Twenty-First-Century Climate Change Hot Spots in the Light of a Weakening Sun

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(Manuscript received 24 January 2019, in final form 18 January 2020)

ABSTRACT
Satellite measurements over the last three decades show a gradual decrease in solar output, which can be indicative as a precursor to a modern grand solar minimum (GSM). Using a chemistry–climate model, this study investigates the potential of two GSM scenarios with different magnitude to counteract the climate change by projected anthropogenic greenhouse gas (GHG) emissions through the twenty-first century. To identify regions showing enhanced vulnerability to climate change (hot spots) and to estimate their response to a possible modern GSM, a multidimensional metric is applied that accounts for—in addition to changes in mean quantities—seasonal changes in the variability and occurrence of extreme events. We find that a future GSM in the middle of the twenty-first century would temporarily mitigate the global mean impact of anthropogenic climate change by 10%–23% depending on the GSM scenario. A future GSM would, however, not be able to stop anthropogenic global warming. For the GHG-only scenario, our hot-spot analysis suggests that the midlatitudes show a response to rising GHGs below global average, while in the tropics, climate change hot spots with more frequent extreme hot seasons will develop during the twenty-first century. A GSM would reduce the climate change warming in all regions. The GHG-induced warming in Arctic winter would be dampened in a GSM due to the impact of reduced solar irradiance on Arctic sea ice. However, even an extreme GSM could only mitigate a fraction of the tropical hot-spot pattern (up to 24%) in the long term.

1. Introduction
While a large number of studies provide some evidence that the decadal solar variability, the 11-yr Schwabe cycle, is connected to tropospheric weather patterns (e.g., Kodera and Kuroda 2002; Matthes et al. 2006; Ineson et al. 2011; Gray et al. 2013; Andrews et al. 2015; Thiébemont et al. 2015) via a complex chain of feedback mechanisms (Gray et al. 2010), the consequences of centennial irradiance changes are by far less understood. This applies to the centennial solar imprints on terrestrial climate during the last 12 000 years but in particular to a potential modulation of anthropogenic climate change by centennial irradiance changes in the upcoming decades. A period of at least three consecutive decades in which a threshold of 15 sunspots is not exceeded is defined as a grand solar minimum (GSM) (Usoskin et al. 2007). These periods are characterized by a virtual absence of the 11-yr cycle and a reduced irradiance throughout the solar spectrum owed to an overall weak magnetic field of the sun. Anomalies in the content of cosmogenic $^{14}$C in different paleo-archives reveal at least 27 of such events during the Holocene (Usoskin et al. 2007).

The last GSM, the Maunder Minimum (1645–1715) (Eddy 1976), coincided with temperatures below average and a time of severe hardship especially in Europe (e.g., Luterbacher et al. 2004). The sequence of the 11-yr solar cycles during the last three decades points to a potential end of the current persistent period of high solar activity, also named modern grand solar maximum, and reveals a realistic chance for a downturn in solar energy, such as the Maunder Minimum or the weaker Dalton Minimum (about 1790–1830), until the end of the twenty-first century (Abreu et al. 2008; De Jager and Duhau 2009; Lockwood 2013; Roth and Joos 2013; Zolotova and Ponyavin 2014; Steinhiiber and Beer 2013; De Jager et al. 2016; Sánchez-Sesma 2016). This assumption is based on the duration of the current grand solar maximum, the exceptional deep solar minimum of solar cycle 23, and the lowest solar maximum in 100 years of solar cycle 24 (Janardhan et al. 2011; Lockwood 2011;
Nandy et al. 2011). The quantification of the implications of such a projected decrease in solar forcing is important, given the ongoing discussion about the role of natural climate drivers that might mitigate the anthropogenic imprints in the future development of twenty-first-century climate. Previous studies investigating the impact of a potential GSM on twenty-first-century climate change focused on the global mean climate (Feulner and Rahmstorf 2010; Meehl et al. 2013; Anet et al. 2013) or put emphasis on the Northern Hemisphere (NH) winter and the underlying mechanisms (Ineson et al. 2015; Maycock et al. 2015; Chiodo et al. 2016; Arsenovic et al. 2018). Even though available literature suggests that the regional response to a modern GSM could significantly exceed the global signal (a global cooling between −0.1 and −0.35 K), a detailed analysis of the regional effects of a potential twenty-first-century GSM, addressing the aggregate response of different climate indicators, is missing. Most studies were limited to the analysis of the near-surface temperature response, neglecting the possible impacts of a severe solar downturn on other climate variables, for example, precipitation or seasonal extreme events. Furthermore, some of the models used to simulate a future GSM suffer from model simplifications, for example, lack of interactive ozone chemistry or a proper representation of the middle atmosphere (Feulner and Rahmstorf 2010; Ineson et al. 2011; Maycock et al. 2015).

