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

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Antarctica and its surroundings are one of the main areas for biases in climate models, mostly due to uncertainties in the representation of 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.

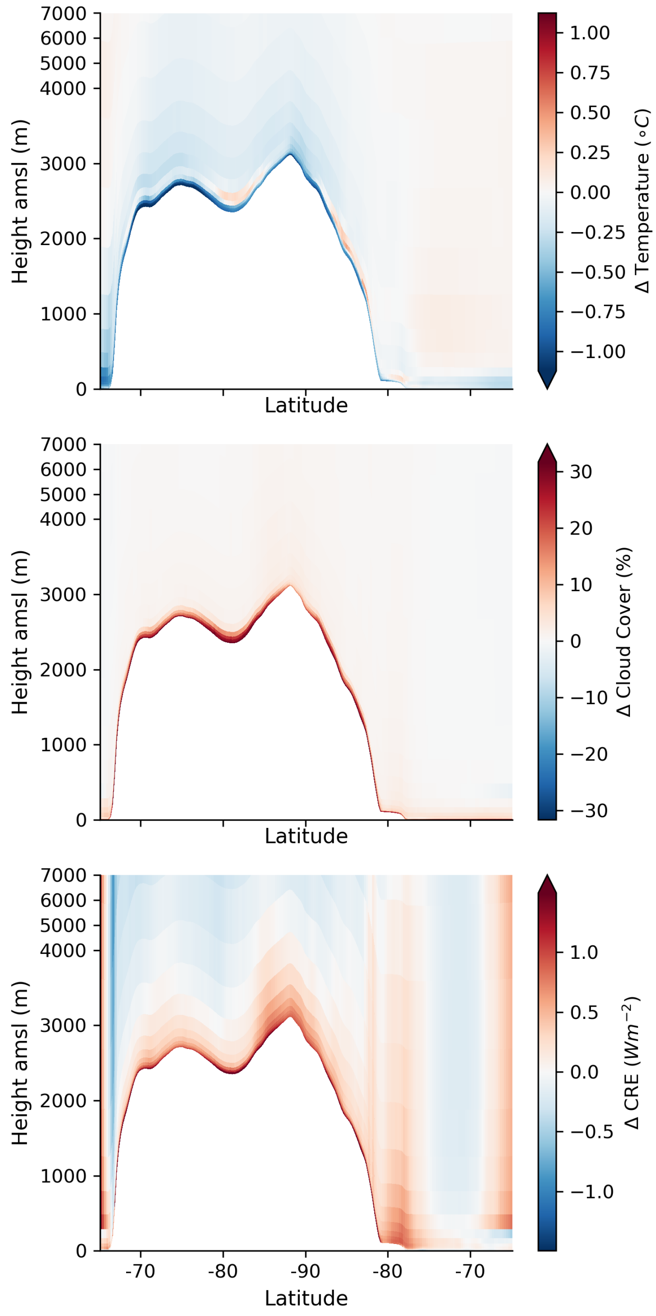

Figure 1: **Difference in temperature and cloud properties between MAR with and without blowing snow.** A) Cross-section of temperature differences between MAR with blowing snow turned on, and MAR without blowing snow (positive means MARbs is warmer), along the path shown in **MISSING FIGURE XX**. B) 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 macrophysical 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.

