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Brief Communication: "Reduction of the future Greenland ice sheet surface melt with the help of solar geoengineering"

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Abstract.

The Greenland Ice Sheet (GrIS) will be losing mass at an accelerating pace throughout the 21st century, with a direct link between anthropogenic greenhouse gas emissions and the magnitude of Greenland mass loss. Currently, approximately 60 % of the mass loss contribution comes from surface melt and subsequent meltwater runoff, while 40 % are due to ice calving. Where most of the surface melt occurs (in the ablation zone), most of the energy for the surface melt is provided by absorbed shortwave fluxes, which could be reduced by solar geoengineering measures. However, so far very little is known about the potential impacts of an artificial reduction of the incoming solar radiation on the GrIS surface energy budget and the subsequent change in meltwater production. By forcing the regional climate model MAR with the latest CMIP6 future scenarios ssp245, ssp585 and associated G6solar experiment from the Earth System Model CNRM-ESM2-1, we estimate the local changes due to the reduction of the solar constant on the projected GrIS surface mass balance (SMB) decrease. Overall, our results show that even in case of low mitigation greenhouse gas emissions scenario (ssp585), the Greenland surface mass loss can be brought in line with the medium mitigation emissions scenario (ssp245) by reducing the solar downward flux at the top of the atmosphere by ~40 W/m2 or ~1.5 % (using the G6solar experiment). In addition to reduce Global Warming in line with ssp245, G6solar also decreases the efficiency of surface meltwater production over the Greenland ice sheet by damping the well-known positive melt-albedo feedback which mitigates the projected Greenland ice sheet surface melt increase by 6 %. However, only more constraining geoengineering experiments than G6solar allows to maintain positive SMB till the end of this century without any reduction in our greenhouse gas emissions.

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1 Introduction

The Greenland ice sheet (GrIS) is projected to contribute several centimetres to global mean sea-level rise until 2100, mainly as a result of the projected surface meltwater runoff increase due to Global Warming (Hofer et al. 2020, Goelzer et al., 2020). Knowing that both Antarctic and Greenland ice sheets are already losing mass more in line with the extreme high-emission scenarios from IPCC AR5 (Slater et al., 2020), the most direct way to reduce the sea level rise contribution from Greenland is to reduce our Greenhouse Gases (GHG) emissions, as there is a factor of 3 between the Greenland ice sheet surface melt in an extreme high-emission world (ssp585) vs in a scenario more closely aligned to the Paris Agreement (ssp126) (Goelzer et al., 2020).

One possibility to mitigate sea level rise in a scenario where we would otherwise overshoot the global warming limits set out in the Paris Agreement is the employment of solar geoengineering measures (Tilmes et al., 2020). Solar geoengineering describes a set of proposals to scatter incoming light or increase outgoing longwave radiation to offset the reduction in outgoing longwave radiation due to elevated GHG concentrations (Shepherd et al., 2009). Of the various proposals, stratospheric aerosol geoengineering has received the greatest attention to date, as research suggests it is feasible and relatively cheap to deploy using custom-designed aircraft (~$18 billion per degree Celsius offset per year) (Smith, 2020), and that it could be highly effective at offsetting climate changes (Irvine et al., 2019).

