

S.1 Regional atmospheric climate model RACMO2

For this study we use output of the regional atmospheric climate model RACMO2, originally developed at the Royal Netherlands Meteorological Institute (KNMI) *Van Meijgaard et al.* (2008), and extended with a multi-layer (100) two-way coupled snow model (*Ettema et al.*, 2010) and a drifting snow scheme (*Lenaerts et al.*, 2012) to better represent conditions in the polar regions. Surface meltwater is allowed to penetrate to deeper layers, where it can be retained or refrozen as described in *Bougamont and Bamber* (2005). As soon as all the layers have reached their maximum retention capacity, runoff initiates. Although meltwater penetration is a highly heterogeneous process (piping, horizontal and vertical transport (*Parry et al.*, 2007), at an 11 km resolution a homogeneous description, including the formation of ice lenses, is acceptable. Recently, a grain size dependent albedo scheme has been implemented in RACMO2 (*Kuipers Munneke et al.*, 2011) for a better simulation of the transition from accumulation to ablation conditions on ice sheets in a warming climate (*Van Angelen et al.*, 2012).

The good agreement between RACMO2 and GRACE (Fig. S1), including the strong mass loss in the summer of 2012, underlines the capability of RACMO2 to correctly simulate the SMB of the Greenland ice sheet in a warming climate. Figure S1 can be used as validation for the retention/refreezing scheme in RACMO2. Since model accumulation is well-evaluated (*Ettema et al.*, 2009), as is melt extent (*Fettweis et al.*, 2011), refreezing/retention is the only remaining unknown. Refreezing and retention in absolute sense are very sensitive to small changes in the refreezing scheme due to the albedo-feedback (*Van Angelen et al.*, 2012). However, a recent study in the framework of the new IPCC report demonstrated that the uncertainty in retention/refreezing among different regional climate models is estimated at 40 Gt/yr, or 20% of the average refreezing. The uncertainty in year to year variability is much smaller, i.e. 4 Gt. This demonstrates that uncertainty in the retention scheme has a relatively small impact on the final results.

The RACMO2 domain covers Greenland, its surrounding oceans including Iceland and Svalbard and the Canadian Arctic Archipelago. The model resolution is 11 km horizontally and there are 40 levels in the vertical. At the boundary, a relaxation zone of 32 grid points (350 km) is used for the relaxation from the GCM forcing fields to the RACMO2 interior grid.

For the initialization of the snow pack, output for September 1989, (i.e. before Greenland warming started), of a previous RACMO2 simulation over Greenland (*Ettrema et al.*, 2010) is used for both the RACMO2-fERA and the RACMO2-fHadGEM2 simulations. Analysis of snow density and temperature profiles show that the top 20 m of the snow pack adjust within a few years to the climate conditions of the specific forcing. This adjustment is clearly visible in Figure 3, where the total amount of pore space in the top 20 m shows a drop after the model start-up, and becomes constant until warming begins in the 1990's. The 20 years (1970-1989) used here are thus sufficient for the snow pack to adjust to the HadGEM2 forcing.

Forcing fields from the HadGEM2-ES scenario run used in this study were available until November 2009. Therefore, 2008 is the last complete year in the RACMO2-fHadGEM2 simulation and we use the 20-yr period 2079-2098 in our analysis.

S.2 Model evaluation

For the 20 year period 1992-2011 there is a 1.0 K warm bias in T_{2m} for the summer months (JJA) averaged over the GrIS for the RACMO2-fHadGEM2 simulation compared to RACMO2-fERA (Table S1). The discrepancy is largest over the northern part of the ice sheet (~ 1.5 K) and smallest over the central dome and the south-western ablation area (< 0.5 K). Considering precipitation, RACMO2-fHadGEM2 is $\sim 6\%$ wetter and the patterns are in very good agreement (Fig. S2). Also the seasonal cycle for temperature, melt-extent and precipitation are in good agreement for the two simulations (Fig. S3). Due to the warm summer bias, the surface mass balance in RACMO2-fHadGEM2 shows a wider ablation area along the south-west and north of the GrIS compared to RACMO2-fERA, but once more the patterns are very similar (Fig. S4). Averaged over the GrIS, the total SMB for the 1992-2011 period is 104 Gt lower for the RACMO2-fHadGEM2 simulation. The standard deviation of annual SMB values for the HadGEM2 simulation (144 Gt) is larger than the difference between the two simulations, so we conclude that the GrIS is in the same climate regime in both simulations. This is further illustrated in Fig. S5 where the correlation between summer temperature (JJA) and SMB is shown for both climate realizations. The

linear dependency of SMB on temperature is close to -100 Gt K^{-1} and similar for both simulations. For the present day climate, anomalies of the individual surface mass balance components show very good agreement (inset Fig. 4). This supports the assumption that anomalies can be used to assess 21st century GrIS mass loss.