In the following, we will provide a comprehensive analysis that allows us to 1) determine regional climate vulnerability against the background of anthropogenic greenhouse gas (GHG) emissions, 2) identify regional hot spots of twenty-first-century climate change, 3) reassess the response of identified regional hot-spot clusters under a potential twenty-first-century solar downturn, and 4) provide a detailed assessment of possible regional climate change mitigation effects induced by a hypothetical twenty-first-century GSM. To quantify the effects of a potential GSM, data from three climate change projections covering the period 1960–2095, conducted with the state-of-the-art chemistry–climate model (CCM) ECHAM/Modular Earth Submodel System (MESSy) Atmospheric Chemistry (EMAC) (Jöckel et al. 2006) coupled to an interactive ocean model were analyzed. To assess the uncertainties associated with the potential magnitude of a modern GSM we used two Maunder Minimum reconstructions for our GSM projections, which represent the upper and lower bounds of available datasets to simulate a twenty-first-century solar downturn (please see section 2a for a detailed discussion of the solar datasets). The datasets incorporate decreases in both total solar irradiance (TSI) and spectral solar irradiance (SSI). The experiments under GSM conditions were compared to a reference simulation with ongoing 11-yr solar cycle. In our analysis we applied a method to locate climate change hot spots (Diffenbaugh and Giorgi 2012). Note that the term “hot spot” is used here as a synonym for regions that are projected to be particularly affected by climate change during the twenty-first century. They are identified by a metric that represents the aggregate climate change responses of seven climate indicators, such as mean temperature and precipitation, their variability, and the frequency of extreme events. While climate change impacts are expected to depend on local factors leading to different types of impact, such as more frequent heat waves or an enhanced risk of flooding, the hot-spot metric is useful to identify parts of the world (hot spots) that show the strongest integrated response to global climate change across the most relevant meteorological quantities.

In section 2, we introduce the applied model, experimental setup, and analysis methods. Section 3a presents the global annual mean and boreal winter responses of individual climate indicators to two different GSM scenarios and assesses their mitigation potential in a moderate climate change scenario. Section 3b applies the hot-spot technique to determine regions that are particularly affected by aggregate climate change and addresses the question how the identified hot spots would be affected by a GSM. In section 4 the results are summarized and discussed.

2. Methods

a. Model and experimental setup

Our simulations have been conducted with the EMAC CCM (version 1.10) (Jöckel et al. 2006). The dynamical core of EMAC consists of the atmosphere general circulation model (AGCM) ECHAM5 (Rocheiner et al. 2006) in a configuration of T42 (2.8° longitude × 2.8° latitude) and L39 (39 hybrid pressure levels up to 0.01 hPa, about 80-km altitude). Heterogeneous and homogeneous chemical reactions that particularly concern ozone chemistry are calculated by the Module Efficiently Calculating the Chemistry of the Atmosphere (MECCA) (Sander et al. 2005). To account for realistic feedbacks of the wavelength-dependent radiation change to middle atmosphere temperature and ozone, a shortwave radiation scheme [Freie Universität Berlin Radiation (FUBRAD)] covering the solar spectrum in 55 spectral bands between 121.6 and 690 nm was used (Nissen et al. 2007; Kunze et al. 2014). EMAC is coupled to the Max Planck Institute Ocean Model (MPI-OM) (Jungclaus et al. 2006) using a resolution of 1.5° × 1.5°.

To investigate the effect of a solar downturn during the twenty-first century, we applied two future GSM
scenarios and compared their climate response to a reference (REF) simulation with an ongoing 11-yr solar cycle (Fig. 1a). In the REF simulation solar cycles 19–23 correspond to observations (Lean et al. 2005). For the projected solar cycles 24–32, the observed solar cycles are repeated according to the Chemistry–Climate Model Initiative (CCMI) recommendations (Eyring et al. 2013). The GSM simulations were initialized with data of the REF simulation for December 2007, with the historical period (1960–2007) being a joint basis for all simulations. To apply a less abrupt transition to GSM conditions the projected solar cycle 24 has been replaced by the weaker historical solar cycle 14 in the GSM simulations. After this cycle a linear decrease in TSI and SSI to values of Maunder Minimum reconstructions is assumed. The solar forcings of the simulations “weak GSM” (wGSM) and “strong GSM” (sGSM) are based on reconstructions of Krivova et al. (2010) and Shapiro et al. (2011), respectively. Figure 2 shows in green (blue) the differences in solar spectral irradiance between the wGSM (sGSM) simulation during 2027–82 and the mean of the REF simulation over all solar cycles between 1960 and 2100, integrated for each of the 55 bands of FUBRAD. The reconstruction for the Maunder Minimum period by Shapiro et al. (2011) is discussed controversially within the solar physics community regarding a potential overestimation of the decrease in solar output during the last GSM (e.g., Judge et al. 2012; Egorova et al. 2018). In fact, Feulner (2011) and Schurer et al. (2014) show that climate simulations for the last millennium reveal too-low global temperatures during the last GSM and the first half of the twentieth century.

FIG. 1. Time series of the total solar irradiance boundary conditions (W m$^{-2}$) for (a) the reference (REF) simulation and (b) the GSM simulations.

