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What influence will future solar activity changes over the 21st century have on projected global near-surface temperature changes?

Gareth S. Jones,[1] Mike Lockwood,[2] and Peter A. Stott[1]

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[1] During the 20th century, solar activity increased in magnitude to a so-called grand maximum. It is probable that this high level of solar activity is at or near its end. It is of great interest whether any future reduction in solar activity could have a significant impact on climate that could partially offset the projected anthropogenic warming. Observations and reconstructions of solar activity over the last 9000 years are used as a constraint on possible future variations to produce probability distributions of total solar irradiance over the next 100 years. Using this information, with a simple climate model, we present results of the potential implications for future projections of climate on decadal to multidecadal timescales. Using one of the most recent reconstructions of historic total solar irradiance, the likely reduction in the warming by 2100 is found to be between 0.06 and 0.1 K, a very small fraction of the projected anthropogenic warming. However, if past total solar irradiance variations are larger and climate models substantially underestimate the response to solar variations, then there is a potential for a reduction in solar activity to mitigate a small proportion of the future warming, a scenario we cannot totally rule out. While the Sun is not expected to provide substantial delays in the time to reach critical temperature thresholds, any small delays it might provide are likely to be greater for lower anthropogenic emissions scenarios than for higher-emissions scenarios.

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1. Introduction

[2] The Intergovernmental Panel on Climate Change (IPCC) reported in its Fourth Assessment Report in 2007 that “most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations” [*IPCC*, 2007, p. 10], where “very likely” corresponds to a 90% confidence level. Climate model simulations show greater consistency with observed variations and trends in global near-surface temperatures over the 20th century when they include both anthropogenic and natural forcings than when they include natural forcings only [*Hegerl et al.*, 2007]. A range of studies have detected the influence of different factors on changes in a variety of climate indices [e.g., *International Ad Hoc Detection and Attribution Group*, 2005; *Stott et al.*, 2010] with anthropogenic influences being a dominant factor over recent decades. These assessments thus add confidence in the climate model projections of future climate changes due to increases in greenhouse gas concentrations. The projections of future climate change by 2100, associated with a number of different scenarios of future anthropogenic emissions, span likely ranges (>66%) from 1.1–2.9 K for the low-emission B1 SRES scenario to 2.4–6.4 K for the high-emission A1FI SRES scenario [*Meehl et al.*, 2007]. Currently, plans to mitigate this projected warming and the possible associated impacts, have concentrated on controlling CO_2 and other greenhouse gas emissions. While the IPCC assessed research that investigated the impact of natural forcing factors on past climate, researchers have not methodically examined what impact future changes in natural external forcing factors may have. There is the potential for natural external climate forcing factors to add to or to subtract from the projected anthropogenic warming. A possible downturn in solar activity [*Abreu et al.*, 2008; *Barnard et al.*, 2011] has been suggested to have the potential to help climate change mitigation efforts or to “buy time” to adapt to the projected climate changes [*Clark*, 2006; *McKie*, 2006; *Whitehouse*, 2007]. It is therefore of great interest to examine what plausible change in future solar activity could happen and what possible impact on climate may follow.

[3] Changes in the Sun’s activity are one of the factors associated with variations in Earth’s climate since the preindustrial era, albeit considered to be amongst the smallest in magnitude and less well understood of forcing factors [*Haigh*, 2003; *Lean et al.*, 2005; *Foukal et al.*, 2006; *Forster*

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[1] Met Office Hadley Centre, Exeter, UK.
[2] Department of Meteorology, University of Reading, Reading, UK.

et al., 2007; *Gray et al.*, 2010]. The most obvious and least controversial mechanism for the Sun to influence climate is through changes in total solar irradiance (TSI) [*Gray et al.*, 2010; *Lockwood*, 2010]. Climate modeling and detection and attribution studies show that changes in TSI have a relatively small influence on global temperatures changes over the 20th century, with anthropogenic influences dominating the observed warming [*Jones et al.*, 2003; *Stott et al.*, 2003; *International Ad Hoc Detection and Attribution Group*, 2005; *Nozawa et al.*, 2005; *Shiogama et al.*,2006; *Stone et al.*, 2007; *Benestad and Schmidt*, 2009]. In the last thousand years or so of the preindustrial era solar activity may have played a relatively important role influencing climate, competing with volcanic activity and human driven land use changes for a dominant influence [e.g., *Goosse et al.*, 2006; *Hegerl et al.*, 2003; *Tett et al.*, 2007; *Mann et al.*, 2009]. A number of studies suggest significant zonal/regional and seasonal impacts on surface climate and at all altitudes over the 11 year solar cycle [*Meehl et al.*, 2009; *Frame and Gray*, 2010; *Rind et al.*, 2008; *Lean and Rind*, 2008; *Lockwood et al.*, 2010a].

[4] While the Sun's activity has a clear variation over an approximate 11 year cycle (which historically has varied between 9 and 13 years in duration) accurate predictions of the magnitude of upcoming solar maxima are notoriously difficult [*Schatten*, 2002; *Svalgaard et al.*, 2005; *Hathaway and Wilson*, 2006; *Brajsa et al.*, 2009; *Dikpati et al.*, 2010; *Petrovay*, 2010, cited 5 October 2011]. The level of relatively high solar activity seen over the last 60 years, that has been referred to as a "grand maximum," is possibly going to end within the next 20 years [*Abreu et al.*, 2008; *Lockwood et al.*, 2009; *Lockwood*, 2010; *Barnard et al.*, 2011].

[5] There have been a few attempts at predicting longer-term solar activity into the 21st century [e.g., *Clilverd et al.*, 2003; *Hiremath*, 2008; *Mordvinov and Kramynin*, 2010; *Barnard et al.*, 2011] on the basis of repeating interpreted past cycles of solar activity into the future. As far as we are aware there have been, up to now, no specific predictions or projections of future TSI changes beyond the next solar cycle [*Lean*, 2001; *Woods and Lean*, 2007; *Lean and Rind*, 2009].

[6] Most studies of future climate change have assumed no future explosive volcanic activity and either no variations or just an 11 year cycle in TSI with an amplitude similar to that over the last decades of the 20th century [e.g., *Stott et al.*, 2006]. The main reason for adopting these assumptions is the inherent unpredictability of solar and volcanic activity. Some studies have attempted to account for uncertainty in natural forcing on future model projections by using simulations of past variability from natural forcings as an approximation for the future [*Stott and Kettleborough*, 2002; *Kettleborough et al.*, 2007], by adding in randomly timed volcanic eruptions [*Hansen et al.*, 1988] or by repeating historic volcanic activity and reducing solar activity to a level typical of the Maunder Minimum [*Feulner and Rahmstorf*, 2010].

[7] In this study we use a distribution of 21st century TSI variations constructed from variations in past solar irradiance reconstructions to examine, in a probabilistic sense, the future impact of plausible changes in the Sun. In sections 2–4 we will describe how the future projections of TSI are created, the simple model to emulate the global mean responses of a climate model, and the results.