References

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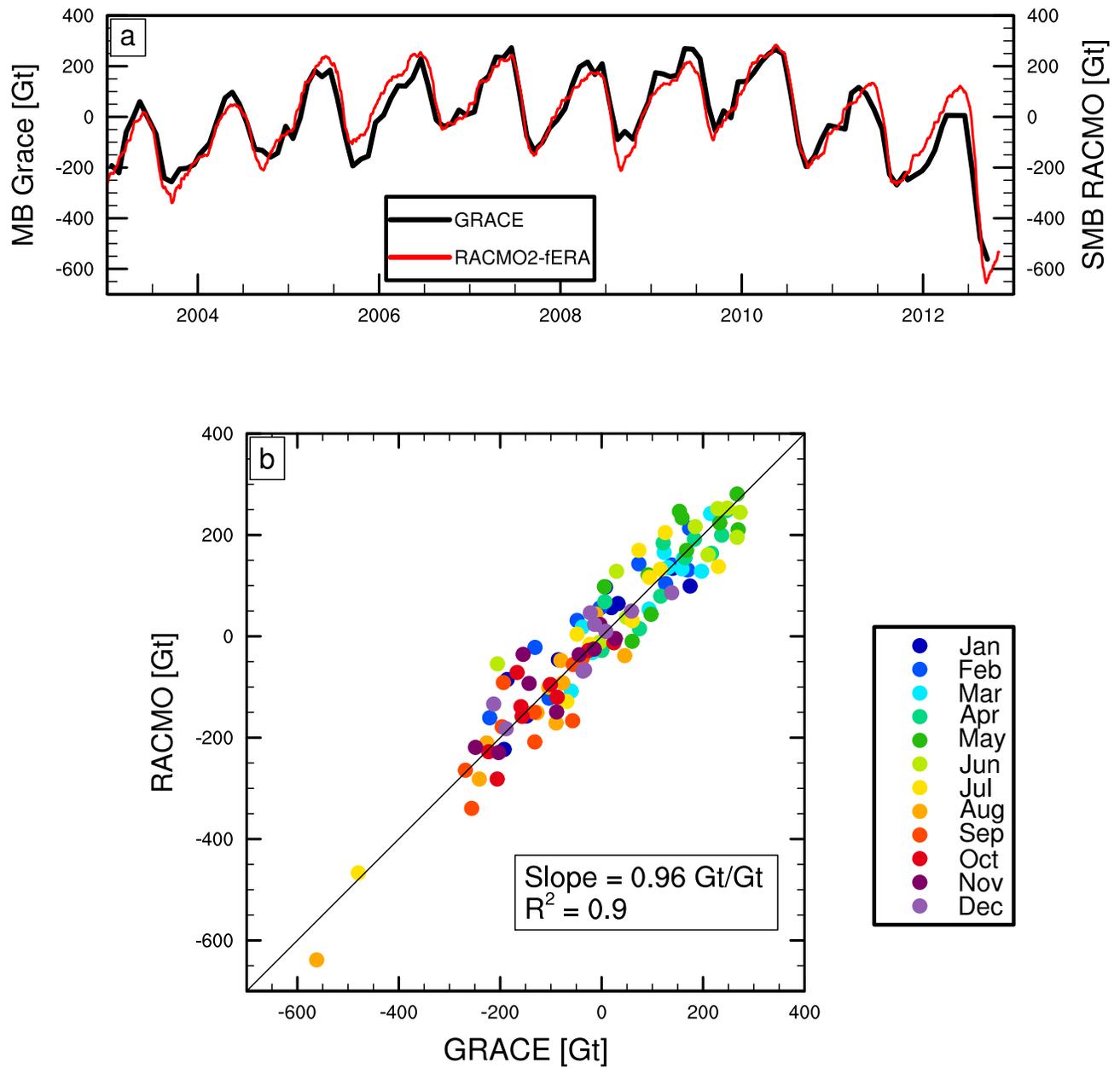


Figure S1: a) Time series of de-trended mass balance observations from GRACE (black) and daily cumulative SMB calculations from RACMO2 (red). b) Monthly mass balance for GRACE vs RACMO2-fERA.

