Deriving Snow Cloud Characteristics from CloudSat Observations

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Abstract

There has been so far no global estimate of snowfall. CloudSat has, for the first time, provided an opportunity for us to conduct such an estimate. The present study seizes this opportunity and attempts to investigate the global snowfall characteristics using its cloud radar observations. The retrieval methodology developed in this study includes two parts: first, determining whether a radar echo corresponds to snowfall (instead of rainfall), and second, converting radar reflectivity to snowfall rate. The first part is a snow-rain threshold based on multi-year land station and shipboard present weather reports, and the second part is based on backscatter computations of nonspherical ice particles and in situ measured particle size distributions. Using the above retrieval method, global CloudSat data over one year were analyzed. The results show that: (1) In the southern hemisphere, there is an almost zonally orientated high snowfall zone centered around 60ºS, where both snowfall frequency and rate are high. In the northern hemisphere, however, heavy/frequent snowfall areas are mostly locked to geographical locations. (2) Zonally and annually averaged snowfall rate has its maximum value around 2 mm day⁻¹, which is about 1/3 of the zonally averaged rainfall values found in the tropics, signifying the importance of snowfall in hydrological cycle. (3) Vertical profiles of snowfall rate have the greatest variability in the lowest levels. While near surface snowfall rate generally increases with cloud top height, there seems to be two prevailing groups of clouds with very different growth rate of snowfall as cloud top height increases. (4) The characteristics of the vertical distribution of snowfall rate are quite similar for over-ocean and over-land snow clouds, except that over-land snow clouds seem to be somewhat shallower than those over ocean.
1. Introduction

Although rain and snow are just two different forms of precipitation, their hydrological-climatological impacts are very different. Over land, accumulated snow may stay on the ground for months, resulting in different hydrological and radiative consequences from those by rain [e.g., Barnett et al. 1989; Walsh 1995]. Over ocean, falling snow has complex interaction with ocean surface because it both freshens and cools (through snow melting) the ocean surface water. How snowfall impacts on ocean surface buoyancy in the high latitudes (e.g., North Atlantic), and therefore on deep-water formation, remains largely unknown [Curry et al. 1996; Liu and Curry, 1997]. Despite the importance of snow precipitation, there have been no global maps of snowfall amount produced on the basis of observational data although snowfall frequency maps have been generated from observations at ground weather stations and from transit ships [Petty, 1995; Dai, 2001]. To measure snowfall globally, satellite observations become inevitable.

Unlike satellite rainfall estimations that have a history of several decades [e.g., Smith et al., 1998; Adler et al., 2001; Kummerow et al., 2001], the research on satellite snowfall estimation is still in a very early stage. There have been very few space-borne sensors suitable for detecting falling snow. Passive satellite sensors such as high-frequency microwave radiometers have been used in detecting snowfall events [Liu and Curry, 1997; Chen and Staelin, 2003; Kongoli et al., 2003; Skofronick-Jackson et al., 2004; Noh et al., 2006]. These studies have resulted in very encouraging results for moderate and heavy snowfall events. Theoretical studies on the sensitivity of passive microwave radiation to ice particles and their size distributions have been conducted by
Bennartz and Petty [2001] and Bennartz and Bauer [2003]. Space-borne active sensors that can be used to estimate both horizontal and vertical snowfall distributions have not been available until the Cloud Profiling Radar (CPR) on CloudSat [Stephens et al., 2002], which was launched in April 2006. Therefore, the CPR observation provides the first opportunity to survey the horizontal and vertical snowfall structures over a global scale. Taking advantage of this opportunity, the primary goal of this study is to derive the statistics of the snowfall horizontal and vertical distributions.

