Future climate warming increases Greenland Ice Sheet surface mass balance variability

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The integrated surface mass balance (SMB) of the Greenland Ice Sheet (GrIS) has large interannual variability. Long-term future changes to this variability will affect GrIS dynamics, freshwater fluxes, regional oceanography, and detection of changes in ice volume trends. Here, we analyze a simulated 1850-2100 GrIS SMB time series from the Community Earth System Model, currently the only global climate model that realistically simulates GrIS SMB. We find a significant increase in interannual integrated SMB variability over time, which we attribute primarily to a shift to a high-variability melt-dominated SMB regime due GrIS ablation area growth. We find temporal increases to characteristic ablation and accumulation area specific SMB variabilities to be of secondary importance. Since ablation area SMB variability is driven largely by variability in summer surface melt, variability in the climate processes regulating the energy fluxes that control melting will likely increasingly regulate future melt-dominated GrIS SMB variability.

1. Introduction

The Greenland Ice Sheet (GrIS) is one of the Earth's two major ice sheets and is currently losing mass [*Shepherd et al.*, 2012; *Hanna et al.*, 2013] with mass loss partitioned roughly equally between decreases in the integrated surface mass balance (iSMB, the difference between integrated accumulation and surface ablation) and increases in discharge from glacier acceleration [*van den Broeke et al.*, 2009]. Multiple models project a large decline in iSMB to negative values by the end of the 21st century in response to anthropogenic forcing, implying eventual loss of the ice sheet [*Vizcaíno et al.*, 2013a; *van Angelen et al.*, 2013a; *Fettweis et al.*, 2013]. Superimposed on observed iSMB trends is large interannual iSMB variability [*Box et al.*, 2006, 2012; *Hanna et al.*, 2008], including extreme events such as the 1998, 2007, 2010 and 2012 SMB minima [*Mernild and Liston*, 2012; *van Angelen et al.*, 2013b; *Tedesco et al.*, 2013]. This variability is important for several reasons. First, it affects ice dynamics via the impact of supra-glacial melt on basal sliding [*Schoof*, 2010] and via the effects of subglacial freshwater discharge on fjord circulation and outlet glacier melting [*Sciascia et al.*, 2013]. Second, on a larger scale, iSMB variability contributes to variability in the GrIS-sourced freshwater flux to the ocean [*Bamber et al.*, 2012], which could alter local and regional patterns of ocean circulation [*Marsh et al.*, 2010; *Fichefet et al.*, 2003] and long-term sea-level trends. Lastly, increases in iSMB variability limit the ability to detect changes in GrIS volume trends [*Wouters et al.*, 2013].

These factors highlight the need to better understand historical and future trends in interannual GrIS iSMB variability. To date, studies have mainly provided time-invariant variability estimates for the recent historical period [e.g. *Box et al.*, 2006; *Ettema et al.*, 2009; *Vizcaíno et al.*, 2013b; *van Angelen et al.*, 2013b]. We build on these studies by a) analyzing time-varying interannual GrIS iSMB variability trends ('interannual' is implied hereafter) generated by a coupled Community Earth System Model (CESM) simulation spanning 1850-2100 under historical and Representative Concentration Pathway 8.5 (RCP8.5) forcing [*van Vuuren et al.*, 2011], and b) by clearly identifying the physical processes controlling the simulated variability changes that we find.

