Brief communication: Interest of a regional climate model against ERA5 to simulate the near-surface climate of the Greenland ice sheet

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Abstract. The ERA5 reanalysis, recently made available by the European Centre for Medium-Range Weather Forecasts (ECMWF), is a new reanalysis product at a higher resolution which will replace ERA-Interim, considered to be the best reanalysis over Greenland until now. However, so far very little is known about the performance of ERA5 when compared to ERA-Interim over the Greenland Ice Sheet (GrIS). This study shows (1) that ERA5 improves not significantly the ERA-Interim comparison with near-surface climate observations over GrIS, (2) polar regional climate models (e.g. MAR) are still a useful tool to study the GrIS climate compared to ERA5, in particular in summer, and (3) that MAR results are not sensitive to the forcing used at its lateral boundaries (ERA5 or ERA-Interim).

1 Introduction

Reanalyses are global datasets describing the recent history and current state of the atmosphere, land surface, and oceans. They merge sparse observations into a space- and time-continuous product over the whole Earth. These datasets, commonly used in geophysical sciences, enable for instance to evaluate recent climate trends (e.g., Belleflamme et al., 2015; Hanna et al., 2018) and to constrain numerical climate models at their boundaries (e.g., Stark et al., 2008; Fettweis et al., 2017; Noël et al., 2018).

The ERA5 reanalysis (Hersbach and Dick, 2016), recently made available by the ECMWF, is a new reanalysis product that will soon replace ERA-Interim, considered until now as the best reanalysis over Greenland (Chen et al., 2011; Jakobson et al., 2012; Lindsay et al., 2014; Fettweis et al., 2017). In addition to the model improvements listed in Hersbach and Dick (2016), ERA5 is available at higher spatial resolution (0.3°) than ERA-Interim (0.75°). This new generation of reanalysis products has been already evaluated over North America as forcing field for a land surface model (Albergel et al., 2018), over Europe (Urraca et al., 2018) and over the Arctic Ocean (Wang et al., 2018) but not yet over the Greenland Ice sheet (GrIS).

Because of the finer resolution of ERA5 (∼31 km over the equator and ∼15 km over Greenland), the question of the relevance of using regional reanalyses (e.g. Arctic System Reanalysis, ASR, Bromwich et al., 2016, 2018) or polar-oriented regional climate models (RCMs) (e.g., Fettweis et al., 2017; Noël et al., 2018) to study the near-surface climate of the GrIS can be raised. The spatial resolutions are now more similar while the time and spatial evolution of snow pack properties, and the surface energy balance (Rae et al., 2012), remain poorly represented in global reanalyses (e.g., Bougamont et al., 2007;

Reijmer et al., 2012; Goelzer et al., 2013; Vaughan et al., 2013; Vernon et al., 2013; van Kampenhout et al., 2018). Moreover, in the context of the substitution of the ERA-Interim reanalysis, it is relevant to assess the new product, ERA5, as a forcing dataset for climate models or positive degree day models simulating the surface mass balance (SMB), not yet represented in global reanalyses.

5   The main goals of this study are (1) to evaluate ERA5 against ERA-Interim and ASR reanalyses by comparison with a set of near-surface climate observations covering the GrIS not assimilated in the reanalyses (Ahlstrom et al., 2008), (2) to highlight the added value of using the state-of-the-art RCM MAR (Modèle Atmosphérique Régional, Fettweis et al., 2017) forced by both ERA-Interim and ERA5 to simulate the near-surface climate of the GrIS, and (3) to evaluate the sensitivity of MAR based near-surface climate to the forcing used (ERA-Interim and ERA5 reanalyses) at its lateral boundaries.

2   Data and methodology

2.1   Reanalyses

2.1.1   The ERA-Interim reanalysis

The fourth generation reanalysis from the ECMWF (ERA-Interim, Dee et al., 2011), available at a spatial resolution of $\sim$ 0.75°(about 41 km at Greenland) and a time resolution of 6-hourly for analysis fields, has been widely used over the Arctic

15 (e.g., Kapsch et al., 2014; Simmons and Poli, 2015; Bieniek et al., 2016) and especially over Greenland (e.g., Lucas-Picher et al., 2012; Bennartz et al., 2013; Merz et al., 2013; Cox et al., 2014). The ERA-Interim reanalysis (EI hereafter) is considered as the reference in this study.

