospheric shortwave model, and the computed fluxes were compared with surface pyranometer observations.

The Min and Harrison algorithm has been incorporated into an ARM Value-Added Product (VAP) called MFRSRCLDOD (short for: Cloud Optical Depth from MFRSR). This version of the VAP (1 min) uses the total transmission at 415 nm from the MFRSR. Therefore, the results are only valid for "horizontally homogeneous" stratiform clouds with optical depths larger than approximately 7 μm. The retrieval assumes a single cloud layer consisting solely of liquid water drops. As specified by Min and Harrison (1996), the wavelength at 415 nm was chosen because of the lack of gaseous absorption and the relatively constant surface albedo (in the absence of snow) at this wavelength.

The MFRSRCLDOD VAP (henceforth referred to as "the VAP") retrieves cloud optical depth (τ) from the MFRSR measurements. If the LWP is available from a coincident MWR observation, then the droplet effective radius (r_e) can be determined. Knowledge of the estimated re can be used to improve the estimate of τ because there is a slight dependence on the extinction coefficient, single scattering albedo, and asymmetry parameter on effective radius at this wavelength. However, if the MWR's LWP is not available, then the VAP assumes that re = 8.0 μm. The primary output variables from the VAP are τ and r_e.

The VAP also provides 1-sigma uncertainties for τ and r_e by propagating the uncertainties in the top-of-atmosphere irradiance (I_0), the measured irradiance (I), the MWR's LWP, and the surface albedo.

2.0 Input Data

The input files for this VAP are standard ARM netCDF products. To run this VAP properly, we need the following input files and data[1]. Although specific datastreams are listed only for the SGP Central Facility, the VAP can also be run at the SGP extended facilities and at other fixed and mobile sites. Occasionally datastreams may vary slightly between sites/facilities. Information about specific datastreams required to run at other sites is available from the configuration files.

[1] For details of the input variables, see Appendix A.

2.1 Multifilter Rotating Shadowband Radiometer Instrument

sgpmfrsrE13.b1 – 20 s data

This datastream contains the observed irradiance data (I) from the MFRSR.

2.2 Microwave Radiometer Instruments

sgpmwrret1liljclouC1.c1 or sgpmwrlosC1.a1

The LWP from the MWR. The VAP was updated in 2011 to use the Microwave Radiometer Retrievals (MWRRET) datastream (Turner et al. 2007; Gaustad and Turner 2009) as the preferred source of LWP, but will use the MWRLOS datastream if MWRRET is not available.

2.3 Langley Value-Added Product

sgpmfrsrLangleyE13.c1 – 2 data points per day

This VAP provides the top-of-atmosphere irradiance (I_0) data.

2.4 Short Wave Flux Analysis Value-Added Product

sgp15swfanalsirs1longC1.c1

This VAP provides ancillary data for cloud sky cover fraction. The VAP product is described by Long and Gaustad (2004).

2.5 TSI Sky Cover

sgptsiskycoverC1.b1

This datastream provides the cloud sky cover fraction if the Shortwave Flux Analysis VAP is not available. The thin and opaque cloud percentages are summed to give a total cloud sky cover fraction equivalent to that in the shortwave flux analysis VAP.

2.6 Cloud Base Height Value-Added Product

sgparsclbnd1clothC1.c1

This VAP provides ancillary data for analyses regarding the height (and by inference the phase) of the clouds. The VAP product is described by Clothiaux et al. (2001).

2.7 Infrared Sky Temperature

sgpirtC1.b1

This datastream contains the observed infrared sky temperature.

2.8 Surface Albedo

The VAP requires an estimate of the surface albedo at 415 nm. The VAP currently uses a fixed value of 0.036 as representative of the green vegetation. Because the VAP is not particularly sensitive to the value of the albedo if it is small, this value is used at SGP, Tropical Western Pacific (TWP), and ARM Mobile Facilities (AMF) sites without significant snow cover. At a site like North Slope of Alaska (NSA) when you have frequent snow-covered ground with high albedo, an accurate albedo is important. We have currently run the VAP at NSA using the SURFSPECALB (Surface Spectral Albedo) VAP as input. This needs significant work to validate and refine, so the data have been placed in the evaluation area until such time as they can be further improved.

3.0 Output Data

The name of the output file is:

<SSS>MFRSRCldOD1Min<FF>.c1.YYYYMMDD.hhmmss – 20 s data

where:

SSS	–	the site of the instrument
MFRSR	–	the main instrument name
CldOD1Min	–	identifies that this is Min's version 1 VAP
FF	–	facility
YYYY	–	year, MM - month of the year, DD - day of the month, hh - hour of the day, mm - minute of the hour, ss - second of the minute of data start

The detailed variable description is in Table B.1 of Appendix B.

This VAP generates four quicklook plots:

1. SSSmfrsrcldod1minFF.c1.YYYYMMDD.hhmmss.Io.png
2. SSSmfrsrcldod1minFF.c1.YYYYMMDD.hhmmss.effective_radius.png
3. SSSmfrsrcldod1minFF.c1.YYYYMMDD.hhmmss.lwp.png
4. SSSmfrsrcldod1minFF.c1.YYYYMMDD.hhmmss.optical_depth.png

The first plot is the I_0 calibration plot shown in Figure 1 and discussed in Section 4.0. The other three quicklooks illustrate the cloud optical properties and are discussed in Section 5.0.

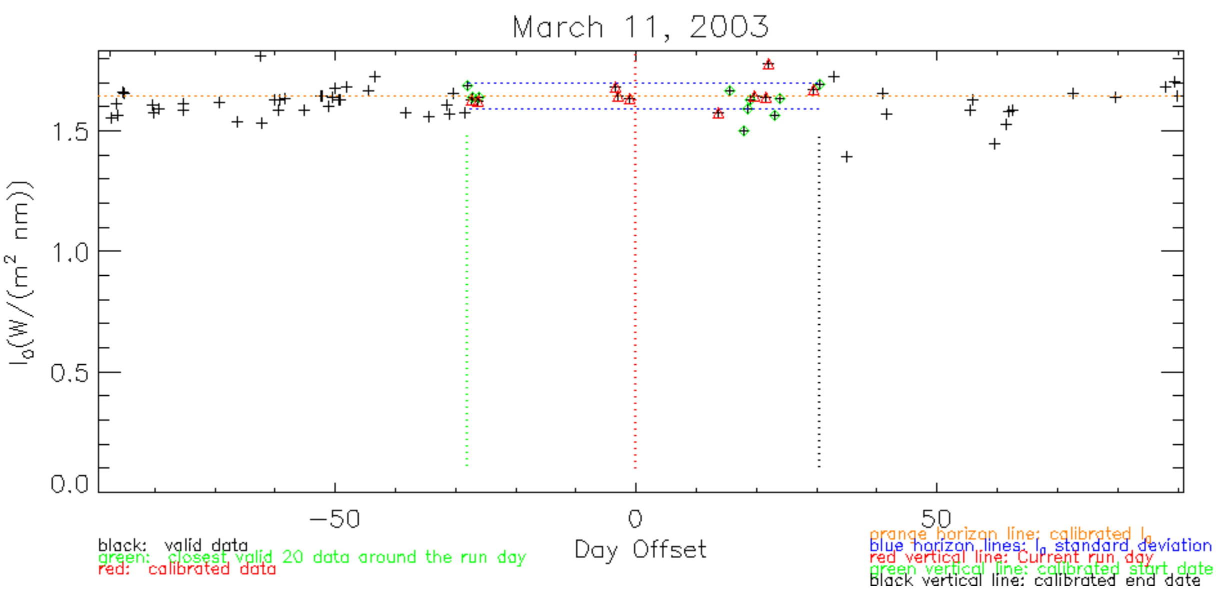

Figure 1. I_0 calibration quicklook plot.

