SUPPLEMENT

Assessment of future wind speed and wind power changes over South Greenland using the MAR regional climate model: Supplementary work

Clara Lambin[1] | Xavier Fettweis[1] | Christoph Kittel[1,2] | Michaël Fonder[3] | Damien Ernst[3,4]

[1]Department of Geography, University of Liège, Liège, Belgium

[2]Université Grenoble Alpes/CNRS/IRD/G-INP, IGE, Grenoble, France

[3]Department of Electrical Engineering and Computer Science, University of Liège, Liège, Belgium

[4]LTCI, Telecom Paris, Institut Polytechnique de Paris, Paris, France

Correspondence
Email: clara.lambin@uliege.be

Funding information

In this Supplement can be found the evaluation of MARv3.12 forced with ERA5 at 15 km of spatial resolution against *in situ* observations from weather stations of the KATABATA project, DMI and PROMICE databases. Figures of the seasonal anomaly between the five CMIP6 ESM-forced MAR simulations and the reference for 1981-2010 as well as a multi-level figure of wind speed changes at 10 m above ground level (a.g.l.), 50 m and 500 hPa from 1981 to 2100 can also be found here.

S.1 Evaluation of MAR wind speed outputs

The first step of the evaluation of MAR wind speed outputs was, for each station, to find the corresponding cell of the MAR grid in MAR-eval. Therefore, for each station, all the land (i.e., surface elevation greater than 0) grid cells for which the distance between their centre and the station was equal or inferior to the spatial resolution were inspected and the grid cell with the closest altitude to that of the station was kept. Wind speed, temperature and surface pressure were then extracted from MAR-eval, from 2016 to 2018 for pixels corresponding to DMI and PROMICE stations and from September 2020 to the end of August 2021 for grid cells corresponding to KATABATA stations.

Subsequently, observed hourly temperature at 2 m above ground level (a.g.l.) and hourly surface pressure (except for KATABATA stations for which it was not available) were compared with the MAR-eval temperature at 2 m and surface pressure to check for potential outliers. Therefore, KATABATA time series, which have a time-step of 20 minutes, were resampled in hourly time series by applying an hourly average. The PROMICE and DMI data were directly downloaded as hourly time series. Moreover, time-steps with erroneous data in the observed temperature and surface pressure time series were removed from the corresponding observed wind speed time series. This was carried out to account for potential instrumentation problems a station might encounter in the extreme Greenlandic climatic conditions such as sensor icing or toppling over under high-speed wind gusts (Cappelen et al., 2001). During this data inspection, it appeared that only a few time-steps had visually obvious erroneous temperature observations for IKM in 2016 and NUN in 2017. All DMI and PROMICE stations have a correlation of R>0.98 (not shown) between their measured surface pressure and the surface pressure of MAR-eval, suggesting that the stations were functioning correctly at the time. This was confirmed with the temperature correlation for which R in each case was greater than 0.88 (not shown), once the erroneous observations had been removed from the above-cited time series, namely IKS in 2016 and NUN in 2017. It should be noted that to calculate the surface pressure and temperature correlations, the MAR-eval time steps for which the corresponding observation data was missing were removed from the time series. For the KATABATA stations, because the surface pressure data was not available, only the temperature was inspected to check for potential instrumentation problems. No obvious erroneous data was visuallly found in the time series.

After time-steps with outliers and missing data were removed from both observation and MAR-eval wind speed time series, their correlation, bias, RMSE and centred RMSE (RMSEC) were calculated on the whole 3-year time series for DMI and PROMICE stations and on the available time period of the KATABATA stations. For DMI and PROMICE stations, the statistics were also calculated for summer and winter time series. Summer time series consist of the succession of the three summers (June-July-August (JJA)) of 2016, 2017 and 2018. The same goes for winters (January-February-March (JFM)). For KATABATA and DMI stations, the data was compared with simulated wind speed at 10 m a.g.l., as it is the height at which observed wind speed is measured by these stations. However, data from the PROMICE stations was compared with simulated wind speed at 2 m a.g.l.. As explained in Section 3.2 of the main paper, the PROMICE sensors do not measure wind speed at 10 m but rather between 0 and 3.1 m a.g.l.. Indeed, because the stations are located in an area with high snowfall accumulation, the height at which PROMICE stations record wind speed varies through the year. The yearly average height at which PROMICE stations record wind speed, derived from measured heights a.g.l., is close to 2 m and this is why this level has been chosen in MAR-eval for comparison with the PROMICE data. The results of this evaluation are listed in Table S.1 for the KATABATA stations and in Table S.2 for the DMI and PROMICE stations. It is important to keep in mind that the NAR time series only covers 2018, and the same goes for IKS which only covers 2016-2017. For DMI stations, the hourly wind gusts data were compared with MAR-eval regular 10 m hourly averaged wind speed to evaluate the capacity of MAR to simulate wind speed maxima. The regular 10 m MAR-eval hourly averaged wind speed was chosen because MAR does not simulate wind gusts as an independent variable. The results are listed in Table S.3.

