HAL
open science

Assessing the simulation of snowfall at Dumont d'Urville, Antarctica, during the YOPP-SH special observing campaign

Marie-laure Roussel, Valentin Wiener, Christophe Genthon, Etienne Vignon, Eric Bazile, Cécile Agosta, Alexis Berne, Claudio Durán-alarcón, Jean-louis Dufresne, Chantal Claud

To cite this version:

Marie-laure Roussel, Valentin Wiener, Christophe Genthon, Etienne Vignon, Eric Bazile, et al.. Assessing the simulation of snowfall at Dumont d'Urville, Antarctica, during the YOPP-SH special observing campaign. Quarterly Journal of the Royal Meteorological Society, 2023, 149 (753), pp.1391-1406. 10.1002/qj.4463 . hal-04087230

HAL Id: hal-04087230

https://hal.science/hal-04087230v1

Submitted on 3 May 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Assessing the simulation of snowfall at Dumont d'Urville, Antarctica, during the YOPP-SH special observing campaign

Marie-Laure Roussel[1] | Valentin Wiener[1] | Christophe Genthon[1] | Etienne Vignon[1] | Eric Bazile[2] | Cécile Agosta[3] | Alexis Berne[4] | Claudio Durán-Alarcón[5] | Jean-Louis Dufresne[1] | Chantal Claud[1]

[1]Laboratoire de Météorologie Dynamique, Institut Pierre-Simon Laplace, Sorbonne Université/CNRS/École Polytechnique – IPP, Paris, France

[2]Centre National de Recherches Météorologiques, GMAP, Météo-France, Toulouse, France

[3]Laboratoire des Sciences du Climat et de l'Environnement, IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, Gif-sur-Yvette, France

[4]Environmental Remote Sensing Laboratory, Swiss Federal Institute of Technology in Lausanne, Lausanne, Switzerland

[5]CESAM - Centre for Environmental and Marine Studies, Department of Physics, University of Aveiro, Aveiro, Portugal

Correspondence
Marie-Laure Roussel, Laboratoire de Météorologie Dynamique, Ecole Polytechnique, Palaiseau, 91128, France
Email: marie-laure.roussel@lmd.polytechnique.fr

Funding information
CALVA, French Polar Institute, Grant Number: 103; EECLAT, CNES/CNRS

The performance of a set of atmospheric models and meteorological reanalyses in the representation of precipitation days in Antarctica is assessed using ground-based observations such as a precipitation gauge and a Micro Rain Radar during the Year Of Polar Prediction Special Observing Period at Dumont d'Urville (November 2018 - February 2019), East Antarctic coast. The occurrence of precipitation is overall well predicted but the number of days and intensity with snowfall are overestimated by the models. This is reflected by high values of bias, probability of detection and false alarm ratios, in particular for reanalyses, due to too frequent simulated precipitating days. The Heidke skill score shows the overall great contribution of the models in the forecasting of precipitating days, and the best performances are achieved by numerical weather prediction models. The chronology is better represented when the models benefit from the data assimilation of in-situ observations, such as in reanalysis or weather forecasting models. Precipitation amounts at the surface are overestimated by most of the models. In addition, data from a ground-based

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/qj.4463

This article is protected by copyright. All rights reserved.

Accepted Article

radar make it possible to evaluate the representation of the vertical profiles of snowfall rate. We can show that an excessive sublimation in the atmospheric boundary layer can compensate for overly strong precipitation flux in the mid and low troposphere. Therefore the need to expand the measurement of precipitation across the atmospheric column using radars is highlighted, in particular in Antarctica where the cold cloud microphysics is poorly known and observations are particularly rare.

KEYWORDS
Antarctica, snowfall, YOPP, observations, precipitation radar, meteorology

1 | INTRODUCTION

The Antarctic continent - 14 million square km-wide and almost totally covered by ice - is the largest continental reservoir of fresh water on Earth. Assessing the future evolution of the inlandsis mass balance is therefore critical in a context of climate change. The surface mass balance (SMB) of the Antarctic ice sheet is the net snow accumulation at its surface. The SMB is mainly fed by precipitation whereas surface loss is due to surface - and drifting - snow sublimation and runoff of melted water to the ocean. The main focus of this study is the Antarctic precipitation, which is expected to increase by the end of the century according to climate scenarios from the Coupled Model Intercomparison Project (CMIP) ([Palerme et al., 2017], Vignon et al. [2021]). When it comes to precipitation in Antarctica, the different climate models are in great disagreement for present climate. While there was no significant improvement between the CMIP5 and CMIP6 results (Roussel et al. [2020]), the reliability of the precipitation change in future scenarios is questionable and there is an urgent need to evaluate and improve the models. The evaluation of models requires reference observational data and a well defined evaluation set-up. Satellite data are very useful to study the atmospheric column : thanks to the measurements from the Cloud Profiling RADAR (CPR) onboard the CloudSat satellite, the first model-free surface snowfall climatology over Antarctica have been constructed (Palerme et al. [2014], Palerme et al. [2019]) then further expanded by adding the vertical component in Lemonnier et al. [2020]. These dataset make it possible to assess some spatial and temporal characteristics of the vertical distribution of antarctic precipitation. However they have important limitations, such as the long revisit time, a short period of operation (from 2007 to 2010), and the absence of measurements below 1200 meters (so-called blind zone, Maahn and Kollias [2012]), where the most intense snowfall occurs and where the sublimation by katabatic winds takes place (Grazioli et al. [2017b], Durán-Alarcón et al. [2019], Vignon et al. [2019b]).

The Year Of Polar Prediction in the Southern Hemisphere (YOPP-SH) campaign which took place between 2017 and 2019 is a unique opportunity to carry out an in-depth evaluation of models thanks to the large amount of observational data collected and the simulations provided by climate and weather prediction centers. The YOPP was part of the Polar Prediction Project (PPP) of the World Weather Research Program (WWRP) initiated by the World Meteorological Organisation (WMO) whose main objectives were i) to improve the meteorological observations at the poles, ii) to enhance the prediction capabilities of Numerical Weather Prediction (NWP) models at high-latitudes,

Accepted Article

This article is protected by copyright. All rights reserved.

1477870x, ja, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.4463 by Cochrane France, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

iii) to advance our understanding of the dynamical and physical processes that govern the polar climates and their interactions with mid- and low-latitudes (Bromwich et al. [2020]). In the context of the YOPP-SH campaign our work supports the first objective, but since the measurements we used are continuous it will also contribute to the second objective over a longer term - applying the same method of study to this longer data set. A Special Observation Period (SOP) took place at both poles, with a particular focus at so-called *Supersites* - i.e. specific points of interest with an enhanced observational system - such as the French scientific station Dumont d'Urville (DDU) in coastal Adélie Land, East-Antarctica (see section 2.1 for the description of the site). At this station, the frequency of observations was increased and dedicated simulations have been run to cover the campaign between the period from November 2018 to February 2019. This study is then a good indicator of the quality of the models and reanalyses, which are involved in the SMB analyses. Beyond WMO standards, the station is also equipped with a Micro Rain RADAR (MRR) which is very useful for evaluating the vertical structure of precipitation. Although the ground-based MRR data only make it possible to evaluate the precipitation modeled at a specific location, they provide information along the vertical and in particular on the lower layers of the atmosphere, and with a very fine temporal resolution (Lemonnier et al. [2021], Vignon et al. [2019a]). While it is common-practice to evaluate the surface precipitation as simulated by models, this approach misses the relative importance of certain physical processes in the atmospheric column such as such as precipitation sublimation - which takes place above the surface and impacts substancially the final result at the ground - especially in case of katabatic winds (Grazioli et al. [2017b]) which are prevailing at DDU. Thus the MRR data make possible an analysis of the vertical profile of precipitation.

Beyond a NWP model assessment, all the observational data acquired during the YOPP-SH SOP make it possible to carry out an process-oriented evaluation of climate models and atmospheric reanalyses and to put the results in perspective of the SMB estimates over coastal Antarctica from those models. We focus on two operational analyses, two reanalyses and two climate models including a global atmospheric model and a regional one in the vicinity of the DDU station : ARPEGE (Action de Recherche Petite Echelle Grande Echelle) outputs of the operational NWP model with a zoom focused on the Dome-C - about 1000km from DDU, IFS (Integrated Forecast System) outputs of the operational NWP model, LMDZ zoomed on DDU, MAR, ERA5 and MERRA2 reanalysis (see Section 2.3 for a complete description of the models). The objective is to carry out an in depth evaluation of the performances of the different types of models. To this end, a comparison with the observational data of the occurrences and quantities of snowfall flux at the surface and along the vertical is carried out. A detailed presentation of the observations and model output data used in this work is given in Section 2. Section 3 presents the meteorological conditions at DDU station during the YOPP campaign, with a particular focus on days with snowfall. Then, the results of the evaluation of the models are given in Section 4. Section 5 closes the paper with a general discussion and conclusions.