Since CPR does not scan, it only observes a strip of ~ 1.5 km on Earth’s surface for each passing orbit, which limits the ability of obtaining snowfall distribution by CloudSat measurement alone. One other possibility is to retrieve snowfall through measuring the scattering signature of falling snowflakes by high-frequency (>89 GHz) passive microwave radiometers, which are currently on several satellites. For example, using Advanced Microwave Sounding Unit – B (AMSU-B) observations, Skofronick-Jackson et al. [2004] and Noh et al. [2006], respectively, retrieved the snowfall distributions over eastern United States and over the Sea of Japan; their results are compared reasonably well with surface radar measurements. To develop such passive microwave snowfall retrieval algorithms as those based on Bayes’s Theorem, it is required as a-priori to have a database that relates snowfall profiles to microwave brightness temperatures. The global coverage of CPR observations makes it possible for us to build such a diversified database for passive microwave snowfall algorithms. Therefore, a second purpose of the study is to produce a collection of snowfall profiles, which later can be used to build a database used in passive high-frequency microwave
snowfall retrieval algorithms. Future combination of the active and passive satellite observations will greatly improve snowfall data availability.

The CPR observed quantity is radar reflectivity. Prior to obtaining snowfall characteristics from CPR data, it is needed first to determine whether the radar return is from rainfall or snowfall, and then convert the radar reflectivity to snowfall rate if it is due to snowfall. In this study, the conditional probability of snowfall given a surface air temperature is evaluated using 10 years of weather reports from both land stations and shipboard measurements around the globe. The rain-snow threshold is then determined as the surface air temperature at which the conditional snowfall probability reaches 50%. Converting radar reflectivity to snowfall rate is based on a newly derived reflectivity ($Z_e$) – snowfall rate ($S$) relation. In deriving the $Z_e$-$S$ relation, backscatter by nonspherical snowflakes is studied using discrete dipole approximation [Draine and Flatau, 1994], and the snowflake size distributions are based on previous in situ observations [Braham, 1990; Lo and Passarelli, 1982]. The detailed description of the above derivations is given in section 2. Using the $Z_e$-$S$ relation, snowfall rate is calculated; its characteristics including horizontal and vertical distributions and their variability are analyzed using one year of CPR data. The analyzed results will be shown in section 3. Conclusions are given in section 4.

2. Data and Methods

2.1 CPR Data

The principal data used for deriving snowfall characteristics are the observations by CPR onboard CloudSat. The CPR is a 94-GHz nadir-looking radar that measures the
power backscattered by clouds and precipitation as a function of distance from the radar. Its minimum detectable radar reflectivity factor was designed to be -26 dBZ at pre-launch although analysis of in-orbit observational data has shown that the sensitivity is better than the specification at about -30 dBZ. The standard CloudSat product 2D-GEOPROF (Release version 4) [Mace, 2007] is used, which includes radar reflectivity in 150 bins in the vertical with a bin size of about 240 m. The footprint size of radar reflectivity profiles is 1.4 km (cross-track) and 2.5 km (along-track). The bin that corresponds to surface return is also specified in the product. To remove surface contaminated data, data of the lowest 4 bins (~1 km) for over-ocean and the lowest 5 bins (~1.2 km) for over-land observations were excluded in the data analysis. In the following, the snowfall rate derived from the radar reflectivity at the 5th (6th) bin is called “near surface snowfall” for over-ocean (over-land) observations. All “near surface” snowfall results derived in this study are based on radar observations at the 5th or 6th bin, which may have caused some shallow snowfall events being missed.

In addition, two-meter air temperature from ancillary data product ECMWF-AUX [Partain, 2007] was used to determine whether surface precipitation is rainfall or snowfall. The ECMWF-AUX contains atmospheric variables from European Centre Medium range Weather Forecasting (ECMWF) model analysis, interpolated to the location of CPR bins.

