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

Stefan Hofer,[1*] Charles Amory,[2] Christoph Kittel,[2] Tim Carlsen[1] and Trude Storelvmo[1]

[1]Department of Geosciences, University of Oslo, Oslo, Norway
[2]Laboratory of Climatology, Department of Geography, University of Liège, Belgium

*Corresponding author: Stefan Hofer, stefan.hofer@geo.uio.no

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

Introduction

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

Antarctica is the largest body of ice on the planet and it contains the coldest places on Earth. It contains ice mass equivalent to roughly **XX m** of global sea level rise, roughly 10 times more than the Greenland Ice Sheet (**cite XX**). The interior plateau of the Antarctica reaches up to elevations of **XX m**, and is marked by very cold and dry conditions (**cite XX**). However, there are marked differences in the present climatic conditions between East and West Antarctica, and especially between the edges and the inner plateau. While West Antarctica, and especially the northwards reaching mountainous Antarctic peninsula receive ample precipitation and are rather cloudy, weather systems never reach the interior of Antarctica, where most of the precipitation falls as diamond dust under extremely cold "clear" sky conditions (cite XX).

Due to strong radiative cooling in the interior plateau, strong and perpetual katabatic winds emerge, redistributing snow mass from the interior towards the edges and ice shelves, where the up to **XX m** high plateau slopes steeply towards sea level (**CITE XX**).

Second paragraph: describing BS as near-surface clouds + source of moisture and condensation nuclei for additional cloud formation in the lower atmosphere

Third paragraph: What are the open questions? i) Does BS lead to improved representation of cloud properties in the model and ii) how does it affect the representation of clouds?

Clouds are known to notably affect the present and future climates of polar ice sheets [**Izeboud2020**, **Hahn2019**, 1, 2, 3]. Clouds have the ability to amend incoming shortwave and longwave fluxes, depending on the cloud phase, height and particle size distribution, impacting the rate of surface melt and snowpack warming. Blowing snow, while not accounted for in most global and regional climate models, can change the vertical structure and radiative impact of clouds, most notably because blowing snow sublimation changes the atmospheric humidity and temperature distribution (cite Louis 2020). Blowing snow particles can also act as ice nucleating particles for cloud formation, which also impacts the longevity, structure and cloud-phase distribution within pre-existing clouds. 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.

Fourth paragraph: How are we planning to address the questions? Two sets of simulations + satellite products

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 a mean 0-500 m difference of **XX** $\pm$ **XX °C** in elevations greater than 2000 m above mean sea level (Fig.1 A). This cooling of the near-surface atmosphere in our MAR blowing snow simulations, when compared to MAR without blowing snow, is most likely due to the efficient sublimation of airborne blowing snow particles due to the dry (and cold) surroundings over the interior Antarctic plateau. Conversely, over the steep slopes and the flat, low-lying ice shelves surrounding the grounded ice, this decrease in temperature in the blowing snow simulations is less notable. The mean 0-500 m above surface difference lies at **XX pm XX °C**. The contrasting picture between the flat interior and the steeper and lower margins of Antarctica is likely due to two effects: 1) Due to the on average lower relative humidity and the greater water vapour gradients, the airborne blowing snow particles are more readily sublimated in the drier interior plateau than over the margins. This change of phase from solid to gaseous requires energy from the surrounding air to break up the bonds between the H_2O molecules (**CITE CC**), leading to a drop in temperature. 2) Due to strong adiabatic mixing and turbulence in areas where the gravitational pull accelerates the katabatic winds down steep terrain, the snow particles are not confined to the very stable boundary layer anymore. Therefore, the sublimational cooling is less concentrated and subsequently also lower in magnitude over the margins of Antarctica and the ice shelves.