2 | DATA & METHODS

2.1 | Presentation of the DDU station

The Dumont D'Urville (DDU) station is located at latitude 66.663°S and longitude 140.0°E (local time : UTC + 10H) on the Petrel's Island at about 5km off the coast of Adélie Land (see Figure 1). This is a privileged point for observation, in particular thanks to the many instruments which are deployed there. DDU is located in a region affected by the katabatic winds that are very frequent on the East Antarctic coast. It is a coastal site that receives a significant amount of precipitation, estimated at about 667mm.year^{-1} in Jullien et al. [2020]. Thus its location and the presence of its operational meteorological station (König-Langlo et al. [1998]) since 1956 have motivated various studies and have led to some field campaigns concerning the study of precipitation, such as the APRES3 (Antarctic Precipitation, Remote

This article is protected by copyright. All rights reserved.

Accepted Article

1477870x, ja, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.4463 by Cochrane France, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Sensing from Surface and Space) project that ran from 2015 to 2019 and during which instruments (including a MRR and a precipitation gauge) were deployed at the station to measure snowfall quantities (Genthon et al. [2018]) (in mm of liquid water equivalent). During the YOPP-SH campaign from november of 2018 to february of 2019, DDU has been chosen to be a *supersite*.

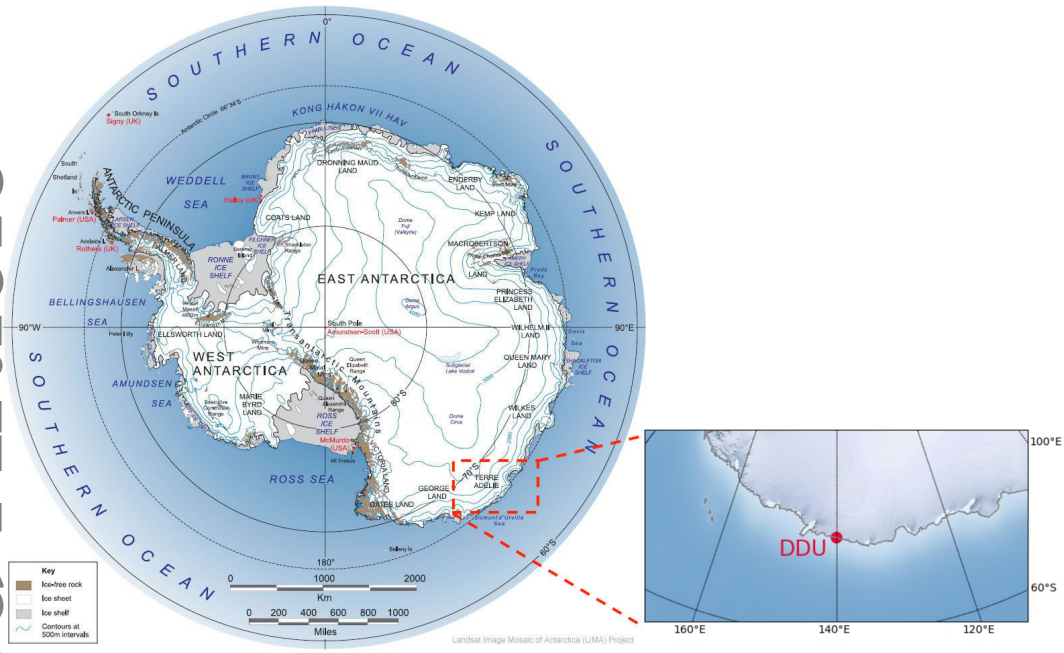

FIGURE 1 Map of Antarctica and the Southern Ocean produced by the LIMA (Landsat Image Mosaic of Antarctica) Project (left) zoomed on the East coast (right). Blue lines indicates the topography of Antarctica. Research stations are in red text, ice-free rock areas in brown, ice shelves in gray and names of the major ocean water bodies in blue uppercase text (USGS [2022]). The DDU station is indicated by a red dot.

2.2 | Ground-based observations and satellite remote-sensing measurements

2.2.1 | Snow gauge

Surface snow precipitation is measured using a OTT PLUVIO2 precipitation gauge (Grazioli et al. [2017a], Genthon et al. [2018]). The gauge measures the mass of precipitation falling in a bucket installed on a scale that detects mass changes. It is worth emphasizing that this system cannot distinguish between the accumulation of snow due to snowfall from accumulation due to blowing snow. A wind shield reduces the undercatch of airborne falling particles but the weather conditions at DDU are so extreme (severe gusts occasionnally reaching 50m.s^{-1}, wind direction changes and turbulences) that recorded measurements may be affected by artifacts. Here phantom events due to vibration and blowing snow were removed with MRR data using the method of Grazioli et al. [2017a]. However, phantom mass measurements due to strong wind events that occured simultaneously with snowfall (both measured by the snow gauge and the MRR) cannot be corrected because it is difficult to filter only the component due to turbulence in the measured signal.

Accepted Article

This article is protected by copyright. All rights reserved.

1477870x, ja, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.4463 by Cochrane France, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

2.2.2 | MRR

The METEK MRR is a 24.3GHz K-band radar and its half-power beamwidth is 2° - corresponding to a radius of 50km at 3000m above ground level. It was installed in a radome in November 2015 and provides since then vertical profiles of reflectivity (Z) and Doppler velocity with a vertical resolution of 100m up to 3000m. Data have been processed following the processing chain for snow hydrometeors developed by Maahn and Kollias [2012]. Snowfall rates (S) are computed every 10 seconds using the Z-S relationship derived in Grazioli et al. [2017a] for DDU conditions, which was also calibrated during an austral summer season (in 2015-2016). The first valid range gate is at 300 m a.g.l., which can be compared to the measurements of snowfall at the surface by the precipitation gauge. It is worth noting that this Z-S relationship has been developped at the lowest available radar gate (300m), which has an impact on the parameters chosen because they are calibrated for certains types of particles which vary with altitude, from 1000m and in particular above 2000m, because of the different properties of hydrometeors. The confidence interval of the parameters of the law given in Grazioli et al. [2017a] then makes it possible to evaluate an uncertainty range on the snowfall profile (see Figure 8).

2.2.3 | Weather sensors and monthly climatological tables

The scientific station at Dumont d'Urville is instrumented with an operational meteorological station operated by the French weather service Meteo-France according to the World Meteorological Organization (WMO) standards. Standard measurements of meteorological variables (2-m temperature and humidity, 10-m wind, and surface pressure) are collected all year long at a 1-min temporal resolution. Radiosondes are launched daily and up to 3 times a day during the YOPP SOP. Visual observations of present weather (cloud cover, cloud type, precipitation type) are also made every day at 00, 03, 06, 09 and 21 UTC (no observation during local "night"). Daily summaries are reported in climatological monthly tables (TCM). It is worth noting that visual observations are not completely objective and may also be tainted by errors. Present weather information is also available in the automatic weather report (see Table S.4). It is particularly interesting because it informs about the type of precipitation which is visually observed during the past hour.

2.3 | Data from atmospheric models and meteorological reanalyses

This section presents the different models involved in the evaluation. Detailed information concerning the horizontal, vertical and temporal resolutions of the datasets used is given in Table S.1. We have analysed output from individual weather forecasting models (2), atmospheric circulation models (2) and reanalyses (2) which where freely accessible for the time period of our study. Since we simultaneously study outputs of forecasting models (with a forecasting time step), quantities calculated from analyses of forecasting models, as well as models nudged towards continuous reanalyses, we must pay attention to the temporal dimension of the data compared. The daily totals of the different models (computed using UTC times) will be analysed and precipitation occurences will be seen as forecast hereinafter, whether they are predictions from weather forecasting models or outputs from nudged climate models. For forescasting models, the daily average will be computed with all the time steps from the run of 00H this day. However for climate models and reanalyses there is no forecasting time step. The daily average is therefore calculated respectively from all the hourly (or tri-hourly) results of the simulation and analysis of the day.

This article is protected by copyright. All rights reserved.

Accepted Article

1477870x, ja, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.4463 by Cochrane France, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

2.3.1 | Simulations from Numerical Weather Prediction models: ARPEGE and IFS

ARPEGE-SH

ARPEGE (Action de Recherche Petite Echelle Grande Echelle) is a global hydrostatic model of NWP (e.g. Pailleux et al. [2014]). It is developed by Meteo-France and used for weather forecasting. The model has sometimes been used for Antarctic studies (Ricaud et al. [2020]). The cloud microphysics of ARPEGE has four pronostic variables for precipitation (cloud ice and water, solid and liquid precipitation). ARPEGE-SH is the dedicated configuration built for the YOPP-SH campaign. This specific configuration of the operational model is used with a higher resolution (around 7.5km) over Antarctica (with a zoom centered on Dome-C, 123.3E 75.1 S, East Antarctic Plateau) than for the NWP operational version over France (see Table S.1). A 4DVar assimilation was performed every 6 hours with the *in-situ* (radiosondes, aircrafts, ground-based stations, buoys and ships datasets) and satellite observations used by the operational version of ARPEGE. We focused only on the 24 first hours (over 78) of the forecasts initialized at 0:00 UTC (10:00 LT) every day for the DDU supersite for which two nearest grid points have been extracted for ARPEGE (one point is over sea and one is over land).

