

Influence of surface snow properties on a 89 GHz brightness temperature extreme event at Dome Fuji, Antarctica

Claudio Stefanini, Giovanni Macelloni, Marion Leduc-Leballeur, Ghislain Picard

Abstract—Microwave brightness temperatures observed in Antarctica at 89 GHz from the Advanced Microwave Sounding Unit B (AMSU-B) point out an exceptional decrease of 57 K at Dome Fuji (77.31° S, 39.70° E) during the 2019–2020 summer. The grain size index based on 89 and 150 GHz from AMSU-B and independent observations at 89 GHz from the Advanced Microwave Scanning Radiometer 2 (AMSR-2) also show concurrent unusual values. To explain such event, a theoretical analysis was carried out by means of a radiative transfer model. We explore the sensitivity of brightness temperature to surface snow properties focusing on December, just before the decrease, and April, at its end. Results confirm that this variation is mainly related to an increase in snow grain size. A decrease in snow density is also involved as suggested by the increase in brightness temperature at 1.4 GHz from Soil Moisture and Ocean Salinity (SMOS) and in the polarization ratio at 36 GHz from AMSR-2. Extreme values observed at multiple frequencies, as well as peculiar atmospheric conditions explored in a previous study, confirm the uniqueness of this event at least on decennial scale.

Index Terms—Cryosphere, modeling, microwave radiometry, AMSU-B.

I. INTRODUCTION

Passive microwave observations over Antarctica have been collected for more than 40 years at different frequencies. They allow monitoring the ice sheets at different depths, from a few centimeters at >100 GHz to several hundred meters at 1.4 GHz [1], [2]. First studies used 19 and 37 GHz to investigate surface or near-surface properties such as air temperature changes [1], snow layering [3], snow grain size [4], and snow density [5]. Snow accumulation has been estimated from 7 GHz [6]. More recently it was demonstrated that also at 1.4 GHz information about snow surface properties and the process of metamorphism can be derived [7], [8].

A grain size index (GSI) has been developed from 89 and 150 GHz brightness temperatures (T_B) by [9] as a proxy of the snow grain radius in the topmost centimeters of the snowpack. The study of some summer extreme increases in GSI observed on the East Antarctica highlighted that these variations are deeply connected with the meteorological conditions at seasonal and inter-annual time scales [10].

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Meteorological features such as low wind speed and low skin temperature during the summer were identified as the main drivers leading to these unusual grain size conditions. The most intense seasonal event has been identified at Dome Fuji during the 2019–2020 austral summer, when the snow grains reached the largest size as well as the fastest growing rate [10].

These observations could help to detect sharp changes in surface properties and monitor the effect of anomalous atmospheric conditions. Besides, coarse-grained snow has a lower albedo than thinner, therefore changes in snow grain size can impact the overall energy balance of the region and influence local and regional climate conditions [9].

In this paper, the Dome Fuji event was analyzed by means of snow emission modeling in order to better understand the quantitative relationship between T_B and surface properties at 89 GHz during the austral summer, beyond the GSI proxy. Section II presents the satellite and meteorological datasets. Section III describes the electromagnetic model for the T_B simulations, the thermal model to estimate the snowpack temperature and the atmospheric model to describe the attenuation of the microwave signals. Section IV presents simulation results and discusses them with information coming from other frequencies. Section V draws conclusions.

II. DATA

A. AMSU-B

From the Advanced Microwave Sounding Unit B (AMSU-B) we selected T_B at 89 and 150 GHz in the range of incidence 0–25° (downloaded from <https://www.avl.class.noaa.gov/>). The *grain size index* (GSI), defined as $GSI = 1 - T_B(150\text{ GHz})/T_B(89\text{ GHz})$ [9], is computed for Dome Fuji from July 2012 to June 2023. It is a proxy of the near-surface snow grain radius, therefore it provides approximate information only, and may also be influenced by other snow and atmospheric properties.

