



Katabatic winds diminish precipitation contribution to the Antarctic ice mass balance

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Edited by Dennis L. Hartmann, University of Washington, Seattle, WA, and approved August 25, 2017 (received for review May 8, 2017)

Snowfall in Antarctica is a key term of the ice sheet mass budget that influences the sea level at global scale. Over the continental margins, persistent katabatic winds blow all year long and supply the lower troposphere with unsaturated air. We show that this dry air leads to significant low-level sublimation of snowfall. We found using unprecedented data collected over 1 year on the coast of Adélie Land and simulations from different atmospheric models that low-level sublimation accounts for a 17% reduction of total snowfall over the continent and up to 35% on the margins of East Antarctica, significantly affecting satellite-based estimations close to the ground. Our findings suggest that, as climate warming progresses, this process will be enhanced and will limit expected precipitation increases at the ground level.

Antarctica | precipitation sublimation | katabatic wind

Precipitation in Antarctica falls almost exclusively as snowfall (1). As the dominant input term, precipitation is a key component in the ice sheet mass balance, and changes to this balance can directly affect the sea level at the global scale (2–5). Over Antarctica, snowfall is still not well-quantified and less documented than elsewhere. This is partly because of the lack of measurements covering the processes from precipitation formation to ground deposition. After the recent momentum of atmospheric research in the polar regions (6) and thanks to the latest technological advances in the field of remote sensing, such measurements are starting to be regularly collected in various locations of the continent (7–9).

The challenges affecting in situ snowfall observations are the extremely low temperatures and snowfall rates in the interior and the wind regime close to the coasts. Over the continental margins, persistent katabatic winds blow all year long (10, 11). They originate from the cold and dry inner continent and therefore, supply the lower troposphere with large masses of unsaturated air. Surface temperature inversion and the absence of orographic barriers allow katabatic winds to develop into some of the strongest, most persistent, and most directional near-surface winds on Earth (10–12). The effect of these winds on the transport and sublimation of snow after deposition at the surface has been studied, modeled, and quantified (13, 14). This process turned out to be of primary importance for the ice sheet mass balance (3), in particular in the eastern part of the continent. The interaction of katabatic winds with snowfall, however, remains unknown, despite the importance of precipitation for the ice sheet mass balance.

From November of 2015 to November of 2016, we conducted a field campaign dedicated to the monitoring of precipitation (9) at the Dumont d'Urville (DDU) station on the coast of East Antarctica (66.6628 S, 140.0014 E). We obtained unprecedented weather radar measurements of precipitation in Adélie Land by means of a scanning X-band polarimetric radar (deployed from December of 2015 to January of 2016) and a K-band vertically profiling radar (operating since November of 2015). These radar

data allowed us to unveil the typical spatial structure of precipitation in the vertical dimension in particular. Because of its strong katabatic wind regime, Adélie Land is particularly well-suited for studies of katabatic winds and their interactions with precipitation.

Results

Low-Level Sublimation of Precipitation. Our observations at DDU consistently show that snowfall is frequently either not reaching the ground (virga) or strongly decreasing in intensity in the lower kilometer of the atmosphere (Fig. 1). This suggests that the precipitation undergoes a significant sublimation process close to the ground. Daily losses of precipitation mass over the vertical column caused by sublimation can get close to 100% when snowfall intensities at the ground level are low and decrease to about 20% in the most intense snowfall cases (Fig. S1). The available remote sensing measurements over a full year exhibit a clear signal of low-level sublimation: the maximum snowfall accumulation occurs $\sim 0.7 \pm 0.05$ km above the surface, just above the typical top height of the katabatic flow coming from the inner continent, while near the surface, yearly accumulation values are about 25% lower than the maximum ones (Fig. 2).

These observations give us insight into the origin of this process of low-level sublimation of precipitation (LSP) observed in the data, which is driven by the wind regime and atmospheric

Significance

Precipitation over Antarctica remains largely unknown, despite its crucial role in the surface mass balance of the Antarctic ice sheet. Using unprecedented observations covering an entire year, this work describes a previously unknown mechanism that leads to the sublimation of a large fraction of snowfall in the lower atmosphere, resulting from the interaction of precipitation and katabatic winds. Snowfall sublimation in the atmosphere, caused by katabatic winds, is in the order of 35% in the margins of East Antarctica. This process critically affects the interpretation of satellite-based remote sensing observations close to the ground and suggests that snowfall sublimation in a warming climate may counterbalance the expected increase of precipitation.