IFS

The IFS (Integrated Forecasting System) model is a global NWP model developed at the European Centre for Medium-range Weather Forecasts (ECMWF). Its cloud microphysics scheme is described in ECMWF [2021]. The ECMWF contribution to the YOPP dataset archive consists of two different products that have been made available for the whole campaign : one operational ensemble medium-range forecast - performed at around 18km resolution with hourly outputs of selected meteorological fields from IFS - and one dedicated short-range research run which is similar to the operational control forecast of the ensemble run. In this work we evaluate the second product for which we could access only the daily averages from the original forecasts. The YOPP dataset can be founded on the ECMWF website (ECMWF [2017]) and it is presented thoroughly in Bauer et al. [2020].

2.3.2 | Reanalyses datasets : ERA5 and MERRA2

ERA5

ERA5 is a global reanalysis of the atmosphere produced by the ECMWF based on the IFS model (version CY41R2) and its data assimilation system (Hersbach et al. [2020]). Numerous atmospheric, land and oceanic variables are computed on a 30 km resolution grid. Since 2019, ERA5 supercedes the previous ERA-Interim reanalyses dataset - for the whole time period since 1979. For this reanalysis, we computed the instantaneous solid precipitation fluxes by applying the methods used in line in the IFS model - detailed in the description of the model (see S.3).

MERRA2

The Modern-Era Retrospective analysis for Research and Applications, (MERRA) is a global reanalysis based on the Goddard Earth Observing System Version 5 (GEOS5) Earth System Model - which is a set of atmospheric, ocean and land model components developed by the Global Modeling and Assimilation Office (GMAO) of the National Aeronautics and Space Administration (NASA) - and with an advanced assimilation system including several *in-situ* and space-based meteorological observations. Since 2016, the second version MERRA2 (Gelaro et al. [2017]) supersedes the original MERRA dataset, providing data from 1980 on a 50km resolution grid. The dataset used in this study can be founded on the NASA Goddard Earth Sciences (GES) Data and Information Services Center (DISC) website (GMAO [2015]).

This article is protected by copyright. All rights reserved.

Accepted Article

1477870x, ja, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.4463 by Cochrane France, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

2.3.3 | Simulations from climate models: LMDZ and MAR

LMDZ

The LMDZ General Circulation Model is the atmospheric component of the Institut Pierre Simon Laplace (IPSL) - Earth system Coupled Model (Boucher et al. [2020]), historically and still actively used in CMIP. LMDZ has been long used for Antarctic climate studies (e.g. Genthon et al. [2002], Krinner et al. [2019]) and its physics has been evaluated and improved for Antarctic conditions, especially regarding boundary-layer (Vignon et al. [2017]) and precipitation processes (Lemonnier et al. [2021]). The 6th and most recent version of the model that is used in this paper is presented in Hourdin et al. [2020] and the cloud and precipitation parametrization is thoroughly described in Madeleine et al. [2020]. For this study, we have carried out LMDZ simulations with the zooming capability of the model (see Table S.1) in a nudged mode, as described Vignon et al. [2018]. The zoom consists in stretching the horizontal Arakawa-C 64 x 64 grid in both latitude and longitude in order to obtain a refined domain of 62 km x 62 km centered on DDU (see Figure S.1). A nudging on the temperature, humidity, zonal and meridional wind component with ERA-Interim reanalyses is applied outside the zoom region with a time-scale of 6 hours. Therefore, the subcomponents of the physics of the model can be evaluated apart from likely deficiencies in the represention of the large-scale atmospheric dynamics and makes it possible to perform a chronologic comparison with in situ data from the DDU observatory.

MAR

The Regional Atmosphere Model (MAR) is a limited-area regional model (Gallée [1995]). It has been specificaly developped for polar regions and is thoroughly used for Antarctic studies (Agosta et al. [2019], Kittel et al. [2021], Amory et al. [2021]). In this study, we used MAR version 3.11, as in Kittel et al. [2021], solving conservation equations for five water species : snow particles, cloud ice crystals, rain drops, cloud droplets, and water vapor (Kessler [1995], Gallée [1995]). Airborne particles can be advected vertically from one atmospheric layer to another and contribute through sublimation to the heat and moisture budget of the atmosphere (Agosta et al. [2019], Le Toumelin et al. [2021]). Limited area requires forcing at the limits of the domain. MAR simulations used in this study are made with ERA5 nudging (from mid-troposphere to the top) on a grid of 6000 x 7000 km^2 (see Table S.1 for details) around the Antarctic continent.

2.4 | Evaluation methodology

To assess the prediction quality of the six simulations and reanalyses we evaluated both the accuracy of the timing of the precipitation occurences and that of the amount of snowfall during the campaign. At the ground surface, the reference used for total snowfall is the data from the snow gauge OTT PLUVIO2. The surface solid precipitation was extracted from modeling datasets to perform the surface comparison. Along the vertical, the reference observational dataset is that from the MRR, which is compared to the profiles of solid precipitation fluxes from the simulations and reanalyses. As all the simulations and reanalyses are not available with hourly timesteps, we chose to make the comparison at the daily time scale. We also choose to consider PLUVIO2 as the daily surface reference to keep a single framework between comparisons of occurrences and quantities. Thus daily observed snowfall accumulations - according to the reference selected (PLUVIO2 for surface snowfall or MRR for snowfall on the vertical column) - are considered as individual events and compared to those that have been predicted.

This article is protected by copyright. All rights reserved.

Accepted Article

1477870x, ja, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.4463 by Cochrane France, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

2.4.1 | Grid point selection

Three grid points (see Table S.2 - note that non zero altitudes on ocean surface are due to the spectral representation of the surface geopotential - and Figure 2 - note that some points are overlapping) were selected for each model studied : the closest to the real coordinates of the DDU station, the closest fully oceanic grid point (i.e. the closest with 100% of type "sea") and the closest fully terrestrial grid point (i.e. the closest with 100% of type "land"). For ARPEGE and MAR, only two points are extracted because the closest point is already fully oceanic or terrestrial. A preliminary comparison of the three grid points, based on surface and vertical snowfall amounts (see Table S.3), made it possible to assess that the most accurate representation of snowfall amounts is the one of the closest grid point regardless of the surface type for most of the outputs. Therefore we only analyse the detailed comparison between the simulations or reanalyses and the observations for the closest grid point whatever the nature of surface.

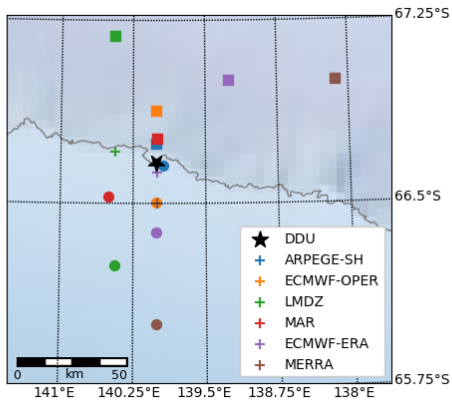

FIGURE 2 Location of the models grid points. Crosses, circles and squares respectively indicate the nearest, oceanic and terrestrial grid points. Some points are overlapping, see Table S.2 for grid points information. Real coordinates of DDU are indicated by a black star. The grey line represents the actual coastline.

2.4.2 | Thresholding and classification of days with snowfall

Precipitation events are considered at the daily time scale. In order to filter the instrumental noise as well as spurious numerical precipitation in models, it is necessary to determine precipitating days that are considered as significant or non-negligible. The snow gauge having already been filtered out using data from the lowermost MRR gate data, it is considered that any precipitating day with more than 0 mm is not negligible. Also, the manufacturer's manual indicates that a native threshold of 0.1mm per hour is already taken into account in the raw results of the snow gauge. Across the vertical atmospheric column, it can happen that values measured by the MRR are masked. They are echoes filtered out by the processing algorithm depending on a threshold set to distinguish if the reflectivity is strong enough to be considered. We then choose to consider that these cases of undefined values are non-precipitating days - given that there are no zero values in the MRR dataset - except for the cases where the quality variable indicates an absence of data. It is also necessary to consider that the sensivity of the MRR decreases vertically because electronic and thermal noise increase with altitude. By construction, the minimum reflectivity detectable by the MRR increases with

This article is protected by copyright. All rights reserved.

Accepted Article

1477870x, ja, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.4463 by Cochrane France, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

the square of the distance from the instrument. To take this into account, we choose to filter out the data according to the value of the Signal to Noise Ratio (SNR), which guarantees that a clearly visible signal is kept. Thus a minimal value of SNR is considered in order to remove precipitation measurements that are strongly impacted by noise before any comparisons. The choice of this threshold as well as its impact on the observations are detailed in S.7. In the model comparison (not in models statistics), we choose a threshold of 0.28mm per day. This criterion has been established by Palerme et al. [2014] to optimize the agreement between observations (CloudSat in Palerme et al. [2014], MRR here) and the numerical simulations, based on a comparison between ERA-Interim and CloudSat datasets. We choose to use this threshold for consistency with the previous works and in order to be able to extend this study thereafter to a comparison of the reanalyses of the ECMWF with instruments such as that carried on board CloudSat (during its operating period) or the one planned for the future EarthCare satellite platform.