2. Method

2.1. Solar Forcing

[8] The solar modulation parameter ϕ is a measure of the shielding effect that the Sun's open flux magnetic field has on the galactic cosmic ray flux reaching Earth. *Steinhilber et al.* [2008] have used a composite of cosmogenic isotopes to generate a reconstruction of ϕ, over the last 9,300 years: this shows that previous such grand maxima have lasted for only a few decades. The 1920 level of ϕ of 600 MV is here used as a threshold for a grand maximum and 24 events crossing this threshold are used to construct a superposed-epoch composite of the variations in ϕ during and after each solar grand maximum [*Lockwood*, 2010, Figure 6]. Assuming that the current solar activity is similar in behavior to previous grand maxima and will follow a similar evolution, allows us to make an analogue forecast of future solar activity levels. In the years following previous grand maxima, solar activity sometimes dropped to very low "grand minimum" levels, with a 8% chance that within 40 years of the end of the current high activity level that the Sun will be in similar state to that during the Maunder Minimum [*Lockwood*, 2010]. However, there is a 50% probability that this will occur in the next 100–200 years.

[9] It is possible to relate the ϕ variations with historic TSI changes and thus from the composited variations of ϕ produce a range of future TSI projections. *Lockwood and Stamper* [1999] found a correlation between open solar flux, Fs, and TSI over the solar cycle and assumed it to also apply to centennial variations. This relationship has been supported by the low Fs observed during the recent minimum, which has been reported to have been accompanied by a lower minimum in TSI than during previous solar cycle minima [*Fröhlich*, 2009; *Schrijver et al.*, 2011]. From the TSI-Fs relationship found by *Fröhlich* [2009] and a theoretical equation between Fs and ϕ, *Steinhilber et al.* [2009] generated a TSI reconstruction which has considerable similarities to those derived from sunspot number data. We here derive relationships by regressing 25 year means of the modulation parameter ϕ against a variety of historic reconstructions of TSI, similarly averaged, over the period of the TSI reconstruction. The relationship between the TSI's solar cycle amplitude and its 25 year mean is also found, which is used to add variations over an assumed 11 year cycle to the TSI estimates on the basis of ϕ (as employed for other solar and heliospheric parameters by *Barnard et al.* [2011]). We use three different historic TSI reconstructions, covering the last three or so centuries, which have been produced recently (Figure 1): L00 [*Lean*, 2000], K07 [*Krivova et al.*, 2007], and L09 (J. L. Lean, Calculations of solar irradiance, http://www.geo.fu-berlin.de/en/met/ag/strat/forschung/SOLARIS/Input_data/Calculations_of_Solar_Irradiance.pdf, accessed 2 June 2009). The TSI reconstructions were also spliced to a composite of satellite TSI observations covering 1979–2009 (obtained from http://www.pmodwrc.ch/) to enable recent measurements of the low solar minimum to be included. The latest IPCC report assessment was that the rise in TSI since the preindustrial era was smaller (+0.08% between 1750 and the present day) than reported in the previous IPCC reports,

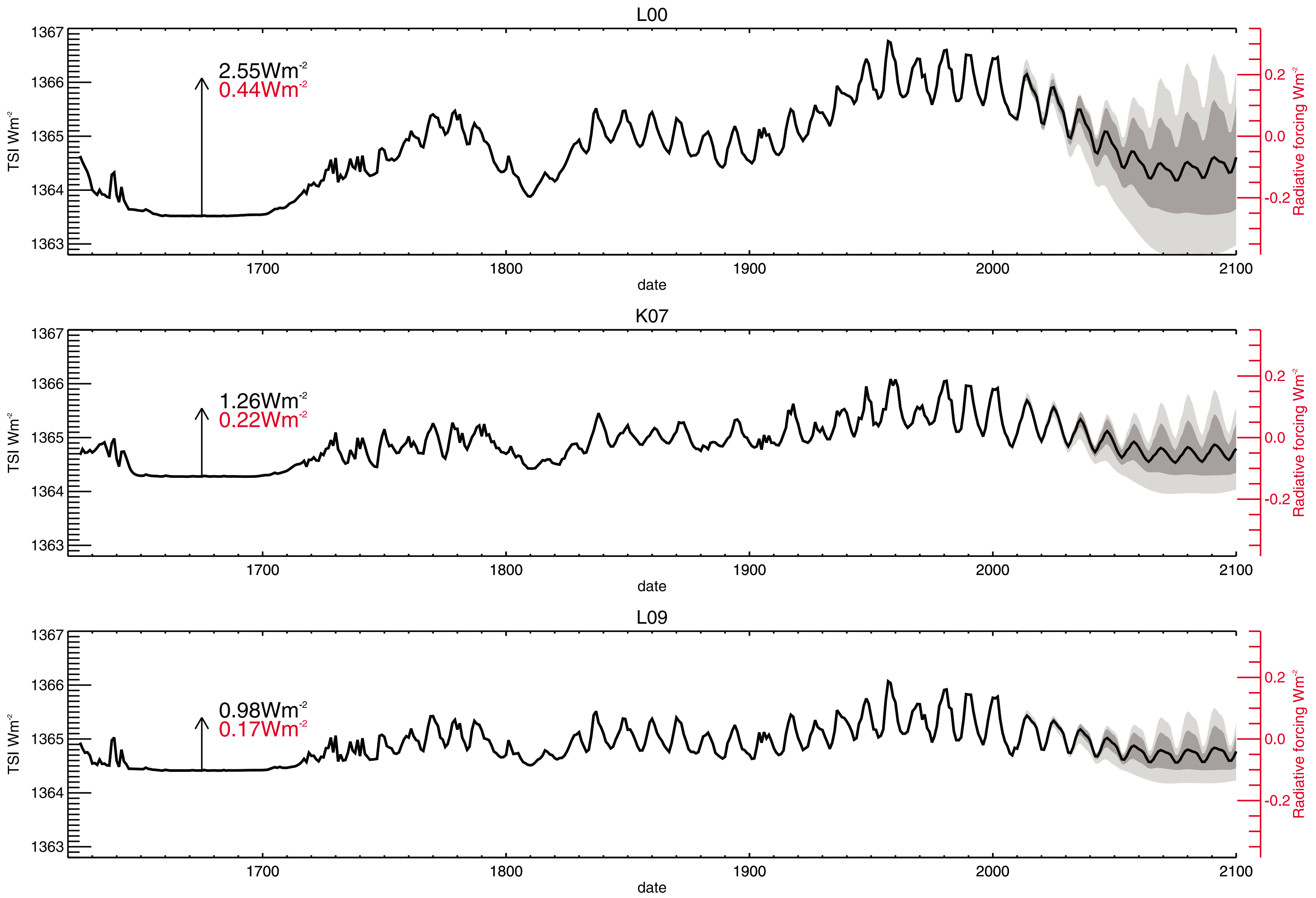
L00
TSI Wm^{-2}
1367
1366
1365
1364
1363
2.55Wm^{-2}
0.44Wm^{-2}
1700
1800
1900
2000
2100
date
0.2
0.0
-0.2
Radiative forcing Wm^{-2}
K07
TSI Wm^{-2}
1367
1366
1365
1364
1363
1.26Wm^{-2}
0.22Wm^{-2}
1700
1800
1900
2000
2100
date
0.2
0.0
-0.2
Radiative forcing Wm^{-2}
L09
TSI Wm^{-2}
1367
1366
1365
1364
1363
0.98Wm^{-2}
0.17Wm^{-2}
1700
1800
1900
2000
2100
date
0.2
0.0
-0.2
Radiative forcing Wm^{-2}