FIG. 2. Differences in solar spectral irradiance at the top of the atmosphere (%) between the weak GSM (green) and strong GSM (blue) simulations during 2027–82 and the mean of the reference simulation over all solar cycles between 1960 and 2100.
compared to proxies and observations, if a solar forcing according to the Shapiro et al. (2011) dataset is applied. Nevertheless, estimating the amplitude of a potential future GSM is highly uncertain, and the reconstruction of Shapiro et al. (2011) offers the chance to study an upper limit of solar-induced climate change mitigation for the twenty-first century, although it might be questionable. During the GSM core period (2027–82) TSI is reduced by approximately 1.3 and 5.8 W m\(^{-2}\) in the wGSM and sGSM simulations, respectively, compared to the REF simulation. After the core period, the solar boundary conditions of the GSM simulations return to normal conditions and end with the repetition of solar cycle 14 (Fig. 1b). Except for the solar forcing, all boundary conditions are identical in the GSM and REF simulations. All simulations include the effects of climate change according to an intermediate scenario for the increase in GHGs (RCP6.0) (Meinshausen et al. 2011), as well as stratospheric ozone depletion and future recovery according to the A1 scenario of ozone depleting substances (WMO 2007).

b. Hot-spot quantification

To identify regions that face an overaverage climate response during the twenty-first century we use a hot-spot quantification method that has originally been used for CMIP5 data by Diffenbaugh and Giorgi (2012). It allows for assessing the accumulated climate change impact on a region resulting from changes in the means, variability and extreme values of near-surface temperature and precipitation. To quantify the aggregate climate change, we calculate the local sum of standard Euclidean distances (SED\(_{\text{sum}}\)) from individual standard Euclidean distances (SED\(_{\nu}\)) for seven climate indicators \(\nu\) in each season (DJF, MAM, JJA, SON). SED\(_{\nu}\) corresponds to the square of the ratio of the absolute value of change in climate indicator \(\nu\) at every individual land grid point to the maximum absolute value of change in \(\nu\) identified over all land grid points in the last climate change period (2076–95). By the normalization, it is ensured that all indicators contribute equally to SED\(_{\text{sum}}\). SED\(_{\text{sum}}\) represents thus the changes in a 28-dimensional climate space for future climate change periods, with respect to a baseline period. Its magnitude is a metric of dissimilarity between the baseline period and a respective climate change period and is often regarded as the “distance travelled” in climate space. We included changes in near-surface temperature (\(\Delta T\)) and precipitation (\(\Delta P\)), changes in the variability of the near-surface temperature (\(\Delta T_{\text{var}}\)) and precipitation (\(\Delta P_{\text{var}}\)), and changes in the occurrence frequencies of extremely hot (\(\sum T_{\text{exhot}}\)), dry (\(\sum P_{\text{exdry}}\)), or precipitation-rich (\(\sum P_{\text{exwet}}\)) seasons. An extreme hot season is, for example, assumed if the mean temperature in a future period exceeds the absolute...
maximum temperature of the baseline period. Only climate hot spots in inhabited regions, that is, north of 60°S, are considered.

We classify a region to be a climate hot spot, if the local $S_{E,D,\text{sum}}$ exceeds the global mean in a given climate change period by at least 25%. A climate hot spot is considered intermediate if the regional $S_{E,D,\text{sum}}$ is less than 25% above the global average. Non-hot-spot regions do not exceed the global mean. A more detailed description about the hot-spot quantification and the calculation of significances is given in the online supplemental material.

3. Results

a. The global climate response to rising greenhouse gases and a solar downturn

Before deriving the twenty-first-century hot-spot patterns, we discuss the global mean and spatial climate responses under moderately rising GHG concentrations (RCP6.0) in the REF simulation and the possible implications of a GSM-like solar downturn of different magnitudes (wGSM and sGSM simulations) in three climate change periods (2010–39, 2040–69, 2070–95). Figure 3 shows the evolution of global annual mean near-surface temperature relative to the reference period 1960–99 for the three scenarios. As summarized in Fig. 3, the REF simulation projects an increase in global annual mean near-surface temperature during the first period (2010–39) of 0.85 K relative to 1960–99. In the GSM simulations, where this first period represents the transition to the GSM, the increase in global annual mean near-surface temperature of the REF run is slightly reduced by 0.04 K (4.7%) in the wGSM and by 0.15 K (17.6%) in the sGSM scenarios, with the difference to the REF run being statistically significant at this stage in the more severe scenario only. In period 2 (2040–69), which falls into the GSM core period, both scenarios show a significantly reduced global warming by 0.19 K (12.4%) in the wGSM and by 0.42 K (28%) in the sGSM scenarios, compared to the REF simulation (+1.5 K). During this period, the REF simulation shows an increase in global near-surface temperature of 0.23 K decade$^{-1}$, while the wGSM and sGSM simulations reveal weaker positive trends of 0.15 and 0.10 K decade$^{-1}$, respectively. Nevertheless, the wGSM simulation quickly catches up with the REF simulation during period 3 (2070–95), that is, the transition period back to normal solar conditions. The relative GSM-induced cooling in the wGSM simulation falls in the range of previous model results of a future solar downturn (e.g., Meehl et al. 2013; Ineson et al. 2015; Arsenovic et al. 2018). At the end of the twenty-first century, both the REF and wGSM simulations show a comparable increase in global annual mean near-surface temperature of +2.28 and +2.18 K, respectively. Only the sGSM simulation projects a significant mitigation of global warming up to −0.45 K (−19.7%) by the end of the solar downturn (Fig. 3). This prolonged effect during the decline of the sGSM is due to the extreme reduction of TSI (Fig. 1b) in the sGSM scenario in conjunction with a slow response of the oceans to the reduced TSI. Figure 4a shows the development of the annual global mean ocean temperature
as a function of ocean depth for the REF simulation relative to 1960–99. It can be seen that a mean warming of the global ocean up to \( \sim 1.8 \) K at the surface can be expected as a consequence of steady rising anthropogenic GHGs. Due to thermal inertia, the deeper ocean layers lag the surface warming by several decades. For instance, while the uppermost 50 m of the global ocean experience a warming of \( \sim 0.6 \) K by 2030, it takes about four decades until the same amount of warming has passed through the top 350 m of the global ocean column. The temperature anomalies between the REF and the wGSM and sGSM simulations (Figs. 4b,c) show that even a weak GSM leads to a detectable near-surface relative cooling down to the mixed layer (about 50 m). Especially in the case of the sGSM experiment, the periodicity of the 11-yr solar cycle in REF is rendered by the negative anomalies in the global ocean temperature. Furthermore, the magnitude of the anomalies seems to be anticorrelated with the amplitude of the respective solar cycle (i.e., the particular strong solar cycles in the 2030s and 2040s). The sGSM experiment induces a distinctly stronger relative surface cooling that spreads through deeper ocean layers (down to 500 m) and slightly delays the GHG-induced warming even at the end of the GSM.