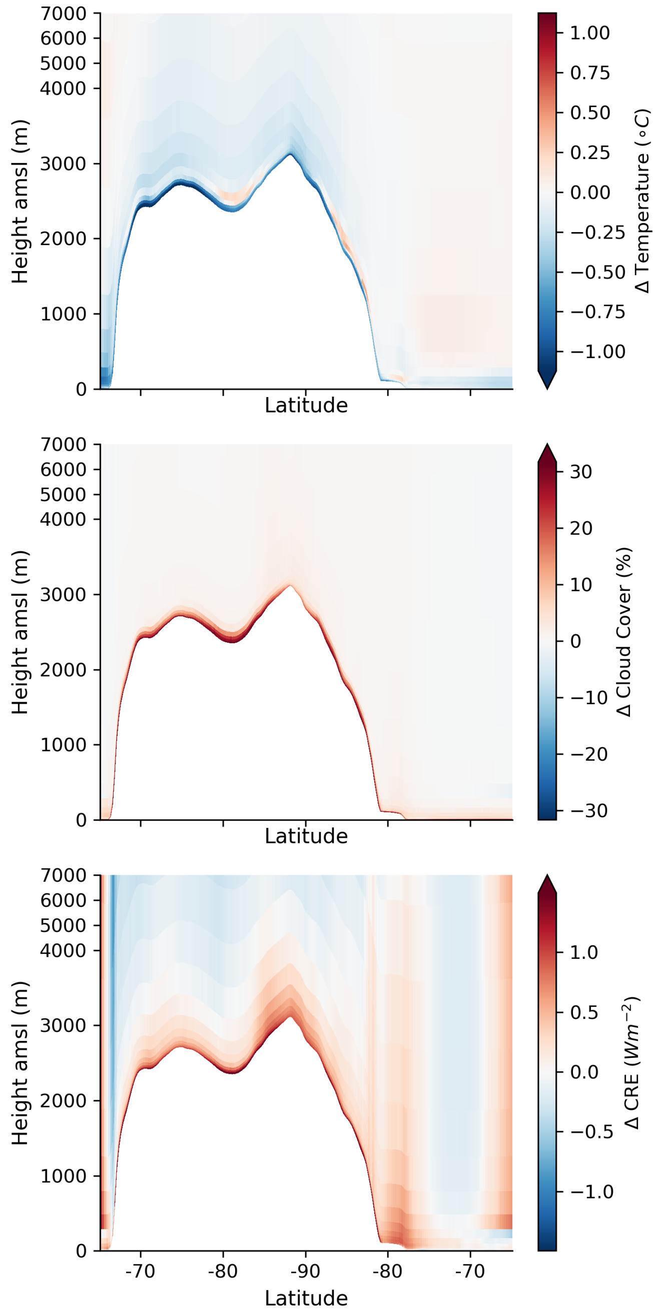

Figure 1: **Difference in temperature and cloud properties between MAR with and without blowing snow.** A) Cross-section of temperature differences between MAR with blowing snow turned on, and MAR without blowing snow (positive means MARbs is warmer), along the path shown in **MISSING FIGURE XX**. B) 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 $\mathbf{XX \pm XX\%}$ in cloud cover. However, there are three overlapping mechanisms that can explain the greater cloud amount over the 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 multiplied 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 ϵ). 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). While we see the strongest effects again in the boundary layer, especially over the steeper margins the CRE is altered to elevations of up to 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 macro-physical cloud properties (IWP, LWP and COD), and therefore the CRE. 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.