2.1.2   The ERA5 reanalysis

The last generation from the ECMWF reanalyses, ERA5 reanalysis (E5 hereafter, Hersbach and Dick, 2016), has a higher

20 spatial ($\sim$ 31 km and about 15 km at Greenland) and temporal (hourly analysis fields and 3-hourly for the ensemble of data assimilation) output-resolution than EI. In the near future, E5 will replace EI. E5 is now available from 1979 to near-real time but should finally cover a period starting in 1950. Beside the higher time and spatial resolution, the main improvements compared to EI consist in a higher number of vertical levels (137 versus 60 in EI), an improved 4D-VAR assimilation system, more consistent sea surface condition input products, a globally better balance between precipitation and evaporation, and more

25 (new) data assimilated (ECMWF, 2018).

2.1.3   The Arctic System Reanalysis

ASR is a regional reanalysis product for the Arctic region (Bromwich et al., 2016). ASR version 2 (called ASR hereafter, Bromwich et al., 2018) has a finer horizontal resolution (15 km) than E5 and has 71 vertical levels. It has a 3 hourly time resolution covering the 2000s (2010 – 2016) using the version 3.6.0 of the Polar Weather Research Forecast model (Polar WRF,

30 Skamarock et al., 2008) and the community WRF data assimilation system based on a 3D-Var technique. ASRv2 improves the

comparison of near-surface climate variables with observations compared to ASRv1 and EI over the Arctic (Bromwich et al., 2018).

2.2 The model MAR

The model MAR is a RCM specifically designed for polar areas (Amory et al., 2015; Lang et al., 2015; Kittel et al., 2018; Agosta et al., 2019) and abundantly evaluated over Greenland (e.g., Fettweis et al., 2011, 2017). In this study, we use the last version of MAR (3.9.6). The main improvements compared to the previous MAR version used in Delhasse et al. (2018) are related to the computational efficiency of the model and its numerical stability. MAR is forced at its lateral boundaries (temperature, specific humidity, wind speed, pressure, sea surface temperature and sea ice concentration) by EI and E5 reanalyses over Greenland at a spatial resolution of 15 km over 2010 – 2016. The MAR lateral boundaries are chosen to be far enough to enable the model to simulate its own climate in the atmospheric boundary layer over Greenland. These simulations are respectively called hereafter MAR_{EI} and MAR_{E5}.

2.3 Obervations

2.3.1 PROMICE network

The PROMICE (Program for Monitoring of the Greenland Ice Sheet) network (Ahlstrom et al., 2008) provides daily measurements from automatic weather stations (AWS) mainly over the melting area of the GrIS since mid-2007. We use the raw output data without any corrections from 21 of the 25 AWS available (see section 2.3.2). Note that PROMICE observations are neither assimilated in the reanalyses nor in MAR such that our comparison is independent from the observations.

2.3.2 AWS

Among the time series from the 25 AWS available in the PROMICE dataset, we dismissed the ones out of the considered period in this study (2010 – 2016). The remaining 21 AWS (Figure 1) are listed in supplementary materials (Table S2), as well as the corresponding differences in elevation for model grid points. For each of the studied variables (pressure, 2-m temperature, 10-m wind speed, short-wave and long-wave downward radiative fluxes), we excluded the AWS with: (1) differences between all the interpolated elevations of the four models (see section 2.3.3) and the actual AWS elevation higher than 250 m , (2) unfavourable comparisons resulted from measurement errors in the observed time series, and (3) unfavourable statistics (correlation and RMSE) for the four models (MAR, ASR, E5 and EI) suggesting a likely influence of local surface conditions not represented at the spatial resolutions of the models used here. The AWS excluded and the reasons for their exclusion are listed in Table S1.

