3rd URSI AT-AP-RASC, Gran Canaria, 29 May – 3 June 2022

Evidence of sublimation in the vertical profiles of radar reflectivity and its impact on snowfall estimation at the ground at Mario Zucchelli Antarctic Station

Alessandro Bracci[(1),(2)], Luca Baldini[(1)], Nicoletta Roberto[(1)], Elisa Adirosi[(1)], Mario Montopoli[(1)], Claudio Scarchilli[(3)], Paolo Grigioni[(3)], Virginia Ciardini[(3)], Vincenzo Levizzani[(4)] and Federico Porcù[(2)]

(1) National Research Council of Italy, Institute of Atmospheric Sciences and Climate (CNR-ISAC), 00133 Rome, Italy
(2) Department of Physics and Astronomy "Augusto Righi", University of Bologna, 40126 Bologna, Italy
(3) Laboratory for Measurements and Observations for Environment and Climate, ENEA, 00123 Rome, Italy
(4) National Research Council of Italy, Institute of Atmospheric Sciences and Climate (CNR-ISAC), 40129 Bologna

Abstract

Snow is the main positive component of surface mass balance in Antarctica. Therefore, accurate snow measurements of snowfall play a crucial role in characterizing the Antarctic ice sheet's variability and its impact on the sea-level rise. The remote sensing of precipitation and in situ measurements are, in general, challenging tasks and even more difficult in an environment like Antarctica. Radar profilers are increasingly used in Antarctic research stations to highlight snowfall processes through vertical reflectivity profiles and improve the quantitative precipitation estimation, also exploiting the synergy with surface measurements. This work summarizes the field campaign experience at the Italian Antarctic station "Mario Zucchelli," analyzing the vertical profiles of reflectivity collected by a Micro Rain Radar (MRR), set with a vertical resolution of 35 m and a temporal resolution of 1 min. Such an MRR set up allowed us to use a trustworthy range gate just 105 m above the ground, thus avoiding contamination of clutter. Factors influencing the behavior of vertical profiles are analyzed, emphasizing the sublimation process and its implications on surface snowfall estimation at the ground.

1. Introduction

Snow is the main positive component of surface mass balance in Antarctica. Therefore, accurate snow measurements of snowfall play a crucial role in characterizing the variability of the Antarctic ice sheet and its impact on the sea-level rise on a climatic scale. Quantitative estimation of snowfall measuring snow, whether performed with remote sensing techniques or in-situ devices is a difficult task is a challenging task. This is particularly true for measurements conducted in extreme conditions like those in Antarctica. In recent years, several scientific stations have been exploring the synergy among different instruments to achieve more accurate quantitative snowfall measurements at the surface and a better knowledge of snow properties and snow processes in polar regions. A popular approach is combining profiles of power spectra collected by Micro Rain Radar, a 24-GHz radar profiler matufactured by Metek GmbH, with snow microphysics estimations collected at the surface by a disdrometer. Such a configuration for snowfall observation has been adopted since 2016 at the Italian research station "Mario Zucchelli" (MZS, 74.7° S, 164.1° E, 10 m a.s.l.) located at Terra Nova Bay, an inlet along the coast of the central part of the Victoria Land, edged by the Transantarctic Mountains Range, at the western margin of the Ross Sea, and the confluence of two glaciers [1]. At the moment, two MRR-disdrometer pairs are running at MZS [1,2]. The measurements illustrated here are collected by the MRR (specifically an MRR-2) and Parsivel disdrometer (OTT GmbH) of the Institute of Atmospheric Science and Climate of the National Research Council of Italy (CNR-ISAC). The MRR is located 2 m far from the Parsivel and was set with a vertical resolution of 35 m and a temporal resolution of 1 min to obtain the first trustworthy measurement at just 105 m above the ground. Using this configuration a better match of MRR measurements with disdrometer measurements are expected [2]. This configuration is unique in Antarctica, where most of the MRRs, including the other one running at MZS, use a vertical resolution of 100 m, implying a maximum height of more than 3 km and a higher height of the first bin unaffected by clutter. A popular technique to process MRR measurements in order to improve the performance of snow retrieval in conditions of low signal-to-noise ratio is adopted [3].

