

# The contribution of blowing snow to cloud properties and the atmospheric radiative budget over Antarctica

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1 Over Antarctica and the Southern Ocean climate models often struggle to correctly model  
2 clouds. Over the Antarctic Ice Sheet, temperature inversions and strong temperature  
3 gradients between the cold interior and the edges lead to strong katabatic downslope  
4 winds, transporting snow and moisture from the interior towards the peripheral regions  
5 at the southern edge of the Southern Ocean's storm track. These blowing snow layers  
6 are usually 100-200 m thick, but can reach a thickness of more than 500 m and can be  
7 advected offshore from Antarctica over open ocean waters (Scarchili et al., 2010; Palm  
8 et al., 2017). However, the impacts of moisture and wind-induced snow mass transport  
9 (i.e. ice nucleating particles) on cloud structure and development over Antarctica has not  
10 been thoroughly investigated and most state-of-the-art climate models do not account for  
11 its presence. Here, we use a regional climate model with a newly developed fully active  
12 blowing snow scheme and satellite data, to show that accounting for drifting snow notably  
13 alters the spatial distribution, vertical structure and radiative contribution of clouds over  
14 Antarctica and its periphery. Additionally, our results indicate that the advection of blow-  
15 ing snow and air with a higher humidity content over the Southern Ocean also impacts  
16 clouds and their microphysics in areas outside of Antarctica. While our study area is lim-  
17 ited to 60S, our results highlight the need to study the impact of missing blowing snow  
18 processes on the future evolution of clouds not just over Antarctica, but potentially also  
19 over the Southern Ocean, an area with significant uncertainties in future climate projec-  
20 tions.

## 21 Introduction

22 **First paragraph:** Main facts about Antarctica and clouds there Radiative effects, influence on  
23 surface temperature (SEB). a bit about melt (even in winter; see Kuipers-Munneke 2014).

24 Antarctica is the largest body of ice on the planet and it contains the coldest places on Earth.  
25 It contains ice mass equivalent to roughly 58 m of global sea level rise [1], roughly 10 times  
26 more than the Greenland Ice Sheet which contains about 7.4 m [2]. The interior plateau of  
27 Antarctica reaches up to elevations of more than 3000 m, and is marked by very cold and dry  
28 conditions. However, there are marked differences in the present climatic conditions between  
29 East and West Antarctica, and especially between the edges and the inner plateau. While West  
30 Antarctica, and especially the northwards reaching mountainous Antarctic peninsula receive  
31 ample precipitation and are rather cloudy [3], rarely reach the interior of the ice sheet, where in  
32 some parts a notable share of the precipitation accumulates as diamond dust, hoar and drifting  
33 snow under extremely cold conditions [4] **Charles add citations.**

34 Due to strong radiative cooling in the interior plateau, strong and perpetual katabatic winds  
35 emerge, redistributing snow mass from the interior towards the edges and ice shelves, where the  
36 up to roughly 3 km high plateau slopes steeply towards sea level.

37 Clouds are known to notably affect the present and future climates of polar ice sheets [5, 6, 7,  
38 8, 9]. Clouds have the ability to amend incoming shortwave and longwave fluxes, depending  
39 on the cloud phase, height and particle size distribution, impacting the rate of surface melt and  
40 snowpack warming [3, 10, 11]. Blowing snow, while not accounted for in most global and  
41 regional climate models, can change the vertical structure and radiative impact of clouds, most  
42 notably because blowing snow sublimation changes the atmospheric humidity and temperature  
43 distribution [12, 13, 14, 15] . Blowing snow particles can also act as ice nucleating particles for  
44 cloud formation, which also impacts the longevity, structure and cloud-phase distribution within  
45 pre-existing clouds. While the the near-surface air temperatures in the interior of Antarctica are  
46 often below  $-37^{\circ}\text{C}$ , where homogenous cloud droplet glaciates all clouds, above the boundary  
47 layer mixed-phase clouds can still exist in the Antarctic interior [16]. Additionally, optically

thick blowing snow layers can act as a cloud themselves, increasing the atmospheric longwave emissivity and shortwave transparency of the atmosphere. However, so far very little is known about how clouds are influenced by blowing snow processes in climate models, and how accounting for blowing snow over the current climate influences key polar cloud-, and therefore climate processes.

Here, we use two regional climate model simulations spanning the period of 1979-2019, one with a dynamic representation of blowing snow and one without, to assess the impact of accounting for blowing snow on Antarctic clouds and radiative fluxes. We compare our two simulations to satellite products of cloud cover and the ERA5 reanalysis product, to show whether accounting for drifting snow only amends or also improves the representation of polar clouds. However, due to the remote location and complications of detecting cloud structure and microphysics from satellites over highly reflective surfaces, we don't expect to comprehensively address whether blowing snow improves cloud representation over Antarctica. Nevertheless, our results deliver a clear indication that accounting for blowing snow over polar ice sheets changes the 3D-structure of clouds, their phase and ultimately their contribution to the surface energy budget. In conclusion, not accounting for drifting snow in future projections of the Antarctica climate and sea level rise contribution might significantly bias the drawn conclusions.