4.0 Algorithm/Method

The functioning heart of this VAP is the Nonlinear Least Squares retrieval algorithm of Min and Harrison (1996). This algorithm uses a parameterization of the scattering properties at 415 nm on the effective radius and LWP using Mie theory. The algorithm uses an adjoint formulation of the radiative transfer to maintain accuracy and improve its execution speed. It uses an iterative approach to retrieve both cloud optical depth and effective radius if an estimate of LWP is provided; otherwise the effective radius is assumed and the algorithm returns only optical depth.

The algorithm requires the atmospheric transmittance at 415 nm. This is easily computed using the observed irradiance I and the top of the atmosphere irradiance I_0, where I_0 is computed from Langley regressions on clear days. Because data from the MFRSR are used to obtain both I and I_0, the absolute calibration of the instrument is not required to get accurate observations of the atmospheric transmittance.

A previously developed Langley analysis VAP routinely analyzes the MFRSR data and computes I_0. However, the most accurate values of I_0 are obtained only on days that are free of clouds and stable. Furthermore, a maximum of two Langley regressions could be computed for a single day. Because the current VAP is concerned with cloud properties, the I_0 values used in the current VAP are computed from I_0 values determined on nearby clear sky days. We have automated a procedure to determine an accurate value of I_0. The VAP reads in all of the I_0 data that were determined to be good by the Langley analysis VAP for 3 months before and after the day currently being processed. From this large data set, we select the 20 closest in time I_0 values at SGP, and the 10 I_0 values closest in time at TWP and AMF sites.

We then follow the procedure outlined by Michalsky et al. (2001) to select the best half of a given number of points; the mean value of these points is used as the I_0 for the processing. At SGP, 10 out of 20 points were used to define the average I_0, but at TWP and AMF sites, where clear skies are less frequent, we reduced this requirement to five out of 10 points. The uncertainty in I_0 represented by the standard deviation about the mean I_0 value of the 10 points is propagated to provide uncertainties in the retrieved cloud properties. Figure 1 shows a quicklook plot that displays all of the I_0 values determined by the Langley algorithm VAP, the 20 closest points, and the mean and standard deviation of the I_0 value used in the VAP.

In 2010, the Langley VAP was updated to address the fact that quarterly calibrations to the MFR heads were causing discontinuities in the Langley data. Rather than using the already calibrated irradiance data and calculating I_0 in units of "$W/m^2/nm$," the new version of the Langley VAP removes the calibration factor from the irradiance data before calculating I_0 and hence reports I_0 in units of "counts." This new version of the Langley code was applied to the MFRSR data at different points in time at different sites/facilities and all of the historical data have not yet been reprocessed. To move ahead with processing of the MFRSRCLDOD VAP without waiting for historical reprocessing of the Langley data, a command line option specifying the expected units of the I_0 value was implemented. If the units are "$W/m^2/nm$," the VAP calculates the transmittance as before, but if the units are "counts" the transmittance is calculated by first multiplying the irradiance value by the calibration factor (read from the mfrsr.b1 file for the given day) to convert the irradiance to counts and then dividing by the I_0 value. For either case, the VAP checks the units of the input I_0 values and does not include any points in the average that do not match the units specified on the command line. At times immediately around the transition period from the old units to new units, there may not be enough valid I_0 values with the correct units. Therefore at this time, we do not run MFRSRCLDOD on data within +/- 1.5 months of the transition at each site. The dates of the transition at each site are listed in Table A.1. Once the historical Langley data have been reprocessed at each site, they will also be reprocessed through the MFRSRCLDOD VAP.

The LWP from the MWR, while not critical for the execution of the VAP, permits the retrieval of effective radius. The preferred datastream for LWP is the MWRRET VAP datastream (Turner et al. 2007; Gaustad and Turner 2009), but if it is not available the standard MWRLOS datastream is used instead. The VAP applies some simple quality control to ensure that the reported LWP is valid. If the observed brightness temperature at either MWR frequency is below the cosmic background or above 100K (the latter condition is usually indicative of rain) then the LWP value from the MWR is not used in the retrieval. Furthermore, because the uncertainty in the MWR's retrieval LWP is approximately 20 g m^{-2} (Westwater et al. 2001), the VAP does not use the MWR's observed LWP in the retrieval if the LWP is below this threshold. When no LWP is available, the retrieval algorithm assumes that the effective radius is 8 μm.

The temporal resolution of the MFRSR irradiance data is 20 s, and therefore the ancillary inputs are interpolated to this time. Interpolation of the LWP is usually required. The LWP is interpolated across gaps of a maximum of 5 min. If the temporal gap is larger than this, then the retrieval is run without LWP input for those MFRSR samples.

Because this VAP can be run at sites that have an MFRSR but not an MWR, such as the ARM extended facilities, if an input LWP value is not provided then the VAP uses the retrieved optical depth and assumed effective radius to provide an estimate of the LWP using

$$LWP = (2/3) * \rho * \tau * r_e$$

where ρ is the density of liquid water, τ is retrieved by the VAP, and re was assumed. This provides estimates of the LWP at sites where MWRs are not deployed. However, due to the natural variability in re the uncertainty in this derived LWP is large. A flag, 'lwp_source', is set in the output file and indicates whether the output LWP is from the MWR (and if so, which datastream and variable) or from this calculation.

The retrieval algorithm operates at two temporal resolutions. It provides "instantaneous" retrievals at the nominal 20-s resolution of the MFRSR and "average" retrievals where the data have been averaged for 5 min centered upon the output sample time. The average retrievals are less sensitive to the spatial inhomogeneities in the cloud, which affect the diffuse irradiance field.

As indicated above, the VAP provides 1-sigma uncertainties for both the retrieved optical depth and effective radius by propagating the uncertainties in the input and assumed parameters. The uncertainty in the I_0 value is the standard deviation about the mean I_0 as described above. If the LWP is available from the MWR, the uncertainty in the LWP is assumed to be 20 g m^{-2}. The uncertainty in the observed irradiance is assumed to be 1%. The surface albedo, which is taken to be 0.036 at 415 nm in non-snow-covered conditions, is assumed to have an uncertainty of ±0.01. These uncertainties are propagated individually using finite differences and are combined as the root sum of squared errors (i.e., these uncertainties are assumed to be independent). The uncertainty in the retrieved optical depth is dominated by the uncertainty in I_0, while the uncertainty in the LWP is the dominant term in the effective radius uncertainty. Figure 2 and Figure 3 present examples of distributions of each component of the total uncertainty to the uncertainty in τ and r_e, respectively, as well as the distributions of the total uncertainty in each retrieved variable for data from the SGP site over a 6-month period.

Finally, this VAP provides some ancillary data to help the analyst find cases where the retrieval is valid. The Fractional Sky Cover from the Shortwave Analysis VAP (Long and Gaustad 2004) or the TSISKYCOVER datastream is included because the retrievals from this VAP are only valid in overcast scenes. Cases with sky cover <0.7 are flagged as bad and cases with 0.7 <= sky cover <= 0.9 are flagged as indeterminate. The cloud base height from the Active Remote Sensing of Clouds (ARSCL) VAP (Clothiaux et al., 2001), along with the infrared thermometer sky brightness temperature, are included because the retrievals are also only valid for single layer liquid water clouds. Because cloud phase depends on the site, season, and cloud type, and because cloud base information is not available at the extended facilities, we do not currently flag data based on the cloud base height. However, when available, the user should use these fields to help select the proper cases to analyze.

