Impact of a potential 21st century "grand solar minimum" on surface temperatures and stratospheric ozone

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[1]   We investigate the effects of a recently proposed 21st century Dalton minimum like decline of solar activity on the evolution of Earth's climate and ozone layer. Three sets of two member ensemble simulations, radiatively forced by a midlevel emission scenario (Intergovernmental Panel on Climate Change RCP4.5), are performed with the atmosphere-ocean chemistry-climate model AOCCM SOCOL3-MPIOM, one with constant solar activity, the other two with reduced solar activity and different strength of the solar irradiance forcing. A future grand solar minimum will reduce the global mean surface warming of 2 K between 1986–2005 and 2081–2100 by 0.2 to 0.3 K. Furthermore, the decrease in solar UV radiation leads to a significant delay of stratospheric ozone recovery by 10 years and longer. Therefore, the effects of a solar activity minimum, should it occur, may interfere with international efforts for the protection of global climate and the ozone layer. **Citation:** Anet, J. G., et al. (2013), Impact of a potential 21st century "grand solar minimum" on surface temperatures and stratospheric ozone, *Geophys. Res. Lett.*, *40*, 4420–4425, doi:10.1002/grl.50806.

1.   Introduction

[2]   Model simulations of 21st century climate undertaken under the CMIP5 project [e.g., *Knutti and Sedláček*, 2012] show global temperature increases of 1 ± 0.4 K for the RCP2.6 scenario, 1.8 ± 0.5 K for RCP4.5, 2.2 ± 0.5 K for RCP6.0, and 3.7 ± 0.7 K for RCP8.5 (Representative Concentration Pathways) [e.g., *van Vuuren et al.*, 2011]. The ranges reflect intermodel differences for a given scenario but do not include uncertainties in future natural forcings. In the CMIP5 protocol, volcanic effects are assumed to be negligible and solar activity is chosen to mimic the last solar cycle. Recently, the possibility of a future grand solar minimum was proposed to occur in the 21st century [*Abreu et al.*, 2010; *Lockwood et al.*, 2009; *Steinhilber and Beer*, 2013]. The cooling associated with a potential solar activity decline might have implications for global warming, atmospheric dynamics, weather patterns, and air chemistry, in general, and for stratospheric ozone, in particular. Studies using different climate models and scenarios of solar activity changes [*Feulner and Rahmstorf*, 2010; *Rozanov et al.*, 2012a; *Meehl et al.*, 2013] concluded that global warming could be partially compensated by about 0.25 to 0.5 K.

[3]   Uncertainties in the magnitude of the solar contribution are partially related to different experimental designs: *Feulner and Rahmstorf* [2010] used a model of intermediate complexity with a simplified treatment of the stratospheric processes and obtain a reduction of the warming by 0.26 K. They adopted the greenhouse gas emissions following the Special Report on Emissions Scenarios A1B and applied solar activity changes without spectral resolution via a total solar irradiance (TSI) decrease by 0.08% and 0.25%. Resulting changes in ocean and land surface temperatures affect the entire atmosphere via the hydrological cycle. This mechanism is known as the bottom-up mechanism [e.g., *Gray et al.*, 2010]. On the other hand, the efficiency of the top-down mechanism [e.g., *Gray et al.*, 2010] was probably underestimated because of the very low changes in the middle atmosphere induced by the small amplitude of the ultraviolet (UV) part of the spectrum and of the missing energetic particles. To overcome this shortcoming, *Rozanov et al.* [2012a] applied the chemistry-climate model solar-climate-ozone links (CCM SOCOL) in the time slice mode driven by the changes of energetic particle precipitation and spectral solar irradiance (SSI) taken from the reconstructions by *Shapiro et al.* [2011] for Dalton minimum conditions. However, these simulations were performed without interactive ocean. *Meehl et al.* [2013] used the atmosphere-ocean chemistry-climate model (AOCCM) WACCM driven by a TSI drop by 0.25% during 50 years in the middle of the 21st century using the RCP4.5 emission scenario and with an SSI decrease constructed by scaling of the solar irradiance from the Naval Research Laboratory spectral solar irradiance (NRLSSI) data [*Lean et al.*, 2005]. They obtained a reduction of global warming by 0.24 K. There is presently a lively discussion of the very uncertain SSI variations over the recent past solar cycles [*Haigh et al.*, 2010; *Lean and DeLand*, 2012]. As *Meehl et al.* [2013] prescribed –0.25% less irradiance in the entire spectrum by taking the mean of the 1975, 1986, and 1996 solar minimum values of the NRLSSI data of *Lean et al.* [2005], the overall drop in UV is weaker than in the *Shapiro et al.* [2011] forcing, thus reducing the magnitude of the top-down mechanism.