B. AMSR-2

The Advanced Microwave Scanning Radiometer 2 (AMSR-2) on-board Japan's Global Change Observation Mission 1st - Water "SHIZUKU" (GCOM-W1) satellite provides T_B at 89, 36 and 18 GHz at horizontal and vertical polarizations and for incidence angle of 55°. Daily mean T_B are extracted over Antarctica from the Level 3 product provided by the JAXA's Globe Portal System (G-Portal, <https://gportal.jaxa.jp/>) in the Southern polar stereographic projection with a resolution of 25 km. Data from July 2012 to June 2023 are considered here.

C. SMOS

The Soil Moisture Ocean Salinity (SMOS) satellite from the European Space Agency (ESA) provides a multi-angular T_B at 1.4 GHz. From the SMOS Level 3 product delivered by the Centre Aval de Traitement des Données SMOS (<https://www.catds.fr/>, [11]) we extracted daily T_B from July 2012 to June 2023 over the 50–55° range of incidence angles. The product is georeferenced on the Equal-Area Scalable Earth version 2.0 (EASE-Grid2) grid in the Southern Hemisphere Azimuthal projection with a 25 km resolution.

D. OLCI

The Ocean and Land Colour Instrument (OLCI) instrument on board the ESA's Copernicus Sentinel-3A/B is used to estimate the specific surface area (SSA) of snow at 1 cm below the surface [12]. The grain radius r is then computed as $r = 3/(\rho_{ice} \cdot SSA)$ where $\rho_{ice} = 917 \text{ kg m}^{-3}$ is the ice density.

E. ERA5

Meteorological parameters on single and pressure levels are taken from the ERA5 reanalysis produced by the European Centre for Medium-Range Weather Forecasts [13, ECMWF]. Data are provided over a regular latitude-longitude grid of 0.25° resolution, and we reprojected them to the Southern polar stereographic projection. We considered daily mean over 2012–2023 and also hourly values as input for the snowpack temperature estimation.

III. METHODS

A. Snow Microwave Radiative Transfer model

T_B simulations at 89 and 150 GHz were conducted with the Snow Microwave Radiative Transfer model (SMRT; [14]). Among the available electromagnetic scattering theories in SMRT, we selected the symmetrized strong contrast expansion method to ensure a continuous scattering function over the whole range of ice fractions (i.e. snow density) allowing a good description at intermediate densities ($\sim 500 \text{ kg m}^{-3}$) and high frequencies [15]. In the model, the snowpack is represented as a multi-layered medium, each layer being defined by the thickness, density, temperature and microwave grain size [16]. We used the scaled exponential microstructure model, recommended to simulate high microwave frequencies [17], [18], and a newly defined microwave grain size which is the product of the Porod length and a polydispersity $K = 0.63$ optimized for the Antarctic Plateau [16].

The simulations are performed at 0–25° of incidence angle matching to the AMSU-B observations. At 89 and 150 GHz, the microwave emanation depth (also known as penetration depth or e-folding depth) is estimated a few centimetres [1], [9], therefore we defined the snowpack as a stack of 5 cm layers from the surface to 2 m in depth, then an infinite ice layer for completion. Over the 2 m snowpack, the density is kept constant (350 kg m^{-3} [19], [20]), and the snow grain radius profile decreases linearly from 0.10 mm at the surface [20] to 0.15 mm at 50 cm and from 0.15 mm at 50 cm to 0.30 mm at 1 m [5]. Below 2 m, the infinite layer has a density at 350 kg m^{-3} , and radius at 0.30 mm.

B. Snowpack temperature

The temperature profile required by SMRT is estimated with the surface energy budget and thermal diffusion model called Minimal Firm Model [9], [21], [22] (MFM, <https://github.com/ghislainp/mfm>). We used as inputs skin temperature, 2 m temperature, 10 m wind speed, snowfall, surface pressure, cloud cover and surface downward long-wave and short-wave radiation flux from the hourly ERA5 reanalyses. The output are averaged to obtain the daily snowpack temperature profiles in December and April. The 10 m temperature in depth is fixed at 222.7 K, equal to the annual mean temperature at Dome Fuji [13], [23].