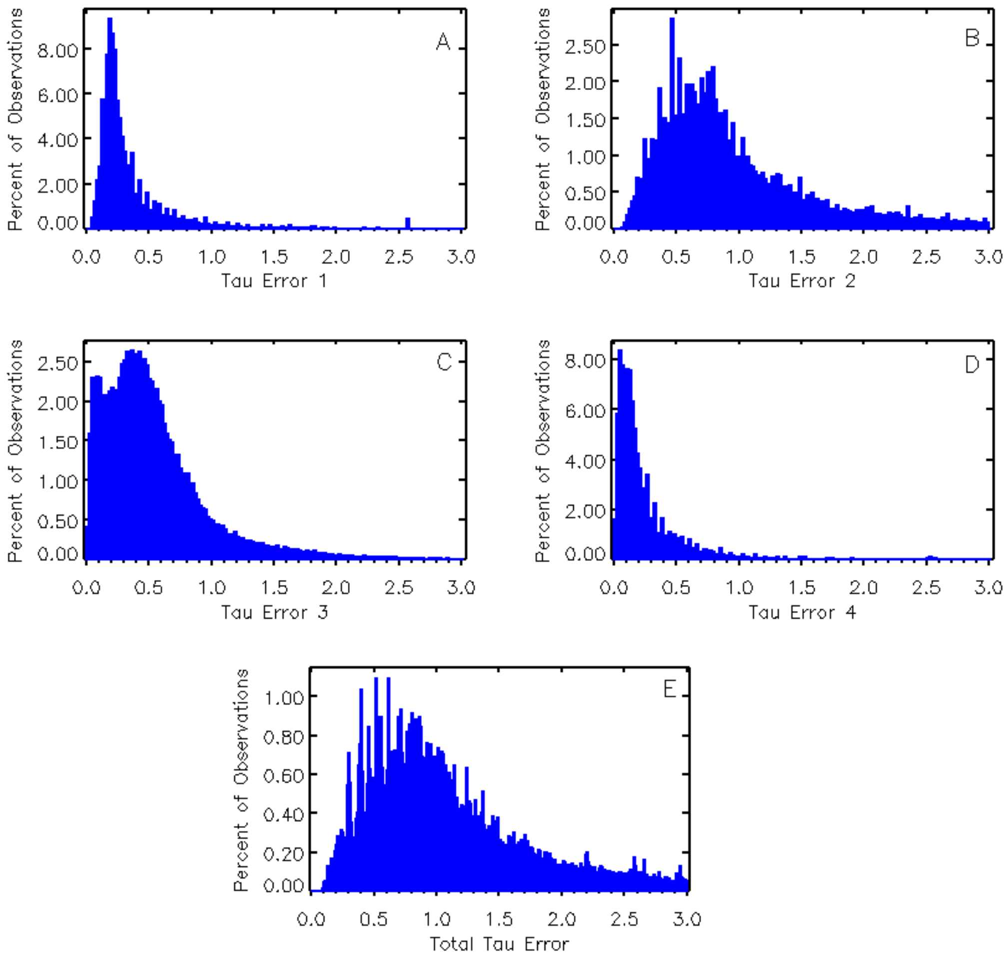

Figure 2. Distribution of the uncertainties in cloud optical depth for uncertainties in A) I, B) I_0, C) LWP, and D) surface albedo. Panel E shows the distribution of the total uncertainty in the cloud optical depth for this 6-month period (January–June 2003).

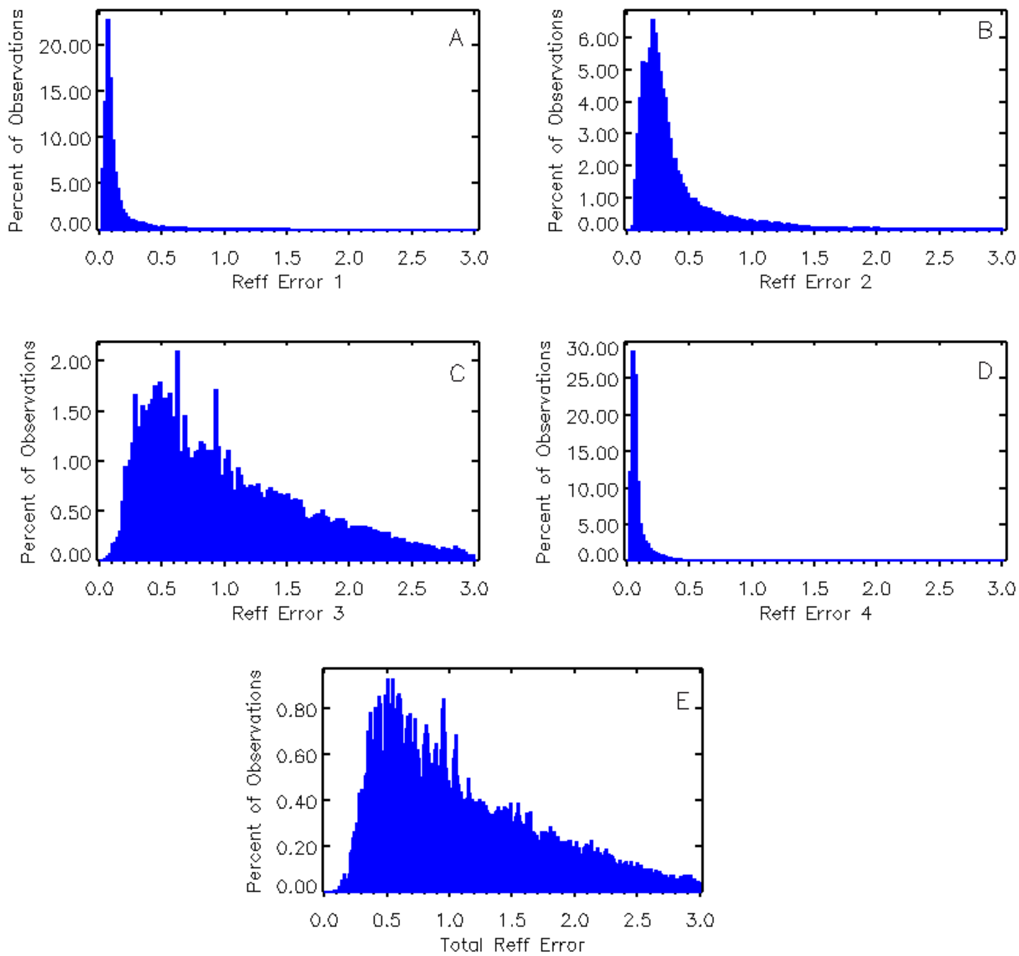

Figure 3. Distribution of the uncertainties in effective radius for uncertainties in I, B) I_0, C) LWP, and D) surface albedo. Panel E shows the distribution of the total uncertainty in the cloud optical depth for this 6-month period (January–June 2003).

