A Shallow Cumuliform Snowfall Census Using Spaceborne Radar

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ABSTRACT

The first observationally based near-global shallow cumuliform snowfall census is undertaken using multiyear CloudSat Cloud Profiling Radar observations. CloudSat snowfall observations and snowfall rate estimates from the CloudSat 2C-Snow Water Content and Snowfall Rate (2C-SNOW-PROFILE) product are partitioned between shallow cumuliform and nimbostratus cloud structures by utilizing coincident cloud category classifications from the CloudSat 2B-Cloud Scenario Classification (2B-CLDCLASS) product. Shallow cumuliform (nimbostratus) snowfall events comprise about 36% (59%) of snowfall events in the CloudSat snowfall dataset. The remaining 5% of snowfall events are distributed between other categories. Distinct oceanic versus continental trends exist between the two major snowfall categories, as shallow cumuliform snow-producing clouds occur predominantly over the oceans. Regional differences are also noted in the partitioned dataset, with over-ocean regions near Greenland, the far North Atlantic Ocean, the Barents Sea, the western Pacific Ocean, the southern Bering Sea, and the Southern Hemispheric pan-oceanic region containing distinct shallow snowfall occurrence maxima exceeding 60%. Certain Northern Hemispheric continental regions also experience frequent shallow cumuliform snowfall events (e.g., inland Russia), as well as some mountainous regions. CloudSat-generated snowfall rates are also partitioned between the two major snowfall categories to illustrate the importance of shallow snow-producing cloud structures to the average annual snowfall. While shallow cumuliform snowfall produces over 50% of the annual estimated surface snowfall flux regionally, about 18% (82%) of global snowfall is attributed to shallow (nimbostratus) snowfall. This foundational spaceborne snowfall study will be utilized for follow-on evaluative studies with independent model, reanalysis, and ground-based observational datasets to characterize respective dataset biases and to better quantify CloudSat snowfall detection and quantitative snowfall estimate uncertainties.

1. Introduction

Accumulating surface snowfall is generated from cloud structures with varying vertical extent and underlying formation mechanisms. For instance, mid-latitude winter cyclones with complex dynamical forcing produce snowfall from incipient cloud structures typically extending into the mid- to upper troposphere. Common examples of snowfall events associated with deeper clouds in the continental North American region include U.S. East Coast winter storms (e.g., Kocin and Uccellini 1990), lee cyclogenesis events in the U.S. Great Plains (e.g., Rauber et al. 2014), and fast-moving “Alberta clipper” systems that originate on the lee side of the Canadian Rocky Mountain system and produce snowfall across much of central and eastern North America (e.g., Thomas and Martin 2007; Plummer et al. 2014). Alternatively, snowfall produced by shallow clouds—where “shallow” is generically defined as lower-tropospheric cloud-top heights—commonly occurs in many locations, especially near larger bodies of water in the mid- and high latitudes. Lake-effect snow is a well-documented form of shallow cumuliform snowfall resulting from cold-air outbreaks in the wake of midlatitude cyclones that interact with unfrozen or partially frozen bodies of water.
shallow snowfall from an active spaceborne remote sensing perspective using CloudSat observations, with overwater snowfall production that is particularly inaccessible to ground-based radars being the primary motivating factor to undertake this study.

CloudSat (Stephens et al. 2002) carries the W-band (94 GHz) Cloud Profiling Radar (CPR; Tanelli et al. 2008) that has collected data since its 2006 launch. While CloudSat was designed as primarily a cloud remote sensing mission, its high-latitude coverage (up to \(-82^\circ\) latitude) and high radar sensitivity (\(-28\) dBZ) make it very suitable for snowfall-related research. Numerous recent investigations have highlighted CloudSat’s importance to the snowfall remote sensing community, both in proof-of-concept studies comparing CloudSat observations and snowfall rate retrievals with ground-based radar observations (e.g., Hudak et al. 2008; Matrosov et al. 2008) and for studies using extended CloudSat observations to assess global snowfall distribution and to quantify uncertainties related to single-frequency, W-band snowfall retrievals (e.g., Liu 2008; Kulie and Bennartz 2009; Riley et al. 2011; Wang et al. 2013; Behrangi et al. 2014). Additional recent studies have focused on CloudSat snowfall estimates in specific high-interest locations like Antarctica to assess CloudSat snowfall retrievals with independent remote sensing, reanalysis and ground-based datasets (Boening et al. 2012; Palerme et al. 2014; Milani et al. 2015).

This investigation’s shallow snowfall focus builds on previous global spaceborne radar studies of shallow rainfall. Investigators have utilized Tropical Rainfall Measuring Mission (Simpson et al. 1988; Kummerow et al. 1998) Precipitation Radar observations to characterize shallow, tropical precipitation occurrence and global rain fraction (e.g., Short and Nakamura 2000; Schumacher and Houze 2003; Liu and Zipser 2009). CloudSat observations have also been used for shallow rainfall retrievals, especially associated with marine stratocumulus clouds (e.g., Lebsock and L’Ecuyer 2011; Lebsock et al. 2011; Rapp et al. 2013). CloudSat’s ability to detect shallow snowfall has been highlighted in recent studies. Liu (2008) indicated both oceanic and land shallow snowfall modes when analyzing dominant mean reflectivity profiles associated with CloudSat-indicated snowfall events [e.g., see Fig. 11 in Liu (2008)]. Liu (2008) also noted intense snowfall rates associated with shallow radar reflectivity profiles and suggested lake-effect snow as the most likely mechanism to explain this trend. Kulie and Bennartz (2009) also discussed a globally significant shallow snowfall mode when illustrating the sensitivity of a vertical continuity reflectivity threshold created to mitigate potential ground clutter contamination over land. The ad hoc vertical continuity

