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DOE/SC-ARM-TR-140

Droplet Number Concentration Value-Added Product

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Revised March 2021

ARM

DISCLAIMER

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Summary

The ndrop_mfrsr value-added product (VAP) provides an estimate of the cloud droplet number concentration of overcast water clouds retrieved from cloud optical depth from the multi-filter rotating shadowband radiometer (MFRSR) instrument and liquid water path (LWP) retrieved from the microwave radiometer (MWR). When cloud layer information is available from vertically pointing lidar and radars in the Active Remote Sensing of Clouds (ARSCL) product, the VAP also provides estimates of the adiabatic liquid water path and an adiabatic parameter (beta) that indicates how divergent the LWP is from the adiabatic case. Quality control (QC) flags (qc_drop_number_conc), an uncertainty estimate (drop_number_conc_toterr), and a cloud layer type flag (cloud_base_type) are useful indicators of the quality and accuracy of any given value of the retrieval.

Examples of these major input and output variables are given in sample plots in section 6.

Acronyms and Abbreviations

ACI	aerosol-cloud interactions
ADI	ARM Data Integer
ARM	Atmospheric Radiation Measurement
ARSCL	Active Remote Sensing of Clouds
ASR	Atmospheric System Research
CAPI	Cloud-Aerosol-Precipitation Interactions
MFRSR	multi-filter rotating shadowband radiometer
MPL	micropulse lidar
MWR	microwave radiometers
netCDF	Network Common Data Form
NFOV	narrow field-of-view
PI	principal investigator
QC	quality control
SGP	Southern Great Plains
VAP	value-added product

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1.0 Introduction

Cloud droplet number concentration is an important factor in understanding aerosol-cloud interactions. As aerosol concentration increases, it is expected that droplet number concentration, N_d, will increase and droplet size decrease for a given LWP (Twomey 1977). This has a great impact on cloud albedo as smaller droplets reflect more shortwave radiation. However, the magnitude and variability of these processes under different environmental conditions is still uncertain. McComiskey et al. (2009) have implemented a method, based on Boers and Mitchell (1994), for calculating Nd from ground-based remote sensing measurements of optical depth and LWP. They show that the magnitude of the aerosol-cloud interactions (ACI) vary with a range of factors including the relative value of the cloud LWP, the aerosol size distribution, and the cloud updraft velocity. Estimates of Nd under a range of cloud types and conditions, and at a variety of sites, are needed to further quantify the impacts of ACI.

In order to provide data sets for studying ACI to the Atmospheric System Research (ASR) science community, the McComiskey et al. (2009) method has been implemented as the Droplet Number Concentration (hereafter, NDROP) value-added product (VAP), proposed by the Cloud-Aerosol-Precipitation Interactions (CAPI) working group.

2.0 Input Data

The required input data are a time series of LWP, optical depth (tau), cloud boundaries, and cloud base temperature and pressure for liquid clouds. Default values of cloud base temperature and pressure are used when measurements are not available, but the retrieval is more accurate with good estimates of these quantities from measurements.

LWP is available from the mwrret1lilj product, which is valid solely for the two-channel microwave radiometers (MWRs). A new version of the LWP retrieval, mwrret2turner, which uses a new microwave absorption model and can be applied to three-channel MWRs to provide increased accuracy for low LWP clouds, is planned and some principal investigator (PI)-level data exists. The VAP is currently designed to work with the mwwret1lilj datastream, but there will be added capability to use the mwrret2turner datastream when it is available.

The current implementation of the NDROP VAP uses optical depths obtained from the mfrsrcldod1min product. However, these optical depths are only valid for overcast liquid water clouds. Users are also interested in optical depth and cloud-aerosol interactions for broken clouds. Thus, a retrieval of optical depth from the narrow field-of-view 2 (NFOV2) instrument is also planned. The NFOV2 instrument does not exist at all sites and VAP-level data from this instrument is not yet available. There will be capability added to use the NFOV optical depth datastream when it is available.

Cloud boundary information is available from the Active Remote Sensing of Clouds (ARSCL) products. If ARSCL is not available, cloud base height is determined from the ceilometer datastream, vceil25k. Cloud base temperature and pressure are derived from combining the cloud base height information with the Merged Sounding product.

The input data sets are gridded onto a common temporal grid using Atmospheric Radiation Measurement (ARM; ARM Data Integer (ADI)) functions.

3.0 Algorithm and Methodology

A flowchart of the NDROP VAP algorithm is given below. A description of the major processes is given in the following sections.

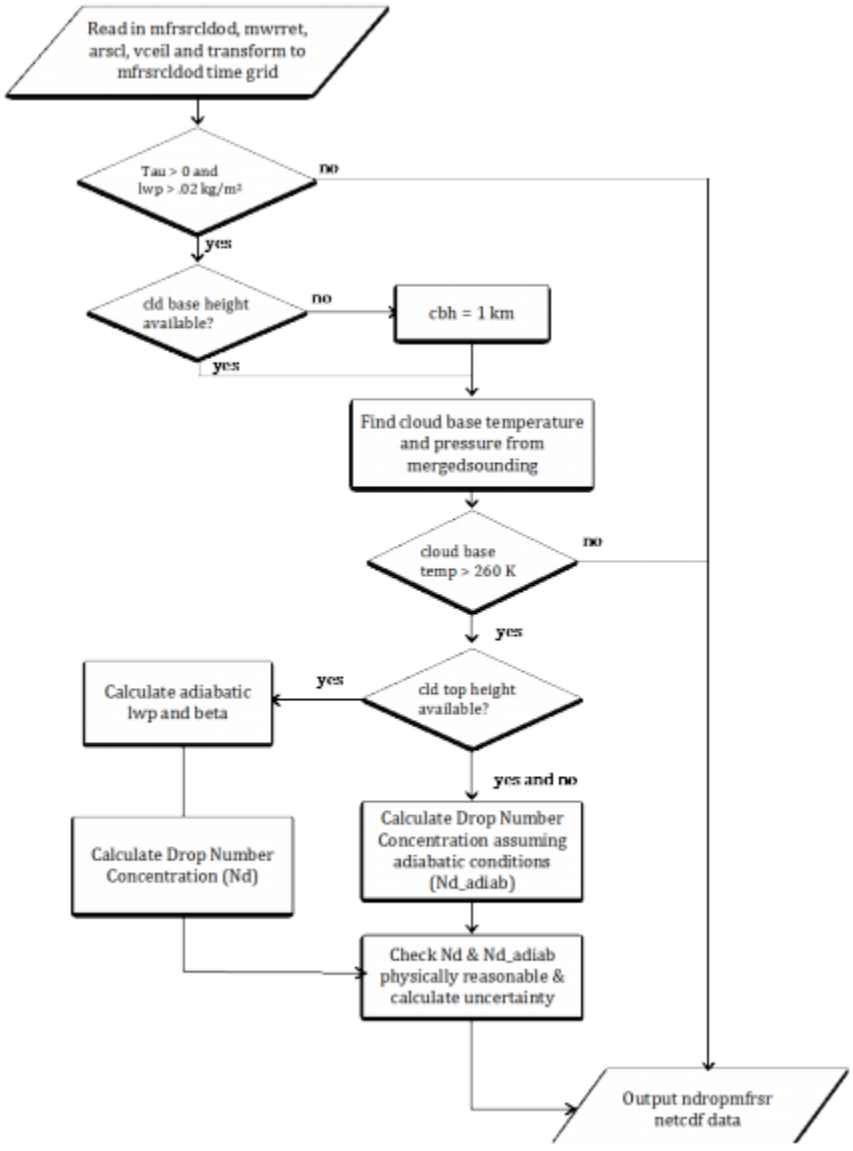

Figure 1. A flowchart of the NDROP VAP algorithm.

3.1 Calculating Adiabatic LWP and Beta

When cloud base thickness is available, adiabatic LWP and an estimate of the adiabaticity parameter (β) are calculated.

