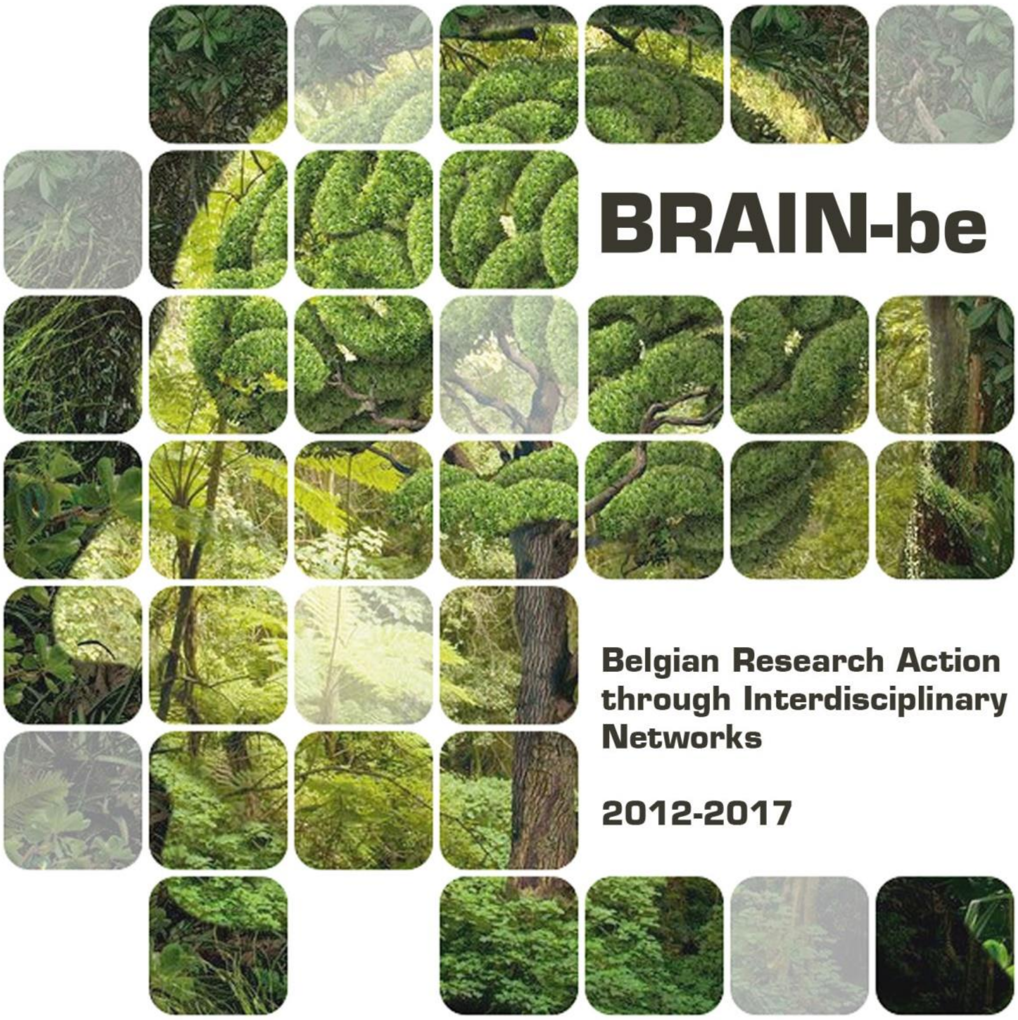

Mass2Ant

East Antarctic surface mass balance in the Anthropocene: observations and multiscale modelling

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NETWORK PROJECT

Mass2Ant

East Antarctic surface mass balance in the Anthropocene: observations and multiscale modelling

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FINAL REPORT

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Foreword

This report is the final one of the project MASS2ANT- East Antarctic surface mass balance in the Anthropocene: observations and multiscale modelling, funded in the framework of the BRAIN program of the Belgian Science Policy Office. It follows the requirements and the canvas of the Belgian Science Policy Office. It is not intended to present all the scientific results obtained by the project in a comprehensive way and we strongly recommend the readers to refer directly to the scientific papers obtained as an outcome of the project and listed in section 6 to have more complete information about those scientific results.

ABSTRACT.

Context

Climate is changing rapidly at high southern latitudes. This has large consequences in the region but also globally as Antarctica and the Southern Ocean play a major role in the Earth's heat and carbon budget as well as in sea level changes. However, while some changes observed at high southern latitudes can unambiguously be related to human activities, the origin of other changes is less clear and this lack of understanding limits our ability to perform accurate projections of future changes.

Objectives

The objective of Mass2Ant was to reduce our uncertainty on the drivers of the changes in the surface mass balance in Antarctica and, from this, on sea level rise. The specific focus was on the Princess Ragnhild Coast, East Antarctica, because of its complex topography and dynamics, taking advantage of the location of the Princess Elisabeth Station in the region. Large local to regional changes are observed there and we intended to determine how to connect them to the large-scale variations and thus have an integrated view of the contribution of the region to the mass balance of the Antarctic ice sheet.

Conclusions

Changes in temperature and in atmospheric circulation have a strong effect on snow accumulation in Antarctica. In West Antarctica, the impact of the variability of the large-scale atmospheric circulation is major at multiannual timescales while the rise in the moisture content of the atmosphere with increasing temperature will leads to higher accumulation in the future, in particular during storms, in most of Antarctica. The situation is more uncertain at the regional scale in coastal East Antarctica because of the large number of processes at play. The methodology developed in the project, combining different types of observations and models of different resolutions allows a quantification of the uncertainties associated with regional processes and a better understanding of those processes that is a necessary step for improved projections.

Keywords

Antarctica, sea-level, ice core, radar, snow accumulation, atmospheric circulation, surface mass balance, remote sensing.

1. INTRODUCTION

Polar regions have been the scene of some of the most striking climate changes observed in recent decades. In the Arctic, the rise in surface air temperature has outpaced the global mean by at least a factor of three and summer sea ice extent has decreased by more than 10% per decade since the beginning of the satellite era in 1979 (Serreze et al., 2019). In the southern hemisphere, after a period characterized by a slight increasing trend, the Antarctic sea ice extent has plummeted, reaching its absolute minimum in February 2023 (NSIDC 2023). The Antarctic ice shelves that surround Antarctica and contribute to the stability of the ice sheet have lost mass at an increasing rate over the past decades (Rignot et al. 2019). Even the South Pole has reached some record high temperatures recently (Clem et al. 2020).

Those regional changes in polar regions have a global impact. Among many examples, one of the most critical points is that any change in the Antarctic ice sheet mass balance directly affects global sea level. Furthermore, the Southern Ocean is estimated to be responsible for 67-98% of the global ocean heat uptake over 2006-2013 (Roemmich et al. 2015). It also plays a dominant role in the uptake of carbon released by human activities, mitigating thus changes in temperature and atmospheric CO_2 concentration.

However, the high latitude dynamics of the southern hemisphere are still poorly understood. The spatial and temporal coverage of observations is generally not sufficient to describe precisely the processes at play. Antarctica and the Southern Ocean are also regions where start-of-the-art general circulation models (GCMs) display large biases. This introduces large uncertainty in future projections of climate change. For example, a few years before the beginning of the Mass2Ant project, the Fifth Assessment Report from the Intergovernmental Panel on Climate Change (IPCC AR5) underlined the *low confidence* in projections of Antarctic sea ice extent (Collins et al. 2013) and on the Antarctic ice sheet contribution to future sea level changes (Church et al. 2013). This motivated the launch of a project focused on the high latitudes of the Southern Hemisphere and more specifically on the mass balance of Antarctica.

2. STATE OF THE ART AND OBJECTIVES

The mass balance (MB) of the grounded Antarctic ice sheet can be defined as the difference between surface mass balance (SMB, i.e. the difference between incoming and outgoing mass at the ice sheet surface due to precipitation, melting, sublimation and wind transport), and the flux of ice across the grounding line (solid ice discharge D), i.e. MB = SMB–D. Although uncertainties are present in both SMB and D, the SMB is particularly poorly evaluated, partly because it is characterized by strong spatial and temporal variations in snowfall and snow redistribution (Lenaerts et al. 2019). The amount of snowfall, which is the largest driver of Antarctic SMB, highly depends on the local topography, resulting in strong spatial SMB variations within kilometers (e.g. Lenaerts et al., 2014; Agosta et al., 2019). Moreover, wind plays an important role in redistributing this snow over short and large distances depending on the local wind conditions (Palm et al., 2017). These local conditions are in turn partly controlled by large scale phenomena (e.g. synoptic-scale atmospheric systems, sea ice) that exhibit strong multi-decadal variations. Therefore, if one wants to understand Antarctic SMB, it is essential to assess its spatial and temporal variability. Multiple SMB time series that cover several decades or centuries are thus required to estimate the dominant patterns and the magnitude of natural fluctuations, which is a necessary step to increase the robustness of Antarctic projections.

It is impossible in the framework of one single project to address, for the whole continent, all the challenges imposed by this large spatial and temporal SMB variability. We have thus decided to focus on East Antarctica, more specifically on the Princess Ragnhild Coast (PRC) (Figure 1). This is based on several arguments. First, data are sparse in East Antarctica and additional information is strongly needed. Second, no clear conclusion on the recent evolution of the surface mass balance in the region can be derived from existing information as some recent ice cores indicate a significant SMB increase since the 1950's while others have a stable or decreasing trend over the same period (Philippe et al., 2016, Thomas et al. 2017). An increasing SMB trend would be consistent with the expected snowfall increases as a result of higher temperatures related to atmospheric warming and might indicate an influence of global climate change. However, before reaching any conclusion, the changes in the region should be better documented. Third, the region is close to the Princess Elisabeth Station which provides the adequate logistics for the required field campaigns.

The main goals of the project were:

1. to estimate the evolution of the surface mass balance in the Princess Ragnhild Coast (PRC) region during the last 300 years in order to put the recent changes in a longer perspective;
2. to compare the changes in the Princess Ragnhild Coast region to other areas in Antarctica to determine the similarities and differences in their evolution;
3. to identify the processes at the origin of the changes and to determine if Earth System Models are able to reproduce them adequately.

This would ultimately reduce our uncertainties in the projections of the future changes in SMB and thus of sea level rise.

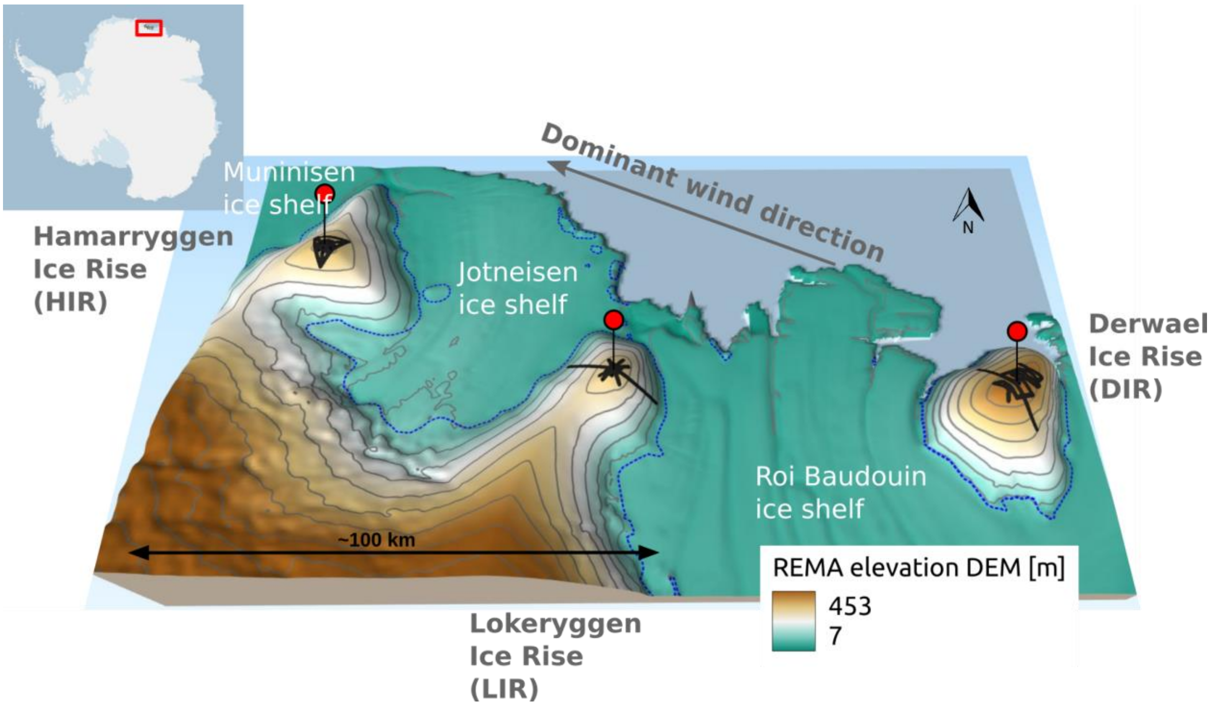

Figure 1: The main region of interest, with the location of the three ice rises with the ice cores and radar surveys highlighted (Figure from *Cavitte et al., 2022*).

3. METHODOLOGY

We have combined different approaches that build on new observations, existing databases and model results. Firstly, new ice cores have been collected and compared to other cores in East Antarctica to capture the spatial and temporal SMB variability. Secondly, we have combined meteorological observations, statistical downscaling, high resolution regional and global modelling to understand and assess this variability at the local and regional scale. The potential links between regional and large-scale processes have been analyzed by combining proxy data from the ice cores (e.g. water stable isotopes for precipitation source and links to temperature, seasonal and longer-term variability of sea ice extent/open water proxies), radar-derived SMB, model results and simulations with data assimilation. Finally, the origin of future changes in snow accumulation have been diagnosed.

The different methodologies applied are briefly described below while the main results obtained are discussed in the next section. Papers obtained as a direct outcome of the project are given in italics and the references are provided in section 6 while other references are listed at the end of section 4. We define the different spatial scales in relation to the scale of variability as follows: below 20 km (local scale), between 20 and 200 km (regional scale), and above 200 km (large scale).