Figure 1

Table 1. Description of the HadCM3 Simulations and Forcing Factors Used in This Study

Forcing Factor	Description	Simulation Reference
GHG	response to well-mixed greenhouse gases	*Tett et al.* [2002]
ANTHRO	same as GHG with tropospheric and stratospheric ozone and sulphate aerosols	*Tett et al.* [2002]
NATURAL	response to volcanic and solar forcings	*Tett et al.* [2002]
SOLAR	response to amplified solar irradiance changes	*Stott et al.* [2003], *Jones et al.* [2003]
VOLCANIC	response to amplified volcanic stratospheric aerosols changes	*Stott et al.* [2003], *Jones et al.* [2003]
ALL	as in ANTHRO and NATURAL	*Stott et al.* [2000]

consistent with the K07 and L09 reconstructions, albeit the scientific understanding of this assessment was ranked as low [*Forster et al.*, 2007]. We include the older L00 reconstruction as a sensitivity test as it yields larger past, and thus future, changes than the other two. While we do not rule out the possibility of the larger past TSI variations of L00, there is much higher confidence in the K07 and L09 reconstructions. From the superposed-epoch composite of the variations in ϕ following past grand maxima, the mean, ±1 standard deviation and absolute deviations of the possible future variations in TSI are calculated associated with each of the three TSI reconstructions (Figure 1).

2.2. Simple Climate Model

[10] Climate models are one of the major tools in the investigation of climate processes. One of their major advantages is being able to explore the impact on climate of different combinations of forcing factors. This has been done to investigate future global mean climate change due to different scenarios of anthropogenic emissions [*Meehl et al.*, 2007], and our aim is to similarly investigate the impact on future climate of a range of solar irradiance scenarios throughout the 21st century. However, it is computationally expensive to produce many simulations of climate change using a sophisticated climate model, such as a fully coupled atmospheric ocean general circulation model (AOGCM). In this study we use a simple climate model to emulate an AOGCM with the aim to reasonably simulate its global, land and sea temperatures variations for different forcing factors. We follow a method used by *Harris et al.* [2006] to tune or calibrate simple climate models to emulate more sophisticated AOGCMs in a perturbed physics ensembles study. Simple climate models have also been used to emulate a range of climate models responses to different future scenarios contributing to the IPCC's assessment of projections of 21st century climate change [*Meehl et al.*, 2007; *Meinshausen et al.*, 2011].

[11] The AOGCM used here is HadCM3 [*Stott et al.*, 2000, and references therein], a climate model that has been used extensively and has been demonstrated to simulate much of the variability and many of the changes in observed climate and has been the basis of many studies. The model is particularly useful as there are a number of simulations available driven with different forcing factors that will aid in the calibration process (Table 1). The simple model used is a box diffusion energy balance model [*Rowntree*, 1998] (hereafter referred to as EBM), comprising six ocean levels and six land levels with heat diffusion through the separate land and ocean levels and surface levels are coupled via a single atmospheric layer, and is a variant of models used in other studies [*Huntingford and Cox*, 2000; *Harris et al.*, 2006]. For the purposes of this study as it is not imperative to be able to tune all the EBM's parameters simultaneously the default model parameters are as described by *Rowntree* [1998] apart from two parameters; the climate sensitivity parameter (λ) and ocean vertical heat diffusivity (κ_d). The climate sensitivity parameter [*Forster et al.*, 2007], equivalent to the inverse of the climate feedback parameter [*Randall et al.*, 2007], is the global mean equilibrium near-surface temperature change for a unit change in radiative forcing. For changes in carbon dioxide concentrations, this can be calculated as the ratio of the temperature change for a doubling of CO_2 (also often known as the equilibrium climate sensitivity) to the associated radiative forcing. Using the derived value of HadCM3's equilibrium climate sensitivity of 3.3 K [*Williams et al.*, 2001; *Randall et al.*, 2007, Table 8.2] and the radiative forcing for a doubling of CO_2 (ΔF_{2x}) of 3.74 W m^{-2} [*Gregory et al.*, 2004], we obtain $\lambda_{CO_2} = 0.88$ K W^{-1} m^2. Fixing this value of λ_{CO_2}, the EBM was calibrated to a HadCM3 simulation with a 1% annual increase of CO_2 concentration [*Williams et al.*, 2008] to obtain the ocean heat diffusivity for ocean, κ_d. The radiative forcing (δF(c))

Figure 1. Total solar irradiance (TSI) reconstructions and projections used in this study. In each of the three TSI historic reconstructions used (L00, K07, and L09) the data in the 1979–2009 period have been replaced by the Physikalisch-Meteorologisches Observatorium Davos satellite TSI reconstruction (http://www.pmodwrc.ch/). Each data set has been offset such that the mean of 1700–2003 is equal to 1365 W m^{-2}. The values adjacent to the arrow are the increase from the Maunder Minimum to present day, with TSI in black and an estimate of the radiative forcing in red. From 2009 to 2100 the mean, ±1 standard deviation (dark gray shading), and absolute limits (light gray shading) of the range of TSI projections estimated from past ϕ variations are shown. The lack of an 11 year cycle in the lower limits of the projected TSI is a consequence of using the relationship between the amplitude of the 11 year cycle and the 25 year mean of the TSI reconstructions. During low TSI the 11 year cycle amplitude is also small, as seen in the TSI reconstructions during the 17th century. The estimate of the radiative forcing (axis on the right) is with respect to the TSI value of 1365 W m^{-2}. The radiative forcings are estimated by multiplying the change in TSI by 0.25 and 0.7 to account for the sphericity and albedo of the Earth, respectively, following *Lean and Rind* [1998] and *Forster et al.* [2007].

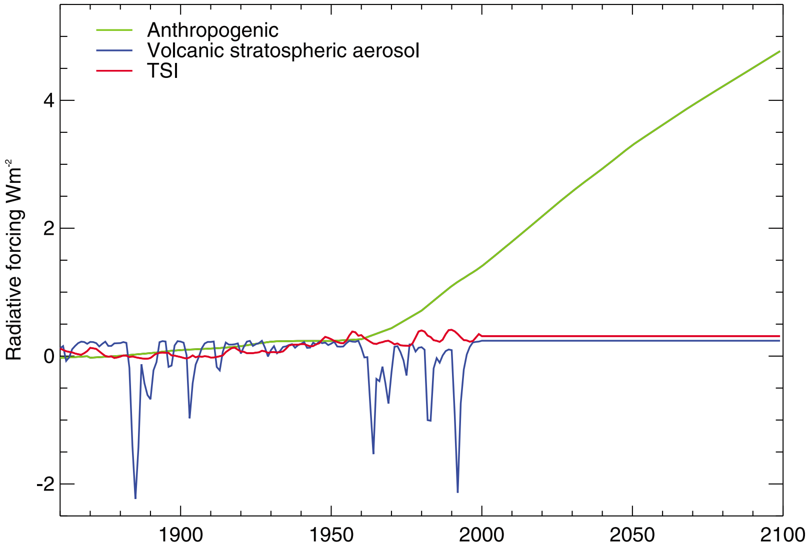

Figure 2. Forcing factors and their estimated tropospheric radiative forcings as diagnosed and estimated from the HadCM3 simulations [*Stott et al.*, 2000; *Tett et al.*, 2002]. The anthropogenic forcings in the period following the year 2000 are consistent with the B2 SRES scenario. The solar and volcanic influences are extended beyond 2000, as described by *Stott et al.* [2000].

applied to the EBM was calculated by using the relationship $\delta F(c) = \Delta F_{2x}/ln(2) \times ln(c/c_o)$, where c_o and c are the reference and at time of interest CO_2 concentrations. The method of downhill simplex [*Press et al.*, 1992; *Harris et al.*, 2006] was used to find the most appropriate value of κ_d by minimizing the mean square error between the EBM's land and sea temperatures and the global mean land and sea near-surface temperature anomaly for 20 year mean variations of the HadCM3 1% CO_2 simulation. The value of κ_d was found to be 1.677 ± 0.771 cm^2 s^{-1}. The uncertainty (±2 standard deviations) was calculated by adding estimates of climate internal variability, sampled from a HadCM3 control, to the HadCM3 data being calibrated against, and finding the spread of κ_d values.