Following Boers and Mitchell (1994) and Bennartz (2007), assuming an adiabatic cloud model, the LWP can be defined as:

$$LWP = \frac{1}{2}(1-\beta)C_w H^2 \quad (1)$$

where H is the cloud thickness, β is a mixing parameter (β = 0 for an adiabatic cloud, 0 < β < 1 for a sub-adiabatic cloud), and C_w is the adiabatic condensation rate, which depends on cloud base temperature and pressure.

The adiabatic LWP is found by setting β = 0, and solving Eq (1) using the cloud height information.

By comparing the measurement of LWP from the microwave radiometer to the calculated adiabatic LWP, it can be estimated how much the cloud has mixed with its environment. As can be seen from Eq (1), we can solve for this mixing or adiabaticity parameter β using the following equation,

$$\beta = 1 - LWP_{mwr}/LWP_{adiab} \quad (2).$$

When implementing this calculation, we constrain β to remain in the physically valid range of 0 to 1, thus if β is less than zero, then we set beta to zero, and if β is greater than 1 we set β to 1. These values are most likely to occur due to uncertainties in the measurements or a mismatch in what different instruments are observing.

3.2 Calculating Droplet Number Concentration

Based on a relationship between the cloud optical depth, the LWP, and the number concentration, the layer-averaged droplet number concentration is calculated. The visible optical depth can be defined as,

$$\tau = \frac{3}{5}\pi Q_{ext}\left[\frac{3}{4\pi\rho_l}(1-\beta)C_w\right]^{2/3}[kN_d]^{1/3}H^{5/3} \quad (3)$$

where τ is cloud optical depth, Q_{ext} is scattering efficiency, ρ_l is the density of water, k is the cube of the ratio of the volume radius to the effective radius, and N_d is the layer-averaged droplet number concentration.

From Eq (1) and Eq (3), the droplet number concentration can be derived as:

$$N_d = \left[\frac{2^{-5/2}}{k}\right]\left[\frac{3\pi}{5}Q_{ext}\right]^{-3}\left[\frac{3}{4\pi\rho_l}\right]^{-2}\tau^3 LWP^{-5/2}([1-\beta]C_w)^{1/2} \quad (4),$$

which can then be simplified to

$$N_d = C_1 k^{-1}\rho_l^2\tau^3 LWP^{-2.5}[(1-\beta)C_w]^{0.5} \quad (5)$$

Where the constant, C_1, is given by

$$C_1 = \left(2^{-5}/_2\right)\left(\frac{3\pi}{5}Q_{ext}\right)^{-3}\left(\frac{3}{4\pi}\right)^{-2} \quad (6).$$

Assuming $Q_{ext} = 2$, this corresponds to $C_1 = 0.05789$ (unitless). Following Brenguier et al. (2011), it is assumed k = 0.74.

Two cloud droplet number concentration variables are calculated: drop_number_conc and drop_number_conc_adiabatic. The variable drop_number_conc_adiabatic is a simpler calculation where β=0 is assumed. In reality, the adiabatic fraction is quite variable and likely depends on cloud type. Thus, for the drop_number_conc variable, if cloud thickness is available, the best estimate of β is used as described in section 3.1. For situations where cloud boundaries are not available, β=0 is assumed.

3.3 Calculate Droplet Number Concentration Uncertainty

An estimate of the uncertainty in the droplet number concentration variables is also given in the variable drop_number_conc_toterr. Because the equation is fairly straightforward, it is simply calculated by assuming the uncertainty of the Gaussian error propagation (see Equation 12 in Bennartz 2007). There are a few variations from his equation because satellite data is not used, and they do not have a cloud fraction issue, estimating beta rather than using a fixed value.

Our error equation is thus:

$$\left[\frac{\partial N}{N}\right]^2 = \left[\frac{\partial k}{k}\right]^2 + \left[\frac{3\partial\tau}{\tau}\right]^2 + \left[\frac{5}{2}\frac{\partial W}{W}\right]^2 + \left[\frac{1}{2}\frac{\partial\beta}{\beta}\right]^2 + \left[\frac{1}{2}\frac{\partial C_w}{C_w}\right]^2 \quad (7).$$

For most of the inputs, errors are not well known, so following Bennartz, we make some simple assumptions: delta_k = 10%; delta_beta = 10%, delta_cw = 5%.

An estimate of the error in optical depth is given in the MFRSRCLDOD data product, so the relative error in optical depth (delta_tau) is calculated by dividing that error (cldtaui_toterror) by the optical depth at each time step.

For LWP, the error in the MWR is assumed to be +/- 20 g/m2, so the relative error in LWP (delta_lwp) is calculated as 20.0/LWP for each time step.

4.0 Output Data

This section gives a summary of the main scientific output variables and other variables useful in interpreting when the algorithm is the most accurate. A full list of output variables is given in the sample netCDF header in Appendix B.

4.1 Scientific Output Variables

The primary output variable from this VAP is the droplet number concentration (drop_number_conc) and an accompanying error estimate (drop_number_conc_toterror). The adiabatic droplet number concentration (drop_number_conc_adiab) is a simpler calculation that assumes the cloud is adiabatic.

In addition, adiabatic calculations are of scientific value. These variables include an adiabaticity parameter (beta), the calculated adiabatic LWP (adiab_lwp). Beta gives an estimate of how far from adiabatic a given cloud LWP is with beta=0 being adiabatic. The full details of the adiabatic calculations are given in section 3.2.

4.2 Interpreting Output Data

In addition to the uncertainty variable (drop_number_conc_toterr), there are other useful QC flags and variables that give some indication of when the calculated droplet number concentration is most accurate.

The bit-packed quality control (QC) flag associated with droplet number concentration (qc_drop_number_conc) indicates when no observed cloud top or base is available. When no cloud top is available the adiabaticity parameter (beta) cannot be calculated and so an adiabatic cloud is assumed. When no cloud base is available both the adiabaticity and a default cloud height must be assumed. A QC bit is also set to indeterminate when the calculated droplet number concentration is greater than 10^{10} drops per cubic meter (10,000 drops per cubic centimeter), which likely indicates an error in the observations or retrieval rather than a physically observed value. We found that unrealistically high values often correspond to small measured LWPs, when the LWP is close to the limit the MWR is capable of measuring. This is why we restrict our retrieval to LWP > 0.02 kg/m^2.

Another important variable to take into account is the cloud_base_type flag. When Active Remote Sensing of Clouds (ARSCL) data is available, this variable keeps track of whether there are multiple liquid layer clouds (a value of 3 indicates multiple liquid layers). If this is the case, then the droplet number calculation is likely to be more uncertain because it assumes only one cloud layer, but the LWP from the microwave radiometer and the optical depth from the MFRSR measure the effect of all clouds in the column. The user can eliminate these cases if only choosing retrievals with a cloud_base_type value of 1.

Finally, the user may wish to screen the droplet number concentration by the variable cloud_base_temperature. It was chosen to run the retrieval for all clouds with base temperatures warmer than 260 kelvin (K). This is an arbitrary threshold, allowing some potentially supercooled liquid water cloud cases and possibly some ice clouds. Users can screen the data for cloud base temperatures warmer than 273 K if they wish to impose a stricter threshold to screen out potential ice clouds.