2.2 Separation of Rain and Snow Profiles

From radar reflectivity alone, it is difficult to separate the radar profiles that are associated with surface snowfall from those with rainfall. Although a melting layer with a
bright-band in the radar reflectivity profiles indicates rainfall at surface, there are two problems preventing this method to effectively separate snow and rain profiles. First, a bright-band only appears in stratiform precipitations where no significant updraft exists cross the melting layer, which makes this method unusable for convective clouds. Second, according to data analysis performed in this study, the lowest altitude where CPR data are uncontaminated by surface reflections is around 1.2 km above surface. Therefore, it is hard to detect melting layer if it exists below 1.2 km. To determine whether the precipitation reaching to the surface is snow or rain, we first studied the conditional probability of solid precipitation at a given surface air temperature using present weather reports from land stations and ships. The land station data used here are from global synoptic weather reports archived at the National Center for Atmospheric Research (NCAR) [DS464.0, http://dss.ucar.edu/datasets/ds464.0]. The same dataset (but for different time period) has been used by Dai [2001] to study the frequency of global precipitation. In the datasets, present and past weather is reported every 3 hours in coded format, as defined by the World Meteorological Organization (WMO) [WMO, 1988]. While this dataset contains present and past weather codes starting from early 1975, only the present weather data (occurred at the time of observation) for the recent 10 years (March 1997 to February 2007) were used for the current analysis. A similar dataset from shipboard weather reports, called International Comprehensive Ocean-Atmosphere Data Set (ICOADS), is also archived at NCAR [DS540.0, http://dss.ucar.edu/datasets/ds540.0]. The present weather reports in ICOADS dataset for the recent 12 years (January 1995 to May 2007) were used for the analysis presented here. The same dataset
(but different time period) has been used by Petty [1995] and Dai [2001] to study oceanic precipitation frequencies.

From these weather reports, first, those observations that have non-drizzle precipitation were extracted, of which distinction between liquid (rain) and solid (snow) precipitations was further conducted according to the weather code. Then the conditional probability of snow precipitation was calculated as a function of surface air temperature, as shown in Fig. 1. The figure shows that the probability varies in a similar fashion for over-ocean and over-land environments with the transition from liquid to solid precipitation occurring mostly between air temperature of 4°C to -1°C. Above 4°C, some 90% (95%) of land (oceanic) precipitation are rain, while below -1°C, some 95% of precipitation are snow. The 50% probability occurs at air temperature around 2°C regardless of surface type. In the following, the 2°C surface air temperature (from ECMWF analysis) will be used as the threshold to separate between snow and rain radar profiles. Bennartz [2007] studied the likelihood of solid precipitation in relation to freezing level height, and found that the likelihood of solid precipitation is 50% for a freezing level height of 600 m. His result is comparable to the finding of this study.

2.3 $Z_c$-S Relation

Since snowflakes have comparable size to the radar wavelength of CPR (3.2 mm), the scattering properties of the particles are largely deviated from Rayleigh relations and can no longer been approximated by those of equal-volume spheres [Liu, 2004, Kim, 2006; Hong, 2007]. Compared to rain cases, the radar reflectivity versus snowfall rate
(Ze-S) relation is therefore further complicated by particle shape and orientation in addition to particle size distribution. Matrosov [2007] developed a Ze-S relation for 94 GHz radar by assuming that the snowflakes are oblate spheroids with an aspect ratio of 0.6 and preferably orientated horizontally. To derive a new Ze-S relation based on ice particle shapes that more closely resemble natural snowflakes, in this study, three particle types – rosettes (with 3-, 4-, 5- and 6-bullet), sectors and dendrites are designed and used to represent snowflakes. Assuming random orientation, their backscatter cross sections are computed using discrete dipole approximation (DDA) method [Draine and Flatau, 1994; Liu, 2004]. The density and area ratio versus maximum dimension relations for these particles are based on Heymsfield and Miloshevich [2003] and Heymsfield et al. [2002]. Detailed description of these particles and their scattering characteristics can be found in Liu [2004].

Snowfall rate (liquid equivalent), S, and (equivalent) radar reflectivity factor, Ze, may be expressed by the following equations:

\[
S = \int D N(D)v(D)m(D)/\rho_w dD ,
\]

and

\[
Z_e = \frac{\lambda^4}{\pi^5 |K|^2} \int D N(D)\sigma_{bsc}(D)dD ,
\]