C. Atmospheric microwave emission and transmission

The atmosphere influences the microwave emission from the Earth surface: 1) emission coming from the surface is attenuated by the atmosphere, 2) the atmosphere emits radiation due to its own temperature in both upward and downward direction [24]. The last contribution, once reflected by the surface, is then redirected toward to the sensor and contributes to the measured T_B . In general, the atmospheric contribution at these frequencies is low over the Antarctica Plateau because of the low atmospheric humidity and high elevation (low atmospheric mass / high geopotential) [21]. The upward T_B^\uparrow and downward T_B^\downarrow atmospheric brightness temperature and transmittance t are computed with a simple non-scattering microwave radiative transfer model [25]. The model inputs are air temperature, geopotential height, water vapor density and ozone molecules density over the 24 pressure levels provided by ERA5 from the ice surface up to 40 km above the considered point.

The calculated T_B^\uparrow , T_B^\downarrow , transmittance t are calculated in December and April for 89 and 150 GHz from 0 to 25° of incidence angle. Their variability within this incidence range is low in these atmospheric conditions (standard deviation of 0.1 and 0.3 K for T_B and ~ 0.001 for t), and we used the mean values during T_B simulations to save computational resources (Table I).

TABLE I
 T_B^\uparrow , T_B^\downarrow , t IN DECEMBER AND APRIL FOR 89 AND 150 GHz OVER DOME FUJI ACCORDING TO THE ROSENKRANZ'S (1998) MODEL.

	89 GHz		150 GHz	
	December	April	December	April
T_B^\uparrow	7.3 K	5.9 K	7.8 K	3.5 K
T_B^\downarrow	10.5 K	9.1 K	12.0 K	7.6 K
t	0.969	0.974	0.967	0.985

IV. ANALYSIS

A. Brightness temperature observations

Fig. 1a shows 89 GHz T_B from AMSU-B from July 2012 to June 2023 at Dome Fuji. The 11-year T_B time series shows an annual variation between December and April of $46.1 \pm 1.9 \text{ K}$ over July 2012–June 2023, which at first order follows the air temperature seasonal variations (Fig. 1b, $48.3 \pm 3.2 \text{ K}$ on

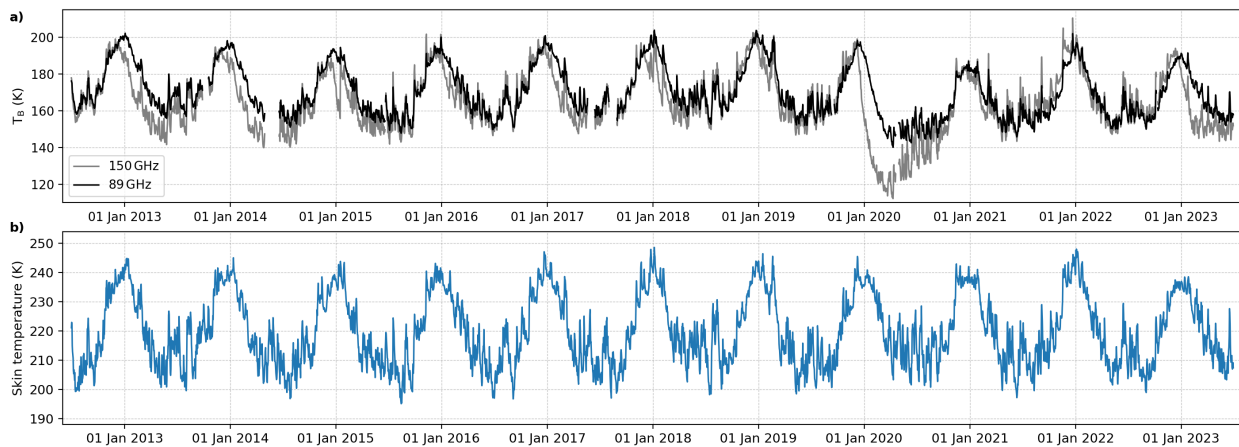


Fig. 1. a) T_B from July 2012 to June 2023 at Dome Fuji at 89 GHz (black) and 150 GHz (grey) from AMSU-B, and b) skin temperature from ERA5.

average). A faster and higher seasonal decrease happened from December 2019 and reached a minimum on 10 April 2020. T_B decreased by 57 K in four months reaching 140.1 K. This minimum was never observed during the 11-year studied period, and is about 15 K lower than the usual minimum of this month. After this, T_B slowly increased, but remained lower than usual during the whole winter. From AMSU-B, we also observed a decrease of 82 K at 150 GHz, while the climatological value is 57.3 ± 3.4 K (Fig. 1a).