5.0 Example Plots

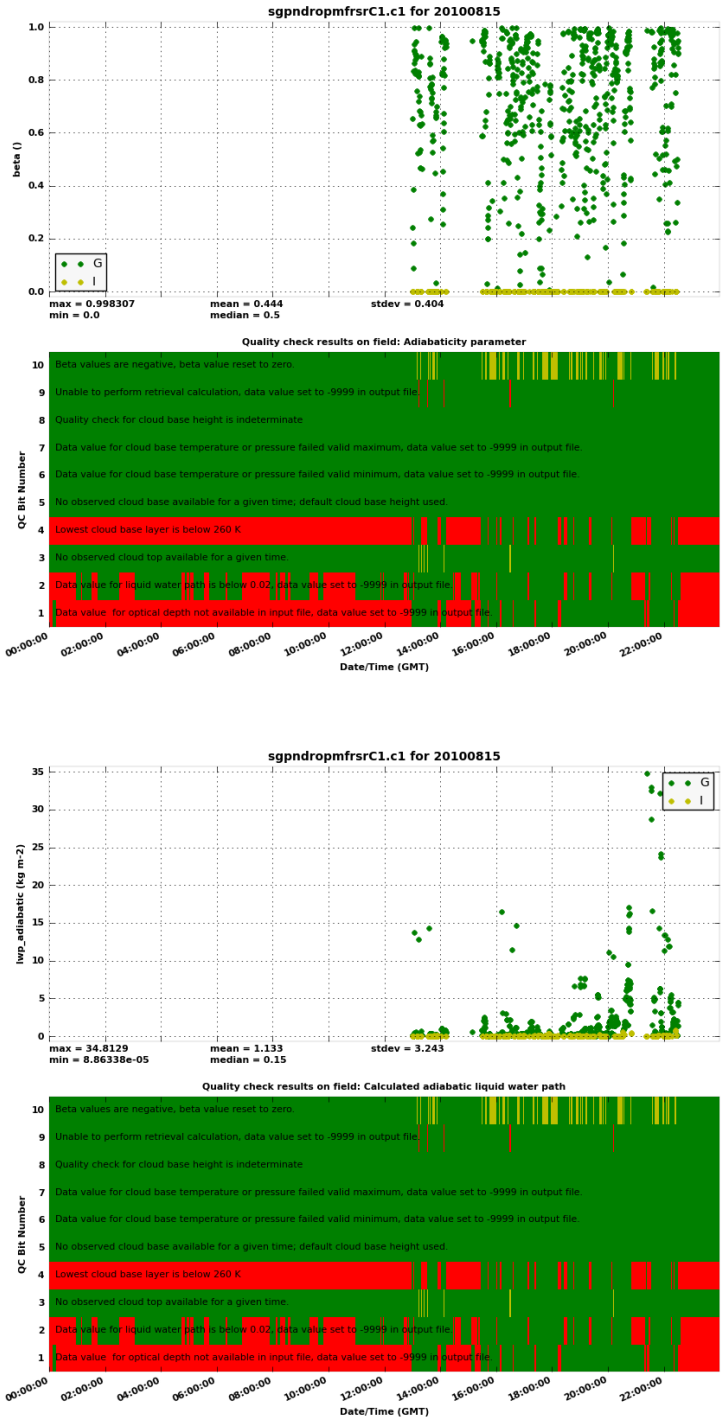

Figure 2. Example of adiabatic output variables from 8/15/2010.

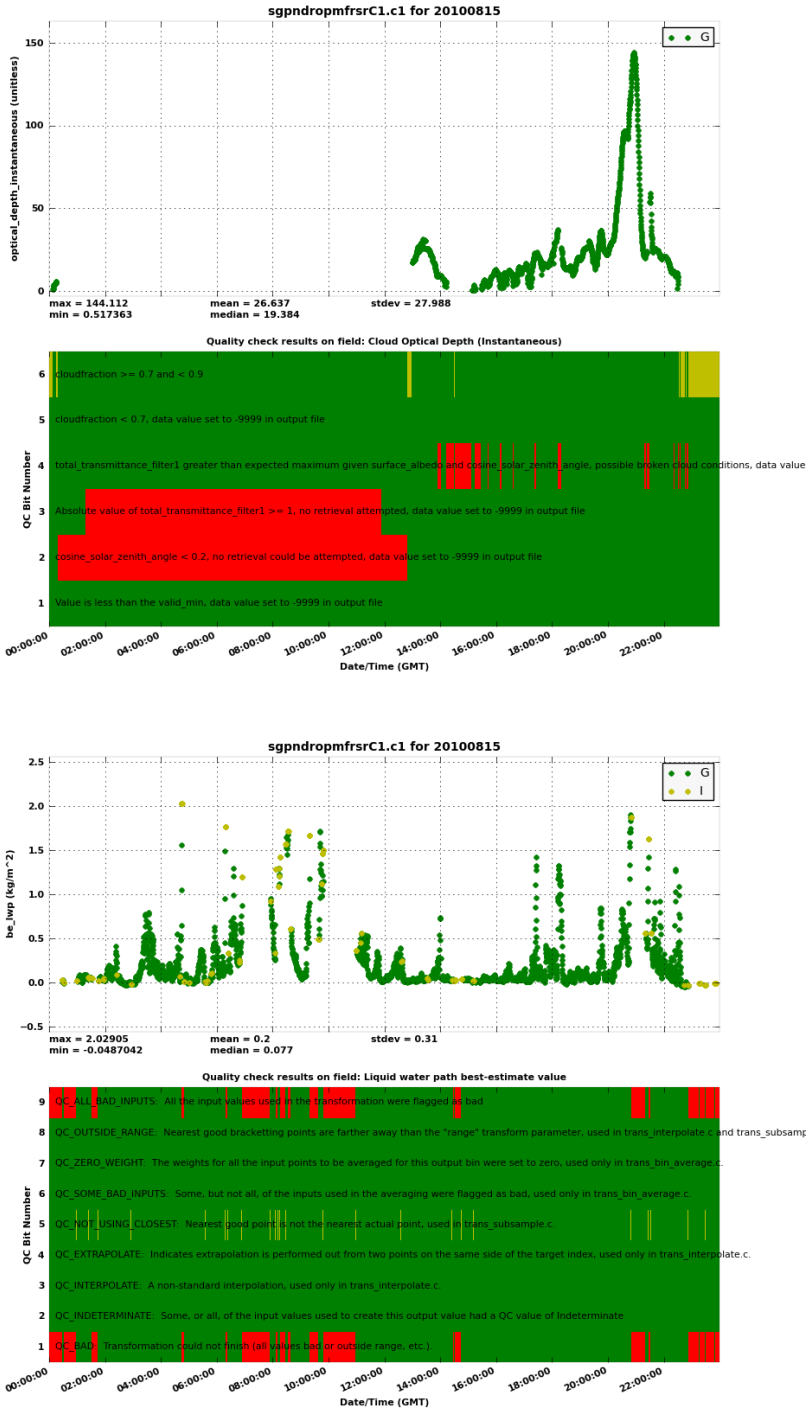

Figure 3. Main input variables—tau from MFRSRCLDOD and LWP from MWR.