Additional supporting information may be found in the online version of this article.

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Shapiro et al. [2011] assumed that the minimum state of the quiet Sun in time corresponds to the observed quietest areas on the present Sun, which they represented by the "model of faint supergranule cell interior" from *Fontenla et al.* [1999]. The resulting amplitudes of their secular solar irradiance change is larger than the other recently published estimates (see, e.g., discussion in *Lockwood* [2011]). This influence should be clearly seen in the ozone response and probably in the winter time temperature but not much in the annual mean temperatures.

[4] The potential drop in the solar UV activity can substantially affect the ozone layer [*Anet et al.*, 2013], which in turn affects stratospheric temperature, circulation, tropospheric climate, and the UV intensity reaching the ground. The implications of a solar activity decline for the expected stratospheric ozone recovery later in this century [*WMO*, 2011] have not yet been considered in the literature. Here we analyze the influence of a strong UV decrease [*Shapiro et al.*, 2011] and the concomitant changes in energetic particles on climate and global ozone. We use the results of transient 100 year long ensemble simulations with the AOCCM SOCOL-MPIOM (Max Planck Institute ocean model). The model is driven by three scenarios of the future spectral solar irradiance, each with two members with identical anthropogenic forcing (RCP4.5) [see *van Vuuren et al.*, 2011]. It uses a comprehensive middle-atmospheric chemical scheme and a fully coupled deep ocean. Compared to *Meehl et al.* [2013], the applied solar forcing is much stronger in the UV spectrum and lasts for a longer time, because grand minima usually last for 70 to 110 years. Moreover, we improve the approach of *Meehl et al.* [2013] keeping the 11 year solar cycle and decreasing the solar irradiance slowly to the new minimum, making it more realistic.

2. Model Description and Experimental Design

[5] The experiments are run with the AOCCM SOCOL-MPIOM which emerges from the CCM SOCOL version 3 [*Stenke et al.*, 2012] coupled to the Max Plank Institute ocean model [*Marsland et al.*, 2003] using the OASIS3 coupler [*Valcke*, 2013]. The CCM SOCOL v3 is based on the global climate model ECHAM5 [*Roeckner et al.*, 2003] and includes the chemical module MEZON (model for evaluation of ozone trends). The model is used in the middle atmosphere (MA) mode and does not include interactive vegetation. MA-ECHAM5 hands over temperature and tracer fields to MEZON, which calculates chemical transformations of 41 gas species participating in 200 gas phase, 16 heterogeneous, and 35 photolytic reactions. The resulting tendencies of chemical species are then returned to MA-ECHAM5. Our experiments are performed with T31 spectral resolution, which equals to an average grid space of 3.75° (≈ 400 km). In vertical direction, the model domain is divided into 39 layers from the ground to 0.01 hPa. For more details, see *Stenke et al.* [2012].

[6] Three experiments are carried out, each consisting of two 100 year long simulations. The only difference between the experiments is the solar forcing. One experiment, named henceforward CONST, is forced by a perpetual repetition of the solar cycles 22 and 23 until the year 2100. The second and third experiments, thenceforth called WEAK and STRONG, follow the scenario of an oncoming grand solar minimum reaching its minimum in 2090, with TSI being 4
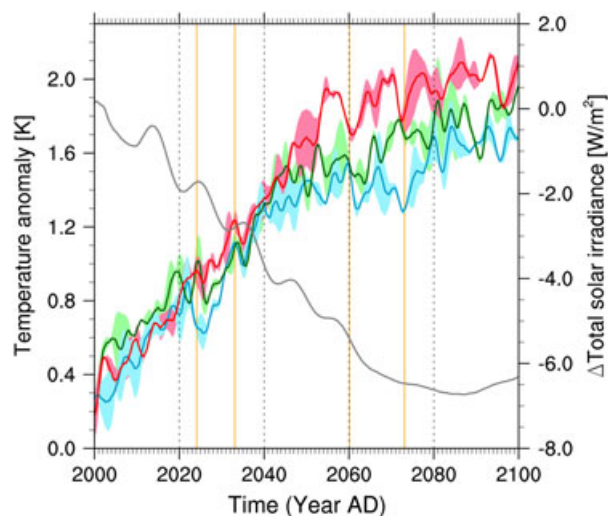