[12] The calibration process was repeated for HadCM3 simulations that had been forced by total solar irradiance and stratospheric volcanic aerosol variations separately [*Stott et al.*, 2003], this time keeping κ_d fixed and tuning for λ, using the same method described above. The radiative forcing estimates applied to the EBM were derived from the same HadCM3 simulations. For the EBM the climate sensitivity parameters for solar and volcanic forcing factors were calculated to be $\lambda_{sol} = 0.49 \pm 0.04$ K W^{-1} m^2 and $\lambda_{vol} = 0.48 \pm 0.06$ K W^{-1} m^2, respectively. Low climate sensitivity parameters, or efficacies <1 [*Hansen et al.*, 2005], have been noted before for solar and volcanic forcing factors in HadCM3 [*Gregory et al.*, 2004; *Jones et al.*, 2005] and in some other models [*Forster et al.*, 2007]. Differences in the spatial distribution of the radiative forcings can cause differences in efficacies [*Joshi et al.*, 2003; *Hansen et al.*, 2005].

[13] The EBM parameters found were tested by comparing the EBM output with HadCM3 simulations other than those used in the calibration process [*Tett et al.*, 2002; *Johns et al.*, 2003; *Stott et al.*, 2003; *Jones et al.*, 2003]. The radiative forcing estimates input to the EBM for the forcing factors (Figure 2) were deduced from the HadCM3 simulations. Of particular relevance is the TSI forcing which was used (an extended data set documented by *Lean et al.* [1995]) and where the TSI was kept constant after 2000 equal to the average of the 1989–1999 period. For simulations driven with different combinations of forcing factors, the temperature responses were obtained by adding together the individual EBM response to the different factors using the appropriate climate sensitivity parameter. For instance, to compare with the HadCM3 simulation containing natural-only forcing factors the results from the EBM (with λ_{vol}) driven with volcanic radiative forcing was added to the

Table 2. Root-Mean-Square Errors (RMSE) Between HadCM3 and EBM Simulations on Nonoverlapping 20 Year Average Global Mean Near-Surface Temperatures

HadCM3 Simulation (Period Covered)	EBM (Forcing Factor)	RMSE (K)
GHG (1860–1999)[a]	EBM (GHG)	0.048
GHG (1860–2099)	EBM (GHG)	0.093
NATURAL (1860–1999)[a]	EBM (SOLAR) + EBM (VOLCANIC)	0.018
ANTHRO (1860–1999)[a]	EBM (ANTHRO)	0.066
ANTHRO (1860–2099)	EBM (ANTHRO)	0.089
ALL (1860–1999)[a]	EBM (ANTHRO) + EBM (SOLAR) + EBM (VOLCANIC)	0.054
ALL (1860–2099)	EBM (ANTHRO) + EBM (SOLAR) + EBM (VOLCANIC)	0.054

[a] Average of four different initial condition ensemble members.

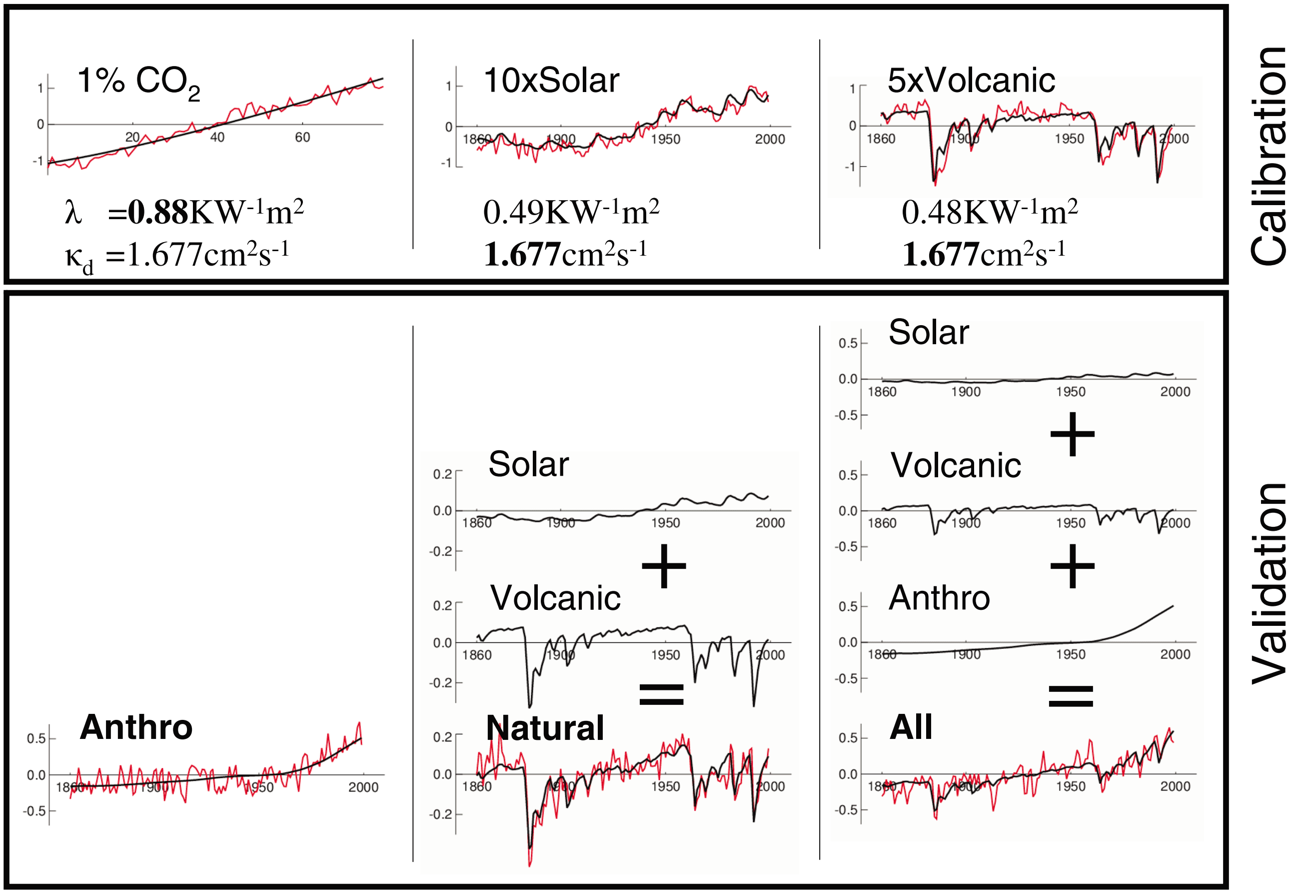

Figure 3. Schematic of the methodology used for simple climate model calibration. All plots show global mean temperature anomalies (K, with respect to whole period) changing over time (years). (top) Calibration: EBM (black line) driven by associated radiative forcing with climate sensitivity parameter fixed for the 1% annual increase in CO_2 concentration case and then ocean heat diffusivity tuned to minimize the mean-square error of land and sea temperature difference with HadCM3 simulation (red line). For solar and volcanic cases the ocean heat diffusivity for the ocean is fixed, and the climate sensitivity parameter is chosen to minimize the cost function. (bottom) Validation: To test how well the EBM emulates global mean near-surface temperatures simulated by HadCM3, the EBM (black lines) is compared with HadCM3 simulations (red lines) driven by different combinations of forcing factors.