2.3.3 Comparison method

At the time of the beginning of our study, only the period 2010 – 2017 was available for E5, while ASRv2 is available until 2016. We have therefore limited the comparison to the time period spanning 2010 – 2016.
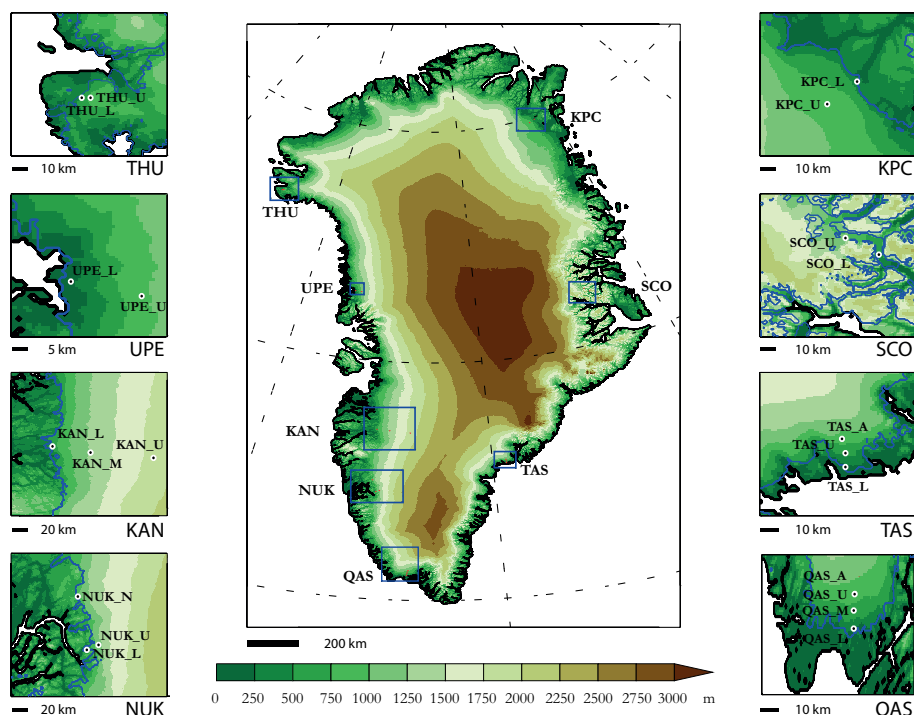
Figure 1. Localisation of the 21 AWS from the PROMICE network used in the study. Blue line in sub-maps represent the limit between the ice sheet and the tundra.

Here we assess the near-surface climate of the GrIS simulated by E5 against PROMICE observations at a daily time scale. We also compare it to the previous reanalysis generation, EI, the regional reanalysis ASR and two MAR simulations. Four variables are evaluated here as proxy of the near-surface climate: 2-m temperature (T2M), 10-m wind speed (W10M), short-wave downward radiative flux (SWD) and long-wave downward radiative flux (LWD).

5   Modelled values of these essential climate parameters are computed for each AWS location followowing an average-distance-weigthed values of the four nearest grid point. To evaluate modelled values, we compare the correlation, the root mean square error (RMSE), the centred RMSE (RMSEc) and the mean bias (MB) between daily observations and each modelled datasets. These statistics are calculated for each day of AWS observations, averaged over 2010 − 2016 and for all AWS, by applying a weighted average according to the number of available observations for each station.

10   For T2M statistics, we tried to correct modelled temperature values from the altitude difference between the station and the model interpolated elevation with a variable vertical temperature gradient. As the comparisons were not improved, we concluded that applying such a correction would add more uncertainties than using the raw modelled fields without any correction.

3 Results

Results of the comparison between daily observations and model values for the four main variables are listed in Table 1. Before analysing each variable in the next sections, it should be noted that all the models succeed in representing the daily variability of the surface pressure and then the synoptic circulation with correlation reaching 0.99 (listed in supplementary materials,
5   Table S3 – S7).

3.1 Temperature

All models have correlations higher than 0.96 at the annual scale and higher than 0.82 in summer with PROMICE based T2M and a RMSE representing about 30% of the daily variability and then the biases can be considered as not statistically significant.

Concerning the reanalysis products, it should be noted that ASR outperforms the ERA reanalyses and that E5 does not
10   outperform EI: despite E5 having a higher correlation in summer (0.85 VS 0.83), EI has a smaller RMSE in summer than E5 (2.60 °C vs 1.98 °C).

The analysis of MAR_{EI} and MAR_{E5} against ERA demonstrates the added values of MAR. The yearly absolute value of MB are clearly smaller for the temperature simulated by MAR. In summer the temperature bias from both MAR simulations are the highest but the same simulations shows the lowest RMSE(c) and highest correlation with observations (0.87). Both ERA
15   reanalyses perform worse than MAR, while ASR shows similar statistics as MAR.