Figure 1. Globally averaged surface air temperature evolution for CONST (red), STRONG (blue), and WEAK (green) smoothed with a full width half maximum Gaussian filter over 24 months. Spread of the two runs per experiment is illustrated as pastel envelope. Anomalies (in Kelvin) are shown relative to the averaged 1986–2005 temperatures. Grey curve: total solar irradiance anomaly relative to the average TSI of the 1995–2005 period following *Shapiro et al.* [2011]. Orange vertical lines: years of hypothetical volcanic eruptions.

and 6 W/m² lower in WEAK and STRONG, respectively, as compared to CONST. In Figure 1, the grey curve shows the deviation of the total solar irradiance from the 1995–2005 averaged value [*Shapiro et al.*, 2011]. The oscillation shows the underlying 11 year solar cycle. These quantities are further used as proxies to calculate the future evolution of the SSI, the *Ap* index (describing the geomagnetic activity) and the ionization rate by galactic cosmic rays, which are necessary to drive the model [*Rozanov et al.*, 2012b]. The 4 and 6 W/m² lower TSI in WEAK and STRONG represent TSI decreases of 0.3% and 0.45%, respectively. The corresponding maximum changes of the spectral irradiance for the different bands of the ECHAM5 radiation code in WEAK are –10% for 180–250 nm, –1.5% for 240–440 nm, –0.2% for 440–690 nm, +0.01% for 690–1190 nm and 1190–2380 nm, and –0.03% for 2380–4000 nm (Figure S1 of the supporting information). The SSI changes for STRONG are larger by roughly a factor 1.5. All simulations start from the year 2000. WEAK and STRONG are initialized by restart files for this year from four 400 year long transient simulation starting from 1600, while CONST was branched from two of the 400 year long transient simulations at the year 2000. The concentrations of greenhouse gases (GHGs), ozone destroying substances (ODSs), as well as anthropogenic NOₓ and CO emissions are set following the CMIP5 RCP4.5 scenario. The tropospheric aerosols are adapted from CAM3.5 simulations with a bulk aerosol model driven by CCSM3 (CMIP4) sea surface temperatures and the 2000–2100 CMIP5 emissions (S. Bauer, personal communication, 2011). Stratospheric aerosols were kept at background levels excepted for four assigned volcanic eruptions (a Fuego-like volcanic eruption in 2024, a smaller volcanic eruption in 2033, an Agung-like volcanic eruption
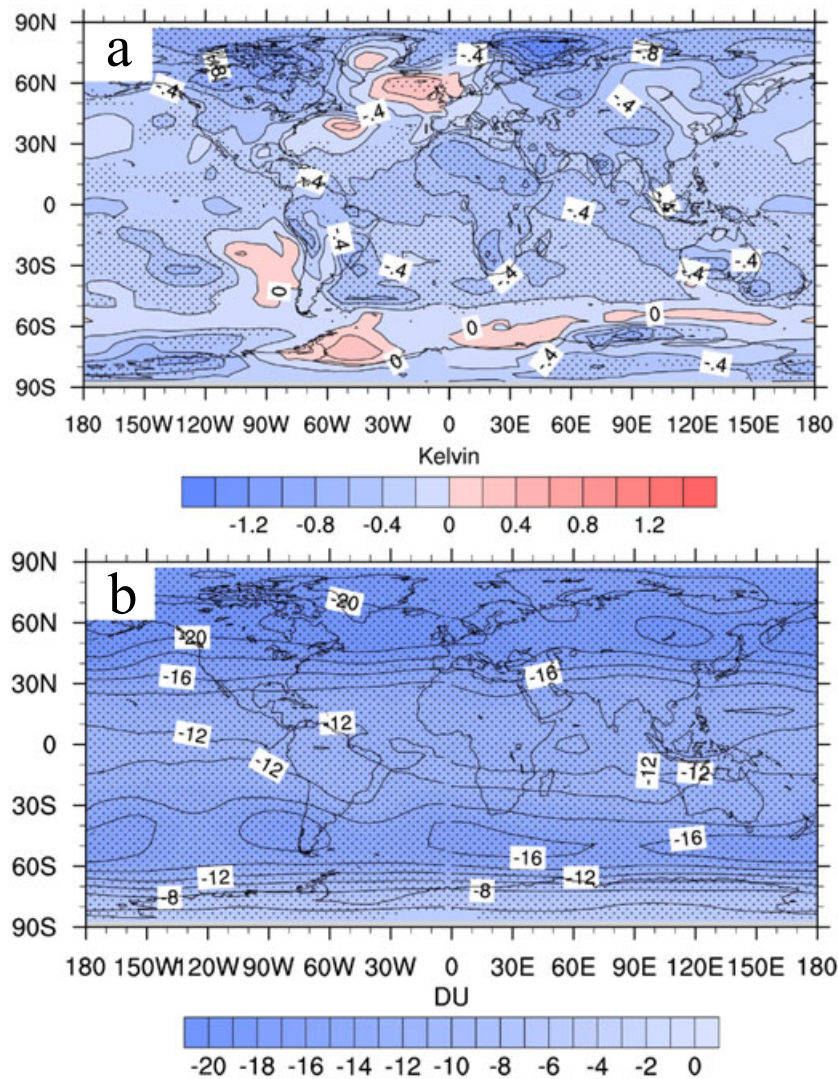
Figure 2. (a) Surface air temperature difference between STRONG and CONST, averaged over the ensemble members in the 2081–2100 period. (b) Total column ozone difference between STRONG and CONST, averaged over the ensemble members in the 2081–2100 period. Stippling denotes the areas where the differences are statistically significant at the 5% level using a *t* test.