RACMO2-fERA

RACMO2-fHadGEM2

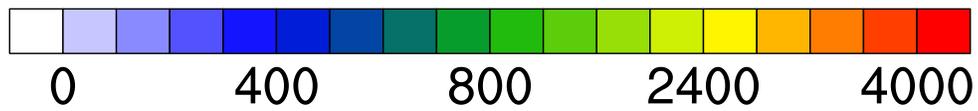
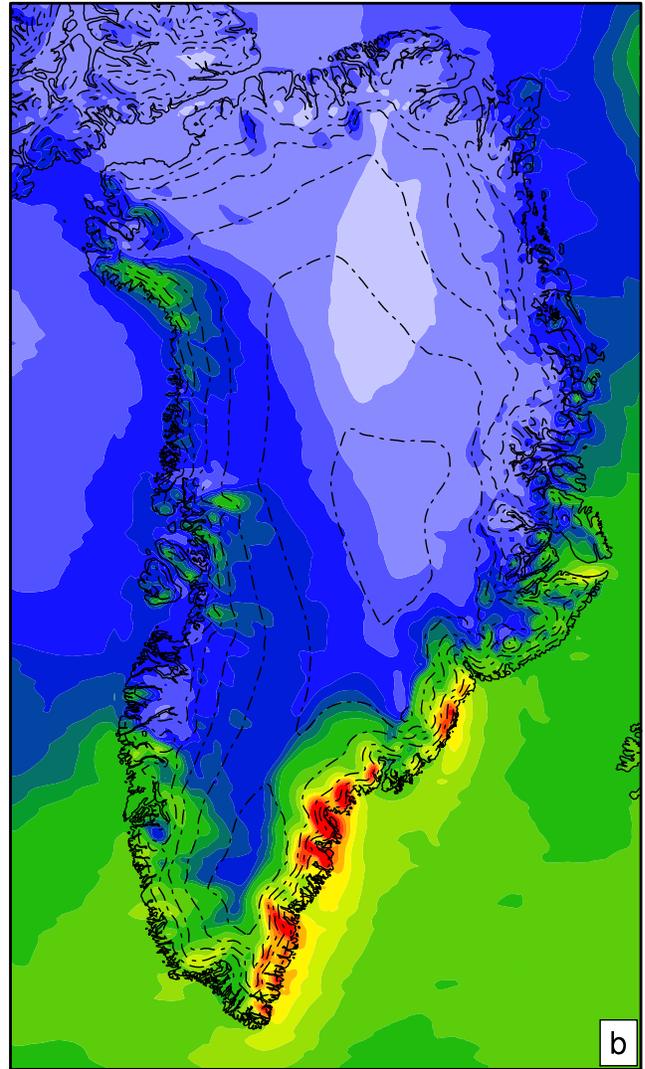
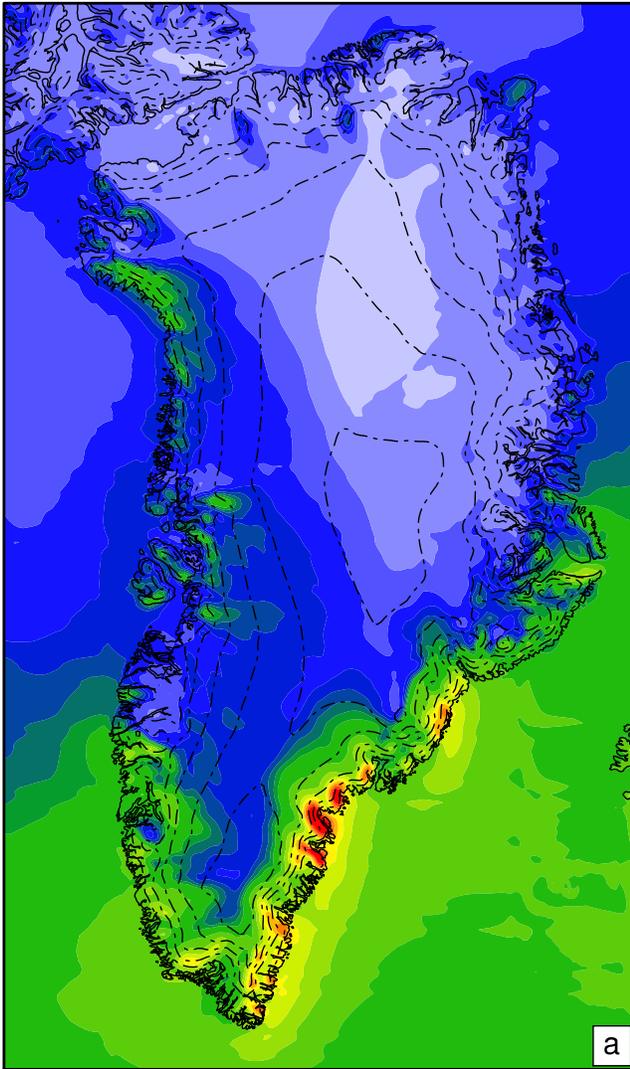


Figure S2: Yearly averaged precipitation (mm w.e.) for the period 1992-2011 for RACMO2-fERA (a) and RACMO2-fHadGEM2 (b). Dashed contours are 500 m elevation intervals.