2. Methods

CESM [*Hurrell et al.*, 2013] includes the Community Atmosphere Model (CAM) and Community Land Model (CLM) at 0.9° x 1.25° resolution and the Parallel Ocean Program (POP) and Community Ice Code (CICE) ocean/sea ice models at 1° resolution. It explicitly resolves Arctic interannual climate variability [*de Boer et al.*, 2012]. Uniquely among global climate models, the CESM also includes un-bias-corrected energy-balance-based calculations of GrIS SMB [*Lipscomb et al.*, 2013], which account for detailed snow/ice surface processes such as albedo evolution, snow compaction and refreezing [*Flanner et al.*, 2007]. SMB calculations are carried out within CLM over multiple elevation classes, and the resulting SMB is remapped to present-day GrIS geometry at 5 km resolution [*Bamber et al.*, 2001]. This technique (detailed in the Auxiliary Material and *Lipscomb et al.* [2013]) allows for explicit resolution of the currently narrow GrIS ablation area within a global model simulation. CESM-simulated SMB has been comprehensively validated by *Vizcaíno et al.* [2013b] against 475 in-situ and remotely-sensed observations [*Cogley*, 2004; *Bales et al.*, 2009; *Ettema et al.*, 2009; *van de Wal et al.*, 2012], GRACE data [*Velicogna*, 2009], and relative to SMB calculated by the high-resolution 11-km RACMO2 regional climate model [*van Angelen et al.*, 2013b]. These comparisons (detailed further in the Auxiliary Material, Auxiliary Figures 1-3, and *Vizcaíno et al.* [2013b]) clearly highlight that CESM realistically simulates recent historical GrIS SMB in terms of magnitude, spatial distribution, and (importantly for this study) historical variability. The success of the CESM in accurately capturing the present state of GrIS SMB, along with its ability to simulate multi-century anthropogenically-driven climate trends, makes CESM uniquely well-suited to the current study.

The simulation we analyze here was initialized from a multi-century pre-industrial CESM control run, followed by a 100-year pre-industrial spin-up with SMB calculations enabled. From this steady state, the model was integrated forward under historical forcing from 1850-2005 and RCP8.5 forcing from 2006-2100. RCP8.5 is currently the most extreme Intergovernmental Panel for Climate Change forcing scenario, and results in net radiative forcing of 8.5 W/m^2 by 2100. Under this forcing scenario, we analyze the variability in SMB and its components (snowfall and runoff). We define that variability at year t as one standard deviation (σ) of the detrended time series over a 31-year window centered on t. Detrending was carried out using using empirical mode decomposition (Auxiliary Material). To exclude spurious initial and final variability values and to minimize aliasing, we calculate pre-industrial, present and future variability from 31-year averages of annual variability values for the periods 1865-1895, 1970-2000, and 2055-2085.

3. Results

Simulated 1865-1895 GrIS iSMB variability was 90 Gt/yr (Figure 1). For the 1970-2000 period, variability increased to 112 Gt/yr, and for the 2055-2085 period iSMB variability grew to 165 Gt/yr, an increase of 84% relative to 1865-1895 (48% relative to 1970-2000). Both changes are significant at the 99% confidence level. The frequency of years exceeding present-day iSMB variability bounds increased by 220% between 1970-2000 and 2055-2085, relative to the moving climatological iSMB mean. Thus we project that an anthropogenically-driven iSMB decline over the 21st century will be accompanied by a significant increase in iSMB variability. The present-day CESM-simulated variability agrees well with the variability simulated by a reanalysis-forced RACMO2 simulation (121 Gt/yr during 1992-2011) [*van Angelen et al.*, 2013b]. In addition, *van Angelen et al.* [2013a] indicate that RACMO2 forced by RCP4.5 HadGEM2-ES output captures a strong future iSMB variability increase (+35 Gt/yr between 1992-2011 and 2079-2098), providing independent corroboration of increased iSMB variability under climate warming. However, *van Angelen et al.* [2013a] do not elaborate on mechanisms behind the RACMO2 variability increase.

To explore the physical mechanism(s) behind increased GrIS iSMB variability in CESM, the overall iSMB time series was separated into contributions from the ablation and accumulation areas (Figure 1). These co-vary in extent in response to short-term climate variability and longer-term trends (Figure 2). The preindustrial overall iSMB correlated most highly with accumulation area iSMB (r = 0.90 between 1850-1880). By 2070-2100, however, the ablation area had emerged as the dominant control on overall iSMB

(r = 0.96), indicating a long-term shift to an iSMB variability regime dominated by ablation area processes. Furthermore, a dramatic 180% increase in ablation-area iSMB variability between 1865-1895 and 2055-2085 is the primary cause for the increase in total iSMB variability, when compared to the modest 13% accumulation-area iSMB variability increase over the same period.