Note that AMSR-2 observations (not shown) also recorded an exceptional decrease of 65-70 K at 89 GHz, above the climatological mean of 50.7 ± 5.9 K and 52.1 ± 7.0 K for horizontal and vertical polarization, respectively. The difference with AMSU-B derives from the different incidence angle.

In the T_B decreasing period, the skin temperature decreased by 45 K, which is within the average seasonal variations. This suggests that the 89 GHz observations are affected by others factors than temperature as $\sim 75\%$ of the total T_B variations observed at 89 GHz and $\sim 50\%$ of the total variations at 150 GHz can be explained by the seasonal temperature variations. The sensitivity to snow grain size and density in surface is analyzed in the following.

B. Sensitivity tests

In order to explore the complete range of variability of the T_B at 89 GHz, two specific dates were considered for the simulations. The first case study is on 10 December 2019 when the T_B at 89 GHz reached its annual maximum. The surface temperature of the snowpack was 245 K according to the ERA5 skin temperature. The second case study is on 10 April 2020 when the T_B at 89 GHz reached its annual minimum with a ERA5 skin temperature of 205 K. Since the GSI is a combination of the 89 and 150 GHz, we also simulated the behavior of the 150 GHz T_B .

To evaluate the T_B sensitivity to the surface snow properties, we varied the snow grain radius in the first layer (5 cm thick) from 0.05 to 0.50 mm, and for three values of surface layer density (200, 300 and 400 kg m^{-3}). Fig. 2a,b show the simulated T_B at 89 GHz for 10 December 2019 and 10 April

2020, respectively, for the three values of surface density. Fig. 2c,d show the same at 150 GHz. The shadows in figures refer to a variation of the skin temperature of ± 2 K and the consequent modified snowpack temperature profiles estimated by the MFM, in order to appreciate a possible uncertainty of the ERA5 estimation [26]. Simulation results show low sensitivity to this uncertainty.

The simulations at 89 GHz show that the observed decrease of 57 K from December to April corresponds to an increase of the radius of 0.23 and 0.25 mm at 200 and 400 kg m^{-3} , respectively. At 150 GHz, the observed T_B decrease of 82 K corresponds to an increase of 0.14 and 0.24 mm respectively (Fig. 2, Table II). The difference is linked to a distinct sensibility of the two frequencies, being the emanation depth ~ 20 cm at 89 GHz and ~ 4 cm at 150 GHz [9]. Thus, the snow temperature closer to the surface experience larger oscillations and generate a larger T_B annual variability at 150 GHz than 89 GHz. The simulations show that the measured minimum

TABLE II
EMANATION DEPTHS AT 89 AND 150 GHz, OBSERVED T_B DECREASE FROM DECEMBER 2019 TO APRIL 2020 AND MODELED CHANGES IN THE SNOW GRAIN RADIUS CONSIDERING THREE DIFFERENT SURFACE DENSITIES.

		89 GHz	150 GHz
	Emanation depth	~ 20 cm	~ 4 cm
	T_B decrease	57 K	82 K
Radius change	at 200 kg m^{-3}	0.23 mm	0.14 mm
	at 300 kg m^{-3}	0.23 mm	0.15 mm
	at 400 kg m^{-3}	0.25 mm	0.24 mm

T_B (Fig. 2b, d) can be only explained by a large value of the snow grain radius. The surface density variation also affect T_B at both frequencies, but an increase in grain size is always needed to explain the whole observed decrease in T_B .

C. Indications from independent measurements

The sensitivity analysis show that both snow grain size and surface density influence the 89 GHz T_B . To untangle their respective influence, we considered also independent datasets to better describe the snow surface changes.