The spatial annual mean GHG-induced warming pattern in the REF simulation during period 2 (2040–69) is presented in Fig. 5a. All regions are facing a severe increase in near-surface temperature in the middle of the twenty-first century. Some regions actually exceed the global average of \(+1.5 \) K by a factor of 2, as, for example, NH high latitudes, which are affected by an increase in near-surface temperature larger than 3 K. During the GSM core period, both GSM simulations show a weaker warming in almost all regions (Figs. 5b,c). Especially the polar latitudes of the NH show distinct (and statistically significant) negative temperature anomalies between 0.4 and 0.8 K with respect to the underlying GSM scenario. Additionally, under sGSM conditions, vast parts of the lower latitudes and the Southern Hemisphere (SH) reveal a strong significant cooling.

The sensitivity of northern high latitudes to climate change is more evident during winter. Figure 6a depicts the long-term seasonal mean (DJF) GHG-induced warming between the reference period (1960–99) and period 2 (2040–69) in the REF simulation. The seasonal signals at polar latitudes exceed the annual mean response by up to several kelvins—an effect that is known as Arctic amplification (AA) with strongest influences during NH winter season (Serreze and Barry 2011). One major factor controlling the intensity of the AA is the amount of declining sea ice due to anthropogenic warming, especially during autumn when the sea ice extension reaches its minimum, but the solar radiation is still strong enough to warm the upper-ocean layers in high latitudes. The more sea ice melts during the melting season, the less relatively warm ocean waters are isolated from the cold Arctic atmosphere. This in turn leads to a delay in new sea ice formation and an increase in upward heat fluxes from the ocean to the atmosphere in the subsequent winter season. As a result, particularly...
strong temperature reactions between 6 and 8 K appear in the Bering, Beaufort, and Kara Seas. Under GSM conditions this warming is reduced by up to 2 K. This particularly strong response might be attributed to the fact that the decrease in solar energy in the GSM experiments leads to less sea ice decline in late autumn, that is, the period when the formation of new sea ice is still delayed in the REF simulation (Figs. 7a–c). As a result, the future increase in upward heat flux in the NH winter season found under REF conditions is markedly lower under the additional impact of a GSM (Fig. S1 in the online supplemental material). This dampens the AA and explains the strong reduction in warming, that is, the relative cooling, of high latitudes during winter if a GSM is assumed.

The above-described temperature responses to the wGSM and sGSM scenarios in northern winter are consistent with a shift in the North Atlantic Oscillation (NAO) variability mode toward a more negative phase. This is associated with positive mean sea level pressure (MSLP) anomalies at polar latitudes and negative anomalies at midlatitudes of the North Atlantic–European sector in winter (Figs. 8a,c). Compared to the REF simulation in the middle of the twenty-first century, precipitation is projected to decrease during a GSM over central and northern Europe, while winters in southern Europe and the Mediterranean should become wetter (Figs. 8b,d). The precipitation changes in the wGSM and sGSM simulations with respect to the REF simulation in 2046–65 are of comparable magnitude to the changes in the REF simulation between the baseline period of 1986–2005 and 2046–65 (~0.1–0.4 mm day$^{-1}$) but opposite to REF in the northern and southern European regions. The precipitation anomalies during a solar downturn would thus reduce the expected climate change–induced wettening of northern Europe and drying of the Mediterranean as shown in our REF simulation (Fig. S2).