Author contributions: J.G., C.G., and A.B. designed research; J.G. and A.B. performed research; J.G., J.-B.M., H.G., R.M.F., C.G., G.K., and A.B. analyzed data; J.G., C.G., and A.B. conducted field work; J.-B.M. ran the LMDZ model; H.G. ran the MAR model; R.M.F. ran the ECMWF IFS model; and J.G. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1707633114/-DCSupplemental.

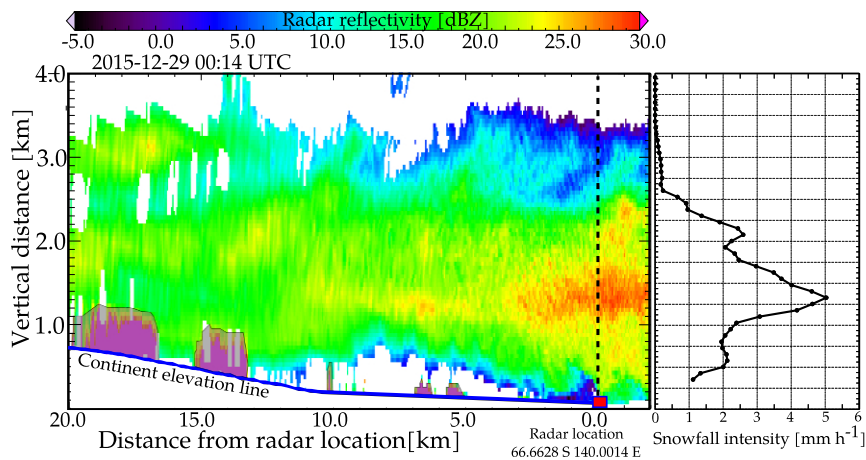


Fig. 1. Evidence of low-level sublimation from a vertical cross-section of weather radar measurements performed in DDU on December 29, 2015. The cross-section is conducted in the direction of the Antarctic plateau at a true azimuth of 203° . The variable that is color-coded in the cross-section is the radar reflectivity Z_H (expressed in dBZ) linked to snowfall rate through a power law (details are in *Materials and Methods*), while snowfall intensity in a column over the radar location is shown as an individual profile. The areas where radar measurements are corrupted by ground clutter over the continent are shadowed in gray.

stratification near the ground level. Close to the surface, the wind is usually strong enough to lift and recirculate deposited snow, and air is moistened and often saturated by the sublimation of drifting and blowing snow (14, 15) that can be lifted up to (but rarely exceeds) 300 m above the surface (16) (Fig. 3). Because of the temperature inversion at the top of this near-saturation layer, the air above remains dry and unsaturated (below roughly 1,200 m for DDU). Aloft ($>1,200$ m), saturation or oversaturation is the necessary condition for the nucleation and growth of ice crystals up to the size required to precipitate. The air coming from the continent accelerates as the slope of the terrain becomes steeper, associated with adiabatic warming (17, 18). This adiabatic warming further enhances subsaturation in the dry layer by decreasing the relative humidity of the descending air mass. In the very proximity of the ocean, where the slope of the terrain abruptly decreases to zero, the katabatic airflow slows down. The dry air accumulates and gradually saturates until the structure of the dry layer observed over the escarpment and near the coasts is dissipated over the ocean (18). Because of the persistent outflow and accumulation of dry air, the margins of the Antarctic continent, where precipitation is much higher than on the elevated plateau, are the areas where snowfall sublimation is the most important (Fig. S2).

LSP at the Continental Scale. The analysis above shows the importance of the LSP mechanism on total precipitation at DDU. What about the rest of Antarctica? Measurements of vertical profiles of precipitation being very rare (collected at three locations so far), the same approach cannot be used to investigate LSP at the continental scale. A first important indication is given by the analysis of the long records of radiosounding data available in Antarctica: katabatic winds and an unsaturated low-level troposphere are observed over the majority of the margins of East Antarctica as shown in the sounding statistics in Fig. S3. Favorable conditions for the occurrence of the LSP mechanism hence do exist in Antarctic regions other than Adélie Land. To study the LSP mechanism at the Antarctic continental scale and given the very few precipitation datasets collected so far in Antarctica, we, therefore, use output from three different and complementary atmospheric models (*Materials and Methods*): a high-resolution research model [Modèle Atmosphérique Régional (MAR)], an operational global model [European Centre for Medium-Range Weather Forecasts Integrated Forecast System (ECMWF IFS)], and a global climate model [Labora-

