CloudSat Algorithm Uncertainty Synthesis

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The purpose of this document is to provide a synthesis report of the documented uncertainties in the CloudSat algorithms and provide references to the peer reviewed literature and other documents supporting those uncertainties.

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1 2B-GEOPROF

The basic 2B Geoprof algorithm is described at a good level of detail. The primary uncertainties are described in Tanelli et al. (2008). The evolution of the assessment of performance and calibration, are reported at Science Team and Mission Operations meetings, but are not documented in a published paper or product document at this time. The product include a radar-only cloud mask. Marchand et al., (2008) includes estimates of false an failed detection rates in the reference below. That document was written when R03 was available.

The changes from R03 to R04 were very small, with perhaps the largest change being the attempted subtraction of surface clutter. The clutter subtraction made only a small improvement to the false/failed detection rates, and a summary of the clutter situation for R04 is provided in the "data quality statement" online at the Data Processing Center (http://www.cloudsat.cira.colostate.edu/data-products/level-2b/2b-geoprof?term=42).

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Tanelli, S., S. L. Durden, E. Im, K. S. Pak, D. G. Reinke, P. Partain, J. M. Haynes, and R. T. Marchand, 2008: CloudSat's Cloud Profiling Radar After Two Years in Orbit: Performance, Calibration, and Processing. *IEEE Transactions on Geoscience and Remote Sensing*, **46**, 11, 3560-3573, doi: 10.1109/TGRS.2008.2002030

Roger Marchand, Gerald G. Mace, Thomas Ackerman, and Graeme Stephens, 2008: Hydrometeor Detection Using Cloudsat—An Earth-Orbiting 94-GHz Cloud Radar. *J. Atmos. Oceanic Technol.*, **25**, 519–533. doi: 10.1175/2007JTECHA1006.1

2 2B-CLDCLASS/2B-CLDCLASS-Lidar

The evaluation of 2B-CLDCLASS and 2B-CLDCLASS-Lidar cloud type outputs is a very challenging task due to lacking collocated data and the large spatial variability of clouds. But different steps were done to ensure the quality of products. The algorithms are based on two-dimensional cloud structure and properties together with the expert knowledge. The two-dimensional cloud structure together with precipitation occurrence from CloudSat radar allows for the straightforward identification of non-precipitating or precipitating low, middle, and high clouds. Results were evaluated by the developer granule by granule to make sure false classifications are below 5% based on the first year CloudSat measurements. The algorithms are based on a heritage algorithm used for ground-based multi-sensor measurements, which was evaluated with human observations (Wang and Sassen 2001). As illustrated in the ground-based results, cloud boundaries from lidar and radar measurements allow us to put clouds at right height ranges while human observations often have large errors in cloud base height estimations to result in classification errors.

2B-CLDCLASS and 2B-CLDCLASS-Lidar cloud types are also evaluated statistically. Sassen and Wang (2008) compared 1-year CloudSat results with surface climatology and the ISSCP product and showed that our results are consistent with previous global cloud type distributions. But there are some differences that provide insights into the limitations of CloudSat measurements and the other dataset. For example, CloudSat-only measurements fail to detect significant amount fair weather cumulus due to their small horizontal extend and containing small liquid droplets. Huang et al. (2015) systematically studied cloud type dependent water content and showed physically consistent results as we expected with an example result given in Fig. 1.

Furthermore, a key input, precipitation occurrence, for the classification algorithm is carefully evaluated by Hudak et al. (2008). Their results indicated that the skill scores of the CloudSat precipitation occurrence product were excellent when spatially mismatched cases were removed. Also independently evaluations are done by other researchers based on CloudSat validation campaign cases (Noh et al. 2011) or scientific studies (Naud et al. 2015).

All these indicate that 2B-CLDCLASS and 2B-CLDCLASS-Lidar are performed well and statistically are within 5% false classification limit other than one main known issue in 2B-CLDCLASS, which is the separation of stratus (St) and stratocumulus (Sc). St and Sc clouds are low clouds affected by surface clustering and often have weak signals below the CloudSat detection limit. These make it difficult to separate low clouds into St and Sc reliably with CloudSat radar only measurements. With additional lidar measurements, 2B-CLDCLASS-Lidar does a better job in St and Sc separation, but the uncertainty is still larger than other types of clouds. Therefore, we recommend combining St and Sc together for analyses while we explore new ways to improve the separation.