To explain the overall iSMB variability increase, we first tested the hypothesis that a combination of increases in characteristic ablation-area and accumulation-area specific surface mass balance (sSMB, the local vertical SMB flux, units m/yr water equivalent) variabilities alone could be responsible for the overall iSMB variability change. To isolate these variabilities, grid cells undergoing exclusively ablation or accumulation for the entire simulation were gathered in separate 'ablation-only' and 'accumulation-only' bins from which mean sSMB variability trends were extracted (Auxiliary Figures 4-5). The mean sSMB in the accumulation-only area increased from 0.31 to 0.37 m/yr w.e. between 1865-1895 and 2055-2085, and the corresponding spatial-mean *variability* increased from 0.06 to 0.08 m/yr w.e. (28%). These increases were related to increases in interior mean snowfall and snowfall variability, respectively. In contrast, the mean ablation-only area sSMB decreased from -1.1 m/yr w.e. to -2.4 m/yr w.e., and the corresponding *variability* increased from 0.41 to 0.52 m/yr w.e. (28%). This increased variability was not caused by increased variability of the net summertime ablation-only area surface energy balance components (Auxiliary Figure 6), but rather by a lengthening of the ablation area bare-ice season (Auxiliary Figure 7). This increases the dependence of ablation-area sSMB variability on summer shortwave radiation variability by lengthening the exposure time of low-albedo glacial ice (which also contributed to a GrIS-wide July albedo decrease of 0.03 over the 21st century [*Vizcaíno et al.*, 2013a]).

The 28% increases in characteristic accumulation-only and ablation-only sSMB variabilities are notable and reflect the impact of climate change on GrIS snowfall and melting processes, respectively. However, these changes alone cannot quantitatively explain the much larger 84% increase in overall iSMB variability. For this reason, we turn to our second hypothesis, that growth of the high-variability ablation area is behind the overall increase in iSMB variability. Ablation area sSMB variability is substantially higher than accumulation area sSMB variability, with the area-mean ratio ($R_{abl:acc}$) between constant-ablation and constant-accumulation area sSMB variabilities ranging from 6.5 to 11.5 (with a time mean 8.9, Auxiliary Figure 8). This high $R_{abl:acc}$ is also found in observational time series of SMB at representative locations [*Van de Wal et al.*, 2005; *van der Veen and Bolzan*, 1999] and in RACMO2 model simulations [*Ettema et al.*, 2009] (Auxiliary Material), and arises from a high ratio between the variability of the primary sSMB components in the ablation-only and accumulation-only areas: meltwater runoff and snowfall, respectively (10.4, Auxiliary Figure 9). The contrast in sSMB variabilities and the sSMB gradient across the climatological equilibrium line altitude (ELA), are clearly apparent in Figures 3a and 3b.

High ablation area sSMB variability relative to accumulation area sSMB variability suggests that if the ablation area were to expand, the overall GrIS iSMB variability would increase due to a shift from a low-variability accumulation-dominated iSMB regime towards a high-variability, melt-dominated iSMB regime. In support of this reasoning, a

16% decrease in the accumulation area ratio (AAR, the ratio of the accumulation area to the total ice sheet area, Figure 2) is captured by the model as a result of anthropogenically-driven climate warming and increased melting [*Vizcaíno et al.*, 2013a], and Figure 3c highlights that the largest increases in sSMB occur between the 1865-1895 and 2055-2085 ELAs, where accumulation area is transformed to ablation area during the simulation. To estimate the standalone effect of ablation area expansion on overall iSMB variability, we performed two sensitivity experiments. First, ablation-area and accumulation-area sSMB variabilities were held constant at their initial pre-industrial levels, and the AAR was varied according to the trend from the full simulation (Auxiliary Material). The long-term 16% decrease in the AAR, with sSMB variabilities held constant, produced a 59% increase in overall iSMB variability between 1850 and 2100. Second, we held the AAR fixed and varied only the sSMB variabilities, which yielded a lower 28% increase in overall iSMB variability. The difference between these two experiments confirms that expansion of the high-variability ablation area is approximately twice as effective as increased sSMB variability in changing iSMB variability, and is thus primarily responsible for driving the overall GrIS iSMB variability increase in the coupled simulation.

4. Discussion and Conclusions

We conclude that a significant, anthropogenically-forced increase in simulated GrIS iSMB variability between 1850-2100 results primarily from ablation area expansion and a resulting shift from an accumulation-dominated to a melt-dominated SMB variability regime. We find simulated standalone increases to characteristic ablation and accumulation area sSMB variabilities to be of secondary importance to the overall iSMB increase.

