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The Cryosphere
Discussions

How does a change in climate variability impact the Greenland ice-sheet surface mass balance?

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Abstract. The future of the Greenland ice-sheet largely depends on the changing climate. When ice-sheet models are run for time periods that extend far beyond the observational record they are often forced by climatology instead of a transient climate. We investigate how this simplification impacts the surface mass balance using the Bergen Snow Simulator. The model was run for up to 500 years using the same atmospheric climatology, but different variability, as forcing. We achieve this by re-arranging the years in the ERA-interim reanalysis while leaving the intra-annual variations unchanged. This changes the surface mass balance by less than 5 % over the entire Greenland ice sheet.

However, using daily averages as forcing introduces large changes in intra-annual variability and thereby overestimates the Greenland-wide surface mass balance by 40 %. The biggest contributor is precipitation followed by temperature. The most important process is that small amounts of snow fall from the daily climatology overestimate the albedo, leading to an increased SMB. We propose a correction that distributes the monthly precipitation over a realistic intra-monthly variability. This approach reduces the SMB overestimation to 15-25 %. We conclude that simulations of the Greenland surface mass and energy balance should be forced with a transient climate. Particular care must be taken if only climatological data is available for simulations with a model that was calibrated with transient data. If daily transient data cannot be used, at least the precipitation should follow a natural daily distribution.

1 Introduction

The Greenland ice sheet is one of the main contributors to sea level rise. Ice-sheet models are run to project the future of the ice-sheet. Future projections show that uncertainty associated with the atmospheric climate forcing becomes the dominant component within the next century (Aschwanden et al., 2019). The climate forcing itself is inherently uncertain due the used boundary conditions (like an emission scenario) (O'Neill et al., 2016) but also depends on the used climate model, which remains a major source of uncertainty until the end of the century (Holube et al., 2021). Furthermore, ice-sheet models may be forced with a multiyear climatology, monthly or daily data with unclear consequences due to the non-linearity, increased melt at warmer temperatures, of the SMB.

Paleo simulations of ice-sheets are often based on proxy temperature reconstructions (Van de Berg et al., 2008; Robinson et al., 2011). Because proxy data has a limited temporal resolution, it is often impossible to accurately reconstruct inter- and

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intra-annual variability. While it is common practice to use a constant temperature index to interpolate between the coldest (Last Glacial Maximum) and the warmest (Present Day) state (e.q. Forsström and Greve, 2004; Alvarez Solas et al., 2018), it has not been studied what impact additional variability on short time scales would have. The effect of additional non-resolved variability may be an even larger issue as the most common temperature proxies used are ice cores, which in turn rather reflect the precipitation events than only climatological temperatures (Madsen et al., 2019). Proxies vary greatly in their temporal resolution, so we investigate the variability on multiple time scales (50 - 500 years). Although the initial question arises from proxy and climate reconstruction it is equally applicable to projections of the distant future of the Greenland ice sheet.

In this study, we perform simulations using the latest version of the BEr*gen* Snow SImulator (BESSI) (Zolles and Born, 2021). Prior model parameter tuning was performed relative to the GRACE satellite data set and RACMO simulations (Noël et al., 2018; Fettweis et al., 2020a; Holube et al., 2021). The model is designed for the simulations of long time scales, leading to a trade off between complexity and computational efficiency. Therefore, we need a representative climate forcing for longer time periods.

Input data to force BESSI is derived from the ERA-interim reanalysis data set, instead of using an artificial inter-annual variability or internal climate model variability (Semenov, 2008; Verdin et al., 2018) based on a climatology. Firstly, the rapidly increasing temperature over the last 50 years is a good example of a non-representative climatological average. Secondly, ERA-interim provides a reasonable natural variability and daily data is available over the entire Greenland Ice-sheet at a sufficiently high spatial resolution (Berrisford et al., 2011). Potential climate model data for climate reconstructions and projections will be of a similar or lower resolution. Climate variability of different time scales is achieved by a reordering the individual years. The ultimate test is weather a re-arranged forcing mimics reality by simulating the same SMB as the transient - real - forcing. For a longer simulation duration the ERA-interim period is copied multiple times. We use ERA-interim as its resolution is of the same order of magnitude as most Global Circulation climate Models (GCM) and refrain from higher resolution models like MAR (Fettweis et al., 2017) or RACMO (van Meijgaard et al., 2008) as those will not be available for the most of the past (last glacial) and are computationally demanding. We choose the current rapid climate change as it provides an upper uncertainty estimate for the entire glacial. Furthermore, the model sensitivity of the surface mass balance model has been evaluated prior for this time period (Zolles and Born, 2021).

This leaves us with three goals of the study:

- Quantify the uncertainty associated with inter-annual variability and climatological forcing
- Identify the reasons for and potentially reduce this uncertainty
- Find a procedure to create a representative climate forcing for the past based on temperature proxies

In section 2 we will give a brief description of the surface mass balance model and the set-up of the climate ensemble used in this study. The results in section 3 are split into the uncertainty of inter-annual variability, individual forcing variables, and precipitation and associated albedo impact. After that, we discuss our findings in section 4 and conclude in section 5.

2 Model setup

2.1 Snow model - BESSI

The study uses the Bergen Snow SImulator (BESSI), which calculates the mass and energy balance with a daily time step (Born et al., 2019). It compares well to other surface mass balance models over Greenland with a slight positive bias for melt regions (Fettweis et al., 2020a). The latest model version is described in detail in Zolles and Born (2021) so that we will only provide an abridged description here. The model domain is based on a stereo-graphic projection of Greenland and uses an equidistant grid with a resolution of 10 km. The model uses a mass based vertical grid of 15 layers, with up to 500 kgm^{-2}. The model uses five input fields with a daily resolution: surface temperature, total precipitation, dew point, and down-welling long- and shortwave radiation. A full energy balance is calculated at the surface including diffusion of heat in the snow pack and latent contributions from freezing and melting of water and liquid precipitation. Liquid water in the snow is explicitly represented. Mass changes due to melting, precipitation, or sublimation processes. The model parameters have been tuned using a multi-variate calibration towards RACMO (Noël et al., 2018) and the GRACE data set.