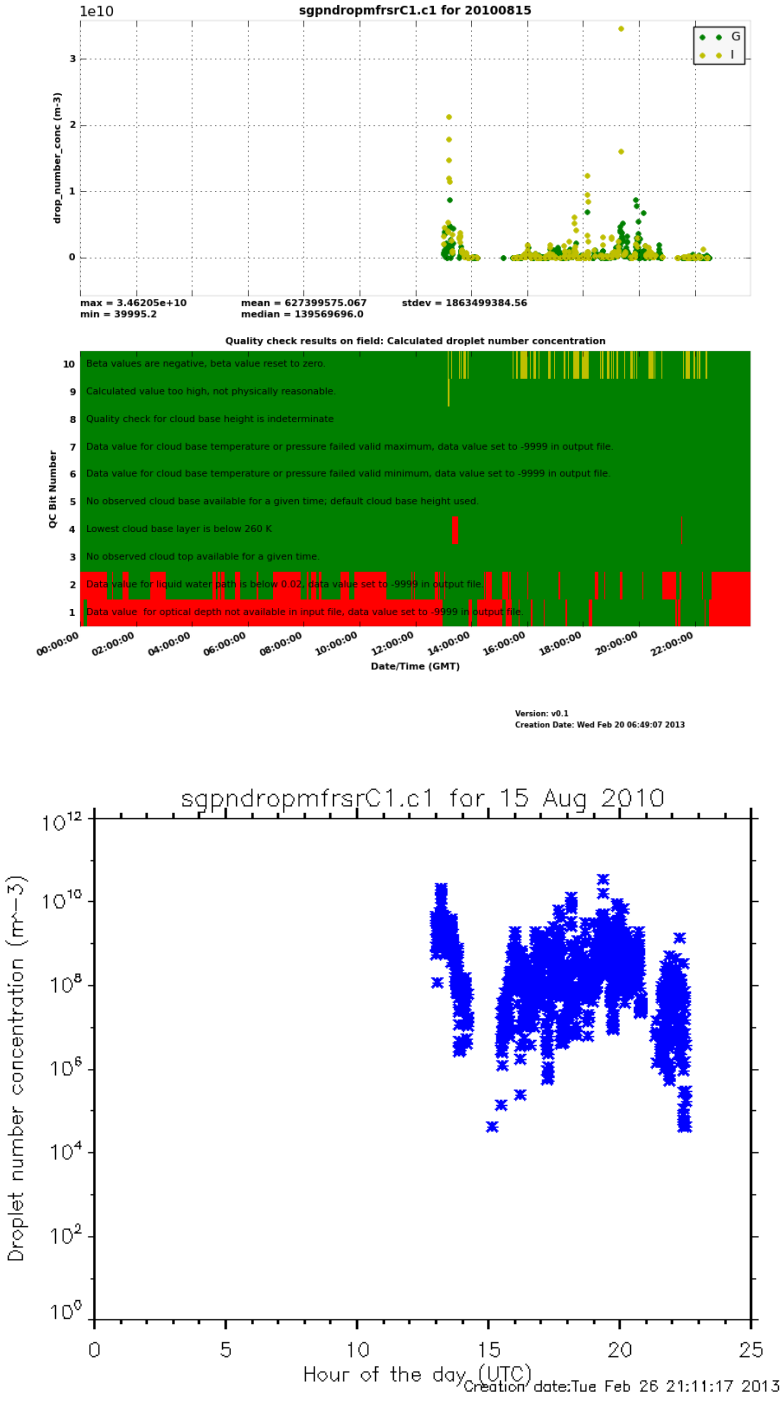

Figure 4. Output (a) Droplet Number Concentration with QC flags; (b) Drop Number Concentration shown with log scale.

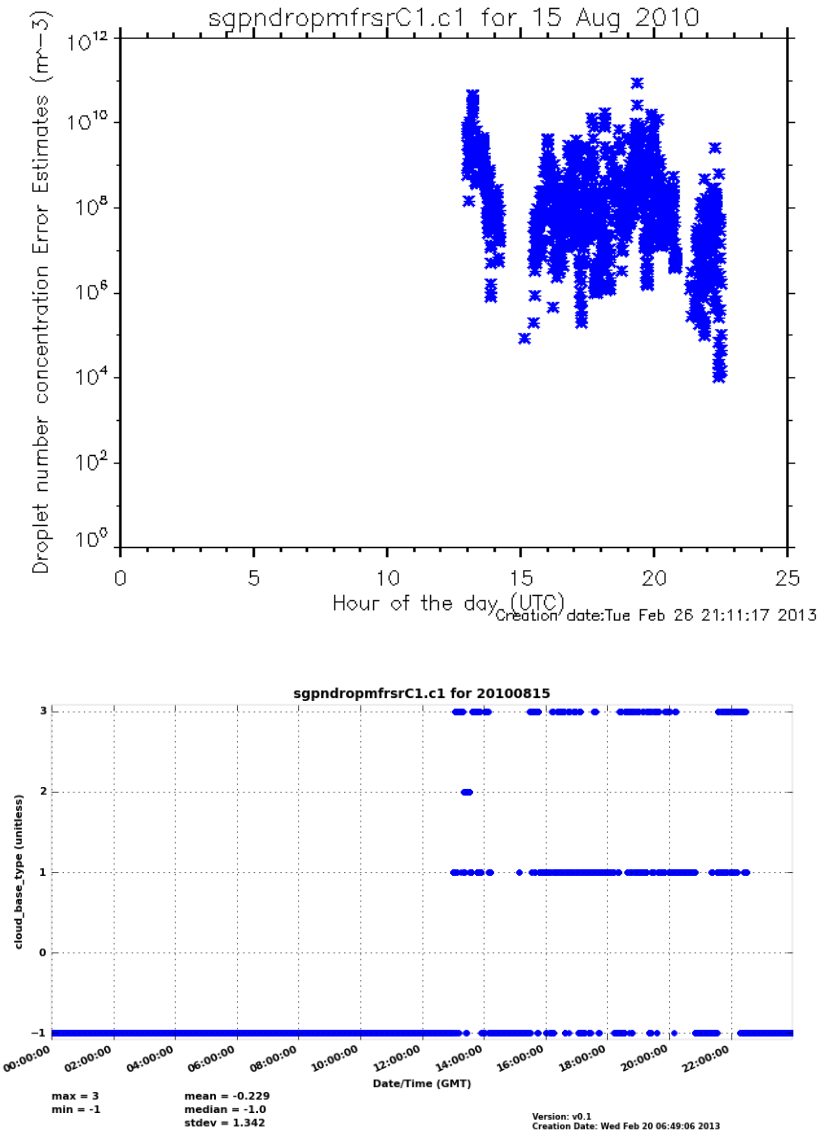

Figure 5. Drop Number Concentration Error Estimates, and cloud base type flag (1= single liquid water layer).

6.0 References

Bennartz, R. 2007. "Global assessment of marine boundary layer cloud droplet number concentration from satellite." *Journal of Geophysical Research – Atmospheres* 112(D2): D02201, https://doi.org/10.1029/2006JD007547

Brenguier, J-L, F Burnet, and O Geoffroy. 2011. "Cloud optical thickness and liquid water path – does the k coefficient vary with droplet concentration?" *Atmospheric Chemistry and Physics* 11(18): 9771–9786, https://doi.org/10.5194/acp-11-9771-2011

Boers, R, and RM Mitchell. 1994. "Absorption feedback in stratocumulus clouds: Influence on cloud top albedo." *Tellus A* 46(3): 229–241, https://doi.org/10.3402/tellusa.v46i3.15476

McComiskey, A, G Feingold, AS Frisch, DD Turner, MA Miller, JC Chiu, Q Min, and JA Ogren. 2009. "An assessment of aerosol-cloud interactions in marine stratus clouds based on surface remote sensing." *Journal of Geophysical Research – Atmospheres* 114(D9): D09203, https://doi.org/10.1029/2008JD011006

Appendix A
Input Data

Table A.1 lists the ARM datastreams used in the MFRSRCLDOD version of the NDROP VAP, along with the specific variables in the files that are used in processing.

Table 1. Datastream and variables.

Datastream	Variable Name	Variable Long Name
mfrsrcldod1min.c1	Optical_depth_instantaneous	Cloud Optical Depth (Instantaneous)
	Cldtaui_toterror	Instantaneous Cloud Tau Total Uncertainty
mergesonde1mace.c1 interpolatedsonde.c1	Bar_pres	Barometric pressure
	Height	Height
	Temp	Temperature
mwrret2turn.c1 mwrret1liljclou.c1 mwrret1liljclou.c2	Be_lwp/phys_lwp	Liquid water path best-estimate value
arsclbnd1cloth.c1 arsclkazrbnd1kollias.c0 arsclkazrbnd1kollias.c1 arsclwacrbnd1kollias.c1	CloudBaseBestEstimate/ cloud_base_best_estimate	Cloud Base Height Best Estimate
	CloudLayerBottomHeightMplZwang/ cloud_layer_base_height	Bottom Height of Hydrometeor Layer
	CloudLayerTopHeightMplZwang/ cloud_layer_top_height	Top Height of Hydrometeor Layer
ceil.b1	First_cbh	Lowest cloud base height detected
	second_cbh	Second-lowest cloud base height
	Third_cbh	Third cloud base height