\[\text{1 Near global” and “global” are used interchangeably throughout the text when discussing CloudSat observations, where “global” is understood to represent the latitudinal coverage of CloudSat between \(-82^\circ\).}\]
A shallow snowfall census is further motivated by the recent launch of the Global Precipitation Measurement (GPM) mission (Hou et al. 2014). GPM and its constellation satellites utilize passive microwave radiometers that have produced a rich legacy of global precipitation retrievals (e.g., Huffman et al. 2001, 2007, 2009). Shallow snowfall is a unique precipitation mode emanating from cloud structures associated with potentially unique microphysical composition and radiometric signatures (Noh et al. 2006; Wang et al. 2013), so developing a database of shallow snowfall events concurrent with microwave radiometer observations is crucial to develop and evaluate GPM snowfall retrievals. Combined CloudSat and Advanced Microwave Scanning Radiometer for Earth Observing System (AMSR-E) observations from the so-called afternoon constellation, or A-Train, can be leveraged for such purposes (e.g., Kulie et al. 2010; Wang et al. 2013). In fact, a database of CloudSat and AMSR-E observations is used in the at-launch operational version of GPM snowfall retrievals for cold surfaces at high latitudes (Kummerow et al. 2015). Further motivation to develop a shallow snowfall data record is also provided by recent studies that predict shallow lake-effect snowfall events may be significantly altered by a warming climate at higher latitudes (e.g., Burnett et al. 2003; Kunkel et al. 2009; Notaro et al. 2014). Recent research using model output has also posited that future Arctic precipitation may substantially increase, largely driven by local surface evaporation effects—the prime mechanism causing overwater shallow snowfall—due to diminished sea ice coverage (Bintanja and Selten 2014). The CloudSat data record serves as a valuable reference to monitor future changes in shallow snowfall frequency and location, especially if long-term active spaceborne observations capable of observing shallow snowfall follow CloudSat.

This study will therefore explore shallow snowfall from a spaceborne remote sensing perspective. The following key questions will be addressed in this investigation:

- Can CloudSat observations and data products successfully partition snowfall to produce a near-global snowfall census separated by different snowfall modes (e.g., shallow cumuliform vs nimbostratus snowfall-producing cloud structures)?
- Where does shallow cumuliform snowfall preferentially occur and is it the predominant snowfall mode anywhere? Do distinct land versus ocean shallow snowfall signatures exist in the dataset?
- How much does shallow snowfall typically contribute to the total annual snowfall accumulation both globally and regionally?

A description of the data and methods used in this study is provided in section 2, while section 3 provides an overview of global snowfall partitioned between different snowfall modes. Section 4 provides a summary and discussion, including future research pathways related to this study.

2. Data and methods

a. CloudSat product description

CloudSat CPR observations and affiliated products are the primary data sources used in this study. The CPR is a near-nadir-pointing, nonscanning radar with a mean spatial resolution of ~1.4 (cross track) × ~1.8 km (along track) and produces vertical radar reflectivity factor (hereafter referred to as “radar reflectivity” or “reflectivity” for brevity) profiles with 240-m grid spacing in the CloudSat data products. The following level 2 products
TABLE 1. CloudSat products and parameters used in this study from each respective product.

<table>
<thead>
<tr>
<th>CloudSat product</th>
<th>Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>2B-GEOPROF</td>
<td>Radar reflectivity factor, land–sea flag, elevation, latitude, and longitude</td>
</tr>
<tr>
<td>ECMWF-AUX</td>
<td>Temperature profiles</td>
</tr>
<tr>
<td>2C-SNOW-PROFILE</td>
<td>Near-surface snowfall rate</td>
</tr>
<tr>
<td>2B-CLDCLASS</td>
<td>Cloud classification</td>
</tr>
<tr>
<td>2C-PRECIP-COLUMN</td>
<td>Surface type, sea surface temperature, and cloud-top height for lowest significant cloud layer</td>
</tr>
</tbody>
</table>

(2006–10 data period also aligns with near-coincident AMSR-E observations when compared against Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) lidar observations, respectively (Marchand et al. 2008). If 2C-PRECIP-COLUMN flags near-surface observations as “mixed possible” or “mixed certain,” the 2C-SNOWPROFILE algorithm uses a snow discrimination algorithm based on ECMWF-AUX surface temperature, an assumed lapse rate, and an idealized melting model. The internal 2C-SNOWPROFILE phase algorithm allows a 240-m layer depth for snow to significantly melt. This assumed melting layer depth enables snowfall retrievals to be made for surface temperatures up to ~1.5°C. The 2C-SNOWPROFILE optimal estimation scheme is constrained by a priori snow microphysical properties (e.g., observed mass–size relationships and particle size distributions collected during field campaigns, plus modeled backscatter properties of nonspherical frozen hydrometeors) and provides snow size distribution parameter and snowfall rate uncertainty estimates combined with snowfall rate retrievals (Wood et al. 2014, 2015).

Ground clutter is also partially mitigated by taking advantage of the 2C-SNOWPROFILE snow retrieval status (SRS) flag that highlights CPR snowfall retrievals associated with a strong vertical radar reflectivity gradient in the lowest bins. Observations associated with strong vertical reflectivity or snowfall rate gradients might be indicative of ground clutter. Global maps of this flag (not shown) systematically indicate ground clutter in a few select locations (e.g., Antarctica and Greenland), so snowfall rate retrievals from higher in the column are utilized to alleviate potentially clutter-infected observations [see Milani et al. (2015) for further details].