Ice coring, climate proxies, snow observations and radar surveys

To document the spatial and temporal SMB variability at PRC, two new ice cores were drilled (208 and 262-meter-long), one at the summit of the Lokeryggen ice rise (LIR), named FK17, and one at the summit of the next ice rise to the west, Hammarryggen ice rise (HIR), named TIR18 (Figure 1). A portable Eclipse drilling system (available at Princess Elisabeth Base) has been used for that purpose.

A suite of physico-chemical measurements were performed on the top 120 m of the two ice cores at high-resolution (typically 5 cm) in order to reconstruct the SMB history (dating and annual layer thickness) at the location of the ice cores: high-precision ice density, $\delta^{18}O$, δD, ECM (DC electrical conductivity), major ions of interest for reconstruction of the seasonal cycle and therefore annual snow/firn/ice thickness (Na, $nssSO_4$, MSA, Na/SO_4, NO_3,...). Some of these species also are potential sea ice extent proxies or could allow to identify changes in air mass trajectories.

Complementary detailed ApRES (phase sensitive radio echo sounder), GPR (ground penetrating radar) and surface strain network data were collected in the vicinity of the ice rises' summits to support the choice for the location of the drilling site, assess the local variability in SMB and obtain the vertical strain rates necessary for the correction of the annual layer thickness for vertical deformation (Philippe et al., 2016 and new developments from repeated ApRES profiles).

In the perspective of discussing the drivers for the regional surface mass balance variability, water stable isotopes and some of the major ions (MSA, $nssSO_4$, Na, SO_4/Na…) known to indicate past sea ice extent, were compared to and calibrated versus satellite records of sea ice extent in the recent times (post-1970).

As an example, and as previous campaigns were described in our previous reports, we give some more details on the 2021-2022 fieldwork season (Figure 2). During that field season, we collected further GPR data over the Lokeryggen ice rise, to (1) extend the existing 2017-2018 radar survey closer to the grounding line and (2) collect a dense grid in the vicinity of the FK17 ice core collected in 2017. For the first goal, we collected a 26 km-long GPR transect going from east to west over the ice rise with cross overs with the previous survey, to examine the spatial variations in SMB across the entire ice rise all the way to both grounding lines. For the second goal, we collected a dense 200 x 200 m GPR gridded survey centered on the FK17 ice core, and a second one, rotated by 45 degrees from the first grid, so as to obtain a high resolution GPR-derived SMB record. In addition, a shallow 11m ice core was drilled within these two grids to ensure that the GPR isochrones younger than 2017 can be dated. The GPR were processed in the field and the two radar grids have since been traced as part of a Bachelor student project. The11 m ice core was recently measured using a Continuous Flow Analysis set up (CFA) at the British Antarctic Survey (BAS) ice core lab, through a collaboration with Elisabeth Thomas and her team. The processing of the data is underway and the age-depth scale will then be used to date the radar layering.

During this most recent field season, we also collected four additional ice cores: two either side of the ice rise crest, so as to investigate whether the kilometre-scale variation in snow accumulation at the surface described in *Kausch et al (2020)* resulted in chemical variations in the recovered archives. Using the traced IRHs from the *Kausch et al. (2020),* and those traced in the *Cavitte et al. (2022),* we chose two locations with a relatively low accumulation rate and two locations with a relatively high accumulation. All four ice cores were drilled to a depth of 8 m, which was judged to be sufficient to sample the past 10 years. These are highlighted as orange pentagons on Figure 2 (left). These ice cores have recently been measured using a CFA set up coupled to a suite of instruments and detectors at the British Antarctic Survey ice core lab, concurrently with the 11 m main core. The processed data will soon be available for further analysis.

Another goal of the fieldwork was to collect further ApRES data at the FK17 ice core site so that a full vertical velocity profile could be obtained at the ice divide, in collaboration with Carlos Martin at BAS. We also collected a set of 20 pRES measurements along the east-west radar transect (10 east and 10 west) in order to characterize whether there could be a Raymond effect due to the ice divide. The analysis is still underway.

Taking advantage of the trip to and from the station to the Lokeryggen ice rise, we sampled snow along the traverse every 5 km to document the spatial variability of the snow chemistry on the way out, and resampled on the way back every 10 km to investigate the effects of storms on the chemistry over the 3 weeks that we were in the field. One day was also spent sampling snow across the Roi Baudouin Ice Shelf, going from the coast to the grounding line in order to examine the snow sea salt and impurity concentration variations with distance from the ocean. The samples will be analysed this year at the ULB lab.

Finally, laser-scans (TLS) of the snow surface were taken at the 5 ice core locations on the ice rise to study the spatial variability of the snow surface roughness. Each location was scanned twice to study the temporal evolution, in particular pre and post snow storms. The data is being analysed at TUD.

We refer the readers to the 2021-2022 annual report for more details on the 2021-2022 field season.

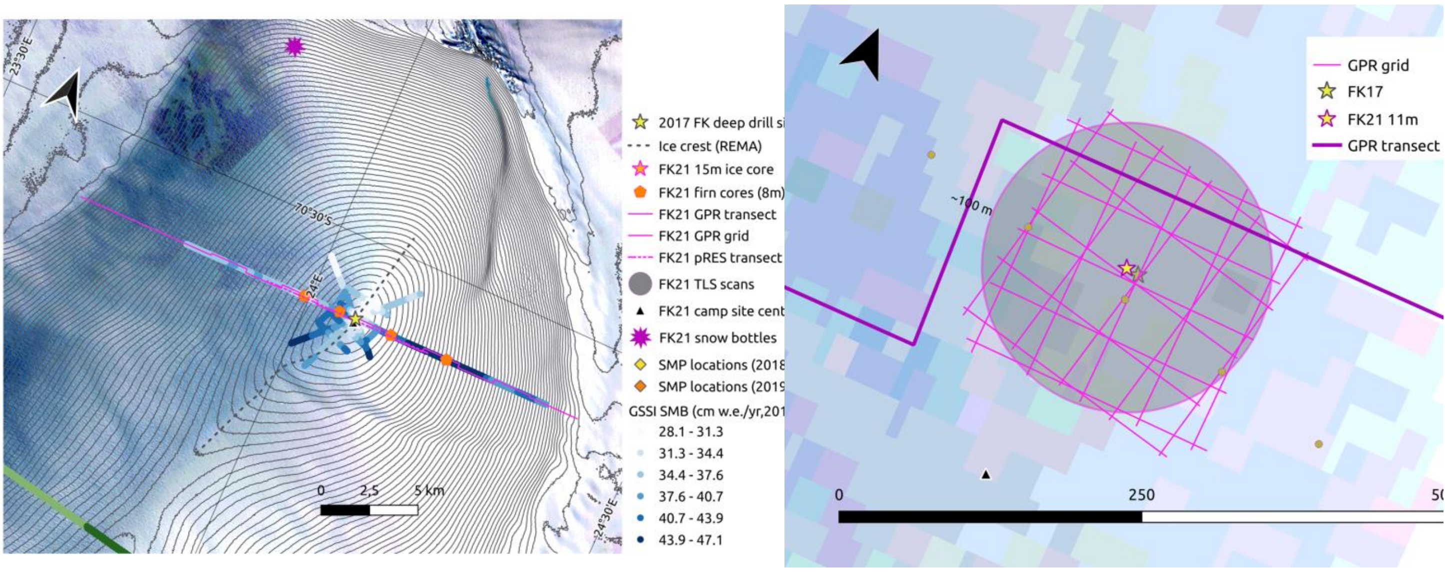

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Figure 2. (Left) east-west radar transect collected over the Lokeryggen ice rise to connect the two grounding lines. (Right) the two rotated dense GPR grids, with the 11 m ice core highlighted by a yellow star.

Analyses of GPR data

In order to analyze the differences between the local records of SMB given by ice core data and regional changes, we used the in-situ data over the three ice rises (Hammarryggen, Lokeryggen and Derwael) along the Princess Ragnhild Coast, collected as part of Mass2Ant. The SMB measured in ice cores is susceptible to local redistribution of the snow at the surface, due to wind-topography interactions. Detailed GPR surveys were collected between 2012 and 2018 over each ice rise and connected to the ice core sites. We therefore traced as many internal reflectors as possible in each survey, that we dated using the ice core age-depth-density data (Philippe et al., 2016; *Wauthy et al, in review*). With its ability to provide SMB data at a highly detailed spatial resolution (measured in meters along a radar transect and kilometers across track, depending on the survey design), GPR has the potential to bridge the spatial divide between local ice core records and models which have a spatial resolution on the order of kilometers or more.

We calculated SMB for every radar data point in each survey, to obtain a 3D view of the SMB field that we could then compare to the ice core point measurements of SMB (*Cavitte et al. 2022*). Because a depth-density profile is needed to convert the snow/ice thickness accumulated into a mass, and because density varies a lot across space, we calculated the best-fit depth-density profile at every radar data point by fitting the GPR isochrone depths and ages (in collaboration with Brooke Medley at the NASA Goddard Space Flight Center). We then calculated the mean SMB and the temporal variability of the SMB derived from the GPR data, over various surface areas centered on the ice core sites. We were able to compare the radar-derived spatial mean values to those measured from the ice core, at each of the three ice rises. This allowed us to assess the spatial representativeness of each ice core (see section 4).

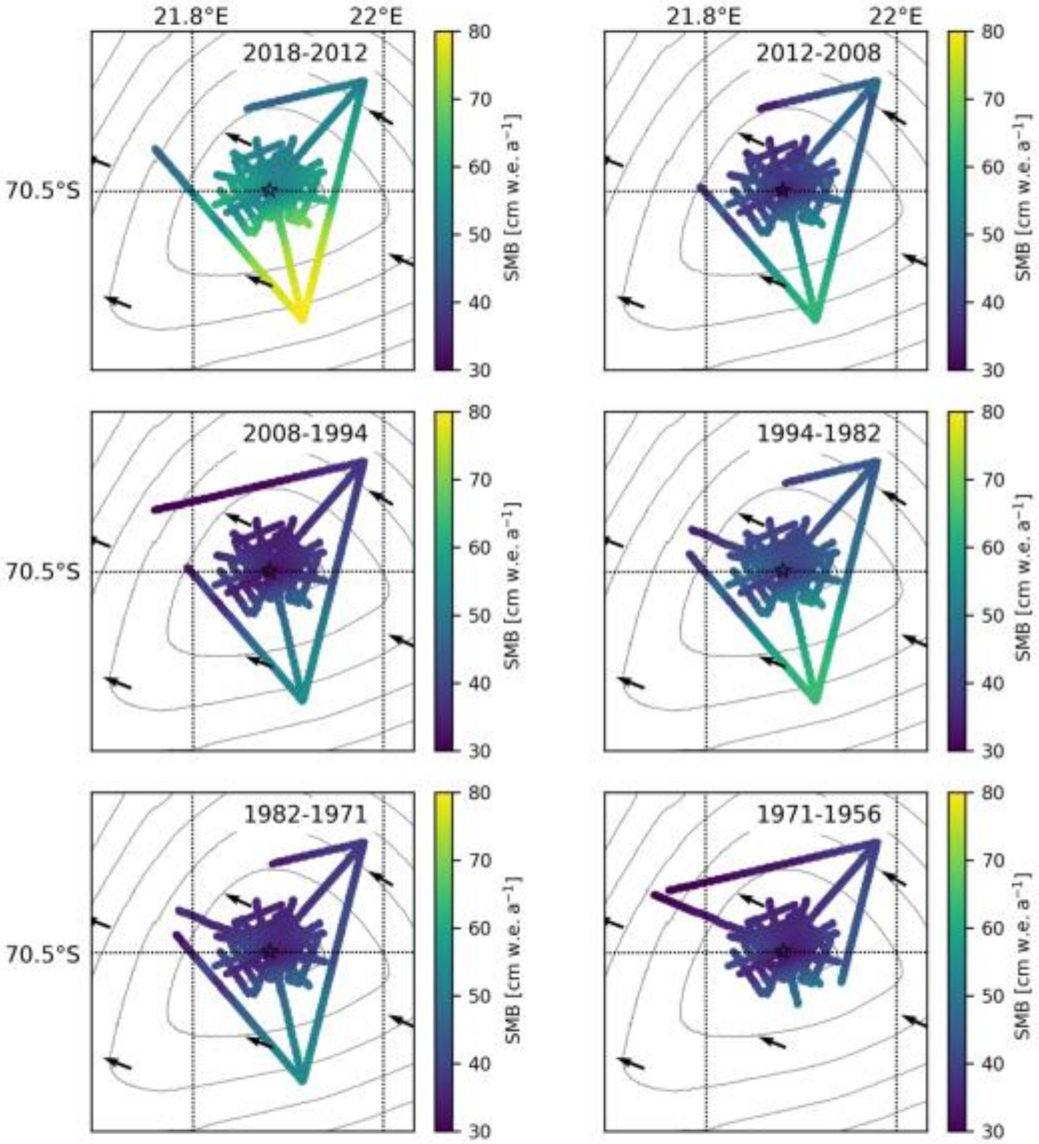

Figure 3. SMB calculated for each time period represented between two successive GPR isochrones. The spatial patterns are a result of the interactions between the surface topography and the dominant wind direction. *Figure from Cavitte et al. (2022)*.

Snow observations

We have collected and analyzed Snow Micro Pen (SMP) measurements, which were taken across the ice rises. These measurements provide high vertical resolution information regarding snow density and microstructure in roughly the top meter of the snowpack. We derived the 2D density, grain size and exponential correlation length distribution across the ice rises in the first meter of the snowpack. We used these measurements together with the data from the automatic weather stations (AWS, see below) and the radiative transfer model SMRT (Picard et. al, 2018) to model the synthetic radar backscatter of the snowpack and compare it to the observed Sentinel 1 backscatter in order to understand what the connections are between radar backscatter and snow parameters.

Furthermore, *Keenan et al. (2021)* describe and evaluate modifications to the land surface snow model, SNOWPACK. In this study, we demonstrate that a new drifting snow scheme improves SNOWPACK's representation of near-surface snow and firn density. In addition to being useful for interpretation of previously collected SMP measurements, these SNOWPACK model modifications will allow for improved satellite altimetry-based ice sheet mass balance assessments by improving the efficacy of volume to mass conversions which rely on model estimates of snow and firn density.