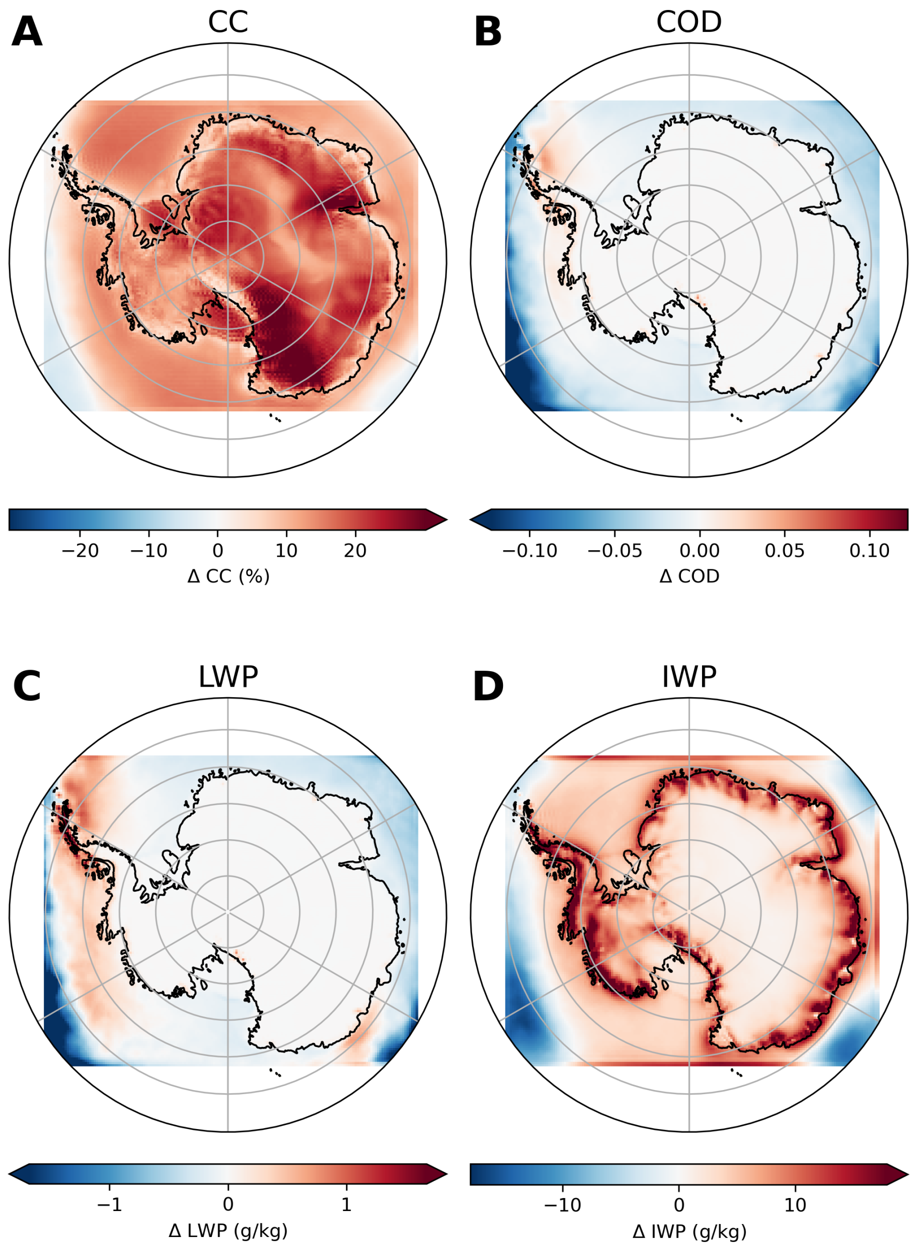

Figure 2: **Difference in cloud properties between MAR with and without blowing snow.** A) Difference in cloud cover (%) between the two MAR simulations. Red colors indicate a greater cloud cover percentage in MAR with active blowing snow parameterisation. B) Same as A) but for the difference in cloud 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 Souther 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 (**Sotiroupoulou**). 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.