Until now, the precise impact of such solar geoengineering measures on the future Greenland ice sheet surface melt remains highly uncertain because it was evaluated only with global models run at too coarse spatial resolution not resolving the ablation zone and using very simple snow models (Irvine et al., 2018; Moore et al.; 2019). As shown in Fettweis et al. (2020), the polar regional climate models offer a unique opportunity to refine these estimates with a polar-oriented sophisticated physics, a full representation of the snow-atmosphere interactions as well as a spatial resolution adequate to explicitly resolve the narrow GrIS ablation zone (van de Berg et al., 2020). Moreover, regional models enable us to explore local impacts from geoengineering measures with unchanged boundary conditions. To this end, we have used the state-of-the-art polar regional climate model MAR (Fettweis et al.; 2020) to downscale a future simulation of the G6solar geoengineering experiment (described in Section 2) over the GrIS. This G6solar experiment assumes a continuously decreasing solar constant from 2015 until it reaches -1.5 % in 2100 and, has been designed to mimic the global warming signal seen in the ssp245 scenario (a scenario with ~4.5 Wm-2 total forcing in 2100), despite ssp585 GHG emissions (~8.5 Wm-2 in 2100, O'Neill et al.; 2016). This setup enables us to study in Section 3 the impact of such geoengineering measures in case of an extreme emissions scenario, but also enables us to assess whether a decrease in GHG emissions or a decrease in incoming solar radiation to reach 4.5 W/m² radiative forcing would be more efficient at mitigating Greenland's sea level rise contribution during the 21st century. Finally, some sensitivity experiments are presented in Section 4 to estimate what

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geoengineering measures should be to maintain a positive GrIS surface mass balance (SMB) without any reduction of our GHG emissions.

2 Data

The regional climate model MAR (version 3.11), run at resolution of 20km as in Tedesco and Fettweis (2020) over 1970-2100, is used here to downscale the future scenario ssp245, ssp585 and G6solar performed with the CMIP6 Earth System Model CNRM-ESM2-1 (Séférian et al., 2019). The latter simulates a global warming in 2100 in the likely range of the CMIP5 ensemble mean (Séférian et al., 2019) and is the only model from the CMIP6 data base providing 6 hourly outputs, (needed to force MAR at its lateral boundaries) for the G6solar experiment. The radiative scheme of MARv3.11 has been adapted to deal with the GHG concentrations and the solar constant time series which have been used to constrain CNRM-ESM2-1. We refer to Kravitz et al. (2016) and O'Neill et al. (2016) for the description of the scenarios used here and to Fettweis et al. (2020) about the MAR presentation and evaluation. Compared to MAR forced by the ERA5 reanalysis over 1981-2010, the biases of SMB as well as of the near-surface summer temperature over the GrIS simulated by MAR forced by CNRM-ESM2-1 using the historical simulation are not statistically significant (see Fig. S1 in Supplementary Material). This means that the CNRM-ESM2-1-based future MAR projections are not impacted by significant biases over the current climate as discussed in Fettweis et al. (2020). Finally, it is important to note that MAR is not coupled with an ice sheet model as in Le Clec'h et al. (2019) and then that the present-day ice-sheet topography and extent are used here during the whole simulation.

3 Results and discussion

The G6solar experiment is an idealized scenario of solar geoengineering which has the same GHG concentrations as the ssp585 scenario but which aims to maintain temperatures at the same level as the ssp245 scenario through a reduction in the solar constant (an idealization of the effects of stratospheric aerosol geoengineering). In CNRM-ESM2-1, G6solar offsets most of the warming seen in ssp585 but does not fully restore temperatures to the levels of the ssp245 scenario with global temperatures 0.5 °C above this level at the end of the century (see Fig 1a). Over Greenland, the free atmosphere temperature in summer, gauged here at 600hPa and driving the GrIS surface melt variability (Fettweis et al.; 2013), is found to be roughly +5.9 °C higher with ssp585, +3.4 °C with G6solar, and +3.0 °C with ssp245 over 2081-2100 compared to the current climate (1981-2010).