toire de Météorologie Dynamique Zoomed (LMDZ)], which is the atmospheric component of an Earth System Model used in CMIP5 (19). The simulations of all three atmospheric models reproduced a similar structure of precipitation with respect to the observations, although the height of the snowfall maximum varies between 0.9 and 1.2 km above the surface and the amplitude of the losses is lower than observed. This points to a robust dynamical origin of the process, which is, therefore, not strongly affected by differences between the models' parameterizations of microphysical processes. MAR, at 5-km resolution, better reproduces the full vertical structure of precipitation and better matches the location of the maximum and the amplitude

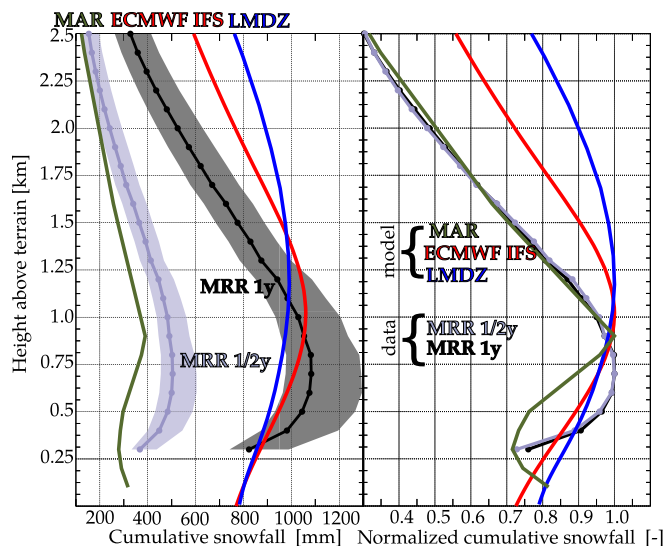


Fig. 2. Cumulative snowfall as a function of height above terrain in DDU as obtained by ground-based radar measurements and numerical atmospheric models. We obtained the curves over the 1-y period from November of 2015 to October of 2015 (MRR 1y, LMDZ, and ECMWF IFS) or the half-year period from November of 2015 to May of 2016 (MAR and MRR 1/2y). *Left* shows absolute cumulative snowfall curves, while *Right* shows the same curves normalized by their respective maximum value. The three models (ECMWF, MAR, and LMDZ) run at different resolutions, and with different physical parametrizations, all show low-level sublimation.

