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Estimating radar reflectivity - Snowfall rate relationships and their uncertainties over Antarctica by combining disdrometer and radar observations

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ABSTRACT

Snowfall rate (SR) estimates over Antarctica are sparse and characterised by large uncertainties. Yet, observations by precipitation radar offer the potential to get better insight in Antarctic SR. Relations between radar reflectivity (Ze) and snowfall rate (Ze-SR relations) are however not available over Antarctica. Here, we analyse observations from the first Micro Rain Radar (MRR) in Antarctica together with an optical disdrometer (Precipitation Imaging Package; PIP), deployed at the Princess Elisabeth station. The relation $Ze = A^*SR^B$ was derived using PIP observations and its uncertainty was quantified using a bootstrapping approach, randomly sampling within the range of uncertainty. This uncertainty was used to assess the uncertainty in snowfall rates derived by the MRR. We find a value of $A = 18$ [11–43] and $B = 1.10$ [0.97–1.17]. The uncertainty on snowfall rates of the MRR based on the Ze-SR relation are limited to 40%, due to the propagation of uncertainty in both Ze as well as SR, resulting in some compensation. The prefactor (A) of the Ze-SR relation is sensitive to the median diameter of the snow particles. Larger particles, typically found closer to the coast, lead to an increase of the value of the prefactor ($A = 44$). Smaller particles, typical of more inland locations, obtain lower values for the prefactor ($A = 7$). The exponent (B) of the Ze-SR relation is insensitive to the median diameter of the snow particles. In contrast with previous studies for various locations, shape uncertainty is not the main source of uncertainty of the Ze-SR relation. Parameter uncertainty is found to be the most dominant term, mainly driven by the uncertainty in mass-size relation of different snow particles. Uncertainties on the snow particle size distribution are negligible in this study as they are directly measured. Future research aiming at reducing the uncertainty of Ze-SR relations should therefore focus on obtaining reliable estimates of the mass-size relations of snow particles.

1. Introduction

The Antarctic Ice Sheet (AIS) is the largest ice body on earth, having a volume equivalent to 58.3 m global mean sea level rise (Vaughan et al., 2013). In order to understand future changes regarding the mass of the AIS and its impact on sea level rise, information on present-day precipitation amounts is indispensable (Bromwich et al., 2004; Genthon et al., 2009; Palerme et al., 2017). Precipitation is the dominant source term in the surface mass balance of the AIS. However, this quantity is not well constrained in both models and observations (Bromwich et al., 2004; Palerme et al., 2014). Most climate models have physics that are not adapted for the Antarctic climate, leading to high biases compared to local observations or reanalysis products (Agosta et al., 2015). Direct observations over the AIS are also not coherent, as they are sparse in space and time and since acquisition techniques differ. These records are usually determined from ice cores, satellite products or stake measurements. Observations are often disturbed by blowing snow, which makes the distinction between transported and precipitating

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snow impossible (Knuth et al., 2010). This also impedes the use of precipitation gauges over Antarctica, as blowing snow may enter the gauge, while high wind speeds may lead to an undercatchment of precipitation (Yang et al., 1999). As a result, precipitation observations stay mostly limited to continent-wide averages (e.g. Vaughan et al., 1999).

One potential technique to constrain precipitation involves the use of a radar, which has been demonstrated to effectively detect frozen precipitation (Matrosov et al., 2008). Radar-based methods often use power-law relations between the measured equivalent radar reflectivity factor (Ze or Z = 10log $_{10}$(Ze/Ze$_0$), where $Ze_0 = 1\ mm^6\ m^{-3}$) and the melted liquid equivalent snowfall rate (SR) (Sekhon and Srivastava, 1970; Battan, 1973). Several authors have derived a power law ($Ze = A*SR^B$) for snowfall during different meteorological conditions for different locations (e.g. Rasmussen et al., 2003; Matrosov, 2007; Kulie and Bennartz, 2009). Matrosov et al. (2009) state that characteristic values of the exponent B for dry snowfall relations are generally in the range 1.3–1.55 (when Z is in dBz and SR is in $mm\ h^{-1}$). The prefactor A exhibits stronger variability and its range varies from about 30 (for aircraft-based size distributions and smaller density particles) to 140 (for surface-based size distributions) (Matrosov et al., 2009). It must be noted that these relations depend on snowflake characteristics which can show large spatial and temporal variations. Therefore, information about the physical properties of the snowflakes needs to be known in order to derive Ze-SR relations. e.g. shape, diameter, particle size distribution (PSD), terminal fall velocity and mass (or density).

A variety of interrelated snowflake characteristics are important when converting Z into SR (Huang et al., 2015). Mass and terminal fall velocity both depend on the shape of the particle and the range of variability of different relations can be several orders of magnitude (e.g. Locatelli and Hobbs, 1974; Mitchell et al., 1990; Brown and Francis, 1995; Brandes et al., 2008; Heymsfield and Westbrook, 2010). This also implies that the uncertainty of the Ze-SR is of a much higher magnitude than for liquid precipitation (where the dependence of terminal fall velocity or drop mass is better constrained) (Matrosov, 2007; Matrosov et al., 2009).