As already shown by Fettweis et al. (2013), the future weak increase in snowfall (a few %) does not compensate for the large increase in meltwater runoff (> +250 %) driving the projected decrease in SMB. As the surface melt quadratically increases with the summer temperature, the SMB decrease in ssp585 is significantly larger than in ssp245 and G6solar (see Fig. 1b). Over 2081-2100, the negative SMB anomaly in G6solar is however about 55 GT/yr larger than in ssp245 because CNRM-

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ESM2-1 projects summers over Greenland about +0.4 °C warmer with G6solar than with ssp245. But if we integrate these SMB anomalies from 2015, the sea-level rise equivalent in 2100 is similar between ssp245 and G6solar, which is only half as large as in ssp585 (see Fig. 2). In agreement with previous CMIP5-based projections (Franco et al., 2013, Hofer et al., 2019), the surface melt acceleration mainly results from the increase of both the absorbed solar radiation (as a result of the melt-albedo positive feedback) and the longwave radiation in summer (see Fig. 1c). Due to higher GHG concentrations and summer free atmosphere temperatures in G6solar, the projected downward infrared energy increase is higher in G6solar than in ssp245 but as a result of the solar constant decrease, the projected absorbed solar radiation increase from both G6solar and ssp245 are similar. By damping the melt-albedo positive feedback in G6solar and then the absorbed solar radiation (Fig. 1d), the increase of surface meltwater runoff with the mean JJA GrIS near-surface temperature is lower in G6solar than in ssp245 and in ssp585 (see Fig. 1e). Moreover, as CNRM-ESM2-1 does not project any general atmospheric circulation change over Greenland in summer, the amplitude of the warming is the only difference between ssp245 and ssp585. This means that for a same temperature anomaly (e.g. + 3 °C), we have roughly the same meltwater runoff increase in both ssp245 and ssp585 (~ +450 GT/yr) than in G6solar (~ +415 GT/yr).

Finally, to isolate the effects of the reduction in incoming sunlight over the GrIS from the general reduction in temperature in the G6solar experiment, we show results for a scenario in MAR where the G6solar climate boundary conditions are used to force MAR over 2081-2100 but with the default solar constant value in the MAR radiative scheme, i.e. the one used in ssp585 (Fig 2). Over the period 2081-2100, this sensitivity experiment (increasing the incoming solar radiation of ~+3 W/m^2 over Greenland in summer) shows a 40 GT/yr (resp. 35 GT/yr) ~ 6 % larger surface melt (resp. meltwater runoff) increase than the standard G6solar experiment. This means that a simple reduction of the solar constant only above Greenland according to G6solar mitigate the projected Greenland ice sheet sea level contribution to ~6%. Moreover, even at the global scale (Fig. 1f), the relatively smaller mass losses seen in the G6solar experiment than in the ssp245 and ssp585 scenarios for same temperature anomalies can been seen, again highlighting the significance of the reduction in shortwave radiation above Greenland on surface melt.

4 Sensitivity experiments

As discussed above, for SMB simulations with the same climate boundary conditions, a decrease of 1.5 % of the solar constant dampens the surface melt acceleration over the GrIS ablation zone by about 6 %. However, this is not enough to maintain a positive GrIS SMB over 2081-2100 with the ssp585-based GHG concentrations. Therefore, we present in this section some more constraining idealised geoengineering experiments which allow to keep a positive GrIS SMB, in the aim of estimating what geoengineering measurements are required to maintain a stable GrIS till the end of this century without any reduction of our GHG emission.

By adding an additional decrease of 5 % (resp. 10 %) of the G6Solar-based solar constant into the MAR radiative scheme in

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the G6solar experiment, the surface melt increase could be dampened by 13 % (resp. 24 %) yielding a SMB of -18 GT/yr (resp. +86 GT/yr) instead of –130 GT/yr over 2081-2100. As the G6Solar-based lateral forcings of MAR has been unchanged in these MAR sensitivity experiments, it is important to note that only the local impact above Greenland of such a reduction of the solar constant is evaluated here while it should significantly further mitigate the Global Warming at the global scale if it was accounted for in the ESM forcing. This suggests that a stronger reduction of the solar radiation than in G6solar is required to mitigatethe GrIS surface mass loss resulting from no reduction in our GHG emission.