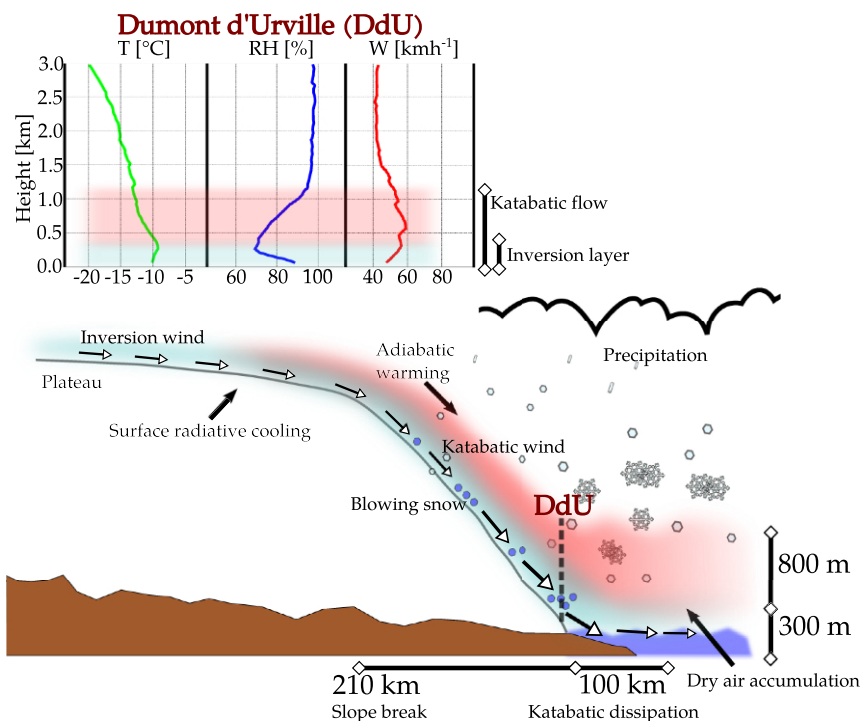


Fig. 3. Mechanisms leading to sublimation enhancement over the coastal locations at the margin of the Antarctic ice sheet. The spatial scales are approximated from the section crossing DdU in the direction of maximum slope toward the plateau. Accumulation of air with low relative humidity near the Antarctic margins leads to an enhancement of sublimation. The curves of relative humidity (RH), temperature (T), and wind speed (W) correspond to the median profiles of these variables obtained from the daily radiosonde measurements conducted at 00 UTC for the period from November of 2015 to November of 2016 conditioned on precipitation occurrence. They highlight the typical stratification of the atmosphere during snowfall events at this location.

of sublimation, while ECMWF IFS (≈ 10 km) and LMDZ (≈ 70 km) locate the maximum higher and reproduce a smoother cumulative precipitation profile, probably because of their lower spatial resolution. Blowing snow in MAR is assigned to the same water category as snowflakes. This explains the apparent increase of precipitation below 300 m of altitude, because blowing snow and precipitation particles cannot be separated in the model. The ECMWF IFS model does not consider blowing snow and its feedback on air humidity, but it assimilates the atmospheric soundings data over several locations in Antarctica. Differences between the three models above the level of maximum snowfall (Fig. 2) result from the various microphysical parametrizations and cloud-to-snow conversion rates used by the models.

By looking at the simulations of the ECMWF IFS model over the entire continent, we observe that, in several regions forming a belt around the margin of East Antarctica, more than 40% of the snowfall sublimates in the lower kilometer of the atmosphere before reaching the ground (Fig. 4 and Fig. S3). Sublimation larger than 30% in relative terms is also observed over many ice shelves, but the absolute amounts sublimated at these locations are at least an order of magnitude smaller than the values observed on the margins of East Antarctica. Given the proximity to the mountain ranges of the Antarctic Peninsula, foehn winds may play a role in the case of the Larsen ice shelf (20), and the accumulation of air originating on the plateau and crossing the trans-Antarctic mountains may affect the Ross ice shelf (21) as well. Finally, the contribution of sublimation is low both in relative and in absolute terms on the elevated part of the continent, and a clear link with topography through wind channeling is observed, especially on the margins of East Antarctica (Fig. 4). We estimate from ECMWF IFS simulations that, over the year

of measurements (November of 2015 to November of 2016), at least 651 Gt water equivalent snowfall sublimated because of the LSP process described above. This corresponds to 17% of the total snowfall on the entire Antarctic continent never reaching the ground. It is worth noting that this percentage has roughly the same magnitude (10–15%) as the estimated proportion of snow sublimating after deposition (13, 22). On the margins of East Antarctica (defined here from 30°W to 150°E), where snowfall accumulation is larger than in the interior, the contribution of snowfall sublimation is larger: 35% for all of the regions where the surface is lower than 1 km above sea level.

Discussion and Conclusion

The influence of LSP on the vertical structure of precipitation raises the question of the interpretation of satellite-borne radar precipitation measurements over the Antarctica continent (23, 24) that are currently the only model-free source of information able to cover the entire continent. These measurements must be discarded close to the surface because of ground clutter contamination of the radar signal (24), and the measurements at a certain height (1.2 km for CloudSat and around 0.8 km expected for EarthCare) above the surface are used as a proxy for near-ground precipitation. The vertical structure in Fig. 2 and the sublimation belt observed in Fig. 4 suggest that satellite retrievals overestimate precipitation in the areas where sublimation dominates the low-level structure of precipitation in the satellite blind range. As shown in Fig. S4, the expected biases of satellite estimates are indeed nonuniformly distributed over the continent, with significant overestimations that can be on the order of 50% in the areas of katabatic channeling as a consequence of the nonuniform distribution of the height of LSP (Fig. S5).