## Results

### Influence of blowing snow on the vertical atmospheric structure

Explicitly modelling blowing in snow in MAR leads to a notable change in the atmospheric structure of the lowermost 100s of meters above ground (Fig.1 A-C). Over the flat interior of the Antarctic Ice Sheet, the first few 100 m show a strong decrease in atmospheric temperature, with

70 a mean 0-500 m difference of  **$-0.64 \pm 0.40$**  °C in elevations greater than 2000 m above mean  
71 sea level (Fig.1 A). This cooling of the near-surface atmosphere in our MAR blowing snow  
72 simulations, when compared to MAR without blowing snow, is most likely due to the efficient  
73 sublimation of airborne blowing snow particles due to the dry (and cold) surroundings over the  
74 interior Antarctic plateau. Conversely, the lower grounded ice and the low-lying ice shelves  
75 surrounding the Antarctic Ice Sheet (<100 m above sea level), this decrease in temperature in  
76 the blowing snow simulations is less notable. The mean 0-500 m above surface difference lies  
77 at  **$-0.21 \pm 0.14$** °C. The contrasting picture between the flat interior and the steeper and lower  
78 margins of Antarctica is likely due to two effects: 1) Due to the on average lower relative  
79 humidity and the greater water vapour gradients, the airborne blowing snow particles are more  
80 readily sublimated in the drier interior plateau than over the margins. This change of phase from  
81 solid to gaseous requires energy from the surrounding air to break up the bonds between the H<sub>2</sub>O  
82 molecules, leading to a drop in temperature. 2) Due to strong adiabatic mixing and turbulence  
83 in areas where the gravitational pull accelerates the katabatic winds down steep terrain, the  
84 snow particles are not confined to the very stable boundary layer anymore. Therefore, the  
85 sublimational cooling is less concentrated and subsequently also lower in magnitude over the  
86 margins of Antarctica and the ice shelves.

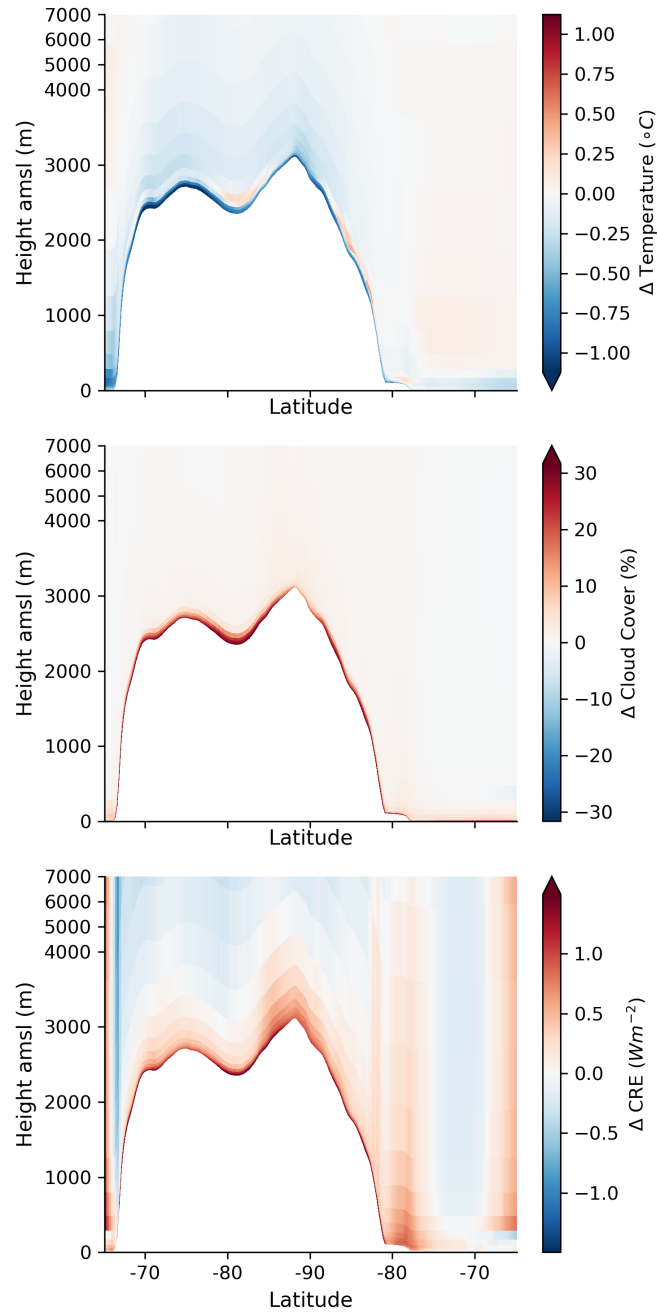


Figure 1: **Difference in temperature and cloud properties between MAR with and without blowing snow.** A) Cross-section of temperature differences between MAR with blowing snow turned on, and MAR without blowing snow (positive means MARb is warmer), along the path shown in **MISSING FIGURE XX**. B) Same as panel A), but showing the difference in cloud cover (in %) between the two simulations. C) Same as panel A) and B), but for the difference in the cloud radiative effect ( $Wm^{-2}$ ).