results from the EBM (with λ_{sol}) driven with solar radiative forcing. The assumption that large scale climate responses from models can be linearly combined is generally considered to be reasonable [*Gillett et al.*, 2004] but may not be appropriate in all circumstances [*Ming and Ramaswamy*, 2009]. The EBM driven with anthropogenic radiative forcing uses the climate sensitivity parameter of λ_{CO_2}. Table 2 shows the validation results of a comparison of the EBM with the HadCM3 simulations by measuring the root-mean-square error of the temperatures. The errors are relatively small compared to the climate changes being simulated. Figure 3 shows a schematic of the calibration and validation process. Figure 4 shows an ensemble of global mean near-surface temperature changes simulated by HadCM3 driven by changes in anthropogenic, solar and volcanic factors [*Stott et al.*, 2000] over the historic and 21st century periods. The response from the sum of the EBMs, each with their appropriate climate sensitivity parameter, forced with solar, volcanic and anthropogenic forcings (EBM_ALL) is also shown. The EBM's response compares very favorably with the average of the ensemble of HadCM3 historic simulations throughout the 1860–2100 period (Table 2), supporting the assumption that climate responses can be linearly combined. As the EBM has not been tuned to the HadCM3 simulations shown in Figure 4 and Table 2, there is increased confidence that the EBM can be used to reasonably emulate the global mean temperature response of HadCM3 to any given radiative forcing. The EBM's response to using radiative forcings from different SRES emission scenarios [*Johns et al.*, 2003] is also shown in Figure 4.

[14] The simulations for the 21st century for HadCM3 and EBM_ALL (anthropogenic forcings given by the B2 SRES emissions scenario) have a warming of 2.55 and 2.47 K, respectively, by 2090–2099 relative to 1980–1999. This is consistent with the projected warming (and likely range) for the B2 scenario of 2.4(1.4 to 3.8) K reported in the latest IPCC report [*IPCC*, 2007]. The next stage of the analysis requires replacing the solar forcing, used in the EBM response in Figure 4, with the different historic TSI

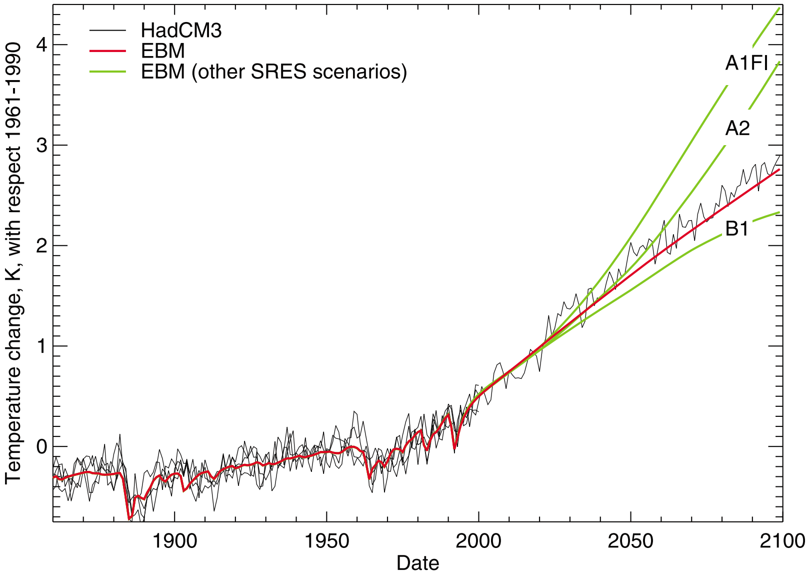

Figure 4. Annual global mean near-surface temperature anomalies from individual ensemble members of HadCM3 simulations forced with anthropogenic and natural factors [*Stott et al.*, 2000] (black line) compared with the equivalent EBM simulation (red line), produced from the sum of the EBMs driven with anthropogenic, solar, and volcanic radiative forcings (EBM_ALL). The simulations through the 21st century are forced with the radiative forcings associated with the B2 SRES scenario. The EBM forced with other SRES scenarios (as labeled) is also shown (green line).

reconstructions (L00, K07, and L09) and their respective extrapolations into the future, as described in section 2.1.

3. Results

3.1. Solar Response the Same as HadCM3

[15] The near-surface climate responses to the L00, K07, and L09 TSI reconstructions are calculated using the EBM. The TSI reconstructions are extended into the 21st century by using the mean, ±1 standard deviations and absolute ranges of the associated future TSI projections as shown in Figure 1. As described above, the EBM response to each TSI series is added to the EBM responses for the volcanic and anthropogenic forcings to obtain historic and projected changes for each TSI reconstruction (named EBM_L00, EBM_K07, and EBM_L09; see Figure 5). For instance EBM_L09 is the sum of the EBM forced with the L09 TSI, the EBM forced with the volcanic changes and the EBM forced by the anthropogenic influences, each with their own associated climate sensitivity parameters (Figure 3).

[16] The global mean temperature changes for EBM_L00 (Figure 5, top) are very similar to EBM_ALL as the TSI used for the latter simulation [*Lean et al.*, 1995] has very similar variations over the 20th century as L00. For the 1900–1949 period both simulations have a warming of 0.058 K decade^{-1} with the solar component contributing 0.016 K decade^{-1} and the remaining warming caused by the anthropogenic and volcanic influences in equal measure. Both EBM_K07 and EBM_L09 have less warming in the 1900–1949 period, 0.048 K decade^{-1}, consistent with the smaller increase in TSI that those reconstructions have in that period, contributing only 0.006 K decade^{-1}. Observed global annual mean near-surface temperatures from four data sets are also shown in Figure 5 to allow a simplistic comparison between the models and observational changes over the historic period and to give a context to the scale of the changes in the future.