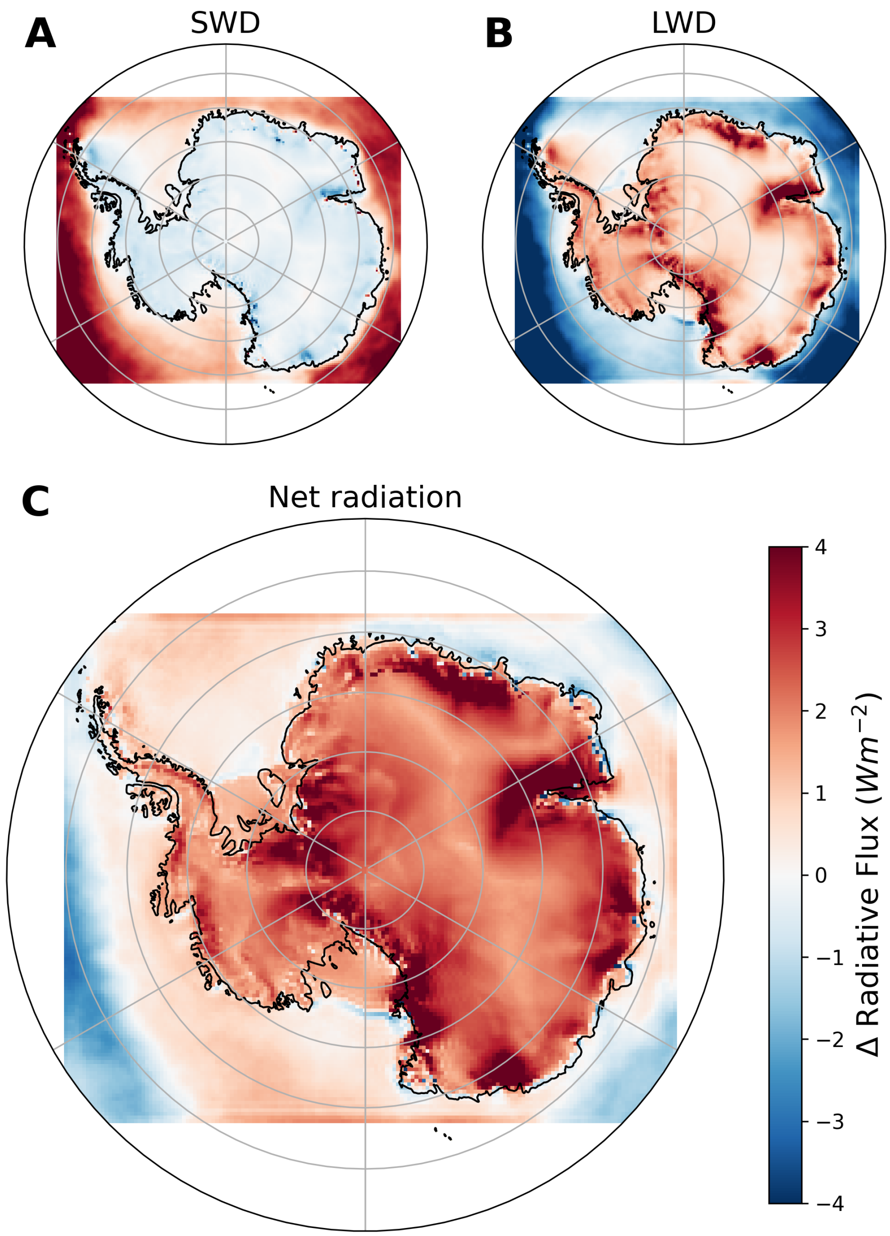

Figure 2: **Difference in radiative components at the surface between MAR with and without blowing snow.** A) Difference in incoming shortwave radiation (SWD) at the surface in Wm^{-2}. Red color indicates a greater downwelling shortwave flux in MAR with active blowing snow parameterisation. B) Same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

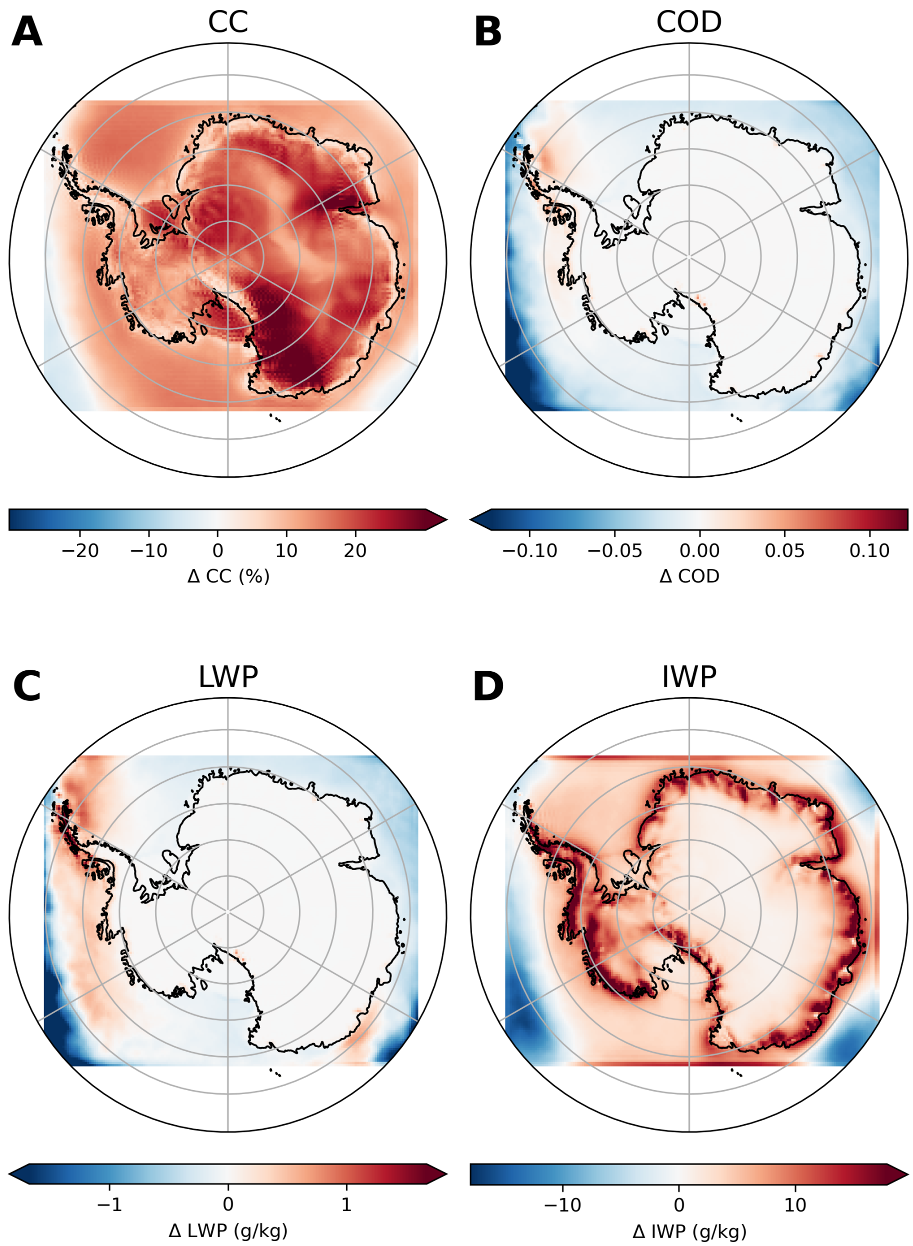

Figure 3: **Difference in cloud properties between MAR with and without blowing snow.** A) Difference in cloud cover (%) between the two MAR simulations. Red colors indicate a greater cloud cover percentage in MAR with active blowing snow parameterisation. B) Same as A) but for the difference in cloud 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).

Discussion

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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].

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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/).