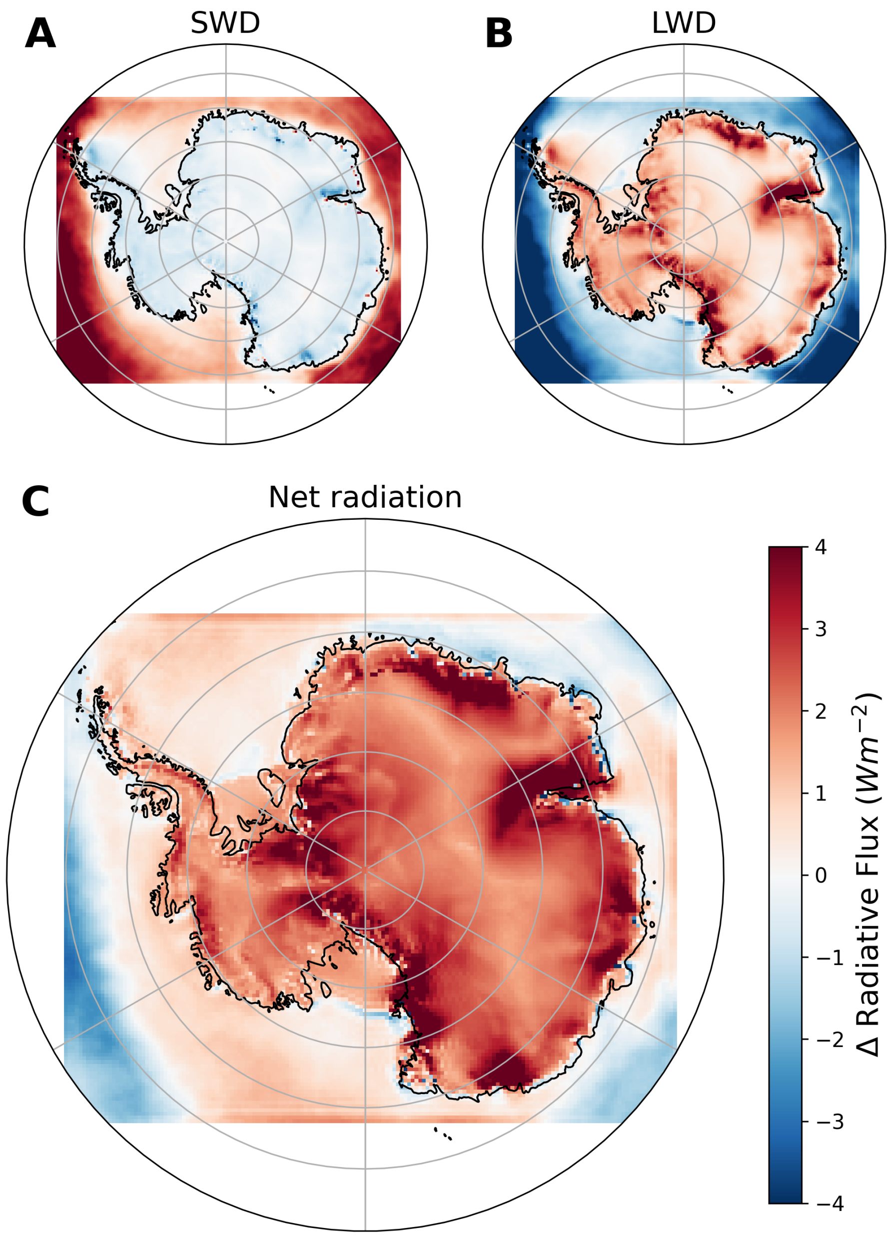

Figure 3: **Difference in radiative components at the surface between MAR with and without blowing snow.** A) Difference in incoming shortwave radiation (SWD) at the surface in Wm^{-2}. Red color indicates a greater downwelling shortwave flux in MAR with active blowing snow parameterisation. B) Same 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 [2]. 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 **XX $\pm$ XX Wm^{-2}**. Conversely, over the open ocean we see a notable increase in SWD by up to **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 XX Wm2**, while it decreases over the ocean due to competing effects of changes in the cloud macrophysics upon the SW and LW CRE (**CITE 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 **+ XX WM2** 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).