5.0 Examples

This VAP runs on a daily basis. Four quicklook plots are generated every day; one is the I_0 calibration in Figure 1 as explained before and the other three are multi-panel plots showing retrieved cloud properties, quality control flags, and source flags. More details about the quality control (qc) flags are given in Section 6.0. Figure 4 through Figure 6 give examples of the quicklooks for March 11, 2003, at SGP E13. The valid MFRSR data start around 13:50 Universal Time Coordinates (UTC) and ends around 24:00. An overcast liquid water cloud persisted during this time period, as evidenced by the low cloud base heights and high values of cloud fraction (bottom two panels in Figure 4). The top panel of Figure 4 shows the derived cloud optical depth data for instantaneous (20-s) and averaged (5-min) resolutions and the next panel shows the quality control checks on the instantaneous optical depth values. In general, the retrievals were good throughout the cloud period, although there were a few indeterminate values near sunrise/sunset. Data are flagged as bad/missing at night when MFRSR data are not as available. Figure 5 (top panel) shows the LWP values that were either input from the MWR or derived from the MFRSR.

The middle and bottom panels show the quality control checks on the LWP and the source for LWP values, respectively. During most of the period from 14:00 to 24:00 UTC, the LWP is derived from the 'be_lwp' variable in the MWRRET datastream (Gaustad and Turner 2009) and the data is flagged as good. However, during parts of the period between 18:30 and 24:00 UTC, data from the MWR are not available so LWP is derived from the MFRSR optical depth using an assumed effective radius of 8 μm. These LWP values are flagged as indeterminate because the true effective radius is not known.

Figure 6 shows the retrieved instantaneous and averaged effective radius, quality control checks on the effective radius, and the cloud fraction and cloud base heights. As in Figure 4, data at night are flagged as bad/missing because MFRSR data are not available. During the day, the effective radius values are flagged as good when independent measurements of LWP are available, and flagged as indeterminate when LWP is not available and the assumed value of 8.0 μm is used (periods between 18:30 and 24:00 UTC).

The 6 months of data from January 1 to June 30, 2003, are show in Figure 7 and the distributions of the cloud properties for this period are shown in Figure 8. Only valid data meeting the following criteria are included in Figure 7 and Figure 8. The criteria are cloud fraction >90 %, cloud base height <4 km, optical depth >7, effective radius ≠8.00 μm (because an effective radius equal to 8 μm implies that the LWP from the MWR was not available or not used), and effective radius >0.

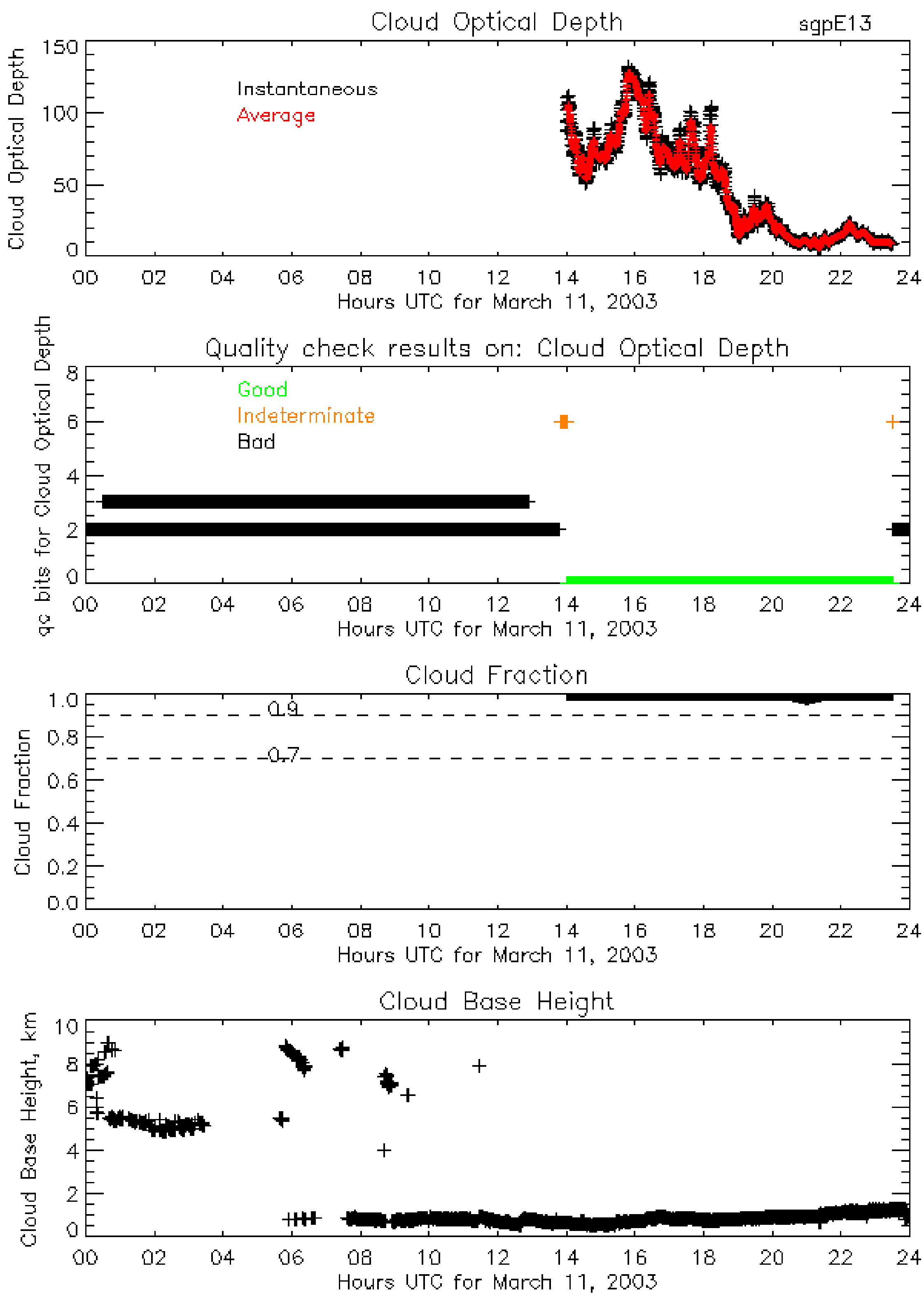

Figure 4. Quicklook image showing cloud optical depth, qc flags on optical depth, cloud fraction, and cloud base height for March 11, 2003, at SGP E13.