In agreement with observations [e.g. *Van de Wal et al.*, 2005], ablation-area sSMB variability in CESM is primarily regulated by variability in surface runoff, which is in turn controlled primarily by variability in summer absorbed shortwave radiation. This relationship implies that, because of increasing ablation area, future melt-dominated GrIS SMB variability will be increasingly tied to the variabilities of incoming shortwave radiation and surface albedo, which are themselves impacted by regional circulation variability, clouds, and ice-sheet surface feedbacks [*Box et al.*, 2012]. In light of the projected shift to a melt-dominated GrIS SMB variability regime, analysis of future changes to these mechanisms is therefore a logical extension of the work presented here, and should be guided by observational studies of GrIS melt variability, including recent melt extremes [e.g. *Hanna et al.*, 2012, 2013; *Bennartz et al.*, 2013]. Better understanding the evolving coupling between GrIS summer melt variability and climate is critical, given that this relationship will increasingly control future melt-dominated iSMB variability, with follow-on impacts to ice dynamics, GrIS-sourced ocean freshwater fluxes, ocean circulation, sea level rise, and identification of anthropogenically-forced GrIS volume trends.

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References

Bales, R., Q. Guo, D. Shen, J. McConnell, G. Du, J. Burkhart, V. Spikes, E. Hanna, and J. Cappelen (2009), Annual accumulation for Greenland updated using ice core data developed during 2000-2006 and analysis of daily coastal meteorological data, *Journal of Geophysical Research*, *114*, D06,116, doi:10.1029/2008JD011208.

Bamber, J., M. van den Broeke, J. Ettema, J. Lenaerts, and E. Rignot (2012), Recent large increases in freshwater fluxes from Greenland into the North Atlantic, *Geophysical Research Letters*, *39*, L19,501, doi:10.1029/2012GL052552.

Bamber, J. L., R. L. Layberry, and S. Gogineni (2001), A new ice thickness and bed data set for the Greenland ice sheet 1: Measurement, data reduction, and errors, *Journal of Geophysical Research*, *106*, 33,773–33,780.

Bennartz, R., M. Shupe, D. Turner, V. Walden, K. Steffen, C. Cox, M. Kulie, N. Miller, and C. Pettersen (2013), July 2012 Greenland melt extent enhanced by low-level liquid clouds, *Nature*, *496*, 83–86, doi:10.1038/nature12002.

Box, J., D. Bromwich, B. Veenhuis, L.-S. Bai, S.-H. Wang, J. Stroeve, T. Haran, J. Rogers, and K. Steffen (2006), Greenland ice sheet surface mass balance variability (1988–2004) from calibrated polar MM5 output, *Journal of Climate*, *19*, 2783–2800, doi: 10.1175/JCLI3738.1.

Box, J., X. Fettweis, J. Stroeve, M. Tedesco, D. Hall, and K. Steffen (2012), Greenland ice sheet albedo feedback: thermodynamics and atmospheric drivers, *The Cryosphere*, *6*, 821–839, doi:10.5194/tc-6-821-2012.

Cogley, J. (2004), Greenland accumulation: An error model, *Journal of Geophysical Research*, *109*, D18,101, doi:10.1029/2003JD004449.

de Boer, G., W. Chapman, J. Kay, B. Medeiros, H. Shupe, S. Vavrus, and J. Walsh (2012), A characterization of the present-day Arctic atmosphere in CCSM4, *Journal of Climate*, *25*, 2676–2695, doi:10.1175/JCLI-D-11-00228.1.

Ettema, J., M. van den Broeke, E. van Meijgaard, W. J. van de Berg, J. Bamber, J. Box, and R. Bales (2009), Higher surface mass balance of the Greenland ice sheet revealed by high-resolution climate modeling, *Geophysical Research Letters*, *36*, L12,501, doi:10.1029/2009GL038110.

Fettweis, X., B. Franco, M. Tedesco, J. van Angelen, J. Lenaerts, M. van den Broeke, and H. Gallee (2013), Estimating the Greenland ice sheet surface mass balance contribution to future sea level rise using the regional atmospheric climate model MAR, *The Cryosphere*, *7*, 469–489, doi:10.5194/tc-7-469-2013.