2.2 Atmospheric climate forcing

We use the daily ERA-interim reanalysis data from 1979-2017 (Uppala et al., 2011). The input variables of atmospheric temperature, precipitation, dew point, and short and long-wave radiation are bi-linearly interpolated to a 10x10 km grid over Greenland. This initial forcing data of 39 years is then taken 12 times to represent longer time periods. We define the natural transient forcing as the ERA-interim forcing in the true historical order and then looping forward and backward (F-BWD). This means the following order 1979-2017-1979-2017-1979-.. .

We arrange the original transient forcing in four different ways: repeating the ERA-interim forcing in its original order multiple times (forward, FWD), repeating the same data in reverse order (backward, BWD), alternating between FWD and BWD to avoid the abrupt transition between the forcing years 2017 and 1979 (forward-backward, F-BWD), and again the same in reverse (backward-forward, B-FWD). This already creates synthetic time series with different frequencies (Fig. 1). However, to achieve even lower frequencies with the same data we also re-arrange the original transient forcing based on the Greenland ice-sheet wide average annual air temperature. This changes the order of the 39 years in the record. Note that this does not break the consistency between the atmospheric variables, or add energy or mass to the atmospheric system relative to the original natural forcing. Temporal continuity is only broken at the year break with arguably negligible consequences.

The other time series are the temperature ordered forcing with different frequencies (rows) and sequential arrangement (columns, similar to the first row). All these time series have the same average forcing values, respectively the daily same climatology, but different temporal variability. They are obtained by ordering the 12 cycles of 39 years by the Greenland wide temperature from the coldest of the series to the warmest. Afterwards depending on the chosen frequency we sample every n-th member of this series starting at the coldest/warmest year, where n is the frequency and once the end of the series is reached we start over at the 2nd member sampling every n^{th} member thereafter, this is repeated in total n times for one time series.