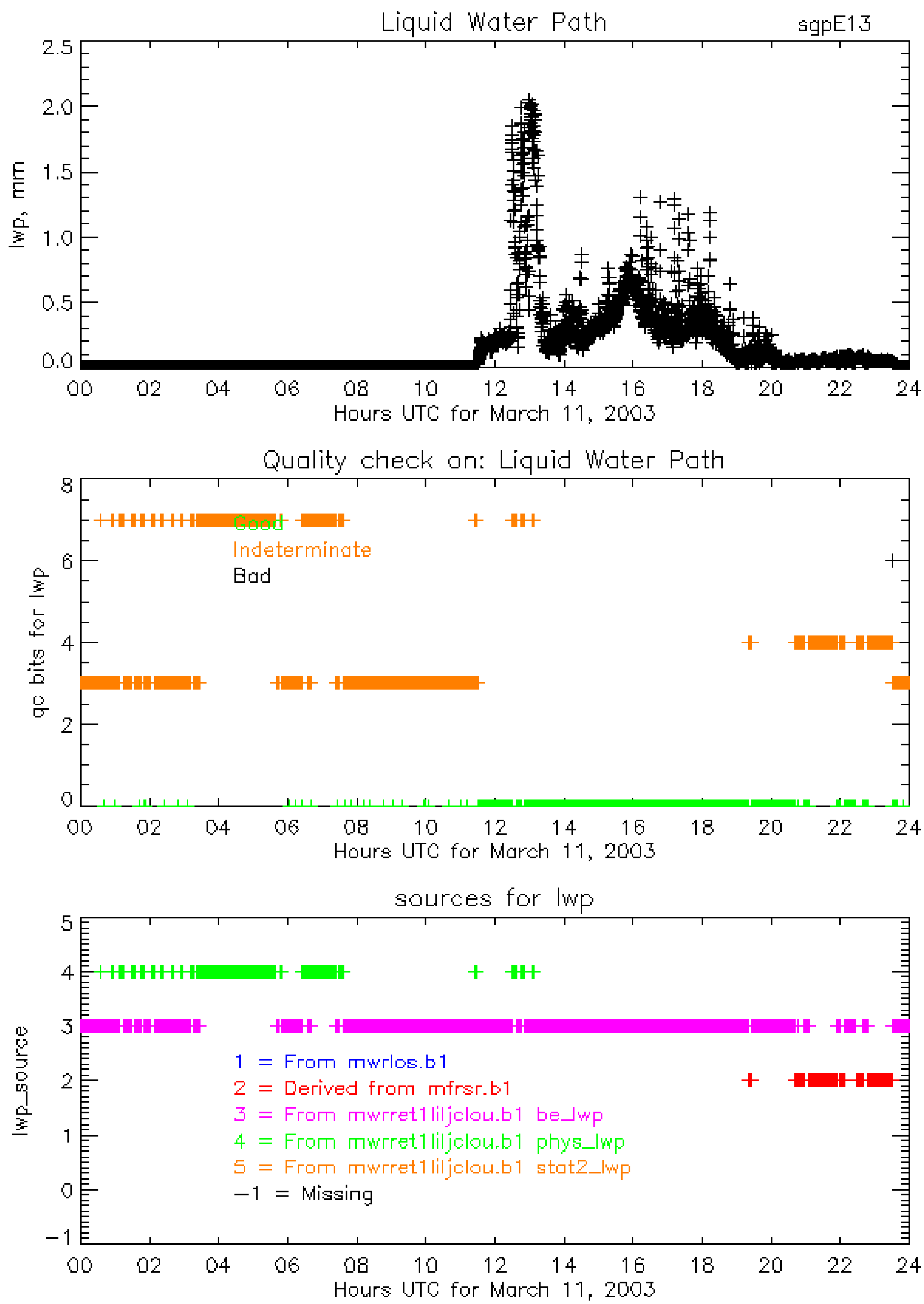

Figure 5. Quicklook image showing LWP, qc flags on LWP, and LWP source for March 11, 2003, at SGP E13.

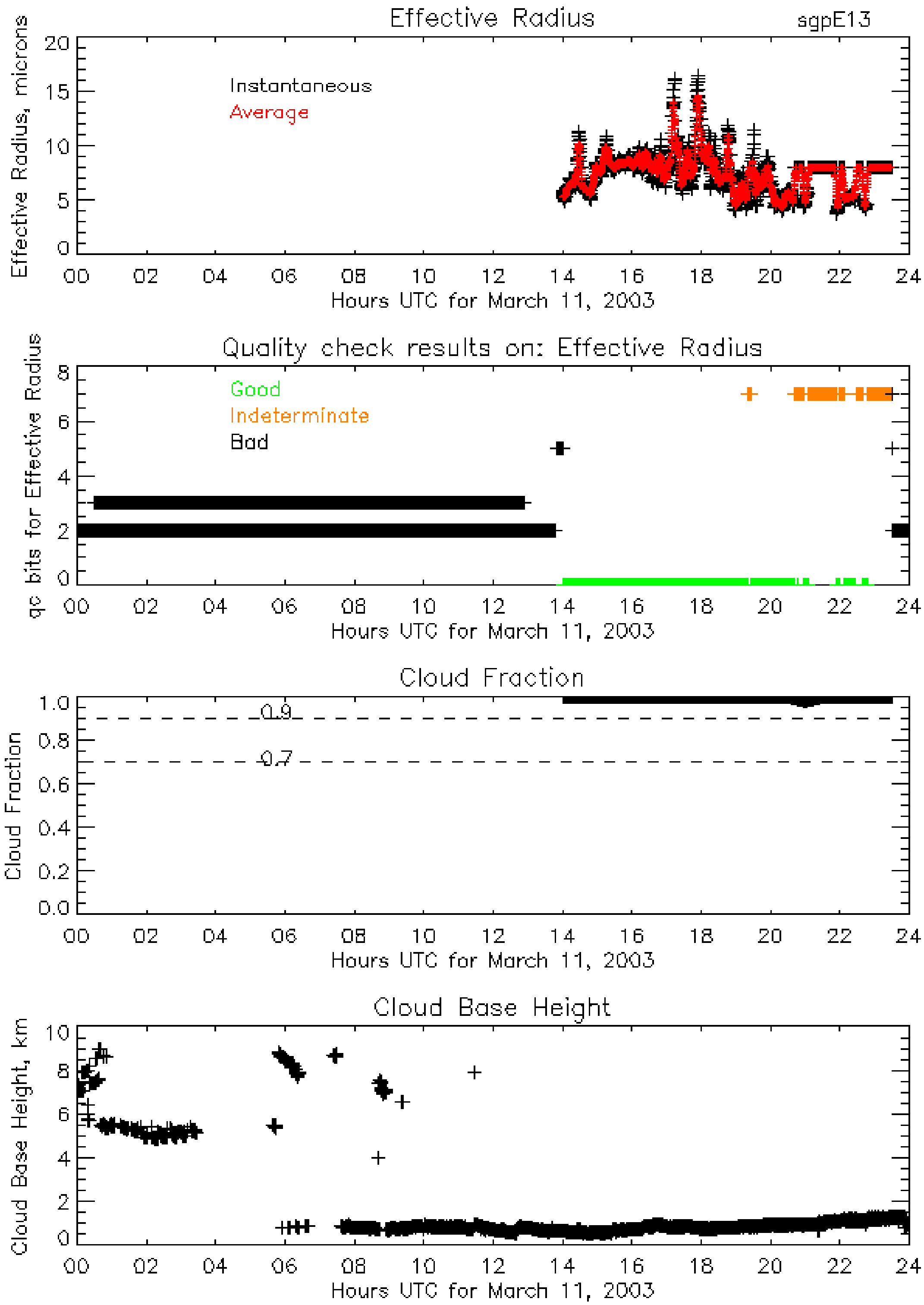

Figure 6. As in Figure 4, but for effective radius.