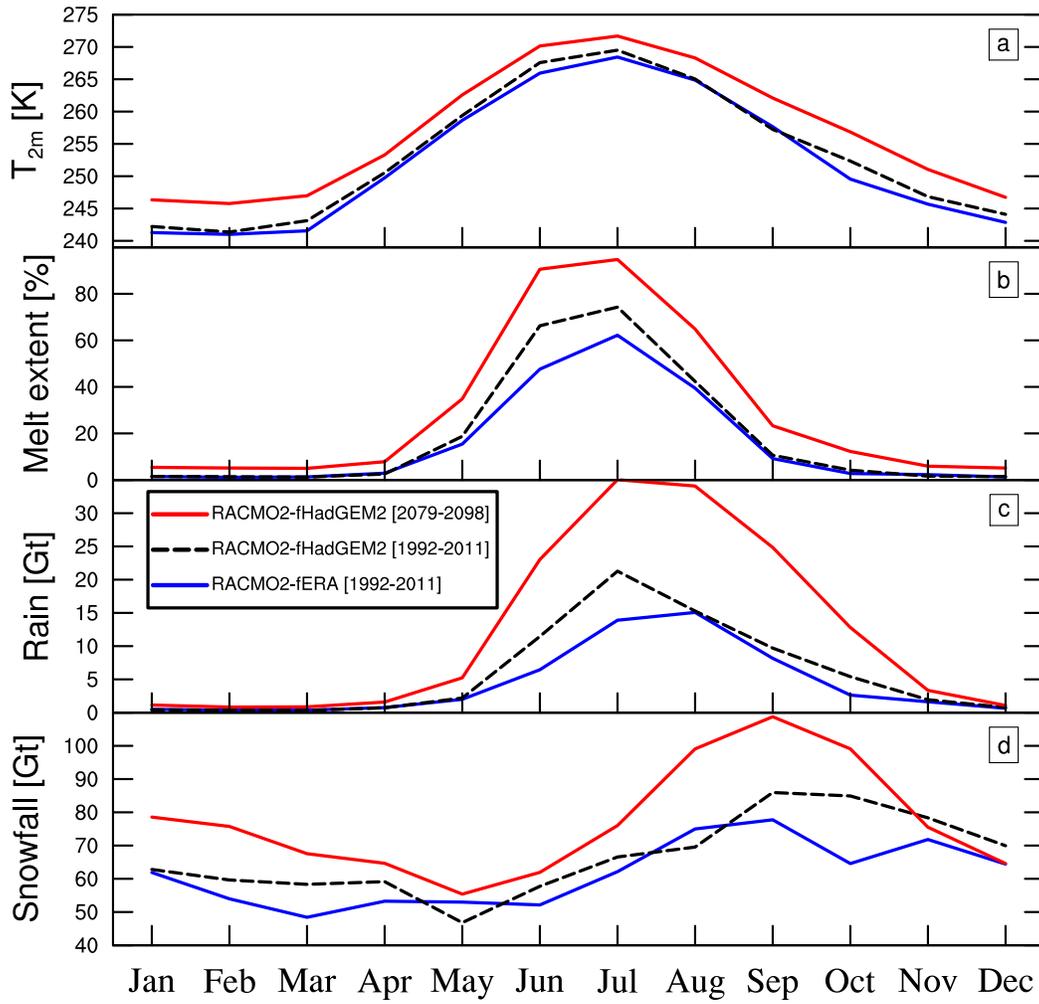


Figure S3: Seasonality in 2 m temperature (a), melt-extent (b), rainfall (c) and snowfall (d) for RACMO2-fERA (1992-2011) and RACMO2-fHadGEM2 (1992-2011 and 2079-2098).