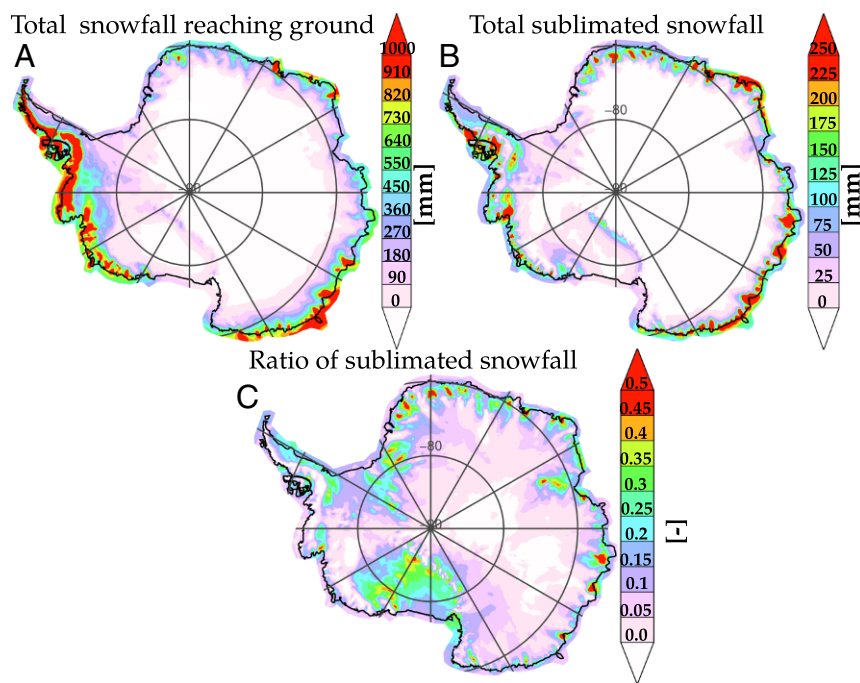


Fig. 4. Quantification of the contribution of sublimation of snowfall over the Antarctic continent. The accumulated sublimation over the year of interest (November of 2015 to October of 2016) is obtained from a series of daily 24-h forecasts from the operational ECMWF IFS model. (A) Total yearly snowfall reaching the ground level. (B) Absolute yearly contribution of sublimation. (C) Sublimation ratio: ratio of total sublimated snowfall over maximum snowfall in the vertical column. The solid blue line indicates a ground altitude of 1,000 m above sea level. Details are provided in *Materials and Methods*. It is worth mentioning that snowfall values over the Antarctic peninsula and in some locations of East Antarctica are often larger than 1,000 mm. The color scale is limited at 1,000 mm to enhance readability.

While LSP is significant in Antarctica, we anticipate that favorable conditions may also exist in the Arctic. The occurrence of low-level sublimation in the Arctic has been hypothesized (25), and recent remote sensing measurements (26) showed precipitation structures similar to the ones that we observed in Antarctica. The LSP mechanism leading to the observed sublimation belt will be sensitive to climate change. Warming currently affects mostly West Antarctica, but it is expected to affect East Antarctica in the coming decades (27). The nonlinearity of the Clausius–Clapeyron effect implies that a temperature increase over the coastal regions leads to a much larger increase of absolute humidity to reach saturation than the same temperature increase over the colder plateau. Indeed, an increase in temperature of 1 °C results in an increase of saturation vapor pressure with respect to ice e_i about six times larger at -10 °C than at -30 °C, with all else unchanged. Because the low-level air of the Antarctic margins originates from the colder plateau, the degree of subsaturation of this layer will increase in a warming climate. On one hand, increased moisture-holding capacity of the atmosphere at higher temperatures tends to increase snowfall amounts (2, 28–30). On the other hand, changes in synoptic wind patterns and dynamics also modulate the signal (31). Our results show that additional complexity arises from the changes in moisture and strengths of katabatic winds. The evolution (and sensitivity) of snowfall with climate change in Antarctic coastal regions already affected by ice loss from their ice shelves (32) will depend on large-scale atmospheric feedbacks as well as on local changes in katabatic winds. An increase in LSP associated with warmer temperatures could partly counterbalance snowfall increase on the margins of the continent by decreasing the fraction of snowfall that reaches the ground.