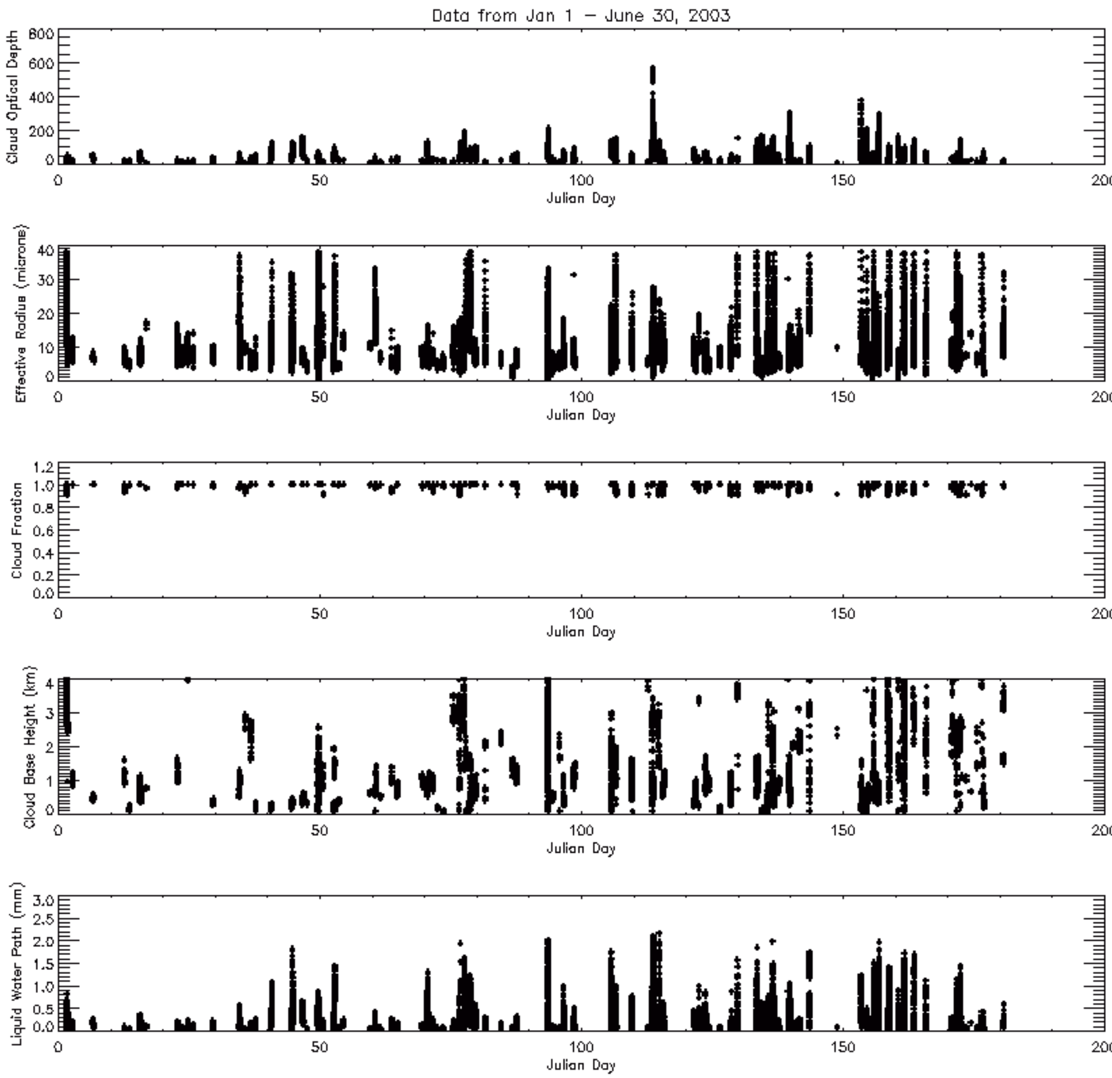

Figure 7. Retrieved cloud optical properties for 6 months of data at the SGP Central facility starting 1 January 2003. A) retrieved τ, B) retrieved re, C) cloud fraction from Shortwave Flux Analysis VAP, D) cloud base height from ARSCL VAP, E) LWP from the MWR.

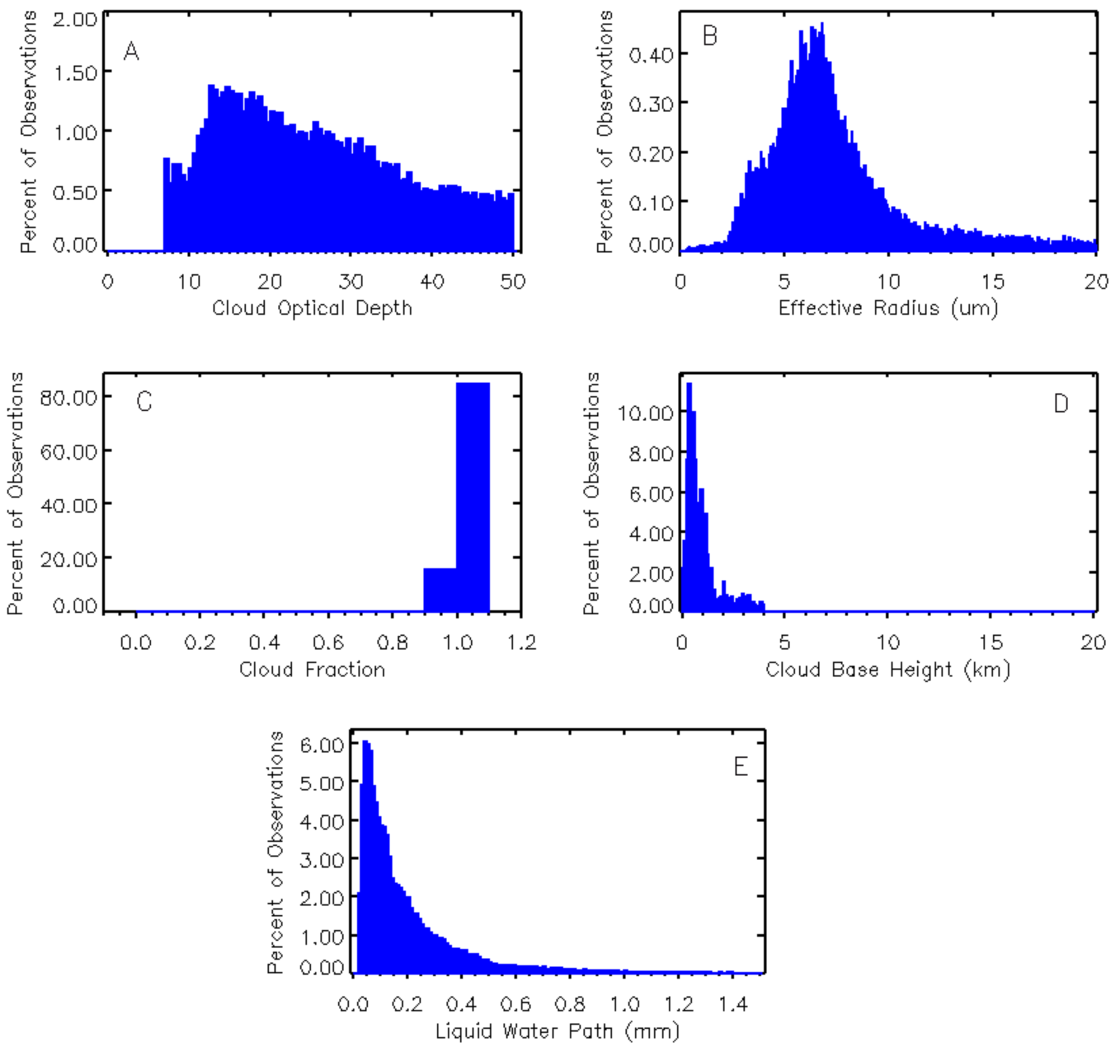

Figure 8. Distributions of the retrieved cloud optical depth (A) and effective radius (B) from 1 January to 30 June 2003. Panel C, D, and E show the corresponding cloud fraction, cloud height, and LWP.