We also took laser-scans (TLS) of the snow surface to measure surface roughness at different locations along the Lokeryggen ice rise and Hamarryggen ice rise. Each location was scanned twice, to study temporal changes of the surface (Figure 4). Both Root Mean Squared (RMS) height and the autocorrelation length are calculated from the TLS point cloud to capture the vertical and horizontal component of surface roughness. While initial results confirm a rough to smooth surface state change from before to after a storm, as was observed in the field, the processing of the laser point clouds requires more careful testing. Processing of the data is computationally expensive and currently small spatial subsets are analysed to determine the optimal processing approach. A 2D Power Spectrum Density is calculated for such a subset, which provides information about different spatial scales of roughness. In further steps the processing will be upscaled to determine a representative surface roughness value for the scanned field.

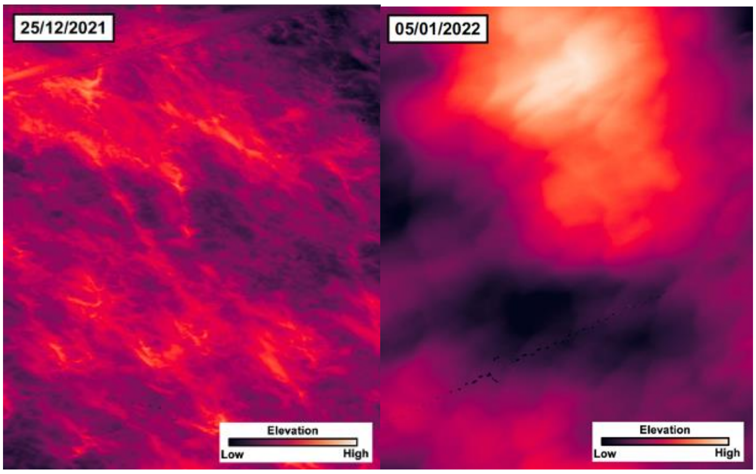

Figure 4: snow surface elevation of a subset from TLS data at location FK before (left) and after (right) a storm.

Meteorological observations and high-resolution modelling

To understand and assess the SMB variability at the local and regional scale, we combined meteorological observations with GPR observations across the ice rises, high resolution modelling in SnowModel and RACMO, and satellite data for SMB extrapolation.

We combined the SMB reconstructed from the GPR data with the regional SMB distribution modelled by RACMO2 and the local SMB distribution over the ice rise modelled by SnowModel to quantify the magnitude of the local and regional effects on the SMB, what drives them and how well they are captured within the models. The goal of this was twofold: (i) to reveal mechanisms that control the SMB on and around an ice rise and (ii) to better understand how SMB rates recovered from ice cores drilled into ice rises relate to the surrounding ice shelf.

The installation of two weather stations on both the windward and leeward side of the Lokeryggen ice rise in combination with GPR transects across both ice rises allowed determining the effect of local-regional scale phenomena (e.g. wind shadowing) on the surface mass balance. On the other hand, SnowModel (Liston and Elder, 2006; Gascoin et. al., 2013), a spatially-distributed snow model adapted for the study of snow redistribution by wind, allowed to quantify the effect of snow redistribution on the local scale variability in SMB. SnowModel allows to simulate the evolution of snow depth and SMB at fine scale (i.e. at 90 m spatial resolution corresponding to the TanDEM-X 90 m DEM), thereby specifically incorporating the effect of wind on SMB. The model was forced by meteorological data from RACMO2 over the Lokeryggen ice rise, and couples four submodels at the forcing data time step (typically 1 h), effectively resolving the mass balance of the snowpack at each time step. Moreover, the high resolution RACMO2 modelling allowed extrapolating the importance of the local-regional scale phenomena over larger areas and back in time. As such, it provided insights in the representativeness of the new local ice cores at the regional scale and in the regional drivers for SMB variability. This is described in detail in *Kausch et al. (2020)* where we assess the connection between snowfall variability and wind erosion to provide a better understanding of how ice rises impact SMB variability, how well this is captured in the regional atmospheric climate model RACMO2 and the implications of this SMB variability for ice rises as an ice core drilling site.

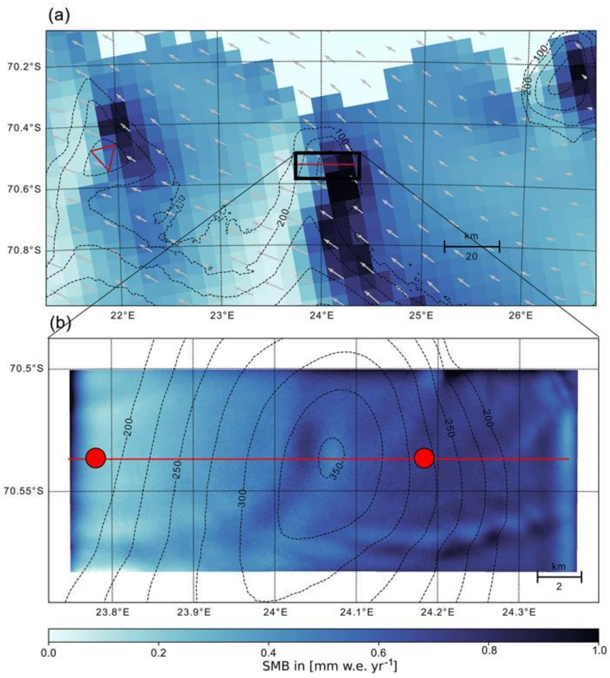

Figure 5. SMB modelled by RACMO2 **(a)** and SnowModel **(b)** for the time period of 2011 to 2017 with topography contour lines based on the 90 m TanDEM-X digital elevation model (DLR 2018) and RACMO2 wind vectors (grey arrows). The simulated area by SnowModel is marked in **(a)** with a black box. The red lines show the location of the recorded GPR tracks. Figure from *Kausch et al. (2020).*

Finally, in *Kausch et. al. (in prep.),* we developed a remote sensing approach to relate Sentinel-1 cross-polarization ratio σ_{hh}/σ_{hv} to SMB that allows us to extrapolate SMB across larger scales. In this framework, we aimed to establish an empirical relationship using field measurements from the ice rises in PRC sampled within this project. More specifically, the SMB of the ice rises was reconstructed using ground penetrating radar data and compared to the incidence angle corrected, four-year average of the Sentinel-1 cross-polarization ratio σ_{hh}/σ_{hv}.

To make the link between the continental scale controls on Antarctic SMB and the local scale controls on SMB over the Princess Ragnhild Coastal region, we examined the Antarctic SMB at the regional scale (Figure 6). For this, we examined the relationship between SMB and surface air temperatures (SAT) (*Cavitte et al., 2020*) following from *Dalaiden et al (2020a)* but at the model grid scale resolution. For this, we used 4 isotope-enabled GCMs and a regional climate model (RACMO) using both its 27 km and 5.5 km grid scale resolutions. In each case, we examined the strength of the correlation between the modeled SMB and the modeled SAT per grid cell, as well as that between SMB and $\delta^{18}O$ for the iGCMs. We then compared these model results to similar correlations between SMB-SAT and SMB- $\delta^{18}O$, this time using in-situ observations based on ice core compilations of $\delta^{18}O$ and SMB (Thomas et al., 2017; Stenni et al., 2017), and weather station measurements of SAT (Nicolas and Bromwich, 2014). This study allowed us to corroborate the results obtained at the continental scale by *Dalaiden et al. (2020a)*, and to start highlighting the areas of the Antarctic continent where the SAT-SMB relationship is more complex.

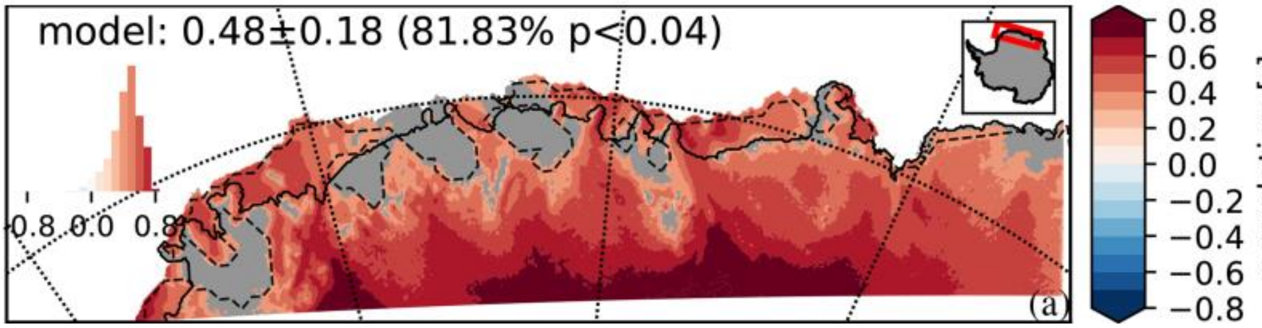

Figure 6. Annual correlation between SMB and SAT for the RACMO model at the (a) 5.5 km spatial resolution along the Dronning Maud Land coast. In gray are the statistically insignificant areas. Adapted from *Cavitte et al. (2020).*

Statistical downscaling

Statistical downscaling has been used to understand and assess the SMB variability at local scale and determine its link with large and regional-scale processes. It has the advantage over the dynamical downscaling given by high resolution modelling that it is faster and more flexible since it only requires to build a statistical relation between the variables at different spatial scales, in particular here between RCMs, global models and the local scale SMB observations. The statistical downscaling methodology applied here is based on the construction of an analogs database and has been applied on an ensemble of 10 historical climate runs from

CMIP6/CESM2 to obtain the spatio-temporal distribution of daily snowfall over Dronning Maud Land (DML) for the period 1850 to 2014 (*Ghilain et al, 2022*). The meteorological fields from two reanalyses (ERA-Interim and ERA5) have been used for the construction of the analog database, based on the association of the principal components from four large-scale atmospheric fields with the local precipitation from the Regional Climate Model RACMO2.3. The results have been compared to yearly snow accumulations estimated from ice core records (from the project, but also from internationally compiled databases (Thomas et al, 2017) and other available spatial reconstructions (Medley and Thomas, 2019; Rotschky et al, 2007). In addition, the impact of the choices in the methods and data used has been quantified, providing an estimation of individual uncertainties. The resulting database (daily and yearly snowfall and the necessary data for weather patterns analysis and reconstruction of the database) have been published on a free-access storage with permanent identifier (http://doi.org:10.5281/zenodo.4287517).

In practice, the daily snowfall has been derived at a 5.5 km resolution over DML in a 3 steps method: 1. the building of an analogs database compiling the daily associations between snowfall from the RACMO2.3 RCM and weather patterns (empirical orthogonal functions - EOFs- and principal components weights -PCs- of four different atmospheric fields) from reanalyses (ERA-Interim, ERA5) over a recent period (30 years); 2. calculate the bias correction of 10 members from climate historical runs CESM2 over 1850 to 2014; 3. obtain an estimation of the downscaled daily snowfall from the corrected weather patterns of CESM2 (step 2) through the search in the analogs database of step 1.

The results have been stored in a database (Figure 7): 1. the time series of daily snowfall for each of the 5.5 km grid cells of the domain for each CESM2 member, and for each reanalysis used for step 1; 2. the yearly accumulation maps at a 5.5 km resolution for each CESM2 member (and for each reanalysis used for step 1); and 3. the EOFs and PCs from both reanalyses and the emulated PCs from CESM2, allowing the analysis of weather patterns occurrence and possible re-computation of the database with other hypotheses.

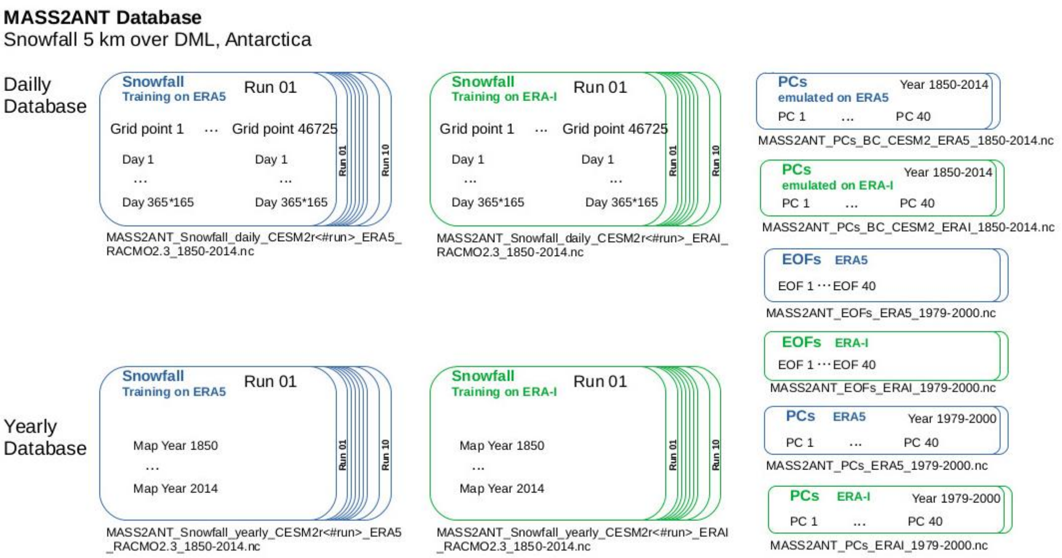

Figure 7: Files included in the MASS2ANT downscaling database.

The comparison of the downscaled daily (and annual) snowfall accumulations with accumulation estimated from ice core records shows a good overall match and thus a large bias reduction compared to the use of CESM2 without downscaling (Figure 8). As a result of the use of the RCM in building the analogs database (step 1), the spatial patterns from the RACMO2.3 are translated in the new reconstruction. Compared to other constructions (e.g. Figure 9), the new resolution achieved is of interest in the interpretation of ice core records and in view of more detailed analysis of the spatial redistribution of the surface mass balance over DML.