Low-level sublimation of snowfall involves a mass of water of at least the same magnitude as for processes occurring after ground deposition. Given this magnitude and in the light of

future climate scenarios, our study shows that snowfall sublimation should be explicitly considered and monitored as an individual term of the ice sheet mass balance.

Materials and Methods

Radar Data in DDU. The raw data collected with a vertically pointing K-band Micro Rain Radar (MRR) (33) were processed with the algorithm detailed in ref. 34 and then converted to snowfall rate with a relation trained locally at the time resolution of 1 h. The profile of Fig. 2 has been obtained by cumulating the profiles for the period ranging from November 22, 2015 to November 12, 2016 (MRR 1 y) and from November 22, 2015 to May 31, 2016 (MRR 1/2 y). The error range results from the confidence interval of the exponent and prefactor parameters of the reflectivity to snowfall rate power law. The power law takes the form $Z = 75.8S^{0.9}$, with reflectivity Z expressed in millimeters⁶ meter⁻³ and averaged at 1-h time resolution instead of the native resolution of the processed data that is 30 s. The snowfall rate S is obtained in millimeters hour⁻¹. MRR data were collected at 100-m (vertical) radial resolution, and the first valid measurement, which is used as a proxy for a near-ground value, is collected at the third range gate. The center of this gate is, therefore, 300 m above ground, and the gate covers the height range 300 ± 50 m. The reflectivity data collected by a second (X-band) radar system were used as a reference to validate and calibrate the MRR measurements. The X-band polarimetric radar was deployed from December of 2015 to February of 2016, and as a scanning radar, it was able to provide the spatial information shown in Fig. 1. Detailed information about the radar data collected in DDU and their conversion into snowfall intensity can be found in ref. 9.

Numerical Weather Model Data. The models used in the study were ECMWF IFS, MAR, and LMDZ.

The operational global numerical weather prediction system at the ECMWF IFS provides twice daily high-resolution analysis and forecasts with a grid spacing of ~ 10 km. The versions of the forecast model during this period were 41r1 and 41r2 with 137 vertical levels and a first level at 10 m. The model has variables for cloud fraction, cloud liquid, cloud ice, rain, and snow and associated parameterizations of microphysical processes (35, 36). Here, we use a 3-h time series from short-range 24-h forecasts initialized at 00 coordinated universal time (UTC) every day for

the year corresponding with the observations from November of 2015 to November of 2016. The effects of spin up of precipitation in the first hours of the forecast have been verified to be, for the domain of interest, negligible. The data are interpolated to a 0.25° latitude/longitude grid for faster processing. For the analysis in Fig. 4 and Figs. S2 and S3, we used ECMWF IFS, because data were available on the entire Antarctic domain, and they include the assimilation of available measurements. At DDU, where reference observations have been collected by the MRR down to 300 m above ground (minimum observable height), the total sublimation from ECMWF IFS, down to 300 m above ground as well, is about 27%, while it is 32% from MRR data. ECMWF IFS sublimation down to 10 m above ground (as shown in Fig. 4C and Fig. S3) is 36%. It is worth noting that ECMWF IFS does not directly simulate blowing snow that leads to resaturation of the lowest layer of the atmosphere (37) but assimilates atmospheric soundings where this resaturation appears (Fig. 3 and Fig. S3).

MAR is a limited area atmosphere, blowing snow, and snow pack coupled research model. Atmospheric dynamics is based on the hydrostatic approximation of the primitive equations (38), and the parameterization of turbulence in the surface boundary layer takes into account the stabilization effect of the blowing snow flux (39). The blowing snow model used in MAR is described in refs. 40 and 41. MAR was set up over Adélie Land (Antarctica), with a horizontal resolution of 5 km over 136 × 136 grid points. Lateral forcing and sea surface conditions were taken from the global reanalysis (called ERA-Interim) provided by the ECMWF (42). There were 26 levels in the vertical, with a higher vertical resolution in the low troposphere. The first level is situated very close to the ground (0.15 m), as blowing snow is explicitly modeled. The simulation shown in Fig. 3 was performed from the November 1, 2015 to May 31, 2016.

The LMDZ global climate model was run using a zoom over the region of the DDU station and a 6-h relaxation of the winds to ECMWF reanalysis data. This relaxation was active outside the stretched domain to represent the global synoptic conditions and progressively reduced inside the domain. The model was run with a horizontal resolution of 70 km in the vicinity of the station and 79 vertical levels, with a first level at 8 m. Cloud and precipitation physics of the model are described in ref. 43.