respectively. In these equations, D is the maximum dimension of the snowflake, N(D) is the particle size distribution, v(D) is terminal velocity, m(D) is particle’s mass, \(\rho_w\) is the density of liquid water, \(\lambda\) is wavelength, K is a function of dielectric constant of water, and \(\sigma_{bsc}(D)\) is the backscatter cross section of the snowflake with the maximum dimension D. Results from in situ observations showed that the snow particle size
distributions generally follow an exponential form, while the intercept and slope vary, among other things, with the intensity of snowfall [Gunn and Marshall, 1958; Sekhon and Srivastava, 1970; Braham, 1990]. The uncertainty of the size distribution is a major error source for the $Z_e$-S relation. If dual-wavelength [e.g., Matrosov, 1998] and/or additional Doppler spectrum measurements [e.g., Mace et al., 2002] were available for CPR, this error could be reduced. However, since CPR is a single wavelength radar without Doppler measurement, the retrieval error due to the uncertainty in size distribution will remain. In this study, an exponential form of particle size distribution, $N(D)=N_0\exp(-\Lambda D)$, was used with the values of $N_0$ and $\Lambda$ taken from observational data published by Braham [1990] (his Table 4) and Lo and Passarelli [1982] (their Fig.8). In the Braham distribution, $D$ was given by the maximum dimension measured by 2D probes in the direction either along or cross the aircraft flight direction, whichever was larger. For terminal velocity, the 15 relations given by Locatelli and Hobbs [1974] (their Table 1) for various types of ice particles are used. To be consistent with their observations, the size range of ice particles corresponding to these terminal velocity relations are also adopted from the Locatelli and Hobbs study.

In Fig.2 shown are the $Z_e$-S relations computed using (1) and (2) for rosettes, sectors and dendrites. The following mathematical expression is derived using least-square fitting of the data points in the figure:

$$Z_e = 11.5 \cdot S^{1.25} ,$$

where $Z_e$ in mm$^6$m$^{-3}$, and $S$ in mm h$^{-1}$. The above relation is incidentally quite similar to that of Matrosov [2007], which is also shown in the figure by dashed line. However, the spreading of $S$ values is quite large at any given $Z_e$ (about an order), indicating that not
knowing the particle shape and size distribution will contribute large uncertainties (random error) to the snowfall rate retrievals. On logarithm scale, the correlation coefficient of the above fitting is 0.92 while r.m.s difference of ln(S) between data points in the figure and computed by (3) is 0.47. Because of dln(S)=dS/S, it is estimated that the relative error (∆S/S) solely due to the spreading of data points around the fitting curve is then about 50%. Additionally, it should be mentioned that melting snow particles are not considered in this study. The liquid-coated particles exhibit higher radar reflectivity than snowflakes, which causes overestimation of snowfall rates, particularly in warmer temperatures.

3. Results

In deriving global snowfall statistics, CloudSat data from 1 July 2006 through 30 June 2007 (one year) have been analyzed. Figure 3 shows (a) the number of CPR radar reflectivity profiles, (b) the number of profiles that correspond to 2-m air temperature colder than 2°C (hereafter they are called “cold samples” or “cold profiles”), and (c) the number of “snow profiles” that are defined here to have near surface radar reflectivity greater than -10 dBZ and 2-m air temperature colder than 2°C in 5° (latitude) x 5° (longitude) boxes observed during the one year period. The number of profiles ranges from ~70,000 to ~100,000 within each 5° x 5° box with more observations in the high latitude boxes than in the low latitude ones, except for outside 85° latitudes where the satellite does not reach. The distribution of the number of cold samples depends on both latitude and surface type. In general, except for a few mountain areas, cold samples do not exist in latitudes lower than ~30°. In the northern hemisphere, the number of cold
samples is distributed in a similar shape of the continents. In particular, there is a local maximum of the number of cold samples over the Tibetan Plateau. In the southern hemisphere where the distribution of the number of cold samples is largely zonal, a sharp polarward increase of cold samples occurs near 60°S. Here, a threshold of -10 dBZ at the lowest uncontaminated (5th bin for over ocean and 6th bin for over land) radar reflectivity is used for identifying snow profiles. The selection of the threshold is somewhat arbitrary, but is corresponding to a very low snowfall rate of ~0.02 mm h⁻¹ when applying (3). The sample numbers of snow profiles are much lower than the cold sample numbers, and the maxima (~15,000 within a 5° x 5° box) are not near the poles.