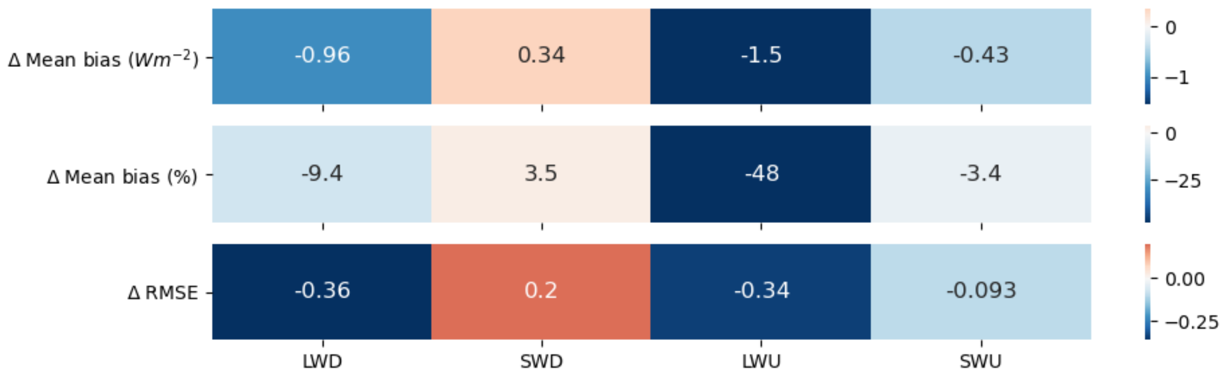

Figure 4: **Difference in radiative components at the surface between MAR with and without blowing snow.** A) Difference in incoming shortwave radiation (SWD) at the surface in Wm^{-2}. Red color indicates a greater downwelling shortwave flux in MAR with active blowing snow parameterisation. B) Same 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 ($R = SWD * (1 - \alpha) + LWD - LWU$).

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.

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

Discussion

Main References

[1] Stefan Hofer et al. "Decreasing cloud cover drives the recent mass loss on the Greenland Ice Sheet". In: *Science Advances* 3.6 (2017). DOI: 10.1126/sciadv.1700584.

[2] Stefan Hofer et al. "Cloud microphysics and circulation anomalies control differences in future Greenland melt". In: *Nature Climate Change* 9.7 (2019), pp. 523–528. DOI: 10.1038/s41558-019-0507-8.

[3] K. Van Tricht et al. "Clouds enhance Greenland ice sheet meltwater runoff". In: *Nature Communications* (2016). DOI: 10.1038/ncomms10266.

[4] X. Fettweis. "Reconstruction of the 1979-2006 Greenland ice sheet surface mass balance using the regional climate model MAR". In: *The Cryosphere* 1.1 (Oct. 2007), pp. 21–40. DOI: 10.5194/tc-1-21-2007.

[5] Xavier Fettweis et al. "Estimating the Greenland ice sheet surface mass balance contribution to future sea level rise using the regional atmospheric climate model MAR". In: *The Cryosphere* 7.2 (2013), pp. 469–489. DOI: 10.5194/tc-7-469-2013.

[6] Xavier Fettweis et al. "Reconstructions of the 1900–2015 Greenland ice sheet surface mass balance using the regional climate MAR model". In: *The Cryosphere* (2017). DOI: 10.5194/tc-11-1015-2017.

[7] Hubert Gallée and Guy Schayes. "Development of a Three-Dimensional Meso-γ Primitive Equation Model: Katabatic Winds Simulation in the Area of Terra Nova Bay, Antarctica". In: *Monthly Weather Review* 122.4 (1994), pp. 671–685. DOI: 10.1175/1520-0493(1994)122<0671:DOATDM>2.0.CO;2.

[8] Hubert Gallée and Hubert Gallée. "Simulation of the Mesocyclonic Activity in the Ross Sea, Antarctica". In: *Monthly Weather Review* (1995).

[9] Christoph Kittel et al. "Sensitivity of the current Antarctic surface mass balance to sea surface conditions using MAR". In: *Cryosphere* 12.12 (2018), pp. 3827–3839. DOI: 10.5194/tc-12-3827-2018.

[10] Alison Delhasse et al. "Brief communication: Impact of the recent atmospheric circulation change in summer on the future surface mass balance of the Greenland Ice Sheet". In: *The Cryosphere* 12.11 (Oct. 2018), pp. 3409–3418. DOI: 10.5194/tc-12-3409-2018.

[11] C. Lang, X. Fettweis, and M. Erpicum. "Stable climate and surface mass balance in Svalbard over 1979-2013 despite the Arctic warming". In: *The Cryosphere* 9.1 (Jan. 2015), pp. 83–101. DOI: 10.5194/tc-9-83-2015.