RACMO2-fERA

RACMO2-fHadGEM2

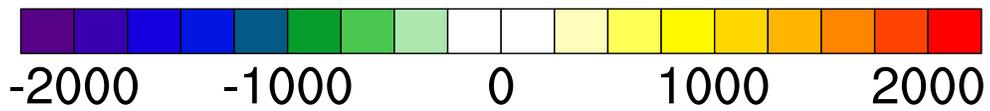
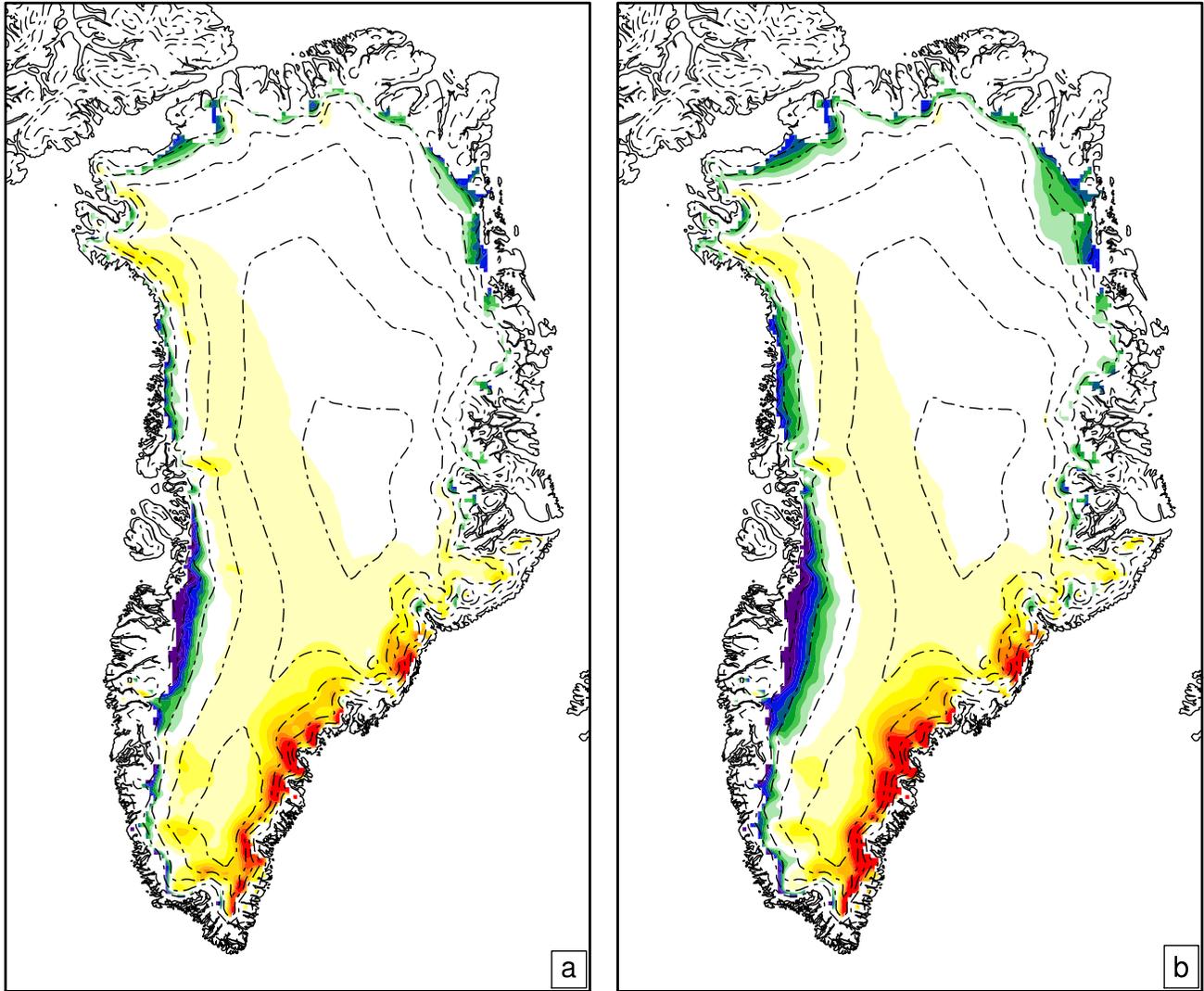


Figure S4: Yearly averaged SMB (mm w.e.) for the period 1992-2011 for RACMO2-fERA (a) and RACMO2-fHadGEM2 (b). Dashed contours are 500 m elevation intervals.