To understand the statistical characteristics of the radar profiles, we computed the 2-dimensional histogram of the radar echo occurrence, which is the number frequency of observations in each 250 m (height) x 2.5 dBZ (radar reflectivity) bin, normalized so that the maximum frequency is 100. The results are shown in Fig.4. The data are separated by 2 surface types, i.e., land or ocean, and 3 profile types, i.e., all profiles – all profiles outside 30°S-30°N latitudinal belt, cold profiles – of the above profiles, those having 2-m air temperature colder than 2°C, and snow profiles – of cold profiles, those having near-surface radar reflectivity higher than -10 dBZ. For the land profiles, actual land surface level (instead of sea level height) was used as reference to measure height. While the general pattern of the histogram for cold profiles is similar to that for all profiles, larger frequencies are distributed at lower altitudes for the cold profiles’ histogram than for the all profiles’ histogram, suggesting that clouds for cold profiles are shallower in general. However, there is a distinct difference between the over-ocean and over-land histograms. For over-ocean profiles, there is a persistent occurrence of low level clouds/precipitation
in addition to a higher level radar return maximum that lowers its altitude as radar reflectivity increases. For over-land profiles, the double-maxima pattern does not show in the all profile and cold profile histograms; only a pattern of gradual decrease of frequency upward. The double maxima pattern is further investigated by plotting the frequency of occurrence of cold cloud top heights (as defined here by the highest level with radar reflectivity greater than -24 dBZ) in Fig.5. It is seen that there are two maxima of frequencies of cloud top height at ~ 6.5 km and near surface for over-ocean clouds while there is only the near surface maximum for over-land clouds. The double layer nature of over-ocean clouds will be further discussed later in section 3.2.

For the snow profiles, the over-ocean and over-land histograms have a similar pattern that indicates maximum frequency occurs at low radar reflectivity at high altitudes and shifts to higher reflectivity as altitude lowers. However, compared to over-land histogram, the maxima in over-ocean histogram occur at higher altitudes for the same radar reflectivity. For example, at radar reflectivity of -15 dBZ, the maximum frequency for ocean profiles is at ~ 5 km while it is ~ 3.5 km for land profiles. This implies that snow clouds are generally shallower over land than over ocean, an opposite trend to convective rain clouds in the tropics [Liu and Fu, 2001; Takayabu, 2002].

3.1 Horizontal Distribution

Using the snowfall threshold derived in section 2.2 and the $Z_c$-S relation derived in section 2.3, the snowfall frequency and snowfall rate were computed in each $5^\circ \times 5^\circ$ box based on the one year CloudSat data. In Fig. 6, we show the global distributions of (a) frequency of total precipitation (near-surface radar reflectivity greater than -10 dBZ),
(b) frequency of snowfall (near-surface radar reflectivity greater than -10 dBZ and 2-m air temperature colder than 2°C), (c) mean snowfall rate in mm day$^{-1}$ (averaging all observations including zeros), and (d) conditional mean snowfall rate in mm day$^{-1}$ (averaging only those pixels with $Z_e$ > -10 dBZ). The total precipitation frequency has its maxima in the mid latitudes (around 60°S or 60°N), with values exceeding that in the Intertropical Convergence Zone (ITCZ). Similar results have been shown by Petty [1995]. As can be seen from Fig. 6b, the mid latitude frequency maxima are largely contributed by snowfall, particularly for the southern hemisphere where snowfall frequency exceeds 25% at many locations. There is a distinct difference for snowfall distributions between northern and southern hemispheres. While snowfall (both frequency and rate) are largely distributed zonally in the southern hemisphere, snowfall events in the northern hemisphere seem to be more concentrated to several locations, such as the coastal regions of Gulf of Alaska, east coast of Newfoundland and Labrador Sea, the large region covering east of Greenland, North Europe and Arctic Ocean, and the east coast of Siberia. The frequent snowfall occurring at east coast of Newfoundland and Labrador Sea was earlier reported by Liu and Curry [1997]. A surprising result is the frequent occurrence and the large rate of snowfall over the southern oceans along the Antarctic coast, which has not been reported before to the author’s knowledge. Another feature worth mentioning is that the conditional mean snowfall rate occurs to the equatorward edges of the snowfall zones, suggesting that while snowfall events are less frequent in the lower latitudes; but when it snows, it tends to snow heavier than in the higher latitudes.
Figure 7 shows the zonally averaged values of the snowfall frequencies and rates, also distinguished by whether the snowfall events are over land or over ocean. The asymmetry of the snowfall frequency and rate distributions for the two hemispheres is clear. The maximum snowfall frequency is about 25% for southern hemisphere (peaks near 75°S) and ~15% northern hemisphere (at the northernmost latitudes of CloudSat observations). The mean snowfall rate peaks at 60°S in the southern hemisphere and near northernmost regions of CloudSat observations in the northern hemisphere. It should be mentioned that errors in the snowfall rate estimates are large (about 50%) for any individual profiles due to the scatter of the $Z_e$-S relation (Fig. 2). Therefore, it should be cautioned when reading the averaged snowfall values where the number of snow profile samples (Fig.3c) is small.