We apply this threshold on the whole vertical by considering that the numerical error in the models does not depend on the altitude. In order to analyse their occurrence, we further classify days with snowfall at the surface into six quantitative classes : intense with 10 mm or more per day, medium with 5 to 10 mm per day, small with 1 to 5 mm per day, very small with 0.28 to 1 mm per day, negligible with less than 0.28 mm per day, and null event with exactly 0 mm per day. The lastest category has very different results depending on the model conventions to treat the absence of precipitation (see Figure 5) or low precipitation values - some models may have non-zero values due to numerical accuracy and rounding errors.

2.4.3 | Evaluation of the detection of snowfall occurence

A contingency table is used to assess the quality of the simulations and reanalyses results about daily occurence of snowfall regardless of quantity, except the minimal threshold of 0.28mm per day for daily snowfall that is chosen to distinguish days with precipitation from those without (or negligible) precipitation in the measurements or numerical outputs. A dichotomous result based on the threshold mentioned above is attributed for each day and at each level (for the comparison with the MRR dataset - considering the closest model level to the level of the MRR). In the special case of the inter-comparison between observations (see Figure S.3), the minimum threshold retained to consider precipitating days is 0mm.day^{-}1. An additional comparison has been made between visual and instrumental observations of surface snowfall occurences (see S5) showing a good agreement between human observations and data from the snow gauge. In this study, the following basic scores are analysed to investigate the quality of the predicted precipitation occurence, with H, FA, M and CR being respectively Hits, False Alarms, Misses and Correct Rejects :

- Bias (B) : $Bias = \frac{H+FA}{H+M}$ Ratio of forecasted days with snowfall over observed ones. If $B > 1$ (respectively $B < 1$), then the model over-estimates (respectively under-estimates) the occurence. The perfect score is 1.
- Probability Of Detection (POD) : $POD = \frac{H}{H+M}$ Proportion of hits among forecasted days with snowfall. It is sensitive to hits but ignores false alarm. The perfect score is 1.
- False Alarm Ratio (FAR) : $FAR = \frac{FA}{H+FA}$ Ratio of predicted days with snowfall on unobserved ones. The perfect score is 0.
- Heidke Skill Score (HSS) : $HSS = \frac{2*(H*CR-FA*M)}{(H+M)*(M+CR)+(H+FA)*(FA+CR)}$ It measures the performance of forecasting against a random forecast. A negative value indicates that the random forecast is better. 0 means that the model has no particular skill. The perfect value is 1.

This article is protected by copyright. All rights reserved.

Accepted Article

1477870x, ja, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.4463 by Cochrane France, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

3 | METEOROLOGICAL CONDITIONS IN ANTARCTICA AND AT DUMONT D'URVILLE DURING THE YOPP CAMPAIGN

3.1 | Standard meteorological variables during the YOPP campaign

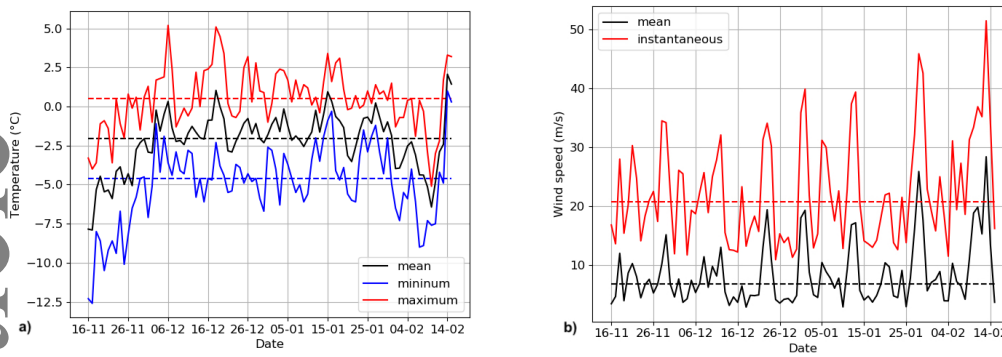

FIGURE 3 **a)** Time series of the daily mean of hourly 2-m temperature in degrees Celsius (minimum, maximum and mean temperatures are respectively in solid blue, red and black lines). **b)** Time series of the daily mean of hourly 10-m wind speed in m.s^{-1} on the right (mean and instantaneous wind speed are respectively in solid black and red lines) during the YOPP-SH campaign measured by the Météo-France sensors at the DDU station (November 2018 - February 2019). Median values are shown in dashed lines.

The climate at DDU station is milder than inland but very windy. As it is located on the east coast where the altitude is close to sea level, the site is strongly influenced by synoptic systems transiting over the Southern Ocean is not negligible as well as the warming by the ocean (König-Langlo et al. [1998]). The temperatures rarely fall below -30°C and the maximum can exceed 0°C. Winds at DDU are mostly katabatic winds forming on the slope of the continent with an easterly direction (Vignon et al. [2019b]). Their strength can be particularly strong when the synoptic conditions favor a plateau-to-ocean pressure gradient force (Bromwich and Parish [1998]). The direction - from South East to South at DDU - is determined by the slope and deviated by the force of Coriolis. The main direction of the winds at DDU during YOPP-SH is between 90 and 130 degrees, which corresponds to katabatic winds. This type of wind is typical of the off-seasons and when the synoptic situation is favorable - especially after the passage of a low pressure at the north of Terre Adélie. The dry air carried by a katabatic wind significantly influences the lower layers of the atmosphere at the coasts, notably through the sublimation of precipitation. Snowfall at DDU is mostly associated with the passage of a warm front of an extratropical cyclone transiting over the Southern Ocean (Jullien et al. [2020]). Dry katabatic winds sublimate a substantial part of the precipitation (Grazioli et al. [2017b]) especially during the pre-frontal and post-frontal phase of the precipitation event (Jullien et al. [2020]). As summer temperature can sometimes exceed 0°C, rainfall occasionally occurs (Vignon et al. [2021]) especially when a strong blocking anticyclone forms to the north east of the station. A study carried out by Grazioli et al. [2017a] over one year has shown that the annual precipitation amount at DDU would be between 740 and 989 mm. The evolution of the temperature and wind force variables recorded during the YOPP campaign all well as statistics are presented in the Figure 3. During the YOPP campaign, the daily average of the hourly maximum temperature have been 0.5°C with only 8 days of positive daily mean temperature. The daily average of the hourly minimum and mean temperatures have been respectively -4.6°C and -2.0°C. Over 92 days, the daily average of hourly maximum temperature remained below 0°C for 34 days and

This article is protected by copyright. All rights reserved.

Accepted Article

1477870x, ja, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.4463 by Cochrane France, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

the daily average of hourly minimum temperature did not exceed -5°C for 38 days (see Figure 3). Most of the wind blowing at the station is easterly or south-easterly and ranges between 7 to 14 m·s^{-1} (not shown). The daily average of the hourly mean wind speed and hourly instant wind speed during the campaign are 6 and 21 m·s^{-1}. The strength of the hourly gusts averaged over the day exceeded 28 m·s^{-1} for 25 days out of 92 days of the campaign.

3.2 | Days with snowfall observed during the YOPP campaign

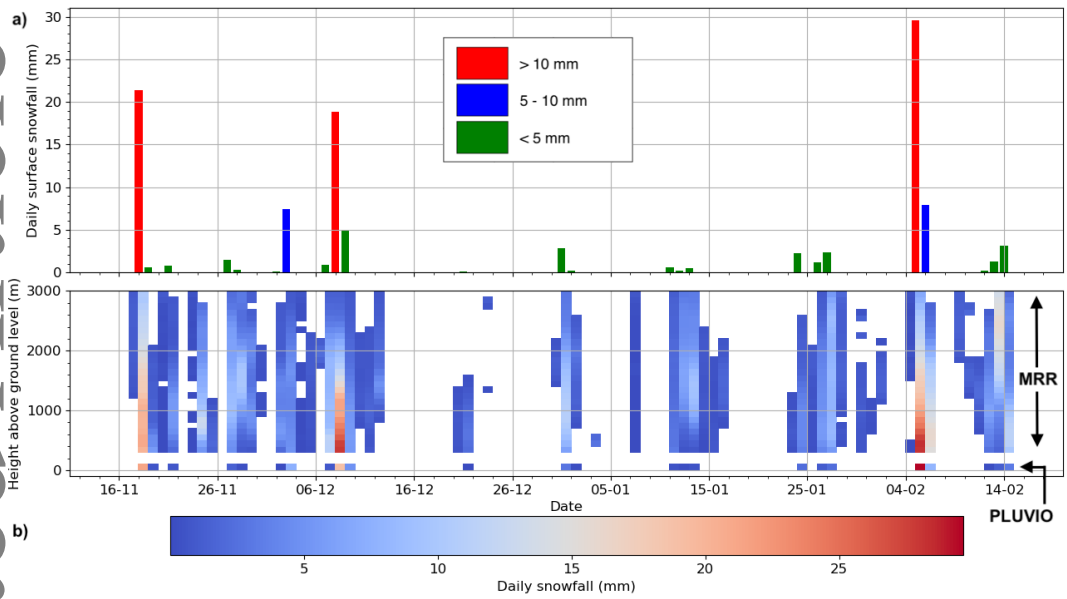

FIGURE 4 **a)** Time series of the surface snowfall measured by the snowgauge during the YOPP period (red : days with intense snowfall, blue : medium, green : small and very small). **b)** Time series of the vertical snowfall flux measured by the MRR during the YOPP period (white : no or negligible precipitation) and the surface snowfall measured by the snowgauge