Appendix B
Output Data

```
netcdf sgpndropmfrsrC1.c1.20100101.000000 {
dimensions:
    time = UNLIMITED; // (4319 currently)
    height = 266;
variables:
    int base_time;
        base_time:string = "2010-01-01 00:00:00 0:00";
        base_time:long_name = "Base time in Epoch";
        base_time:units = "seconds since 1970-1-1 0:00:00 0:00";
        base_time:ancillary_variables = "time_offset";
    double time_offset(time);
        time_offset:long_name = "Time offset from base_time";
        time_offset:units = "seconds since 2010-01-01 00:00:00 0:00";
        time_offset:ancillary_variables = "base_time";
    double time(time);
        time:long_name = "Time offset from midnight";
        time:units = "seconds since 2010-01-01 00:00:00 0:00";
    int qc_time(time);
        qc_time:long_name = "Quality check results on field: Time offset from midnight";
        qc_time:units = "unitless";
        qc_time:description = "This field contains bit packed integer values, where each bit represe
nts a QC test on the data. Non-zero bits indicate the QC condition given in the description for those bits;
a value of 0 (no bits set) indicates the data has not failed any QC tests.";
        qc_time:bit_1_description = "Delta time between current and previous samples is zero.";
        qc_time:bit_1_assessment = "Indeterminate";
        qc_time:bit_2_description = "Delta time between current and previous samples is less than th
e delta_t_lower_limit field attribute.";
        qc_time:bit_2_assessment = "Indeterminate";
        qc_time:bit_3_description = "Delta time between current and previous samples is greater than
 the delta_t_upper_limit field attribute.";
        qc_time:bit_3_assessment = "Indeterminate";
        qc_time:delta_t_lower_limit = 20.;
        qc_time:delta_t_upper_limit = 20.;
        qc_time:prior_sample_flag = 1;
        qc_time:comment = "If the \'prior_sample_flag\' is set the first sample time from a new raw
file will be compared against the time just previous to it in the stored data. If it is not set the qc_time
value for the first sample will be set to 0.";
        qc_time:flag_method = "bit";
    float height(height);
        height:long_name = "Height above mean sea level";
        height:units = "m";
        height:standard_name = "altitude";
    float optical_depth_instantaneous(time);
        optical_depth_instantaneous:long_name = "Cloud optical depth instantaneous";
        optical_depth_instantaneous:units = "unitless";
```

optical_depth_instantaneous:valid_min = 0.f;
optical_depth_instantaneous:missing_value = -9999.f;
optical_depth_instantaneous:source = "sgpmfrsrcldod1minC1.c1:optical_depth_instantaneous";
optical_depth_instantaneous:ancillary_variables = "qc_optical_depth_instantaneous";
int qc_optical_depth_instantaneous(time);
qc_optical_depth_instantaneous:long_name = "Quality check results on field: Cloud optical de
pth instantaneous";
qc_optical_depth_instantaneous:units = "unitless";
qc_optical_depth_instantaneous:description = "This field contains bit packed integer values,
where each bit represents a QC test on the data. Non-zero bits indicate the QC condition given in the
descr
iption for those bits; a value of 0 (no bits set) indicates the data has not failed any QC tests.";
qc_optical_depth_instantaneous:flag_method = "bit";
qc_optical_depth_instantaneous:bit_1_description = "Value is less than the valid_min, data v
alue set to missing_value in output file";
qc_optical_depth_instantaneous:bit_1_assessment = "Bad";
qc_optical_depth_instantaneous:bit_2_description = "cosine_solar_zenith_angle < 0.2, no retr
ieval could be attempted, data value set to missing_value in output file";
qc_optical_depth_instantaneous:bit_2_assessment = "Bad";
qc_optical_depth_instantaneous:bit_3_description = "Absolute value of total_transmittance_fi
lter1 >= 1, no retrieval attempted, data value set to missing_value in output file";
qc_optical_depth_instantaneous:bit_3_assessment = "Bad";
qc_optical_depth_instantaneous:bit_4_description = "total_transmittance_filter1 greater than
expected maximum given surface_albedo and cosine_solar_zenith_angle, possible broken cloud
conditions, data
value set to missing_value in output file";
qc_optical_depth_instantaneous:bit_4_assessment = "Bad";
qc_optical_depth_instantaneous:bit_5_description = "cloudfraction < 0.7, data value set to m
issing_value in output file";
qc_optical_depth_instantaneous:bit_5_assessment = "Bad";
qc_optical_depth_instantaneous:bit_6_description = "cloudfraction >= 0.7 and < 0.9";
qc_optical_depth_instantaneous:bit_6_assessment = "Indeterminate";
float bar_pres(time, height);
bar_pres:long_name = "Barometric pressure";
bar_pres:units = "Pa";
bar_pres:valid_min = 1000.f;
bar_pres:valid_max = 110000.f;
bar_pres:missing_value = -9999.f;
bar_pres:source = "sgpmergesonde1maceC1.c1:bar_pres";
bar_pres:ancillary_variables = "qc_bar_pres";
int qc_bar_pres(time, height);
qc_bar_pres:long_name = "Quality check results on field: Barometric pressure";
qc_bar_pres:units = "unitless";
qc_bar_pres:description = "This field contains bit packed integer values, where each bit rep
resents a QC test on the data. Non-zero bits indicate the QC condition given in the description for those bi
ts; a value of 0 (no bits set) indicates the data has not failed any QC tests.";
qc_bar_pres:flag_method = "bit";
qc_bar_pres:bit_1_description = "Transformation could not finish (all values bad or outside
range, etc.).";
qc_bar_pres:bit_1_assessment = "Bad";
qc_bar_pres:bit_2_description = "Transformation resulted in an indeterminate outcome.";

qc_bar_pres:bit_2_assessment = "Indeterminate";
float temp(time, height);
temp:long_name = "Temperature";
temp:units = "K";
temp:valid_min = 183.15f;
temp:valid_max = 323.15f;
temp:missing_value = -9999.f;
temp:source = "sgpmergesonde1maceC1.c1:temp";
temp:ancillary_variables = "qc_temp";
int qc_temp(time, height);
qc_temp:long_name = "Quality check results on field: Temperature";
qc_temp:units = "unitless";
qc_temp:description = "This field contains bit packed integer values, where each bit represe
nts a QC test on the data. Non-zero bits indicate the QC condition given in the description for those bits;
a value of 0 (no bits set) indicates the data has not failed any QC tests.";
qc_temp:flag_method = "bit";
qc_temp:bit_1_description = "Transformation could not finish (all values bad or outside rang
e, etc.).";
qc_temp:bit_1_assessment = "Bad";
qc_temp:bit_2_description = "Transformation resulted in an indeterminate outcome.";
qc_temp:bit_2_assessment = "Indeterminate";
float lwp_meas(time);
lwp_meas:long_name = "Measured liquid water path";
lwp_meas:units = "kg m-2";
lwp_meas:standard_name = "atmosphere_mass_content_of_cloud_liquid_water";
lwp_meas:missing_value = -9999.f;
lwp_meas:valid_min = -50.f;
lwp_meas:source = "sgpmwrret1liljclouC1.c2:be_lwp";
lwp_meas:ancillary_variables = "qc_lwp_meas";
int qc_lwp_meas(time);
qc_lwp_meas:long_name = "Quality check results on field: Measured liquid water path";
qc_lwp_meas:units = "unitless";
qc_lwp_meas:description = "This field contains bit packed integer values, where each bit rep
resents a QC test on the data. Non-zero bits indicate the QC condition given in the description for those bi
ts; a value of 0 (no bits set) indicates the data has not failed any QC tests.";
qc_lwp_meas:flag_method = "bit";
qc_lwp_meas:bit_1_description = "Transformation could not finish (all values bad or outside
range, etc.).";
qc_lwp_meas:bit_1_assessment = "Bad";
qc_lwp_meas:bit_2_description = "Transformation resulted in an indeterminate outcome.";
qc_lwp_meas:bit_2_assessment = "Indeterminate";
float cloud_base_height(time);
cloud_base_height:long_name = "Altitude of cloud base used in retrieval";
cloud_base_height:units = "m";
cloud_base_height:missing_value = -9999.f;
cloud_base_height:standard_name = "cloud_base_altitude";
cloud_base_height:ancillary_variables = "cloud_base_type source_cloud_base
qc_cloud_base_hei
ght";
int qc_cloud_base_height(time);
qc_cloud_base_height:long_name = "Quality check results on field: Altitude of cloud base use