In the boundary layer, accounting for drifting snow also increases cloud formation over the Antarctic continent (Fig.1B). Our results show that the strongest increase in 2000-2019 average cloud cover over the interior plateau strongly overlap with the changes in temperature seen in Figure 1A. In elevations above 2000 m above mean sea level the lowermost 500 m of the atmosphere show an increase of  $+17.3 \pm 11.2\%$  in cloud cover. Again, over lower elevations (<100 m) the signal is lower, with an increase in cloud cover of  $+12.0 \pm 8.4\%$ .

Generally, there are three overlapping mechanisms that can explain the greater cloud amount over Antarctica, when accounting for blowing snow. 1) Blowing snow particles can act as additional nuclei on which ice can grow or help with ice growth through the Wegener-Bergeron-Findeisen process. Ice crystal number concentration can potentially multiply through secondary ice processes **cite Sotiropoulou**. 2) The sublimation of airborne snow particles leads to a cooling of the surrounding air, while increasing the specific humidity, both bringing the environment closer to saturation (**Cite Amory saturation**). 3) Thick blowing snow layers themselves act as a cloud, due to their ability to interact with incoming solar radiation (i.e. a cloud optical depth > 0) and their influence on the atmospheric longwave emissivity (i.e. they increase the atmospheric longwave emissivity  $\epsilon$ ). It is likely that in most cases these three processes can act simultaneously. Additionally, even state-of-the-art active satellite products like the **Cloudsat-Calipso XX**, have a vertical resolution of 240-480 m when looking at their cloud-related datasets. This limitation in vertical resolution renders it quite unlikely that blowing snow is detected as a cloud from remote sensing platforms, especially over highly-reflective surfaces.

Accounting for blowing snow also alters the cloud radiative effect (Fig.1 C). Again, we see the most notable changes in the boundary layer over the interior plateau of Antarctica. In areas above 2000 m above mean sea level, the CRE increases by  $+0.9 \pm 0.4 \text{ Wm}^{-2}$  in the lowermost 500 m of the atmosphere. Conversely, the changes in the cloud radiative effect are virtually

negligible over the margins and ice shelves with  $0.1 \pm 0.3 \text{ Wm}^{-2}$ .

While we see the strongest effects again in the boundary layer of the interior plateau, especially over the steeper margins the CRE is altered up to elevations of roughly 5000 m. This vertical influence on the CRE might be due to the fact that airborne blowing snow particles can be mixed to layers above the boundary layer in zones with stronger adiabatic mixing and turbulence, i.e. over the steeper slopes where the katabatic winds are the strongest. Subsequently, these additional ice crystals can influence the macrophysical cloud properties (ice water path, liquid water path and cloud optical depth), and therefore the cloud radiative effect. Additionally, because of changes in the vertical temperature distribution and humidity due to blowing snow sublimation, also the effectiveness and temperature of the layers that emit the longwave radiation can be altered between the two simulations.