[17] We compare the mean temperature for 2090–2099 for the EBM_ALL with the different solar projection EBMs to examine to relative changes. For EBM_L00, the mean change with respect to EBM_ALL is −0.14 K with an absolute maximum deviation of −0.24 K, corresponding to solar activity reaching its absolute minimum level, and minimum deviation of −0.03 K, corresponding to solar activity returning to a grand maximum (Figure 5). For both EBM_K07 and EBM_L09 the deviations are smaller with even in the extreme cases of solar activity being lower than during the Maunder Minimum temperatures only deviating by at most −0.13 K. These results suggest that if the climate responded to solar activity as HadCM3 does then, with the assumptions already discussed, the likely (>66%) range of temperature changes relative to the anthropogenic warming is −0.19 to −0.08 K for the L00, −0.11 to −0.06 K for the K07 and −0.10 to −0.06 K for the L09 TSI reconstructions. As we assume the temperature responses from the EBMs can be added linearly, the temperature deviations are the same when other SRES scenarios (Figure 4) are used instead of the B2 SRES scenario in the EBM with anthropogenic forcing. However, the proportion of the warming that may be reduced by a decrease in future solar activity is greater for the lower-emission scenarios (e.g., B1) and lower for the higher-emission scenarios (e.g., A1FI).

[18] We have not explored the impact of model uncertainty on these results, or the impact of model structure uncertainty, as the EBM is tuned to a solitary model, HadCM3. Another study [*Feulner and Rahmstorf*, 2010] examined the impact of future solar activity on climate using a coupled model of intermediate complexity. That study

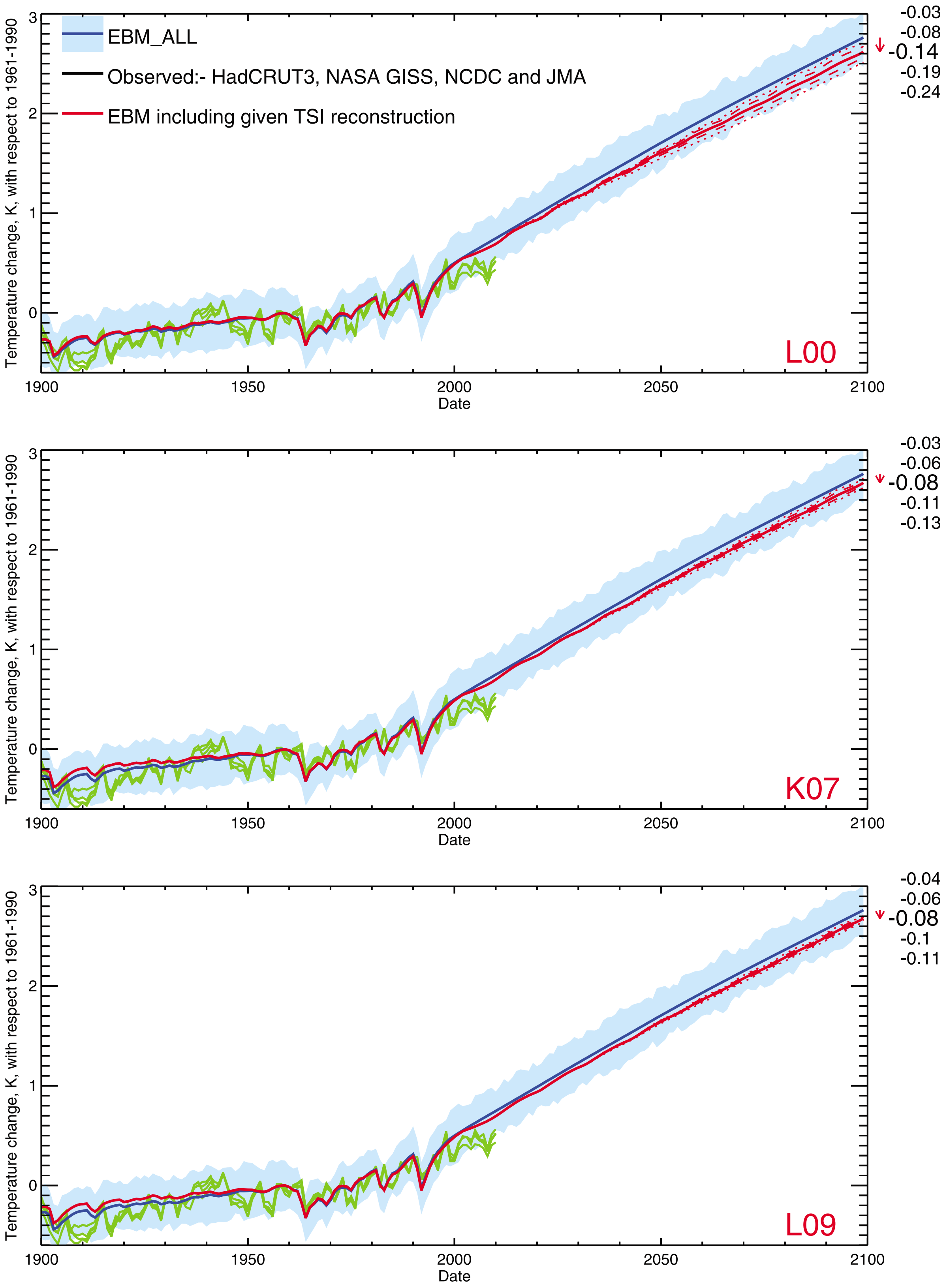
EBM_ALL
Observed:- HadCRUT3, NASA GISS, NCDC and JMA
EBM including given TSI reconstruction
-0.03
-0.08
-0.14
-0.19
-0.24
L00
-0.03
-0.06
-0.08
-0.11
-0.13
K07
-0.04
-0.06
-0.08
-0.1
-0.11
L09
Temperature change, K, with respect to 1961-1990
3
2
1
0
1900
1950
2000
2050
2100
Date

Figure 5

examined two cases where the solar activity decreased to Maunder Minimum like conditions during the 21st century, with changes of −0.08% and −0.25% in TSI relative to 1950s levels. The study found changes in global annual mean temperature of approximately −0.10 and −0.26 K by 2100 for the two estimated changes in TSI relative to two anthropogenic warming scenarios. We applied the same decreases in TSI (−0.08% and −0.25%), and found temperature deviations of −0.09 and −0.26 K, very close to *Feulner and Rahmstorf*'s [2010] results.

3.2. Amplified Solar Cycle Response

[19] The near-surface temperature response over recent solar cycles (1950–2000) is small in HadCM3, with the average global mean change from solar minimum to maximum approximately 0.03 K. Other climate models give similar small variations [*Wigley and Raper*, 1990; *Stevens and North*, 1996; *Foukal et al.*, 2004; *Cahalan et al.*, 2010]. There is some empirical evidence, from a range of studies that use regression techniques on observed temperature changes and estimates of the time histories of different climate factors and indices, that the global mean temperature response to recent solar cycles may produce changes from solar minimum to maximum of 0.1 K or larger [*White et al.*, 1997; *Douglass and Clader*, 2002; *Camp and Tung*, 2007; *Lean and Rind*, 2009]. While such empirical regression studies can show correlations of solar changes with surface climate they may not always show real associations and therefore caution should be exercised in inferring causality. Such potential pitfalls as overfitting of forcing indices with climate indices, degeneracy between different forcing factors, understated uncertainties in the response to forcing factors and in the regression indices have been reported in perfect model studies [*Ingram*, 2006; *Benestad and Schmidt*, 2009; *Stott and Jones*, 2009].