The combined use of MRR-disdrometer pairs has been the subject of recently published studies on snow estimation in polar and high-latitude environment [1-2,4–6]. The recent one [2] based on the MZS instruments has allowed to develop a method to determine the prevailing class of snow particles falling at heights close to the surface. In turn, this has allowed estimating snowfall rate through applying radar equivalenet reflectivity-snowfall rate (*Ze-SR*) relationship appropriate for the prevailing detected type of hydrometeors. The approach, validated for 52 events collected in the Antarctic summer seasons of 2018-2019 and 2019-202 for a total of 23566 minutes of snowfall

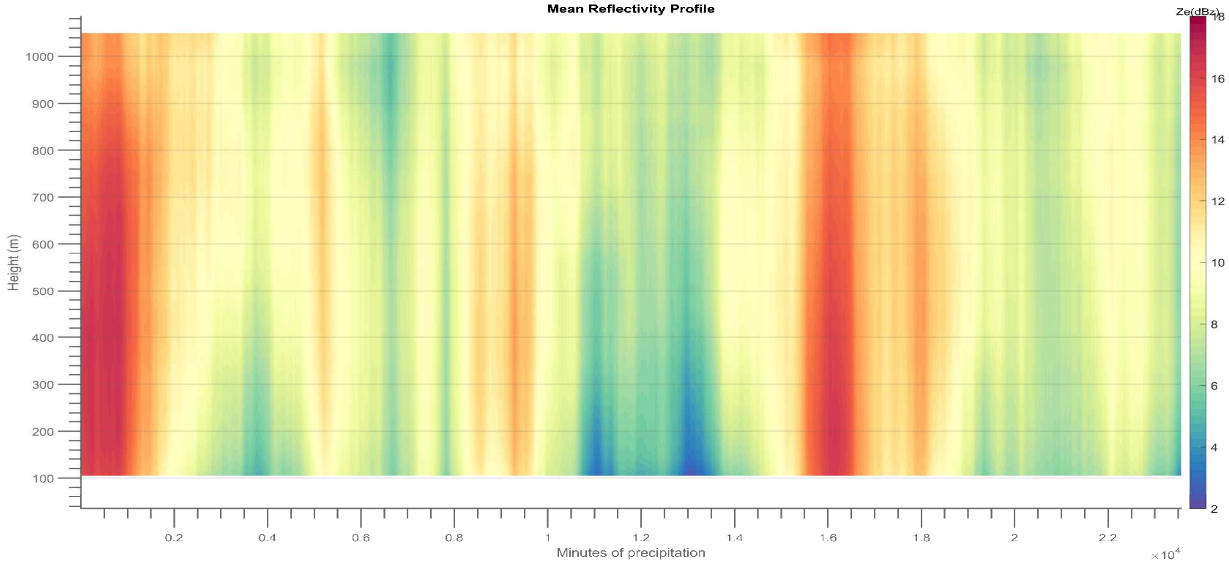

Figure 1: Reflectivity profiles at MZS of the whole precipitation dataset (23.566 minutes of precipitation).

measurements, provides snowfall estimates that are more in agreement with those from a weighing pluviometer collocate nearby. This summary paper illustrates relevant findings related to the analysis of vertical profiles of reflectivity, highlighting the advantage of high-resolution measurements to point out important processes, such as the sublimation in the low levels.

2. Vertical profiles of reflectivity

Fig. 1 shows all the MRR reflectivity profiles collected at MZS in the mentioned seasons, ranging from 105 m up to 1050 m, after applying a 6-hours moving average to make the graphical representation more informative. The figure highlights the peculiar precipitation regime of Antarctica, consisting of a few but very significant snowfall events.
Vertical profiles with high *Ze* values along the whole measurement range alternate with profiles with low *Ze*. Moreover, in the cases of lower reflectivity profiles, reflectivity decreases approaching the surface. This process can be ascribed to the mechanism of precipitation sublimation in the lower atmospheric layers in case of temperature inversion and unsaturated air conditions [7], particularly effective in the coastal region of Antarctica due to the intrusion of drier air from the Plateau driven by the katabatic wind. A reduction of reflectivity values is particularly evident in the lowest atmospheric layers (from 100 m to 300 m) of some precipitation events, along with a peak of reflectivity at 600-700m height. Fig. 2 represents the average and the median profiles, highlighting the behaviour described. In general, an increase in mean and median of reflectivity is found from 1 km to 400 m above the ground (the variation in the two highest MRR range gates is likely related to low SNR). Processes such as growth by vapor deposition, riming, or aggregation of ice crystals may produce a variation in the particle size distribution (PSD) along the profile leading to the observed increase of reflectivity values. However, a steep decrease of reflectivity is noted below 400 meters, likely related to sublimation processes, as also pointed out by the high occurrence of profiles with reflectivity between 0 and 5 dBZ in the lower atmospheric layers. It should be pointed out that different behaviours were found for different Antarctic stations (referred to Dumond D'Urville and Princess Elizabeth [8]). In particular, relevant differences can be identified when the mean reflectivity profile values are compared. It should be reminded that the MRR used in this work has a higher resolution than the MRRs used in the mentioned stations, implying that the first reliable measurement is at 100-meter (this work) and 300-meter height (other stations). Fig. 3 highlights the advantages of setting the MRR with a denser vertical resolution precisely because of the decrease in Ze values in the lower layers.
This fact is indeed essential because the reflectivity values of the lowest range gate are input of a *Ze-SR* relationship for quantitative snowfall estimation at surface.