Ze depends on $E[\sim m(D)^2]$ where m denotes the particle mass and E stands for the expected value which we integrated over the size distribution (Field et al., 2005; Hogan and Westbrook, 2014). SR depends on $E[v(D)\ m(D)]$, where v is the terminal fall velocity of the particle (Matrosov et al., 2008; Huang et al., 2015). Understanding how these uncertainties behave remains however a paramount question (Berne and Krajewski, 2013).

In order to constrain the uncertainty of the Ze-SR relation, information about the microphysical structure of the snowflakes is needed (Wood et al., 2015). In the early years, these characteristics were obtained by capturing individual snow particles e.g. on a glass plate covered with oil or a petri dish to derive its shape and mass (Nakaya and Terada, 1935; Kajikawa, 1972; Mitchell et al., 1990), while terminal fall velocities were recorded by manual timing (Nakaya and Terada, 1935) or by detecting disturbances in light beams (Locatelli and Hobbs, 1974). The disadvantage of these methods is their labour intensity. During the last decades, video disdrometers are used as the standard to estimate snow microphysical properties and to obtain information on snowflake size spectra (e.g. Brandes et al., 2007; Huang et al., 2010; Szyrmer and Zawadzki, 2010; Zhang et al., 2011; Huang et al., 2015). These instruments have the advantage to capture large samples at high resolution for longer time-spans (Brandes et al., 2007; Wood et al., 2013).

Antarctica has a unique precipitation climate as accumulation is composed of few large snowfall events. These storms are often associated with atmospheric rivers bringing moisture from mid-latitudes to inland regions (Gorodetskaya et al., 2014). Therefore, the main goal of the paper is to derive a Ze-SR relation that takes into account the specific conditions of this region. This relation can then be used to transform radar reflectivity measurements obtained by precipitation radars into snowfall rates. Gorodetskaya et al. (2015) used for the first time in Antarctica radar-derived snowfall estimates in order to assess relative contribution of precipitation to the surface mass balance compared to other components. Applying a range of Ze-SR relationships for dry snow, significant uncertainties were found especially for intense precipitation events. Here we show that adding snow particle microphysical measurements to the radar substantially reduce this uncertainty. Furthermore, a large part of the paper focuses on obtaining a rational estimate of the uncertainty of Ze, SR and the Ze-SR relation at the Princess Elisabeth station in Dronning Maud Land, East Antarctica for the first time. First, an overview of the instrumentation used in the study is presented. Next, we focus on the particle characteristics that are used as input for Ze and SR estimates based on disdrometer measurements. Here, every term is discussed separately and a rational estimate of their uncertainties is calculated. These are subsequently used to calculate the Ze-SR relation and its uncertainty. The uncertainty is subdivided in different terms regarding their nature. Finally, the applicability of this relation and its uncertainty estimate for the Antarctic region are discussed.

2. Material and methods

2.1. Instrumentation

Long-term direct and reliable measurements of meteorological conditions over the AIS are scarce due to its harsh physical environment and difficult accessibility. To tackle this problem, in 2009, a limited-maintenance atmospheric observatory was installed on the zero-emission Princess Elisabeth station in the escarpment zone of the East Antarctic plateau (71°57′ S, 23°21′ E; 1392 m a.m.s.l., 173 km from the coast) in Dronning Maud Land, north of the Sør Rondane mountain chain on Utsteinen ridge (a detailed description of the site can be found in Gorodetskaya et al. (2013)). Z measurements are recorded since 2010 by use of a vertically pointing Micro Rain Radar-2 (MRR) operating at a frequency of 24 GHz (Klugmann et al., 1996). Although the MRR was originally designed for the detection of liquid rain, the potential of millimeter radars to efficiently detect snowfall was demonstrated by Matrosov et al. (2008) and Berne and Krajewski (2013) and has been evaluated specifically for our type of low-cost radar by Kneifel et al. (2011). Furthermore, the standard postprocessing method has a lower bound sensitivity of approximately +3 dBz. This would imply that light snowfall events, which are common over inland Antarctica (Gorodetskaya et al., 2015), would be missed. Therefore, the operational MRR procedures to derive standard radar variables like Z or Doppler velocity were modified for snowfall. A new method, developed by Maahn and Kollias (2012), was applied to fully exploit the MRR hardware in case of solid precipitation, increasing its sensitivity up to −14 and −8 dBz, depending on vertical range.

The development of a Ze-SR relation requires information of snow particle microphysical characteristics. In order to bridge this gap, a Precipitation Imaging Package (PIP; Newman et al. (2009)) was installed at the station in January 2016, which operated until the end of May 2016. The field unit consists of a video system inside a heated housing, plus a halogen lamp that is located 3 m from the camera. The PIP is setup at the edge of the roof of the Princess Elisabeth station, towards the upstream side of the dominant wind direction (Fig. 1). The optical axis is oriented perpendicular to the climatological mean wind, as suggested by Newman et al. (2009). The field of view of the camera is 640 × 480 pixels, while the depth of field equals approximately 60 times the particle diameter (Newman et al., 2009). Pixel size accords to 0.1 mm. The system is connected to a datalogger which is particularly suitable for long-duration, unattended operation because the software provides data compression, while the hardware can operate for months in harsh winter conditions (Newman et al., 2009). The high speed camera takes pictures at a rate of 360 frames per second. The background of these images are white and snow particles passing between