in 2060, and another smaller volcanic eruption in 2073, [see *Arfeuille et al.*, 2013]).

3. Results

[7] All runs follow a distinct warming path, yielding 1.96 ± 0.12 K (CONST), 1.75 ± 0.14 K (WEAK), and 1.61 ± 0.12 K (STRONG) change in the global annual mean surface temperature, averaged over the 2081–2100 period relative to the 1986–2005 reference period, respectively (Figure 1). The results of CONST is in a good agreement with the CMIP5 RCP4.5 multimodel mean global warming of 1.8 K [*Knutti and Sedláček*, 2012]. While the warming trend of 0.24 ± 0.04 K/decade is very similar in all simulations from 2000 to 2045, the model projects a clear separation thereafter. While WEAK develops a reduced warming rate of 0.09 ± 0.04 K/decade for the second half of the century, STRONG enters a reduced warming phase of 0.08 ± 0.04 K/decade until the end of the century. Similar to WEAK, CONST shows a transition to a weaker warming rate phase of $0.11 \pm$

0.03 K/decade. The decrease of the global warming rate after 2045 in CONST is related to the declining CO_2 and CH_4 emission rates according to RCP4.5. The 2081–2100 mean temperatures are 0.21 ± 0.26 K higher in CONST than in WEAK and 0.35 ± 0.24 K higher than in STRONG. The decelerated global-averaged warming is comparable to the results of *Meehl et al.* [2013] and also compares well to the simulation with strong solar forcing (–0.25% in TSI) of *Feulner and Rahmstorf* [2010]. In our simulations, the major volcanic eruptions in 2023 and 2060 lead to a pronounced decrease in global temperatures right after the events, but temperatures recover in 2–5 years time. The two smaller eruptions have no detectable effect on temperatures. The simulated patterns of GHG warming are in good agreement with the results of other models [*Meehl et al.*, 2005; *Washington et al.*, 2009; *Knutti and Sedláček*, 2012] (Figure S2). The temperature difference between the period 2081–2100 and 1986–2005 of CONST shows the most pronounced positive differences over the Arctic due to polar amplification [e.g., *Serreze and Barry*, 2011]. Other
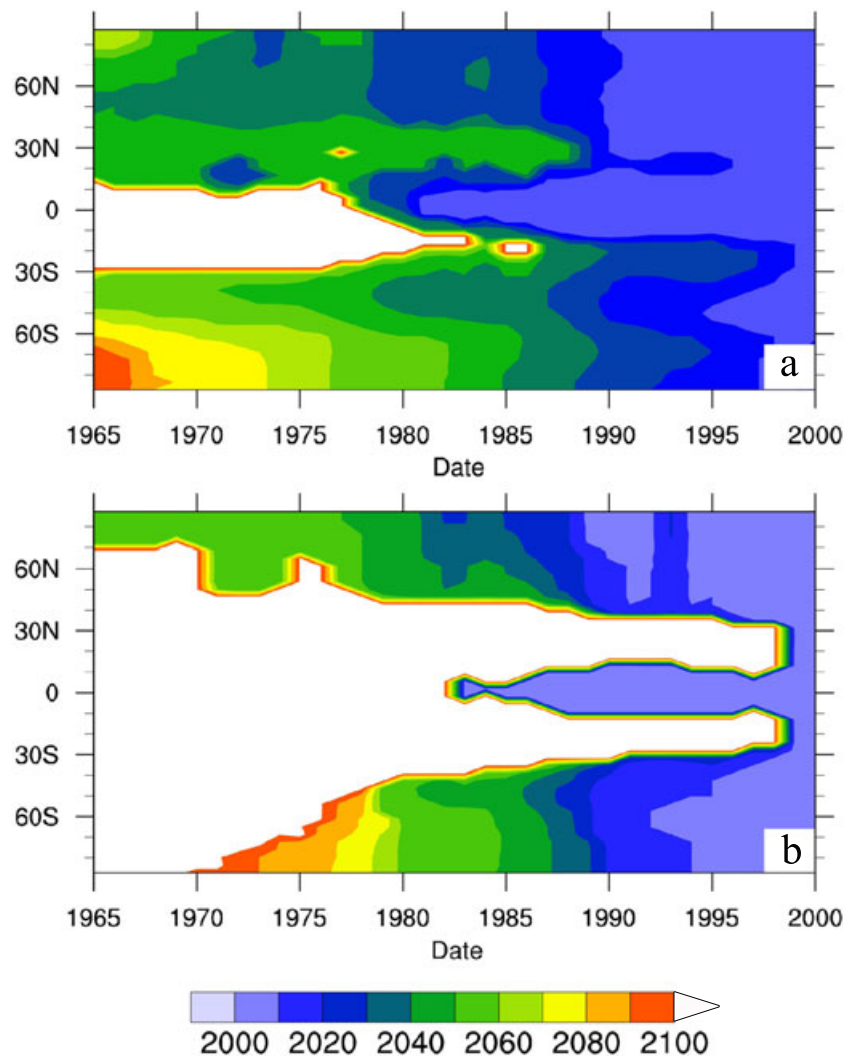