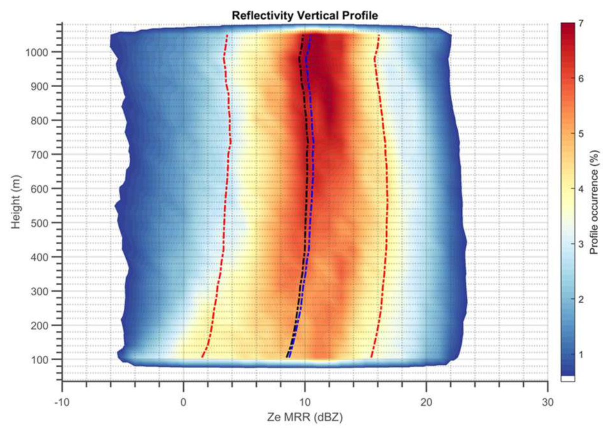

Figure 2: Occurrence of the MRR reflectivity profiles considering the whole precipitation dataset. The dashed lines represent the mean (blue), the median (black), and the standard deviation (red) vertical profiles, respectively.

3. Sublimation effects and impact on surface snowfall estimation

Although sampling precipitation close to the ground is advantageous for more accurate surface snow estimates, some height corrections should be applied to consider the sublimation processes. The trend of the lower reflectivity levels can be extrapolated towards the surface to account for horizontal displacement and sublimation below the lowest measurement level as in [5] for the Princess Elizabeth station. The extrapolation for the MZS MRR mean profiles, obtains a similar value (1.54 dBZ) considering 315m as the lowest MRR level (Fig. 3, yellow line). Nevertheless, implementing the extrapolation in the actual lowest MRR level at MZS (i.e., 105m) results in a lower *Ze* value at the ground because the decrease in reflectivity appears as enhanced in the levels closer to the ground (red line).

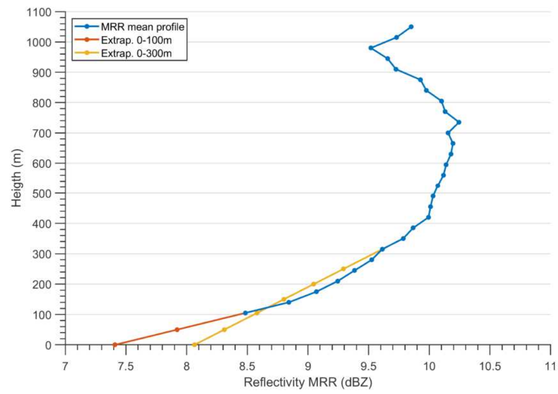

Figure 3: Mean of the vertical MRR reflectivity profiles (blue line) considering the whole MZS precipitation dataset. Yellow and red lines are the extrapolations towards the surface.

The last considerations support the choice of using higher MRR resolution in estimating precipitation at the ground: especially in Antarctica, an MRR coarser resolution and the application of height correction are not able to properly take into account the decrease of *Ze* closer to the surface.

How correct extrapolation of reflectivity approaching the surface impacts the quantitative precipitation estimation (QPE) at the ground calculated using *Ze-SR* relationships is estimated. Accumulated precipitation at different heights (i.e., 315m, 525m, 735m, 980m, 1050m) was calculated by using the MRR and disdrometer measurements and the *Ze-SR* relationships, chosen according to hydrometeor classification [2], to quantify the benefit of sampling at low heights. The results are shown in Fig. 4. Accumulated precipitation values ranging from 100.9 mm w.e. at 525m to 81 mm w.e. at the height of 980m. The best estimation for QPE at the ground (84.6 mm w.e. at 105m) appears to align with the values calculated at the highest range gates. On the contrary, it differs much from the values found for the middle layers. It is worth also underlining that considering the MRR measurement at 300m to calculate the QPE of a location leads to an overestimation of about 15% with respect to the QPE calculated through the reflectivity factor at 105m (97.9 vs. 84.6 mm w.e.).