The 2B-CLDCLASS product is used to discriminate shallow cumuliform (e.g., stratocumulus or cumulus) versus precipitating stratiform (e.g., nimbostratus) snow-producing
cloud structures. The 2B-CLDCLASS cloud classification algorithm uses space-based active (CloudSat CPR and CALIPSO) and passive [Moderate Resolution Imaging Spectroradiometer (MODIS)] remote sensing observations to identify cloud properties such as vertical and horizontal cloud extent, precipitation occurrence, cloud temperature and maximum reflectivity, and upward radiance [see Wang and Sassen (2007) and Sassen and Wang (2008) for further theoretical framework]. This information allows cloud structures to be classified as cumulus, stratocumulus, stratus, nimbostratus, alto-type clouds, deep convective, and cirrus. While the algorithm takes into account cloud features (cloud base, precipitation production, size, etc.) previously quantified in the literature, it also uses the more complex CloudSat data to craft a decision tree. The algorithm first identifies cloud layers or clusters. It then determines if clouds are precipitating, using measured precipitation and cloud-top height. Using maximum reflectivity, the height at which it occurs, and the cloud base and top, the algorithm then distinguishes between high and low clouds.

b. Snowfall partitioning methodology and examples

Nonzero, near-surface 2C-SNOW-PROFILE snowfall retrievals are partitioned into a shallow cumuliform (“shallow” is hereafter often used for brevity) snowfall dataset using coincident 2B-CLDCLASS “stratocumulus” and “cumulus” cloud classifications. Near-surface snow observations from all other 2B-CLDCLASS cloud categories are retained, with “nimbostratus” clouds serving as the second important snowfall category analyzed in this study. Snowfall occurrences coincident with other cloud-type retrievals will be briefly discussed even though they comprise only a small percentage of the CloudSat snowfall database.

As defined by the stratocumulus and cumulus cloud categories, shallow convective snow-producing clouds are usually linked with boundary layer processes (lake-effect snow, overland boundary layer rolls, etc.), while the nimbostratus designation is associated with horizontally contiguous reflectivity structures that are typically, but not universally, thicker than shallow cumuliform clouds. The 2C-PRECIP-COLUMN lowest significant cloud-layer height in the column is used to define the snow-producing cloud structure thickness for each CloudSat snowfall observation (“snowfall” or “snowfall observation” is hereafter applied to CloudSat-detected snowfall events that have a valid reflectivity and snowfall rate retrieval in the designated near-surface bin). The lowest significant cloud-layer height (“cloud thickness” for brevity) above ground/ocean level (AGL) is used rather than the absolute maximum reflectivity-defined cloud-top height to avoid misclassification due to multilevel cloud structures. Figure 1 illustrates the distinct cloud thickness distributions for the shallow and nimbostratus snowfall categories based on 2B-CLDCLASS classifications. The shallow snowfall normalized cloud thickness distribution peaks between ~1 and 2 km and exhibits a very narrow distribution. Almost 99% of all cumuliform snow-producing clouds are associated with cloud thicknesses less than 3 km, thus serving as justification to apply the “shallow” qualifier to such snow-producing clouds. Conversely, the nimbostratus normalized cloud thickness distribution is much broader and centered near 4–5 km. While over 77% of nimbostratus clouds exceed the 3-km cloud thickness threshold, the nimbostratus cloud thickness distribution overlaps the cumuliform/shallow category in the sub-3-km range, thus indicating a mode of nimbostratus snowfall-producing cloud that does not possess extensive vertical development. Cloud thickness is therefore not an exclusive discriminant between the two primary snow categories, but the nimbostratus category is more likely to be associated with deeper cloud structures than the cumuliform category.

The snowfall partitioning scheme adopted in this study is not the first published attempt at categorizing CloudSat snowfall events based into shallow versus deeper structures. Wang et al. (2013) presented a partitioning methodology to discriminate shallow versus deeper snowfall events using CloudSat reflectivity characteristics. Wang et al. (2013) classified shallow snowfall events with CloudSat-estimated cloud-top
 heights lower than 5 km. Furthermore, shallow snow occurrences were further subdivided into isolated (<40 km) versus extended (>40 km) categories based on the horizontal radar reflectivity continuity. The Wang et al. (2013) analysis focused on cloud liquid water content trends in the shallow versus deep cloud structures, with direct applications to passive microwave remote sensing. Note that the Wang et al. (2013) snowfall event partitioning methodology would most likely produce a different spatial shallow snowfall occurrence map when compared to the results presented in section 3. For instance, any nimbostratus snowfall events with cloud-top heights lower than 5 km would be classified as shallow events using the Wang et al. (2013) methodology. The shallow cumuliform versus nimbostratus categories are preferred for this study since we are most interested in discriminating shallow convective cumuliform clouds from nonconvective snowfall.

Figures 2–4 show three snowfall cases near Greenland to highlight typical structures associated with shallow cumuliform and nimbostratus snowfall events, thus providing valuable context to the global snowfall partitioning results presented in section 3. Figure 2 (from CloudSat orbit 14138 on 24 December 2008) is an illustrative shallow cumuliform snowfall case. Figure 2 shows convective snow forced by a postfrontal cold-air outbreak interacting with unfrozen North Atlantic Ocean waters near Greenland (the Greenland coastline and land surfaces are indicated by the thick black line at the northernmost latitudes). Cloud-top heights for this event are confined to less than \( \sim 2\text{–}3 \text{ km AGL} \), and the cellular convective nature of this snowfall event is an obvious defining feature. Maximum CPR radar reflectivities exceed \( \sim 15 \text{ dBZ} \) in the convective cores, with corresponding 2C-SNOW-PROFILE liquid equivalent snowfall rate retrievals between 1 and 2 mm h\(^{-1}\). The 2B-CLDCLASS product labels these shallow convective clouds as stratocumulus structures, and the snowfall partitioning scheme thus places them in the shallow cumuliform snowfall category.

Figure 3 is a continuation of the same orbit shown in Fig. 2 (note the 64\(^{\circ}\)N latitude end and start point for each
respective figure), but this section of the CloudSat overpass is entirely over the Greenland Ice Sheet and captures a large-scale snowfall event associated with a midlatitude cyclone. Cloud-top heights are generally between 4 and 6 km AGL over the ice sheet. Fall streaks emanating from small-scale upper atmosphere convective cells are apparent throughout much of this segment of the snowfall event, similar in appearance to the snowfall-generation processes associated with the cold sector of a midlatitude winter cyclone described by Rauber et al. (2014). Maximum near-surface reflectivities are generally below \( \sim 10 \text{ dBZ} \), with a few embedded regions exceeding 10 dBZ. CloudSat-derived snowfall rates are fairly light and do not exceed \( \sim 0.4 \text{ mm h}^{-1} \) for the entire span shown. Because of the extended cloud-top heights and mostly contiguous radar reflectivity field, the 2B-CLDCLASS product indicates mostly nimbostratus cloud structures for the vast majority of the precipitating observations shown in Fig. 3. The only nimbostratus exception affiliated with this snowfall event is located at the far southernmost edge of the cloud structure that is labeled as stratocumulus where cloud-top heights are much lower.