Finally statistics of MAR experiments reveals that MAR_{E5} is colder in summer than MAR_{EI}, but they produce similar temporal variability.

Two distinct elements can explain the statistical differences between the representation of T2M by the models considered here. First, the difference in altitude between the station and the corresponding interpolated model elevation, which mainly
20   influences the annual MB. For example, the interpolated elevation of the EI grid is 770 m higher at AWS QAS_L (see Table S2 in supplementary materials) while the difference in altitude is lower for the other models (151 m for E5, 6 m for ASR and 119 m for MAR). This difference lead to a negative MB of EI (-4.81 °C, Table S12) and erroneously suggests that this model is colder at this location. The second element influencing the modelling of T2M is the better representation by the two regional models (MAR and ASR) of the physical processes at the surface of the GrIS. This consequently results in a better
25   representation of surface-atmosphere interactions, which are influenced by the melt of the snow pack when the excess energy is used to melt snow or ice and not to warm the surrounding air and by the density of the snow pack which is better modelled in the polar RCMs. The influence of better resolving the surface processes (i.e. melt-albedo feedback) which are driving the near-surface temperature and melt variability is particularly relevant in summer when the statistics of both ERA datasets are worse than those of RCMs.

30   The finer resolution of the regional models and the inherently better representation of the topography could also play an important role in the better representation of climate variables. However it appears to be not relevant here, since the new reanalysis E5 has a resolution similar to MAR and ASR, and E5 does not perform better than EI. For example, AWS where difference in elevation are less or equal to 100 m (NUK_U, KPC_U, KAN_U, UPE_U, TAS_A, NUK_N), T2M from EI and

Table 1. Mean bias, RMSE, centered RMSE (RMSEc) and correlation between daily observations from the PROMICE dataset and MAR_{EI}, MAR_{E5}, EI, E5 and ASR. Annual and summer statistics are given for the 2-m temperature (T2M), the 10-m wind speed (W10M), the longwave downward radiative flux (LWD) and the shortwave downward radiative flux (SWD) over 2010 – 2016.

		Annual				Summer			
		Mean Bias	RMSE	RMSEc	Correlation	Mean Bias	RMSE	RMSEc	Correlation
T2M ($°C$)	MAR_{EI}	0.01	2.42	2.29	0.97	0.72	1.68	1.24	0.87
	MAR_{E5}	-0.04	2.41	2.28	0.97	0.44	1.69	1.24	0.87
	EI	-1.08	3.65	2.85	0.97	0.22	1.95	1.41	0.83
	E5	-0.11	3.18	2.55	0.97	0.19	2.60	1.49	0.85
	ASR	-0.47	2.54	2.14	0.98	-0.07	1.98	1.26	0.86
Mean obs 2010 – 2016		-9.29				1.45			
Std obs 2010 – 2016		9.33				2.28			
Wind Speed (ms^{-1})	UV1 MAR_{EI}	1.31	2.32	1.85	0.83	0.96	1.78	1.34	0.77
	UV2 MAR_{EI}	-0.17	1.93	1.84	0.82	-0.26	1.55	1.34	0.75
	UV1 MAR_{E5}	1.42	2.39	1.87	0.83	1.05	1.83	1.37	0.76
	UV2 MAR_{E5}	-0.06	1.93	1.86	0.82	-0.17	1.55	1.38	0.75
	EI	-0.96	2.31	1.91	0.80	-0.96	1.86	1.37	0.74
	E5	-0.87	2.07	1.61	0.86	-0.78	1.84	1.21	0.82
	ASR	1.52	2.72	1.95	0.83	1.10	2.30	1.42	0.78
Mean obs 2010 – 2016		5.52				4.33			
Std obs 2010 – 2016		3.10				1.96			
LWD (Wm^{-2})	MAR_{EI}	-11.35	26.11	23.08	0.87	-15.11	23.93	18.22	0.80
	MAR_{E5}	-10.58	26.20	23.54	0.87	-15.12	24.33	18.61	0.79
	EI (forecast)	-19.60	28.28	19.26	0.92	-15.58	23.39	15.11	0.86
	E5 (forecast)	-15.58	23.02	16.18	0.94	-11.23	19.41	13.50	0.89
	ASR (forecast)	-16.55	25.48	18.98	0.92	-12.91	20.69	15.22	0.86
Mean obs 2010 – 2016		233.72				275.28			
Std obs 2010 – 2016		45.87				28.23			
SWD (Wm^{-2})	MAR_{EI}	-7.18	32.52	31.15	0.97	-2.98	45.74	44.18	0.88
	MAR_{E5}	-7.95	32.80	31.30	0.97	-4.42	46.07	44.41	0.88
	EI (forecast)	-5.55	29.21	27.67	0.98	-1.4	42.34	38.22	0.91
	E5 (forecast)	-2.98	26.98	25.59	0.98	-3.68	41.53	37.10	0.91
	ASR (forecast)	6.80	30.31	29.09	0.97	22.87	48.69	41.88	0.89
Mean obs 2010 – 2016		126.96				264.43			
Std obs 2010 – 2016		127.05				91.83			