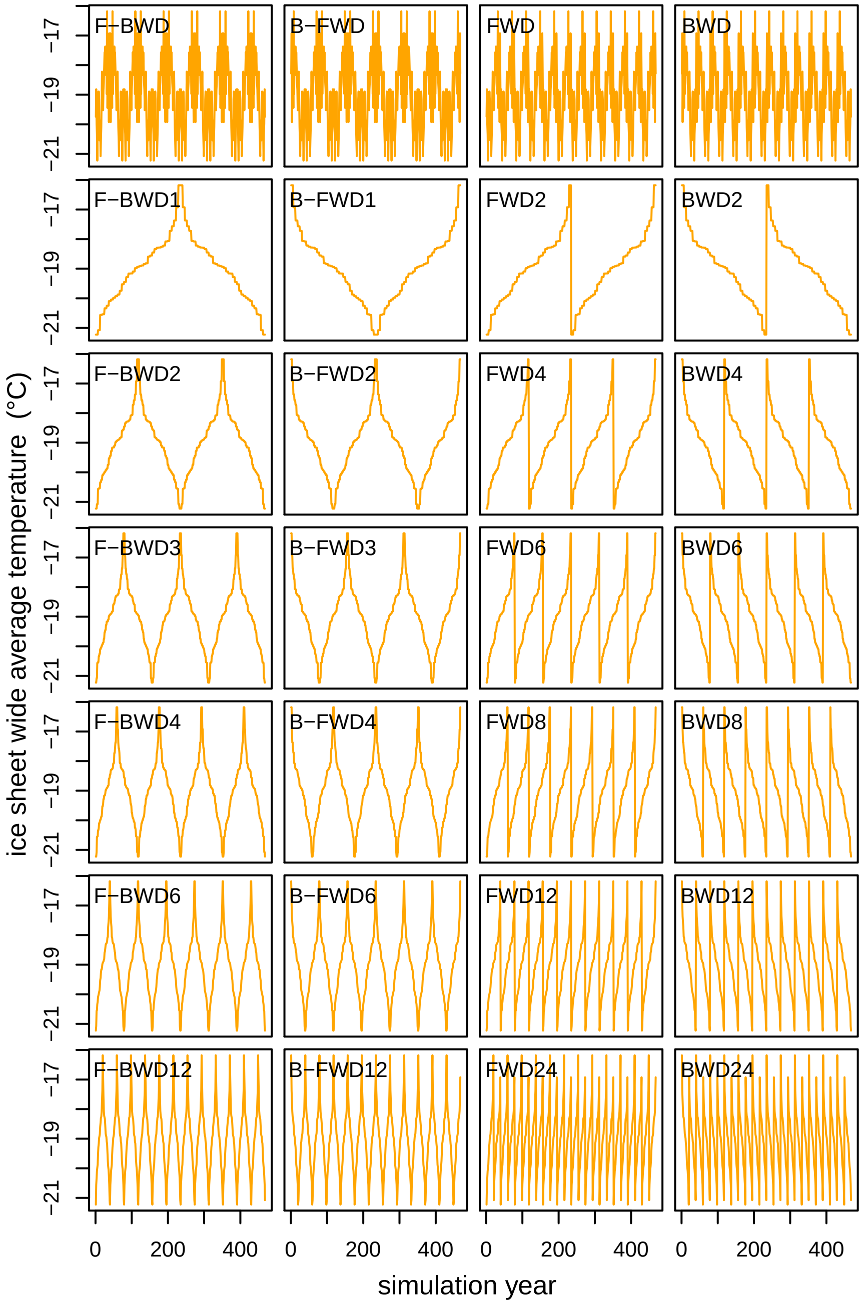

Figure 1. 28 different temperature time series based on 12 cycles of ERA-interim forcing. Each of them consist of the 12x39 years of ERA-interim which are ordered by temperature with different reoccurring frequencies. The first row shows the normal ERA-interim sequence (1979-2017) with different reoccurring patterns (2017-1979-2017x6,1979-2017-1979x6,1979-2017x12,2017-1979x12). Rows three to six show the temperature ordered sequence with increasing frequencies, with row one starting cold (F-BWD) and row two starting warm (B-FWD). Instead of looping back and forth from cold to warm the last two rows (orange) only increase/decrease in temperature and once the maximum/minimum is reached it starts over with the coldest/warmest forcing year again.

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These individual forcings allow us to investigate the sensitivity and feedback of the SMB to different inter-annual variability and, for example, extended warm periods.

2.3 Simulations

All simulations are spun up with 500 years of ERA-interim F-BWD to reach a stable firn cover. We then simulate the surface mass balance with the different forcing time series (sec. 2.2). The surface mass balance is calculated for five different total simulations with a duration of 78, 117, 156, 234 and 468 years, to mimic different temperature proxy resolutions

The first set of simulations use the unaltered transient climate forcing only reordered in time (FWD/BWD/F-BWD/F-BWD 1-12). The second set of simulations mixes climatological and transient forcing. Lastly, we investigate the impact of the temporal precipitation distribution by simulating 468 years with the same monthly precipitation average but different sub-monthly frequency.

3 Results

Inter-annual variability - ordering The average surface mass balance of the Greenland ice sheet is around 200 $\mathrm{kg\,m^{-2}\,yr^{-1}}$ independent of the ordering of the forcing years (fig. 2). The lowest SMB occurs if multiple warm years happen after each other, corresponding to a low frequency (second row FWD/BWD/F-BWD/F-BWD 1). The memory effect of the firn cover to extended warm periods is rather low on an integrated level, though in the extreme case of only one cycle the SMB is slightly lower on the second cooling branch than the warming one. Within each frequency BWD (last column) always shows the lowest SMB, because it starts with the warmest year and no protective firn cover can be built up first to reduce the amount of ice exposure. Note that we do not simulate changes in surface elevation, which could cause a significant positive feedback at multi-centennial time scales.

While the temporal order for the forcing years is of marginal influence ($< 5\%$ difference in SMB) over the entire ice-sheet, it is larger on a regional level. The variability mainly impacts the SMB around the equilibrium line, with a standard deviation of up to 500 $\mathrm{kg\,m^{-2}\,yr^{-1}}$ on the local scale (fig. 3). The standard deviation is also quite high in the northeast.

As proxy resolution is variable we also study additional simulation lengths of 78, 117, 156, and 234 years, corresponding to two, three, four, and six ERA-interim cycles. The general results are similar for shorter simulation periods (78, 117, 156, and 234 years instead of 468), though the difference between the simulations decreases, as with fewer ERA-interim cycles the duration of extended warm or cold periods decreases (not shown).

Climatological forcing / Intra-annual variability As the order of the inter-annual variability has a low impact, can we actually use daily climatologies? We study the impact of the daily climatology for every variable individually and only for the B-FWD case. Two mixed data sets are created, one where all but one variable are held at their climatological averages, and vice versa, where only one variable uses the climatology. Based on the results from the previous section we select the B-FWD member as a representative for the transient forcing, as the other reordered time series yieled similar SMB values.