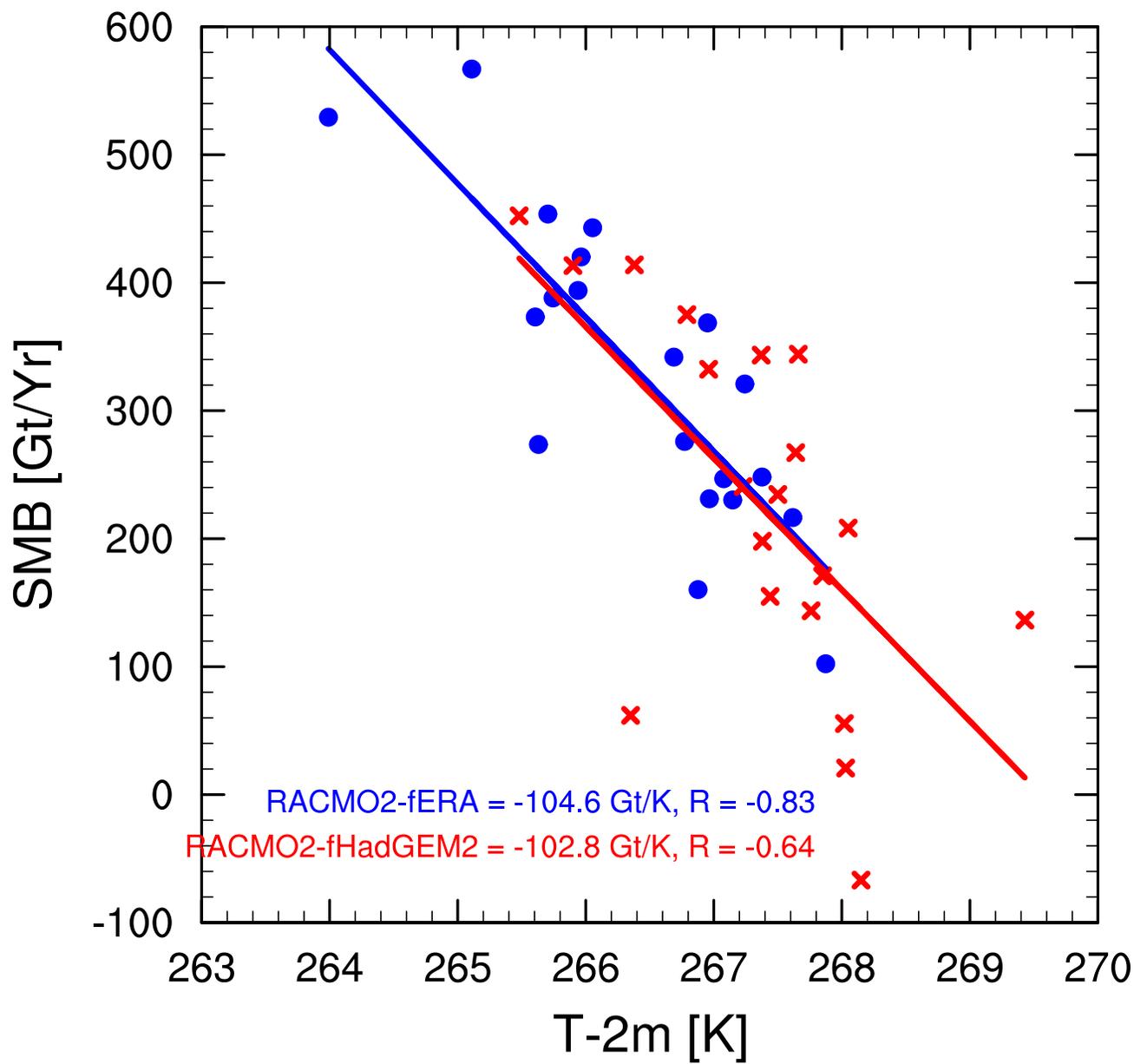


Figure S5: SMB as function of JJA 2 m temperature for the 1992-2011 period for RACMO2-fERA (blue) and RACMO2-fHadGEM2 (red).