The described anomalies in MSLP and precipitation in boreal winter of the wGSM and sGCM simulations are indicative of an indirect dynamical response to the reduced solar forcing by the “top-down mechanism” (TDM), which modulates stratosphere–troposphere coupling via a solar-driven pathway involving a dynamical response to changes in ultraviolet solar irradiance (Kodera and Kuroda 2002). As postulated by this mechanism, we find a significantly weaker stratospheric polar night jet in our simulations under both GSM conditions and an associated southward shift of the polar front jet stream in the troposphere in December and January, with significant changes extending into the troposphere and to the surface in December of the sGSM simulation (Figs. S3 and S4). Changes in mean sea level pressure, suggesting a negative-NAO-like response to the
solar forcing, appear in both the wGSM and sGSM runs in December and January, with statistical significance (>95%) being reached in December. The more effective downward propagation of the solar signal to the lower troposphere and surface in early boreal winter can be explained by the fact that the solar-induced upper-stratospheric zonal wind anomalies more effectively modify the propagation conditions for the downward signal transfer in early winter than in January or February, when enhanced upward-propagating planetary waves overlap the TDM, as was also found by Matthes et al. (2006). These strong seasonal dependencies explain the missing significance in the MSLP pattern (Figs. 8a,c), if the solar signal is averaged over the complete winter season.

Apart from the relative cooling during NH winter, another interesting aspect maximizes in this season at high latitudes under GSM conditions. South of Greenland significant, positive anomalies in sea surface temperature emerge in both the wGSM and sGSM simulations (Figs. 6b,c). This area is particularly influenced by the subpolar gyre (SPG), which transports relatively warm seawater from lower latitudes to the polar sea surface mixing layer. Since the SPG is part of the Atlantic meridional overturning circulation (AMOC), the warm patch in our simulations might hint at a strengthening of the AMOC under GSM conditions. The same pattern with opposite sign was associated by Caesar et al. (2018) with a weakening of the AMOC. Indeed, Anet et al. (2013) find some indication of a stronger AMOC in their GSM simulations, and Menary and Scaife (2014) observe a slight strengthening of the AMOC during epochs when the solar forcing is assumed to be comparably weak (e.g., during the late nineteenth or the early twentieth century). However, these findings are in contrast with other studies (e.g., Ineson et al. 2015) where a GSM seems to lead to a faint weakening of the AMOC. Additional studies suggest that volcanic eruptions are more effective at modulating the AMOC via complex sea ice–ocean–atmosphere mechanisms (e.g., Miller et al. 2012; Schleussner and Feulner 2013) or claim that the internal variability of the NAO might be a crucial factor (e.g., Lohmann et al. 2009). Regarding this topic there is no consensus within the scientific community, and it is beyond the scope of this study to provide a detailed analysis of the AMOC under GSM conditions.

b. The twenty-first-century climate change hot-spot pattern under GSM conditions

We now expand our analysis of the previous section from the responses of individual meteorological quantities to the identification of the aggregate response of a combination of meteorological quantities as a
measure for the overall impact of climate change and its potential mitigation by a GSM. We first identify regional hot spots of anthropogenic climate change in the REF simulation by applying the method of Diffenbaugh and Giorgi (2012) as described in section 2. We derive the spatial SED$_{sum}$ values for three selected 20-yr periods (2016–35, 2046–65, and 2076–95) with respect to the baseline period of 1986–2005 (Figs. 9a–c). Note that these periods were chosen to enable a comparison with existing literature (Diffenbaugh and Giorgi 2012) and are therefore different from those in section 3a. During the early twenty-first century (Fig. 9a), a rather homogeneous pattern of aggregate climate change response with SED$_{sum}$ values between 0.5 and 1 emerges. Regions exceeding the global average of 0.88 by 25% in this early stage of climate change are largely confined to low latitudes, while the NH high and middle latitudes show relatively low values.

Around midcentury, a differentiation of local SED$_{sum}$ values and a hot-spot pattern start to emerge (Fig. 9b). This pattern is characterized by an expansion of tropical climate hot spots within the Amazon basin and to the SH midlatitudes of Africa. In Southeast Asia the tropical regions (Malaysia, Indonesia, and Papua New Guinea) show the strongest sensitivity to anthropogenic climate change. While moderate values of aggregate climate change are present in eastern subtropical and NH polar regions, the northern midlatitudes are affected below average by aggregate climate change in this period.

During the late twenty-first century, the global mean of SED$_{sum}$ increases by $\sim$33% from 1.33 to 1.77, and the hot-spot pattern in the inner tropics further grows in magnitude and regional dispersal (Fig. 9c). Some local SED$_{sum}$ exceed the global average by more than 50%, whereby Africa in particular experiences a southward expansion of above-average aggregate climate change. Besides distinct hot-spot regions within the inner tropics, some areas show an intermediate hot-spot character; these include Australia, South/Southeast Asia, and North Africa with the Sahel. As in the other regions, the aggregate climate change of the northern middle to high latitudes increases toward the end of the twenty-first century, with southern Europe becoming a local European climate hot spot, however,
and weakest, respectively, aggregate climate change due to the projected rise of anthropogenic GHGs. The identified spatial and temporal hot-spot pattern corresponds closely to the multimodel mean analyses of CMIP5 ensembles (Diffenbaugh and Giorgi 2012) and demonstrates the comparable performance of our model with respect to its sensitivity to rising GHGs.