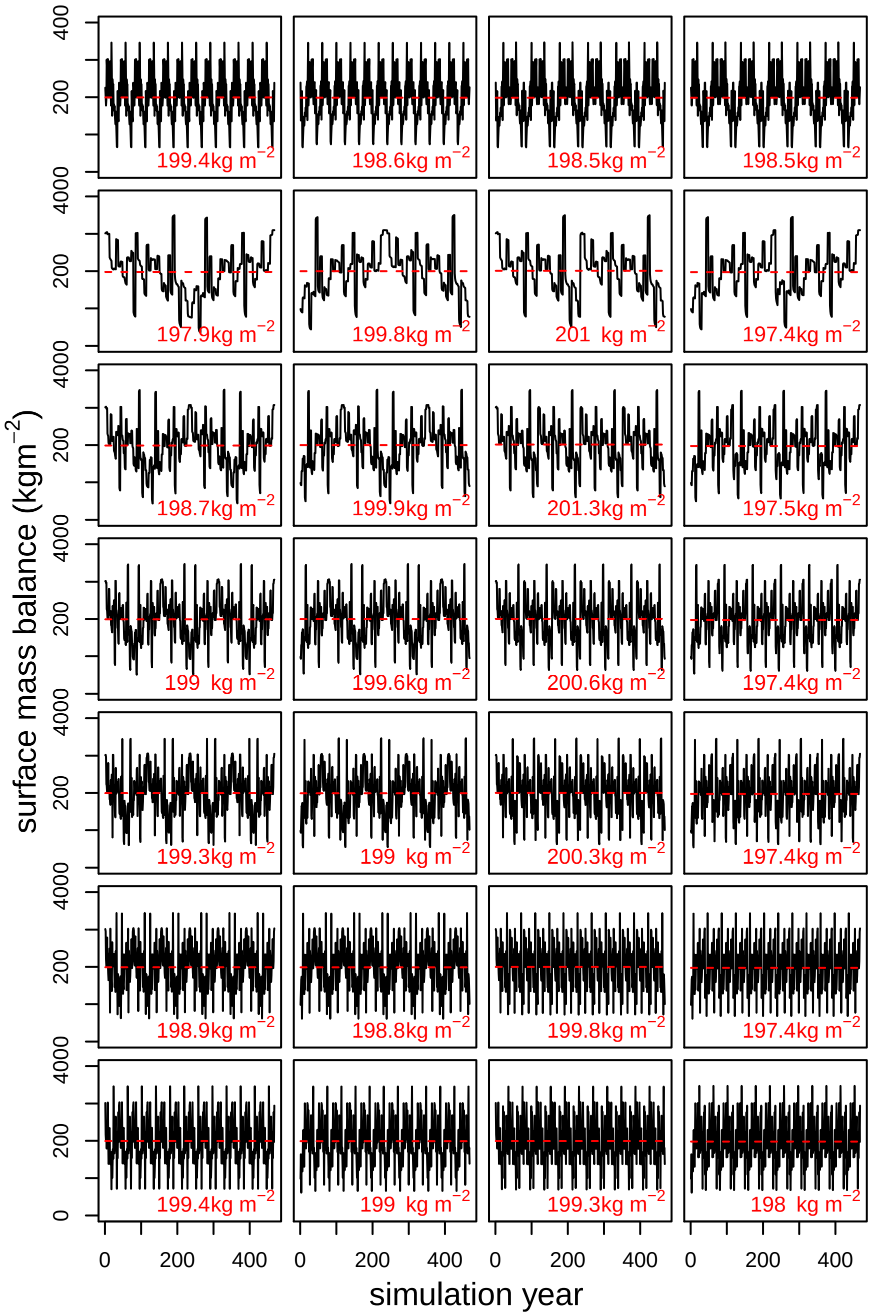

Figure 2. The SMB response of the Greenland ice-sheet to climate forcing with different inter-annual variability. Each box displays the annual surface mass balance over the entire simulation period of 468 years in black and the mean in red. The respective forcing is in the same order shown in figure 1, with F-BWD,B-FWD,FWD,BWD from left to right. The difference between the SMB with the different forcing is below 5 %.

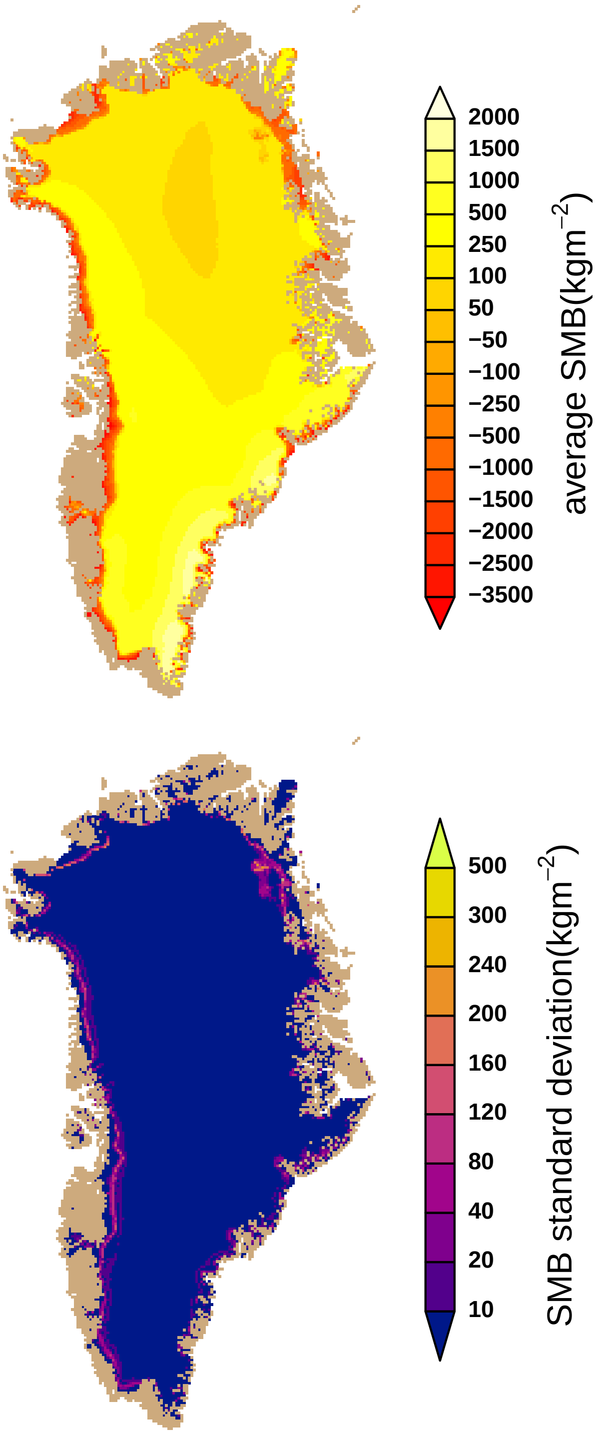

Figure 3. The average SMB and its standard deviation of the 28 simulations with different inter-annual variability order. The individual ensemble members all have the same climatology. The variation in the SMB is greatest around the equilibrium line and the northeast.

The daily climatology leads to a drastic overestimation of the SMB by 40 % (274 $\mathrm{kg\,m^{-2}\,yr^{-1}}$ Fig. 4 a,b.). We further investigate this overestimation by studying the impact of the individual forcing variables: using a transient forcing for all but one variable, which comprises of daily climatological averages (right), and the climatological forcing is mixed with one transient variable (left) (fig. 4 c-l). The SMB of these simulations exceed the transient forcing (4 b), meaning that daily climatologies always lead to an SMB increase. This is no surprise due to the non-linearity of the SMB to energy input. There is a clear difference in the impact of the individual variables. While the climatological dew point only slightly changes the SMB (fig. 4 l), the radiation components increase the SMB by 5 % (fig. 4 h, j). Average temperatures increase the SMB by 15% (fig. 4 d) and daily averages of precipitation increase the SMB by 30% (fig. 4 f). Vice versa the complementary effect is true for climatological forcing (fig. 4 c, e, g, i, k), with climatological forcing with transient precipitation showing the lowest SMB (fig. 4 e).