d in retrieval";
qc_cloud_base_height:units = "unitless";
qc_cloud_base_height:description = "This field contains bit packed integer values, where eac
h bit represents a QC test on the data. Non-zero bits indicate the QC condition given in the description for
those bits; a value of 0 (no bits set) indicates the data has not failed any QC tests.";
qc_cloud_base_height:flag_method = "bit";
qc_cloud_base_height:bit_1_description = "Data value for optical_depth_instantaneous not av
ailable in input file, data value set to missing_value in output file.";
qc_cloud_base_height:bit_1_assessment = "Bad";
qc_cloud_base_height:bit_2_description = "Data value for lwp_meas is below 0.02, data value
set to missing_value in output file.";
qc_cloud_base_height:bit_2_assessment = "Bad";
qc_cloud_base_height:bit_3_description = "The input cloud base height is not the closest nei
ghbor.";
qc_cloud_base_height:bit_3_assessment = "Indeterminate";
qc_cloud_base_height:bit_4_description = "No observed cloud base available; default cloud_ba
se_height used.";
qc_cloud_base_height:bit_4_assessment = "Indeterminate";
float cloud_top_height(time);
cloud_top_height:long_name = "Altitude of cloud top used in retrieval";
cloud_top_height:units = "m";
cloud_top_height:missing_value = -9999.f;
cloud_top_height:standard_name = "cloud_top_altitude";
cloud_top_height:ancillary_variables = "qc_cloud_top_height";
int qc_cloud_top_height(time);
qc_cloud_top_height:long_name = "Quality check results on field: Altitude of cloud top used
in retrieval";
qc_cloud_top_height:units = "unitless";
qc_cloud_top_height:description = "This field contains bit packed integer values, where each
bit represents a QC test on the data. Non-zero bits indicate the QC condition given in the description for
those bits; a value of 0 (no bits set) indicates the data has not failed any QC tests.";
qc_cloud_top_height:flag_method = "bit";
qc_cloud_top_height:bit_1_description = "Data value for optical_depth_instantaneous not avai
lable in input file, data value set to missing_value in output file.";
qc_cloud_top_height:bit_1_assessment = "Bad";
qc_cloud_top_height:bit_2_description = "Data value for liquid water path not available in i
nput file.";
qc_cloud_top_height:bit_2_assessment = "Bad";
qc_cloud_top_height:bit_3_description = "No observed cloud top available.";
qc_cloud_top_height:bit_3_assessment = "Bad";
float cloud_thickness(time);
cloud_thickness:long_name = "Cloud thickness";
cloud_thickness:units = "m";
int cloud_base_type(time);
cloud_base_type:long_name = "Type of cloud at cloud base";
cloud_base_type:units = "unitless";
cloud_base_type:flag_values = -1, 1, 2, 3;
cloud_base_type:flag_meanings = "no_source_available liquid ice multiple_liquid_layers";
cloud_base_type:flag_1_description = "Liquid";
cloud_base_type:flag_2_description = "Ice";
cloud_base_type:flag_3_description = "Multiple liquid layers";

```
    float cloud_base_temperature(time);
        cloud_base_temperature:long_name = "Temperature of cloud base used in retrieval";
        cloud_base_temperature:units = "K";
        cloud_base_temperature:valid_min = 183.15f;
        cloud_base_temperature:valid_max = 550.f;
        cloud_base_temperature:missing_value = -9999.f;
        cloud_base_temperature:ancillary_variables = "cloud_base_type source_cloud_base
qc_cloud_bas
e_temperature";
    int qc_cloud_base_temperature(time);
        qc_cloud_base_temperature:long_name = "Quality check results on field: Temperature of cloud
base used in retrieval";
        qc_cloud_base_temperature:units = "unitless";
        qc_cloud_base_temperature:description = "This field contains bit packed integer values, wher
e each bit represents a QC test on the data. Non-zero bits indicate the QC condition given in the descriptio
n for those bits; a value of 0 (no bits set) indicates the data has not failed any QC tests.";
        qc_cloud_base_temperature:flag_method = "bit";
        qc_cloud_base_temperature:bit_1_description = "Data value for optical_depth_instantaneous n
ot available in input file, data value set to missing_value in output file.";
        qc_cloud_base_temperature:bit_1_assessment = "Bad";
        qc_cloud_base_temperature:bit_2_description = "Data value for lwp_meas is below 0.02, data v
alue set to missing_value in output file.";
        qc_cloud_base_temperature:bit_2_assessment = "Bad";
        qc_cloud_base_temperature:bit_3_description = "Not used";
        qc_cloud_base_temperature:bit_3_assessment = "Bad";
        qc_cloud_base_temperature:bit_3_comment = "This bit is not applicable to this variable. It
will never be set.";
        qc_cloud_base_temperature:bit_4_description = "Lowest cloud base layer is below 260 K";
        qc_cloud_base_temperature:bit_4_assessment = "Bad";
        qc_cloud_base_temperature:bit_5_description = "No observed cloud base available; default clo
ud_base_height used.";
        qc_cloud_base_temperature:bit_5_assessment = "Indeterminate";
        qc_cloud_base_temperature:bit_6_description = "Data value failed valid_min, data value set t
o missing_value in output file.";
        qc_cloud_base_temperature:bit_6_assessment = "Bad";
        qc_cloud_base_temperature:bit_7_description = "Data value failed valid_max, data value set t
o missing_value in output file.";
        qc_cloud_base_temperature:bit_7_assessment = "Bad";
    float cloud_base_pressure(time);
        cloud_base_pressure:long_name = "Air pressure of cloud base used in retrieval";
        cloud_base_pressure:units = "Pa";
        cloud_base_pressure:standard_name = "air_pressure_at_cloud_base";
        cloud_base_pressure:valid_min = 1000.f;
        cloud_base_pressure:valid_max = 11000.f;
        cloud_base_pressure:missing_value = -9999.f;
        cloud_base_pressure:ancillary_variables = "cloud_base_type source_cloud_base
qc_cloud_base_p
ressure";
    int qc_cloud_base_pressure(time);
        qc_cloud_base_pressure:long_name = "Quality check results on field: Air pressure of cloud ba
se used in retrieval";
```

qc_cloud_base_pressure:units = "unitless";
qc_cloud_base_pressure:description = "This field contains bit packed integer values, where e
ach bit represents a QC test on the data. Non-zero bits indicate the QC condition given in the description f
or those bits; a value of 0 (no bits set) indicates the data has not failed any QC tests.";
qc_cloud_base_pressure:flag_method = "bit";
qc_cloud_base_pressure:bit_1_description = "Data value for optical_depth_instantaneous not
available in input file.";
qc_cloud_base_pressure:bit_1_assessment = "Bad";
qc_cloud_base_pressure:bit_2_description = "Data value for lwp_meas is below 0.02, data valu
e set to missing_value in output file.";
qc_cloud_base_pressure:bit_2_assessment = "Bad";
qc_cloud_base_pressure:bit_3_description = "Not used";
qc_cloud_base_pressure:bit_3_assessment = "Bad";
qc_cloud_base_pressure:bit_3_comment = "This bit is not applicable to this variable. It wil
l never be set.";
qc_cloud_base_pressure:bit_4_description = "Lowest cloud base layer is below 260 K";
qc_cloud_base_pressure:bit_4_assessment = "Bad";
qc_cloud_base_pressure:bit_5_description = "No observed cloud base available; default cloud_
base_height used.";
qc_cloud_base_pressure:bit_5_assessment = "Indeterminate";
qc_cloud_base_pressure:bit_6_description = "Data value failed valid_min, data value set to m
issing_value in output file.";
qc_cloud_base_pressure:bit_6_assessment = "Bad";
qc_cloud_base_pressure:bit_7_description = "Data value failed valid_max, data value set to m
issing_value in output file.";
qc_cloud_base_pressure:bit_7_assessment = "Bad";
int source_cloud_base(time);
source_cloud_base:long_name = "Source of cloud base height information";
source_cloud_base:units = "unitless";
source_cloud_base:description = "This field contains integer values which should be interpre
ted as listed.";
source_cloud_base:flag_method = "integer";
source_cloud_base:flag_1_description = "sgparsclbnd1clothC1.c1:CloudBaseBestEstimate";
source_cloud_base:flag_2_description = "sgpvceil25kC1.b1:first_cbh";
source_cloud_base:flag_3_description = "1000_meters_default";
float beta(time);
beta:long_name = "Adiabaticity parameter";
beta:units = "unitless";
beta:missing_value = -9999.f;
beta:comment = "Calculated by comparing measured liquid water path to calculated adiabatic l
iquid water path";
beta:ancillary_variables = "qc_beta";
int qc_beta(time);
qc_beta:long_name = "Quality check results on field: Adiabaticity parameter";
qc_beta:units = "unitless";
qc_beta:description = "This field contains bit packed integer values, where each bit represe
nts a QC test on the data. Non-zero bits indicate the QC condition given in the description for those bits;
a value of 0 (no bits set) indicates the data has not failed any QC tests.";
qc_beta:flag_method = "bit";
qc_beta:bit_1_description = "Data value for optical_depth_instantaneous not available in in
put file, data value set to missing_value in output file.";