Figure 10 shows the annual mean relative differences in aggregate climate change between the GSM and the REF simulations. Table 2 includes additionally the absolute SED\textsubscript{sum} for the REF simulation and the relative differences, if a GSM (weak or strong) is assumed. Differences were calculated for individual hot-spot regions and the class mean response (and deviation) in three hot-spot classes (hot spot, intermediate hot spot, and non-hot spot) for the three climate change periods. Tables S1 and S2 summarize the responses to a GHG-induced warming (REF) and a potential GSM mitigation of all seven climate indicators during the GSM core period (2046–65) in the NH winter and summer seasons. In these seasons both the anthropogenic and GSM-induced signals are strongest and dominate the local SED\textsubscript{sum}s. During the transition period to GSM conditions (2016–35), the global aggregate climate change is only slightly dampened by −1.56% under the influence of a weak GSM (Fig. 10a). The class spread within each of the individual hot-spot classes exceeds the individual mean response, indicating that no robust mitigation signals are found (Table 2). In contrast, the early stage signal of the sGSM simulation shows a 6-times-stronger (−9.63%) dampening on global average (Fig. 10d) and a (significant) mean response in the identified climate hot spots of almost −16% (Table 2). During the GSM core period, the main features of GSM-induced anomalies in aggregate climate change seem to be robust, independent of the magnitude of the assumed GSM scenario; however, the mitigating effects of a strong GSM are markedly more intense. In the period 2046–65, global average SED\textsubscript{sum} is reduced by about 10% under wGSM and more than 22% under sGSM conditions compared to the REF simulation (Figs. 10b,e). The equatorial/southern Africa hot spot shows the strongest mitigation effect in both GSM scenarios compared to the REF simulation. Under the influence of a weak GSM, the overall aggregate climate change in this region would be reduced by 14%, while in the case of a strong GSM it would be less by about one-third (31%). Hence, the implications of a strong GSM would be to transfer equatorial/southern Africa from one of the most severe climate change hot spots to an intermediate hot spot (according to the definition of this study) around midcentury, assuming the applied forcing and response of our model are realistic.
Table 1. The aggregate climate change in distinct regions during the late twenty-first century (2076–95). The regions are classified by the magnitude of their mean standard Euclidean distance \((\text{SED}_{\text{sum}})\). Hot spots of aggregate climate change are assumed if the global mean is exceeded by at least 25%. An intermediate hot spot is determined if \(\text{SED}_{\text{sum}}\) is higher than the global mean but does not exceed 25%. Non-hot-spot regions have an \(\text{SED}_{\text{sum}}\) not exceeding the global mean.

<table>
<thead>
<tr>
<th>Considered as</th>
<th>Region</th>
<th>Mean SEDsum</th>
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<tbody>
<tr>
<td>Hot spot</td>
<td>Tropical Southeast Asia</td>
<td>2.34</td>
</tr>
<tr>
<td></td>
<td>Amazon basin (west)</td>
<td>2.29</td>
</tr>
<tr>
<td></td>
<td>Central America</td>
<td>2.26</td>
</tr>
<tr>
<td></td>
<td>Equatorial/southern Africa</td>
<td>2.21</td>
</tr>
<tr>
<td>Intermediate hot spot</td>
<td>Australia</td>
<td>1.81</td>
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<tr>
<td></td>
<td>South/Southeast Asia</td>
<td>1.79</td>
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<tr>
<td></td>
<td>North Africa/Sahel</td>
<td>1.79</td>
</tr>
<tr>
<td>Non-hot spot</td>
<td>South America (midlatitudes)</td>
<td>1.57</td>
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<tr>
<td></td>
<td>Europe</td>
<td>1.55</td>
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<tr>
<td></td>
<td>Russia</td>
<td>1.40</td>
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<tr>
<td></td>
<td>North America</td>
<td>1.34</td>
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In the tropical hot-spot regions, near-surface temperature turns out to be the most sensitive to a GSM, showing a significant relative cooling in DJF and JJA (Tables S1 and S2) due to reduced solar irradiance. The strongest (and in the sGSM simulation highly significant) tropical temperature and precipitation response, however, occurs during NH winter (DJF) in both GSM simulations. In this season, the signals are characterized by a cooling and enhanced precipitation especially in tropical Southeast Asia, the Amazon basin, and Central America. In the sGSM simulation the occurrence frequency of extremely hot DJF seasons is also significantly reduced in those regions (e.g., \(-25\%\) to \(-30\%\) in tropical Southeast Asia or the Amazon basin).

In the NH middle and high latitudes, that is, a non-hot-spot region, the anomalies in \(\text{SED}_{\text{sum}}\) are primarily driven by negative temperature and precipitation anomalies during NH winter (Table S1). This is consistent with the change to a more negative NAO phase and the associated changes in mean sea level pressure and precipitation induced by the “top-down mechanism” in the GSM simulations, as explained in more detail in section 3a.

It is noteworthy that those regions that will be less affected by anthropogenic climate change during the twenty-first century (non–hot spots in Table 1) are projected to profit by a potential solar downturn comparable to the hot spots’ regions. As a consequence, this would weaken the contrast in vulnerability between high and low latitudes.

4. Summary and discussion

To estimate if a distinct future solar downturn might counteract GHG-induced climate change, two CCM climate change projections of the twenty-first century incorporating GSM scenarios of different magnitude were compared with a reference simulation assuming the same moderate increase in GHGs (RCP6.0 scenario) but solar variability according to the 11-yr solar cycle. While both applied GSM scenarios are based on reconstructions of the solar irradiance during the Maunder Minimum, they differ considerably in magnitude and represent a conservative (and probably more realistic) as well as an upper-level estimate of a potential future GSM. The global and annual mean temperature responses to the GSM and the seasonal signals in NH winter were investigated. Using a hot-spot quantification technique, regions with future above-average aggregate climate change were identified.