Groisman and Easterling [1995] analyzed surface gauge-measured snowfall records for the region south of 55°N in Canada. The time series of annual snowfall (in mm) of their data are shown in Fig. 8a, along with the latitudinal distribution of our CloudSat over-land retrievals averaged between the longitudes of 55ºW and 125Wº (Fig.8b). It is seen from Fig.8a that the annual snowfall in this region is around 225 mm, or ~0.6 mm day$^{-1}$ in mean snowfall rate. Referring to Fig.8b, our retrievals show that the mean snowfall rate between 45°N to 55°N over land regions ranges from 0.4 to 1.0 mm day$^{-1}$, suggesting that our retrievals are generally in the ballpark of the climatology. The maximum of the zonally averaged snowfall rate is about 2 mm day$^{-1}$ (1.5 mm day$^{-1}$) in the southern (northern) hemisphere. According to Tropical Rainfall Measuring Mission (TRMM) results [Kummerow et al., 2000], the zonal mean rainfall rate at ITCZ is ~ 6
mm day$^{-1}$, implying that the maximum of zonal mean snowfall in southern (northern) hemisphere can be as large as $1/3$ ($1/4$) of that of ITCZ rainfall.

The over-land versus over-ocean difference of zonal mean snowfall frequency and rate is small and mainly shows in the southern hemisphere. However, the conditional mean snowfall rates, particularly those within 45°S/N, are very different between over land and over ocean. The large values of conditional mean snowfall rates over land suggest that occasional occurrence of heavy snowfall events in the lower latitudes. The PDFs of snowfall rate (in logarithmic scale, Fig. 9) shows that snowfall rates less than 1 mm h$^{-1}$ dominate the spectrum. For southern hemisphere, the PDF for ocean is broader than that for land, manifesting the fact that most oceanic snowfall areas are equatorward where heavier snowfall occurs more often. For northern hemisphere, the PDFs for land and ocean are almost identical.

3.2 Vertical Distribution

Using the one year global CPR data, the mean snowfall profile of all data with near surface radar reflectivity greater than -10 dBZ was first computed, and then EOF (Empirical Orthogonal Function) analysis was performed to the variances, separating profiles over land and over ocean. The results are shown in Fig.10, with Figs.10a and b showing the (conditional) mean profiles of snowfall rates and Figs.10c and d showing the vertical distributions of the 3 leading EOFs that together explain 93% (95%) of the variances for ocean (land) profiles. Except that the mean profile for over-land profiles is somewhat shallower than that for over-ocean profiles, there is not much difference between over-land and over-ocean profiles in terms of the magnitude and pattern of the
mean profiles as well as the variances as described by the EOFs. The conditional mean snowfall rate near surface is about 0.35 mm h\(^{-1}\) and decreases with the increases of height until it vanishes at around 8 km. The greatest variability of the snowfall rate profiles as described by the 1\(^{st}\) EOF (explains \(\sim 75\%\) of the variance) shows a pattern of gradual increase of the absolute value of amplitude downward, indicating that the magnitude of variation among profiles has its maximum near surface and gradually decreases with the increase of height.