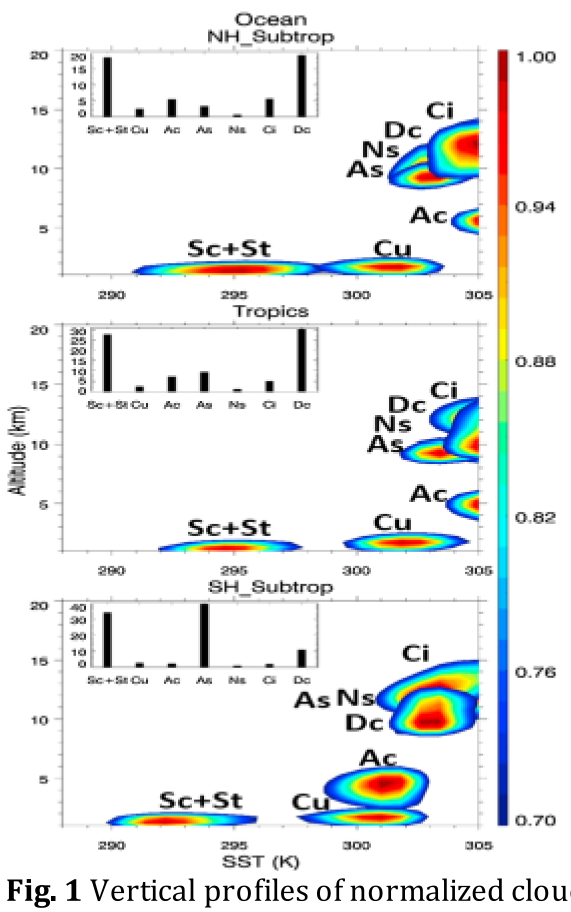

Fig. 1 Vertical profiles of normalized cloud water content (CWC) of different cloud types from 1 year CloudSat/CALIPSO observations sorted by sea surface temperature (K) over

the ocean area in the (top) Northern Hemisphere (NH) subtropics (15°–30°N), (middle) tropics (15°S–15°N), and (bottom) Southern Hemisphere (SH) subtropics (15°–30°S). The bar chart within each panel shows the average of all the CWCs (mg/m3) that are greater than 70% of the maximum CWC for each cloud type. See text for more details of the plotting method. (from the Figure 6 of Huang et al. 2015).

References:

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3 2B-CWC-RO/2B-CWC-RVOD

The 2B-CWC-RO and 2B-CWC-RVOD products provide estimates of liquid and ice cloud properties derived from vertical profiles of W-band radar reflectivities from the Cloud Profiling Radar coupled with a priori assumptions about cloud particle microphysical and scattering properties and their uncertainties. For the 2B-CWC-RVOD product, the radar reflectivity observations are supplemented with observation-based estimates of the visible cloud optical depth. Along with bulk properties such as water content and water path, these products estimate vertical profiles of parameters for the assumed lognormal size distributions. Retrievals are performed separately for liquid and ice phases, then combined using a temperature-based relationship that allows mixed liquid and ice to exist between specified temperature ranges.

Estimates of the random uncertainties in the retrieved quantities are provided in the products themselves and are obtained via the retrieval process and by uncertainty propagation assuming gaussian statistics. The uncertainties in these quantities result from uncertainties in the W-band reflectivities measured by the Cloud Profiling Radar, from uncertainties in the radar forward model used by the retrieval, from a priori assumptions about the background distribution of the retrieved parameters, and from uncertainties in the a priori assumptions about particle microphysical and scattering properties. The formulations used for these uncertainties are provided by Austin et al. (2009) for ice cloud property retrievals and by Austin and Stephens (2001) for liquid cloud property retrievals. Additional uncertainties arise within mixed phase layers due to uncertainties in the coincident temperature profiles from the ECMWF-AUX product and in the assumed relationship between temperature and the balance of ice and liquid in the layers, but these uncertainties have not yet been characterized.