Fichefet, T., C. Poncin, H. Goosse, P. Huybrechts, I. Janssens, and H. Le Treut (2003), Implications of changes in freshwater flux from the Greenland ice sheet for the climate of the 21st century, *Geophysical Research Letters*, *30*(17), n/a–n/a, doi:10.1029/2003GL017826.

Flanner, M., C. Zender, J. Randerson, and P. Rasch (2007), Present-day climate forcing and response from black carbon in snow, *Journal of Geophysical Research*, *112*, D11,202, doi:10.1029/2006JD008003.

Hanna, E., P. Huybrechts, K. Steffen, J. Cappelen, R. Huff, C. Shuman, T. Irvine-Fynn, S. Wise, and M. Griffiths (2008), Increased runoff from melt from the Greenland Ice Sheet: a response to global warming, *Journal of Climate*, *21*, 331–341, doi: 10.1175/2007JCLI1964.1.

Hanna, E., J. Jones, J. Cappelen, S. Mernild, L. Wood, K. Steffen, and P. Huybrechts (2012), The influence of North Atlantic atmospheric and oceanic forcing effects on 1900–2010 Greenland summer climate and ice melt/runoff, *International Journal of Climatology*, *33*, 862–880, doi:10.1002/joc.3475.

Hanna, E., F. Navarro, F. Pattyn, C. Domingues, X. Fettweis, E. Ivins, R. Nicholls, C. Ritz, B. Smith, S. Tulaczyk, P. Whitehouse, and H. Zwally (2013), Ice-sheet mass balance and climate change, *Nature*, *498*, 51–59, doi:doi:10.1038/nature12238.

Hurrell, J. W., M. Holland, P. Gent, S. Ghan, J. Kay, P. Kushner, J.-F. Lamarque, W. Large, D. Lawrence, K. Lindsay, W. Lipscomb, M. Long, N. Mahowald, D. Marsh, R. Neale, P. Rasch, S. Vavrus, M. Vertenstein, D. Bader, W. Collins, J. Hack, J. Kiehl, and S. Marshall (2013), The Community Earth System Model: A framework for collaborative research, *Bulletin of the American Meteorological Society*, *94*, 1339–1360, doi:10.1175/BAMS-D-12-00121.

Lipscomb, W., J. Fyke, M. Vizcaíno, W. Sacks, J. Wolfe, M. Vertenstein, T. Craig, E. Kluzek, and D. Lawrence (2013), Implementation and initial evaluation of the Glimmer Community Ice Sheet Model in the Community Earth System Model, *Journal of Climate*, *26*, 7352–7371, doi:10.1175/JCLI-D-12-00557.1.

Marsh, R., D. Desbruyères, J. L. Bamber, B. A. de Cuevas, A. C. Coward, and Y. Aksenov (2010), Short-term impacts of enhanced Greenland freshwater fluxes in an eddy-permitting ocean model, *Ocean Science*, *6*(3), 749–760, doi:10.5194/os-6-749-2010.

Mernild, S., and G. Liston (2012), Greenland freshwater runoff. Part II: distribution and trends, 1960–2010, *Journal of Climate*, *25*, 6015–6035, doi:10.1175/JCLI-D-11-00592.1.

Schoof, C. (2010), Ice-sheet acceleration driven by melt supply variability, *Nature*, *468*, 803–806, doi:10.1038/nature09618.

Sciascia, R., F. Straneo, C. Cenedese, and P. Heimbach (2013), Seasonal variability of submarine melt rate and circulation in an East Greenland fjord, *Journal of Geophysical Research*, *118*, 1–15, doi:10.1002/jgrc.20142.