The small effect and low variability of the radiation components shows that using climatologies is justified in this case (fig. 4 g-j), as the inter-annual variability of Greenland wide radiation is relatively low anyway. Though it is still connected to a slight bias of 5% in the current climate. The turbulent latent heat flux has a relatively low impact on the Greenland wide SMB (Zolles and Born, 2021), which is in line with the low effect the dew point change has (fig. 4 k, l). While the biggest differences between the previous simulations where found around the equilibrium line (fig. 3), the largest difference between climatological and transient forced SMB simulations is found in the melting region of Greenland (fig. 5). Temperature has the second highest influence, which can be attributed mainly to the non-linearity of the SMB. However, the overestimation by climatological precipitation cannot be explained by the non-linearity, but the albedo. Using a daily climatology leads to small amounts of mostly snowfall every day leading to a surface albedo increase. The annual average albedo increase is up to 0.1 in the melt region of Greenland. The drastic effect of daily climatologies of precipitation can be attributed to this albedo overestimation.

Can we emulate intra-annual variability of precipitation? We have shown that BESSI overestimates the SMB drastically if daily climatologies of precipitation are used. A daily climatology is unrealistic as it has small amounts of snow fall every day. This does not agree with observations of highly event-based precipitation in the Atlantic region (Sodemann et al., 2008). We therefore calculate alternative temporal precipitation distributions by taking monthly averages with a sub-monthly distribution instead. Regular precipitation frequencies of 2, 4, 8, 15, and 30 days are tested as well as the sub-monthly distributions from each of the 39 ERA-interim years. For the ERA-interim based distributions the original daily time series P_{day} is scaled to have the same monthly average:

$$P_{day} = P_{day}^{t} \cdot \frac{\overline{P_m}}{P_m^t} \quad \forall t \in [1979, 2017] \tag{1}$$

with P_m^t as the monthly mean of the year t, and $\overline{P_m}$ the monthly climatological precipitation amount. This correction can be compared to the Delta Method for precipitation (Beyer et al., 2019). We obtain 39 possible precipitation time series, each with a different sub-monthly distribution of the precipitation analogous to the true precipitation of the specific year. Though the monthly sum of precipitation is similar for all the simulations the resulting distributions are quite different. April 2014 was a

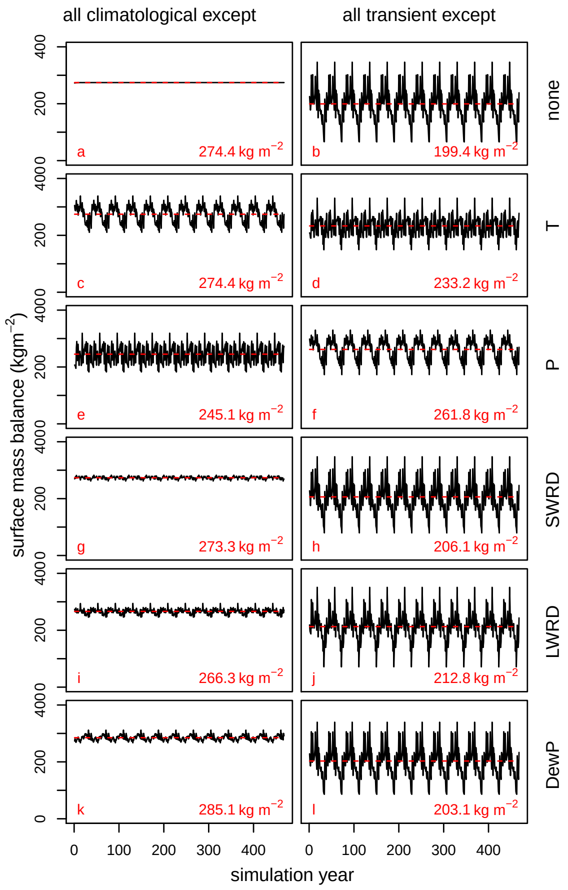

Figure 4. The Greenland wide integrated SMB with climatological and transient forcing. On the left side the model is forced with climatological (daily averages) forcing, with one transient variable in the rows 2-6. Transient forcing mixed with one climatological variable is shown on the right. The climatologically forced SMB model (a) overestimates the SMB relative to the fully transient case (b). If transient variables are taken individually the precipitation lowers the SMB the most (e). Vice versa climatological precipitation distorts the "true" transient SMB the most (f). Climatological dew point, short-wave and long-wave radiation lead to slightly increased SMB (h, j, l).