6.0 Quality Control Flags

ARM standard (bit-packed) qc flags are included on almost all variables in the output file. Exceptions are variables such as ‘lwp_source’, which are themselves flags on a given variable. Here we document the primary qc checks performed in the VAP:

- Valid minimum/maximum tests are performed on each input and output variable; values outside of these ranges are flagged as bad and set to -9999.
- Because the retrieval is only valid for overcast skies, the sky cover or cloud fraction from the shortwave flux analysis is used to assess the validity of the retrieval. Periods with cloud fraction between 0.7 and 0.9 are flagged as indeterminate. Periods with cloud fraction <0.7 are flagged as bad and retrieved data are set to -9999.

- When an input LWP value is not available, the default effective radius of 8.0 μm is used and the effective radius and LWP are flagged as indeterminate.
- The VAP estimates errors in the retrieved effective radius and optical depth by perturbing the input values slightly and re-running the retrieval. For cases where the default effective radius is used, some of these error terms cannot be calculated. In these cases these error terms are flagged as bad and the values are set to -9999. For sites that do not have MWRs, these error terms will always be flagged as bad and set to -9999.
- Along with instantaneous values, the VAP reports values of optical depth, effective radius, and error terms averaged over a 5-minute period. If any of the instantaneous values within that 5-minute period are bad, then the average values for the period are flagged as bad and set to -9999. If any of the instantaneous values used in the average are indeterminate then the average value is also flagged as indeterminate.

7.0 Known Caveats

Known caveats include the following:

- Only valid for overcast conditions where cloud is liquid. Because there is no gaseous absorption at this wavelength (415 nm), the retrieval will be valid for both single layer and multiple layer cloud conditions, as long as all layers are overcast and composed entirely of liquid drops.
- Assumes the surface is not covered with snow or ice. In the future, we plan to bring in additional ancillary data sets to create a snow/ice flag. This will be particularly important for implementation at the NSA site.
- Biases in the MWR's LWP, especially for small optical depths, will bias the retrieved effective radius.

8.0 VAP Updates in 2011−2013

This technical report describes the current version of the MFRSRCLDOD VAP (version 2.6.0), which was released in October 2013. Significant updates were made to the VAP in 2012-2013. A detailed description of the updates, and their impact on the data, is given by McFarlane and Shi (2012). A very brief list of the major updates is included here:

1. When available, the VAP now uses LWP from the MWRRET VAP (Gaustad and Turner 2009), rather than the Microwave Water Radiometer: Water Liquid And Vapor Along Line Of Sight (LOS) Path (MWRLOS) datastream, to retrieve effective radius. The 'lwp_source' flag in the output file indicates the source of the LWP value.
2. The mfrsrcldod1min datastream was changed so that each file contains data from 0000 to 2400 UTC to be consistent with other ARM datastreams and to simplify operation when implemented at other sites. (Previously, datastream was run on a solar day, from 0600 to 0600 UTC at the SGP).
3. Changes in processing were implemented because of changes in Langley VAP, as described in Section 4.0.

4. Quality control flags were added to the VAP output, as described in Section 6.0. Details for reading bit-packed qc flags can be found at https://engineering.arm.gov/~shippert/ARM_bits.html.
5. Changes to the DOD. Numerous small changes were made to the netCDF header, including fixes in variable names (e.g., 'optical_depth_instaneous' corrected to 'optical_depth_instantaneous') and other changes required to meet new ARM DOD standards.
6. Quicklook plots were updated and names were modified to follow new ARM standards.
7. Based on the end-to-end MFRSR reprocessing, we have extended the application of the mfrsrcldod1min VAP to all historical MFRSR data available and to all SGP extended/boundary facilities (previously only E13 data were processed).
8. The VAP was updated to run on TWP and AMF data—including a change to only require 10 rather than 20 good I_0 data points in order to enable it to run on more cases, and using WACRARSCL and TSISKYCOVER when these data sets are the primary cloud boundary and cloud fraction measurements at a site.
9. Preliminary data were run for the NSA Barrow site using the Surface Spectra Albedo (SURFSPECALB) VAP to give the 415 nm albedo. These data have been placed in the ARM database evaluation area until they undergo further validation.
10. The VAP has now been ported to run in the ARM Data Integrator, improving the interaction between the VAP and ARM databases and tools.

9.0 References

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Appendix A

Table A.1 lists the various ARM datastreams used in the VAP for data, along with the specific variables in files that are used in processing. In the datastream names, SSS indicates site (SGP, TWP, or NSA) and FF represents facility (C1, C2, E1, E2, etc.).

Table A.1. Input variables.

Datastream	Variable Name	Variable Long Name	Units
SSSmfrsrFF.b1	cosine_solar_zenith_angle	Cosine Solar Zenith Angle	unitless
	hemisp_narrowband_filter1	Narrowband Hemispheric Irradiance, Filter 1	W/(m^2 nm)
	hemisp_narrowband_filter2	Narrowband Hemispheric Irradiance, Filter 2	W/(m^2 nm)
	hemisp_narrowband_filter3	Narrowband Hemispheric Irradiance, Filter 3	W/(m^2 nm)
	hemisp_narrowband_filter4	Narrowband Hemispheric Irradiance, Filter 4	W/(m^2 nm)
	hemisp_narrowband_filter5	Narrowband Hemispheric Irradiance, Filter 5	W/(m^2 nm)
	direct_normal_narrowband_filter1	Narrowband Direct Normal Irradiance, Filter 1	W/(m^2 nm)
	direct_normal_narrowband_filter2	Narrowband Direct Normal Irradiance, Filter 2	W/(m^2 nm)
	direct_normal_narrowband_filter3	Narrowband Direct Normal Irradiance, Filter 3	W/(m^2 nm)
	direct_normal_narrowband_filter4	Narrowband Direct Normal Irradiance, Filter 4	W/(m^2 nm)
	direct_normal_narrowband_filter5	Narrowband Direct Normal Irradiance, Filter 5	W/(m^2 nm)
SSSmwrret1liljclouFF.c1	be_pwv	Precipitable water vapor best estimate value	cm
	qc_be_pwv	Quality check results on field: be_pwv	unitless
	be_lwp	LWP best estimate value	g m^{-2}
	qc_be_lwp	Quality check results on field: be_lwp	unitless
	phys_lwp	Cloud LWP retrieved using a physical/iterative approach	g m^{-2}
	qc_phys_lwp	Quality check results on field: phys_lwp	
	stat2_lwp	Cloud LWP retrieved using predicted mean radiating temperatures and retrieval coefficients	g m^{-2}
	qc_stat2_lwp	Quality check results on field: stat2_lwp	
	tbsky23	Sky brightness temperature at 23.8 GHz	K
	tbsky31	Sky brightness temperature at 31.4 GHz	K

