The vertical structure of precipitation in Antarctica from CloudSat and surface radars: a tool for meteorological and global climate model evaluation

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Motivations.

The current global warming context is causing significant changes in snowfall in the polar regions, directly impacting the mass balance of the ice caps. Precipitation, which is the only water supply on the ice cap, is poorly estimated on the Antarctic surface. Indeed, ground-based measurements are sparse and difficult in Antarctica and the size of this continent does not allow to cover and study the whole distribution, frequency and rate of precipitation using land-based methods.

The A-Train satellite CloudSat and its cloud-profiling radar (CPR) provided the first real opportunity to estimate precipitation at polar continental scale. The *Palerme et al., 2014* study proposed the first real climatology of precipitation in Antarctica. Recent studies have improved uncertainties *(Lemonnier et al., 2019)* and confirmed the resolution of the grid *(Souverijns et al., 2018)* used by this climatology.

→ Based on CloudSat observations, we propose to explore the vertical structure of precipitation in Antarctica over the 4 years of observation 2007-2010, thus proposing a new diagnostic tool for precipitation evaluation in climate models.

Methods.

The CloudSat CPR is a nadir-looking radar, it measures cloud particles signal backscattered by hydro-meteors. Radar reflectivity profiles are divided into 150 vertical bins at a resolution of 240m. 2C-SNOW-PROFILE product *(Wood et al., 2014)* retrieves profiles of liquid-equivalent snowfall rates. The product is based on assumption of snow particle size distribution, micro-physical and scattering properties which induce many uncertainties in the calculation of the relationship between radar reflectivity and snowfall rate.

The product is gridded at 1° of latitude by 2° of longitude from the 5th vertical bin of the satellite above the surface, to avoid contamination of the ground clutter. The product is complemented by operational temperature, humidity and pressure datasets from the ECMWF, with the same sampling as the 2C-SNOW-PROFILE precipitation product. This new dataset is then averaged annually over the 4 years of CloudSat observation. It can be studied according to a geographical (see *fig. 1*), topographical (coastal regions VS continental shelf, see *fig. 2* and *fig. 3*), and seasonal criteria.

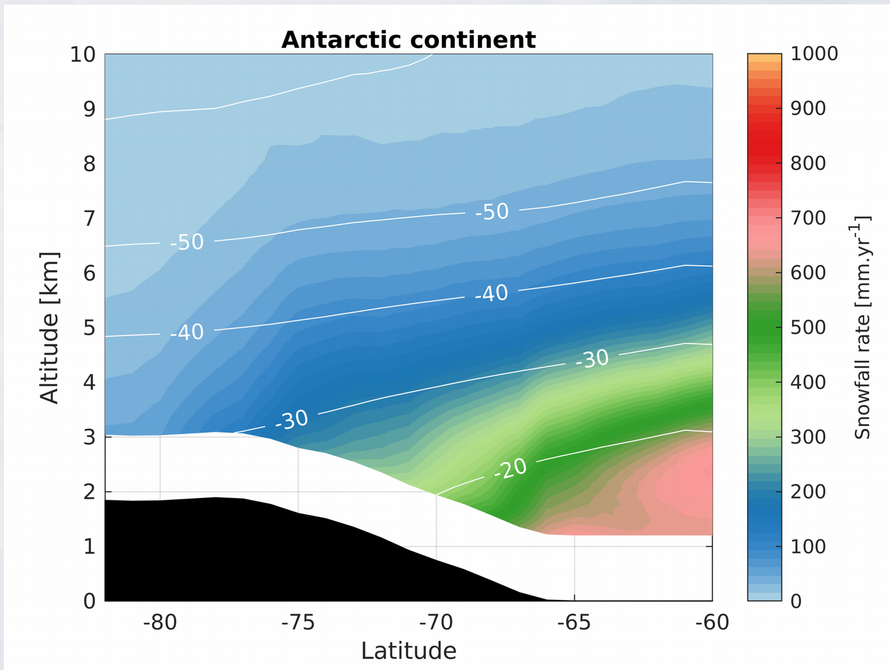

Fig. 1 – Latitudinally average of the precipitation structure and its corresponding atmospheric temperature (white solid lines) for the entire continent.