Retrieved properties may also exhibit biases that arise due to biases in the a priori assumptions about the background distribution of the retrieved properties and in the a priori assumptions about particle microphysical and scattering properties. In the following, these uncertainties for the ice and liquid retrievals are discussed separately.

Ice cloud retrievals

Austin et al. (2009) provide an overview of assessment and comparison studies involving the 2B-CWC-RO retrieval of cloud ice properties. These studies include applying retrievals to synthetic observations derived from extensive aircraft-based in situ measurements (Heymsfield et al., 2008). The assessment by Austin et al. shows the 2B-CWC-RO R04 algorithm produces typical biases in ice water content of -40% to + 25% versus the observationally-derived synthetic data. The larger magnitude, negative biases occur mainly at reflectivities that are very large (~ 40 dBZe) or small (-20 dBZe). Austin et al. further summarizes studies by Wu et al. (2009) and Eriksson et al. (2008) that compared the 2B-CWC-RO R04 CloudSat product against a number of other satellite retrieval products. Although such intercomparisons do not provide unambiguous assessment of the magnitude of retrieval errors, they do provide some insight into the conditions under which retrieval results would be considered less certain.

Protat et al. (2009) performed a comparison of the 2B-CWC-RO and -RVOD CloudSat R04 products, finding the two products to be "statistically virtually identical." They further compared the CloudSat products against retrievals from ground-based radar and lidar observations of tropical ice clouds. The comparisons showed the CloudSat products providing a factor-of-2 larger values in the mean vertical profiles of ice microphysical properties below 10 km altitude compared to the ground-based retrieval results. Better agreement was obtained above 10 km.

Liquid cloud retrievals

Christensen et al. (2013) performed an evaluation of the 2B-CWC-RO and -RVOD retrieval performance for oceanic shallow liquid clouds, comparing the CloudSat products against coincident retrievals from MODIS observations. For cloud-only cases (neither raining nor drizzling), Christensen et al. find CloudSat-derived cloud liquid water paths (LWPs) to exceed those from MODIS by about 50%. Brunke et al. (2010) compared CloudSat cloud liquid water paths against those derived from shipboard microwave radiometer (MWR) measurements in southeast Pacific stratus. They found that the CloudSat LWPs compared well with those derived from the shipboard observations when CloudSat profiles suspected to be contaminated by precipitation were excluded from the comparisons. Their figures suggest that after screening for precipitation the agreement was within about +50% of the shipboard measurements.

Known issues

Several issues affect the currently implemented 2B-CWC-RO and -RVOD algorithms (release R04). These issues are documented at

http://www.cloudsat.cira.colostate.edu/sites/default/files/products/files/2B-CWC-RO P_R04 Data Issues.pdf

and

http://www.cloudsat.cira.colostate.edu/sites/default/files/products/files/2B-CWC-RVOD P_R04 Data Issues.pdf

Briefly, these issue affect the retrieval of liquid cloud properties. The first is due to an error in the liquid dielectric properties used in the liquid cloud radar forward model. The second is caused due to the approach of applying the liquid-only and ice-only retrievals to the full cloudy column. In ice-over-liquid cloud profiles, this causes attenuation effects to be overestimated for the liquid portion of the profile. These two issues will have the most pronounced effects in profiles containing large cloud water contents (e.g., those containing precipitation). The issues will be corrected with the R05 release of the product, but likely contributed to biases in the current R04 product release.

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4 2B-FLXHR/2B-FLXHR-LIDAR

CloudSat's 2B-FLXHR-LIDAR has undergone extensive, regular evaluation against top of atmosphere (TOA) observations from collocated Clouds and the Earth's Radiant Energy System (CERES) observations since the first public release of the dataset in 2008. L'Ecuyer et al. (2008) compared outgoing longwave radiation (OLR) and outgoing shortwave radiation (OSR) estimates from the original 2B-FLXHR dataset against corresponding estimates from CERES. Based two months of data collected in 2007, they report root-mean-square (RMS) differences of 4.3 and 26.7 Wm^{-2} in OLR and OSR, respectively, at 5°/monthly resolution.