Shepherd, A., E. R. Ivins, G. A, V. R. Barletta, M. J. Bentley, S. Bettadpur, K. H. Briggs, D. H. Bromwich, R. Forsberg, N. Galin, M. Horwath, S. Jacobs, I. Joughin, M. A. King, J. T. M. Lenaerts, J. Li, S. R. M. Ligtenberg, A. Luckman, S. B. Luthcke, M. McMillan, R. Meister, G. Milne, J. Mouginot, A. Muir, J. P. Nicolas, J. Paden, A. J. Payne, H. Pritchard, E. Rignot, H. Rott, L. S. Srensen, T. A. Scambos, B. Scheuchl, E. J. O. Schrama, B. Smith, A. V. Sundal, J. H. van Angelen, W. J. van de Berg, M. R. van den Broeke, D. G. Vaughan, I. Velicogna, J. Wahr, P. L. Whitehouse, D. J. Wingham, D. Yi, D. Young, and H. J. Zwally (2012), A reconciled estimate of ice-sheet mass balance, *Science*, *338*(6111), 1183–1189, doi:10.1126/science.1228102.

Tedesco, M., X. Fettweis, T. Mote, J. Wahr, P. Alexander, J. E. Box, and B. Wouters (2013), Evidence and analysis of 2012 Greenland records from spaceborne observations, a regional climate model and reanalysis data, *The Cryosphere*, *7*, 615–630, doi:10.5194/tc-7-615-2013.

van Angelen, J., J. Lenaerts, M. van den Broeke, X. Fettweis, and E. van Meijgaard (2013a), Rapid loss of firn pore space accelerates 21st century Greenland mass loss, *Geophysical Research Letters*, *40*, 2109–2113, doi:10.1002/grl.50490.

van Angelen, J., M. Broeke, B. Wouters, and J. Lenaerts (2013b), Contemporary (1960-2012) evolution of the climate and surface mass balance of the Greenland ice sheet, *Surveys in Geophysics*, pp. 1–20, doi:10.1007/s10712-013-9261-z.

Van de Wal, R., W. Greuell, M. den Broeke, C. Reijmer, and J. Oerlemans (2005), Surface mass-balance observations and automatic weather station data along a transect near Kangerlussuaq, West Greenland, *Annals of Glaciology*, *42*, 311–316, doi: 10.3189/172756405781812529.

van de Wal, R. S. W., W. Boot, C. J. P. P. Smeets, H. Snellen, M. R. van den Broeke, and J. Oerlemans (2012), Twenty-one years of mass balance observations along the K-transect, West Greenland, *Earth System Science Data*, *4*(1), 31–35, doi:10.5194/essd-4-31-2012.

van den Broeke, M., J. Bamber, J. Ettema, E. Rignot, E. Schrama, W. van de Berg, E. van Meijgaard, I. Velicogna, and B. Wouters (2009), Partitioning recent Greenland mass loss, *Science*, *326*, 984–986, doi:10.1126/science.1178176.

van der Veen, C., and J. Bolzan (1999), Interannual variability in net accumulation on the Greenland ice sheet: Observations and implications for mass balance measurements, *Journal of Geophysical Research*, *104*, 2009–2014, doi:10.1029/1998JD200082.

van Vuuren, D., J. E. M. Kainuma, K. Riahi, A. Thomson, K. Hibbard, G. C. Hurtt, T. Kram, V. Krey, J.-F. Lamarque, T. Masui, M. Meinshausen, N. Nakicenovic, S. J. Smith, and S. K. Rose (2011), The representative concentration pathways: an overview, *Climatic Change*, *109*, 5–31, doi:10.1007/s10584-011-0148-z.

Velicogna, I. (2009), Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE, *Geophysical Research Letters*, *36*, L19,503, doi: 10.1029/2009GL040222.

Vizcaíno, M., W. Lipscomb, W. Sacks, and M. van den Broeke (2013a), Greenland surface mass balance as simulated by the Community Earth System Model. Part II: 21st century changes, *Journal of Climate*, *in press*, doi:10.1175/JCLI-D-12-00588.1.

Vizcaíno, M., W. Lipscomb, W. Sacks, J. van Angelen, B. Wouters, and M. van den Broeke (2013b), Greenland surface mass balance as simulated by the Community Earth System Model. Part I: model evaluation and 1850-2005 results, *Journal of Climate*, *26*, 7793–7812, doi:10.1175/JCLI-D-12-00615.1.

Wouters, B., J. Bamber, M. van den Broeke, J. Lenaerts, and I. Sasgen (2013), Limits in detecting acceleration of ice sheet mass loss due to climate variability, *Nature Geoscience*, *AOP*, doi:10.1038/NGEO1874.