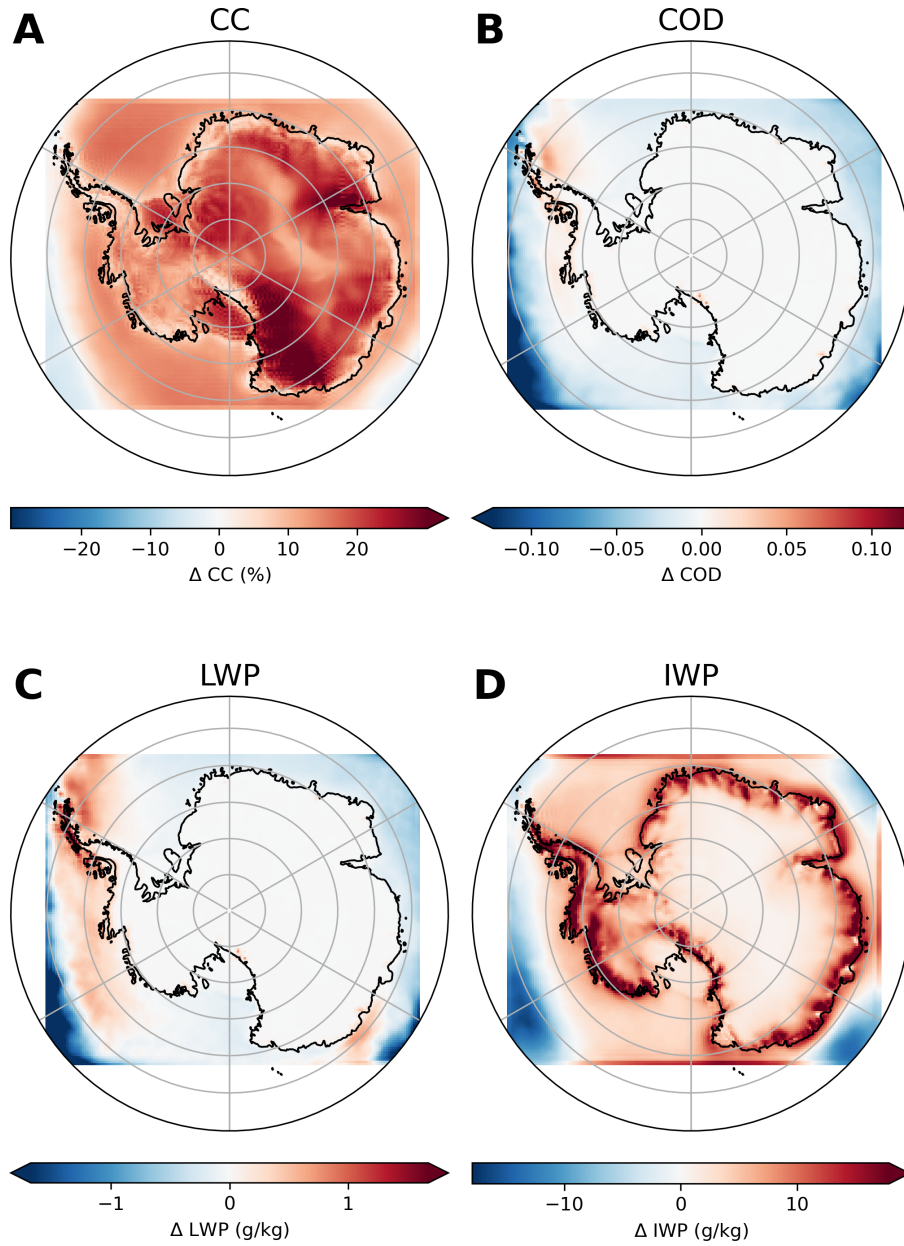


Figure 2: **Difference in cloud properties between MAR with and without blowing snow.** A) Difference in cloud cover (%) between the two MAR simulations. Red colors indicate a greater cloud cover percentage in MAR with active blowing snow parameterisation. B) Same as A) but for the difference in cloud optical depth (COD, unitless) between the two MAR simulations. C) Same as A) but for the difference in liquid water path(LWP, g/kg). D) Same as A) but for the difference in ice water path (IWP, g/kg).

To explore how the macrophysical cloud properties in MAR with snow differ from the base simulation without blowing snow, we show the spatial difference in cloud cover, cloud optical depth, liquid- and ice water path in Fig.2 A-D. Overall, our results show a clear signal of increased cloud cover over most of Antarctica (**AIS:  $XX \pm XX$ , Ocean:  $XX \pm XX$** ). Only over parts of the Southern Ocean do we see a small decrease in clouds (Fig.2A). Over most of Antarctica our results indicate no changes in cloud optical depth (Fig.2B). Interestingly, over the Southern Ocean and near the Antarctic peninsula we see areas with a strong COD increase (maximum **+XX**) and strong decreases (minimum **-XX**). This strong decrease in COD over open ocean waters is mainly a result of a decrease in LWP (Fig.2C), in addition to a decrease in IWP (Fig.2D). This decrease in COD, CC, LWP and IWP over the open ocean could be due to a decrease in cloud lifetime because of extra ice crystal numbers due to blowing snow, potentially increasing the glaciation rate of clouds via the Wegener-Bergeron-Findeisen process (**cite Storelvmo2011, Gallee**) and subsequent increase in precipitation efficiency upstream of the Southern Ocean (**cite Storelvmo2011**).

Conversely, over the drier and colder interior of Antarctica, we see almost no changes in COD, nor in LWP, despite a significant increase in cloud cover (Fig.2A-C). However, our results suggest a widespread increase in cloud ice water path (Fig.2D), with a mean over the AIS of **+XX**. Here, additional airborne particles likely increase the rate of new ice growth due to the Wegener-Bergeron-Findeisen process, which states that ice particles grow at the expense of liquid cloud condensate (**CITE WBF**). In our simulations this process seems to be most efficient over the steeper margins of Antarctica, where 1) snow mass transport increases with stronger katabatic winds, where 2) turbulence mixes snow and ice to higher elevations and where 3) the chances of mixed-phase clouds increases due to an increase in oceanic influence and higher temperatures than over the interior Antarctic plateau. Additionally, new ice particles can also in MAR due to