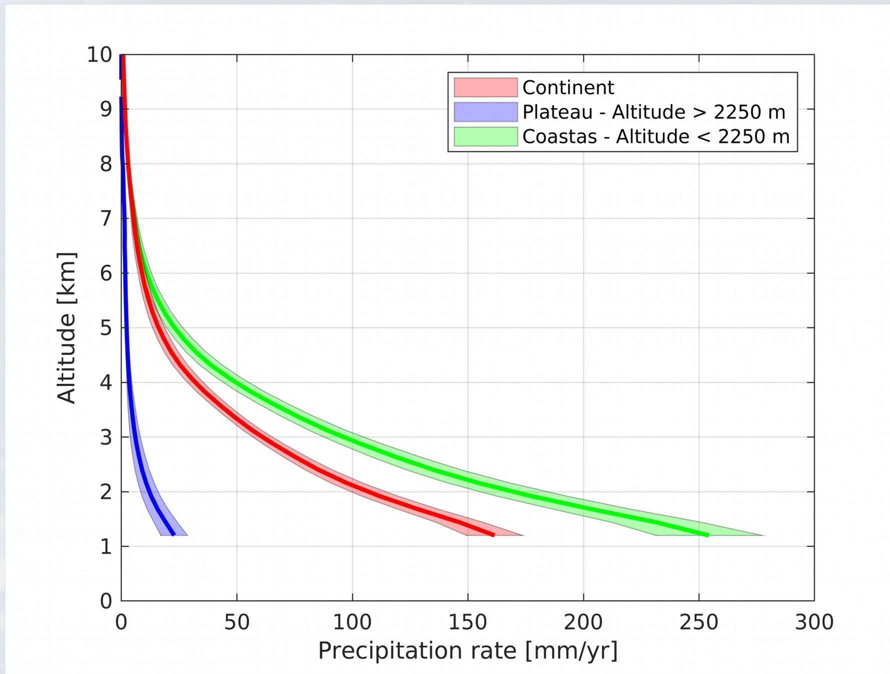

Fig. 2 – Averaged vertical profiles of precipitation over the full period of observation in solid lines, filled areas are the corresponding σ standard deviations over the entire continent in red, over the plateau *(topography > 2250m)* in blue and over the coastal areas *(topography < 2250)* in green.