Before starting the detailed discussion, we point out that our conclusions are based on single transient model realizations for each of the three scenarios, respectively. To quantify the impact of interannual dynamical variability on the model results, large ensembles would be required. Such an ensemble is, however, not feasible at present for a complex CCM including a computationally expensive chemistry scheme. However, as summarized below, the responses to two GSMS of different magnitude in our simulations agree qualitatively with previous work, with generally more pronounced signals for the stronger GSM.

On the global scale, a potential future GSM, developing until midcentury and decaying toward the end of the century, might mitigate the global mean impact of anthropogenic climate change by \(-10\%\) and \(-23\%\), depending on the GSM scenario (Fig. 10). In the middle of the twenty-first century, that is, during the core period of our prescribed GSM scenario, the global warming due to rising GHGs of about 1.5 K relative to 1960–99 is projected to be considerably reduced by about 0.2 and 0.4 K for the weak and strong GSM scenarios, respectively (Fig. 3). However, at the end of the GSM core period, climate change in the GSM simulations quickly catches up to reference conditions. Even for the extreme (and controversial) GSM scenario, the projected GHG-induced warming signals exceed the potential GSM-induced cooling up to 6 times. Our results thus confirm the conclusions of previous studies that a future GSM would not be able to stop global warming (Feulner and Rahmstorf 2010; Anet et al. 2013; Meehl et al. 2013; Ineson et al. 2015).

From a regional perspective, we find that in the middle of the twenty-first century the overall GHG-induced annual mean near-surface warming will be dampened by a solar downturn, with strongest and significant relative cooling of the tropical/subtropical continents, the...
Arctic, parts of the Antarctic, and the tropical Pacific in the strong GSM scenario (Fig. 5). Regionally enhanced responses to both GHG increases and a GSM were found in northern polar latitudes during winter (Fig. 6). The strong warming of the Arctic in our REF simulation, known as Arctic amplification, is qualitatively consistent with the multimodel mean of CMIP5 simulations for the middle of the century and the RCP6.0 GHG scenario (Fig. 12.11 in IPCC 2013). We found that the reduced solar irradiance during a GSM leads to less Arctic sea ice decline in late autumn (Fig. 7) thus contributing to a dampening of the local temperature.
increase up to 2 K in the subsequent winter season. The main features of the regional near-surface temperature responses to the weak and strong GSM scenarios in boreal winter generally agree well with previous model studies, for example, the cooling of Siberia (Meehl et al. 2013; Ineson et al. 2015; Chiodo et al. 2016) and the warming of Greenland (Meehl et al. 2013; Ineson et al. 2015). While the applied models, the considered feedback processes, and the prescribed RCP and GSM scenarios differ from each other in all these studies, the models produce qualitatively comparable temperature responses to a GSM, thus providing confidence in the simulated major tropospheric response patterns to a GSM.

The distinct negative temperature anomalies of both GSM simulations can primarily be attributed to radiative effects. In the tropics, where the solar insolation is intense throughout the year, a significant reduction in TSI can lower surface temperatures more directly compared to the high latitudes, where the solar-induced surface imprints are mainly confined to the dynamically more active autumn/winter season with rather indirect implications, for example, on sea ice. Besides the purely radiatively driven effects, there is further evidence in our simulations that the GSM-related cooling might modulate the mean state of large-scale circulation patterns in the North Atlantic–European sector during winter, and in the tropics. For both GSM scenarios, a shift of the NAO toward a more negative phase was found in early boreal winter, associated with near-surface temperature and precipitation changes of opposite sign in central–northern Europe and southern Europe–Mediterranean area (Fig. 8 and Figs. S3 and S4). While the connection between solar variability and the NAO seems to be uncertain for the 11-yr solar cycle in the observational record (Chiodo et al. 2019), several studies with global models suggest a possible modification of the natural interannual variability of the NAO and Arctic Oscillation (AO) toward their negative phases during periods of prolonged minimum solar activity (e.g., Langematz et al. 2005; Maycock et al. 2015; Ineson et al. 2015). Maycock et al. (2015) and Ineson et al. (2015) found in two GSM simulations stratospheric and tropospheric circulation responses in boreal winter with consistent negative NAO/AO-like patterns. As the regional responses in NH wintertime were stronger in the experiment where only the UV irradiance was enhanced, the authors concluded that they were at least partly driven by the UV changes and the TDM. Similarly, Chiodo et al. (2016) found a negative zonal wind response to a relatively weak solar minimum forcing, which nevertheless seemed to affect the troposphere, in particular the Eurasian cooling, via the TDM.

Table 2. SED$_{sum}$ values in the REF simulation and relative differences (%) between the GSM and the REF simulations for the climate change periods of 2016–35, 2046–65, and 2076–95. The classification of hot spots, intermediate hot spots, and non–hot spots is based on the 2076–95 period. Rows in italic show the mean climate response and the spread of the respective group.
A common result of these studies was that the contribution of the TDM to the surface signals grows with the magnitude of the solar forcing (Chiodo et al. 2016), which is confirmed by the tropospheric responses in the wGSM and sGSM simulations of this study.