Table A.1. (contd)			
Datastream	**Variable Name**	**Variable Long Name**	**Units**
SSSirtFF.b1	sky_ir_temp	Sky Infrared Temperature	K
SSSmwrlosFF.b1	vap	Total water vapor along LOS path	cm
	liq	Total liquid water along LOS path	cm
	tbsky23	23.8 GHz sky brightness temperature	K
	tbsky31	31.4 GHz sky brightness temperature	K
	sky_ir_temp	IR Brightness Temperature	K
SSSmfrsrlangleyFF.c1	barnard_solar_constant_sdist_filter1	solar constant corrected for solar distance for the Direct Narrowband and Filter 1	$W/(m^2$ nm)
	barnard_solar_constant_sdist_filter2	Solar constant corrected for solar distance for the Direct Narrowband and Filter 2	$W/(m^2$ nm)
	barnard_solar_constant_sdist_filter3	Solar constant corrected for solar distance for the Direct Narrowband and Filter 3	$W/(m^2$ nm)
	barnard_solar_constant_sdist_filter4	Solar constant corrected for solar distance for the Direct Narrowband and Filter 4	$W/(m^2$ nm)
	barnard_solar_constant_sdist_filter5	Solar constant corrected for solar distance for the Direct Narrowband and Filter 5	$W/(m^2$ nm)
	barnard_badflag_filter1	Rejection flag for Direct Narrowband Filter 1	unitless
	barnard_badflag_filter2 barnard_badflag_filter3 barnard_badflag_filter4 barnard_badflag_filter5	Rejection flag for Direct Narrowband Filter 2 rejection flag for Direct Narrowband Filter 3 rejection flag for Direct Narrowband Filter 4 rejection flag for Direct Narrowband Filter 5	unitless unitless unitless unitless
SSS15swfanalsirs1longFF.c1	cloudfraction	Estimated Average Fractional Sky Cover over the Hemispheric Dome (cloud fraction)	unitless
SSSarsclbnd1clothFF.c1	cloudbasebestestimate	LASER Cloud Base Height Best Estimate	m AGL
SSStsiskycoverFF.b1	percent_opaque	Percent opaque cloud	%
	percent_thin	Percent thin cloud	%

Appendix B

Table B.1 lists the detailed description of the variables in the MFRSRCLDOD1MIN VAP output file. In addition to the variables listed below, quality control variables are included on every output variable except base_time, time_offset, lwp_source, Io_flag_filter1, and Io_filter1_final. Quality control variables have field names ‘qc_variablename’ where ‘variablename’ is the variable of interest.

Table B.1. Output variables.

Fieldname	Description	Units
base_time	Base Time in Epoch	seconds since 1970/01/01 00:00:00
time_offset	Time offset from base_time	seconds since base_time
time	Time offset from midnight	seconds since midnight
optical_depth_instantaneous	Cloud Optical Depth (Instantaneous)	unitless
effective_radius_instantaneous	Effective Radius (Instantaneous)	microns
optical_depth_average	Cloud Optical Depth (Average)	unitless
effective_radius_average	Effective Radius (Average)	microns
cldtaui_error1	Cloud Taui Error1 (1% uncertainty in total irradiance)	unitless
cldtaui_error2	Cloud Taui Error2 (5% uncertainty in I_0)	unitless
cldtaui_error3	Cloud Taui Error3 (uncertainty in liquid water path (LWP) 0.015 mm larger)	unitless
cldtaui_error4	Cloud Taui Error4 (20% uncertainty in surface albedo)	unitless
cldtaui_error5	Cloud Taui Error5 (uncertainty in 3 μm higher of effective radius when there is noMWR data)	unitless
cldtaui_toterror	Instantaneous Cloud Tau Total Uncertainty	unitless
cldtaua_error1	Cloud Taua Error1 (1% uncertainty in total irradiance)	unitless
cldtaua_error2	Cloud Taua Error2 (5% uncertainty in I_0)	unitless
cldtaua_error3	Cloud Taua Error3 (uncertainty in LWP 0.015 mm larger)	unitless
cldtaua_error4	Cloud Taua Error4 (20% uncertainty in surface albedo)	unitless
cldtaua_toterror	Average Cloud Tau Total Uncertainty	unitless
reffi_error1	Effective Radiusi Error1 (1% uncertainty in total irradiance)	microns
reffi_error2	Effective Radiusi Error2 (uncertainty is standard deviation of calibrated 10 I_0 points)	microns
reffi_error3	Effective Radiusi Error3 (uncertainty in LWP 0.001 mm larger, using scaling factor with 0.015 mm)	microns
reffi_error4	Effective Radiusi Error4 (uncertainty is 0.01 in surface albedo)	microns
reffi_toterror	InstaneousEffective Radius Total Error	microns

Table B.1. (contd)		
Fieldname	**Description**	**Units**
reffa_error1	Effective Radiusa Error1 (1% uncertainty in total irradiance)	microns
reffa_error2	Effective Radiusa Error2 (uncertainty is standard deviation of calibrated 10 I_0 points)	microns
reffa_error3	Effective Radiusa Error3 (uncertainty in LWP 0.001mm larger, using scaling factor with 0.015 mm)	microns
reffa_error4	Effective Radiusa Error4 (uncertainty is 0.01 in surface albedo)	microns
reffa_toterror	Average Effective Radius Total Error	microns
cosine_solar_zenith_angl e	Cosine Solar Zenith Angle	unitless
total_transmittance_filter1	Total Transmission of Narrowband Hemispheric Irradiance, Filter 1	unitless
total_transmittance_filter2	Total Transmission of Narrowband Hemispheric Irradiance, Filter 2	unitless
total_transmittance_filter3	Total Transmission of Narrowband Hemispheric Irradiance, Filter 3	unitless
total_transmittance_filter4	Total Transmission of Narrowband Hemispheric Irradiance, Filter 4	unitless
total_transmittance_filter5	Total Transmission of Narrowband Hemispheric Irradiance, Filter 5	unitless
direct_transmittance_filter 1	Direct transmittance of Narrowband Direct Normal Irradiance, Filter 1	unitless
direct_transmittance_filter 2	Direct transmittance of Narrowband Direct Normal Irradiance, Filter 2	unitless
direct_transmittance_filter 3	Direct transmittance of Narrowband Direct Normal Irradiance, Filter 3	unitless
direct_transmittance_filter 4	Direct transmittance of Narrowband Direct Normal Irradiance, Filter 4	unitless
direct_transmittance_filter 5	Direct transmittance of Narrowband Direct Normal Irradiance, Filter 5	unitless
pwv	Total water vapor along MWR LOS path	cm
lwp	Total liquid water along LOS path, it could come from either MWR or the MFRSR with an assumed effective radius	mm
ir_temp	IR Brightness Temperature	K
cloudfraction	Estimated Average Fractional Sky Cover over the Hemispheric Dome (cloud fraction)	unitless
cloudbasebestestimate	LASER Cloud Base Height Best Estimate	m AGL
lwp_uncertainty	LWP uncertainty if derived from MFRSR	mm
lwp_source	Data source used to determine LWP	unitless
Io_time	Langley time series	day fraction offset from 00:00 on this day
Io_filter1	Solar constant corrected for solar distance for the Direct Narrowb and Filter1	W/(m^2 nm)

Io_filter2	Solar constant corrected for solar distance for the Direct Narrowb and Filter2	W/(m^2 nm)
Io_filter3	Solar constant corrected for solar distance for the Direct Narrowb and Filter3	W/(m^2 nm)
Io_filter4	Solar constant corrected for solar distance for the Direct Narrowb and Filter4	W/(m^2 nm)
Io_filter5	Solar constant corrected for solar distance for the Direct Narrowb and Filter5	W/(m^2 nm)
Io_flag_filter1	I_0 flag rejection flag for Direct Narrowband Filter1	unitless
Io_filter1_final	The final I_0 that used to determine total transmission	W/(m^2 nm)
cal_start_date	Start day for the I_0 data selected for calibration	day fraction offset from 00:00 on this day
cal_end_date	End day for the I_0 data selected for calibration	day fraction offset from 00:00 on this day
Io_filter1_standard_deviation	Standard deviation of I_0 to the closest 10 points around the run day	W/(m^2 nm)