[12] Cécile Agosta et al. "Estimation of the Antarctic surface mass balance using the regional climate model MAR (1979-2015) and identification of dominant processes". In: *Cryosphere* 13.1 (2019), pp. 281–296. DOI: 10.5194/tc-13-281-2019.

[13] A. Delhasse et al. “Brief communication: Evaluation of the near-surface climate in ERA5 over the Greenland Ice Sheet”. In: *The Cryosphere* 14.3 (2020), pp. 957–965. DOI: 10.5194/tc-14-957-2020.

[14] Hubert Gallée, Gilbert Guyomarc’h, and Eric Brun. “Impact Of Snow Drift On The Antarctic Ice Sheet Surface Mass Balance: Possible Sensitivity To Snow-Surface Properties”. In: *Boundary-Layer Meteorology* 99.1 (Apr. 2001), pp. 1–19. DOI: 10.1023/A:1018776422809.

[15] V. Vionnet et al. “The detailed snowpack scheme Crocus and its implementation in SURFEX v7.2”. In: *Geoscientific Model Development* 5.3 (May 2012), pp. 773–791. DOI: 10.5194/gmd-5-773-2012.

[16] IPCC. “Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]” In: *IPCC* (2014). DOI: 10.1017/CBO9781107415324. arXiv: arXiv:1011.1669v3.

[17] M. Tedesco and X. Fettweis. “Unprecedented atmospheric conditions (1948–2019) drive the 2019 exceptional melting season over the Greenland ice sheet”. In: *The Cryosphere* 14.4 (2020), pp. 1209–1223. DOI: 10.5194/tc-14-1209-2020.

Materials and Methods

MAR

MODIS

AVHRR

ERA5

Modèle Atmosphérique Régional (MAR)

For the downscaling of coarse-resolution CMIP5 and CMIP6 data we used the Modèle Atmosphérique Régional (MAR), an open-source and widely used polar regional climate model [1, 2, 4, 5, 6, 7, 8, 9, 10, 11, 12]. MAR consists of a hydrostatic dynamical core which solves the primitive equation set [7, 8]. A full description of the model setup, the underlying physical parameterizations and evaluation of MAR for polar climates are described in [1, 2, 4, 6, 7, 8, 9, 12]. In this study we used the MARv3.9.6 version, evaluated in A. Delhasse et al. [13], and the source code of MAR for the reproduction of this study is available via the MAR hompeage at **http://mar.cnrs.fr**.

Within MAR, the snow and ice properties at the ice sheet-atmosphere interface are calculated in the Soil Ice Vegetation Atmosphere Transfer module (SISVAT) [7]. This module calculates the main snowpack based on the snow module CROCUS [14, 15], but also handles the mass and energy exchange between the atmosphere (e.g. radiation, precipitation, temperature) and the bare-ice surfaces, the snowpack and the Arctic tundra that surrounds the GrIS [4, 7].

For the 6 CMIP5 and 5 CMIP6 future projections we downscaled we prescribed the boundary conditions in exactly the same manner and also used the MAR version and setup throughout. Overall, MAR was forced at its lateral boundaries (pressure, wind speed, temperature, specific humidity), at the top of the stratosphere (temperature, wind speed) and at the ocean surface (sea ice concentration, sea surface temperature) every 6 hours using GCM and ERA-Interim reanalysis fields [4, 5, 9, 12]. We ran MAR at a spatial resolution of 15 km x 15 km on a polar stereographic projection, which represents a significant increase in resolution compared to previous GrIS regional climate projections with MAR in Xavier Fettweis et al. [5], and which was used in the IPCC AR5 [16]. The MAR setup used in this study has been thoroughly compared to observations from weather stations, observed radiative fluxes, satellite cloud cover, satellite albedo and melt extent, ablation and SMB in-situ measurements [1, 4, 6, 13, 17].