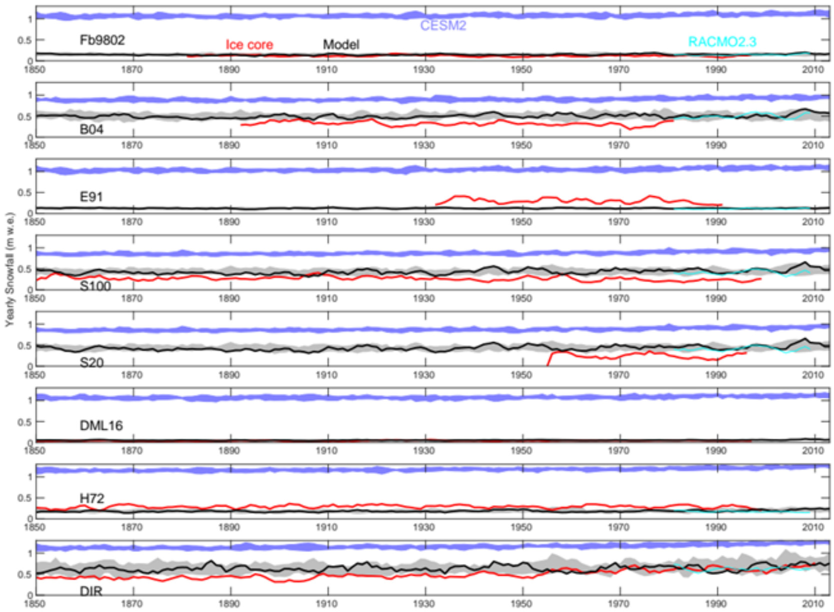

Figure 8. The time series of yearly accumulated snowfall extracted from the database (CESM2 member 1, training with ERA-Interim, and all members in shaded gray) is compared to the SMB estimated from ice cores available from Thomas et al. (2017). RACMO2.3 timeseries have been superimposed (cyan) and the 10 CESM2 simulations (shaded blue).

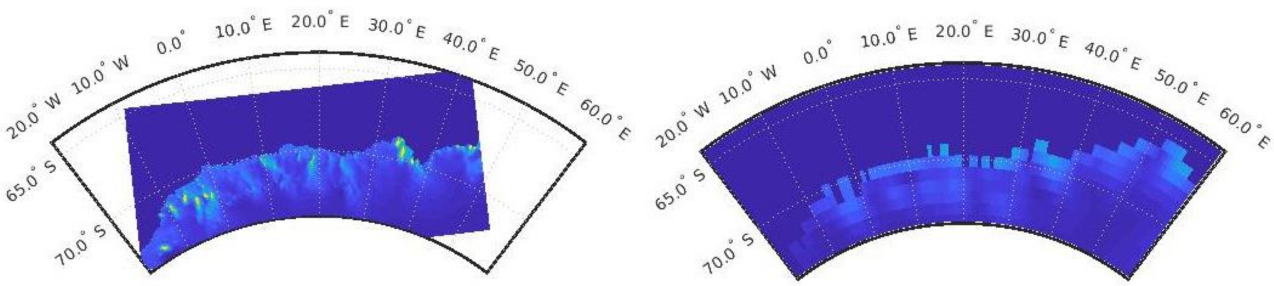

Figure 9. The downscaled CESM2 member 1 averaged over the total period (left)depicts more details than the averaged reconstruction based on the ice core records (right, Medley and Thomas, 2019). This could be useful in future detailed analyses of the ice core records' representativeness (same color scale).

Data assimilation methodology

Paleo data assimilation (PDA) aims at fusing the information from paleoclimate proxies (e.g., ice core records) with the physics of Earth System Models to provide reconstructions of past climate changes over the past centuries (Goosse et al., 2010; Hakim et al., 2016; Steiger et al., 2017). Basically, PDA updates an initial state of the climate system given by model simulations (called prior) with available paleoclimate proxies. The final output is called posterior, reconstruction or paleo-reanalysis. PDA has several advantages compared with simpler statistical methods. In particular, PDA relies on the spatial covariance from the model to spread the local information from paleoclimate proxies to other regions. In addition, it is also possible to reconstruct variables that are not directly connected to observed variables by relying on the covariance between the assimilated variable and the variables of interest. In this project, we used PDA to test the robustness of Antarctic surface air temperature and SMB reconstructions over the past two millennia. Most Antarctic surface air temperature reconstructions consider a stationary relationship between isotope content from ice cores (i.e., $\delta^{18}O$) and surface temperature (Stenni et al., 2017). This has been assessed here (*Klein et al. 2019*) by directly assimilating isotope content ice core records into two climate models that simulate water isotopes (Sjolte et al., 2019; Steiger et al., 2017). The resulting surface air temperature reconstruction is therefore based on the covariance between the isotope content from snowfall and temperature. In another study (*Dalaiden et al. 2020a*), we extend the PDA framework by incorporating snow accumulation records compiled by the CLIVASH2K group (Thomas et al., 2017) in order to analyse to what extent snow accumulation ice core records can be relevant for reconstructing the temperature and the potential use of ice core data to reconstruct open ocean polynyas that could have a large impact in the Dronning Maud land region (*Goosse et al. 2021*).

Causality analysis

A causality approach (Liang et al., 2014; Docquier et al., 2022), recently shown to be a more rigorous approach to pinpoint cause-effect relationships than a simple correlation, has been applied to look at potential imprints of sea ice extent and atmospheric drivers on ice core proxies. Possible cyclicities at various timescales (multidecadal to pluriannual) and trends of the measured species were also studied, e.g. using spectral analyses and more sophisticated methods (i.e. Multivariate Singular Spectrum Analysis – MSSA – or MultiTaper Method – MTM), in an attempt to identify the drivers of the observed spatial and temporal variability, and potentially track changes across the anthropogenic transition.

Moisture budget

We have quantified the contributions of the three main factors controlling continental snow accumulation variability: thermodynamic processes related to the warming atmosphere (Palerme et al., 2017) (i.e., Clausius-Clapeyron relationship), large-scale atmospheric dynamics (Marshall et al., 2017), and synoptic-scale dynamics (Turner et al., 2019) (i.e., storms). We calculated the moisture budget (Seager and Henderson, 2013) for the Antarctic Ice Sheet using atmospheric reanalysis and climate models covering the 20th and 21st centuries. This allowed us to separate the contributions of moisture transported by large-scale atmospheric dynamics from moisture transported by synoptic-scale events. The study (*Dalaiden et al. 2020b*) aims at providing a better understanding of the processes governing snow accumulation variations and to assess the future Antarctic contribution to global sea-level rise and to reduce the uncertainties in the interpretation of ice core records.

4. SCIENTIFIC RESULTS

1. Analysis of the ice core records.

Following the analyses of approximately 5000 samples for the three main groups of parameters (isotopes, ions and conductivity), we dated the top 120 m of our two ice cores back to the end of the 18th century (1793 ± 3 years and 1780 ± 5 years for FK17 and TIR18 respectively). We were then able to study the behavior of climatic indicators derived from this dating: surface mass balance (reconstructed from the annual layer thickness and density profiles and corrected for vertical strain rates) and proxy records, with a focus on their spatial and temporal variability. These data are presented in a paper recently submitted to the Earth System Science Data (ESSD) journal (*Wauthy et al., in review*) and the datasets are available on Zenodo (https://doi.org/10.5281/zenodo.7848435).

Many species measured in our ice cores can be used as paleo proxies. For example, the isotopic composition of the ice ($\delta^{18}O$ and δD) is usually used to reconstruct past temperatures (Dansgaard, 1964; Jouzel et al., 1987), while the deuterium-excess is primarily controlled by evaporation at the source and therefore a tracer of the origin and changes in the trajectory of the air masses (Stenni et al., 2010). Non-sea-salt sulfates ($nssSO_4$, the sulfates not of marine origin - aerosols), on the other hand, can be used to reconstruct past sea ice extent as they are mainly produced by the biological activity which takes place in the sea ice zone (Wolff et al., 2006). SO_4/Na ratio can also be used as a proxy of sea ice extent, since it is fractionated through mirabilite formation at the surface of young sea ice (e.g. Rankin et al., 2000), although it can potentially be blurred by the contribution of non-sea-salt sulfates to the total sulfates (e.g. Vega et al., 2018).

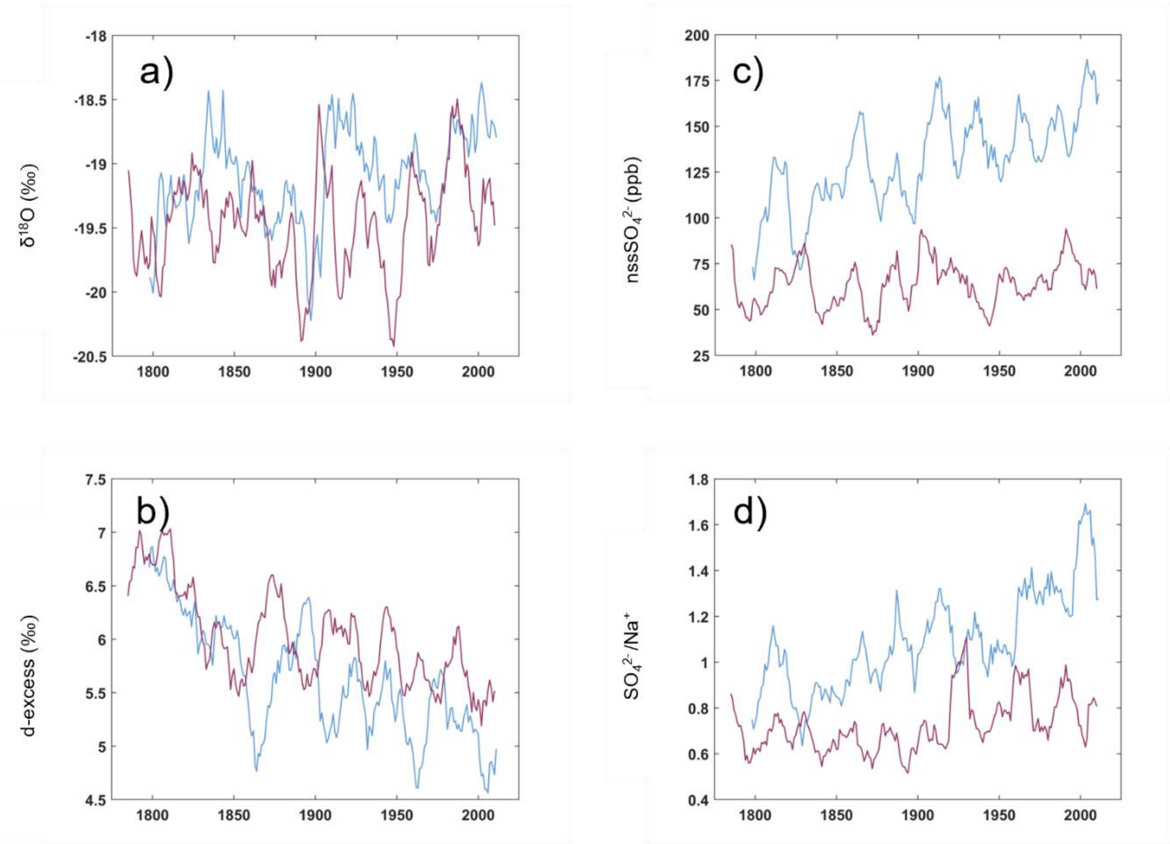

Figure 10. Trends analyses of some species used for dating over the whole dataset: a) $\delta^{18}O$, b) d-excess, c) $nssSO_4$ and d) SO_4/Na. The annual means signal has been smoothed with an 11-yr running mean, for FK17 in blue and TIR18 in burgundy. Figure adapted from Wauthy et al., *in review*.

In our records, $\delta^{18}O$ values (Figure 10a) are less negative during the 1951-2015 period than in the 1816-1950 period, indicating higher temperatures during precipitation. In terms of spatial variability, the mean $\delta^{18}O$ signal is more negative in TIR18 than in FK17, potentially indicating a more continental influence on the precipitation, with colder temperatures, at the Hammarryggen ice rise. Deuterium-excess (Figure 10b) shows a similar decreasing trend at both locations, suggesting a long-term decreasing evaporation efficiency (lower temperature at the source), with slightly lower values at Lokeryggen than Hammarryggen ice rise.

The $nssSO_4$ concentrations (Figure 10c) are increasing in both ice cores, pointing to a globally increased contribution of biological activity. Again, there is a clear regional contrast between the two records since the FK17 record displays a clear long-term trend while the TIR18 record is characterized by an increase between the 1816-1950 period and the 1951-2015 period, however of much smaller amplitude. The SO_4/Na ratio (Figure 10d) is well above the mean sea water ratio (0.25) at both locations, indicating a dominant impact of non-sea-salt sulfates (i.e. biological activity) on the total sulfates, a common feature of coastal ice cores (e.g. Vega et al., 2018), which might be hiding potential fractionation due to mirabilite formation at the sea ice surface. Considering sea salt sulfates and focusing on winter values might reveal trends over time.

Another salient feature of our proxy data sets illustrated in Figure 10 is the potential existence of multidecadal cyclicity. Pilot work using the Multi Taper Method (MTM) show that there is indeed a significant periodicity around 20 years, both at FK17 (Lokeryggen) and TIR18 (Hammarryggen) and for all variables, that might be related to an impact of the Interdecadal Pacific Oscillation. Furthermore, FK17 also shows a significant periodicity around 5-6 years, close to the El Nino periodicity, which is not present at TIR18. However, a first causality study between the main atmospheric indices and our proxy variables does not seem to show any significant relationship at this stage. The analysis of those cores is still in progress and more precise conclusions are expected in the near future.

A better understanding of the processes associated with individual proxies could also help in understanding the more complex SMB records, which also exhibit high spatial and temporal variability (Figure. 11). Indeed, even though the mean surface mass balance – corrected for vertical strain rates – is similar for FK17 and TIR18 (0.57 m i.e. a^{-1} and 0.56 m i.e. a^{-1} respectively), the time evolution of annual records is very different: FK17 oscillates in the long-term with an increasing trend between 1793 and 1825, then a decrease until 1925, followed by an increase and a plateau until 1995 and a recent decreasing trend. TIR18 is characterized by a significant decreasing trend since 1850. This is in sharp contrast with the Derwael ice rise record (IC12 ice core) which shows a significant increase in surface mass balance since the 1950's (Philippe et al., 2016). There is however a good correspondence between FK17 and IC12 across most of the Anthropocene (1870-2000).