Given a fixed near surface snowfall rate, how is the snowfall distributed vertically on average? To answer this question, all observed profiles were divided into groups according to their near surface snowfall rate and the mean profile was computed for each group. The averaged near surface snowfall rate of and the number of profiles in each group are shown in Table 1 and the averaged snowfall rate profiles are shown in Fig.11. As can be expected from Fig. 9, the number of profiles in groups with weaker near surface snowfall rate is much greater than that in groups with heavier near surface snowfall rate. Again, the averaged profiles for over-ocean and over-land environments are quite similar except that the over-land profiles are somewhat shallower than over-ocean profiles when surface snowfall rates are low. From profiles 1 to 7, as surface snowfall rate increases, the snow layer grows deeper, manifesting that heavier snowfall is associated with a thicker cloud layer. However, profiles 8 and 9 do not follow the same trend, indicating that the heaviest surface snowfalls are produced by rather shallow clouds. The explanation to this exception of trend is not immediately clear to me although it is speculated that the last two groups may correspond to shallow convective clouds associated with “lake effect” (cold air passes warm water surfaces creating strong shallow
convections) [e.g., Aonashi et al., 2007], which, while shallow, often produce heavy snowfalls. The prevalence of the two different snow cloud regimes is supported by Fig. 12, in which we show the 2-dimensional PDFs of profiles in a cloud top height (as defined by $Z_e = -24$ dBZ) versus near surface snowfall rate diagram. It is seen that while near surface snowfall rate increases in responding to the rise of cloud top height, there seem to exist two groups of clouds that have different growth rate, particularly for those profiles over oceanic environment. When surface snowfall rate increases to $\sim 2$ mm h$^{-1}$, one group has cloud top height around 10 km while the other group has cloud top height below 3 km. The existence of the two cloud groups is also an important piece of information for us to develop snowfall retrieval algorithms using satellite passive microwave data. In addition to the ice scattering signal in microwave radiometric data, infrared observations of cloud top height will also be beneficial for the passive microwave algorithm to arrive at correct snowfall rate retrievals. Another interpretation of the profiles of No. 8 and No. 9 is that the sharp downward increase of radar reflectivity may be caused by melting snow (liquid-coated particle), which, as mentioned earlier, could result in stronger radar reflectivity than snowflakes.

4. Conclusions

This study intends to provide a first look of the global horizontal and vertical distributions of snowfall rate based on cloud radar data from CloudSat. To accomplish this goal, a snow-rain threshold based on surface air temperature and a radar reflectivity – snowfall rate ($Z_e$-S) relation have been introduced. The former is based on multi-year land station and shipboard present weather reports, and the latter is based on backscatter
computations of nonspherical ice particles and in situ measured particle size distributions. A common problem of the single parameter ($Z_e$) algorithm of snowfall (as well as rainfall) is that it contains large uncertainties as manifested by the broad scatter of points in the $Z_e$-S relation plot (Fig.2). To reduce random errors associated with the $Z_e$-S relation, in this study, only large-scale/long-term averaged quantities of the radar retrievals are examined. The major findings can be summarized as follows.