As proposed by Feldmann et al. (2019), another solution to mitigate the ice sheet melt could be to artificially increase snowfall, bringing additional solid mass over the ice sheet in winter and reducing the surface melt in summer by increasing albedo. By artificially increasing snowfall by 50 % (resp. 25 %) in the atmospheric module of MAR as input of its snow model into the G6solar experiment, the mean future runoff is decreased by 89 GT/yr (resp. 46 GT/yr) while the mean integrated SMB is +293 GT/yr (resp. +83 GT/yr) instead of –130 GT/yr over 2081-2100. This enables to maintain the ice sheet to a state close to the reference one (mean SMB of +380 GT/yr over 1981-2010). Finally, it is interesting to note that over 2081-2100, decreasing the solar constant by 10 % above Greenland corresponds to a similar sea level rise in 2100 than increasing the snowfall by 25 % in G6solar (see Fig. 2).

5 Conclusion

By forcing the regional climate model MAR over the Greenland ice sheet with the ssp245 and ssp585 scenario as well as the G6solar experiment built with CNRM-ESM2-1, we show that a continuous reduction of the solar constant from 2015 onward to reach ~ - 1.5 % in 2100 is enough to mitigate the projected surface mass loss from the Greenland ice sheet by a factor ~2.5 compared to ssp585. In addition to moderating the global warming rate and then the warming of the free atmosphere in the Arctic, the reduction of solar radiation above Greenland in the MAR radiative scheme reduces the projected surface melt increase by ~6 % for the same temperature anomaly than ssp245 or ssp585, by weakly damping the melt-albedo positive feedback. However, for both G6solar experiment and ssp245 scenario, the GrIS SMB is projected to become significantly negative at the end of this century suggesting that G6solar is not enough to avoid a likely overtaking of tipping points (SMB < 0) of the Greenland ice sheet. Only a stronger reduction of solar radiation than that used in G6solar (~-1.5 % in 2100) or an artificial increase of snowfall accumulation with G6solar, as suggested by Feldmann et al. (2019), could slow-down a likely irreversible melt of the Greenland ice sheet if we do not significantly reduce our anthropogenic GHG emissions as framed in the Paris Agreement.

Author contributions. XF and SH prepared the manuscript. XF runs the MAR model using the CNRM-ESM2-1 based 6 hourly outputs provided by RS. All authors commented and improved the manuscript.

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Data availability. All the modelled data sets presented in this study are available from the authors upon request and without conditions.

Competing interests. The authors declare no competing interests.