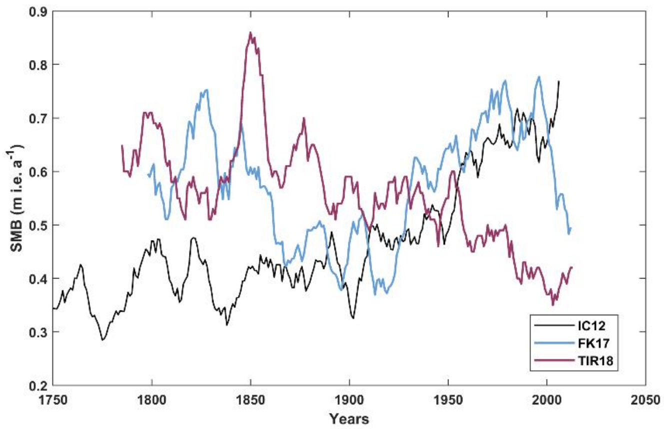

Figure 11. Surface mass balance corrected for vertical strain rates and expressed in meter ice equivalent per year (m i.e. a^{-1}), comparison with the Derwael ice rise record – IC12 (Philippe et al., 2016). Note that these datasets have been smoothed using an 11-yr running mean. IC12 is in black, FK17 in blue and TIR18 in burgundy. Figure adapted from Wauthy et al., *in review*.

Although surface redistribution of precipitation could be responsible for some of the discrepancies between locations, our working hypothesis is one of a regional influence of the air trajectories on SMB, as the air masses first encounter the Derwael ice rise (IC12 site) then Lokeryggen (FK17 site) and finally Hammarryggen (TIR18 site). This might be combined to shorter term events and local trends (e.g., occurrences of "atmospheric rivers", narrow precipitation pathways that can greatly enhance precipitation locally). There could also be competition between coastal air masses and more continental air masses affecting the three ice core locations differently, and this eventually at the sub-annual scale. This is now being analyzed using the HYSPLIT trajectory model which simulates the trajectory of air parcels (Stein et al., 2015).

Although the records cover shorter periods, adjacent ice rises studies have recently been carried out in the Fimbul Ice Shelf area nearby (western DML). Vega et al., (2016) showed that two of the three shallow (~20 m) firn cores display no significant long-term trend (2 decades) while the third one is characterized by a weak decreasing trend along its 50 years record. This is comparable to the decrease observed in a core from the nearby ice shelf, spanning the last 250 years. This confirms the SMB spatial variability along the whole DML coast and highlights the opportunity offered by our records to better study it on longer time scales and to investigate the mechanisms behind the variability at the regional scale.

Finally, high resolution thin section analysis of ice texture and fabrics has been performed to validate fabric evaluation from ApRES measurements at Derwael (IC 12, *Ershadi et al., 2023, submitted*) and to understand the impact of ice properties on the contrasted response of satellite surveys between upwind and downwind sides of ice rises (*Kausch et al., in preparation*).

2 Connecting local-scale and regional-scale SMB variability

Analysis of snow measurements and their spatial variability over the ice rises

The analysis of the SMP measurements shows a clear difference in grain size, density and exponential correlation length between the windward side of the Hammarryggen ice rise (Figure 12), where snow accumulation is high and the leeward side of the ice rise, where snow accumulation is low. The grain size is smaller on the windward side and the metamorphism to larger snow grains happens deeper in the snow pack. The density is also lower on the windward side, but has a higher depth gradient. As a result of this the density becomes laterally homogeneous at a depth of 50 cm *(Wever et al., 2023*).

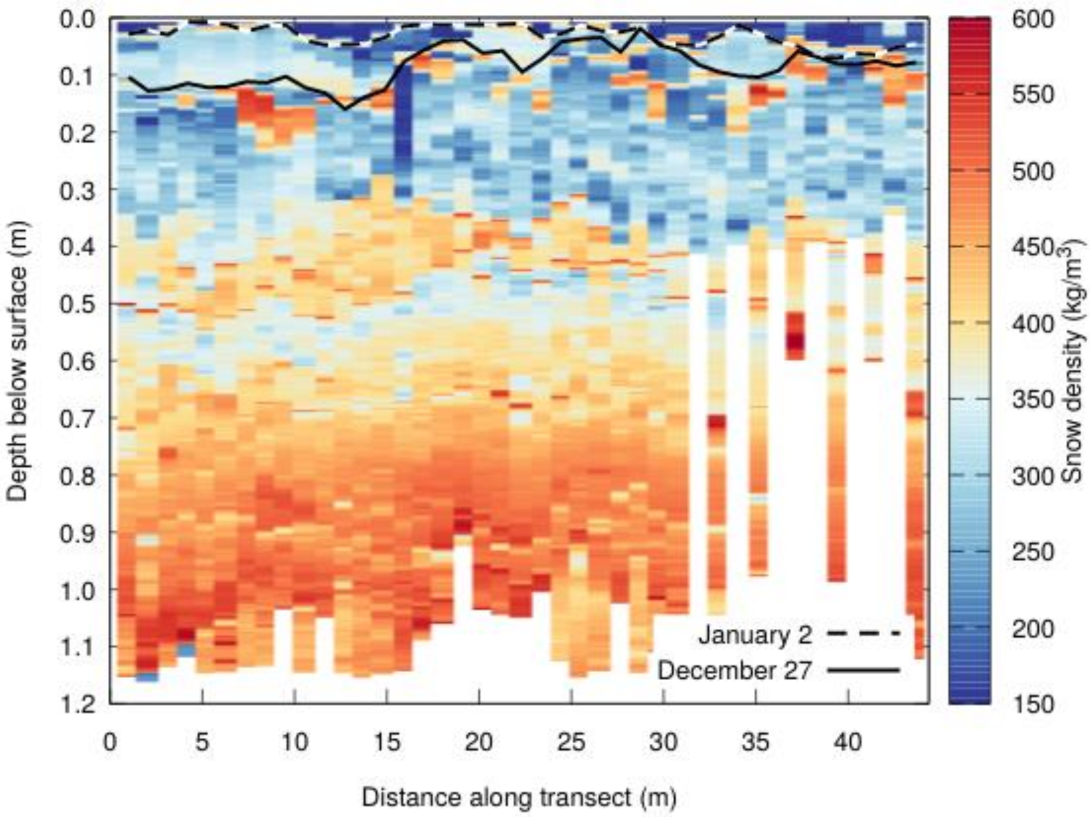

Figure 12. Density with depth on January 4 2019 along a transect over an area surveyed by repeat terrestrial laser scanning on the Hammarryggen ice rise. The solid and dashed lines denote the snow surface at December 27 and January 2, respectively.

The results of *Kausch et. al. (2020)* highlight i) the connection between snowfall variability and wind erosion and ii) provide a better understanding of how ice rises impact SMB variability, iii) how well this is captured in the regional atmospheric climate model RACMO2 and iv) the implications of this SMB variability for ice rises as an ice core drilling site (Figure 13). By combining GPR profiles from two ice rises in Dronning Maud Land with ice core dating, we reconstructed spatial and temporal SMB variations from 1983 to 2018 and compared the observed SMB with output from RACMO2 and SnowModel. We identify two main processes which influence the SMB across the ice rises: a regional snowfall-driven process of higher SMB on the windward side of the ice rises due to orographic uplift and a local wind-driven erosion process, where snow is eroded at the peak of the ice rise and deposited within a couple of kilometers downwind of the peak. Our results show snowfall-driven differences of up to 1.5 times higher SMB on the windward side of both ice rises than on the leeward side as well as a local erosion-driven minimum at the ice divide of the ice rises. RACMO2 captures the snowfall-driven differences but overestimates their magnitude, whereas the erosion on the peak can be reproduced by SnowModel with RACMO2 forcing. Observed temporal variability of the average SMBs, retrieved from the GPR data for four-time intervals in the 1983–2018 range, are low at the peak of the Lokeryggen ice rise (~0.06), while they are higher (~0.09) on its windward side. This implies that at the peak of the ice rise, higher snowfall, driven by orographic uplift, is balanced out by local erosion. As a consequence of this, the SMB recovered from the ice core matches the SMB from the GPR at the peak of the ice rise but not at the windward side of the ice rise, suggesting that the SMB signal is damped in the ice core.

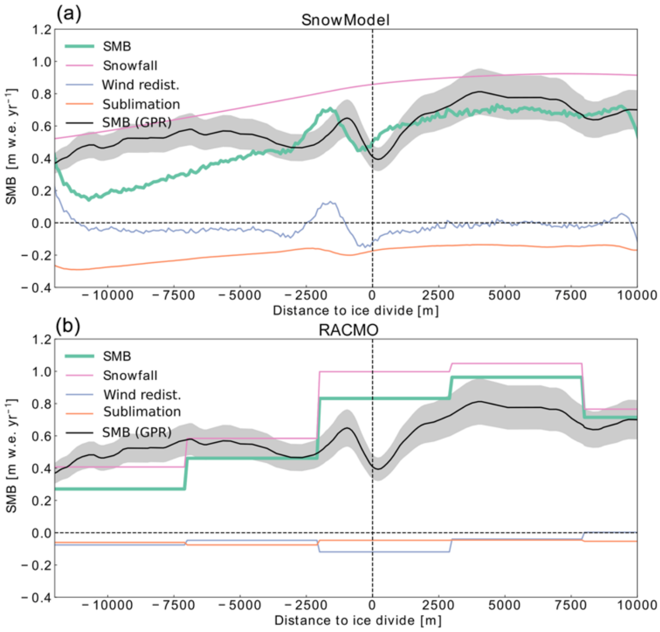

Figure 13. Total SMB and the different components of the SMB across the west-to-east profile of the Lokeryggen ice rise modelled by SnowModel and RACMO2. It shows that both orographic uplift and local wind-driven erosion processes control the SMB at the drilling location. Figure from *Kausch et al. (2020).*

In *Kausch et. al. (in prep)*, where we developed a remote sensing-based method for surface mass balance across east Antarctic ice rises, we show that Sentinel-1 cross-polarization ratio data could be used as a proxy for surface mass balance (Figure 14). We found a correlation between the SMB and the cross-polarization ratio with an R-value of 0.65 when using all available orbits. To understand this relationship, we ran a radiative transfer model (SMRT) together with a physical snowmodel (SNOWPACK), which was forced by field measurements across the Lokeryggen ice rise. The results show generally lower density and grain size in accumulation zones but also higher specific surface area of the grains. Overall, the results show the existence of a relationship between the SMB and the cross-polarization ratio for the study area. This promising relationship could possibly be extended to larger parts of Antarctica in future research.

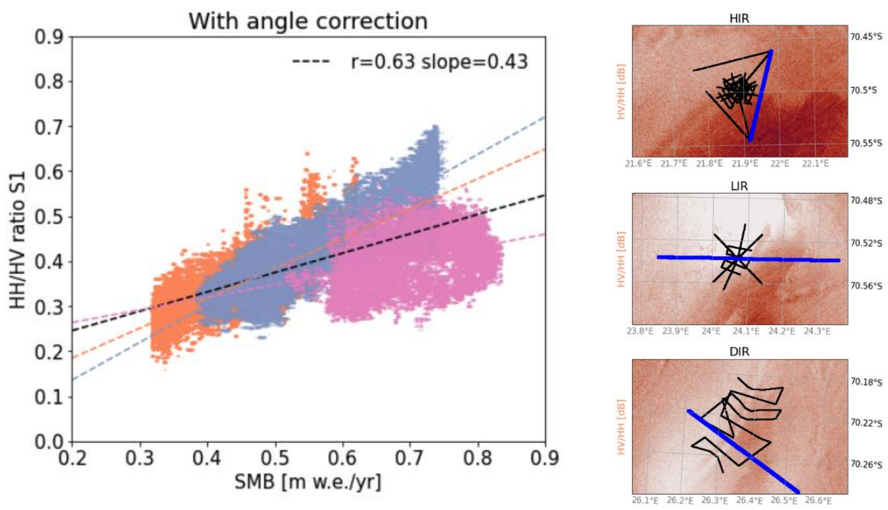

Figure 14 (left) empirical relationship between Sentinel-1 cross polarization ratio and SMB and (right) spatial maps of SMB variability derived from Sentinel-1 cross polarization ratio. Figure from *Kausch et al (in prep)*.

Combining ice core and GPR observations for uncertainty estimates

We have examined the three ice rise sites along the Princess Ragnhild Coast and observed that for each site, there is a clear signature of orographic lifting with high snowfall on the ice rises' windward sides and lower snowfall on their leeward sides. This is visible in the traced GPR isochrone depths as well as in the calculated SMB rates over the GPR survey grids. Overprinted on this ice rise-scale SMB pattern is a kilometer-scale pattern of wind-driven redistribution of the SMB, as previously described in *Kausch et al (2020),* see above. We also observed that the SMB temporal anomalies were homogeneously positive or negative over the ice rises which confirmed that a point measurement should be sufficient to realistically estimate regional SMB on multi-annual to decadal time scales (Figure 15). We observed *(Cavitte et al. 2022)* a difference in the ice core measured SMB and the GPR-derived spatially averaged SMB varying between 7-15 cm water equivalent (w.e.) /yr across the three sites, which corresponds to ~18-40% of the ice cores' mean SMB. This difference being significantly larger than the SMB uncertainties, estimated to be up to 7% of the ice cores' mean SMB, we concluded that ice core measured SMB should be adjusted to be more representative of the larger area if we want to use the ice cores' SMB to assess regional SMB or compare to model simulations. Without this adjustment, the ice cores are representative of an area of up to 500 m radius away from the ice core sites. On the other hand, we observed a difference in SMB temporal variability between 3-8% of the ice cores' mean SMB, which falls within the SMB uncertainties estimated. This suggests that the ice cores extracted from the top of the ice rises have reliable records of multi-year to decadal SMB variability, regardless of the surface area being analyzed. Ice core records can therefore be used to evaluate the temporal variability of the SMB record, understand the influence of modes of variability in teleconnections or be compared to models' simulations of SMB temporal variability without large adjustments.