Figure 4 shows a final CloudSat overpass on 24 December 2008 (orbit 14144) that again captures ocean-induced convective snowfall near Greenland. Similar to Fig. 2, the convective cores contain elevated reflectivities (exceeding \( \sim 15 \text{ dBZ} \)) and retrieved snowfall rates (\( >2.0 \text{ mm h}^{-1} \)). The convective snow shown in Fig. 4 is more vigorous than the earlier CloudSat overpass, as cloud-top heights approach \( \sim 4 \text{ km} \). The 2B-CLDCLASS product, however, indicates a mixture of cumulus and stratocumulus cloud structures associated with this overpass segment due to subtle differences in reflectivity composition or cloud-top height/temperature. Such differences in cloud classifiers are irrelevant for the purposes of this study, however, since both cumulus and stratocumulus classes are considered shallow cumuliform clouds in the snowfall partitioning criteria. The cloud structures shown in Fig. 4 possess similar cloud forcing mechanisms due to air–sea interactions and are most likely microphysically similar mixed-phase clouds.

c. Geographical gridding methodology

CloudSat’s CPR is a nonscanning, near-nadir-pointing radar with a 16-day orbital cycle. Figure 5 shows 2006–10 CloudSat orbital tracks to illustrate the coverage provided by the 16-day orbital cycle over two different regions (Greenland–Iceland–North Atlantic Ocean and

Fig. 3. As in Fig. 2, but for a synoptic snowfall event over Greenland. This is a continuation of the same orbit shown in Fig. 2 as CloudSat traverses Greenland. This case is predominantly classified as nimbostratus (Ns) cloud structures.
western Pacific Ocean). CloudSat observations are gridded into 1° × 1° boxes for many of the results presented in section 3. CloudSat’s coverage is limited to latitudes from 82°N to 82°S, so any gridded products will not contain data exceeding these latitudinal limits. High-latitude areas systematically receive more CloudSat overpasses and denser spatial coverage compared to equatorward latitudes. As shown in Fig. 5, intersecting CloudSat orbital tracks create local maxima that inflate the population of data points in a given 1° grid box. These nodal points are obvious features at equatorward latitudes. High-latitude grid boxes contain over 20000 observations at maximal poleward locations (near 82° latitude) for the 2006–10 period, while midlatitude grid boxes contain a wide sampling range between ~5000 and over 15000 observations per grid box depending on the proximity to overlapping orbital track nodes.

3. Results

a. Global snowfall analysis

A multiyear perspective of all snowfall events contained in the CloudSat snowfall database is first presented in this section. Similar to the shorter-duration snowfall datasets analyzed in earlier CloudSat snowfall studies (e.g., Liu 2008; Hiley et al. 2011), the number of CloudSat-induced snowfall events generally increases poleward in each hemisphere (not shown). The highest counts (>10 000 snowfall events per grid box) occur near 82° latitude in the Northern Hemisphere because of both the higher likelihood of snowfall and increased CloudSat sampling at poleward latitudes (not shown). Localized snowfall count maxima exceeding 5000 counts also occur in some other regions away from higher latitudes (e.g., Southern Hemispheric oceans, North Atlantic Ocean, western Pacific Ocean, Canadian–Alaskan Pacific coastline, southern Greenland, and continental Asia). CloudSat sampling gaps equatorward of ~50° in both hemispheres also exist. Larger grid boxes would mitigate these sampling artifacts, but 1° grid sizes are deemed useful to analyze higher-latitude snowfall with greater spatial resolution.

CloudSat-derived snowfall fractions are shown in Fig. 6a, where snowfall fraction is defined as the ratio of snowfall events to the total number of CloudSat observations in each grid box. Snowfall fraction values are the
preferred method to interpret the CloudSat snowfall dataset since latitudinal sampling differences are minimized. Unlike total snowfall counts, the maximum snowfall fraction values are not exclusively anchored to poleward latitudes near 82°. Notable snowfall fraction maxima exceeding 30% are found in the transoceanic Southern Hemisphere storm-track region between ~60° and 70°S latitudes. Past studies have indicated similar inflated snowfall fraction magnitudes in this region using the first year or two of CloudSat observations (Liu 2008; Ellis et al. 2009; Hiley et al. 2011). Notably, a pronounced snowfall fraction decrease in the Southern Hemispheric latitudinal belt is located in the vicinity of the Ross Sea (75°S, 175°W) and on the lee side of the Antarctic Peninsula (70°S, 65°W) over the Weddell Sea (75°S, 45°W). While the largest Southern Hemispheric snowfall fractions are located over the oceans, continental snowfall maxima over Antarctica are located near the Antarctic Peninsula and Amundsen Sea (73°S, 110°W) coastal regions. A large snowfall fraction gradient also exists between the coast and interior regions of Antarctica, similar to findings presented in Palerme et al. (2014) and Milani et al. (2015).