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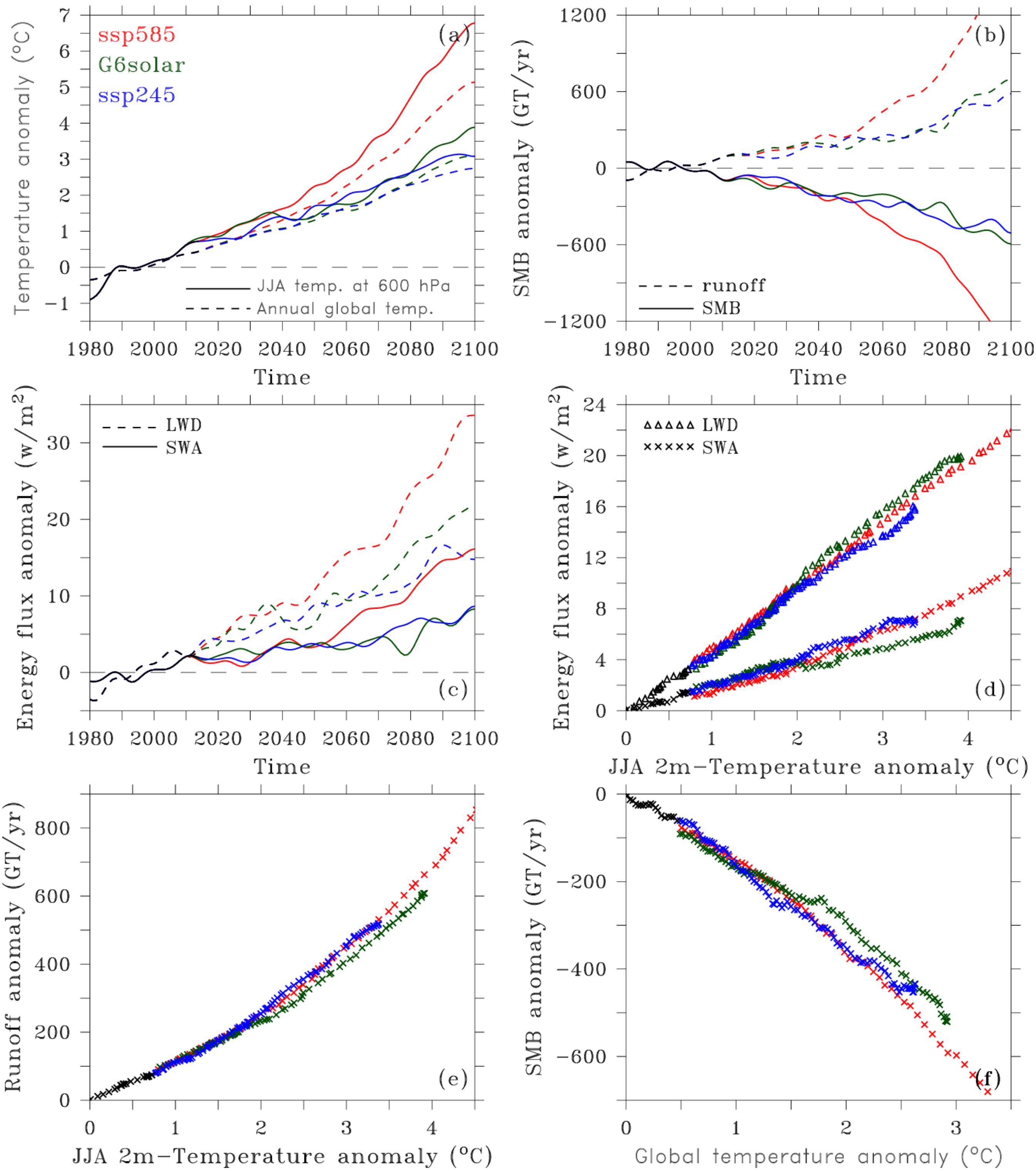

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Figure 1: (a) Time series of the anomalies of the annual global near-surface temperature (in dash) and the JJA (June-July-August) temperature at 600hPa over Greenland (55°N-85°N, 90°W-0°W) as simulated by CNRM-ESM2-1 using the ssp245 (in blue), ssp585 (in red) and G6solar (in green) scenarios (the Historical period is shown in black). A 30yr-running mean has been applied to all the time series (values after 2086 are given by averaging the available values till 2100) and the anomalies are given with respect to the period 1981-2010. (b) Same as (a) but for the Greenland ice sheet surface mass balance (SMB in GT/yr) and meltwater runoff (in dash) as simulated by MAR using the CNRM-ESM2-1-based different scenarios. (c) Same as (b) but for-the mean JJA incoming longwave radiation (LWD in W/m²) and absorbed solar radiation (SWA in W/m²) anomalies averaged over the Greenland ice sheet simulated by MAR. (d) Anomalies of the mean JJA incoming longwave radiation (shown by triangles, in W/m²) and absorbed solar radiation (shown by crosses, in W/m²) simulated by MAR vs the MAR JJA near-surface temperature over the Greenland ice sheet. (e) Same as (d) but for the anomalies of the annual cumulated runoff over the Greenland ice sheet (in GT/yr) projected by MAR. (f) MAR anomalies of the GrIS SMB (in GT/yr) vs annual global mean temperature anomalies from CNRM-ESM2-1 (in °C).

