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CloudSat snowfall estimates over Antarctica and the Southern Ocean: An assessment of independent retrieval methodologies and multi-year snowfall analysis

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ABSTRACT

CloudSat spaceborne radar snowfall retrievals using two different methodologies – the 2C-SNOW-PROFILE (2C-SNOW) CloudSat product and the combined Kulie and Bennartz (2009) technique with the Hiley et al. (2011) reflectivity (Z) to snowfall rate (S) conversion (KBH) - are compared over Antarctica and surrounding Southern Ocean environments. KBH algorithm sensitivity tests are performed to demonstrate how retrievals are affected by algorithm assumptions (e.g., vertical reflectivity continuity test, the choice of near surface bin used to make surface snowfall rate retrievals, and temperature filters). These algorithm components are found to be detrimental to snowfall detection over this region by significantly reducing the snowfall population compared to 2C-SNOW, especially over ocean regions prone to ERA-interim indicated convective snow. After accounting for key algorithm differences, 2C-SNOW mean annual snowfall rates are systematically higher than KBH due to the *Z*-*S* relationship adopted. Spatial annual mean snowfall accumulation differences between the two datasets are minimized over interior Antarctica, but large differences are observed over the ocean. 2C-SNOW *Z*-*S* relationships for all snowfall events ($Z = 10.9\ S^{1.3}$), over ocean and sea ice ($Z = 8.2\ S^{1.3}$), escarpments and Antarctic coastal areas - below 2000 m a.s.l. ($Z = 6.7\ S^{1.4}$), and Antarctic plateau - above 2000 m a.s.l. ($Z = 5.5\ S^{1.6}$) are also derived. A multi-year 2C-SNOW mean annual snowfall analysis is also provided, and comparisons with ERA-Interim snowfall datasets show similar spatial patterns, but magnitude differences over oceans are observed. A monthly 2C-SNOW and acoustic depth gauge analysis is provided to demonstrate qualitative trends in snowfall accumulation between the respective datasets.

1. Introduction

Accurately quantifying atmospheric parameters in polar regions is essential for better understanding the global hydrologic cycle and energy budget, especially since certain higher latitude areas have experienced accelerated warming trends in recent years (Bromwich et al., 2013; Nicolas and Bromwich, 2014; Clem and Fogt, 2015). There are, however, numerous challenging aspects to characterizing important weather and climate parameters and their concomitant variability in polar regions (Lubin and Massom, 2006). For example, surface precipitation that usually occurs in the solid phase at high latitudes is a particularly vexing parameter that often demonstrates extreme spatiotemporal variability. Surface snowfall –which is often very light in polar climates - is also very difficult to detect and quantify using sparse ground measurements and current satellite observations (e.g., Bromwich, 1988; Kulie and Bennartz, 2009; Palerme et al., 2014).

Antarctica and its associated ice shelves has received sustained scientific attention for many decades, but surface precipitation characterization is hindered by a sparse observational network that relies on many different collection tools and methods (e.g., precipitation gauges, snow pits, acoustic instruments, snow stakes, etc.) that measure different frozen precipitation properties with varying sensitivities. Each respective method also contains observational errors that are sometimes difficult to quantify (e.g., Eisen et al., 2008; Knuth et al., 2010).

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Accurate ground-based snowfall measurements also require constant and effective instrument maintenance over the long durations needed to study precipitation. Data, instruments and techniques used affect and make difficult the spatial interpolation of such sparse data (Arthern et al., 2006; Eisen et al., 2008). Preliminary results from a recently established experimental site indicate that light snowfall rates dominate the snowfall rate spectrum, but these prevalent light snow events are interspersed with rare heavy snowfall events that contribute significantly to the surface mass balance (Gorodetskaya et al., 2014, 2015). Further long-term ground-based observational studies are needed to sample widely varying Antarctic environments.

The scientific community has relied heavily on climate models to study Antarctic Surface Mass Balance (SMB) and in particular precipitation among the various SMB components. Modeled precipitation fields have provided important climatic context to assess annual precipitation trends (Bromwich et al., 2011). The polar MM5 model (Guo et al., 2003) for example has been used to characterize the spatio-temporal distribution of Antarctic snowfall and blowing snow (Bromwich et al., 2004). The RACMO2 regional climate model and its updated physics schemes have also improved Antarctic surface energy balance and precipitation estimates (Van Wessem et al., 2014). Numerical model validation, however, is hampered by the aforementioned sparse ground-based observations. Large biases and relatively high errors also affect numerical model and ground-based measurement comparisons (Genthon and Krinner, 2001; Grazioli et al., 2017). Satellite precipitation products, even with known uncertainties and limitations, provide valuable independent datasets to evaluate models on a more spatially and temporally extensive basis compared to ground measurements (Palerme et al., 2017; Tapiador et al., 2017).