Considering the threshold mentionned above of 0.28mm per day, the snowgauge has detected 24 non-negligible days with snowfall during the 92-day campaign. The Figure 4 shows the daily time series of the snowfall measured by the instrument at the surface. During the summer campaign, there were respectively 3, 2 and 19 days of high, medium and low or very low snowfall intensity. The time series of surface precipitation as well as that on the vertical show a drier period from December, 10 to February, 3. The Figure 4 shows a very good agreement between the occurrences observed by the MRR (at its first level) and those of the snowgauge. It is worth noting that the precipitation formed aloft does not always reach the ground surface. So-called virga events can indeed occur at DDU when the precipitation is relatively weak and the low-level sublimation of snowflakes is particularly intense. During the YOPP campaign, 16 days presented a non-zero precipitation measurement by the MRR at the first level while the snowgauge indicated no precipitation at the surface. We will refer to these events as *potential near-surface sublimation days*. The signal of the snowgauge and the standard meteorological variables have been verified to confirm the accuracy of the measurements. All these days have a zero mass balance (precipitation – evaporation) that can be explained by favorable conditions at the surface (low relative humidity, strong wind from the east).

This article is protected by copyright. All rights reserved.

Accepted Article

1477870x, ja, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.4463 by Cochrane France, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

4 | EVALUATION OF THE MODEL PRECIPITATION OCCURENCE AND AMOUNTS

TABLE 1 Scores (Bias, Probability Of Detection and Ratio of False Alarm) of model outputs for the occurence of surface and vertical snowfall during the YOPP campaign respectively compared to observations. Green and red respectively indicates the best and worst score among all models

	Surface				Vertical			
Model / Score	BIAS	POD	FAR	HSS	BIAS	POD	FAR	HSS
ARPEGE-SH	1.78	0.94	0.47	0.57	1.05	0.87	0.17	0.74
ECMWF-OPER	2.11	1.00	0.53	0.51	1.10	0.89	0.19	0.74
LMDZ	1.50	0.78	0.48	0.51	1.13	0.81	0.29	0.57
MAR	1.28	0.89	0.30	0.72	1.20	0.86	0.29	0.60
ECMWF-ERA5	2.28	1.00	0.56	0.46	1.15	0.90	0.21	0.71
MERRA2	2.28	1.00	0.56	0.46	1.14	0.89	0.22	0.71

4.1 | Evaluation at the surface

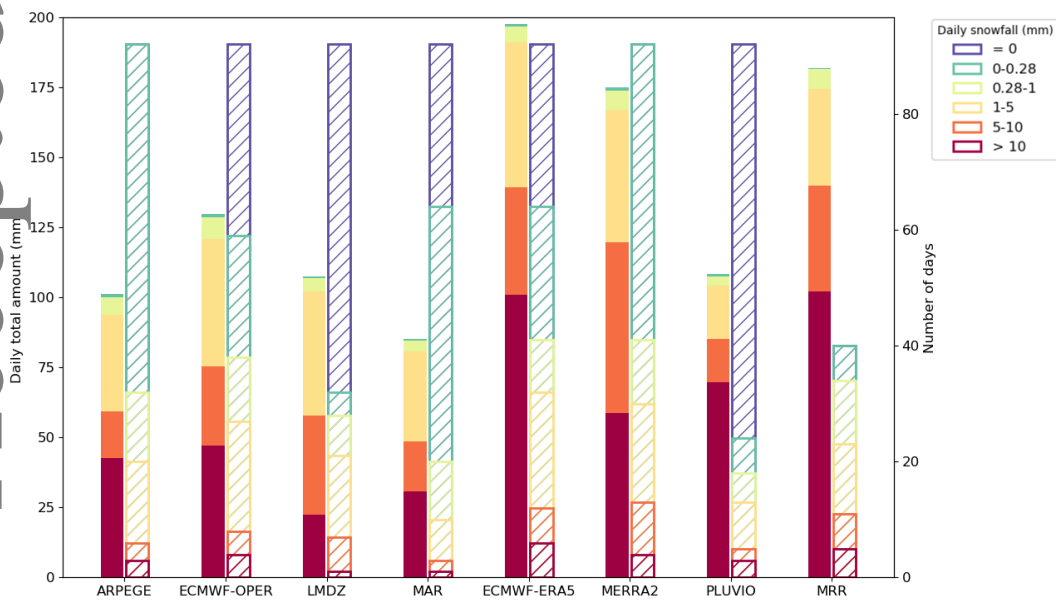

FIGURE 5 Left bars : Total amount of surface snowfall over the YOPP campaign for model outputs and observations classified by daily surface snowfall amount classes (in mm). Right bars : Number of days classified by daily surface snowfall amount classes for model outputs and observations (for the MRR, there is no day with a null daily snowfall because no zero value is present in the dataset)

Accepted Article

This article is protected by copyright. All rights reserved.

1477870x, ja, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.4463 by Cochrane France, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

At the surface, regarding precipitation amounts, the model outputs with best agreement with observations are those from ARPEGE-SH with a global underestimation of 7% of the total accumulation (see the Table 2) and LMDZ with an overestimation of 15%. MAR is underestimating it with an error of 24%. The two reanalyses are overestimating the quantity with larger errors : 61% for MERRA5 and 82% for ERA5. When considering days with snowfall by intensity class, LMDZ reproduces the best distribution of day types with the smallest standard deviation compared to surface observation data (not shown). The repartition of different contribution is illustrated in the Figure 5. ARPEGE and MERRA2 have the most dissimilar repartition from the snow gauge, especially due to a major overestimation of negligible snowfall daily amounts. None of the models represent days with exactly 0mm or with a negligible amount of snowfall (0-0.28mm/day) the same way. However we investigated days with little accumulation considering small (1-5mm/day) and very small (0.28-1mm/day) snowfall amounts : the analysis of the contribution of those days with snowfall shows that their occurences are predominant, and that they are generally well represented in all the models. Regarding the total accumulation, the contribution of days with very weak snowfall is negligible (see Figure 5) and the major part of the overall surface snowfall originates from days with intense, and medium or small snowfall. The time series of accumulated precipitation shown in Figure 6 - shows that reanalyses are well representing the days with intense snowfall but overestimate some medium and small ones. ARPEGE underestimates all strong and medium days with snowfall, MAR overestimates the number of days with negligible snowfall and does not simulate enough intense one. Finally, ARPEGE, IFS and LMDZ do not always simulate intense and moderate daily snowfall amounts well, but the total accumulation over the whole period is within 21 mm of the value recorded at the snow gauge (see Table 2).

TABLE 2 Total surface accumulation in mm for model outputs and observations

	Total surface snowfall
ARPEGE-SH	101
ECMWF-OPER	130
LMDZ	125
MAR	85.1
ECMWF-ERA5	198
MERRA2	175
PLUVIO	109
MRR	182

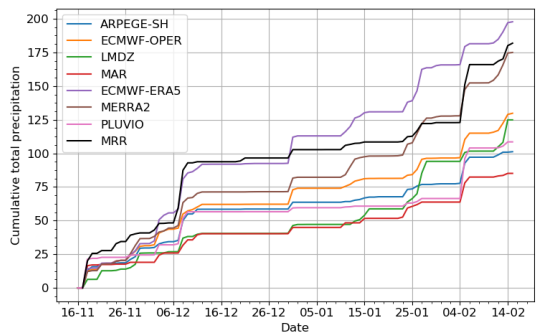

FIGURE 6 Time series of the cumulative surface (or at the lowest available gate i.e at 300 m a.g.l for MRR) snowfall for model outputs and observations

For all models the contribution to the total surface precipitation bias increases with the intensity of the precipitation event. However, the strongest relative errors come from the weakest events: the bias of the weakest events reaches up to 10% for reanalyses, while it does not exceed 1% in the case of very intense events whatever the model (not shown). The HSS value for the models is close but major differences between them are highlighted by the other scores (see Table 1) : ERA5, MERRA2 and IFS have a perfect POD and ARPEGE has also a very high value for this score which is most probably a result of optimal assimilation of observed standard variables at the surface (as temperature, wind speed and humidity) while the other models are merely nudged at boundaries. The time series of the results of the comparison of the models to the snow gauge observations at the surface (see Figure 6) shows that ERA5, MERRA2

This article is protected by copyright. All rights reserved.