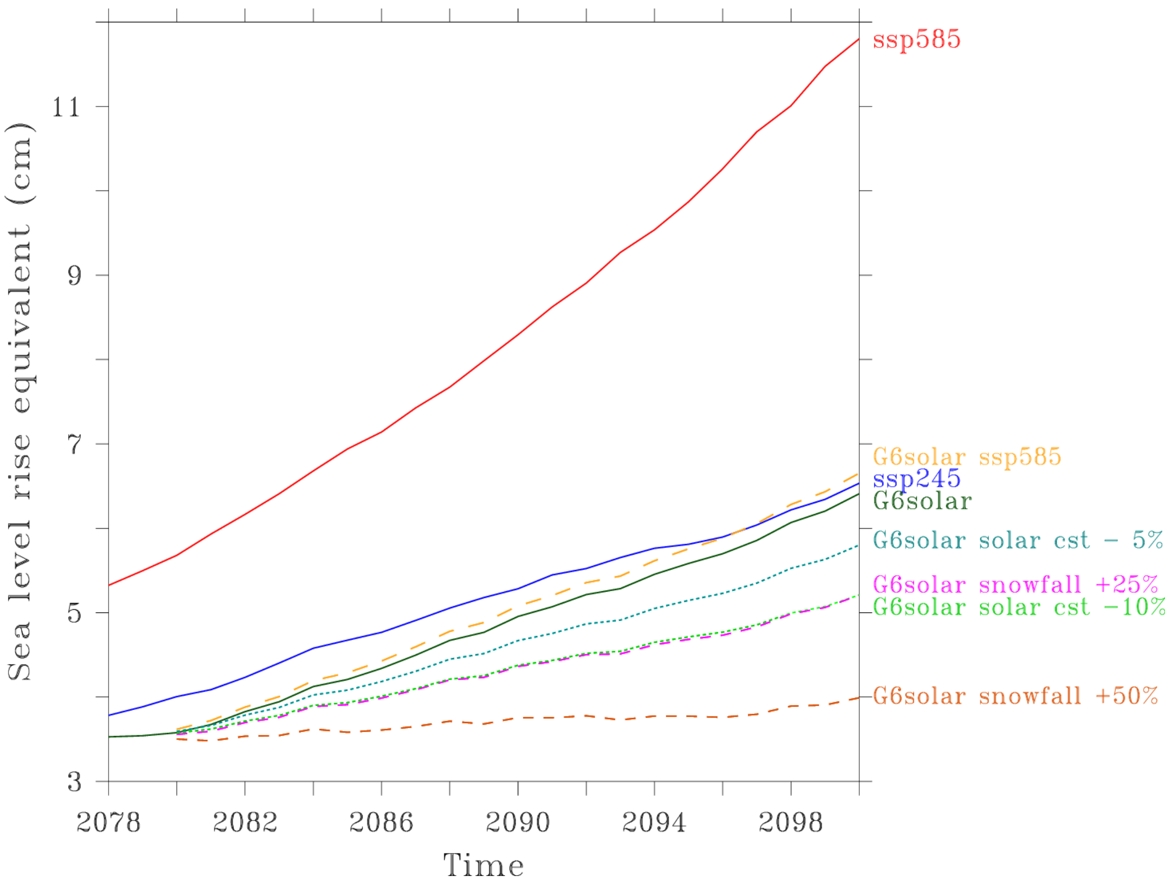

Figure 2: (a) Time series of the cumulated SMB anomalies from 2015 (gauged here in sea-level rise equivalent) as simulated by the 3 main scenarios as well by the G6solar-based sensitivity experiments (G6solar with the solar constant from ssp585, G6solar with an artificial increase of snowfall and G6solar with an artificial decrease of solar constant) starting in 2080. Finally, the three reference runs are displayed as solid lines and the four sensitivity experiments as dashed/dotted lines.