higher relative humidity of the advected air via the gas phase or via heterogeneous and homogeneous freezing (**cite Gallee**). Note however, that the MAR cloud microphysics scheme currently does not account for secondary ice production, where one single ice crystal can turn into multiple ice crystals via collision breakup, drop shattering and rime splintering (**cite Sotiropoulou, Gallee, Storelvmo2011**). However, especially rime splintering and drop shattering need liquid to be present and are most efficient in temperatures above what we observe over Antarctica (**Sotiropoulou**). Therefore, we don't think that the missing drop shattering and rime splintering processes are a major source of uncertainty in our simulations, however, collision breakup in blowing snow clouds could be an important missing multiplier of ice crystal number concentration in our simulations.

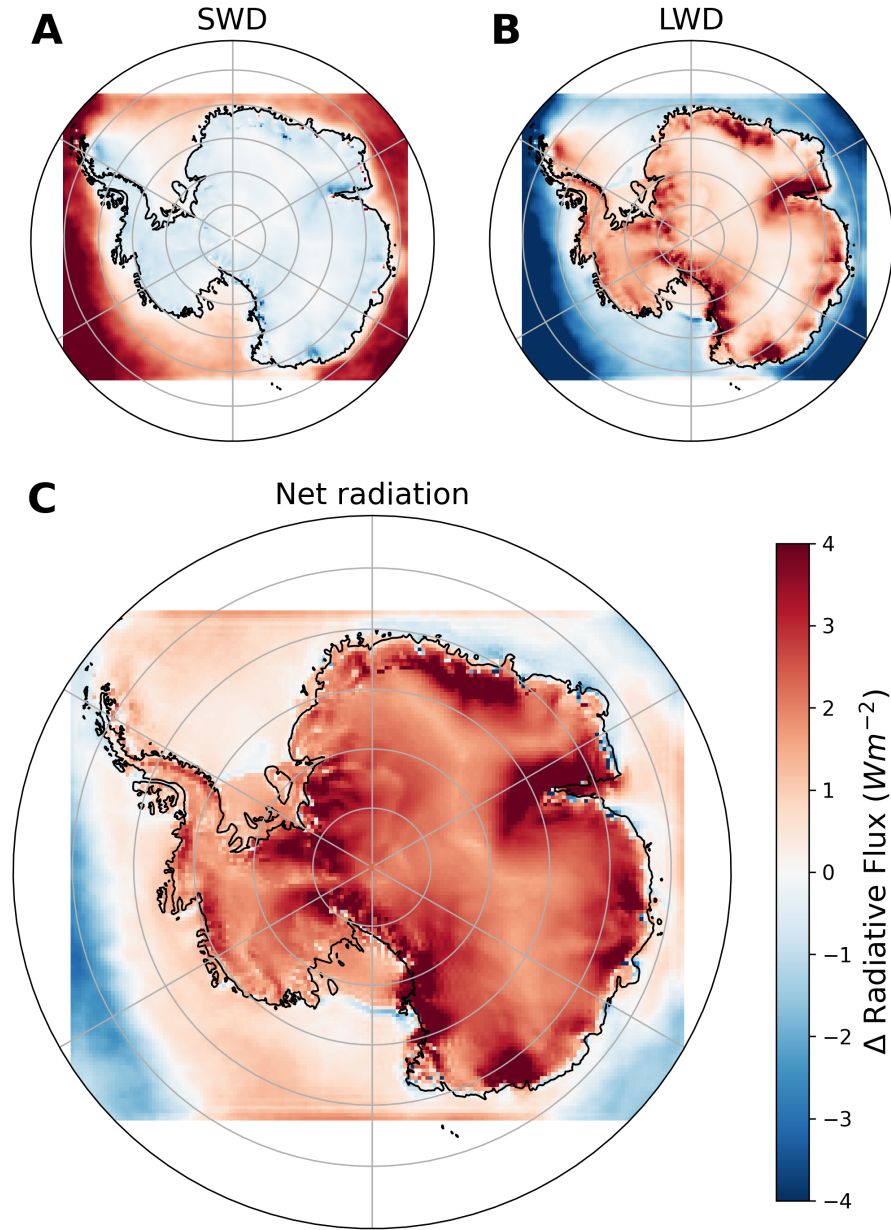


Figure 3: **Difference in radiative components at the surface between MAR with and without blowing snow.** A) Difference in incoming shortwave radiation (SWD) at the surface in  $Wm^{-2}$ . Red color indicates a greater downwelling shortwave flux in MAR with active blowing snow parameterisation. B) Same A) but for the downwelling longwave flux at the surface. C) Same as A) and B), but for the difference in the net radiation at the surface ( $R = SWD * (1 - \alpha) + LWD - LWU$ ).