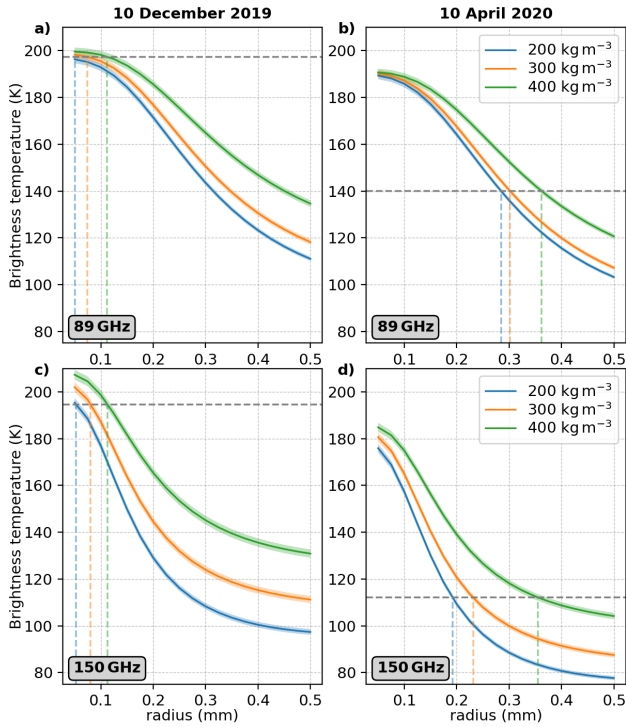


Fig. 2. Simulated brightness temperature at 89 and 150 GHz as a function of the snow grain radius for three surface snow densities (color lines) for the conditions when the observed T_B (dotted gray lines) was a-c) maximum (10 December 2019) and b-d) minimum (10 April 2020). The shadows cover simulations with variations of ± 2 K in the skin temperature.

At 1.4 GHz, T_B in horizontal polarization is usually stable with on average 184.1 ± 2.1 K over July 2012–June 2023. However, between December 2019 and February 2020, T_B increased by about 7 K with a maximum of 188.9 K (Fig. 3b) never observed by SMOS at Dome Fuji over 2012–2023 whereas T_B in vertical polarization remained stable. As snow grains have no influence at 1.4 GHz [27], this is an indicator of a decrease in surface density. Indeed, a previous work highlighted a variation of the 1.4 GHz T_B in horizontal polarization with the same order of magnitude at Dome C in 2014–2015 [7]. It showed that the increase in T_B was related to a decrease in surface density and an increase of the thickness of the uppermost layer, linked to the formation of surface hoar and/or snow accumulation facilitated by a period of a few months with lower than normal speed of wind. In situ measurements at Dome C showed that the surface snow density reached values below 300 kg m^{-3} .

A decrease (increase) in the polarization ratio (H/V) at 36 GHz is linked to an increase (decrease) in the snow density in the topmost 3 cm layer [5]. On average, it has an annual variation of 0.046 ± 0.001 over July 2012–June 2023, with a mean maximum of 0.907 ± 0.002 (Fig. 3c). During the 2019–2020 event, the maximum was 0.915, the highest of the entire time series, and values were maintained high during all January with a mean of 0.911 (+0.025 with respect to 2013–2023 January climatology). This confirms the possibilities of a near-surface density below 300 kg m^{-3} , as in [5]. The polarization ratio reached its maximum in the second half of January, meaning that the snow density of the 0–3 cm layer

had a minimum during this period. The different behavior of 1.4 GHz and 36 GHz (Fig. 3b and c) can be due to a different emanation length of these frequencies but also to the sensitivity of 1.4 GHz to variations in the surface elevation [7]. Snowfall occurred starting from the mid January [10], leading to a possible increase of the first snowpack layer and hence an increase of the 1.4 GHz T_B . By modelling, we examined the effect of an increase of the topmost layer thickness in April, up to +3 cm (i.e. 8 cm in total for the first layer). Simulation showed that for a radius of 0.30 mm and fixed density, the increase of thickness causes a decrease of ~ 10 –15 K (higher for lower density) at 89 GHz and only ~ 2 –5 K at 150 GHz.