Northern Hemispheric snowfall fraction values are lower, on average, compared to the Southern Hemisphere. Notable over-ocean snowfall fraction maxima exceeding 30% are located in the North Atlantic Ocean over the Greenland (75°N, 8°W) and Barents (75°N, 40°E) Seas, while overland snowfall fraction maxima of similar magnitudes are found in a thin strip along the Alaskan and Canadian Pacific coastline and various Greenland regions, especially the southeastern Greenland coastal region. A large swath of the high-latitude Northern Hemisphere contains snowfall fractions near or exceeding 20%, though, including vast regions of the Arctic Ocean, the western Pacific Ocean near Kamchatka (57°N, 160°E), interior Russia (65°N, 90°E), the Himalayan Mountains and nearby Tibetan Plateau, the Norwegian coast (60°N, 8°E), interior northern Canada (Yukon and Northwest Territory regions; 65°N, 135°W), and coastal and interior eastern Canada (Newfoundland, Labrador, and Quebec; 55°N, 65°W).
Complementing the snowfall fraction analysis presented in Fig. 6a, mean annual snowfall rates (liquid equivalent) derived from 2C-SNOW-PROFILE retrievals are shown in Fig. 6b. The highest estimated 2006–10 mean annual snowfall rates (>1000 mm yr$^{-1}$) coincide with many of the regions previously highlighted. These snowfall rate estimates are associated with considerable uncertainties exceeding 50% [see Palerme et al. (2014) for sample CloudSat snowfall estimate uncertainties and Kulie and Bennartz (2009), Hiley et al. (2011), and Wood et al. (2013) for further discussion of CloudSat snowfall retrieval uncertainties due to underlying microphysical assumptions]. The Southern Hemispheric snowfall belt is again a defining feature of this near-global map. The latitudinal belt between $\sim$60° and 70°S receives the largest amount of snowfall, and the oceanic versus continental gradient near and over Antarctica—as well as the Ross and Weddell Sea snowfall minima—are defining features of Southern Hemispheric snowfall distribution. An enhanced Northern Hemispheric snowfall belt occurs from the eastern Canadian provinces northeastward to the extreme North Atlantic Ocean and Barents Sea. The southeast Greenland and Alaskan/Canadian coasts also receive substantially elevated snowfall totals, while the western Pacific Ocean near Kamchatka experiences mean annual snowfall totals exceeding 400 mm yr$^{-1}$. Central Russia and the Himalayan region, both interior continental locations, receive over 400 and 600 mm yr$^{-1}$ of estimated snowfall, as do isolated mountainous regions in both hemispheres. Vast areas of continental North America, Europe, and Asia average between 50 and 300 mm yr$^{-1}$ of snowfall. The Arctic Sea region north of Russia has a relatively homogenous estimated average annual snowfall rate between 150 and 300 mm yr$^{-1}$, while the Arctic Sea north of Alaska and Canada generally receives less snowfall (<150 mm yr$^{-1}$).

b. Snowfall partitioning: General statistics

Table 2 contains frequency of occurrence statistics for 2B-CLDCLASS categories associated with orbital (un-gridded) CloudSat-detected snowfall events. The entire
CloudSat snowfall dataset for the 2006–10 period contains over 49 million probable snowfall events. Shallow cumuliform snowfall comprises ~36% of the CloudSat snowfall dataset, while nimbostratus snowfall events occur more frequently (~59%). The vast majority of shallow snowfall cases are labeled as stratocumulus (~34% of overall database), with a much smaller fraction identified as cumulus (~1.4%) cloud structures.

The shallow cumuliform and nimbostratus snowfall categories comprise over 95% of the CloudSat snowfall dataset, but did not account for all snowfall events in the database. Interestingly, a few other 2B-CLDCLASS categories populate the snowfall database, including altostratus (1.8%), altocumulus (1.3%), and clear/no classification (~2%). The true definition of altostratus and altocumulus clouds as elevated cloud structures should preclude their association with surface precipitation. The 2B-CLDCLASS product, however, designates some near-surface clouds associated with possible surface snowfall events as alto-type clouds. Altostratus and altocumulus snowfall events occur around the globe in mostly small numbers, but higher occurrences of these snowfall categories appear over extremely cold surfaces like interior Antarctica and Greenland, as well as the pan-Artic region near 82°N (not shown). The 2B-CLDCLASS Alto-type snow categories are most likely due to snow-producing clouds in very cold ambient environments, often located at high elevations. These categories are not included in the global spatial maps presented in following sections, although the altostratus cases could arguably be associated with the nimbostratus category since, after inspecting numerous CloudSat overpasses of such events, they seem structurally similar to typical nimbostratus snowfall-producing clouds (not shown). Although snowfall rates associated with alto-type and no cloud classification categories are generally very light, further partitioning studies over Greenland or Antarctica should include these categories to fully account for all snowfall events in these regions. All other 2B-CLDCLASS categories (deep cumulus, stratus, cirrus, and mixed layer) have negligible occurrence rates. These cloud categories will not be considered in the following analyses.

Figure 7 highlights near-surface CPR reflectivity factor distributions for all shallow cumuliform (thick blue) and nimbostratus (thick red) snowfall cases. Additional distributions for shallow cumuliform snowfall events over ocean (blue dashed) and land (blue dash-dotted), as well as nimbostratus snowfall events over ocean (red dashed) and land (red dash-dotted), are also shown. A radar reflectivity bin size of 1 dBZ is used to create the respective distributions. The reflectivity distribution is truncated at ~15 dBZ since CloudSat precipitation products use this value as a minimum threshold to be considered a likely precipitation observation.

<table>
<thead>
<tr>
<th>2B-CLDCLASS category</th>
<th>N</th>
<th>Percentage of CloudSat-observed snowfall events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stratocumulus (Sc)</td>
<td>1.706 × 10^7</td>
<td>34.22%</td>
</tr>
<tr>
<td>Cumulus (Cu)</td>
<td>7.080 × 10^5</td>
<td>1.42%</td>
</tr>
<tr>
<td>Total shallow cumuliform</td>
<td>1.777 × 10^7</td>
<td>35.64%</td>
</tr>
<tr>
<td>Total nimbostratus (Ns)</td>
<td>2.948 × 10^7</td>
<td>59.13%</td>
</tr>
<tr>
<td>Altostratus (As)</td>
<td>8.775 × 10^5</td>
<td>1.76%</td>
</tr>
<tr>
<td>Altocumulus (Ac)</td>
<td>6.631 × 10^5</td>
<td>1.33%</td>
</tr>
<tr>
<td>Deep cumulus (Dc)</td>
<td>8.476 × 10^4</td>
<td>0.17%</td>
</tr>
<tr>
<td>No classification (NC)</td>
<td>9.822 × 10^5</td>
<td>1.97%</td>
</tr>
<tr>
<td>Total other</td>
<td>2.608 × 10^6</td>
<td>5.23%</td>
</tr>
<tr>
<td>Total</td>
<td>4.986 × 10^7</td>
<td>100%</td>
</tr>
</tbody>
</table>