Accepted Article

1477870x, ja, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.4463 by Cochrane France, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

and IFS do not miss a day with snowfall at the surface during the YOPP campaign and ARPEGE only misses a single day with snowfall. ERA5, MERRA2 and IFS have higher bias and ratio of false alarm due to too many precipitating days. MAR and LMDZ have the lowest bias, slightly overestimating the number of days with snowfall. However, the higher number of missed days with snowfall of these models contributes to lower values of POD. MAR has the lowest false alarm ratio because of its under-representation of the number of days with significant snowfall which may be due to too small intensities of snowfall events. MAR and LMDZ have the same missed days with snowfall (around the twentieth day of the campaign - see Figure 6). During *potential near-surface sublimation days*, all the models are only in agreement with the precipitation detection of the rain gauge for one day (out of 16). Ruling out these cases makes it possible to improve the average error of the models of 10mm.

4.2 | Evaluation of the vertical profiles

To perform the comparison between the MRR and the various model outputs, model data have been vertically interpolated (using linear interpolation) on MRR levels. Along the vertical, each score is computed with the daily results of every level of the whole vertical column for each model. The analysis of the total precipitation flux profiles modeled during the period (see Figures 7 and 8) shows that the result closest to the observation by the MRR is that of the ARPEGE model, with the smallest standard deviation (computed with absolute values) compared to the observed profile. IFS has closest values of quantity and height of the maximum value on the vertical compared to the MRR. Despite a small bias in the value of surface snowfall - and all along the atmospheric column - the ERA5 reanalyses have a good representation of the observed distribution as well as a close maximum snowfall flux on the vertical to the MRR one. On the opposite the LMDZ and MAR models have the less consistent shape of vertical distribution with the observation, respectively overestimating and underestimating maximum snowfall flux.

TABLE 3 Cumulative maximum snowfall in the column during the YOPP campaign across all vertical levels for model outputs and MRR observations in mm

	Maximum snowfall in the column
ARPEGE-SH	209
ECMWF-OPER	203
LMDZ	263
MAR	182
ECMWF-ERA5	276
MERRA2	207
MRR	217

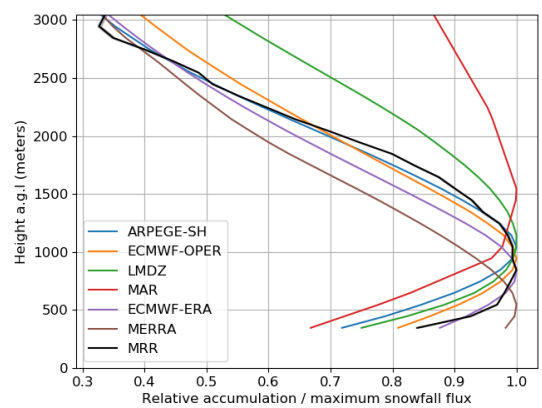

FIGURE 7 Vertical profiles of cumulative snowfall during the YOPP campaign normalized by the maximum snowfall flux in the column for model outputs and MRR observations

This article is protected by copyright. All rights reserved.

Accepted Article

1477870x, ja, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.4463 by Cochrane France, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

TABLE 4 Standard deviation of the vertical distribution of total snowfall during the YOPP campaign for model outputs in mm

	Standard deviation
ARPEGE-SH	9.67
ECMWF-OPER	11.67
LMDZ	24.69
MAR	49.41
ECMWF-ERA5	17.57
MERRA2	17.22

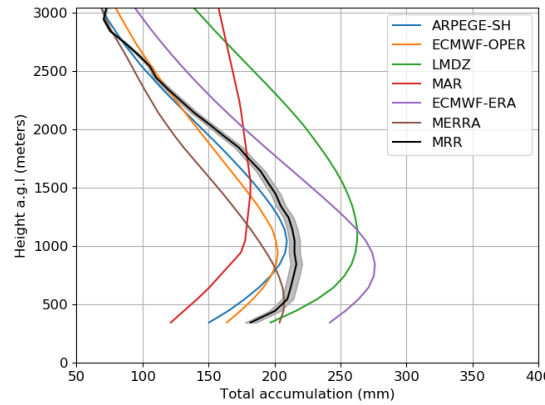

FIGURE 8 Vertical profiles of cumulative snowfall during the YOPP campaign for model outputs and MRR observations (with the centered uncertainty associated at each vertical level in grey color)

In particular, the profiles with relative snowfall values show that the sublimation of precipitation is too strong with respect to the maximum in the profile for all the models in the lower layers of the atmosphere. It should be noted that the quantitative comparison of precipitation modeled by the different models is done with the precipitation values obtained from the reflectivity measurements of the MRR. The uncertainty due to the reflectivity-snowfall conversion ranges from 5% of the measured snowfall quantity at the bottom (lowest available gate i.e at 300m a.g.l) to 2% at the top. All the models have a bias greater than 1 meaning a slight overestimation of occurence of days with snowfall. The ARPEGE and IFS models have the biases closest to 1 as well as high POD values which indicates a good representation of snowfall occurence. This interpretation is confirmed by the greatest values of HSS. The two reanalyses MERRA2 and ERA5 have the best POD which can be explained by a higher number of hits. However, they suffer from higher biases due to a higher number of excess predicted days with snowfall due to an overestimation of the precipitation occurences at DDU, concurring with the results of Jullien et al. [2020]. For the particular case of *potential near-surface sublimation days*, all the models detect a precipitation event in 7 out of 16 cases and the majority of them agree with the MRR in more than half of the cases. The scores for these days are excellent (see Table S.7) confirming that models are particularly performant to detect the precipitation in the vertical column. The vertical analysis shows a precipitation flux tending towards 0 at the surface for the MRR as well as for the models reproducing very well this typical profile of the sublimation phenomenon, which is also confirmed by the very low standard deviations (see Figure S.8 and Table S.6).

5 | DISCUSSION & CONCLUSION

Model-observation intercomparisons along the vertical are rare for precipitation : precipitation from models is generally evaluated at ground level, because surface observations are the primary source of data available as a reference for calibration or validation activities. Although accurate knowledge of average but also extremes surface precipitation is our main goal, it is also important to verify that these precipitations are the result of the right physical processes. The vertical profile offers the possibility to distinguish the altitudes where precipitation forms by condensation from those where it is sublimated, and thus to evaluate these two processes separately. Ideally a good model is able to represent it across the entire atmospheric column in terms of quantity and occurence. It is important for weather prediction

This article is protected by copyright. All rights reserved.

Accepted Article

1477870x, ja, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.4463 by Cochrane France, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

that a model manages well the timing and therefore indirectly the precipitation detection thresholds - because this is what defines whether precipitation occurs or not.

Despite the short time of available data, during the YOPP-SH SOP at DDU the comparison performed in this study between models illustrates the potential of vertical information for model evaluation. YOPP-SH offers a good opportunity to comparatively evaluate the performance of several meteorological and climate models and reanalyses in both weather prediction and nudged mode in the polar environment. Here models have been evaluated at the DDU YOPP-SH supersite during the YOPP austral summer special observing period, for their capabilities with respect to precipitation thanks to ground-based radar data that are now available.

Even though we cannot indubitably ensure that better performances are due to data assimilation in these products, weather prediction models and reanalyses that benefits from the assimilation of observations better represent the occurences of precipitation. The ERA5 and MERRA2 reanalyses faithfully reproduce the chronology of surface precipitation, allowing for example to characterize the water cycle in the region. However their positive bias must be taken into account to make a surface precipitation climatology. The weather prediction models IFS and ARPEGE are reliable in predicting accumulations of surface precipitation at DDU with less than 20% error on the accumulation measured during the campaign. We are fairly confident that the weather forecast models and the reanalyses reproduce the precipitation profiles well. The ARPEGE and IFS models have a correct vertical gradient, testifying to their good representation of hydrometeores growth mechanisms. Contrary to the reanalyses, the MAR model underestimate the total cumulative precipitation at the surface that can be explained by its less accurate representation of the snowfall profile or by its underestimation of days with intense surface snowfall amounts. The LMDZ model produces too much precipitation at altitude but this is compensated by strong sublimation towards the surface so that it has a good estimate of surface accumulation. Regarding the precipitation occurrences, the calculated scores indicate a better success of all the models on all the vertical levels compared to the surface only, especially in case of a near-surface sublimation event. This makes it possible to account for the differences in the vertical distribution of precipitation. This vertical aspect is particularly critical for DDU because of the evaporation near the surface but we can assume that this is also the case for all of Antarctica.