The snow surface roughness also affect the T_B observations, and it could be monitoring with the polarization ratio [5]. The roughness is mainly frequency-dependent. However, in our case, the polarization ratios at 18, 36 and 89 GHz observed from AMSR-2 (not shown) exhibit similar trend and high values (0.854 ± 0.003 , 0.911 ± 0.004 , 0.945 ± 0.003 respectively, in January 2020). This suggests that the surface roughness has a weak effect and the polarization ratio is mainly related to the surface density variations.

In parallel, the GSI increased from December to mid January (Fig. 3d) whereas skin temperature was relatively stable (237.9 ± 2.3 K). The radius estimates from the OLCI SSA (Fig. 3e) also pointed out an increase of grain size in the first centimeter of snow with a maximum at the beginning of January. Then the values decreased but the stable GSI suggest that grain size remained high during a more long time below the surface. Therefore, the decrease in T_B at 89 GHz can be mainly explained by an increase in the grain size, from mid December to mid January, and, with a lower magnitude, by a decrease in snow density. Table III summarize the maximum variations during the 2019–2020 summer.

TABLE III
MAXIMUM VARIATIONS OF THE PARAMETERS OF FIG. 3B-E.

T_B H-pol 1.4 GHz	H/V T_B 36 GHz	GSI	Radius
+8.5 K	+0.034	+0.266	+0.13 mm

V. CONCLUSIONS

We analyzed the stronger than usual decrease in brightness temperature (T_B) at 89 GHz during the 2019–2020 summer at Dome Fuji observed by the AMSU-B and AMSR-2 microwave radiometers. Theoretical analysis has been performed by using the Snow Microwave Radiative Transfer model (SMRT) to assess the sensitivity of this event to changes in snow surface properties. The simulations confirm the sensitivity of 89 GHz T_B to snow grain size and density in the first centimeters.

Additional surface density and snow grain size information during the event have been obtained from T_B at 1.4 GHz from SMOS, polarization ratio at 36 GHz from AMSR-2, the GSI computed from AMSU-B observations and the OLCI snow grain radius. Comparisons show a rapid increase in surface grain size from December to January, installing large snow grains until April, concomitant to snow density lower than usual from January. This corresponds to the signature

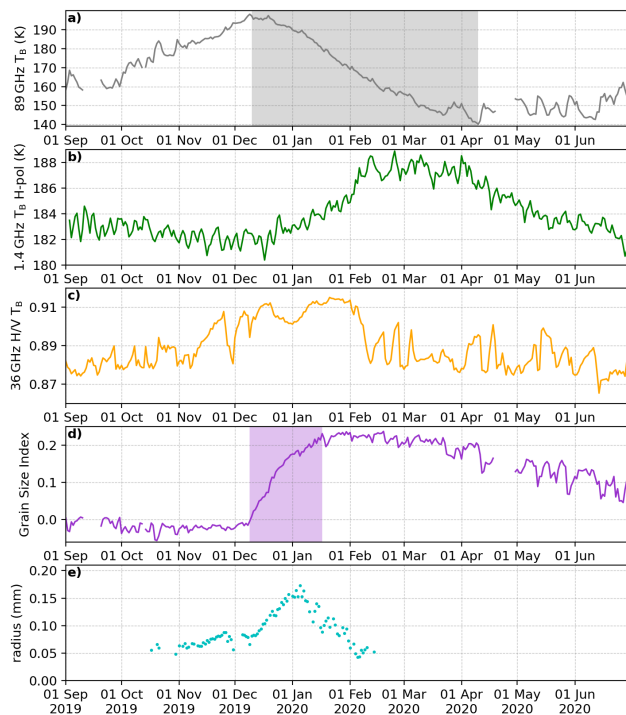


Fig. 3. a) Brightness temperature from 1 September 2019 to 30 June 2020 at Dome Fuji at 89 GHz from AMSU-B, the gray area covers the period from the T_B maximum (10 December) to the minimum (10 April); b) brightness temperature at 1.4 GHz in horizontal polarization from SMOS; c) polarization ratio at 36 GHz from AMSR-2; d) grain size index from AMSU-B, the purple area covers the grain size seasonal increase as defined in [10]; e) snow grain radius from OLCL.

of surface hoar [7]. We conclude that the unusual observed 89 GHz T_B variation can be explained by the presence of unusual large snow grain size and low surface density.