Changes in cloud macrophysical properties due to blowing snow go hand-in-hand with changes in the surface energy budget [6]. In the shortwave part of the spectrum, our simulation with blowing snow models less incoming solar radiation over Antarctica (Fig.3A), mostly due to an increase in cloud cover, and a slight increase in IWP (Fig.2A,D). On average, over the Antarctica Ice Sheet the SWD decrease is  $\mathbf{XX \pm XX \text{ Wm}^{-2}}$ . Conversely, over the open ocean we see a notable increase in SWD by up to  $\mathbf{XX}$ , related to a coincident decrease in cloud cover, LWP, IWP and subsequently also cloud optical depth (Fig. 3A, Fig.2A-D). The second external driver of the surface energy budget, downwelling longwave radiation, our simulation with blowing snow shows the opposite effect: LWD increases over all the Antarctic Ice Sheet (**mean  $\mathbf{XX \text{ Wm}^2}$** , while it decreases over the ocean due to competing effects of changes in the cloud macrophysics upon the SW and LW CRE (**CITE  $\mathbf{XX}$** ).

When looking at the net radiative effect of blowing snow (Fig. 3C), we see that including blowing snow leads to a net warming of **+  $\mathbf{XX \text{ WM}^2}$**  over the Antarctic Ice Sheet. Here, the warming effect is mostly caused by an increase in LWD, most notably over the steep margins. Over the sloping terrain we see an increase in cloud cover, together with the strongest increase in cloud IWP (enhanced WBF process?), causing an enhanced cloud longwave emissivity (Fig. 2D). Conversely, we also see a net cooling effect over open ocean, where we see a decrease in CC, COD, LWP and IWP (Fig.2A-D). However, for future sea level rise projections, the most important result is that blowing snow can induce a warming over Antarctica, where it can potentially enhance melt and mass loss rates over the grounded ice part of Antarctica (Fig.3C).

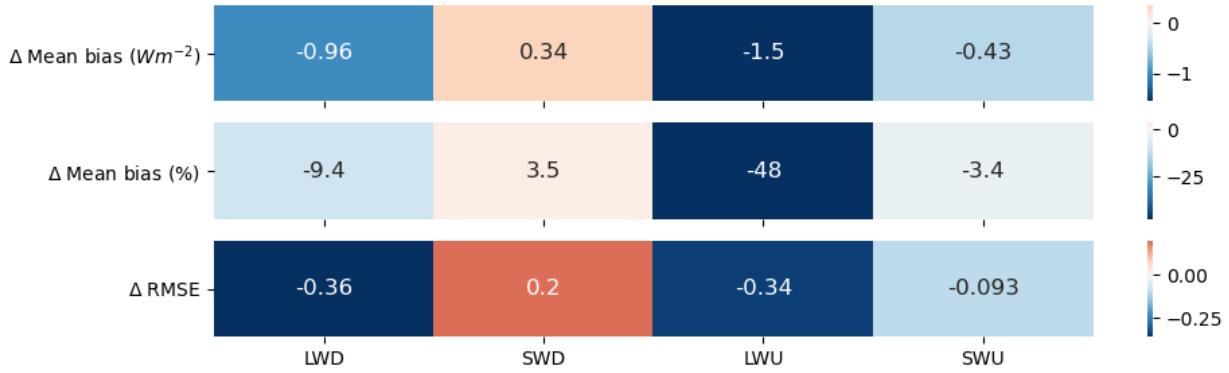


Figure 4: **Statistical comparison of MAR to 19 in-situ weather stations over Antarctica.** **First row:** change in the mean bias ( $Wm^{-2}$ ) when comparing MAR with blowing snow to 19 in-situ observations over the entire Antarctic Ice Sheet. From left to right the numbers indicate the changes for incoming longwave (LWD), incoming shortwave (SWD), outgoing longwave (LWU) and outgoing (reflected) shortwave radiation. Negative numbers indicate a better comparison to the observations when blowing snow is activate in MAR. **Second row:** same a first row but for the percentage reduction/increase in the mean bias when comparing to MAR without blowing snow. **Third row:** same as first row but the change in the root-mean-square-error (RMSE).

When comparing MAR with active blowing snow to 19 in-situ weather station observations across the Antarctic Ice Sheet, we see a reduction in the mean bias (Fig. 4, the mean bias across all station can be found in Supplementary Fig. 5). The reduction of the mean bias in absolute terms is greatest in the longwave part of the spectrum with  $-0.96 Wm^{-2}$  in the downwelling longwave radiation (LWD) and  $-1.5 Wm^{-2}$  in the outgoing longwave radiation (LWU, Fig. 4 first row). Additionally, we see a slight improvement in the outgoing shortwave radiation (SWU), where the mean bias is reduced by  $-0.43 Wm^{-2}$  when accounting for blowing snow, while it is slightly increased in the downwelling shortwave component (SWD) at  $+0.34 Wm^{-2}$ . When we add all the changes in the mean bias of the radiative components we see that accounting for blowing snow in MAR over Antarctica leads to a  $2.65 Wm^{-2}$  better representation of the radiative fluxes when compared to observations ( $-1.50 - 0.96 - 0.43 + 0.34 = -2.65 Wm^{-2}$ ). Overall, we see the greatest improvement in the mean bias in the longwave components of the surface energy budget when explicitly modelling blowing snow over Antarctica.