Figure 7. CloudSat CPR near-surface reflectivity factor distributions for all shallow cumuliform (thick blue) and nimbostratus (thick red) snowfall cases. Additional distributions for shallow cumuliform snowfall events over ocean (blue dashed) and land (blue dash-dotted), as well as nimbostratus snowfall events over ocean (red dashed) and land (red dash-dotted), are also shown. A radar reflectivity bin size of 1 dBZ is used to create the respective distributions. The reflectivity distribution is truncated at ~15 dBZ since CloudSat precipitation products use this value as a minimum threshold to be considered a likely precipitation observation.
Figure 7 indicates systematic intensity differences between the two snowfall modes. Interesting fractional reflectivity trends, however, are associated with elevated reflectivities. While over-ocean/water shallow cumuliform snowfall events are associated with larger peak reflectivity values compared to land, this trend reverses for radar reflectivities exceeding about 14 dBZ. Additionally, the shallow cumuliform snowfall category exhibits an increased reflectivity fraction above about 17 dBZ over land surfaces (blue dash–dotted line in Fig. 7) compared to the nimbostratus category. A secondary overland shallow snowfall radar reflectivity peak also exists at values exceeding 30 dBZ. This secondary peak is an obvious ground clutter signature, as W-band snowfall-related reflectivities cannot theoretically exceed ~20 dBZ because of non-Rayleigh scattering effects (e.g., Matrosov 2007; Kulie and Bennartz 2009). A very small percentage of the CloudSat snowfall database therefore requires further clutter mitigation. Ground clutter associated with abrupt topographical changes may also elevate overland shallow reflectivities under 20 dBZ, but the overland reflectivity increase between about 14 and 20 dBZ may also be plausibly explained by land/orographic enhancement.

Further research beyond the scope of the current study is needed to determine the exact cause of the overland shallow snowfall reflectivity behavior. Irrespective of overland shallow snowfall, overwater shallow snowfall contains a slightly higher fraction of reflectivities exceeding about 15 dBZ compared to the nimbostratus category. This feature most likely reflects intense lake- or ocean-effect snow events as indicated in Figs. 2 and 4. Liu (2008) also found a similar shallow snowfall signature in the highest snowfall rates derived from CloudSat observations. Similar to shallow snowfall, deeper nimbostratus snowfall structures exhibit a slight land (~3 dBZ) versus ocean (~5 dBZ) reflectivity distribution peak difference. The overland nimbostratus snowfall category also displays a subtle secondary “shoulder” near ~6 dBZ associated with lighter nimbostratus snowfall that commonly occurs over cold continental regions like interior Antarctica and eastern Russia (not shown). The shallow snowfall category is dominated by ocean/water events (~71%) compared to overland events (~29%) from a frequency of occurrence perspective. The nimbostratus snowfall dataset has a reduced ocean (~62%–land (~38%) occurrence discrepancy compared to shallow cumuliform snowfall.

**c. Snowfall partitioning: Global analysis**

Figure 6 from the previous section shows the global snowfall viewpoint from CloudSat spaceborne measurements. This study, however, also assesses whether CloudSat can effectively discriminate between different snowfall modes to provide a global shallow snowfall census. Based on previous observational studies, a strong shallow cumuliform snowfall signal should exist over large bodies of water at higher latitudes because of lake- or ocean-forced convective snow (e.g., Figs. 2, 4). Previous observational studies have not, however, determined shallow snowfall frequency or estimated its contribution to total annual snowfall accumulation on a global basis.

Using the snowfall partitioning methodology outlined in section 2, Figs. 8 and 9 present direct evidence that shallow cumuliform snowfall plays a prominent role in global surface snowfall production. Figure 8 illustrates the fraction of snowfall events that are associated with shallow cumuliform and nimbostratus clouds, respectively, for the entire CloudSat snowfall database. The most striking feature shown in Fig. 8 is the stark oceanic versus continental difference between shallow and nimbostratus snowfall fraction, with the open ocean serving as the obvious forcing mechanism to inflate shallow snowfall fraction in many regions. Similarly, Fig. 9 clearly shows the oceanic versus continental dichotomy between mean annual estimated snowfall rate due to nimbostratus and shallow events. Deeper nimbostratus snowfall dominates the contribution to annual snowfall totals presented in Fig. 9b over most continental regions and regions frequently covered by sea ice, while shallow snowfall contributes significantly to annual snowfall totals in select over-ocean regions. While shallow snowfall frequently occurs in many global locations (Fig. 8a), it comprises ~18% of the estimated annual global surface snowfall input for the 2006–10 CloudSat dataset, compared to ~82% for nimbostratus snowfall. These global percentages discount snowfall events associated with other 2B-CLDCLASS categories, which at most comprise another ~1%–2% of annual global snowfall contribution.

In the Northern Hemisphere, large landmasses are typically dominated by nimbostratus snowfall events from both frequency (Fig. 8b) and estimated annual snowfall rate (Fig. 9b) perspective. Distinct land–ocean gradients between shallow and deep snowfall zones also exist in numerous locations. Prominent Northern Hemispheric regions that experience both frequent snowfall (Figs. 6a,b) and widespread shallow snowfall fraction values exceeding 60% include:

- a southwest-to-northeast-oriented swath from the North Atlantic Ocean to Barents Sea from about 45°W to 70°E longitude;
- the Labrador Sea between Greenland and Canada (60°N, 55°W);
- the western Pacific Ocean, including the Seas of Okhotsk (55°N, 150°E) and Japan (40°N, 135°E); and
- the southern Bering Sea between Siberia and Alaska (58°N, 180°).
These Northern Hemispheric regions consistently receive \( \sim 40\%-60\% \) of estimated annual snowfall accumulation from shallow snowfall (Fig. 9a). The Great Lakes region also contains many grid boxes with shallow snowfall fractions exceeding 60\%, but its comparatively small geographical footprint makes it difficult to discern on global maps. The Great Lakes region has motivated significant shallow cumuliform snowfall research (see references in the introduction), but this region pales in comparison to high-latitude over-ocean regions that experience significant amounts of shallow cumuliform snow over vast geographical expanses.