It appears from Table S.1 that the correlation between the wind speed measured by KATABATA stations and wind speed extracted from their corresponding MAR-eval grid cells varies quite considerably between the three stations.

TABLE S. 1 Correlation (R), bias (m/s), RMSE (m/s) and centered RMSE (RMSEC, m/s) between wind speed observation data from the KATABATA stations and MAR wind speed values. The mean wind speed (m/s) and standard deviation (STD, m/s) have been calculated from the observation data.

Station	Statistic	Value	Statistic	Value	Time range (dd/mm/yy)
KAT 6640	**R**	**0.59**	Mean	8.61	06/09/20 - 31/01/21
	Bias	0.88	STD	5.59	
	RMSE	5.37			
	RMSEC	5.30			
KAT 0460	**R**	**0.56**	Mean	6.27	08/09/20 - 31/08/21
	Bias	2.43	STD	4.88	
	RMSE	6.14			
	RMSEC	5.64			
KAT 0680	**R**	**0.83**	Mean	5.86	11/09/20 - 28/02/21
	Bias	3.84	STD	5.56	
	RMSE	5.46			
	RMSEC	3.89			

Note the different time ranges between stations

Only KAT 0680 shows good correlation with MAR-eval (R>0.70). A 3-days running correlation was applied on the KATABATA time series to check for potential time shifts in the data. Although an offset of +2h in regard to UTC time (which is the model time) is suspected for stations KAT 0460 and KAT 0680, the correction of this offset barely improves the correlation with MAR-eval. Scatter plots of wind speed difference between a station and its MAR-eval grid cell versus temperature (observed and modelled) enable one to check for wind sensor icing that would slow down the rotation of the instrument. No evidence of such icing that could explain the poor correlations between KAT 0460 and KAT 6640 with MAR-eval could be found. As for the RMSE and centred RMSE, these were superior to one standard deviation (STD) for KAT 0460. This means that at the location where the observations were recorded, MAR does not represent the wind speed variations well, probably because the environment in which the station is located is inadequately resolved by MAR. The bias of MAR-eval is positive for all KATABATA stations and is the strongest for KAT 0680, representing 65% of the mean observed wind speed. Again, that could be explained by the fact that KAT 0680 is located in a narrow fjord that could act as a protection/shelter from wind, that is not resolved by the model resolution. The RMSE and RMSEC are relatively high with regard to the STD. The RMSEC represents 116% of KAT 0460 STD, 95% for KAT 6640 and 70% for KAT 0680.

As for DMI and PROMICE stations, it appears from Table S.2 that for most stations, the yearly correlation between the observed and the modelled wind speed is good (R>0.70). Stations IKM and UKI have an R=0.69 so their yearly correlation can be considered good as well. Only station ANG shows poor yearly correlation (R=0.55). It should be noted that station ANG is located not very far from stations KAT 6640 and KAT 0460. This supports the fact that the poor correlation with MAR-eval for these stations is more likely linked to their location rather than to instrumentation problems. Moreover, ANG has the same MAR-eval grid cell as KAT 6640 and is only one grid cell away from KAT 0460. Such as for the latter station, ANG has a RMSEC greater than one STD (approximately 104% of it). The poor correlations of stations ANG and KAT 6640 are likely to be due to a lack of topography resolving by the model, as was suggested by previous simulations of MAR at 5 km of spatial resolution, for which correlation with observation data were much better. As an example, the correlation between MAR and observations at 5 km is 0.81 for KAT 6640, 0.80 for KAT 0460 and 0.70 for KAT 0680 for September-December 2020, while it is 0.68 for KAT 6640, 0.71 for KAT 0460 and 0.74 for KAT 0680 at 15 km for the same period. On a seasonal basis, the correlation between the observed and the modelled wind speed is markedly improved in summer compared to winter (delta R$\geq$0.05) for IKS, QAS_L and QAS_M.

Finally, Table S.3 lists the correlation, bias, RMSE and RMSEC between DMI measured wind gusts and MAR-eval 10 m mean wind speed at an hourly scale. Except for ANG, the correlation with MAR is greater than 0.70 for all stations, suggesting that MAR performs well in capturing wind speed maxima. The correlation for wind gusts with MAR is even slightly better than the observed 10 m mean wind speed. The bias of the model is of course negative considering that we take the modelled regular 10 m mean wind speed, as the model does not simulate wind gusts in a separate variable. The bias can represent up to 35% of the observed STD, as is the case for NUN. RMSE and RMSEC are never greater than one STD, which means that MAR shows good performance for representing wind speed maxima.