189 Comparing the change in the mean biases when accounting for blowing snow in MAR to the  
190 initial absolute mean biases of the base model without blowing snow we see a slightly different  
191 weighting (Fig. 4, second row). Our model results with blowing snow show an -48% decrease  
192 of the mean bias in LWU, followed by a -9.4% decrease in the LWD mean bias. Slightly less  
193 pronounced are the changes in SWU with a reduction of -3.4% and a slight increase of 3.5%  
194 in the SWD component (Fig. 4, second row). Conversely, the largest improvement in the  
195 root-mean-square-error (RMSE) occurs in LWD (-0.36, Fig. 4, third row) and LWU (-0.34).  
196 Additionally, accounting for blowing snow leads to a decrease in the RMSE in SWU of -0.09  
197 and a slightly higher RMSE in the SWD component of +0.2. Overall, we again see the most  
198 notable improvement when using the active blowing snow scheme in MAR in the longwave part  
199 of the radiative spectrum, i.e. incoming and outgoing longwave radiation.

## 200 Discussion

## 201 Main References

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## 301 **Materials and Methods**

### 302 **MAR**

### 303 **MODIS**

### 304 **AVHRR**

### 305 **ERA5**

## 306 **Modèle Atmosphérique Régional (MAR)**

307 For the downscaling of coarse-resolution CMIP5 and CMIP6 data we used the Modèle Atmo-  
308 sphérique Régional (MAR), an open-source and widely used polar regional climate model [5,  
309 6, 17, 18, 19, 20, 21, 22, 23, 24, 25]. MAR consists of a hydrostatic dynamical core which  
310 solves the primitive equation set [20, 21]. A full description of the model setup, the underlying  
311 physical parameterizations and evaluation of MAR for polar climates are described in [5, 6, 17,  
312 19, 20, 21, 22, 25]. In this study we used the MARv3.9.6 version, evaluated in A. Delhasse  
313 et al. [26], and the source code of MAR for the reproduction of this study is available via the  
314 MAR homepage at <http://mar.cnrs.fr>.

315 Within MAR, the snow and ice properties at the ice sheet-atmosphere interface are calculated  
316 in the Soil Ice Vegetation Atmosphere Transfer module (SISVAT) [20]. This module calculates  
317 the main snowpack based on the snow module CROCUS [27, 28], but also handles the mass  
318 and energy exchange between the atmosphere (e.g. radiation, precipitation, temperature) and  
319 the bare-ice surfaces, the snowpack and the Arctic tundra that surrounds the GrIS [17, 20].

320 For the 6 CMIP5 and 5 CMIP6 future projections we downscaled we prescribed the boundary

321 conditions in exactly the same manner and also used the MAR version and setup throughout.  
322 Overall, MAR was forced at its lateral boundaries (pressure, wind speed, temperature, specific  
323 humidity), at the top of the stratosphere (temperature, wind speed) and at the ocean surface  
324 (sea ice concentration, sea surface temperature) every 6 hours using GCM and ERA-Interim  
325 reanalysis fields [17, 18, 22, 25]. We ran MAR at a spatial resolution of 15 km x 15 km on a  
326 polar stereographic projection, which represents a significant increase in resolution compared  
327 to previous GrIS regional climate projections with MAR in Xavier Fettweis et al. [18], and  
328 which was used in the IPCC AR5 [29]. The MAR setup used in this study has been thoroughly  
329 compared to observations from weather stations, observed radiative fluxes, satellite cloud cover,  
330 satellite albedo and melt extent, ablation and SMB in-situ measurements [5, 17, 19, 26, 30].

## **Acknowledgments**

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (Grant agreement No. 758005). Computational resources have been provided by the Consortium des Equipements de Calcul Intensif (CECI), funded by the Fonds de la Recherche Scientifique de Belgique (F.R.S.-FNRS) under grant no. 2.5020.11 and the Tier-1 supercomputer (Zenobe) of the Fédération Wallonie Bruxelles infrastructure funded by the Walloon Region under the grant agreement no. 1117545. This work was also supported by the Fonds de la Recherche Scientifique (FNRS) and the Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO) under the EOS Project n° O0100718F. We thank Katherine Thayer-Calder and William Lipscomb for providing 6-hourly output data from CESM2.