A common trait shared among the peak oceanic shallow snowfall regions is reduced or negligible winter sea ice coverage. Other oceanic Northern Hemispheric areas are associated with somewhat elevated shallow snow fractions exceeding \( \sim 40\% \) [e.g., Hudson Bay (60°N, 85°W), Baffin Bay (73°N, 67°W), the Arctic Ocean near Alaska and eastern Siberia, and Kara Sea (77°N, 77°E)], but increased ice cover most likely diminishes shallow snowfall production compared to the peak regions previously mentioned. This potential shallow snowfall–sea ice relationship will be discussed further in section 4.

Many Northern Hemispheric continental regions also display shallow cumuliform snowfall fractions exceeding 40\%, especially many locations over Russia, Europe, north-central Greenland, and mountainous regions of North America (Fig. 8). The contribution to annual snowfall from shallow events is typically depressed in these regions, thus indicating light snowfall rates associated with shallow cumuliform snow (Fig. 9).

Unlike the complicated and regionally variable Northern Hemispheric shallow snowfall pattern, the Southern Hemisphere displays a fairly uniform shallow snowfall frequency (Fig. 8) and contribution to annual snowfall (Fig. 9) gradient from north to south, with equatorward latitudes receiving more shallow snowfall events and surface precipitation flux from shallow snow. The high
d. Snowfall partitioning: Greenland focus

Figures 6–9 illustrate the multiyear CloudSat snowfall dataset from a global perspective, but it is also useful to focus regionally to elucidate details that are difficult to distinguish from the global figures. Figure 10 shows shallow cumuliform and nimbostratus snowfall fraction and mean annual snowfall rate percentage, respectively, near and over Greenland. This region was highlighted in Figs. 6–9 for receiving frequent and abundant snowfall from both shallow (ocean) and deeper nimbostratus (over land and Greenland ice sheet) snowfall. Accumulating snowfall also plays an important role in the Greenland ice sheet mass balance (e.g., Shepherd et al. 2012; Castellani et al. 2015), and snowflake production effectively scavenges supercooled liquid water in high-latitude mixed-phase clouds (e.g., Shupe et al. 2006), thus making this region interesting from multiple scientific perspectives.

Figure 10 highlights a few key features over and surrounding Greenland that warrant further discussion. For instance, the shallow snowfall signature fraction and annual accumulation percentage maxima in the Labrador Sea southwest of Greenland contains snowfall fractions exceeding 70% (Fig. 10a) and estimated accumulation percentages greater than 60% (Fig. 10c). There is also a latitudinal dividing line at ~65°N where shallow snowfall
frequency (accumulation percentage) decreases to mostly under 40% (30%), with a few isolated pixels indicating slightly higher values. This transition from very high to slightly lower shallow snowfall fractions is aligned with the typical maximal sea ice extent between Baffin Bay and the Labrador Sea (see, e.g., National Snow and Ice Data Center monthly ice coverage maps for further details; https://nsidc.org/data/seaice_index/).

The sharp oceanic versus continental shallow snowfall fraction gradient evident near Greenland in Fig. 8 was previously discussed, but details of this gradient over Greenland are difficult to discern in the global map. Since CloudSat products utilize a higher vertical bin over land versus ocean to retrieve snowfall rates, a natural question to pose is whether this land–ocean gradient is amplified by utilizing different vertical bins over different surfaces (i.e., are there less shallow snowfall events over land because of a more restrictive vertical data bin policy applied to land vs ocean observations?). Figure 10, however indicates a relatively thin inland zone of increased shallow snowfall fractions over the west Greenland coast, especially in the northernmost coastal regions near 77°–78°N and Greenland coastal latitudes south of ~70°N. The inland shallow snowfall fraction values are similar to nearby overwater fraction magnitudes and do not indicate land versus water shallow snowfall detection artifacts in this region. Note, however, that this feature is less prominent in the annual accumulation percentage fields. Similarly, Greenland's eastern coast and near-coastal oceanic regions are associated with an obvious shallow cumuliform snowfall shadow, where nimbostratus snowfall structures are prominent compared to shallow cumuliform snow (Figs. 10b,d). This signature is interpreted as a region where convective snow does not readily form close to shore because of increased seasonal ice coverage and/or the lack of significant overwater fetch needed for convective snow showers to form when cold air advects over ice-free water.

A few other inland Greenland snowfall features are also evident in Fig. 10. First, an apparent orographic
snowfall signature is located in southeast and central-east Greenland regions where a gradient in the nimbostratus snow category exists (Figs. 10b,d). This region is one of the snowiest locations in the Northern Hemisphere, similar to other observational and modeling studies over Greenland (Hanna et al. 2006), and is dominated by homogenous and deeper snowfall structures. Second, a large swath of interior north-central Greenland is associated with 30%–40% cumuliform snowfall fractions. This shallow snowfall influence, however, is not reflected as obviously in the accumulation partitioning statistics, as the nimbostratus snow category contributes a disproportionate percentage to the estimated annual snowfall in this region. CloudSat appears to capture lightly precipitating, shallow events over the Greenland ice sheet that might be associated with shallow mixed-phase Arctic clouds (e.g., Shupe et al. 2006, 2013). Further investigation is necessary to confirm this finding, including detailed analyses of CloudSat overpasses in this region. Finally, some Greenland locations are still affected by ground clutter contamination even after adopting a more rigorous approach to detect and mitigate ground clutter compared to previous CloudSat snowfall studies. Figure 10 indicates a few isolated near-coast Greenland pixels where shallow snowfall fraction is extremely inflated, but these points are located within a broader nimbostratus-dominated region. Further clutter mitigation steps should be developed to completely remove these data points from the CloudSat snowfall dataset.