TABLE S. 2 Correlation (R), bias (m/s), RMSE (m/s) and centered RMSE (RMSEC, m/s) between wind speed observation data from DMI and PROMICE stations and MAR-eval wind speeds for 2016-2018. The mean wind speed (m/s) and standard deviation (STD, m/s) have been calculated from the observation data.

Station	Statistic	Winter	Summer	Yearly	Station	Statistic	Winter	Summer	Yearly
ANG	**R**	**0.49**	**0.46**	**0.55**	UKI	**R**	**0.69**	**0.71**	**0.69**
	Bias	1.90	0.35	1.01		Bias	-0.59	0.20	-0.18
	RMSE	6.82	4.61	5.71		RMSE	3.59	2.48	3.28
	RMSEC	6.55	4.59	5.62		RMSEC	3.54	2.47	3.28
	Mean	9.44	6.23	8.02		Mean	7.76	5.11	6.60
	STD	6.05	4.03	5.38		STD	4.78	3.28	4.34
IKM	**R**	**0.66**	**0.70**	**0.69**	QAS_L	**R**	**0.67**	**0.59**	**0.72**
	Bias	1.09	0.14	0.88		Bias	-0.05	-0.59	-0.33
	RMSE	4.84	2.81	4.05		RMSE	3.23	2.02	2.65
	RMSEC	4.72	2.80	3.95		RMSEC	3.23	1.93	2.63
	Mean	8.25	5.19	6.72		Mean	6.38	3.78	5.15
	STD	6.08	3.80	5.22		STD	3.96	2.16	3.56
IKS	**R**	**0.75**	**0.81**	**0.79**	QAS_M	**R**	**0.65**	**0.46**	**0.73**
	Bias	2.47	2.05	2.52		Bias	1.08	-0.28	0.82
	RMSE	5.14	3.38	4.41		RMSE	3.37	1.76	2.81
	RMSEC	4.51	2.70	3.62		RMSEC	3.19	1.74	2.69
	Mean	9.32	5.24	7.04		Mean	7.21	4.36	5.98
	STD	6.62	4.42	5.65		STD	3.20	2.40	3.18
NAR	**R**	**0.79**	**0.82**	**0.81**	QAS_U	**R**	**0.72**	**0.74**	**0.77**
	Bias	1.45	-0.21	0.83		Bias	0.65	-0.21	0.10
	RMSE	3.57	2.09	3.01		RMSE	3.07	1.59	2.49
	RMSEC	3.26	2.08	2.90		RMSEC	3.00	1.58	2.49
	Mean	4.21	3.82	4.22		Mean	6.77	3.90	5.61
	STD	4.63	3.44	4.29		STD	3.55	2.17	3.44
NUN	**R**	**0.79**	**0.81**	**0.83**					
	Bias	-2.11	-0.98	-1.57					
	RMSE	4.44	2.80	3.65					
	RMSEC	3.91	2.62	3.29					
	Mean	12.24	7.76	10.30					
	STD	6.34	4.43	5.91					

Note that these statistics have only been computed from 2016 to 2017 for IKS and only for 2018 for NAR and QAS_M.

TABLE S. 3 Correlation (R), bias (m/s), RMSE (m/s) and centered RMSE (RMSEC, m/s) between wind gust observation data from DMI stations and MAR wind speed values for 2016-2018. The mean gust speed (m/s) and standard deviation (STD, m/s) have been calculated from the observation data.

Station	Statistic	Winter	Summer	Yearly	Station	Statistic	Winter	Summer	Yearly
ANG	**R**	**0.50**	**0.48**	**0.57**	NAR	**R**	**0.81**	**0.86**	**0.84**
	Bias	-0.58	-1.06	-1.19		Bias	-1.65	-2.52	-1.86
	RMSE	7.39	5.12	6.23		RMSE	4.25	3.67	3.84
	RMSEC	7.37	5.01	6.12		RMSEC	3.91	2.67	3.36
	Mean	12.28	7.79	10.29		Mean	7.25	6.10	6.82
	STD	7.65	4.93	6.82		STD	6.72	4.98	6.17
IKM	**R**	**0.69**	**0.74**	**0.72**	NUN	**R**	**0.79**	**0.81**	**0.84**
	Bias	-1.72	-1.47	-1.27		Bias	-5.55	-3.52	-4.76
	RMSE	6.19	3.79	5.01		RMSE	7.55	4.98	6.50
	RMSEC	5.95	3.49	4.84		RMSEC	5.12	3.52	4.43
	Mean	11.52	7.01	9.07		Mean	15.78	10.34	13.49
	STD	8.24	5.14	6.99		STD	7.96	5.85	7.59
IKS	**R**	**0.77**	**0.83**	**0.81**	UKI	**R**	**0.69**	**0.74**	**0.72**
	Bias	-3.31	-1.70	-2.20		Bias	-2.68	-1.29	-2.08
	RMSE	7.30	4.29	5.67		RMSE	4.92	3.03	4.22
	RMSEC	6.51	3.94	5.22		RMSEC	4.13	2.74	3.67
	Mean	15.08	8.96	11.73		Mean	9.56	6.67	8.35
	STD	9.88	6.78	8.52		STD	5.72	4.08	5.25