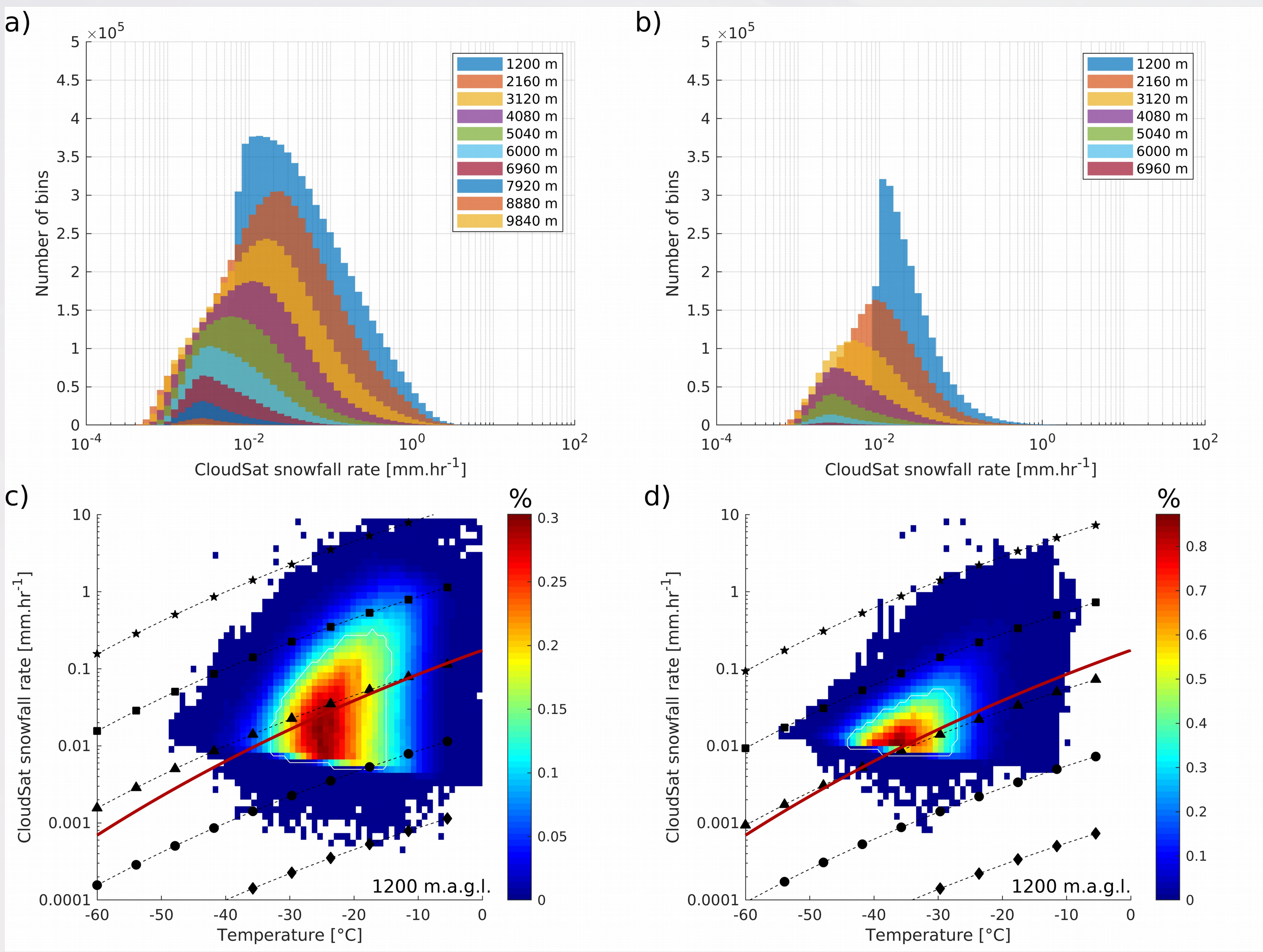

Fig. 3 – Histogram plots of snowfall rates in mm.hr^{-1} and vertical evolutions **a.** for the coastal areas *(topography < 2250 m)* and **b.** for the plateau *(topography > 2250 m)*. **c.** and **d.** present scatter plots of precipitation in mm.hr^{-1} and temperature in °C at 1200 m above ground level over the coastal areas and plateau area respectively. The dark red solid line represents the theoretical precipitation falling at a given sedimentation velocity of 1 m.s^{-1} in function of the temperature. The dashed black lines are the assumptions of theoretical precipitation rates calculated with the moisture convergence equation for vertical wind *w* values of 0.0001 m.s^{-1} *(diamond markers)*, 0.001 m.s^{-1} *(circle markers)*, 0.01 m.s^{-1} *(triangle markers)*, 0.1 m.s^{-1} *(square markers)* and 1 m.s^{-1} *(star markers)*. Colorbars are relative amounts of observations per CloudSat bin. White contours are representing the σ standard deviation of the records distribution per CloudSat bin.

Results and discussions.

General structure of Antarctic precipitation

According to *fig.1*, over the plateau, precipitation rate is low. Along the topographic slope between coasts and plateau, precipitation is increasing as well as temperature. Precipitation over ocean is following isotherms and thus evolving with temperature. There is a divergence between precipitation and temperature over the topographic slope : precipitation rates are drastically decreasing when confronting the plateau.

Fig. 2 presents precipitation profiles over the continent, excluding oceanic precipitation. The plateau is characterized by a very small amount of precipitation all along the profile and a relatively large dispersion : 30 mm.yr^{-1} with a σ-value of almost 50% in the lowest bin. It suggests a high variability over the plateau, coherent with the rare event bringing most of the high continental snow. In comparison with the plateau, coastal profile presents the higher precipitation values and a lower variability. The continental averaged profile is obtained from the combination of both plateau and coastal profiles.

Precipitation distribution over the Antarctic continent

In order to have a better representation of the precipitation over the ice-cap and to develop a new diagnostic tool for models, 2C-SNOW-PROFILE and ECMWF products raw data are extracted over the continental locations and presented on *fig. 3*. **a.** and **b.** highlight that precipitation evolution with altitude appears to be identical above the coasts and plateau, with the position of the distribution peak and the width decreasing in rate and number of observations with altitude. **c.** and **d.** compare CloudSat records with simple assumptions about theoretical precipitation rate. The first assumption is a simple mass-flux density from Clausius-Clapeyron equations *(dark red line)* and the second assumption is based on the convergence of air masses towards the ice-cap *(black lines with markers)*.

→ Since the observed precipitation distributions are higher than a theoretical precipitation rate calculated with Clausius-Clapeyron relationships for a snowfall velocity of 1 m.s^{-1} but cover several orders of magnitude of precipitation calculated by the moisture flow convergence equations, the behaviour and evolution of precipitation seems to be mainly driven by the interaction of topography on large scale movements of air masses.

Conclusion and outlooks.

Precipitation is mostly considered as a surface variable, climatologies typically only reporting the 2D horizontal distribution at the surface. The CloudSat radar dataset now allows to explore the 3D structure of precipitation, and this study proves the interest of studying vertical structures. The 2C-SNOW-PROFILE product has been used to develop a brand new dataset on the three spatial dimensions and the temporal dimension from 2007 to 2010 over the Antarctic continent. This 3D-dataset is constructed and gridded with a 1° of latitude by 2° of longitude and a 240m vertical resolution in order to optimally represent the southern polar climate.

The CloudSat product is also statistically studied without been gridded in order to evaluate the distribution of snowfall rates and associated temperatures over the coastal areas and the plateau at each CloudSat vertical level. This shows that precipitation is mainly driven by large-scale convergence of moist fluxes over the topography.

This new study of the CloudSat precipitation product provides new and innovative tools to evaluate climate models with a three-dimensional view of the atmospheric structure of precipitation.

References & Contacts.

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