Figure 3. Timing of the total ozone column return date in the AOCCM SOCOL-MPIOM. Contours illustrate years of the simulation, in which the total ozone concentration shown on the abscissa is restored, similar to Figure 19 of *Austin et al.* [2010]. (a) Mean of CONST. (b) Mean of STRONG. Ozone column has been averaged with a running mean over 11 years (boxcar). White areas highlight ozone levels which are predicted not to recover to pre-2000 values before 2100. Reference ozone data are provided by the pre-2000 simulations.

strong temperature differences are found over Central Southern America, South Africa, the Himalayan region, and Australia.

[8] Figure 2a shows the differences in the regional pattern of surface air temperatures between STRONG and CONST for the period 2081–2100. The drop in solar activity leads to a significant cooling in the equatorial region and over most of the northern high latitudes. Due to the albedo effect from a positive sea ice anomaly, the northern polar region is cooled by up to 1 K, while the cooling over the southern polar region is less pronounced. The North Atlantic region reacts with a warming due to a 2 Sv stronger reduction of the Atlantic meridional overturning circulation in CONST compared with STRONG. The reason for this reduction is the stronger external forcing in CONST and maybe also a change in the stratosphere-troposphere coupling as suggested by *Reichler et al.* [2012]. Clearly, this needs a more detailed analysis and is beyond the scope of this study. A cooling of up to 0.4 K takes place over large parts of the Pacific, Atlantic, and Indian Oceans. The boreal winter pattern averaged over the same period of time (Figure S3) shows an overall similar pattern as the annual mean, although the cooling over the northern polar region is stronger and temperature anomalies reach up to –1.4 K. The warming signal in the eastern part of the Antarctic Peninsula gets larger due to the sea ice melting process being stronger in CONST, leading to lower salinities. The patterns look very similar when comparing CONST to WEAK, just that the amplitudes of the temperature changes are smaller and less significant (see Figure S4). Overall, a stronger cooling signal over land is evident especially over the Arctic region compared to *Meehl et al.* [2013] due to a stronger solar forcing.