Passive microwave spaceborne sensors on Low Earth Orbiting (LEO) satellites have been successfully utilized to estimate precipitation at higher latitudes (e.g., Huffman et al., 2007). However, light and solid precipitation detection over Antarctica is difficult due to the highly emissive snow/ice surface background combined with low ice water paths in weaker snowfall-producing clouds (Kongoli et al., 2015; You et al., 2017). Several studies have theoretically assessed high frequency passive microwave channels' ability to detect and retrieve snowfall (e.g., Skofronick-Jackson and Johnson, 2011; Munchak and Skofronick-Jackson, 2013). High frequency channels ($>$ 150 GHz) show promise, but the signal is extremely sensitive to highly varying cloud microphysical composition (e.g., Kulie et al., 2010; Johnson et al., 2012), and environmental conditions (e.g., humidity and background surface, as evidenced in Panegrossi et al., 2017). Passive microwave radiometry using water vapor absorption band channels near 183 GHz or brightness temperature differences between vertically and horizontally polarized high frequency channels to eliminate background surface signals also offer promise (e.g., Surussavadee and Staelin, 2009; Laviola and Levizzani, 2011; Gong and Wu, 2017), but these techniques are complicated by Antarctica's dry atmospheric conditions. Dedicated studies to demonstrate the veracity of these techniques for accurate snowfall retrievals in the polar regions are currently lacking. Since upwelling microwave radiation is extremely sensitive to surface snow or ice morphology, an alternative approach evaluated snowfall occurrence by studying surface radiative property fluctuations (Bindschadler et al., 2005). This method, however, does not provide quantitative snowfall estimates. Snowfall detection and retrieval advances are expected with the Global Precipitation Measurement (GPM) mission Core Observatory (CO) (Hou et al., 2014). However, GPM-CO's orbital range between 65°S and 65°N does not enable the use of such a valuable spaceborne observational platform for Antarctica snowfall research.

The most useful tool for snowfall remote sensing at high latitudes is currently the Cloud Profiling Radar (CPR) onboard the CloudSat satellite launched in 2006 (Stephens et al., 2008). The W-band, nadir-viewing CPR provides radar reflectivity profiles, allowing physical retrievals of cloud and precipitation (Stephens et al., 2002; Liu, 2008), and, after adopting relevant cloud microphysical assumptions, quantitative snowfall rate estimates (Hudak et al., 2008; Liu, 2008; Kulie and Bennartz, 2009; Wood et al., 2013). After CloudSat's first operational year, global snowfall studies were published to illustrate CloudSat's unique snowfall observational capabilities (Liu, 2008; Hiley et al., 2011). Because of its high sensitivity to light precipitation, several studies use CloudSat products to assess snowfall detection capabilities of other sensors (Casella et al., 2017; Panegrossi et al., 2017). Multi-year CloudSat snowfall studies with extensive Antarctic region snowfall analyses have also been undertaken in recent years (e.g., Boening et al., 2012; Palerme et al., 2014; Kulie et al., 2016; Kulie and Milani, 2018). A CloudSat snowfall retrieval product has also been released to accommodate global snowfall studies. This product – named 2C-SNOW-PROFILE – provides “near surface” and vertical snowfall rate retrievals for each CPR profile (Wood et al., 2013).

Similarly to Palerme et al. (2014), this study uses a multi-year dataset of CloudSat snowfall retrievals to investigate precipitation characteristics over Antarctica, including spatial distributions of annual snow amounts. Unlike Palerme et al. (2014), we also analyze oceanic regions surrounding Antarctica. Furthermore, we analyze and interpret systematic differences between two CloudSat snowfall retrieval algorithms. The spaceborne results are also compared to ERA-Interim (Dee et al., 2011) reanalysis data and local ground-based Acoustic Depth Gauge (ADG) observations.

The main goals of this study are:

I. Evaluate the CloudSat 2C-SNOW-PROFILE and Kulie and Bennartz (2009) snowfall retrievals to determine if systematic differences exist in the pan-Antarctic and Southern Ocean region. Possible causes of algorithm differences are also explored.
II. Compare CloudSat snowfall retrievals with ERA-Interim (ERA-I) reanalysis and ground-based snow accumulation estimates.
III. Provide a multi-year snowfall “climatology” in the region south of 60°S (including both Southern Ocean and continental Antarctica) using the 2C-SNOW-PROFILE dataset.

2. Data and algorithms

2.1. CloudSat products and algorithms

The CloudSat research satellite's CPR provides critical observations to understand the role of clouds in the climate system (Stephens et al., 2008). CloudSat flies in the Afternoon, or A-Train, satellite formation, providing radar reflectivity factor (hereafter referred to as reflectivity (Z)) profiles of the lowest 30 km of the atmosphere (Tanelli et al., 2008). CPR is a nadir-pointing radar operating at 94GHz frequency (W-band), with a 240 m vertical resolution bin and a $\sim 1.7 \times 1.4\,\text{km}^2$ spatial footprint. The bins near the surface could contain anomalously large reflectivity values, most likely related to ground clutter contamination (Marchand et al., 2008; Tanelli et al., 2008). Depending on the surface type and on the methodology used to estimate precipitation, a defined number of those bins are excluded from the algorithms (see Sections 2.1.1 and 2.1.2 for further details) and a “Near Surface Bin” (NSB) is then defined as the lowest bin actually considered in the algorithms (Liu, 2008), with an elevated height ranging from about 720 m to about 1440 m depending on the algorithm and the surface. This “blind zone” can adversely affect CloudSat surface snowfall estimates in Antarctica depending on precipitation regime (Maahn et al., 2014).

The CPR can experience gaseous and hydrometeor attenuation, although Antarctica's drier, colder environment generally limits W-band attenuation effects. The CPR's sensitivity (around -29 dBZ minimum detectable signal) is sufficient to observe light precipitation and most cloud structures (Haynes et al., 2009). The CPR's sensitivity and orbital range (between 81°N/S latitude) allow it to effectively detect and retrieve snowfall distribution and intensity (Liu, 2008; Kulie and Bennartz, 2009; Hiley et al., 2011; Kulie et al., 2016; Behrangi et al., 2016; Kulie and Milani, 2018). Previous studies indicate that CloudSat