E5 are better represented annually than in summer. By contrast, T2M from both RCMs for the same AWS have significantly better statistics in summer than both ERA reanalyses.

The last point to discuss is the annual T2M representation (correlation 0.98) by ASR which is slightly higher correlated than MAR (correlation 0.97) while the two MAR experiments have a smaller RMSE. The slight distinction of ASR against MAR might be due to the assimilation of observations from DMI (Danish Meteorological Institute) weather stations which are close to several PROMICE AWS. In summer, despite the data assimilation in ASR, MAR still provides the most accurate representation of T2M.

To conclude, MAR shows the best accuracy when modelling T2M which might also lead to a better representation of the surface melt (not evaluated here) and therefore of the SMB.

3.2 Wind speed

W10M in each model is well correlated with observations (annually > 0,80 and in summer > 0,74) and a insignificant RMSE representing 70 % of the daily variability (Table 1), except for ASR in summer.

Generally, wind speed depends on synoptic atmospheric features, but also on interactions with the surface and local topographic conditions, such as glacial valley (e.g. QAS_L). It is difficult for all models to correctly represent the surface wind regime in these areas due to their coarse resolution preventing a detailed representation of the local topography.

E5 is higher correlated to in-situ observations than EI, MAR and ASR at the annual and summer time scales and also has a smaller RMSE and RMSEc. In this case E5 outperforms EI, most likely due to its higher spatial resolution.

Despite the improved representation of W10m in E5, both EI and E5 underestimate W10M (negative bias between -0.96 and -0.78 ms^{-1}) which has already shown by Moore et al. (2016) over Greenland and Jones et al. (2016) over Antarctica. It should be noted that the underestimation of wind speed would be even stronger at the effective height ($\sim$2.5 m) at which the wind is measured by the PROMICE AWS.

W10M in ASR and in both MAR simulations is overestimated with respect to observations (positive bias reaching 1.52 ms^{-1}). But the biases are reduced when the MAR wind speed (UV2 at $\sim$2 m, Table 1) is taken at the height of the AWS measurements. However, the correlation of the wind speed is neither sensitive to the vertical level used in MAR (2 m vs 10 m) nor to switching the forcing from EI to E5.

3.3 Longwave downward radiative flux

Contrary to wind speed and temperature observations that are usually assimilated in reanalyses, observed downward radiative fluxes are usually not. Forecasted radiative fluxes simulated by the three reanalysis models have therefore been used in this study to compare to in-situ observation of radiative fluxes.

Table 1 shows that each model has a satisfactory representation of LWD and differences with PROMICE observations are not significant while all the models underestimate LWD.

E5 provides the best performances for LWD compared to the two others reanalyses with the highest correlation coefficients (0.94 annually, 0.89 in summer) and the smallest RMSE.

The two MAR simulations are quite similar but perform less well than reanalyses. While the temporal variability of LWD is better represented by the reanalyses, the yearly MB are smaller for MAR_{EI} (-11.35 Wm^{-2}) and MAR_{E5} (-10.58 Wm^{-2}) compared to the reanalyses.