This analysis highlights the importance of high frequencies for monitoring of the Antarctic ice sheet and to detect anomalous surface changes, which can impact the surface energy balance.

REFERENCES

- [1] S. Surdyk, "Using microwave brightness temperature to detect short-term surface air temperature changes in antarctica: An analytical approach," *Remote Sensing of Environment*, vol. 80, no. 2, pp. 256–271, may 2002.
- [2] G. Macelloni, M. Leduc-Leballeur, M. Brogioni, C. Ritz, and G. Picard, "Analyzing and modeling the SMOS spatial variations in the east antarctic plateau," *Remote Sensing of Environment*, vol. 180, pp. 193–204, jul 2016.
- [3] G. Macelloni, M. Brogioni, P. Pampaloni, and A. Cagnati, "Multifrequency microwave emission from the dome-c area on the east antarctic plateau: Temporal and spatial variability," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 45, no. 7, pp. 2029–2039, jul 2007.
- [4] L. Brucker, G. Picard, and M. Fily, "Snow grain-size profiles deduced from microwave snow emissivities in antarctica," *Journal of Glaciology*, vol. 56, no. 197, pp. 514–526, 2010.
- [5] N. Champollion, G. Picard, L. Arnaud, É. Lefebvre, G. Macelloni, F. Rémy, and M. Fily, "Marked decrease in the near-surface snow density retrieved by AMSR-e satellite at dome c, antarctica, between 2002 and 2011," *The Cryosphere*, vol. 13, no. 4, pp. 1215–1232, apr 2019.
- [6] R. J. Arthern, D. P. Winebrenner, and D. G. Vaughan, "Antarctic snow accumulation mapped using polarization of 4.3-cm wavelength microwave emission," *Journal of Geophysical Research*, vol. 111, no. D6, 3 2006.