These values were later updated after development of the vastly improved Release 4 2B-FLXHR-LIDAR algorithm (Henderson et al, 2013) demonstrating improved agreement, particularly in shortwave fluxes and on smaller time and space scales. The current Release 5 (R05) 2B-FLXHR-LIDAR dataset improves upon both of its predecessors yielding RMS differences of 4.3 and 13.4 Wm^{-2} in 2.5°/monthly estimates of OLR and OSR relative to CERES (Matus et al, 2016). Each of these studies also reports comparisons against CERES surface flux estimates, enabling vicarious two-point calibration of the product relative to the Baseline Surface Radiation Network (BSRN) observations against which CERES products are routinely compared. Preliminary comparisons suggest that R05 2B-FLXHR-LIDAR surface flux estimates agree with those from CERES to within the error bar assigned to the CERES flux estimates based on their evaluation against BSRN.
While it is very difficult to assess uncertainties in vertically-resolved fluxes and heating rates, this problem was addressed by Protat et al. (2014) who compared CloudSat's 2B-FLXHR-LIDAR against alternative satellite datasets and estimates based on ground-based sensors at the Atmospheric Radiation Measurement (ARM) Tropical West Pacific (TWP) site. The results indicate that each approach has strengths and weaknesses but confirms that 2B-FLXHR-LIDAR generally reproduces vertically-resolved (240 m resolution) longwave and shortwave heating rates from ground-based instrumentation to within 0.2 and 0.15 K d^{-1}, respectively, well within mission requirements.

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5 2C-PRECIP-COLUMN

Precipitation incidence information from 2C-PRECIP-COLUMN has been evaluated against a combination of raingauge, ship-based, and ground-based radar observations spanning diverse regimes across the globe. Ellis et al. (2009) compared CloudSat estimates of precipitation fraction against both gauge-based precipitation occurrence from several island sites in the Global Summary of the Day (GSOD) archive and ship-based observations from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS). At all locations CloudSat precipitation fractions agree with those from ground-based observations to within 15% both on the annual mean and over the seasonal cycle. More recently, Smalley et al. (2014) and Norin et al. (2015) document extensive comparisons of 2C-PRECIP-COLUMN over land rain and snow fractions against equivalent estimates from the NEXRAD and SWERAD radar networks, respectively. Both studies provide conclusive evidence that CloudSat provides more precise delineation of surface precipitation than state-of-the-art ground-based radar networks with the exception of the small region within 50 km of any given ground radar where ground clutter degrades CloudSat observations relative to the ground-based platform.

The microphysical assumptions and physical models at the root of the 2C-RAIN-PROFILE and 2C-SNOW-PROFILE algorithms were also the target of the Light Precipitation Validation (LPVEx) field campaign that took place in Helsinki, Finland in 2010 (L'Ecuyer et al, 2010). This experiment, that was supported by the CloudSat project, provided airborne and ground-based observations of raindrop size distributions, snow particle size distributions, melting-layer characteristics, liquid and ice water content, surface precipitation, and ancillary regime information in little studied high latitude, shallow freezing level environments where satellite precipitation estimates show the widest discrepancies. These data are currently being utilized to evaluate the accuracy of the surface return and melting-layer models employed in 2C-RAIN-PROFILE and to refine snow particle scattering properties in 2C-SNOW-PROFILE (Wood et al, 2014, 2015).

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6 2C-RAIN-PROFILE

The 2C-RAIN-PROFILE product uses observed profiles of radar reflectivity in conjunction with estimates of the Path Integrated Attenuation (PIA) to derive profiles of rain water content and the associated surface precipitation. The retrieval algorithm is described in L'Ecuyer and Stephens (2002). Specific modifications to the retrieval to adapt it to shallow warm precipitation are described in Lebsock and L'Ecuyer (2011). The retrieval relies heavily on the PIA observation, which is derived from the backscattering off of the Earth Surface. Therefore, the retrieval is only performed over ocean surfaces where the surface scattering is a well-characterized function of wind speed and sea surface temperature.