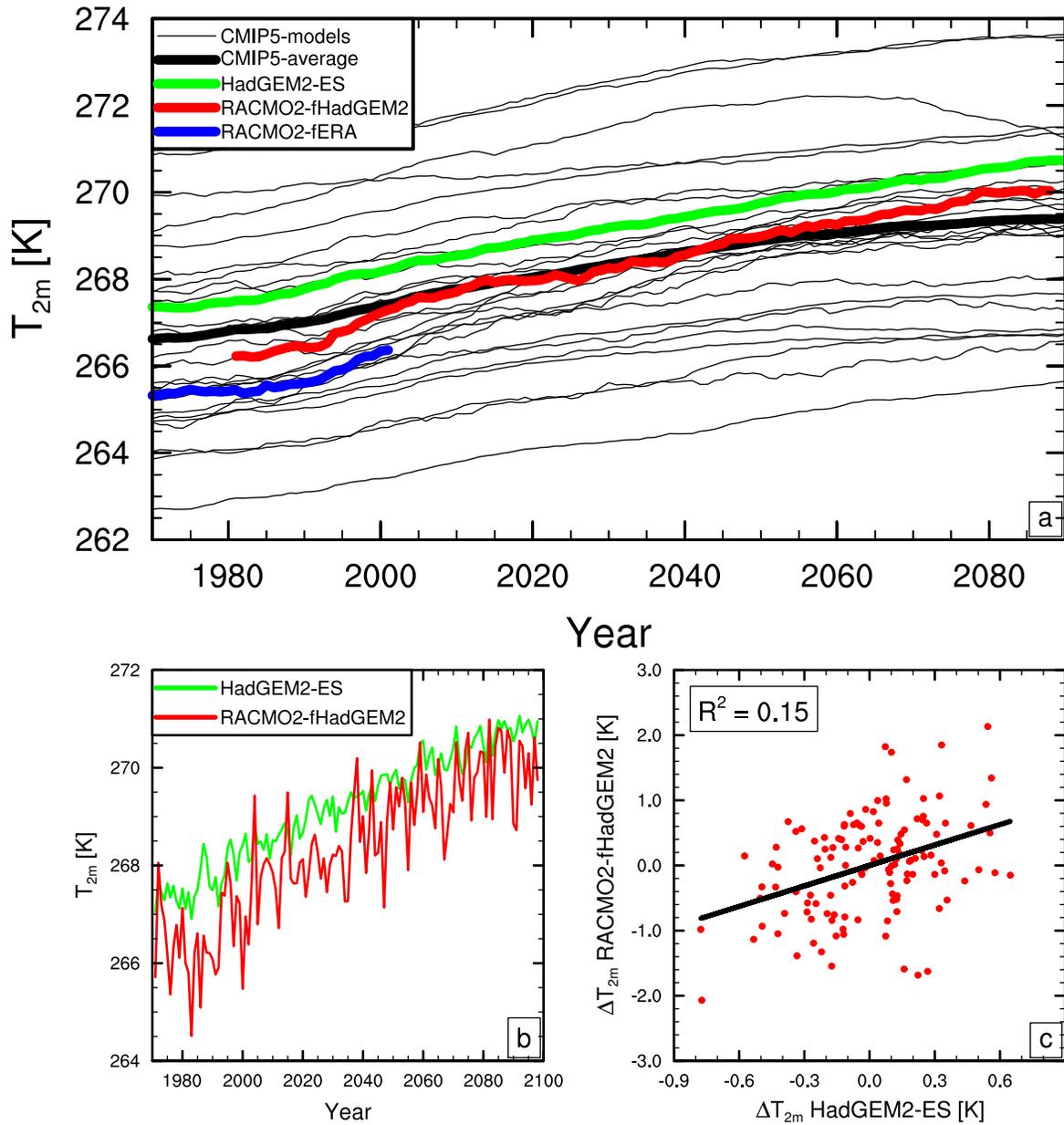


Figure S6: a) 21 year running mean 2 m summer (JJA) temperature averaged over the Greenland ice sheet (GrIS) for all CMIP5 *Taylor et al. (2007)* members, with HadGEM2-ES (green); RACMO2-fHadGEM2 (red) and RACMO2-fERA (blue). b) RACMO2-fHadGEM2 (red) and HadGEM2-ES (green) 2 m temperature averaged over the GrIS. c) De-trended correlation for T_{2m} averaged over the GrIS between HadGEM2-ES and RACMO2-fHadGEM2.