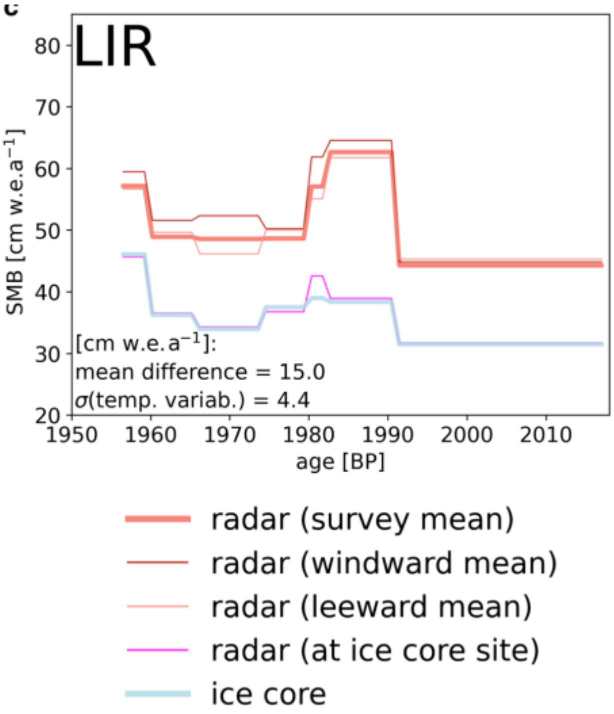

Figure 15. The mean difference between the ice core SMB (in blue) and the radar-derived spatial average over a few km^2 in red. This is for the Lokeryggen ice rise. Figure from *Cavitte et al. (2022).*

Link between temperature and precipitation variability at regional scale

We have shown that the continental-scale positive correlation between SMB and SAT (*Dalaiden et al 2020*) is valid at the regional scale in the models (*Cavitte et al. 2020*), and particularly strong in the Antarctic interior (Figure 16). The correlation in the models is also independent of spatial scales. This is due to snow accumulation over the AIS being dominated by large-scale atmospheric circulation which brings moist warm air from further north. However, in many areas along the coast, this positive correlation is found to be insignificant or negative. We showed then that the lack of positive correlation was linked to wind-driven redistribution of SMB as well as wind-driven changes in the SAT (e.g. Foehn) that can overwhelm the large-scale atmospheric signatures and break the positive correlation. In the observations (ice cores) however, the SMB-SAT correlation is much weaker. By aggregating the ice core records, the SMB-SAT correlation is improved a little but remains ~0.4-0.5 smaller than in the model data. Random noise and local processes affecting the SMB in the ice core data, as well as missing processes (potentially due to the spatial resolution of the grids) in the models are invoked to explain the differences in correlation strengths between models and data.

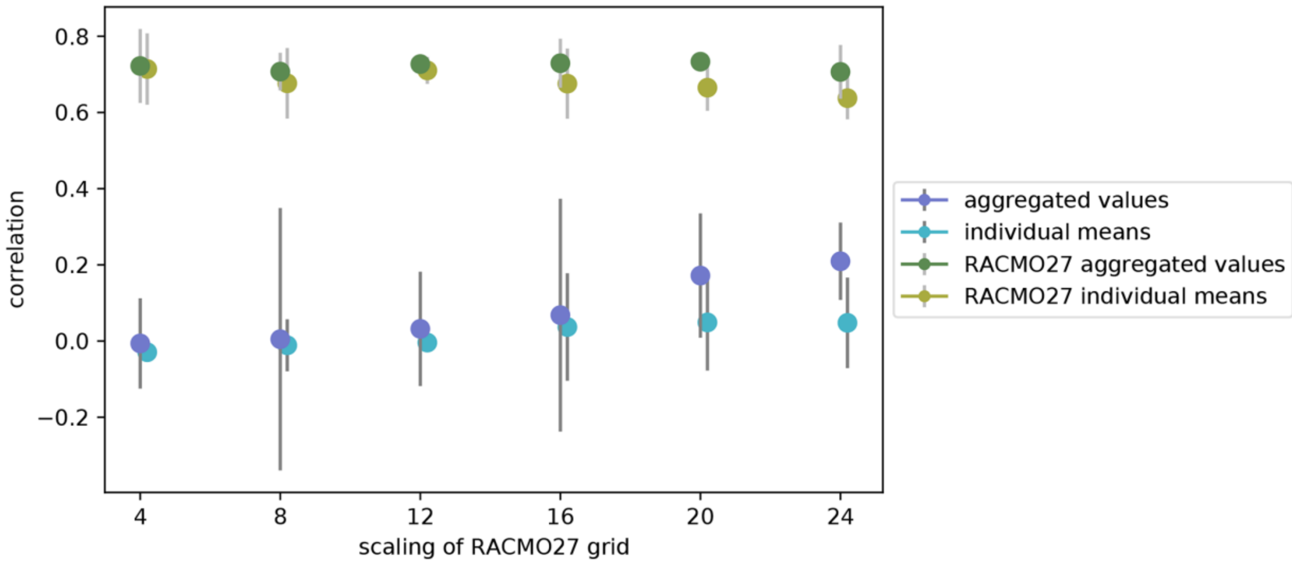

Figure 16. Strength of the SMB–SAT annual correlation as a function of the size of the grid cells chosen to average SMB records for the ice cores (blue) and the RACMO SMB simulations (green). We can see that for the model results, the correlation strength is independent of spatial scale while for the in-situ data, the strength increases a little with averaging, but never matches the model correlation strengths. Figure from *Cavitte et al. (2020)*.

3 Connecting local-scale, regional-scale and large-scale SMB variability

Statistical downscaling

We have proposed in the MASS2ANT project a reconstruction of snowfall evolution over Dronning Maud Land, Antarctica, at 5.5 km resolution using an analog-based downscaling technique. This technique has allowed us to exploit the detailed spatio-temporal estimation of snowfall from 30-year RACMO2.3 simulations in combination with synoptic patterns from recent reanalyses to statistically downscale the historical runs from CMIP6 (CESM2 model). The resulting database stores the ensembles of daily accumulated snowfall from 1850 to 2014, the pertinent information for synoptic patterns analysis (the principal components weights and empirical orthogonal functions from four large-scale meteorological fields), and the annual evolution of accumulated snowfall over Dronning Maud Land. The database can be used to analyze the detailed contribution of snowfall to the surface mass balance over the region, its evolution and its association to synoptic weather conditions. The method can be easily replicated with new RCM and GCM simulations. The files of the dataset (the annual snowfall, the principal components weights and the empirical orthogonal functions) are available on the Zenodo platform (http://doi.org:10.5281/zenodo.4287517). However, due to size limitations, only 2 daily snowfall files out of 20 have been stored there, the whole set is available on request to the RMI partner. The method, validation and description of the dataset is provided in a manuscript published in Earth System Science Data (https://essd.copernicus.org/articles/14/1901/2022/essd-14-1901-2022.pdf).

Testing for dynamical dependence – Application to the surface mass balance over Antarctica

Recently, a rigorous formalism of the rate of information transfer between two variables, $X1$ and $X2$, in deterministic and stochastic dynamical systems has been developed (Liang, 2014). Contrary to the covariance, it provides information on the directionality of the dynamical coupling between observables. This quantity is computed as the difference between the rate of change of the marginal entropy of $X1$ and the rate of change of the marginal entropy of $X1$ when $X2$ is frozen. This formalism has already been tested in various contexts with a lot of success. To exemplify the information provided by the approach, we have tested it in the context of a simple 2-variable linear stochastic system, providing interesting information. Three typical situations are expected: (i) no correlation and no transfer of information, (ii) correlation but no transfer of information, and (iii) correlation with transfer of information. See *Vannitsem et al (2019*) for more details on these different possibilities in the context of a linear system.

It has then been used on reanalysis and long climate model run datasets in order to disentangle the link between the surface mass balance, the large-scale atmospheric dynamics around Antarctica and the local properties of the surface (*Vannitsem et al, 2019*).

Simulation outputs from the coupled global climate model CESM1-CAM5 (Lehner et al., 2015) and MPI-ESM-P (Stevens et al., 2013) covering the 850–2005 period are analyzed. These simulations are driven by both anthropogenic (greenhouse gases, aerosol, ozone, and land use) and natural (solar, volcanic, and orbital) forcing. They were chosen because they provide very long time series at the annual time scale (1,156 years). A brief overview of the quality of their simulated climate is provided in *Dalaiden et al. (2020a)* and *Klein et al. (2019*). These models have been chosen because they reproduce reasonably well the mean state and the correlation between SMB and atmospheric circulation. The ERA-Interim data set (Dee et al., 2011), considered as one of the best reanalysis products for the Antarctic region, reproduces reasonably well the observed state of the surface mass balance (SMB) and the temperature at 2 meters (SAT) and the atmospheric circulation. It is available from 1979 to 2018 at a spatial resolution of 0.75◦. We use the sea ice concentration (SIC) data based on HadISSt and NCEP 2DVAR data before January 2002 (Fiorino, 2004) and on OSTIA afterward (Donlon et al., 2011). The different regions investigated are displayed in Figure 17.

These data sets have also been used here, but the length of the reanalysis data set is small (about 40 years), and much longer time series are needed to get rates of information transfer that are significantly different from 0.

An example of result for the MPI-ESM-P climate model run is displayed in Figure 18. The error bars represent the uncertainty at the 95% level. The observable experiencing the influence of the others is referred as *the Target* in each panel. A first general remark is that many of the observables used display significant correlations with each other, but several of them are not associated with detectable dynamical influences as measured by the rate of information transfer.
Let us now focus on specific interesting cases related to the influence of the large-scale dynamical modes, SIC, and SAT on SMB. For the MPI-ESM-P model (Figure 18), El Niño 3.4

is significantly influencing regional SMB over Regions 2 and 3 that are on opposite sides (East and West) of Antarctica, SAM is influencing Regions 4 and 6, and ZW3, Region 3 only. Interestingly, several highly significant correlations of ZW3 with the SMB over Regions 2, 4, 6, and 7 do not lead to any dynamical dependence. It indicates that previous links expected from the computations of correlations between large-scale modes and observables over Antarctica are not necessarily of dynamical origin but rather a covariability whose origin should be found in the common influence of upstream processes.

This type of analysis has been performed for other links between the different variables selected over Antarctica and for the second model. This is reported in details in *Vannitsem et al (2019)*. The main conclusions that are drawn from the analysis are: (i) The Antarctic Plateau is not influenced by the large-scale modes but well by the SAT and SIC; (ii) the SMB over the Weddell Sea coast and the DML coast are not influenced by the SAT; and (iii) the Weddell Sea coast is not dynamically influenced by the SIC.

To conclude, the analysis of the influence of certain processes on others in climate science is often based on correlation. Although the statistics based on this quantity are useful to have a first clue on the presence of a link between two observables, it cannot be used to infer any dynamical influence between them. Recent developments on information transfer in dynamical systems provide new tools to investigate dynamical interactions that can be used successfully as discussed above and illustrated in Figure 18.

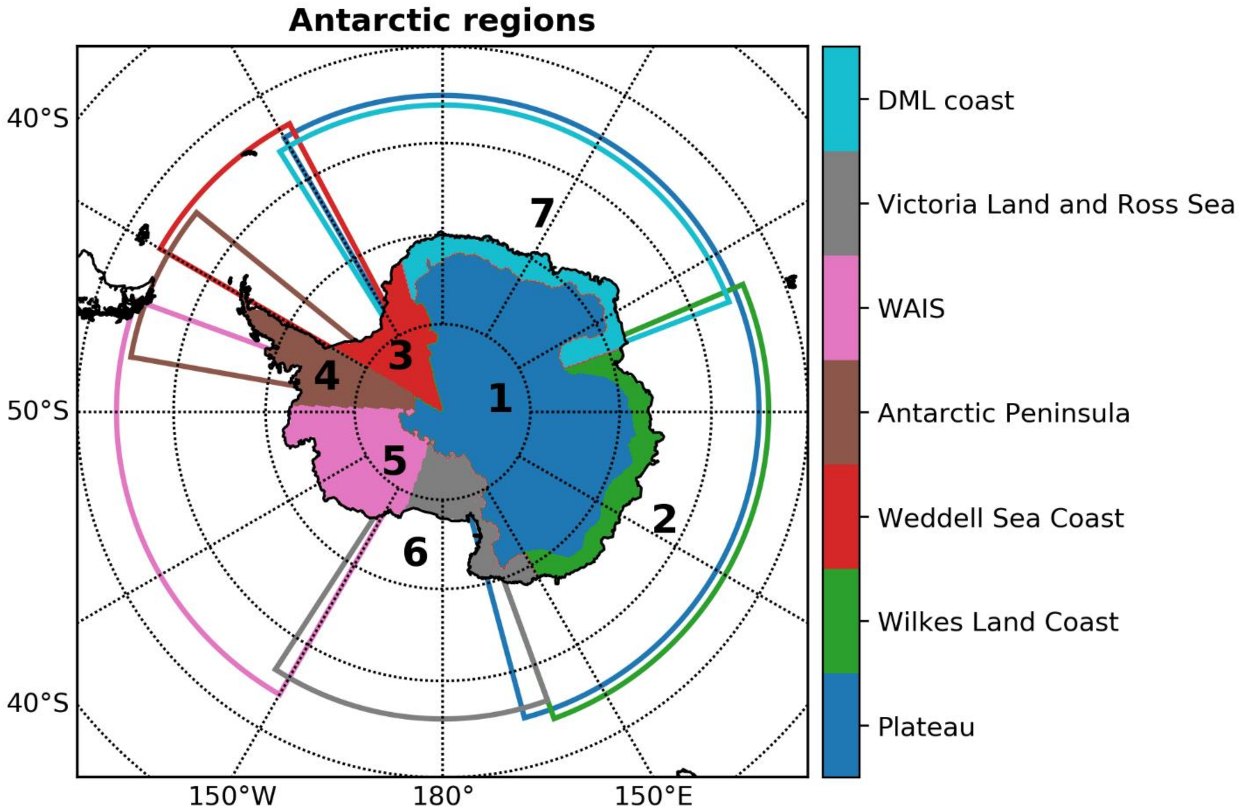

Figure 17: Regional boundaries separating the different regions used in this study. DML = Dronning Maud Land; WAIS = West Antarctica Ice Sheet. Figure from *Vannitsem et al (2019)*.