A fundamental uncertainty in the 2C-RAIN-PROFILE product is sampling bias. First, no quantitative retrievals are available over land surfaces. Second, The radar signal can be fully attenuated by heavy precipitation. In these cases the only a minimum possible rain rate can derived and no profile information is provided. This is a serious limitation in regions where even a moderate amount of the precipitation volume comes from heavy deep convective or stratiform precipitation. Because of this sampling limitatio n CloudSat precipitation estimates are generally best used in concert with estimates from other sensors such as the Tropical Rainfall Measurment Mission (TRMM) (Berg et al., 2010), The Global Precipitation Measurement (GPM) mission, or passive microwave sensors (Behrangi et al., 2012)

The algorithm is best suited to observing shallow rainfall over ocean surfaces in Stratocumulus and cumulus clouds. In this cloud regime, analysis in the South East Pacific has shown that retrieval uncertainty is on the order 20% when compared to in situ radar observations (Rapp et al., 2011).

Fractional retrieval errors are reported with each pixel. These errors are state dependent. In the shallow precipitation for which the algorithm is intended the single pixel errors range between 50% and 200% (Lebsock and L'Ecuyer, 2011).

Radar precision and calibration uncertainty are on the order of 0.16 dBZ and 1 dBZ respectively (Tanelli, 2008). In addition, Lebsock et al (2011) showed that the use of a look-up-table for radar surface cross section resulted in biases on the order of roughly 0.5 dB in the estimated PIA relative to a surface reference technique. These are minor factors in retrieval error relative to algorithm assumptions because of the large diversity in the precipitation drop size distribution and non-uniform-beam-filling effects.

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7 2C-SNOW-PROFILE

The 2C-SNOW-PROFILE product retrieves estimates of snow size distribution parameters using a priori assumptions about snow particle microphysical and scattering properties. The retrieved parameters are used along with the assumed microphysical properties to calculate snow water content and snowfall rate. Uncertainties in the retrieved and calculated values are obtained via the retrieval process and by uncertainty propagation assuming gaussian statistics. The uncertainties in these quantities result from uncertainties in the W-band reflectivities measured by the Cloud Profiling Radar, from uncertainties in the radar forward model used by the retrieval, from a priori assumptions about the background distribution of the retrieved parameters, and from uncertainties in the a priori assumptions about particle microphysical and scattering properties. A detailed assessment of these uncertainties is provided by Wood (2011) and summarized by Wood et al. (2016), while Wood et al. (2015) examines radar forward model uncertainties due to the particle microphysical and scattering property assumptions. Uncertainties in the instantaneous results from a single retrieval lead to fractional uncertainties in estimated snowfall rates and snow water contents that range typically from 50% to 200%. The dominant contributions to these uncertainties are from uncertainties in the forward model, which arise mainly because of the large environmental variability in snow particle size distributions and scattering properties.

Long-term samples of the retrieval results may also exhibit biases that arise due to biases in the a priori assumptions about the background distribution of the retrieved properties and in the a priori assumptions about particle microphysical and scattering properties. Evaluations of these biases is difficult, because requisite direct measurements of snowfall and snow water content are limited and difficult to make. Wood et al. (2016) use surface gauge networks to evaluate spatially gridded long-term snow accumulations from 2CSP. When evaluated on 2x2 degree grid boxes, the 2CSP accumulations and those from GHCN-D agree typically to within +/- 50% of the GHCN-D values. Some differences appear related to spatial sampling differences and elevation effects that are tied to site selection biases for the surface gauge network and so are not attributable in full to retrieval error. The evaluations also suggest there are some locations for which the 2CSP overestimates surface snowfall rates due to ground clutter contamination, a condition which the 2CSP algorithm attempts to flag based on an evaluation of the vertical profile of snowfall rates. Over all grid boxes for which GHCN-D observations are available, the area-weighted mean 2CSP accumulations are approximated 13% larger than those from GHCN-D. Additional evaluations against other surface gauge networks are in progress.

Other studies have evaluated the 2CSP snowfall estimates against those obtained from ground-based weather radar networks (Norin et al., 2015). The snowfall estimates from ground-based weather radars are generally obtained by applying a Z-S or Z-R relationship to the observed radar reflectivities. Norin et al. found evidence that snowfall rates from 2CSP are biased below those obtained from ground radars when reflectivities are very high but are in good agreement, albeit with much scatter, for small and moderate snowfall rates. Because of the uncertainties inherent in such Z-S relationships, such comparisons are difficult to interpret as indicators of the uncertainties in the 2CSP snow retrievals.

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