qc_beta:bit_1_assessment = "Bad";
qc_beta:bit_2_description = "Data value for lwp_meas is below 0.02, data value set to missin
g_value in output file.";
qc_beta:bit_2_assessment = "Bad";
qc_beta:bit_3_description = "No observed cloud_top_height available.";
qc_beta:bit_3_assessment = "Indeterminate";
qc_beta:bit_4_description = "Lowest cloud base layer is below 260 K";
qc_beta:bit_4_assessment = "Bad";
qc_beta:bit_5_description = "No observed cloud base available; default cloud_base_height use
d.";
qc_beta:bit_5_assessment = "Indeterminate";
qc_beta:bit_6_description = "Data value for cloud_base_temperature or bar_pres failed valid_
min, data value set to missing_value in output file.";
qc_beta:bit_6_assessment = "Bad";
qc_beta:bit_7_description = "Data value for cloud_base_temperature or bar_pres failed valid_
max, data value set to missing_value in output file.";
qc_beta:bit_7_assessment = "Bad";
qc_beta:bit_8_description = "Quality check for cloud_base_height is indeterminate";
qc_beta:bit_8_assessment = "Indeterminate";
qc_beta:bit_9_description = "Unable to perform retrieval calculation, data value set to miss
ing_value in output file.";
qc_beta:bit_9_assessment = "Bad";
qc_beta:bit_10_description = "Beta values are negative, beta value reset to zero.";
qc_beta:bit_10_assessment = "Indeterminate";
float drop_number_conc(time);
drop_number_conc:long_name = "Calculated droplet number concentration";
drop_number_conc:units = "m-3";
drop_number_conc:standard_name =
"number_concentration_of_cloud_liquid_water_particles_in_ai
r";
drop_number_conc:valid_min = 0.f;
drop_number_conc:qc_max = 1.e+10f;
drop_number_conc:missing_value = -9999.f;
drop_number_conc:comment = "Uses adiabaticity parameter, beta.";
drop_number_conc:ancillary_variables = "qc_drop_number_conc";
int qc_drop_number_conc(time);
qc_drop_number_conc:long_name = "Quality check results on field: Calculated droplet number c
oncentration";
qc_drop_number_conc:units = "unitless";
qc_drop_number_conc:description = "This field contains bit packed integer values, where each
bit represents a QC test on the data. Non-zero bits indicate the QC condition given in the description for
those bits; a value of 0 (no bits set) indicates the data has not failed any QC tests.";
qc_drop_number_conc:flag_method = "bit";
qc_drop_number_conc:bit_1_description = "Data value for optical_depth_instantaneous not ava
ilable in input file, data value set to missing_value in output file.";
qc_drop_number_conc:bit_1_assessment = "Bad";
qc_drop_number_conc:bit_2_description = "Data value for lwp_meas is below 0.02, data value s
et to missing_value in output file.";
qc_drop_number_conc:bit_2_assessment = "Bad";
qc_drop_number_conc:bit_3_description = "No observed cloud_top_height available.";
qc_drop_number_conc:bit_3_assessment = "Indeterminate";

qc_drop_number_conc:bit_4_description = "Lowest cloud base layer is below 260 K";
qc_drop_number_conc:bit_4_assessment = "Bad";
qc_drop_number_conc:bit_5_description = "No observed cloud base available; default cloud_bas
e_height used.";
qc_drop_number_conc:bit_5_assessment = "Indeterminate";
qc_drop_number_conc:bit_6_description = "Data value for cloud_base_temperature or bar_pres f
ailed valid_min, data value set to missing_value in output file.";
qc_drop_number_conc:bit_6_assessment = "Bad";
qc_drop_number_conc:bit_7_description = "Data value for cloud_base_temperature or bar_pres f
ailed valid_max, data value set to missing_value in output file.";
qc_drop_number_conc:bit_7_assessment = "Bad";
qc_drop_number_conc:bit_8_description = "Quality check for cloud_base_height is indeterminat
e";
qc_drop_number_conc:bit_8_assessment = "Indeterminate";
qc_drop_number_conc:bit_9_description = "Calculated value for drop_number_conc greater than
qc_max, not physically reasonable.";
qc_drop_number_conc:bit_9_assessment = "Indeterminate";
qc_drop_number_conc:bit_10_description = "Data value failed valid_min, value reset to zero."
;
qc_drop_number_conc:bit_10_assessment = "Indeterminate";
float drop_number_conc_toterror(time);
drop_number_conc_toterror:long_name = "Total error on calculated droplet number concentratio
n";
drop_number_conc_toterror:units = "m-3";
drop_number_conc_toterror:valid_min = 0.f;
drop_number_conc_toterror:missing_value = -9999.f;
drop_number_conc_toterror:comment = "Calculated via propagation of errors";
drop_number_conc_toterror:ancillary_variables = "qc_drop_number_conc_toterror";
int qc_drop_number_conc_toterror(time);
qc_drop_number_conc_toterror:long_name = "Quality check results on field: Total error on cal
culated droplet number concentration";
qc_drop_number_conc_toterror:units = "unitless";
qc_drop_number_conc_toterror:description = "This field contains bit packed integer values, w
here each bit represents a QC test on the data. Non-zero bits indicate the QC condition given in the
descrip
tion for those bits; a value of 0 (no bits set) indicates the data has not failed any QC tests.";
qc_drop_number_conc_toterror:flag_method = "bit";
qc_drop_number_conc_toterror:bit_1_description = "Data value for optical_depth_instantaneous
not available in input file, data value set to missing_value in output file.";
qc_drop_number_conc_toterror:bit_1_assessment = "Bad";
qc_drop_number_conc_toterror:bit_2_description = "Data value for lwp_meas is below 0.02, dat
a value set to missing_value in output file.";
qc_drop_number_conc_toterror:bit_2_assessment = "Bad";
qc_drop_number_conc_toterror:bit_3_description = "Data value for drop_number_conc not
availa
ble, data value set to missing_value in output file.";
qc_drop_number_conc_toterror:bit_3_assessment = "Bad";
qc_drop_number_conc_toterror:bit_4_description = "Data value for tau error estimates is not
valid";
qc_drop_number_conc_toterror:bit_4_assessment = "Bad";
float condensation_rate(time);