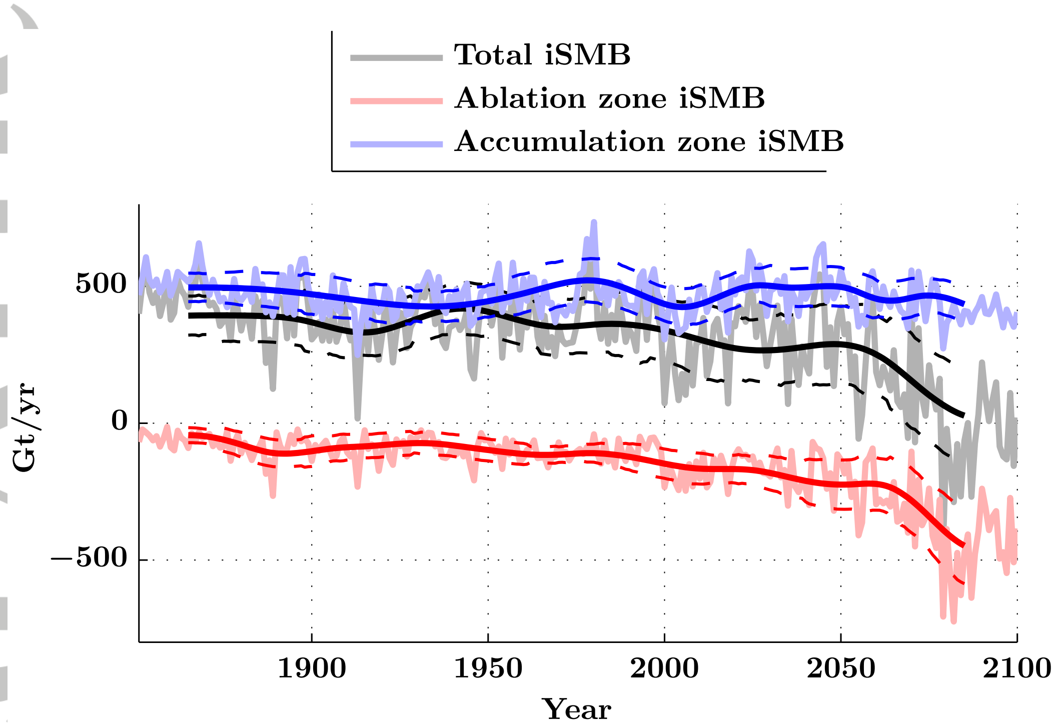

Figure 1. Total iSMB timeseries (black) and component ablation/accumulation iSMB time series (red/blue). These and subsequent time series have the first and final 15 years removed, to account for the 31-year moving standard deviation windowing. This and subsequent plots show raw time series (faded line), smoothed trends (solid line, generated using empirical mode decomposition, Auxiliary Material) and +/- 1 standard deviation (dashed lines).