4. A new expression for sublimation ratio at MZS

A sublimation ratio (*SubR*) was derived starting from the MRR reflectivity profiles of Fig. 1. The snowfall rate for each MRR range gate was obtained using the method presented in [2]. Then the *SubR* for each altitude was calculated as $SubR=(SR_i-SR_{105})/SR_{105}$ being 105m, the height of the first reliable bin, used as the reference height. Results show that a strong sublimation (*SubR* positive) acts in the lower levels with respect to the upper levels in case of weak precipitation, reaching an order of 30 - 40%. Again, the benefit of collecting measurements in the layers closer to the surface comes out by comparing 300 and 100m height where lower values of *Ze* were observed. Conversely, in cases characterized by heavy snowfall, a negative *SubR* is found in upper layers highlighting the occurrence of processes such as growth by vapor deposition, riming, or aggregation of ice crystals.

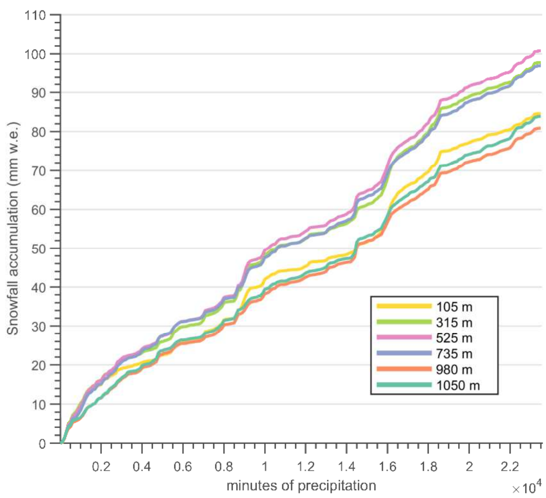

Figure 4: Snowfall accumulated at MZS at different heights calculated by using the Ze-SR relationships as in [2] and the MRR measurements at different range gates.

5. Conclusions

Radar sensing of precipitation is an important tool to obtain information about snowfall intensity and snow particle characteristics, although a synergy with ground disdrometer is beneficial. MRR-2 is a radar profiler that is available at many research stations in Antarctica. It requires some setting that implies a trade-off between height resolution, maximum height at which measurements are collected, and height of the lowest bin with reliable measurements. At MZS, a couple of MRR-2 with different settings has been adopted. The 35-m resolution brings benefits both to surface snowfall estimation and to the characterization of sublimation processes close to the surface. The latter is important since it also affects the comparison between satellite-based remote sensing observations and ground-based measurements of snowfall,