Even if the important information is what remains on the surface, in particular in the contribution to the calculation of the SMB, the vertical is crucial to examine the deficiencies of a model in terms of representation of the processes - for the Antarctic it is particularly important for the parameters of cold microphysics by which water vapor (advected from the ocean) condenses (forming clouds) and whose particles grow by different processes until they fall and become precipitation. Since we show here how important the information along the vertical is to properly evaluate a model in Antarctica, and that now we can obtain observations of precipitation profile from in-situ radar, we recommend to deploy instruments of the same type as the MRR as well as favoring the passage of satellites capable of profiling precipitation above the polar regions as CloudSat did and as EarthCare will soon do.

acknowledgements

The authors would like to dedicate this article to Chantal Claud, who unfortunately passed away while this work was being carried out, in gratitude for her support and her experienced advice. This paper is a contribution to the CALVA project supported by the French Polar Institute (IPEV project 1013) and to the YOPP, a flagship activity of the PPP, initiated by the WWRP of the WMO. This research was carried out in the framework and with support of the French space agency CNES/CNRS GDR EECLAT. CDA thanks FCT/MCTES for the financial support to CESAM (UIDP/50017/2020 and UIDB/50017/2020) through national funds and support to project ATLACE (CIRCNA/CAC/0273/2019) funded by FEDER, through COMPETE2020-Programa Operacional Competitividade e Internacionalização (POCI). We thank

This article is protected by copyright. All rights reserved.

Accepted Article

1477870x, ja, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.4463 by Cochrane France, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

the MAR team which make available the model outputs, as well agencies (F.R.S - FNRS, CÉCI, and the Walloon Region) that provided computational resources for MAR simulations. MLR is supported by a grant of the Ecole Polytechnique - IPP, Paris, France.

authors contribution

MLR carried out the data analysis and wrote the initial draft. CG is in charge of the program which carries out observations and supervises her thesis. EB carried out the ARPEGE simulations and contributed to the modeling aspects of the article. VW performed the LMDZ simulations with the help of EV and CA those with MAR. CDA provided the raw RADAR data processing algorithm and contributed to the analysis of the results. All coauthors contributed to the writing.

conflict of interest

The authors declare that they have no conflict of interest.

references

Agosta, C., Amory, C., Kittel, C., Orsi, A., Favier, V., Gallée, H., van den Broeke, M. R., Lenaerts, J. T. M., van Wessem, J. M., van de Berg, W. J. and Fettweis, X. (2019) Estimation of the antarctic surface mass balance using the regional climate model MAR (1979–2015) and identification of dominant processes. *The Cryosphere*, **13**, 281–296. URL: `https://tc.copernicus.org/articles/13/281/2019/`.

Amory, C., Kittel, C., Le Toumelin, L., Agosta, C., Delhasse, A., Favier, V. and Fettweis, X. (2021) Performance of MAR (v3.11) in simulating the drifting-snow climate and surface mass balance of Adélie Land, East Antarctica. *Geoscientific Model Development*, **14**, 3487–3510. URL: `https://gmd.copernicus.org/articles/14/3487/2021/`.

Bauer, P., Sandu, I., Magnusson, L., Mladek, R. and Fuentes, M. (2020) ECMWF global coupled atmosphere, ocean and sea-ice dataset for the year of polar prediction 2017–2020. *Scientific Data*, **7**.

Boucher, O., Servonnat, J., Albright, A. L., Aumont, O., Balkanski, Y., Bastrikov, V., Bekki, S., Bonnet, R., Bony, S., Bopp, L., Braconnot, P., Brockmann, P., Cadule, P., Caubel, A., Cheruy, F., Codron, F., Cozic, A., Cugnet, D., D'Andrea, F., Davini, P., de Lavergne, C., Denvil, S., Deshayes, J., Devilliers, M., Ducharne, A., Dufresne, J.-L., Dupont, E., Éthé, C., Fairhead, L., Falletti, L., Flavoni, S., Foujols, M.-A., Gardoll, S., Gastineau, G., Ghattas, J., Grandpeix, J.-Y., Guenet, B., Guez, Lionel, E., Guilyardi, E., Guimberteau, M., Hauglustaine, D., Hourdin, F., Idelkadi, A., Joussaume, S., Kageyama, M., Khodri, M., Krinner, G., Lebas, N., Levavasseur, G., Lévy, C., Li, L., Lott, F., Lurton, T., Luyssaert, S., Madec, G., Madeleine, J.-B., Maignan, F., Marchand, M., Marti, O., Mellul, L., Meurdesoif, Y., Mignot, J., Musat, I., Ottlé, C., Peylin, P., Planton, Y., Polcher, J., Rio, C., Rochetin, N., Rousset, C., Sepulchre, P., Sima, A., Swingedouw, D., Thiéblemont, R., Traore, A. K., Vancoppenolle, M., Vial, J., Vialard, J., Viovy, N. and Vuichard, N. (2020) Presentation and evaluation of the IPSL-CM6A-LR climate model. *Journal of Advances in Modeling Earth Systems*, **12**, e2019MS002010. URL: `https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019MS002010`. E2019MS002010 10.1029/2019MS002010.

Bromwich, D. H. and Parish, T. R. (1998) Meteorology of the antarctic. *American Meteorological Society*, 175–200.

Bromwich, D. H., Werner, K., Casati, B., Powers, J. G., Gorodetskaya, I. V., Massonnet, F., Vitale, V., Heinrich, V. J., Liggett, D., Arndt, S., Barja, B., Bazile, E., Carpentier, S., Carrasco, J. F., Choi, T., Choi, Y., Colwell, S. R., Cordero, R. R., Gervasi, M., Haiden, T., Hirasawa, N., Inoue, J., Jung, T., Kalesse, H., Kim, S.-J., Lazzara, M. A., Manning, K. W., Norris, K., Park, S.-J., Reid, P., Rigor, I., Rowe, P. M., Schmithusen, H., Seifert, P., Sun, Q., Uttal, T., Zannoni, M. and Zou, X. (2020) The Year of Polar Prediction in the Southern Hemisphere (YOPP-SH). *Bulletin of the American Meteorological Society*, **101**, E1653 – E1676. URL: `https://journals.ametsoc.org/view/journals/bams/101/10/bamsD190255.xml`.

This article is protected by copyright. All rights reserved.

Accepted Article

1477870x, ja, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.4463 by Cochrane France, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Durán-Alarcón, C., Boudevillain, B., Genthon, C., Grazioli, J., Souverijns, N., van Lipzig, N. P. M., Gorodetskaya, I. V. and Berne, A. (2019) The vertical structure of precipitation at two stations in East Antarctica derived from micro rain radars. *The Cryosphere*, **13**, 247–264. URL: https://www.the-cryosphere.net/13/247/2019/.

ECMWF (2017) Data archive of global meteorological fields from ECMWF integrated forecast system for the year of polar prediction. URL: https://apps.ecmwf.int/datasets/data/yopp.

ECMWF (2021) *IFS Documentation CY47R3 - Part IV Physical processes*. No. 4 in IFS Documentation. ECMWF. URL: https://www.ecmwf.int/node/20198.

Gallée, H. (1995) Simulation of the mesocyclonic activity in the ross sea, Antarctica. *Monthly Weather Review*, 2051–2069.

Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., Randles, C. A., Darmenov, A., Bosilovich, M. G., Reichle, R., Wargan, K., Coy, L., Cullather, R., Draper, C., Akella, S., Buchard, V., Conaty, A., da Silva, A. M., Gu, W., Kim, G.-K., Koster, R., Lucchesi, R., Merkova, D., Nielsen, J. E., Partyka, G., Pawson, S., Putman, W., Rienecker, M., Schubert, S. D., Sienkiewicz, M. and Zhao, B. (2017) The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). *Journal of Climate*, **30**, 5419–5454. URL: https://doi.org/10.1175/JCLI-D-16-0758.1.

Genthon, C., Berne, A., Grazioli, J., Durán Alarcón, C., Praz, C. and Boudevillain, B. (2018) Precipitation at Dumont d'Urville, Adélie Land, East Antarctica: the APRES3 field campaigns dataset. *Earth System Science Data*, **10**, 1605–1612. URL: https://www.earth-syst-sci-data.net/10/1605/2018/.

Genthon, C., Krinner, G. and Cosme, E. (2002) Free and laterally nudged antarctic climate of an atmospheric general circulation model. *Monthly Weather Review*, **130**, 1601 – 1616. URL: https://journals.ametsoc.org/view/journals/mwre/130/6/1520-0493_2002_130_1601_falnac_2.0.co_2.xml.

GMAO (2015) MERRA-2 tavg3_3d_mst_ne: 3d,3-hourly,time-averaged,model-level edge,assimilation,moist processes diagnostics v5.12.4. *Tech. rep.*, Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC). DOI: 10.5067/JRUZ3SJ3ZJ72 (accessed May 8, 2020).

Grazioli, J., Genthon, C., Boudevillain, B., Durán-Alarcón, C., Del Guasta, M., Madeleine, J.-B. and Berne, A. (2017a) Measurements of precipitation in Dumont d'Urville, Adélie land, East Antarctica. *The Cryosphere*, **11**, 1797–1811. URL: https://www.the-cryosphere.net/11/1797/2017/.