In the tropics, our GSM simulations suggest some influence of a solar downturn on the tropical Pacific climate system with implications for the large-scale circulation patterns. While in the REF simulation, the GHG-induced rise in sea surface temperature is stronger in the eastern part of the Pacific throughout the whole projection period (2008–95), a more pronounced relative cooling occurs in the east Pacific leading to a more uniform warming under GSM conditions (Figs 5b,c). This differential cooling leads to a reinforcement in the temperature contrast along the equator compared to the REF simulation, accompanied by a strengthening in the equatorial pressure gradient and stronger trade winds (Fig. S5), increased upwelling of cold ocean water in the east and an overall stronger Walker circulation under GSM conditions. We found that these signals in the climatological mean state of the tropical Pacific climate system increase with the magnitude of the underlying GSM scenario. These results are consistent with Misios et al. (2019) who recently described a slowdown of the Walker circulation under solar maximum conditions. However, a detailed analysis of this topic is beyond the scope of this study and will be subject of a follow-up publication.

Our hot-spot analysis, a novel tool in a GSM study, revealed that the tropical latitudes will severely be affected by anthropogenic climate change as early as in the first third of the twenty-first century. Tropical Southeast Asia, large parts of the Amazon basin, Central America, and equatorial/southern Africa were identified as twenty-first-century climate change hot spots (Fig. 9). Compared to the intermediate and non-hot-spot regions, these areas are particularly affected by both a strong increase in near-surface temperature and in the occurrence frequency of extreme hot seasons. If a future decrease in solar energy is assumed, these tropical hot-spot regions experience the largest mitigation of anthropogenic climate change resulting in weaker surface warming and less frequent extremely hot seasons (Fig. 10). Under the influence of a future GSM, the tropical hot-spot areas additionally reveal overall wetter conditions during DJF with the precipitation anomalies being statistically significant in the sGSM simulation. In the tropical climate, where the interannual variability is rather low, changes in the mean temperature will more easily lead to an increase in extreme hot seasons, thus contributing to the prominent tropical hot-spot pattern in our REF simulation. Hence the relative cooling produced by a GSM stabilizes the climatological mean state, ultimately leading to a smaller number of extreme events during the GSM core period.

The pattern and magnitude of aggregate climate change, and specifically the strong increase in the frequency of extreme hot seasons in the tropical latitudes in our REF simulation, agree well with the multimodel ensemble analysis of Diffenbaugh and Giorgi (2012) and other studies using similar approaches (e.g., Baettig et al. 2007; Williams et al. 2007; Beaumont et al. 2011). These studies (including ours) incorporated changes in the frequency of extreme events, as one factor, to their set of climate change estimators. If this climate estimator is neglected, the rate of climate change, that is, in terms of mean annual temperature, is more prominent in mid- and high latitudes (e.g., Giorgi 2006; Loarie et al. 2009; Sandel et al. 2011). However, including changes in the frequency of extreme events (both temperature and precipitation related) is important, since such kind of events are known to be a serious threat to human health, ecosystems, and economy (e.g., Epstein and Mills 2005). Considering that tropical ecosystems are highly sensitive to extreme weather conditions (e.g., Beaumont et al. 2011; Lo-Yat et al. 2011) and the fact that the proportion of developing countries in tropical regions is overaverage (with implications for effective adaption strategies) (Mirza 2003; Mertz et al. 2009), including this indicator to estimate the future response to climate change is particularly justified.

The hot-spot analysis shows that regions projected to be affected above average by anthropogenic climate change might experience some degree of mitigation of aggregate climate change impacts under the influence of a future GSM. The dampening effects, however, only persist during the core period of a GSM and start to dissolve, as soon as the sun reaches its pre-GSM-level of luminosity. It is important to note that this study has been conducted assuming an intermediate GHG increase throughout the twenty-first century. The current development of carbon dioxide emissions rather suggests the possibility of a stronger human-induced impact on twenty-first-century climate. Hence, even our extreme GSM scenario might overestimate the fractional contribution of a potential future GSM to climate change. This emphasizes the ultimate importance of significant mitigation actions to be taken to reduce anthropogenic imprints in near-to midterm terrestrial climate.

Finally, we note that our conclusions are based on results from a single model and an individual set of external forcings (e.g., the GSM and RCP scenarios). To assess the
uncertainty of the model results induced by the specific model configuration, the representation of the relevant physical and chemical processes and the available GHG and GSM scenarios, a coordinated GSM model intercomparison including simulations with a consistent set of forcings and joint analyses would be necessary. Moreover, the role of internal variability should be studied using multiple realizations in a “large ensemble” approach.

Acknowledgments. The authors thank the graduate research school GeoSim (Helmholtz Association) for the funding of this project. The authors would also like to thank the HL RN (Berlin, Germany) and ECMWF (Reading, United Kingdom) supercomputing centers for generously granting computing time, and Denise Seiling for technical help with the figures. We are also grateful to Georg Feulner, two anonymous reviewers, and the editor for their helpful comments.

Data availability statement: The model data for this study are stored at a permanent archive at the HL RN supercomputing facility and can be made available upon reasonable request by the authors.

REFERENCES