## **Author contributions**

S.H., C.K., C.A., X.F., C.L. and A.T. designed the study. S.H. analyzed the data and wrote the manuscript. C.L. provided the analysis for the supplementary material. X.F. did the MAR simulations. All authors discussed the final version of manuscript.

## **Competing interests**

The authors declare that they have no competing interests.

## **Code and data availability**

All the code used for the analysis in this study is available upon request from the corresponding author (stefan.hofer@geo.uio.no). All the MAR model results are available for download on <ftp://ftp.climato.be/fettweis/MARv3.9/ISMIP6/GrIS/> in the framework of the ISMIP6 exercise (<https://tc.copernicus.org/articles/14/2331/2020/>).

## Supplementary Material

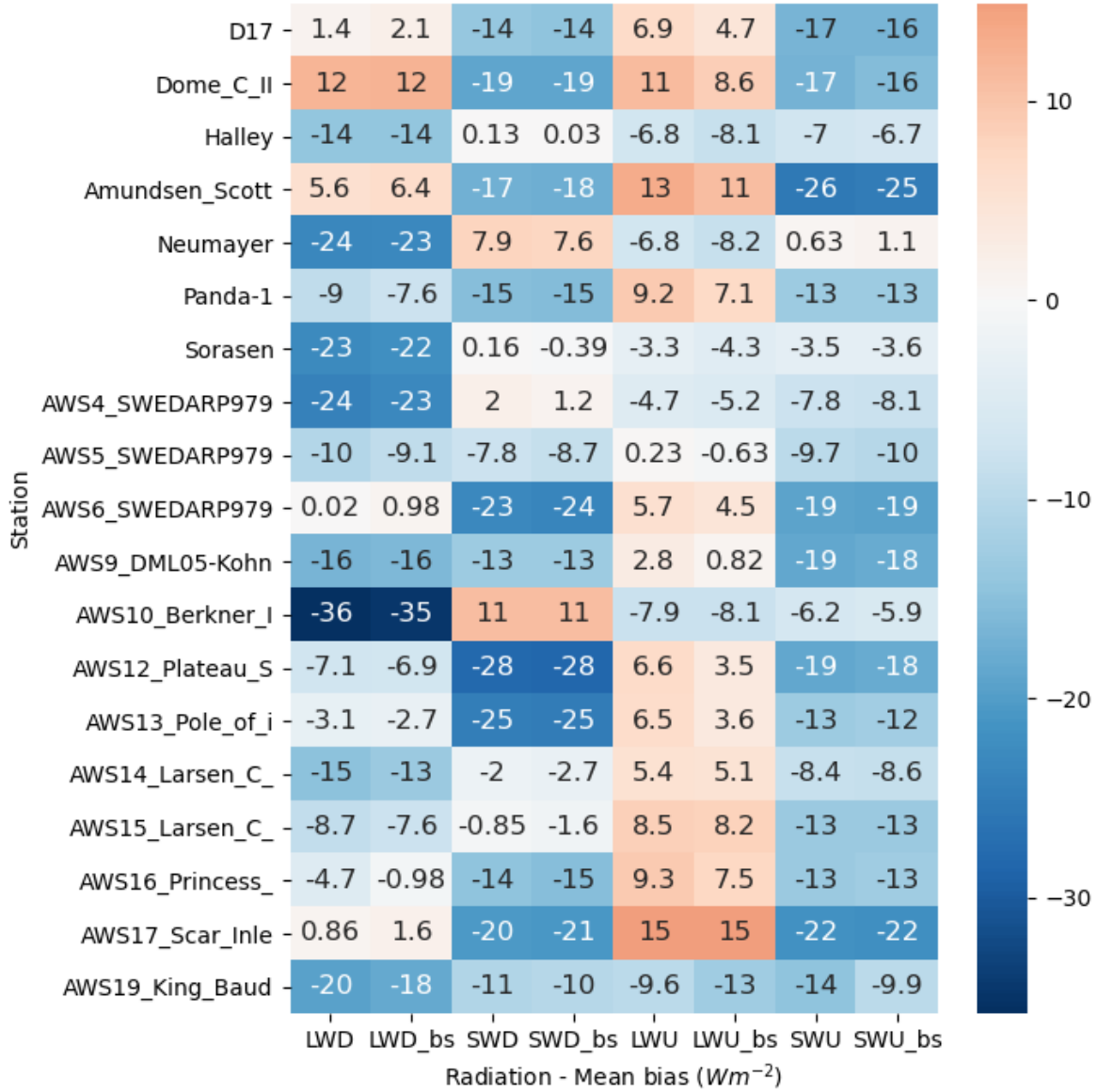


Figure 5: **Complete statistical overview of MAR to 19 in-situ weather stations over Antarctica.** Mean bias (Wm<sup>-2</sup>) of the MAR simulations without blowing snow (e.g. "LWD") and MAR with blowing snow (e.g. "LWD\_bs") compared to Antarctic-wide in-situ observations.