The better LWD statistics of the three reanalyses compared to MAR_{EI} and MAR_{E5} is partly due to the assimilation of the

5 main fields influencing the simulation of cloud cover by reanalyses. They assimilate radiance from satellite data as well as temperature and humidity profiles from radiosondes (Dee et al., 2011; Bromwich et al., 2016). This enables a better representation of incident radiative fluxes, on one hand through the presence or absence of clouds and on the other hand through their microphysical characteristics, including the thickness, water phase or temperature of the clouds. This state of the atmosphere is not assimilated by MAR for which the specific humidity and temperature are only prescribe at its lateral boundaries every

10 6-hours and MAR clouds are the outcome of the model's own climate and microphysics.

3.4 Shortwave downward radiative flux

Table 1 reveals that each model performs well at representing SWD (yearly correlation >= 0.97 and summer correlation >= 0.88) and differences with PROMICE observations are not significant.

Similarly to the LWD statistics, reanalyses better represent SWD than the RCMs, with E5 providing the best statistics.

15 The ASR reanalysis overestimates SWD (yearly MB = 6.80 Wm^{-2} and summer MB = 22.87 Wm^{-2}) when compared to other models (MB = -4 Wm^{-2} on average), as already highlighted by Bromwich et al. (2018). Large LWD and SWD biases in ASR indicate that additional model improvements in Polar WRF are necessary to better capture the radiative cloud effects despite improved model cloud physics between ASRv1 and ASRv2 (Bromwich et al., 2018).

The assessment of SWD as represented by both MAR experiments reveals no significant difference, but a less accurate

20 representation of the SWD temporal variation than in the ERA reanalyses.

In general, the accurate representation by a model for incident radiative fluxes (LWD and SWD) depends on its radiative scheme. The radiative scheme used by MAR is the one from ERA-40 (the previous ECMWF reanalysis before EI) which has been updated for the EI and E5 reanalyses. This argument, combined with the assimilation of observations by reanalyses, in particular of atmospheric humidity and temperature, which enables them a more accurate representation of clouds, justifies the

25 better statistical comparison of the incident radiative fluxes simulated by the ERA reanalyses compared to MAR when forced by these reanalyses.

4 Discussion and conclusions

We have evaluated essential near-surface climate variables (2-m temperature, 10-m wind speed and energy downward fluxes) simulated by the new ERA5 reanalysis against EI, ASR, and MAR forced by EI and by E5 over 2010 – 2016.

30 The first aim was to evaluate E5 against the other reanalyses. The first one is EI, because it is usually used as a reference over Greenland while the second one is ASR, a regional reanalysis specifically developed for the Arctic region. E5 outperforms

EI for almost all variables, but not significantly. ASR is able to model processes temperature more accuratly compared to the other global reanalyses. The near-surface wind speed is underestimated by both ERA reanalyses.

Then we aimed at evaluating the performance of MAR (forced by EI or by E5) against these reanalyses. MAR performs less satisfactory than reanalyses at representing downward energy fluxes because of its relatively old radiative scheme and

5   because it does not assimilate observational data. Despite this weakness, the near-surface temperature, especially in summer, is more accurately represented by MAR, suggesting that there are some error compensations in MAR as already highlighted by Fettweis et al. (2017). A good representation of T2M is very important, because it reflects the interaction between the atmosphere and the ice sheet surface, and it subsequently influences the simulation of the snow and ice melt. In addition to the interest to better simulate SMB, there is still an interest of using polar RCMs like MAR, not constrained by observations, to

10   represent the near-surface climate over Greenland in the ablation zone compared to E5.

Finally, we evaluated the sensitivity of MAR to the lateral forcing: E5 and EI. For each analysed variable, results from both MAR simulations are close to each other, except that MAR$_{E5}$ is a bit colder than MAR$_{EI}$, proving the consistency of the model to simulate its own near-surface climate when forced by reanalysis.

It has recently been announced that E5 will replace ERA-interim after August 2019 and will cover a long and homogeneous

15   period (from 1950 to present). This represents a significant advantage compared to the discontinuity between ERA-40 and ERA-Interim in 1979, which can influence the SMB reconstructions (e.g., Fettweis et al., 2017). In this study we showed that E5 is slightly more efficient to represent the near-surface climate of the GrIS than EI, while the advantage is not statistically significant. However, using E5 over the last 70 years should improve the reliability of the SMB reconstructions from 1950.

Competing interests. The authors declare that they have no conflict of interest.

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