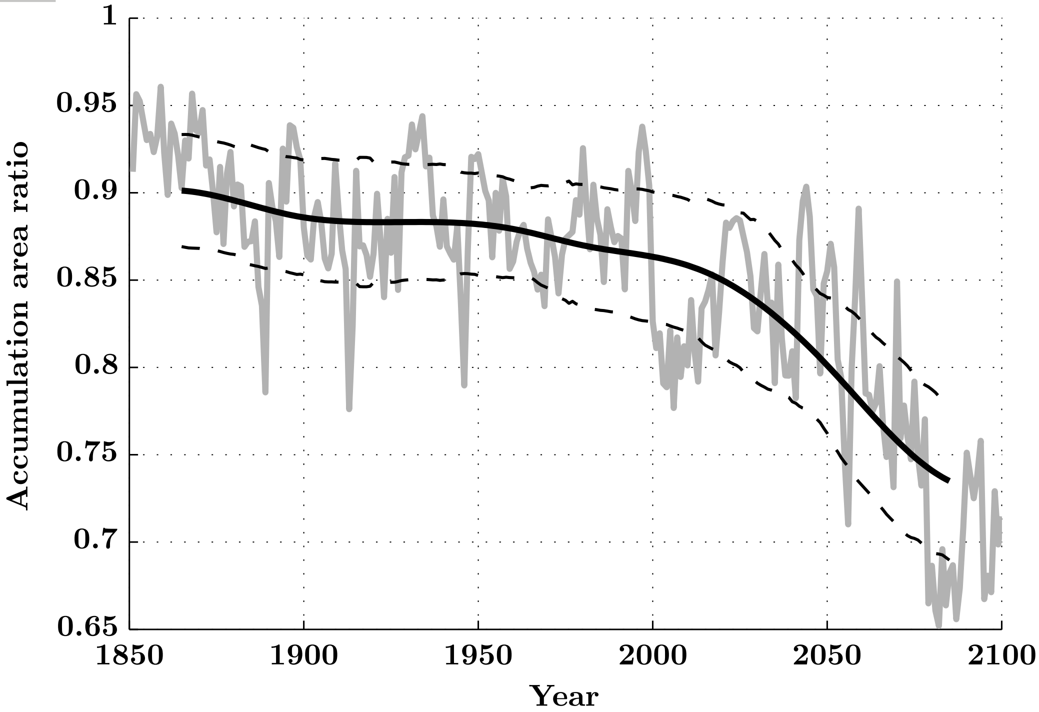

Figure 2. Evolution of the accumulation area ratio (AAR).

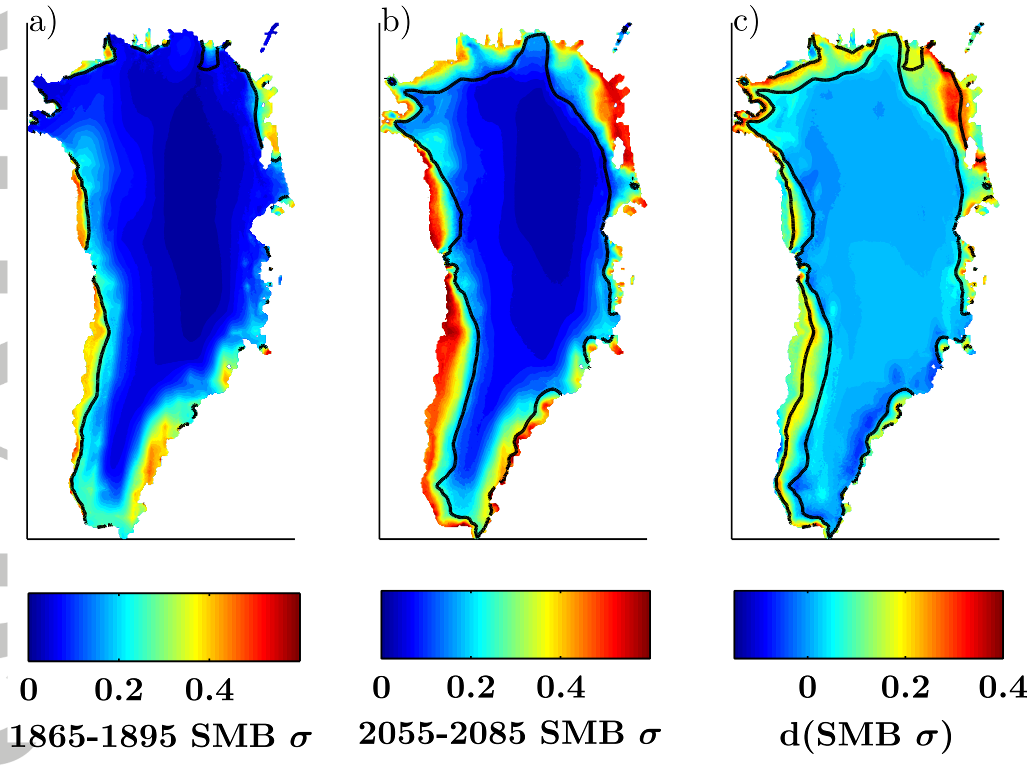

Figure 3. Spatial distribution of sSMB variability (m/yr w.e.) for a) 1865-1895, b) 2055-2085, and c) the difference in variability between the two periods. Also shown are preindustrial and final climatological ELAs (the line separating the accumulation and ablation areas) for a) 1850-1880, b) 2070-2100, and c) both.