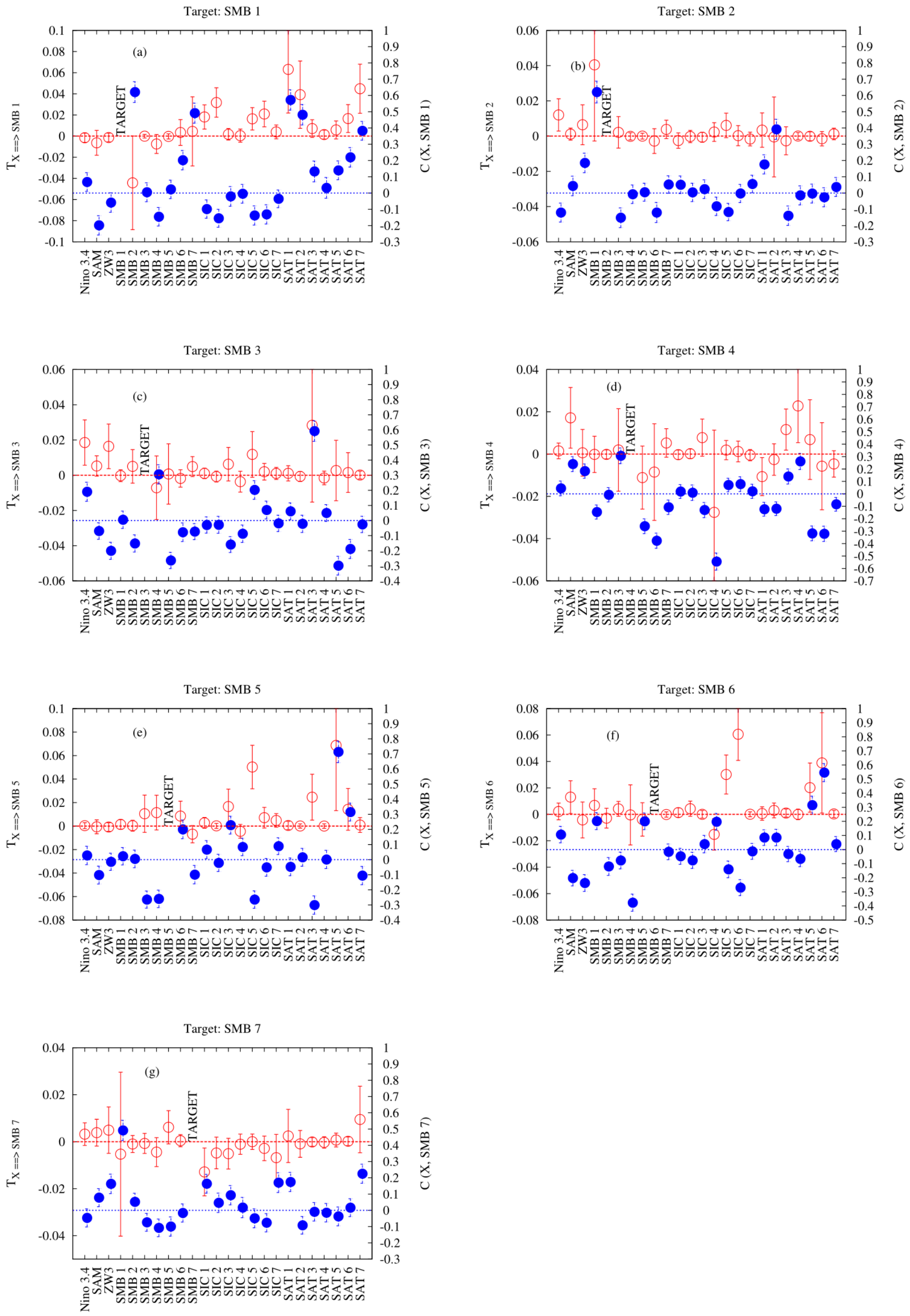

Figure 18. The rate of information transfer and the correlation are plotted as a function of the observables for seven different targeted observables. In (a)–(g), the targeted observable is referred to as the “Target” in the title, and the rate of information transfer from the other observables is plotted in red with the scale on the left vertical axis. The corresponding correlation coefficient is plotted in blue with the scale on the right vertical axis. The data used are coming from one specific run (Run 1) from an ensemble of runs made with the MPI-ESM-P climate model from 850 to 2005. Along the horizontal axis, the different observables used are the sea surface temperature of Nino 3.4 region, the Southern Annular Mode (SAM) index, the zonal wave 3 (ZW3) mode over Antarctica, the sea ice concentration (SIC), and the 2-m surface air temperature (SAT) averaged over the seven regions (Regions 1–7). Figure adapted from *Vannitsem et al (2019*).

Climate variability over the past centuries

Results from the data assimilation experiments show that the well-known covariance between isotope content and temperature in two isotope-enabled models used in data assimilation is correctly reproduced (Klein et al., 2019). However, this covariance is generally weak over different Antarctic regions, limiting the skill of the temperature reconstructions. Furthermore, the strength of the link varies significantly over the past millennium, which further limits the potential skill of temperature reconstructions based on statistical methods that assume the last few decades are a good estimate for longer temperature reconstructions. By considering changes in the $\delta^{18}O$-temperature link through time and space (through data assimilation), we show that we can improve reconstruction skill. The reconstruction skill is higher and more consistent among reconstruction methods when the reconstruction target is the Antarctic rather than smaller subregions.

In a second step, all the available Antarctic snow accumulation ice core records have been added to the $\delta^{18}O$ ice core records (*Dalaid*en et al., 2020a). Solely based on model results, a strong link between surface air temperature and snow accumulation is found (*see also Cavitte et al. 2020,* discussed above). However, reconstructions based on ice cores display a weaker relationship. We argue that it might be related to the non-climatic noise in ice core records or model biases (Neukom et al., 2019). The modelled relationship between surface air temperature and snow accumulation is often stronger than between temperature and $\delta^{18}O$, which indeed suggests that snow accumulation records can be used to constrain past surface air temperature. A new surface air temperature reconstruction is generated by assimilating snow accumulation and $\delta^{18}O$ ice core records in the two same models as the previous step in addition to an additional model, outperforming previous reconstructions. This shows that snow accumulation records are useful for reconstructing the past air temperature variability over the Antarctic Ice Sheet.

4 SMB changes into the future

The analysis of the Antarctic moisture budget shows that the increase in snow accumulation over the Antarctic Ice Sheet over the 20th century is mainly driven by an increase in synoptic-scale events (*Dalaiden et al., 2020b*). Additionally, according to our results, the interannual variability of regional snow accumulation is controlled by both the large-scale atmospheric circulation and short-lived synoptic-scale events. But, when considering the entire continent at the multi-decadal scale, only the synoptic-scale events can explain the expected future snow accumulation increase. In a warmer climate induced by climate change, these synoptic-scale events transport air that can contain more humidity due to the increasing temperatures, leading to more precipitation on the continent. We also highlight that the multi-decadal and interannual snow accumulation variability are governed by different processes and that the mechanisms driving interannual variations cannot be used to predict long-term changes in snow accumulation in the future. As a direct implication, the drivers of the observed year-to-year changes in snow accumulation cannot be directly used to infer future snow accumulation changes, and therefore predict the future contribution of the AIS to global sea-level rise.

5 General conclusions and synthesis

This section is also used as a basis for the summary of the project translated in Dutch and French.

One of the main achievements of the project is the collection and analysis of new data, including two new long ice core records, radar surveys on two ice rises, meteorological and snow observations. We were able to perform all the observations planned in the proposal, despite the strong constraints imposed at the beginning of the project by the cancellation of the first field campaign and later by the restrictions due to the COVID pandemic. We were even able to collect additional observations that were not initially planned thanks to collaborations, synergy with other projects and additional support from BELSPO for the 2021-2022 fieldwork season. Those data have been analyzed and compared to previously published ones and to provide input to models at different scales, from local snow models, to regional and global climate models. All those data are now archived in public, open access repositories and, in addition to our scientific results, will be one of the legacies of Mass2Ant.

The approach used during the course of the Mass2Ant project is unique as it used different types of observations and models, addressing very different spatial and temporal scales. It was only possible thanks to the strong and efficient collaboration between the partners and their combined expertise. This is well illustrated by the list of publications which include, for the large majority of them, authors from at least two groups among the partners.

The analysis of the ice core records and the reconstructions based on data assimilation have allowed us to put the recent changes in a longer-term perspective. It has shown that, in contrast to West Antarctica where relatively clear trends can be seen in many regions over the second half of the 20th century, with a warming and increased snow accumulation (in particular over the Antarctic Peninsula), the situation is more complex over East Antarctica. In the coastal regions of East Antarctica, trends in snow accumulation can be very different in relatively nearby places. Our results, including the explicit identification of causality between the observed changes, suggest that West Antarctica is more directly connected to global climate change and large-scale atmospheric variability than the Princess Ragnhild Coast. This does not mean that this connection with the larger scale does not exist for East Antarctica, but it can be often obscured in records by the effect of local to regional interactions between ocean, ice, topography and atmospheric circulation.

Past and future changes in Antarctica are also linked through the relative contributions of different processes to changes in snow precipitation. Snow precipitation and temperature tend to be connected at all temporal scales with a warming generally associated with more snow precipitation because of the increase of the water pressure at saturation in the air with temperature. This offers the opportunity to improve temperature reconstructions using snow accumulation records in data assimilation and to have a clear target to evaluate the behavior of regional climate models using observations. More precipitation is also expected in the future, mainly because of storms that will bring more moisture to Antarctica in a warmer world.

This link between temperature and precipitation due to storms that last a few days, trends over the 21st century and changes over the past centuries, illustrate well the interest of analyzing jointly the recent past, the more distant one and the future. Nevertheless, we have shown that models tend to overestimate the link between temperature and precipitation compared to observations. This may be due to their overestimation of the role of large-scale changes, arguing for an analysis of the link between local, regional and large-scale changes. This has been achieved in Mass2Ant both on the modelling side by comparing surface mass balance of regional and global models, using also statistical downscaling, and for the observations by comparing ice core records that sample the surface mass balance of individual locations separated by tens to hundreds of kilometers with radar derived surface mass balance that provides estimates over several square kilometers.

By comparing ice core records, local snow observations and ground penetrating radar data as well as model results, we have documented the strong spatial variability of snow accumulation over ice rises and the mechanisms responsible for that variability, in particular the influence of the topography on precipitation and the redistribution by the winds. This implies that the mean accumulation measured by the ice cores can be significantly different from the one at a scale of a few kilometers as estimated in regional models but ice cores generally provide a fair measure of the temporal variability of the accumulation. This large spatial variability imposes also care in the comparison between large-scale simulations and local records.

More generally, the project has shown the strong interest of a complementary approach using different tools to understand the complex changes in regions such as the Princess Ragnhild Coast. Thanks to exchanges within the group, we have been able to have two-way interactions between models and data, data being used to validate the models and models being essential to interpret the data and their limitations. The interest of different types of observations has been highlighted by comparing local snow measurements, ice core records and ground penetrating radar data and we strongly recommend to continue to make all those types of observations in future field work to be able to quantitatively estimate the uncertainties, in particular those of the ice core records, which are our main source of information for the variations longer than a few decades. The joint use of models at different scales has underlined their common behaviors, the additional information brought by higher resolutions, and the interest of statistical downscaling to represent this regional variability using global models. Furthermore, the application of a recent method based on a causality approach on model results has unambiguously identified the dynamical dependences between the variables that could be obscure using simpler diagnostics.

The originality of the approach has allowed us to attract interest and partnerships without which we would not have been able to obtain all the results presented here. Furthermore, Mass2Ant has enabled new collaborations. Ice core records have been included in a data synthesis led by the British Antarctic Survey (UK) and this new synthesis will be used in new reconstructions based on data assimilation. The local information obtained in the project will be a basis for the calibration of satellite data that will lead to better large-scale estimates of the surface mass balance of Antarctica. The analyses of radar data resulted in the development of a new collaboration between UCLouvain, the Norwegian Polar Institute (in

Tromso, Norway) and the National Centre for Polar and Ocean Research (in Goa, India), to expand our analyses to many more coastal ice rises along the Dronning Maud Land coastal region (work ongoing).

Finally, in addition to the scientific results, the illustration of the added-value of common projects carried out by a complementary team and recommendations for future Antarctic projects, our results have been used in assessments that are important bases for decision-making, in particular for the latest assessment report of the Intergovernmental Panel on Climate Change (IPCC AR6). Ice cores are one of the main sources of in-situ SMB data used to evaluate model simulations in Antarctica and assess Antarctic-wide mass balance, an exercise that allows us to determine present and future contributions of the ice sheet to sea level rise, with its worldwide coastal management policy impacts. We have also widely disseminated our results to the general public as described in the next section.

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The publication from the group obtained as a direct outcome of the project are given in section 6.

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5. DISSEMINATION AND VALORISATION

a/ Participation/organisation of seminars

Dalaiden, Q., Goosse, H., Klein, F., Lenaerts, J. (2018): Evaluation of Antarctic Ice Sheet Surface Mass Balance over the Last Millennium, CLIVASH2K workshop, 2018, Davos, Suisse.

Dalaiden, Q., Goosse, H., Klein, F., Lenaerts, J. (2018): Evaluation of Antarctic Ice Sheet Surface Mass Balance over the Last Millennium, CLIVASH2K workshop, 2018, Cambridge, UK.

Klein F.et al. (2018): Assessing the robustness of the Antarctic temperature reconstructions based on water stable isotopes using model results. EGU General Assembly 2018, Vienna, Austria, April 2018 – Poster

Klein F. et al. (2018): Assessing the robustness of Antarctic temperature reconstructions over the past two millennia. SCAR/IASC Open Science Conference 2018, Davos, Switzerland, June 2018 – Poster

Vannitsem, S., P. Ekelmans (2018): Causal dependences between the coupled ocean-atmosphere dynamics over the Tropical Pacific, the North Pacific and the North Atlantic, EGU, Vienna, April 8-13 2018, EGU2018-3683.