[20] Nonetheless, to investigate the sensitivity of our results to a simulation with a larger recent solar cycle response, we scale the temperature responses from the EBM driven by the solar forcing such that the recent solar cycle response is 0.1 K from solar minimum to maximum (or amplitude = 0.05K). This may not be the most appropriate thing to do as it not only scales the solar cycle component of the response, but also the multidecadal solar response. It should, however, provide upper limits to what the maximum responses are. The global mean temperature response of the EBMs driven by the three TSI reconstructions, L00, K07, and L09, are required to be scaled by 3.09, 3.26, and 3.14, respectively, to get a solar cycle response of 0.1 K. Coincidently these values are similar with the scaling deduced in the detection and attribution study of *Stott et al.* [2003] for the multidecadal solar component of 20th century near-surface temperature changes, although there may have been some degeneracy between the greenhouse gas and solar irradiance responses which meant that it might have overestimated the solar contribution. As before, the scaled solar temperature response, derived from the EBMs using the L00, K07, and L09 TSI reconstructions, are added to the anthropogenic and volcanic EBM temperature responses (with the total named EBM_L00x, EBM_K07x, and EBM_L09x, respectively). A consequence of scaling the solar component is that the EBM shows increased warming in the early part of the 20th century, for instance EBM_L09x warms by 0.06 K decade^{-1} over the 1900–1949 period which is closer to the observed trend (Figure 6). As this is not a formal detection analysis, and model and other forcing uncertainties have not been examined, one must be careful to not over interpret the significance of any similarities or differences with observed trends when the solar component has been scaled by an arbitrary amount.

[21] The mean deviation by the end of the 21st century is −0.35, −0.20, and −0.17 K for EBM_L00x, EBM_K07x, and EBM_L09x, respectively (Figure 6). The largest and smallest deviations are found to be −0.69 and −0.02 K for EBM_L00x, −0.46 and −0.04 K for EBM_K07x, and −0.28 and −0.05 K for EBM_L09x. These are larger deviations than in the unscaled solar cycle cases. We stress that these results should be treated as a sensitivity analysis and we do not suggest that these are plausible projections, especially those from the EBM_L00x analysis.

4. Discussion and Conclusions

[22] In this study we have examined the impact of a plausible range of future solar activity on global surface temperatures. By using past solar activity measures calibrated to reconstructions of TSI we are able to estimate the future changes of the Sun, assuming that it will leave the current level of activity in the next 10–20 years. Even in the event of the Sun entering a new Maunder Minimum like activity state the climate response is very small compared to the projected warming due to anthropogenic influences (the probability of this within the next 40 years has been estimated to be 8% by *Lockwood* [2010]. The projected warming of the HadCM3 model for the B2 SRES scenario is 2.55 K by the end of the 21st century with respect to the end of the 20th century and using the most recent TSI reconstructions, a Maunder Minimum like future change gives relative reductions of less than 0.13 K. There is a possibility that by the end of the 21st century solar activity returns to current levels, but as we assume there is a reduction of solar activity in the near future to "normal" levels there may still be a drop in temperature relative to the

Figure 5. Global annual mean near-surface temperature anomalies, with respect to the 1961–1990 period, for EBM_ALL (blue line) and (top) EBM_L00, (middle) EBM_K07, and (bottom) EBM_L09. The solid red line represents the mean of the TSI projections, the dashed red line shows the ±1 standard deviation, and the dotted red line gives the absolute range of the projections. The numbers on the right-hand side represent the deviations for the last 10 years of the 21st century from EBM_ALL, where the middle number is the mean deviation and then outward from that are the ±1 standard deviation and absolute range. Four different global annual mean temperature observational series are also included (green lines); HadCRUT3 [*Brohan et al.*, 2006], NASA GISS [*Hansen et al.*, 2006], NOAA NCDC [*Smith et al.*, 2008], and JMA (Japan Meteorological Agency, Global average surface temperature anomalies, http://ds.data.jma.go.jp/tcc/tcc/products/gwp/gwp.html). The light blue shaded region is the uncertainty range (±2 standard deviations) of an estimate of the internal climate variability, deduced from HadCM3 control simulation.

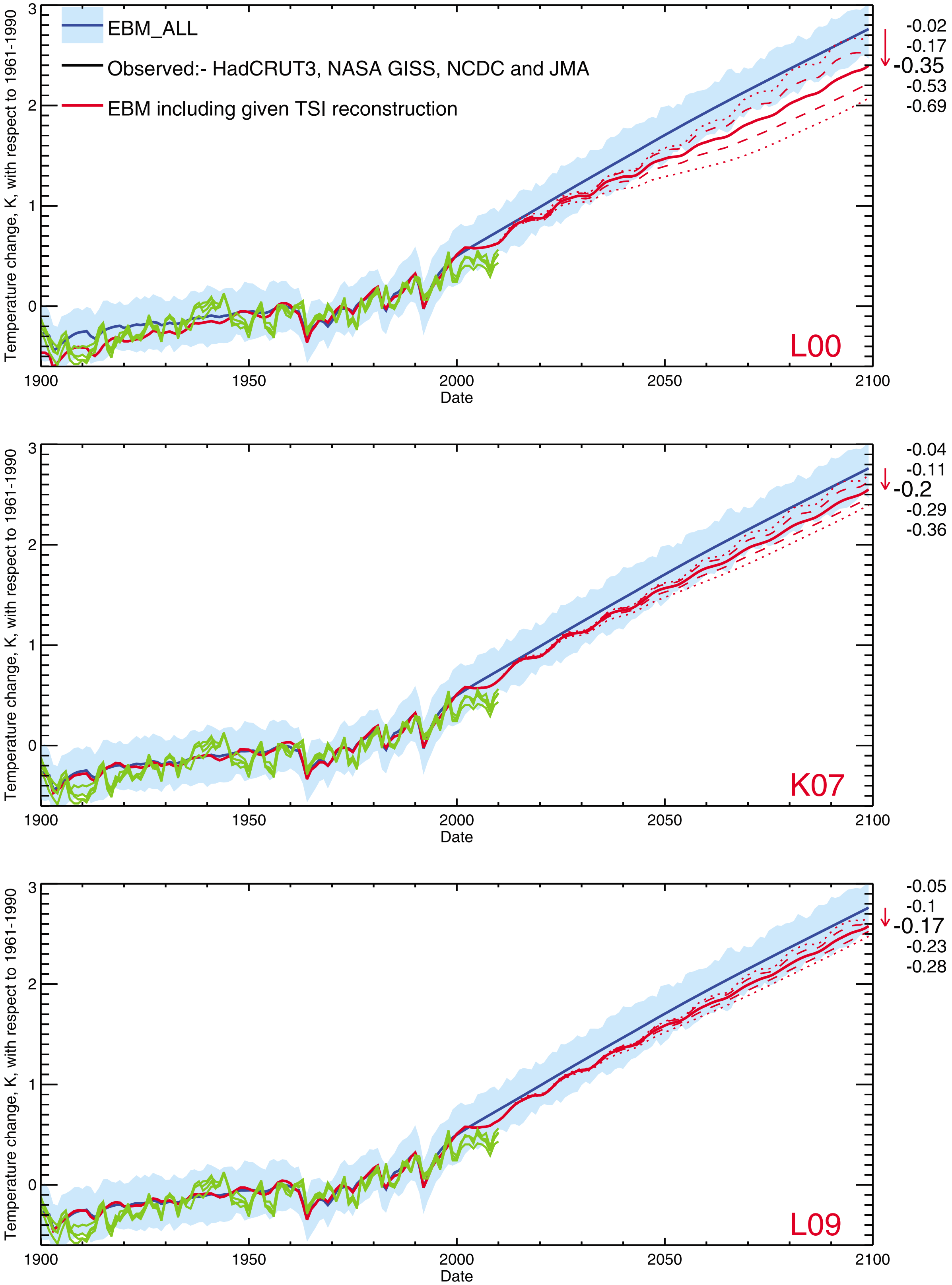

Figure 6. Same as Figure 5, except for the EBM simulations EBM_L00x, EBM_K07x, and EBM_L09x, where the solar responses have been scaled to match a solar cycle minimum to maximum of 0.1 K.

projected end of century warming. A sensitivity analysis assuming that the solar cycle response is larger than climate models simulate still produces small variations over what is projected because of anthropogenic forcings only. Only when an older TSI reconstruction is used and the response of climate models to solar influence amplified are more substantial variations found that could mitigate what is still a relatively small fraction of the projected anthropogenic warming, a scenario which we cannot rule out but given the latest assessment of TSI variations and understanding of the climate system we feel is unlikely.