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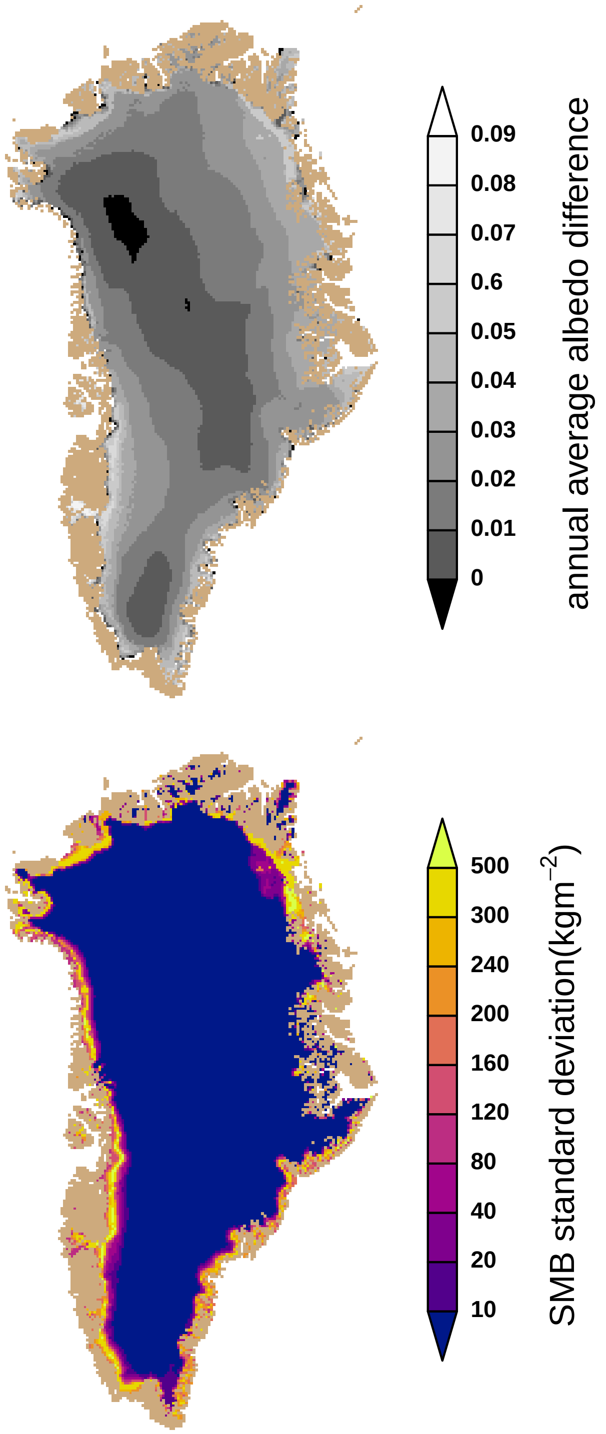

Figure 5. The standard deviation of the SMB for the transient and climatological mixed simulations (fig. 4) on the bottom, and the difference between the transient and the climatological forced surface albedo on the top. The largest standard deviation is in the melt region, due to an up to 0.1 larger annual average albedo.

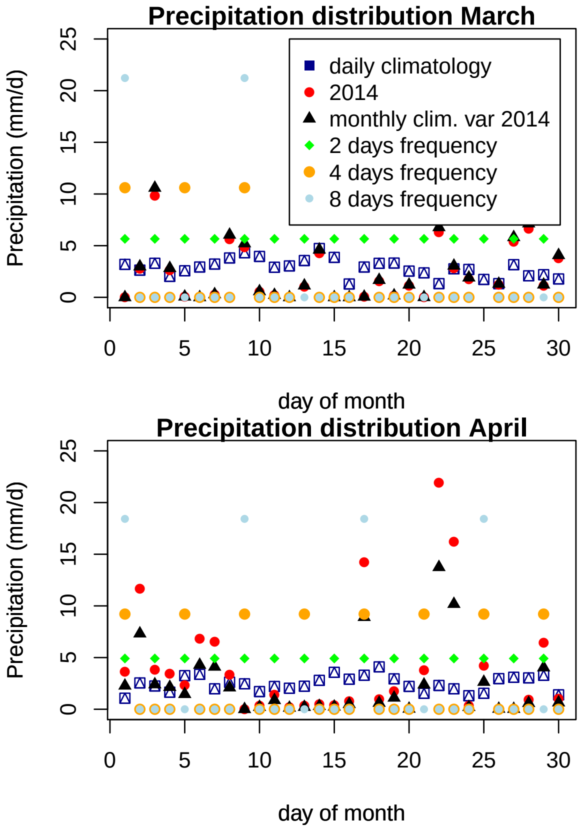

Figure 6. Sub-monthly precipitation distribution for March and April of different simulations. The same monthly precipitation is either distributed via daily climatologies (blue), monthly climatology with the sub-monthly distribution of, for example, 2014 (black) or with regular frequencies (green, orange, light blue). The red distribution is the true distribution for 2014 which is then adjusted to the climatological average (black, eq. 1), as can be seen April 2014 was wetter than the average April of the ERA-interim period.

wet month, so for the resulting forcing it is adjusted to be less but still has four days with precipitation of up and above 10 $kg\ m^{-2}$ (fig. 6).

The simulated SMB depends on the chosen sub-monthly precipitation distribution (fig. 7). For regular precipitation the SMB decreases with precipitation frequency (255/233/200/154 and 87 $\mathrm{kg\ m^{-2}\ yr^{-1}}$ at precipitation every $2^{nd}/4^{th}/6^{th}/15^{th}$ and 30^{th} day). Independent of the forcing type of the other variables introducing a lower frequency than precipitation every day (daily climatology) decreases the SMB, this is also true for the sub-monthly distribution from the individual 39 ERA-interim years (fig. 7c, d). The precipitation heavy years of the unaltered forcing are now showing lower SMBs than in the B-FWD simulation. The monthly climatology (fig. 7d) instead of the daily climatology (fig. 7b) reduces the mass balance by

$30\ \mathrm{kg\ m^{-2}\ yr^{-1}}$, which is much closer to the "true" value of the transient forcing (fig. 7a). The amplitude of this simulations SMB time series is rather low as the same amount of precipitation falls every year, it was investigated further. Instead of using different sub-monthly frequencies every year the distribution from each year ERA-interim year is taken as the forcing for the entire simulation period (as example 2009: fig. 7 f,g; the entire range is given in fig. 8). It spans from 224-253 $\mathrm{kg\ m^{-2}\ yr^{-1}}$. Using the sub-monthly precipitation distribution for the climatology reduces the SMB overestimation from 40% to 10-25%. A Greenland wide regular frequency may by chance show similar values as the transient simulation (8 days in this case), and 2-8 days give SMB values comparable to natural distributions.