Note that these statistics have only been computed from 2016 to 2017 for IKS and only for 2018 for NAR.

S.2 Summer and Winter wind speed anomalies

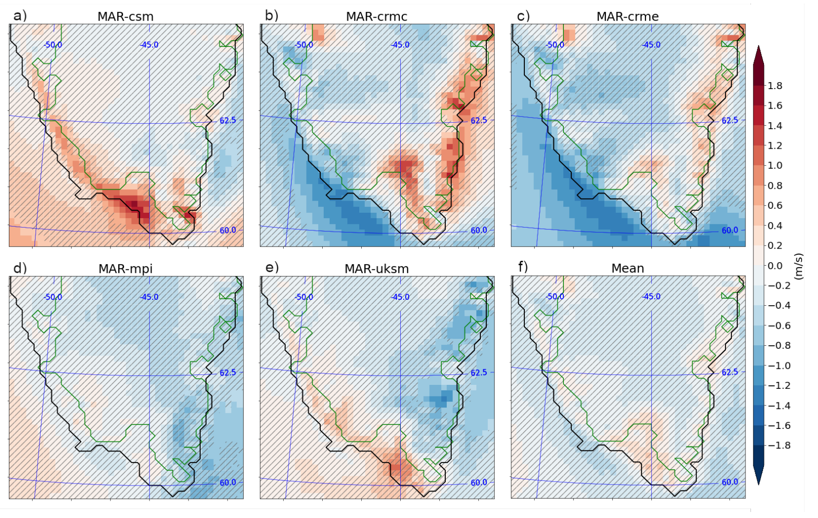

FIGURE S. 1 Summer wind speed anomaly (JJA) between the five ESM-forced simulations and MAR-ERA5-ref from 1981-2010. The hatched area represents the regions where the anomaly is not significant with regard to the summer inter-seasonal variability of MAR-ERA5-ref. The modelled shore line (black), ice sheet contour (green) and longitudes/latitudes (blue) are represented by solid lines. The subplot f) is the mean anomaly of the five simulations.

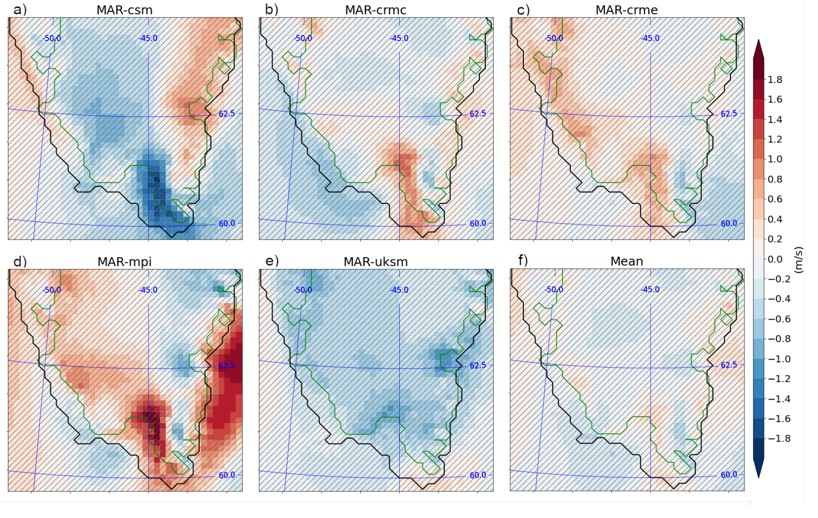

FIGURE S. 2 Winter wind speed anomaly (DJF) between the five ESM-forced simulations and MAR-ERA5-ref from 1981-2010. The hatched area represents the regions where the anomaly is not significant with regard to the summer inter-seasonal variability of MAR-ERA5-ref. The modelled shore line (black), ice sheet contour (green) and longitudes/latitudes (blue) are represented by solid lines. The subplot f) is the mean anomaly of the five simulations.