4. Conclusions

The CloudSat observational dataset provides the first opportunity to study near-global snowfall, and numerous recent investigations have utilized CloudSat for snowfall-related research. This study leverages CloudSat cloud classification and snowfall rate retrieval products to partition 2006–10 CloudSat snowfall observations into shallow cumuliform and nimbostratus snowfall categories, thus creating a unique global census of shallow cumuliform snowfall events. Cumuliform, snow-producing cloud structures display a narrow cloud thickness distribution centered near 1.5 km, while nimbostratus snow-producing clouds exhibit a much broader cloud thickness distribution that peaks near 4 km, thus confirming the notion of two disparate snow-producing cloud types separated both by cloud macrophysical (e.g., cloud thickness plus 2B-CLDCLASS descriptors) and mechanistic (e.g., cloud forcing) properties. Shallow snowfall associated with cloud structures identified as stratuscumulus and cumulus (nimbostratus) clouds are shown to globally comprise ~36% (~59%) of the 2006–10 CloudSat snowfall dataset by occurrence, while constituting ~18% (82%) of the estimated annual global snowfall accumulation in liquid equivalent terms. Certain high snowfall frequency regions, however, experience shallow snowfall occurrence fractions exceeding 60% (e.g., North Atlantic Ocean near Greenland, Barents Sea, western Pacific Ocean, southern Bering Sea, and Southern Hemispheric oceanic storm-track region). These same regions receive an estimated 40%–60% of the annual snowfall accumulation from shallow cumuliform cloud structures. Many other regions also display localized increases in shallow snowfall frequency and accumulation percentage. About 71% (29%) of shallow snowfall events occur over water (land) surfaces, and distinct land–water gradients exist in global shallow snowfall fraction and accumulation percentage maps.

CloudSat Cloud Profiling Radar reflectivity distributions also reveal that shallow snowfall is much lighter, on average, than deeper nimbostratus events—with the possible exception of a high-reflectivity shallow snowfall mode associated with CPR reflectivities exceeding ~15 dBZ that might reflect intense inland lake- or ocean-effect snow. This study also reveals that shallow snowfall events are disproportionately associated with light reflectivity values. About 74% (96%) of all shallow cumuliform snowfall events have near-surface reflectivities below 0 (10) dBZ, while ~36% (91%) of nimbostratus snowfall events fall under these same reflectivity levels. These values are extremely useful for the spaceborne radar community to better define future radar capabilities in an effort to remotely sense as much global snowfall as possible. Both shallow and nimbostratus snowfall categories display land versus ocean near-surface reflectivity distribution differences, with oceanic snow associated with mostly higher near-surface CPR reflectivities. The only exception to this trend is a notable increase in near-surface reflectivity fractions above ~14 dBZ for shallow snowfall over land, with a secondary peak at elevated reflectivity values exceeding 30 dBZ. The secondary peak is almost assuredly related to ground clutter, but further investigation is required to understand whether the other overland reflectivity percentage increase is due to land/orographic enhancement to shallow snowfall. Further clutter mitigation techniques can be tested in regions identified by this study to show systematic clutter contamination symptoms.

This study sets the stage for further follow-on methodological, evaluation, and science-related research studies. This dataset can be further parsed to understand the variability and radar/cloud macrophysical properties of shallow snowfall clouds due to environmental parameters (air–sea temperature gradient and stability, low-level humidity, wind speed, etc.). Seasonal variability
of shallow snowfall occurrence and intensity can also be studied, and the potentially intimate relationship between sea ice coverage and shallow snow production can also be isolated. While this study defines cumuliform snowfall as the only “shallow” snowfall category, cloud thickness distributions show that over 20% of nimbostratus snow-producing clouds have cloud thicknesses less than 3 km. Further work will be undertaken to understand whether certain areas (mountainous and/or cold, elevated regions like Antarctica) are systematically prone to these types of snowfall events.

The snowfall partitioning statistics presented in this study are derived from CloudSat products and their respective inputs, so further work is needed to assess the CloudSat-derived results with independent datasets. For instance, future studies will assess whether numerical models realistically represent shallow convective snowfall and global reanalyses datasets (e.g., spatially, seasonally, and from a precipitation intensity and accumulation fraction perspectives). Additionally, ground-based observational datasets are being developed to assess the CloudSat partitioning statistics. Long-term, vertically pointing radar datasets are available in some high-latitude regions. These radar observations can readily discriminate snowfall modes and can be exploited as an independent assessment tool (e.g., Kneifel et al. 2011; Castellani et al. 2015). Ground-based operational scanning radar networks can also be used to develop multiyear snowfall partitioning statistics to compare with spaceborne results. Remote sensing datasets with concurrent ground-based snowfall accumulation and microphysical measurements will be especially useful evaluative tools for the CloudSat-generated detection and accumulation percentage statistics. It is also conceivable that CloudSat understates the occurrence of shallow cumuliform snowfall, as the CPR may not effectively sample extremely shallow snow events because of its overland “blind zone” in the lowest ~1 km AGL. Uncertainty analyses will be undertaken using ground-based radars to understand the percentage of extremely shallow snowfall events that may be undetected by CloudSat in different meteorological regimes (e.g., Maahn et al. 2014). These independent model and observational datasets will improve snowfall detection uncertainty estimates and identify systematic differences with CloudSat-derived partitioned snowfall statistics to isolate the cause of regional or global biases.

This partitioned snowfall dataset also serves as a valuable tool for other applications. For instance, this dataset can also be used for passive microwave snowfall retrieval development and assessment in the GPM era. CloudSat and microwave radiometer synergy has already been exploited in the at-launch GPM precipitation retrieval algorithm (Kummerow et al. 2015), as well as in recent studies that document complex radiometric signatures associated with snowfall (Kulie et al. 2010; Liu and Seo 2013). GPM snowfall retrieval algorithm evaluations will be undertaken in regions that are prone to shallow snowfall as identified by this study. Follow-on combined radar–radiometer studies will also be performed to understand whether shallow versus deeper snowfall events exhibit unique multifrequency radiometric signatures that can be exploited to improve microwave radiometer snowfall retrievals.

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