The decrease in SMB is due to the non-linearity effect of the SMB, as in dry years earlier ice exposure triggers a feedback. Due to the non-linearity of the mass balance and albedo feedback, the range of these simulations is larger than the amplitude of the single simulation (fig.7 d).

4 Discussion

We study the impact of inter-annual variability by a simple reordering. The SMB shows a low dependency of 5% over 468 years on the order of the forcing. In case of unknown inter-annual variability the use of a climatological forcing over estimates the SMB by 40 % due to the non-linearity of the SMB and albedo overestimation. We try to reduce this effect by instead using only monthly precipitation averages with a sub-monthly distribution. The overestimation is reduced but an uncertainty of 15% based on the chosen distribution is introduced.

Climate model simulations of the same time period vary in their inter-annual variability, they can very well represent the climatology, but not the order. We show that the effect of the order of the inter-annual variability is less than 5 %. This indicates that the memory effect of the Greenland wide integrated SMB to multiple warm or cold years is low enough to be modeled with climate forcing which may not have a realistic temporal variability. Even multiple warmer years over Greenland after each other do not significantly lead to strong feedback. The used ERA-interim period with its temperature trend (Hanna et al., 2021) as the study period can be considered an upper boundary for steady state climate. The simulation lengths were 78,117, 156, 234 and 468 years, and even the extreme case of 12 consecutive years with the warmest temperature the average SMB only decreased by 3.5 %. If the climatology is known and the amplitude of the variability of the forcing data, the order does not really matter, despite the high inter annual variability observed in line with Van den Broeke et al. (2011). In case of climate simulations based on climatologies derived from proxies or other boundary conditions they likely are applicable for SMB simulations as long as the amplitude of the variability is good, even if there is a sub-resolution trend not visible in the proxy data. However, the effect is larger on a regional basis and around the equilibrium line the sensitivity towards this inter-annual variability increases. For the ERA-interim climate the northeast of Greenland with its sparse precipitation and large inter-annual variability in particular shows a standard deviation of up to 300 $\mathrm{kgm^{-2}yr^{-1}}$.

If the inter-annual variability is not known as is most often the case for the distant past or future, the forcing has to be based on climatologies. BESSI uses daily forcing data and is sensitive to daily precipitation. A small amount of snow-fall every day leads to an albedo overestimation as BESSI resolves albedo adjustments on a daily bases. A possible solution is to

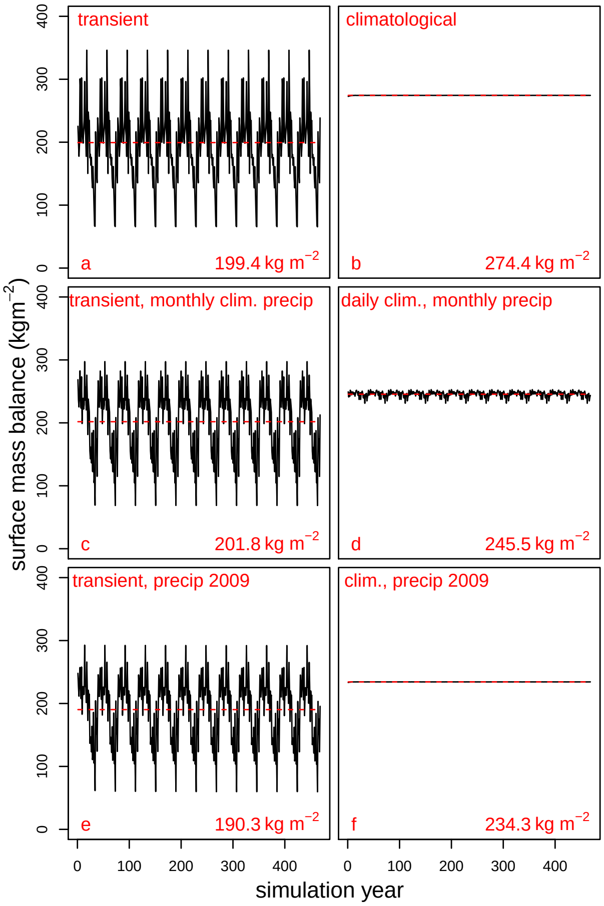

Figure 7. The Greenland-wide integrated SMB forced with different precipitation variability. The SMB time series is shown in black, with the average SMB as a red line. The SMB average value is shown in each panel. The transient B-FWD (a) and the full daily climatology (b) are shown again for direct comparison and are identical to Figure 4. The transient precipitation was scaled to have the same monthly average every year, with the sub-monthly frequency of the individual years, which is combined with either transient forcing (c) or daily climatological forcing (d) of the other variables. Similarly, we combine the sub-monthly precipitation distribution of one year, 2009, with transient (e) and the daily climatological (f) forcing of the other variables. 2009 was chosen as its monthly precipitation distribution is closed to the climatological average.