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

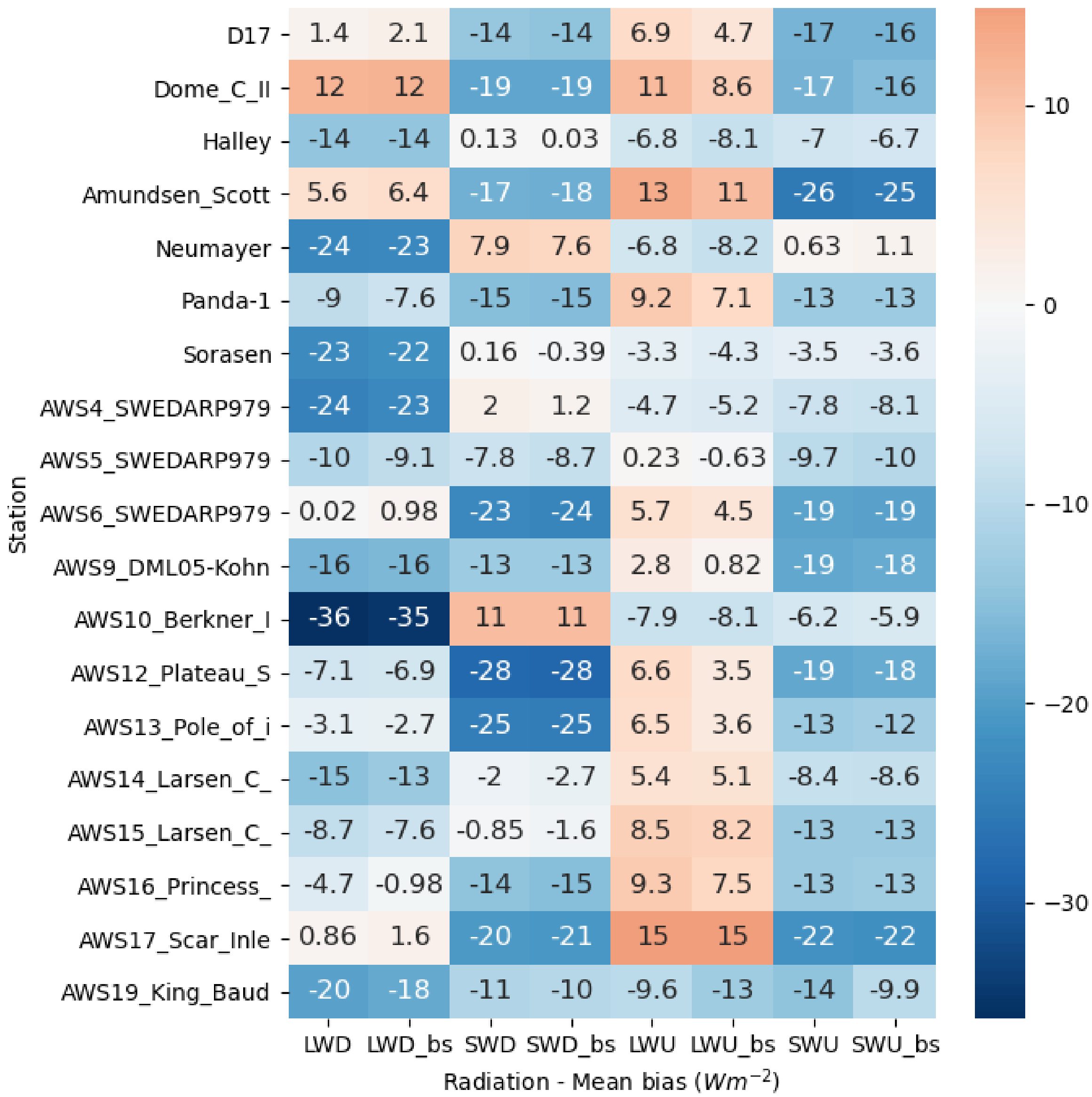

Figure 5: **Difference in radiative components at the surface between MAR with and without blowing snow.** A) Difference in incoming shortwave radiation (SWD) at the surface in Wm^{-2}. Red color indicates a greater downwelling shortwave flux in MAR with active blowing snow parameterisation. B) Same 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 ($R = SWD * (1 - \alpha) + LWD - LWU$).