[23] It is important to bring some context of the size of these deviations by comparing them to the spread of future warming expected from a range of emissions scenarios and modeling uncertainty. *IPCC* [2007] reported ranges of possible near-surface temperature increases by 2100 for different emission scenarios representing uncertainty in the climate sensitivity. The likely ranges (>66%) for the scenarios are between 5 and 11 times wider than the 68% range of the largest deviations by 2100 in EBM_L00x and the range of the best estimates across the different scenarios is over 3 times greater than the absolute range of EBM_L00x. This suggests that the possible mitigation potential for future solar activity changes is much smaller than the known uncertainties and ranges in the future anthropogenic response.

[24] Another way of looking at this is to ask how much delay would there be to when a given temperature threshold is crossed, information which could be useful for helping to adapt to future climate changes. For instance the time when global temperatures warm by 2K, relative to the preindustrial era, could be delayed by several decades if lower-emissions scenarios are followed [*Joshi et al.*, 2011]. Following *Joshi et al.* [2011], this threshold, here equivalent to 1.7 K warming relative to 1961–1990, would be crossed in 2050 by EBM_ALL, and only delayed by at most 4 years in EBM_L09 (Figure 5). In the extreme case, of scaling the solar response and using the older TSI reconstruction, EBM_L00x delays crossing this threshold with a likely range of 8 to 23 years and at most by 31 years (Figure 6). However, if the A1FI SRES scenario (Figure 4) was followed rather than B2 the maximum delay to the threshold crossing of 2042 is only 10 years (not shown). It should be noted that these estimates do not take account of internal climate variability, model and forcing uncertainties [*Joshi et al.*, 2011]. These calculations indicate, independent of uncertainties in future solar forcing and response, that while the Sun is not expected to provide substantial delays in the time to reach possible critical temperature thresholds, any small delays it might provide are likely to be greater for lower-emissions scenarios than for higher-emissions scenarios. In addition to future solar activity leading to small cooling influences not included in the range of 21st century projections reported by the IPCC, there could be additional cooling from any future explosive volcanic eruptions not accounted for in such projections.

[25] How much change there has been in historic TSI is still open to much uncertainty. One very recent study produces a reconstruction that gives an increase in TSI since the Maunder Minimum of 6 W m^{-2} [*Shapiro et al.*, 2011], over twice as large as even the L00 TSI reconstruction, while another study claims that the very quiet Sun in 2009 is characteristic of the Sun during the Maunder Minimum [*Schrijver et al.*, 2011], supporting the small increase seen in K07 and L09.

[26] We here use the total solar irradiance as the primary solar influence on global climate. The TSI variability is dominated by variations in the UV but it has always been considered that changes in the shape of the solar spectrum were sufficiently small that changes in the visible and IR parts of the spectrum were in phase with, and has the same temporal variation waveform as, the UV and hence the TSI. Recent observations by the SIM instruments on the SORCE spacecraft [*Harder et al.*, 2009] suggest that there may be considerable variability in the spectrum of solar irradiance, such that the visible/IR radiation is in antiphase with the UV. Some evidence to support this has been found from ozone abundances by *Haigh et al.* [2010]. The SORCE data are available only for the descent from the last solar maximum to the recent minimum and hence it is not clear to what extent they suggest that previous data and models of the spectral variation were incorrect or if the last solar cycle minimum, unusual in many other respects, was radically different to those observed before [*Lockwood*, 2010; *Lockwood et al.*, 2010b; *Ball et al.*, 2011]. The importance of this is that it is thought that visible/IR variability would be a “bottom-up” influence on climate through surface heating whereas UV variability would be a “top-down” influence through stratospheric changes. The SORCE data suggest the bottom up effect may be in antiphase to the top down and use of a single TSI may not capture the net effect of solar irradiance variability. In other words an increase in solar activity could have a direct cooling influence, and vice versa, contrary to the almost universally held view up to now and which would have wide ranging implications for how the Sun’s influence on climate is modeled. These data also show a larger UV variability then previously estimated with most of the evidence found thus far for top down effects pertaining to climates restricted to certain regions and seasons rather than the global effects discussed here [*Meehl et al.*, 2009; *Frame and Gray*, 2010; *Rind et al.*, 2008; *Lean and Rind*, 2008; *Lockwood et al.*, 2010a; *Ineson et al.*, 2011].

[27] Last, we note for the sake of completeness, that we have not considered a highly controversial proposed mechanism for solar-climate interaction, namely any modulation of cloud cover by air ions generated by galactic cosmic rays (GCRs) (see review by *Gray et al.* [2010]). The evidence for a significant influence of GCRs on global cloud coverage, and then climate change, is not considered to be strong and as the physical mechanisms behind this proposal are uncertain they are not parameterized in climate models [*Gray et al.*, 2010; *Forster et al.*, 2007].

[28] Further research will be needed to better determine solar effects on climate which could be more important on regional scales than global scales and could contribute significantly to decadal variability on such regional spatial scales. It could be that there is some decadal predictability based on such relationships as the Sun cycles from solar minimum to maximum and back again. The focus of this paper is different being on the longer term and investigating whether future predictions in solar output are likely to offset significantly global warming with continued greenhouse gas emissions. Our results show that any future reductions in

solar output are set to produce much smaller levels of global cooling than the levels of global warming predicted under emissions scenarios that do not include mitigation efforts. This conclusion holds even when fairly extreme assumptions are made concerning models' potential underestimate of their global mean temperature sensitivity to possible future secular changes in solar output. While the radiative impact of solar forcings has currently a low level of scientific understanding [*Forster et al.*, 2007], the uncertainty in future solar forcing has a smaller impact on future warming than the uncertainty in future anthropogenic forcing. Long-term accurate measurements of solar irradiance, both total and spectral, will be required to further reduce some of the uncertainties in solar forcing [*Kopp and Lean*, 2011].

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G. S. Jones and P. A. Stott, Met Office Hadley Centre, FitzRoy Road, Exeter EX1 3PB, UK. (gareth.s.jones@metoffice.gov.uk; peter.stott@metoffice.gov.uk)

M. Lockwood, Department of Meteorology, University of Reading, Earley Gate, PO Box 243, Reading RG6 6BB, UK. (m.lockwood@reading.ac.uk)