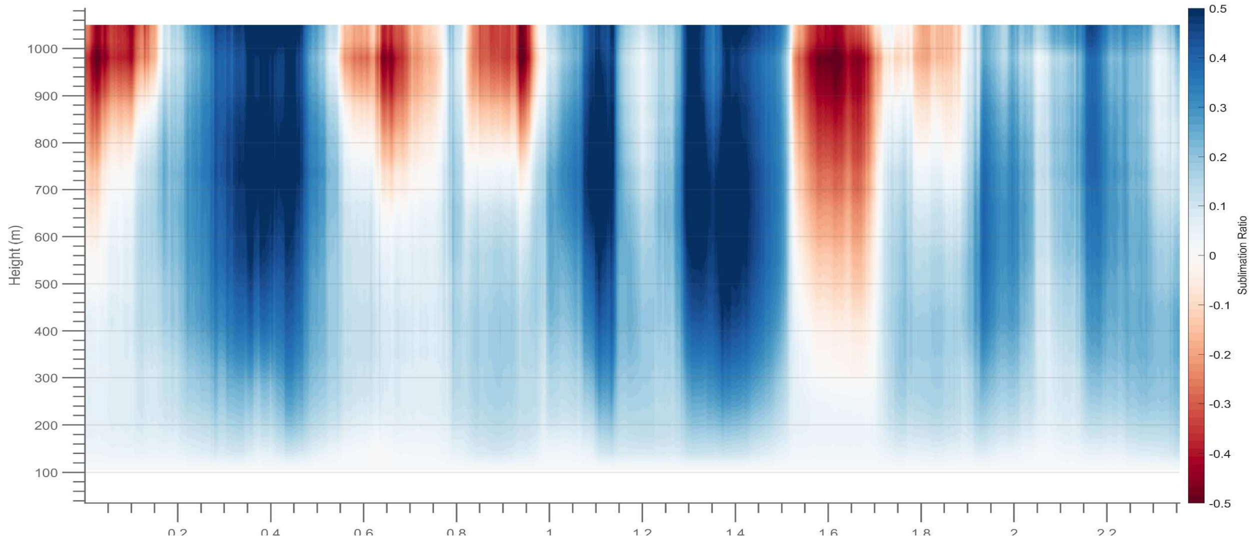

Figure 5: Sublimation Ratio calculated for reflectivity profiles of MRR at MZS.

but also, from a climate modelling perspective, it may counterbalance the expected increase of precipitation in Antarctica.

6. Acknowledgements

This work has been carried out in the framework of the APP (Antarctic Precipitation Properties), MALOX (MAss LOst in wind fluX) and IAMCO (Italian Antarctic Meteo-Climatological Observatory) projects funded by the Italian National Antarctic Program (PNRA) and contributes to the Year of Polar Prediction (YOPP), a flagship activity of the Polar Prediction Project (PPP), initiated by the World Weather Research Programme (WWRP) of WMO. The Antarctic Technical Unit of ENEA and PNRA are acknowledged for the logistic support. A.B. and F.P. acknowledge the support of the Doctoral Programme in Geophysics of the University of Bologna.

References

1. C. Scarchilli, V. Ciardini, P. Grigioni, A. Iaccarino, L. De Silvestri, *et al.*, “Characterization of snowfall estimated by in situ and ground-based remote-sensing observations at Terra Nova Bay, Victoria Land, Antarctica,” *J. Glaciol.*, **66**(260), pp. 1006–1023, Dec. 2020. doi: 10.1017/jog.2020.70.

2. A. Bracci, L. Baldini, N. Roberto, E. Adirosi, M. Montopoli, C. Scarchilli, P. Grigioni, V. Ciardini, V. Levizzani, and F. Porcù, “Quantitative Precipitation Estimation over Antarctica Using Different Ze-SR Relationships Based on Snowfall Classification Combining Ground Observations,” *Remote Sensing*, **5**(1) p. 82, Dec. 2021. doi: 10.3390/rs14010082

3. M. Maahn, and P. Kollias, “Improved Micro Rain Radar snow measurements using Doppler spectra post-processing,” *Atmos. Meas. Tech.*, **5**, pp. 2661–2673, Nov 2012, doi: 0.5194/amt-5-2661-2012.

4. S. Y. Schoger, D. Moisseev, A von Lerber, S. Crewell, and K. Ebell, “Snowfall-Rate Retrieval for K- and W-Band Radar Measurements Designed in Hyytiälä, Finland, and Tested at Ny-Ålesund, Svalbard, Norway,” *J Appl. Meteorol. Climatol.*, **60**(3), pp. 273-289, Mar 2021. doi: 10.1175/JAMC-D-20-0095.1

5. N. Souverijns, *et al.*, “Estimating radar reflectivity - Snowfall rate relationships and their uncertainties over Antarctica by combining disdrometer and radar observations,” *Atmos. Res.*, **196**, pp. 211–223, Nov. 2017. doi: 10.1016/j.atmosres.2017.06.001.

6. J Grazioli, C. Genthon, B. Boudevillain, C. Duran-Alarcon, M. Del Guasta, J.B. Madeleine, A. Berne, "Measurements of precipitation in Dumont d’Urville, Adélie Land, East Antarctica, " *Cryosphere*, **11**, pp. 1797–1811, Aug. 2017, doi:10.5194/tc-11-1797-2017.

7. J. Grazioli, J. B. Madeleine, H. Gallée, R. M. Forbes, C. Genthon, G. Krinner, and A. Berne, "Katabatic winds diminish precipitation contribution to the Antarctic ice mass balance,” *Proc. Natl. Acad. Sci. U.S.A.* **114** (41), pp. 10858-10863; Oct 2017, doi: 10.1073/pnas.1707633114.

8. C. Durán-Alarcón, B. Boudevillain, C. Genthon, J. Grazioli, N. Souverijns, N. P. M, van Lipzig, I. V. Gorodetskaya, A. Berne, “The vertical structure of precipitation at two stations in East Antarctica derived from micro rain radars,” *The Cryosphere*, **13**, pp. 247–264, 2019. doi: 10.5194/tc-13-247-2019.