[9] The well-known pattern of recovery of the ozone layer [e.g., *WMO*, 2011] is shown in Figure S5. Up to 33 Dobson unit (DU) more ozone over the northern polar region and up to 56 DU more ozone in the southern polar region is modeled in CONST by the end of this century compared to levels

of the reference 1986–2005 period. However, the equatorial region and the subtropics of both hemispheres show much smaller or even slightly negative changes around 0 to –4 DU due to the increase of the meridional circulation in the future [e.g., *WMO*, 2011].

[10] The differences in the total column ozone averaged over the last 20 years of the 21st century between STRONG and CONST are depicted in Figure 2b. Over all regions of the world, the model simulates a highly significant decrease of ozone (Student's *t* test on the 1% significance level). The decrease is stronger over the midlatitudes than over the polar and equatorial regions, reaching negative total ozone column anomalies of up to –20 DU. Additionally, the equatorial region experiences loss of ozone of –12 DU on average, while the southern polar region suffers the smallest decrease of –8 DU. Over the northern polar region, a loss of –17 DU on average is simulated. The overall effect, illustrated in Figure S6, shows the changes in total ozone column reached by the end of the century in STRONG compared to the 1986–2005 reference period.

[11] Figure 3 shows the return date of the zonally averaged total column ozone compared to pre-2000 levels in CONST (Figure 3a) and STRONG (Figure 3b). While in CONST, nearly full recovery to the 1960 levels is reached in the extratropics and the poles, STRONG allows the total column ozone not even to reach the 1975 levels over the large areas of the northern subtropics, equatorial regions, and southern hemisphere. The recovery to the preseventies levels at the poles illustrated in Figure 3b thus sets in much later than in CONST.

4. Conclusions

[12] The facts that during the past 10,000 years, about 20 grand solar minima occurred, and that the past decades correspond to a long-lasting solar maximum make, it is very likely that a new grand minimum will occur. Spectral extrapolation indicates that it is likely that this minimum will occur within the next decades. However, it is not possible to predict whether it will be a Dalton or a Maunder minimum type.

[13] Yet, by assuming a Dalton minimum type solar minimum, we show in agreement with *Meehl et al.* [2013] that although the solar minimum results in a reduced global warming, it cannot compensate continuing anthropogenic impacts. Still, the modeled temperatures averaged over the last 20 years of the 21st century are lower by up to 0.3 K—depending on the details of the solar minimum scenario—than the runs with solar constant forcing. Since the duration of the grand minimum assumed in the present work is longer than that of *Meehl et al.* [2013], the apparent weakening of the global warming is more pronounced. Yet, this should not distract from the fact that the general warming is due to anthropogenic emissions and that the grand minimum can at best lead to an episodic reduction of the warming.

[14] Significant cooling pattern changes between the work of *Meehl et al.* [2013] and this one might be due to a stronger decrease in the UV spectrum—leading to a more important cooling especially over the Arctic region. In a future work, we will perform sensitivity experiments to investigate the contribution of the top-down mechanism to the temperature anomaly in the Arctic region.

[15] Although the magnitude of the solar variability is still poorly constrained [see, e.g., *Judge et al.*, 2012; *Solanki and Unruh*, 2013; *Shapiro et al.*, 2013] and remains a bottleneck for the climate studies, this study shows evidence that the strong decrease in UV radiation and in the photolysis rates leads to a significant decrease of ozone especially in the tropics. This reduction in UV slows down or even cancels the recovery of the ozone column, depending on the region. Moreover, due to the net decrease of the UV-absorbing ozone, photoactive radiation between 300 and 320 nm could be enhanced especially over the tropics and subtropics (40°S–40°N) during a future grand solar minimum. This could possibly increase the risk of skin cancer and other diseases [*Setlow*, 1974] in WEAK and STRONG with respect to CONST—and also to present conditions. Future work is needed to investigate the change in erythemal radiation in order to specify health effects.

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