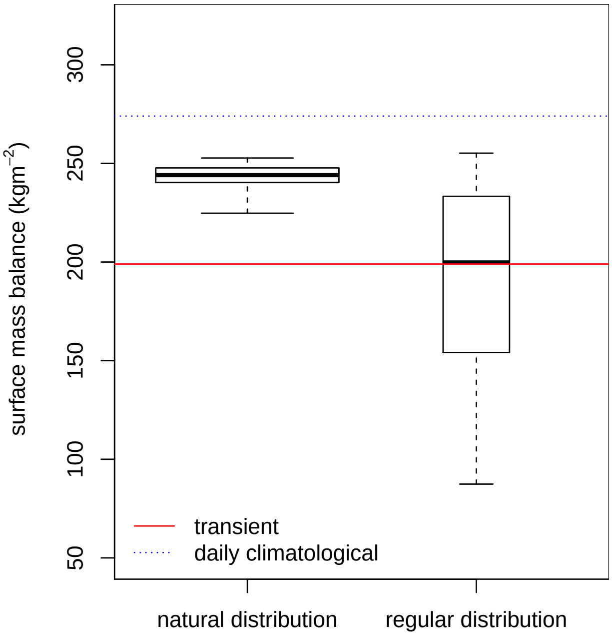

Figure 8. SMB averages for climate forcing with different precipitation variability based on the ERA-interim ensemble. In total 39 different sub-monthly natural precipitation distributions are shown on the left based on monthly averages distributed by the 39 × 12 sub-monthly distributions of each year 1979-2017. The SMB response to regular precipitation on the 2/4/6/15/30th day is on the right. The simulations are forced with the daily climatology of temperature, short and long-wave radiation, and dew point. The width of the boxes is relative to the size of the ensemble (39/5).

parameterize the albedo routine differently for climatology and transient data. Alternatively, the precipitation climatology has to be calculated in a physical more reasonable way which we explore here. We show that monthly climatologies with a natural sub-monthly distribution reduce the SMB overestimation. In practice, there are multiple ways how to define such a distribution: regular or stochastic frequencies for a region using normalized precipitation from reanalysis or climate simulation data. Either approach, may be prone to the sampling period and not invariant in time, and multiple solution may exist. The redistributing of the same precipitation amount at each grid point within a month can change the SMB by 15% (fig. 8). This is to be considered when selecting the fields for projections or reconstructions, purely based on scalar temperature and/or precipitation anomalies of a given field. The precipitation is quite variable in Greenland (Mosley-Thompson et al., 2005), but not only the total amount is important but also its temporal distribution, in particular in the melt region. There is no clear best representative of the precipitation variability among the individual years of the ERA-interim period.

Based on our findings we suggest that in the absence of full climate simulations with natural variability, temperature and precipitation anomalies are applied to a related climatology with sub-monthly frequency in precipitation. Still using climatological forcing may be overestimating SMB, as it does for BESSI, due to the non-linearity of mass balance, which is in line with (Mikkelsen et al., 2018) who found a 13 % overestimation of the SMB if inter-annual temperature fluctuation is not considered. The choice of the representative precipitation distribution which is scaled may be accompanied by an uncertainty of up to 15%.

BESSI does not use sub-daily parameterizations for the daily cycle, which could reduce the effect of small amounts of snow falling every day and the accompanied albedo overestimation while using climatological forcing if considered. Though small amounts of precipitation every day are physical not reasonable for the region and it has to be considered in the snow models. BESSI showed a positive SMB bias in general relative to other snow-models, we cannot state how big the mentioned effects are for the other SMB models (Fettweis et al., 2020b).

We did not try to adjust climatological fields for temperature, or the other forcing variables. Due to the event based nature of the precipitation this has the biggest impact, but daily climatologies overestimate the SMB also due to the other variables too. The effect of the non-linearity alone has been previously studied with the model (Born et al., 2019). We furthermore did not study the impact of precipitation distributions on the point scale.

5 Conclusions

A surface mass and energy balance model was run for up to 500 years with different climate forcing. They all share the same climatology in the five forcing variables, atmospheric temperature, precipitation, long and short-wave radiation, and humidity. While different frequencies of climate variability have very little impact (< 5 %), using an average climate leads to a drastic overestimation (40 %) of the surface mass balance. This is mainly observed around the melt region of the Greenland ice sheet. The biggest contribution to this overestimation is the precipitation forcing (≈30 %), due to the resulting albedo increase. Averaging multiple years to obtain a climatology produces a data set with frequent light precipitation, and a high surface albedo due to the continuous presence of fresh snow. Small amounts of snowfall are not physically reasonable for a region with event based precipitation like Greenland.

To overcome the problem we calculated alternative precipitation climatologies to be used together with daily climatologies of the other variables. Monthly averages following a natural sub-monthly distribution lead to the smallest errors. Though, there is a dependency on the chosen distribution. Using a regular frequency is not feasible as there is a large spatial dependency and empirical relations may change through time periods. We conclude that the surface mass balance model is best forced with transient climate. If daily climatologies with an altered precipitation forcing are used an overestimation of 15-25 % of the SMB should be assumed.

Code availability. The BESSI model code is available on git-hub (https://github.com/TobiasZo/BESSI)

Author contributions. TZ conducted the model tuning and ensemble simulations, the data analysis and wrote the main part of the manuscript. AB contributed to the study design, and the manuscript.

Table A1. The simulations done for this study.

	Years	78 y	156 y	234 y	468 y	# of simulations
ERA-interim	B-FWD	1	1	1	1	4
	F-BWD	1	1	1	1	4
	FWD	1	1	1	1	4
	BWD	1	1	1	1	4
temperature ordered, 6 frequencies	B-FWD	6	6	6	6	24
	F-BWD	6	6	6	6	24
	FWD	6	6	6	6	24
	BWD	6	6	6	6	24
Point wise temperature ordered, 6 frequencies	B-FWD				6	6
	F-BWD				6	6
	FWD				6	6
	BWD				6	6
Daily climatological forcing		1	1	1	1	4
Mixed forcing, 1 climatological variable	T, P, SW, LW, DewP				5	5
Mixed forcing, 1 transient variable	T, P, SW, LW, DewP				5	5
Other precipitation climatologies	Sub-monthly natural				39	39
	Regular 2,4,8,15,30				5	5
	mixed				3	3
						197

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

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