condensation_rate:long_name = "Condensation rate";
condensation_rate:units = "kg m-4";
float drop_number_conc_adiabatic(time);
drop_number_conc_adiabatic:long_name = "Droplet number concentration calculated assuming adi
abatic cloud layer";
drop_number_conc_adiabatic:units = "m-3";
drop_number_conc_adiabatic:standard_name = "number_concentration_of_cloud_liquid_water_parti
cles_in_air";
drop_number_conc_adiabatic:valid_min = 0.f;
drop_number_conc_adiabatic:qc_max = 1.e+10f;
drop_number_conc_adiabatic:missing_value = -9999.f;
drop_number_conc_adiabatic:ancillary_variables = "qc_drop_number_conc_adiabatic";
int qc_drop_number_conc_adiabatic(time);
qc_drop_number_conc_adiabatic:long_name = "Quality check results on field: Droplet number co
ncentration calculated assuming adiabatic cloud layer";
qc_drop_number_conc_adiabatic:units = "unitless";
qc_drop_number_conc_adiabatic:description = "This field contains bit packed integer values, where each bit represents a QC test on the data. Non-zero bits indicate the QC condition given in the descri
ption for those bits; a value of 0 (no bits set) indicates the data has not failed any QC tests.";
qc_drop_number_conc_adiabatic:flag_method = "bit";
qc_drop_number_conc_adiabatic:bit_1_description = "Data value for optical depth not availab
le in input file, data value set to missing_value in output file.";
qc_drop_number_conc_adiabatic:bit_1_assessment = "Bad";
qc_drop_number_conc_adiabatic:bit_2_description = "Data value for lwp_meas is below 0.02, da
ta value set to missing_value in output file.";
qc_drop_number_conc_adiabatic:bit_2_assessment = "Bad";
qc_drop_number_conc_adiabatic:bit_3_description = "No observed cloud_top_height available."
;
qc_drop_number_conc_adiabatic:bit_3_assessment = "Indeterminate";
qc_drop_number_conc_adiabatic:bit_4_description = "Lowest cloud base layer is below 260 K";
qc_drop_number_conc_adiabatic:bit_4_assessment = "Bad";
qc_drop_number_conc_adiabatic:bit_5_description = "No observed cloud base available; default cloud_base_height used.";
qc_drop_number_conc_adiabatic:bit_5_assessment = "Indeterminate";
qc_drop_number_conc_adiabatic:bit_6_description = "Data value for cloud_base_temperature or bar_pres failed valid_min, data value set to missing_value in output file.";
qc_drop_number_conc_adiabatic:bit_6_assessment = "Bad";
qc_drop_number_conc_adiabatic:bit_7_description = "Data value for cloud_base_temperature or bar_pres failed valid_max, data value set to missing_value in output file.";
qc_drop_number_conc_adiabatic:bit_7_assessment = "Bad";
qc_drop_number_conc_adiabatic:bit_8_description = "Quality check for cloud_base_height is in determinate";
qc_drop_number_conc_adiabatic:bit_8_assessment = "Indeterminate";
qc_drop_number_conc_adiabatic:bit_9_description = "Calculated value for drop_number_conc gre
ater than qc_max, not physically reasonable.";
qc_drop_number_conc_adiabatic:bit_9_assessment = "Indeterminate";

qc_drop_number_conc_adiabatic:bit_10_description = "Beta values are negative, beta value res
et to zero.";
qc_drop_number_conc_adiabatic:bit_10_assessment = "Indeterminate";
float lwp_adiabatic(time);
lwp_adiabatic:long_name = "Calculated adiabatic liquid water path";
lwp_adiabatic:units = "kg m-2";
lwp_adiabatic:standard_name = "atmosphere_mass_content_of_cloud_liquid_water";
lwp_adiabatic:valid_min = 0.f;
lwp_adiabatic:missing_value = -9999.f;
lwp_adiabatic:comment = "Uses given cloud boundaries plus cloud base pressure and temperatur
e to calculate adiabatic liquid water path.";
lwp_adiabatic:ancillary_variables = "qc_lwp_adiabatic";
int qc_lwp_adiabatic(time);
qc_lwp_adiabatic:long_name = "Quality check results on field: Calculated adiabatic liquid wa
ter path";
qc_lwp_adiabatic:units = "unitless";
qc_lwp_adiabatic:description = "This field contains bit packed integer values, where each bi
t represents a QC test on the data. Non-zero bits indicate the QC condition given in the description for tho
se bits; a value of 0 (no bits set) indicates the data has not failed any QC tests.";
qc_lwp_adiabatic:flag_method = "bit";
qc_lwp_adiabatic:bit_1_description = "Data value for optical_depth_instantaneous not availa
ble in input file, data value set to missing_value in output file.";
qc_lwp_adiabatic:bit_1_assessment = "Bad";
qc_lwp_adiabatic:bit_2_description = "Data value for lwp_meas is below 0.02, data value set
to missing_value in output file.";
qc_lwp_adiabatic:bit_2_assessment = "Bad";
qc_lwp_adiabatic:bit_3_description = "No observed cloud_top_height available.";
qc_lwp_adiabatic:bit_3_assessment = "Indeterminate";
qc_lwp_adiabatic:bit_4_description = "Lowest cloud base layer is below 260 K";
qc_lwp_adiabatic:bit_4_assessment = "Bad";
qc_lwp_adiabatic:bit_5_description = "No observed cloud base available; default cloud_base_h
eight used.";
qc_lwp_adiabatic:bit_5_assessment = "Indeterminate";
qc_lwp_adiabatic:bit_6_description = "Data value for cloud_base_temperature or bar_pres fail
ed valid_min, data value set to missing_value in output file.";
qc_lwp_adiabatic:bit_6_assessment = "Bad";
qc_lwp_adiabatic:bit_7_description = "Data value for cloud_base_temperature or bar_pres fail
ed valid_max, data value set to missing_value in output file.";
qc_lwp_adiabatic:bit_7_assessment = "Bad";
qc_lwp_adiabatic:bit_8_description = "Quality check for cloud_base_height is indeterminate"
;
qc_lwp_adiabatic:bit_8_assessment = "Indeterminate";
qc_lwp_adiabatic:bit_9_description = "Unable to perform retrieval calculation, data value se
t to missing_value in output file.";
qc_lwp_adiabatic:bit_9_assessment = "Bad";
qc_lwp_adiabatic:bit_10_description = "Beta values are negative, beta value reset to zero."
;
qc_lwp_adiabatic:bit_10_assessment = "Indeterminate";
float saturated_water_vapor_pressure(time);
saturated_water_vapor_pressure:long_name = "Saturated water vapor pressure";
saturated_water_vapor_pressure:units = "Pa";

```
        saturated_water_vapor_pressure:missing_value = -9999.f;
    float lat;
        lat:long_name = "North latitude";
        lat:units = "degree_N";
        lat:valid_min = -90.f;
        lat:valid_max = 90.f;
        lat:standard_name = "latitude";
    float lon;
        lon:long_name = "East longitude";
        lon:units = "degree_E";
        lon:valid_min = -180.f;
        lon:valid_max = 180.f;
        lon:standard_name = "longitude";
    float alt;
        alt:long_name = "Altitude above mean sea level";
        alt:units = "m";
        alt:standard_name = "altitude";

// global attributes:
        :command_line = "ndrop_mfrsr -s sgp -f C1 -D -R -b 20100101 -e 20100102";
        :Conventions = "ARM-1.0";
        :process_version = "v0.1";
        :dod_version = "ndropmfrsr-c1-0.1";
        :site_id = "sgp";
        :platform_id = "ndropmfrsr";
        :facility_id = "C1";
        :data_level = "c1";
        :location_description = "Southern Great Plains (SGP), Lamont, Oklahoma";
        :cloud_base_height_default = 1000.f;
        :delta_beta = 0.1f;
        :delta_k = 0.1f;
        :delta_c2 = 0.05f;
        :input_datastreams = "sgpmfrsrcldod1minC1.c1 : 2.6 : 20100101.000000\n",
            "sgpmergesonde1maceC1.c1 : Unknown : 20100101.000000\n",
            "sgpmwrret1liljclouC1.c2 : 3.2 : 20100101.000009\n",
            "sgparsclbnd1clothC1.c1 : 4.0 : 20100101.000000\n",
            "sgpvceil25kC1.b1 : 10.1 : 20100101.001410";
        :datastream = "sgpndropmfrsrC1.c1";
        :doi = "DOI:10.5439/1131339";
        :doi_url = "http://dx.doi.org/10.5439/1131339" ;
        :history = "created by user sivaraman on machine copper at 2014-05-28 19:51:58, using v0.1"
;
}
```

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