Dalaiden, Q., Goosse, H., Klein, F., Lenaerts, J., Holloway, M., Sime, L., Thomas, L. (2019): How useful is snow accumulation in reconstructing surface temperature?, Antarctic climate symposium, 2019, Bruxelles, Belgique.

Dalaiden, Q., Goosse, H., Klein, F., Lenaerts, J., Holloway, M., Sime, L. & Thomas, L. (2019): How useful is snow accumulation in reconstructing surface temperature? A study using ice core records and climate models, INQUA meeting, 2019, Dublin, Ireland.

De Cruz L., R. Solé-Pomies, S. Vannitsem (2018): Routes to long-term atmospheric predictability in coupled ocean-atmosphere systems, Geophysical Research Abstracts Vol. 21, EGU2019-4366, 2019

Keenan, E., Wever, N., Dattler, M., Lenaerts, J.T.M. (2019): Modeling Antarctic Surface Mass Balance Using a Detailed Multi-Layered Snow Model (poster), International Union of Geodesy and Geophysics (IUGG) General Assembly, Montreal, Canada, 8 – 18 July 2019.

Vannitsem, S., D. Faranda, G. Messori (2019): Attractor dimension of time-averaged climate observables: insights from a low-order ocean-atmosphere model, Geophysical Research Abstracts Vol. 21, EGU2019-4105, 2019.

Wever, N., Keenan, E., Lehning, M., Huwald, H., Lenaerts, J.T.M. (2019): Detailed simulations of spatial snow accumulation patterns and near surface snow properties (poster), American Geophysical Union (AGU) Fall Meeting, San Francisco, CA, USA, 9 – 13 December 2019

Dalaiden, Q., Vannitsem, S., and Goosse, H. (2020): Testing for Dynamical Dependence: Application to the Surface Mass Balance Over Antarctica, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-11492, https://doi.org/10.5194/egusphere-egu2020-11492.

Ghilain, N., Vannitsem, S., Dalaiden, Q., and Goosse, H. (2020): Reconstructing the distribution of surface mass balance over East Antarctica (DML) from 1850 to present day", 2020, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-13959, https://doi.org/10.5194/egusphere-egu2020-13959.

Wauthy, S., Inoue, M., Pattyn, F., Sun, S., Curran, M., Claeys, P, and Tison J.-L (2020): High spatial and temporal variability of surface mass balance at ice rise and promontories in Dronning Maud Land (East Antarctica) Princess Ragnhild Coast (DML): precipitation vs. post-depositional processes, SCAR Online.

Cavitte, M.G.P., Dalaiden, Q., Goosse, H., Lenaerts, J.T.M., Thomas, E.R. (2020): Examining the strength of the link between surface temperature and surface mass balance in ice cores and models over the last centuries in Antarctica, EGU General Assembly 2020, Online, 4–8 May 2020, EGU2020-80, https://doi.org/10.5194/egusphere-egu2020-801

Cavitte, M.G.P., Dalaiden, Q., Goosse, H., Lenaerts, J.T.M., Thomas, E.R. (2020): Comparing the strength of the link between surface mass balance and temperature in ice cores and models in Antarctica over the last centuries, SCAR Online.

Cavitte M.G.P, H. Goosse, S. Wauthy, J-L Tison, T. Kausch, S. Sun, B. Van Liefferinge, M. Inoue, Q. Dalaiden, J.T.M. Lenaerts, S. Lhermitte, F. Pattyn (2021) : Using ground-penetrating radar to determine the representativeness of ice core surface mass balance records at ice rises along the Princess Ragnhild Coast, East Antarctica, April 2021, EGU General Assembly, Vienna, Austria (online), EGU21-2191, https://doi.org/10.5194/egusphere-egu21-2191

Cavitte M.G.P., H. Goosse, S. Wauthy, B. Medley, T. Kausch, J-L Tison, B. Van Liefferinge, J.T.M. Lenaerts, F. Pattyn (2022) : Characterising the spatial footprint of ice cores using radar-derived surface mass balance, RINGS SCAR action group first international workshop.

Cavitte M.G.P., H. Goosse, S. Wauthy, B. Medley, T. Kausch, J-L Tison, B. Van Liefferinge, J.T.M. Lenaerts, F. Pattyn (2022) : Quantifying the spatial representativeness of ice core

surface mass balance records using ground-penetrating radar data in Antarctica, May 2022, EGU General Assembly, EGU22-649, https://doi.org/10.5194/egusphere-egu22-649.

Cavitte M.G.P., H. Goosse, S. Wauthy, B. Medley, T. Kausch, J-L Tison, B. Van Liefferinge, J.T.M. Lenaerts, F. Pattyn (2022): Ground-penetrating radar data as a method to quantify the spatial representativeness of ice core surface mass balance records in Antarctica, April 2022, PAGES Open Science Meeting , Agadir (online).

Cavitte M. G.P. (2022): Do not forget the small datasets, April 2022, AntArchitecture SCAR Action Group workshop, UK (online).

Cavitte M.G.P. (2022): The difficulty of having only access to open source software, April 2022, Polar Radar Science, USA (online).

Cavitte M.G.P. (2022): Back from Antarctica: what it's like to do fieldwork there, February 2022, TECLIM seminar, UCLouvain, Belgium.

Cavitte M.G.P., H. Goosse, K. Matsuoka, T. Meloth, R. Dey, S. Wauthy, D. Verfaillie, B. Van Liefferinge, B. Medley, E. Thomas (2022): Antarctic-wide quantification of ice core SMB spatial representativeness, IPICS International Partnerships in Ice Core Sciences 3rd Open Science Conference

Wauthy S., M. Inoue, S. Vannitsem, F. Pattyn, S. Sun, M. Curran, P. Claeys, J.-L. Tison (2022): High spatial and temporal variability of surface mass balance at ice rises in Dronning Maud Land (East Antarctica): origin, trends and cycles, August 2022, IGS-Cryosphere 2022, Reykjavik, Iceland.

Wauthy S., M. Inoue, S. Vannitsem, F. Pattyn, S. Sun, M. Curran, P. Claeys, J.-L. Tison (2022): Study of surface mass balance at ice rises in Dronning Maud Land (East Antarctica): contrasting spatial and temporal variabilities, October 2022, International Partnership in Ice Core Science, Crans-Montana, Switzerland.

Cavitte M.G.P., H. Goosse, K. Matsuoka, S. Wauthy, R. Dey, V. Goel, J-L Tison, B. Van Liefferinge, T. Meloth (2023): What to watch out for when assimilating ice-cores as regional SMB proxies?, EGU General Assembly (Vienna)

Cavitte M.G.P (2023): Do we care how much snow falls on Antarctica?, Brussels Institute for Advanced Studies (BrIAS) – The past, present and future of food, climate and sustainability, (Brussels)

Cavitte M.G.P., H. Goosse, K. Matsuoka, T. Meloth, R. Dey, S. Wauthy, D. Verfaillie, B. Van Liefferinge, B. Medley, E. Thomas (2023): Antarctic-wide quantification of ice core SMB spatial representativeness, 2k + TSM PAGES workshop (Potsdam)

b/ Outreach activities

A number of outreach activities were carried out around the 2018/2019 and 2021/22 field seasons. These include:

• A blog has been created during the 2018/2019 field campaign, receiving more than 5000 visitors and 25000 visited pages : https://www.bel-antar2018.be/en/, leading to interviews in l'Avenir, Le Soir and for la Première

• Press articles and news:

◦ Bx1 interviews pre and post fieldwork:

▪ https://bx1.be/categories/news/une-mission-belge-en-antarctique-des-scientifiques-de-lulb-uclouvain-sur-le-depart

▪ https://bx1.be/categories/news/antarctique-la-calotte-glaciaire-sous-la-loupe-des-chercheurs-belges

◦ A segment on the RTBF NIOUZZ about the fieldwork

◦ Press releases about the fieldwork on the UCLouvain news (https://uclouvain.be/fr/chercher/actualites/mission-mesurer-la-masse-de-la-calotte-antarctique.html),the ULB news (https://actus.ulb.be/fr/actus/recherche/des-scientifiques-partent-mesurer-la-masse-de-la-calotte-antarctique) and is the basis for an subject at the RTBF (https://www.rtbf.be/article/climat-des-scientifiques-belges-partent-mesurer-la-masse-de-la-calotte-antarctique-1088355)

◦ Photo published in the Louvain[s] magazine of UCLouvain

◦ Blog article in the Princess Elisabeth Antarctica station website news http://www.antarcticstation.org/news_press/news_detail/successful_mass2ant_fieldwork_at_the_lokeryggen_ice_rise and a photo blog http://www.antarcticstation.org/multimedia/picture_gallery/mass2ant_at_lokeryggen_ice_rise

• Sarah Wauthy created a video blog about the fieldwork aimed at all audiences (for which Sarah Wauthy was awarded the Prix de la diffusion scientifique ULB): https://actus.ulb.be/fr/actus/recherche/journal-dune-mission-en-antarctique

• Submitted photos to the Nocturnes on Ice organised by APECS Belgium x IPF at the Natural Sciences Museum in Brussels

•Presented what Antarctic fieldwork is like to primary school children during a visit to the British School in Brussels

The group members also answer regularly to interview from journalists and make presentations is schools, museums (a few examples with links below).

- Interview on Declic (RTBF) LE GRAND DÉBAT – Accélération de la fonte de la banquise : à quel point est-ce préoccupant ? On en parle avec : - François Massonnet, climatologue, professeur à l'UCLouvain et chercheur qualifié FNRS - Frank Pattyn, glaciologue,

- QR l'Actu on La Une on the latest IPCC Synthesis Report, with Marie Cavitte

6. PUBLICATIONS FROM THE PROJECT RESULTS (PEER-REVIEWED)

Klein F., N. J. Abram, M. A. J. Curran, H. Goosse, S. Goursaud, V. Masson-Delmotte, A. Moy, R. Neukom, A. Orsi, J. Sjolte, N. Steiger, B. Stenni and M. Werner, 2019. Assessing the robustness of Antarctic temperature reconstructions over the past two millennia using pseudoproxy and data assimilation experiments. Climate of the Past. 15, 661–684, https://doi.org/10.5194/cp-15-661-2019

Vannitsem, S., Q. Dalaiden, H. Goosse, 2019. Testing for dynamical dependence – Application to the surface mass balance over Antarctica. Geophys. Res. Lett., 46, 12,125-12,135. https://doi.org/10.1029/2019GL084329

Cavitte M.G.P., Q. Dalaiden, H. Goosse, J. Lenaerts, E. R Thomas, 2020. Reconciling the link between surface temperature–surface mass balance between models and ice cores. The Cryosphere 14, 4083–4102 https://doi.org/10.5194/tc-14-4083-2020.

Hubbard, B., Philippe, M., Pattyn, F., Drews, R., Young, T.J., Bruyninx, C., Bergeot, N., Fjøsne, K. and Tison, J.-L., 2020. High-resolution distributed vertical strain and velocity from repeat borehole logging by optical televiewer: Derwael Ice Rise, Antarctica. Journal of Glaciology, 258(66). https://doi.org/10.1017/jog.2020.18

Kausch, T., Lhermitte, S., Lenaerts, J. T. M., Wever, N., Inoue, M., Pattyn, F., Sun, S., Wauthy, S., Tison, J.-L., and van de Berg, W. J., 2020. Impact of coastal East Antarctic ice rises on surface mass balance: insights from observations and modeling, The Cryosphere, 14, 3367–3380. https://doi.org/10.5194/tc-14-3367-2020 .

Dalaiden Q., H. Goosse, F. Klein, J. Lenaerts, M. Holloway, L. Sime and L.Thomas, 2020a. How useful is snow accumulation in reconstructing surface air temperature in Antarctica? A study combining ice core records and climate models. The cryosphere 14, 1187-1207. https://doi.org/10.5194/tc-2019-111 .

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Keenan, E., Wever, N., Dattler, M., Lenaerts, J. T. M., Medley, B., Kuipers Munneke, P., and Reijmer, C., 2021. Physics-based SNOWPACK model improves representation of near-surface Antarctic snow and firn density, The Cryosphere, 15, 1065–1085, https://doi.org/10.5194/tc-15-1065-2021.

Dalaiden Q., H. Goosse, J. Rezsohazy, E. R. Thomas, 2021. Reconstructing atmospheric circulation and sea-ice extent in the West Antarctic over the past 200 years using data assimilation. Climate Dynamics 57, 3479–3503 https://doi.org/10.1007/s00382-021-05879-6.

Lyu Z., H. Goosse, Q. Dalaiden, F. Klein, F. Shi, S. Wagner and P. Braconnot, 2021. Spatial patterns of multi-centennial temperature trend in Antarctica over the 0-1000 CE: insights from ice core records and modeling. Quaternary Science Reviews 271, 107205 https://doi.org/10.1016/j.quascirev.2021.107205.

Goosse H., Q. Dalaiden, M.G.P. Cavitte, L. Zhang, 2021. Can we reconstruct the formation of large open ocean polynyas in the Southern Ocean using ice core records? Climate of the Past 17, 111–131, https://doi.org/10.5194/cp-17-111-2021

Crosta X., Etourneau J., Orme L., Dalaiden Q., Campagne P., Swingedouw D., Goosse H., Massé G., Miettinen A., McKay R., Escutia C., Ikehara M., 2021. Multi-decadal trends in Antarctic sea-ice extent driven by ENSO-SAM over the last 2000 years. Nature Geoscience 14, 156-160. https://doi.org/10.1038/s41561-021-00697-1

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Ghilain, N., Vannitsem, S., Dalaiden, Q., Goosse, H., De Cruz, L., and Wei, W.,2022. Large ensemble of downscaled historical daily snowfall from an earth system model to 5.5 km resolution over Dronning Maud Land, Antarctica. Earth Syst. Sci. Data, 14, 1901–1916. https://doi.org/10.5194/essd-14-1901-2022.

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Wauthy, S. Tison, J.-L., Inoue, M., El Amri, S., Sun, S., Claeys, P., and Pattyn, F.: Physico-chemical properties of the top 120 m of two ice cores in Dronning Maud Land (East Antarctica), Zenodo [dataset],https://doi.org/10.5281/zenodo.7848435, 2023.

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