First, there is an almost zonally orientated high snowfall belt centered around 60°S, where both snowfall frequency and rate are high. To the author’s knowledge, this high snowfall belt has not been previously reported. In the northern hemisphere, however, heavy/frequent snowfall areas are locked to geographical locations, instead of along latitudinal belt. Second, the zonally and annually averaged snowfall rate has its maximum value around 2 mm day$^{-1}$, about 1/3 of the zonally averaged rainfall value found in the ITCZ, which signifies the importance of snowfall in hydrological cycle. Third, the vertical profiles of snowfall rate have the greatest variability in the lowest levels. While near surface snowfall rate generally increases with cloud top height, there seems to have two prevailing groups of clouds with very different growth rate of snowfall as cloud top height increases. It is speculated that one group is associated with low pressure/frontal systems while the other is associated with shallow convections caused by “lake effect”. Finally, in contrast to tropical rain profiles, the characteristics of the vertical distribution of snowfall rate are quite similar for over-ocean and over-land snow clouds, except that over-land snow clouds seem to be somewhat shallower than those over ocean.
This study is a first attempt to survey the global snowfall characteristics from satellite observations. While the retrievals are consistent with climatology at least at one region as shown in Fig. 8, many parts of the retrieval algorithm are still in a stage of “ad hoc”. In particular, the \( Z_e - S \) relation needs to be further examined and improved in the future, when appropriate in situ observations become available. In this sense, the author would like the readers to view the results of this work as a “quick-look”, and to expect further improved results to follow. Two types of approaches should be considered in the future for validating the current and future improved snowfall retrievals. One is to collect quality-controlled historical surface snowfall data at multiple locations, and to compare whether or not the retrievals are in-line with the “snowfall climatology”. This approach does not require additional field observations and can verify the retrieval method qualitatively. The second approach is to use surface areal snowfall observing network (e.g., densely placed snow gauges) to match CloudSat measurement at the same time and with comparable spatial coverage under a special designed field experiment. By measuring such quantities as snow particle shape, size distribution and terminal velocity, etc. in the special experiment, one can also validate the assumptions used in deriving the \( Z_e - S \) relation.

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References


Table 1. Number of profiles in each near surface snowfall rate group

<table>
<thead>
<tr>
<th>No.</th>
<th>Snowfall Rate</th>
<th>Over Ocean</th>
<th>Over Land</th>
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<tr>
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<td>1,013,105</td>
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<td>36,619</td>
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<tr>
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<tr>
<td>9</td>
<td>7.6</td>
<td>249</td>
<td>1,208</td>
</tr>
</tbody>
</table>
Figure Captions

Fig.1. Conditional probability of solid precipitation as a function of surface air temperature derived from global land station and shipboard present weather reports.

Fig.2 $Z_e-S$ relation for three nonspherical snowflakes. A least-square fitting curve and relation by Matrosov [2007] are also shown.

Fig.3 Number of CPR observations within 5º x 5º boxes for (a) all, (b) cold (2-m air temperature colder than 2ºC), and (c) snow (cold samples with near surface radar reflectivity >-10 dBZ) samples during the study period.

Fig.4 The 2-dimensional (height-reflectivity) number frequency histograms of CPR observations in the latitudes north of 30ºN and south of 30ºS for (a) all samples over ocean, (b) cold samples over ocean, (c) snowfall samples over ocean, (d) all samples over land, (e) cold samples over land, and snowfall samples over land.

Fig.5 Frequency of occurrence of cloud top (defined by -24 dBZ) height for cold profiles.

Fig.6 Global distributions of (a) total precipitation frequency, (b) snowfall frequency, (c) mean snowfall rate (times 5 in order to use the same color scale with conditional snowfall rate), and (d) conditional snowfall rate.

Fig. 7 Zonally averaged total or solid precipitation (snowfall) frequency (left column), mean snowfall rate (middle column), and conditional mean snowfall rate (right column). The top, mid and bottom rows are, respectively, for all surfaces, over ocean only and over land only observations.
Fig. 8  (a) Annual snowfall over stations south of 55ºN in Canada (adapted from Groisman and Easterling [1995]), and (b) latitudinal distribution of CPR data retrieved snowfall rate averaged between 55ºW and 125ºW.

Fig. 9 Frequency distribution of snowfall rate (in logarithmic scale), separated by hemispheres and surface types.

Fig. 10 Vertical distributions of (a) conditional mean snowfall rate over ocean and (b) conditional mean snowfall rate over land, (c) 3 leading EOFs over ocean and (d) 3 leading EOFs over land. The EOF analysis is performed to the variance profiles (mean removed). The percentages shown in diagrams (c) and (d) are the percentages of variance explained by the corresponding EOFs.

Fig. 11 Mean profiles for a given near surface snowfall rate for (a) over ocean and (b) over land environments. The sample numbers used in the averaging are given in Table 1.

Fig. 12 The relation between near surface snowfall rate and cloud top height as expressed by snowfall profiles frequency distributions. The frequency values are normalized so that the maximum frequency is 100.
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