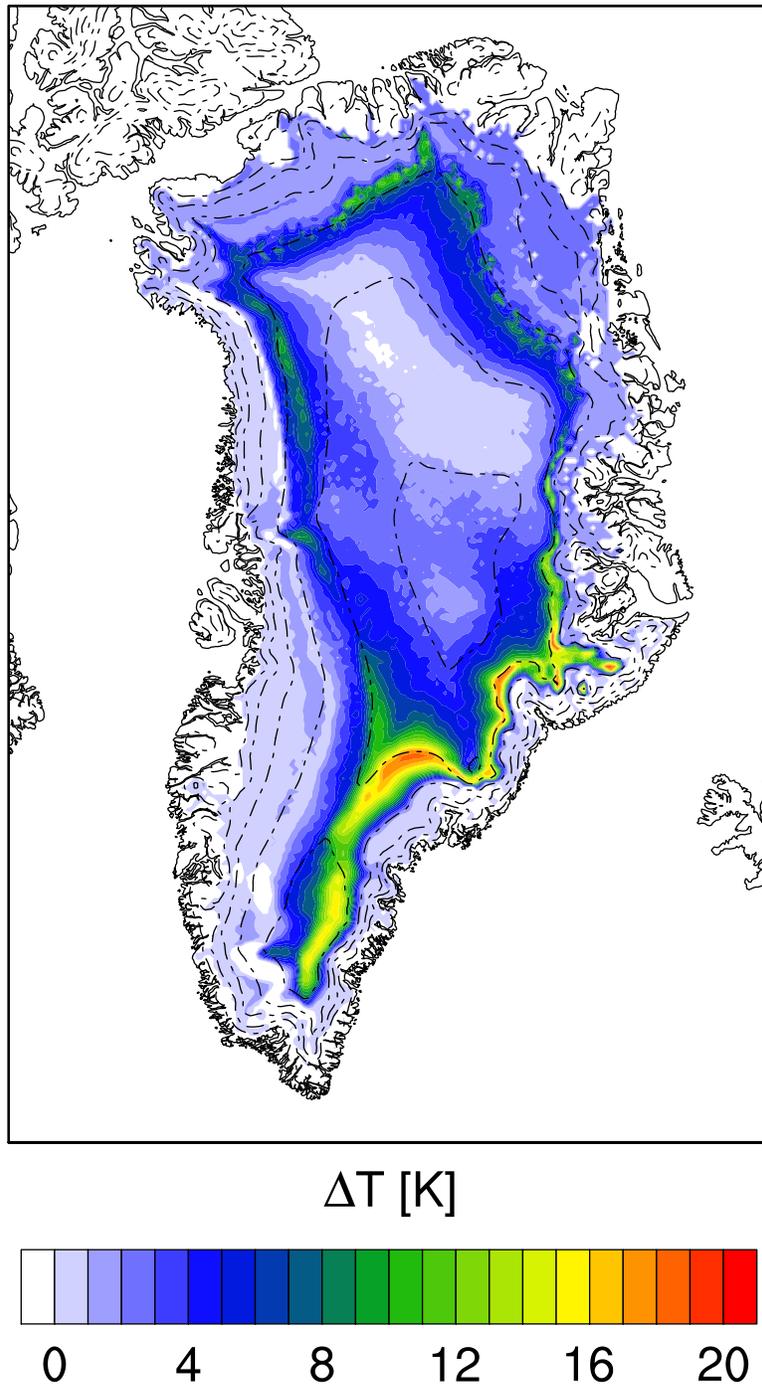


Figure S7: Temperature change averaged over the top 20 m of snow for the RACMO2-fHadGEM2 simulation between 2078-2098 and 1992-2011. Dashed contours are 500 m elevation intervals.

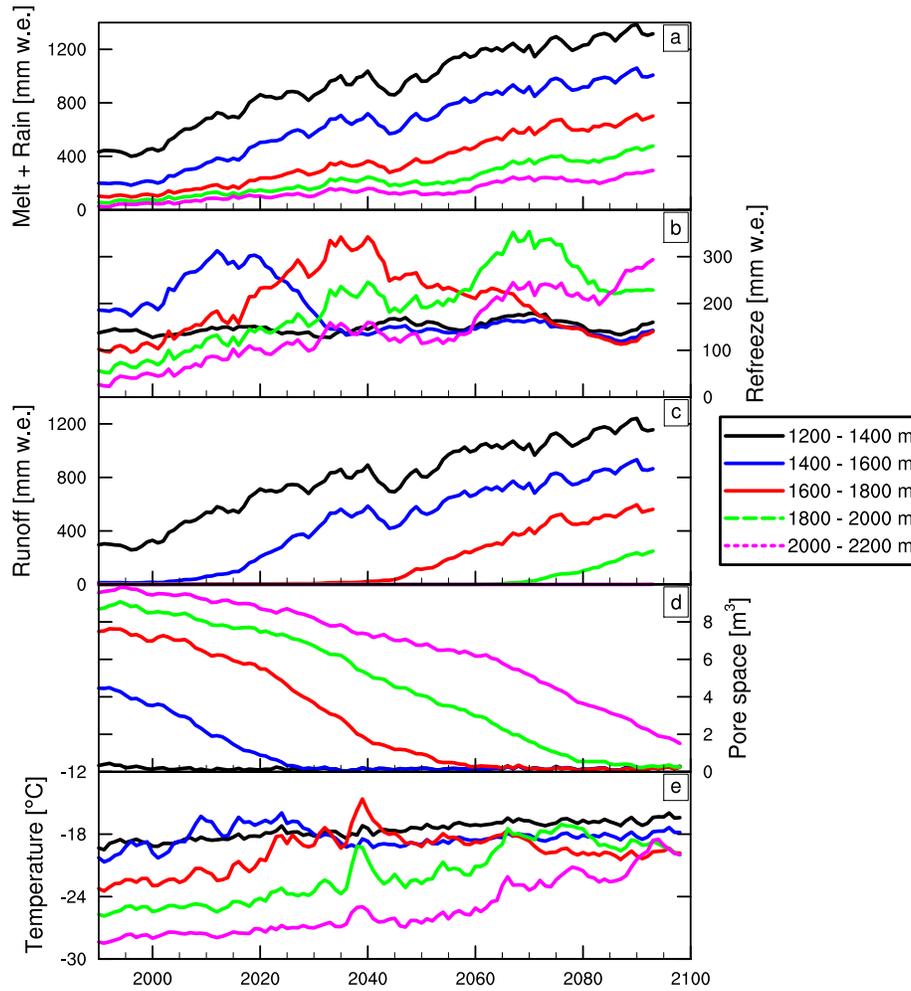


Figure S8: Melt and rain (a), refreezing (b), runoff (c), pore space (d) and temperature (e) in the top 20 m of the snow pack for northeast Greenland binned in 200 m elevation intervals. For melt and rain, refreezing and runoff, an 11-year running average is applied. Throughout the 21st century the production of liquid water (melt + rain) steadily increases. In the first several decades, this liquid water penetrates into the still porous firn and efficiently refreezes, reducing the pore space and heating the snow pack by latent heat release. When pore space in the firn is zero, refreezing is reduced to the amount that can be accommodated by the cold content of the winter snow layer, and runoff is initiated. The fact that runoff starts before all pore space is removed, is the result of averaging over a 200 m elevation bin; at lower altitudes, pore space has disappeared and runoff has started, whereas higher on the ice sheet pore space is still available.