With the first model elevation above the surface ranging from less than 1 m to up to 10 m, different vertical resolutions in the different models can also contribute to different reproduction of the vertical structure of precipitation.

Radiosounding Data. We used atmospheric sounding data in Fig. 3 and Fig. S3. The data are made freely available by the University of Wyoming Department of Atmospheric Science (weather.uwyo.edu/upperair/sounding.html) for several sounding stations. The relative humidity with respect to water RH_w was converted to relative humidity with respect to ice RH_i taking into account the temperature of air (44, 45). The curves in Fig. 3 represent the same measurement period as the MRR radar data, and they are conditioned on precipitation occurrence using the MRR as a reference. The statistics displayed in Fig. S3 cover the period from 2005 to 2016. In this case, as no in situ data are available, they are conditioned on precipitation occurrence from ERA-Interim, which is thought to provide the best reconstruction of precipitation (46). The threshold on precipitation accumulation used to discriminate precipitation occurrence was 0.07 mm in 6 h as suggested for this reanalysis (23).

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Quantification of Total Sublimation. The quantification of sublimation was obtained from the vertical profiles of snowfall intensity. The difference between the maximum snowfall accumulation over the vertical column at a daily timescale and the near-ground accumulation is taken as a proxy for the total sublimation.

Fig. 2, for what concerns the models, is obtained by accumulating snowfall over the same period as when MRR data were available. The total sublimation ratio, shown in Fig. 4A, was obtained by accumulation over 1 y of data aggregated at the daily scale as explained below. For each day i and at each grid point, we calculated the maximum snowfall accumulation over the vertical column C_{\max}^i (in millimeters) and the total near-ground accumulation C_{gr}^i (in millimeters). The height levels vary slightly from profile to profile at the subdaily scale, as they result from the conversion of model levels to heights above ground that depend on the temperature and pressure at these levels. For this reason, they are linearly interpolated into a regular grid ranging from 10 to 4,500 m above ground for the sake of homogeneity. The analysis excludes all profiles that have a positive temperature in degrees Celsius to avoid the process of snow to rain conversion being confused with snowfall sublimation; 0.42% of the profiles over continental Antarctica are removed in this way, with maximum values becoming significant (up to 30%) at the lowest latitude of West Antarctica on the Antarctic Peninsula. The total sublimation ratio in Fig. 4C is obtained over N days as

$$SR = \frac{\sum_i C_{\max}^i - \sum_i C_{\text{gr}}^i}{\sum_i C_{\max}^i} \quad [1]$$

The total sublimation in Fig. 4B for the period under analysis is given by the numerator of Eq. 1. Therefore, the estimation of sublimation is based on daily data. At subdaily scales, the contribution of sublimation can be even larger.

ACKNOWLEDGMENTS. We thank the French Polar Institute, which logistically supported the Antarctic Precipitation: Remote Sensing from Surface and Space (APRES3) measurement campaign. We also thank the University of Wyoming Department of Atmospheric Science for their service in providing atmospheric sounding data and Météo France for the soundings at Dumont d'Urville. We thank Florentin Lemonnier (Laboratoire de Météorologie Dynamique) for the LMDZ runs that he performed and the development team of LMDZ for their major contribution to the improvements of the code: Jean-Yves Grandpeix, Frédéric Hourdin, Catherine Rio, and Etienne Vignon for their contributions to the parametrization of clouds and winds and all of the engineers who allowed LMDZ to run. We are also grateful to T. Battin and A. Rinaldo for their help on an earlier version of this manuscript. J.G. thanks the Swiss National Science Foundation (Grant 200021_163287) for financing his participation in the project. We also acknowledge the support of the French National Research Agency to the APRES3 project. The project Expecting Earth-Care, Learning from A-Train (EECLAT) funded by the Centre National d'Etudes Spatiales (CNES) also contributed support to this work. MAR simulations were performed using high performance computing resources from the French Big National Equipment Intensive Computing (GENCI) from the Institut du Développement et des Ressources en Informatique Scientifique (IDRIS) (Grant 2017-1523) and the High-Performance Computing/Modeling/Numerical and Technological experimentation infrastructure (CIMENT), which is supported by the Rhône-Alpes region (Grant CPER07_13 CIRA).

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