S.3 Multi-level mean wind speed change

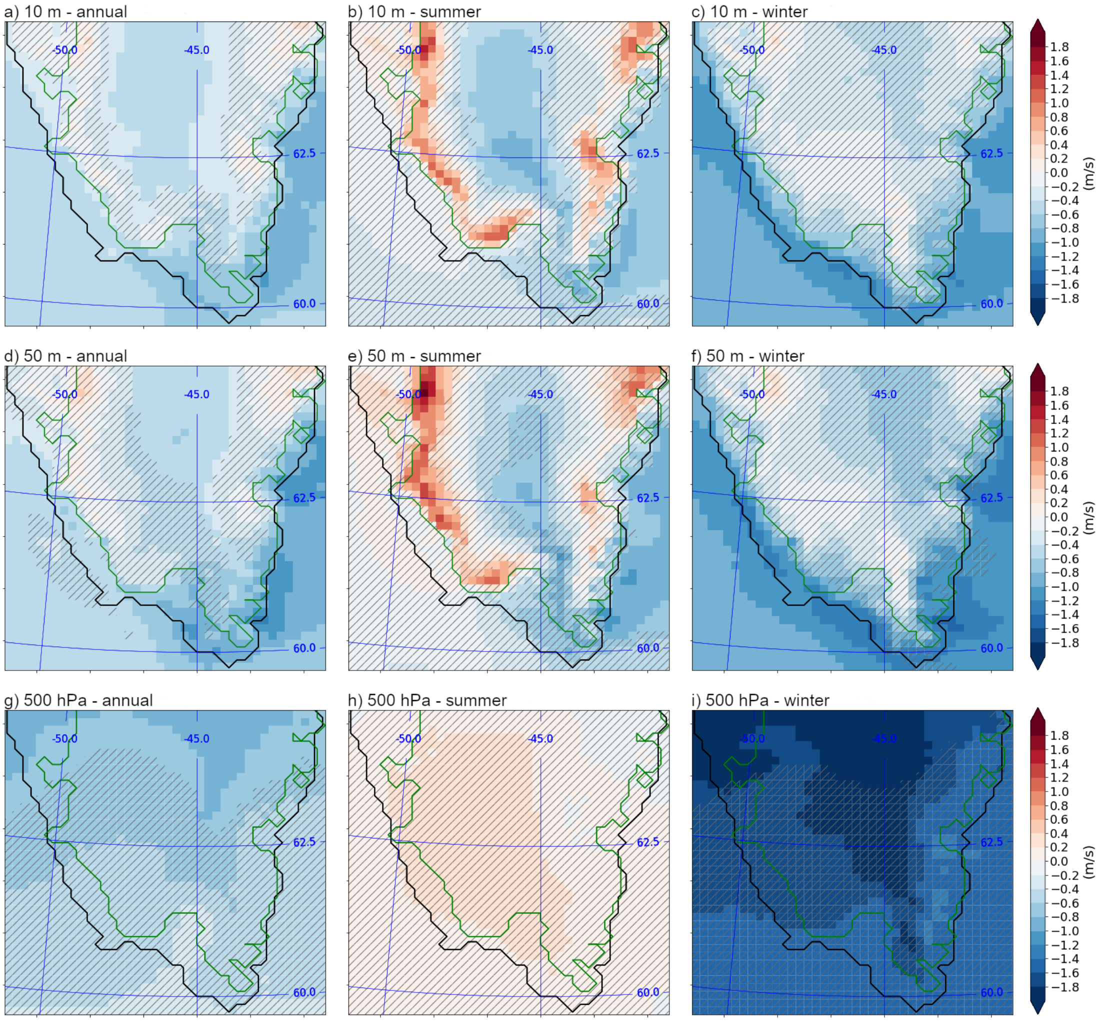

FIGURE S. 3 Mean projected wind speed change between 1981-2010 and 2071-2100 at 10 and 50 m a.g.l. and 500 hPa at annual and seasonal scale (JJA and DJF). Mean of all five ESM-forced MAR simulations. The modelled shore line (black), ice sheet contour (green) and longitudes/latitudes (blue) are represented by solid lines.

references

Cappelen, J., Jørgensen, B. V., Laursen, E. V., Stannius, L. S. and Thomsen, R. S. (2001) The observed climate of Greenland, 1958-99 – with climatological standards normals, 1961-90. *Tech. Rep. 00-18*, Danish Meteorological Institute, Ministery of Transport, Copenhagen,Danemark.