- [7] M. Leduc-Leballeur, G. Picard, G. Macelloni, L. Arnaud, M. Brogioni, A. Mialon, and Y. Kerr, "Influence of snow surface properties on l-band brightness temperature at dome c, antarctica," *Remote Sensing of Environment*, vol. 199, pp. 427–436, sep 2018.
- [8] L. Brucker, E. P. Dinnat, G. Picard, and N. Champollion, "Effect of snow surface metamorphism on aquarius l-band radiometer observations at dome c, antarctica," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 52, no. 11, pp. 7408–7417, nov 2014.
- [9] G. Picard, F. Domine, G. Krinner, L. Arnaud, and E. Lefebvre, "Inhibition of the positive snow-albedo feedback by precipitation in interior antarctica," *Nature Climate Change*, vol. 2, no. 11, pp. 795–798, jul 2012.
- [10] C. Stefanini, G. Macelloni, M. Leduc-Leballeur, V. Favier, B. Pohl, and G. Picard, "Extremes of surface snow grains change in east antarctica and their relationship with meteorological conditions," *The Cryosphere Discussions*, vol. 2023, pp. 1–23, 2023. [Online]. Available: <https://tc.copernicus.org/preprints/tc-2023-61/>
- [11] A. Al Bitar, A. Mialon, Y. H. Kerr, F. Cabot, P. Richaume, E. Jacqueline, A. Quesney, A. Mahmoodi, S. Tarot, M. Parrens, A. Al-Yaari, T. Pellarin, N. Rodriguez-Fernandez, and J.-P. Wigneron, "The global smos level 3 daily soil moisture and brightness temperature maps," *Earth System Science Data*, vol. 9, no. 1, pp. 293–315, Jun. 2017.
- [12] S. Arioli, G. Picard, L. Arnaud, and V. Favier, "Dynamics of the snow grain size in a windy coastal area of antarctica from continuous in-situ spectral albedo measurements," dec 2022.
- [13] H. Hersbach, B. Bell, P. Berrisford, G. Biavati, A. Horányi, J. M. Sabater, J. Nicolas, C. Peubey, R. Radu, I. Rozum, D. Schepers, A. Simmons, C. Soci, D. Dee, and J.-N. Thépaut, "Era5 hourly data on single levels from 1979 to present," 2018.
- [14] G. Picard, M. Sandells, and H. Löwe, "SMRT: an active-passive microwave radiative transfer model for snow with multiple microstructure and scattering formulations (v1.0)," *Geoscientific Model Development*, vol. 11, no. 7, pp. 2763–2788, jul 2018.
- [15] G. Picard, H. Löwe, and C. Mätzler, "Brief communication: A continuous formulation of microwave scattering from fresh snow to bubbly ice from first principles," mar 2022.
- [16] G. Picard, H. Löwe, F. Domine, L. Arnaud, F. Larue, V. Favier, E. L. Meur, E. Lefebvre, J. Savarino, and A. Royer, "The microwave snow grain size: A new concept to predict satellite observations over snow-covered regions," *AGU Advances*, vol. 3, no. 4, jul 2022.
- [17] M. Sandells, N. Rutter, K. Wivell, R. Essery, S. Fox, C. Harlow, G. Picard, A. Roy, A. Royer, and P. Toose, "Simulation of arctic snow microwave emission in surface-sensitive atmosphere channels," apr 2023.
- [18] C. Vargel, A. Royer, O. St-Jean-Rondeau, G. Picard, A. Roy, V. Sasseville, and A. Langlois, "Arctic and subarctic snow microstructure analysis for microwave brightness temperature simulations," *Remote Sensing of Environment*, vol. 242, p. 111754, jun 2020.
- [19] Hondoh, Narita, Hori, Fujii, Shoji, Kameda, Mae, Fujita, Ikeda, Fukazawa, Fukumura, Azuma, Wong, Kawada, Watanabe, and Hideaki, "Basic analyses of dome fuji deep ice core part 2: physical properties," 1999.
- [20] Q. Libois, G. Picard, L. Arnaud, S. Morin, and E. Brun, "Modeling the impact of snow drift on the decimeter-scale variability of snow properties on the antarctic plateau," *Journal of Geophysical Research: Atmospheres*, vol. 119, no. 20, pp. 11,662–11,681, oct 2014.
- [21] G. Picard, L. Brucker, M. Fily, H. Gallée, and G. Krinner, "Modeling time series of microwave brightness temperature in antarctica," *Journal of Glaciology*, vol. 55, no. 191, pp. 537–551, 2009.
- [22] F. Domine, G. Picard, S. Morin, M. Barrere, J.-B. Madore, and A. Langlois, "Major issues in simulating some arctic snowpack properties using current detailed snow physics models: Consequences for the thermal regime and water budget of permafrost," *Journal of Advances in Modeling Earth Systems*, vol. 11, no. 1, pp. 34–44, jan 2019.
- [23] Y. Wang and S. Hou, "Spatial distribution of 10 m firm temperature in the antarctic ice sheet," *Science China Earth Sciences*, vol. 54, no. 5, pp. 655–666, oct 2010.
- [24] P. Rosenkranz, "Rough-sea microwave emissivities measured with the SSM/i," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 30, no. 5, pp. 1081–1085, 1992.
- [25] P. W. Rosenkranz, "Line-by-line microwave radiative transfer (non-scattering)," 2017.
- [26] J. Zhu, A. Xie, X. Qin, Y. Wang, B. Xu, and Y. Wang, "An assessment of ERA5 reanalysis for antarctic near-surface air temperature," *Atmosphere*, vol. 12, no. 2, p. 217, feb 2021.
- [27] C. Mätzler, "Applications of the interaction of microwaves with the natural snow cover," *Remote Sensing Reviews*, vol. 2, no. 2, pp. 259–387, jan 1987.