Grazioli, J., Madeleine, J.-B., Gallée, H., Forbes, R., Genthon, C., Krinner, G. and Berne, A. (2017b) Katabatic winds diminish precipitation contribution to the antarctic ice mass balance. *Proceedings of the National Academy of Sciences*, **114**, 10858–10863. URL: https://www.pnas.org/content/114/41/10858.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horanyi, A., Munoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R., Holm, E., Janiskova, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., De Rosnay, P., Rozum, I., Vamborg, F., Villaume, S. and Thepaut, J.-N. (2020) The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, **146**, 1999–2049. URL: https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.3803.

Hourdin, F., Rio, C., Grandpeix, J.-Y., Madeleine, J.-B., Cheruy, F., Rochetin, N., Jam, A., Musat, I., Idelkadi, A., Fairhead, L., Foujols, M.-A., Mellul, L., Traore, A.-K., Dufresne, J.-L., Boucher, O., Lefebvre, M.-P., Millour, E., Vignon, E., Jouhaud, J., Diallo, F. B., Lott, F., Gastineau, G., Caubel, A., Meurdesoif, Y. and Ghattas, J. (2020) LMDZ6A: The Atmospheric Component of the IPSL Climate Model With Improved and Better Tuned Physics. *Journal of Advances in Modeling Earth Systems*, **12**, e2019MS001892. URL: https://hal.archives-ouvertes.fr/hal-02903162.

Jullien, N., Vignon, E., Sprenger, M., Aemisegger, F. and Berne, A. (2020) Synoptic conditions and atmospheric moisture pathways associated with virga and precipitation over coastal Adélie Land in Antarctica. *The Cryosphere*, **14**, 1685–1702. URL: https://tc.copernicus.org/articles/14/1685/2020/.

This article is protected by copyright. All rights reserved.

Accepted Article

1477870x, ja, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.4463 by Cochrane France, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

Kessler, E. (1995) On the continuity and distribution of water substance in atmospheric circulations. *Atmospheric Research*, **38**, 109–145. URL: https://www.sciencedirect.com/science/article/pii/016980959400090Z.

Kittel, C., Amory, C., Agosta, C., Jourdain, N. C., Hofer, S., Delhasse, A., Doutreloup, S., Huot, P.-V., Lang, C., Fichefet, T. and Fettweis, X. (2021) Diverging future surface mass balance between the antarctic ice shelves and grounded ice sheet. *The Cryosphere*, **15**, 1215–1236. URL: https://tc.copernicus.org/articles/15/1215/2021/.

Krinner, G., Beaumet, J., Favier, V., Déqué, M. and Brutel-Vuilmet, C. (2019) Empirical run-time bias correction for antarctic regional climate projections with a stretched-grid AGCM. *Journal of Advances in Modeling Earth Systems*, **11**.

König-Langlo, G., King, J. C. and Pettré, P. (1998) Climatology of the three coastal antarctic stations Dumont d'Urville, Neumayer, and Halley. *Journal of Geophysical Research: Atmospheres*, **103**, 10935–10946. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/97JD00527.

Le Toumelin, L., Amory, C., Favier, V., Kittel, C., Hofer, S., Fettweis, X., Gallée, H. and Kayetha, V. (2021) Sensitivity of the surface energy budget to drifting snow as simulated by MAR in coastal Adelie land, Antarctica. *The Cryosphere*, **15**, 3595–3614. URL: https://tc.copernicus.org/articles/15/3595/2021/.

Lemonnier, F., Chemison, A., Krinner, G., Madeleine, J., Claud, C. and Genthon, C. (2021) Evaluation of coastal antarctic precipitation in LMDZ6 global atmospheric model using ground-based radar observations. *Arctic and Antarctic Research*, **67**, 147–164.

Lemonnier, F., Madeleine, J.-B., Claud, C., Palerme, C., Genthon, C., L'Ecuyer, T. and Wood, N. B. (2020) CloudSat-inferred vertical structure of snowfall over the antarctic continent. *Journal of Geophysical Research: Atmospheres*, **125**, e2019JD031399. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019JD031399. E2019JD031399 10.1029/2019JD031399.

Maahn, M. and Kollias, P. (2012) Improved micro rain radar snow measurements using doppler spectra post-processing. *Atmospheric Measurement Techniques*, **5**, 2661–2673. URL: https://amt.copernicus.org/articles/5/2661/2012/.

Madeleine, J.-B., Hourdin, F., Grandpeix, J.-Y., Rio, C., Dufresne, J.-L., Vignon, E., Boucher, O., Konsta, D., Cheruy, F., Musat, I., Idelkadi, A., Fairhead, L., Millour, E., Lefebvre, M.-P., Mellul, L., Rochetin, N., Lemonnier, F., Touzé-Peiffer, L. and Bonazzola, M. (2020) Improved representation of clouds in the atmospheric component LMDZ6A of the IPSL-CM6A earth system model. *Journal of Advances in Modeling Earth Systems*, **12**, e2020MS002046. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2020MS002046. E2020MS002046 10.1029/2020MS002046.

Pailleux, J., Geleyn, J.-F., Hamrud, M., Courtier, P., Thépaut, J.-N., Rabier, F., Andersson, E., Burridge, D., Simmons, A., Salmond, D., El Khatib, R. and Fischer, C. (2014) Twenty-five years of IFS/ARPEGE. 22–30. URL: https://www.ecmwf.int/node/17335.

Palerme, C., Claud, C., Wood, N. B., L'Ecuyer, T. and Genthon, C. (2019) How does ground clutter affect CloudSat snowfall retrievals over ice sheets? *IEEE Geoscience and Remote Sensing Letters*, **16**, 342–346.

Palerme, C., Genthon, C., Claud, C., Kay, J. E., Wood, N. B. and L'Ecuyer, T. (2017) Evaluation of current and projected antarctic precipitation in CMIP5 models. *Climate Dynamics*, **48**, 225–239. URL: https://doi.org/10.1007/s00382-016-3071-1.

Palerme, C., Kay, J. E., Genthon, C., L'Ecuyer, T., Wood, N. B. and Claud, C. (2014) How much snow falls on the antarctic ice sheet ? *The Cryosphere*, **8**, 1577–1587. URL: https://www.the-cryosphere.net/8/1577/2014/.

Ricaud, P., Del Guasta, M., Bazile, E., Azouz, N., Lupi, A., Durand, P., Attié, J.-L., Veron, D., Guidard, V. and Grigioni, P. (2020) Supercooled liquid water cloud observed, analysed, and modelled at the top of the planetary boundary layer above Dome-C, antarctica. *Atmospheric Chemistry and Physics*, **20**, 4167–4191. URL: https://acp.copernicus.org/articles/20/4167/2020/.

Roussel, M.-L., Lemonnier, F., Genthon, C. and Krinner, G. (2020) Brief communication: Evaluating antarctic precipitation in ERA5 and CMIP6 against CloudSat observations. *The Cryosphere*, **14**, 2715–2727. URL: https://tc.copernicus.org/articles/14/2715/2020/.

Accepted Article

This article is protected by copyright. All rights reserved.

1477870x, ja, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.4463 by Cochrane France, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License

USGS (2022) Antarctica overview map. URL: https://lima.usgs.gov/documents/LIMA_overview_map.pdf. Accessed February, 27 2022.

Vignon, E., Besic, N., Jullien, N., Gehring, J. and Berne, A. (2019a) Microphysics of snowfall over coastal East Antarctica simulated by polar WRF and observed by radar. *Journal of Geophysical Research: Atmospheres*, **124**.

Vignon, E., Hourdin, F., Genthon, C., Gallée, H., Bazile, E., Lefebvre, M.-P., Madeleine, J.-B. and Van de Wiel, B. J. H. (2017) Antarctic boundary layer parametrization in a general circulation model: 1-d simulations facing summer observations at dome c. *Journal of Geophysical Research: Atmospheres*, **122**, 6818–6843. URL: https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1002/2017JD026802.

Vignon, E., Hourdin, F., Genthon, C., Van de Wiel, B. J. H., Gallée, H., Madeleine, J.-B. and Beaumet, J. (2018) Modeling the Dynamics of the Atmospheric Boundary Layer Over the Antarctic Plateau With a General Circulation Model. *Journal of Advances in Modeling Earth Systems*, **10**, 98–125. URL: https://hal.sorbonne-universite.fr/hal-01727467.

Vignon, E., Roussel, M.-L., Gorodetskaya, I. V., Genthon, C. and Berne, A. (2021) Present and future of rainfall in Antarctica. *Geophysical Research Letters*, **48**, e2020GL092281.

Vignon, E., Traullé, O. and Berne, A. (2019b) On the fine vertical structure of the low troposphere over the coastal margins of East Antarctica. *Atmospheric Chemistry and Physics*, **19**, 4659–4683. URL: https://acp.copernicus.org/articles/19/4659/2019/.

Accepted Article

This article is protected by copyright. All rights reserved.

1477870x, ja, Downloaded from https://rmets.onlinelibrary.wiley.com/doi/10.1002/qj.4463 by Cochrane France, Wiley Online Library on [03/05/2023]. See the Terms and Conditions (https://onlinelibrary.wiley.com/terms-and-conditions) on Wiley Online Library for rules of use; OA articles are governed by the applicable Creative Commons License