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Solar forcing of Earth's surface temperature in PMIP3 simulations of the last millennium

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Abstract

This study quantitatively diagnose the linkage between Total Solar Irradiance (TSI) and Earth's near-surface air temperature (TAS) of past 1000-year as simulated by Paleoclimate Modeling Intercomparison Project 3 (PMIP3) models. The results demonstrate that there is causal feedback of TAS from TSI variations, especially in the tropical and subtropical regions. The consistency between models in simulating solar signal in TAS responses is significant in these regions with more than 70% selected models showing agreement. There is no agreement between models in simulating TSI-TAS relationship in mid and high latitude regions.

Keywords: **solar forcing; Granger causality; last millennium; fraction of Earth surface; near-surface air temperature**

1. Introduction

Solar forcing is suggested as one of the most important natural factors of climate in preindustrial times of last millennium (Rind, 2002; Shindell *et al.*, 2003; Muscheler *et al.*, 2004, 2007; Solanki *et al.*, 2013). However, the causal impact of solar activity on surface climate of this period is neither proven nor clear. Here, we test for causality between solar forcing and Earth's surface climate (i.e. near-surface air temperature) of past 1000-year model simulations using bivariate vector autoregressive time series models and Granger causality tests.

This predictive definition of causality has been recently used in numerous studies focusing on the long term cause and effect of observational solar activity to climate in the industrial period from 1850 until today (Reichel *et al.*, 2001; Triacca, 2001; Attanasio *et al.*, 2012; Pasini *et al.*, 2012; Stern and Kaufmann, 2013) or in climate science in general (Kaufmann and Stern, 1997; Mokhov and Smirnov, 2006; Mosedale and Stephenson, 2006; Elsner, 2007; Kodra *et al.*, 2010).

While Pasini *et al.* (2012) and Attanasio *et al.* (2012) conclude that there is no clear evidence of Granger causality between observed total solar irradiance (TSI) and global temperature, Stern and Kaufmann (2013) suggest that the influence of solar irradiance to temperature change is weak during industrial times. The study of Reichel *et al.* (2001) shows that the cause and effect relationship is present between observed solar forcing and Northern Hemisphere land air temperature for the twentieth century. Other studies focused on preindustrial times and found solar signal in climate response (Phipps *et al.*, 2013; Schurer *et al.*, 2013). These studies have investigated the Sun–climate relationship with respect to global temperature or Northern and Southern Hemisphere mean temperature. However, the climate system is much more variable than represented by the global mean temperature or Northern and Southern Hemisphere mean temperature, and the increased (decreased) TSI does not show consistency of warming (cooling) climate from one region to another (Hughes and Diaz, 1994; Bradley, 2000; Rind, 2002). Besides, the climate response can be largely examined for by simple energetic considerations on global scale, but understanding the effects to regional climate is more difficult (Solanki *et al.*, 2013). Hence, the regional impacts of solar variations should be addressed.

In this paper, we explore the hypothesis that the solar signal is more sensitive in some regions of the Earth surface than others. By using the notion of Granger causality, we do not focus on investigating the absolute impacts of special solar forcing to Earth's surface climate (e.g. change of global mean temperature from solar minima to maxima) but do focus on detecting solar signal in the long period variability of regional Earth's surface climate if it exists.

2. Data

We use annual mean near-surface air temperature (TAS) data from the Paleoclimate Modeling Intercomparison Project 3 (PMIP3) model simulations of past 1000-year. The data is available from 850 to 1850. The models were forced with Total Solar Irradiance reconstructions from either Vieira *et al.* (2011) or Delaygue and Bard (2011) or Steinhilber *et al.* (2009) or Wang *et al.* (2005), as outlined in Table 1. Table 1 also notes the volcanic forcing (from either Crowley *et al.* (2008) or Gao *et al.* (2008)) used in each simulation. Other forcings include orbital variations, well-mixed greenhouse gases variations, land cover change and solar-related ozone change. The full details of climate forcing reconstruction options for the PMIP3 past 1000-year simulations are described in Schmidt *et al.* (2011) and Schmidt *et al.* (2012).

3. Methods

The notion of Granger causality was first introduced by Granger (1969) as follows: A variable Y is causal for another variable X if knowledge of the past values of Y is helpful in improving the prediction of X.

Following Mosedale and Stephenson (2006), bivariate vector autoregressive (VAR) time series models are used to TSI variations and TAS. At large spatial scale, the responses of the considered variable might be assumed as linear and additive to an external forcing (Stone *et al.,* 2009). Thus, the use of linear model of vector autoregression is appropriate for examining the responses of TAS to TSI. The pth order vector autoregressive VAR(p) is defined by:

$$X_t = \sum_{i=1}^{p} \alpha_i X_{t-i} + \sum_{i=1}^{p} \beta_i Y_{t-i} + \varepsilon_t \tag{1}$$

where X_t is the TAS at year t, Y_t is the TSI at year t and $p \geq 1$ is the order of the causal model. The terms α_i and β_i are regression coefficients, ε_t is noise residual in the regression. The data of X and Y are detrended and normalised to produce stationary time series before computation. The causal model shown in Equation (1) might have uncertainties introduced by neglecting the influence of other important forcings. This might lead to false conclusion about Granger causality (Lütkepohl, 1982). In this study, although the statistical model in Equation (1) omits other important variable (i.e. volcanic radiative forcing), it has similar results if this variable is included (not shown). Note that, solar forcing and volcanic forcing are suggested to be the main drivers of climate change of preindustrial era (Crowley, 2000; Shindell *et al.,* 2003; Hegerl *et al.,* 2007; Schurer *et al.,* 2013).

The procedure for testing Granger causality is summarised as follows. First, the best order p for the VAR time series models is selected by using the definition of Schwarz criterion or Bayesian information criterion (Schwarz, 1978). The optimal order is normally less than 6 for our current datasets, thus, we decide to limit the maximum order at 8, indicating that the Sun-climate relationship is only investigated at lagged timescale shorter than 10-year.

Second, Granger causality tests a complete model against a null model of no causality. The complete model is given in Equation (1). The null model is obtained by setting the $\{\beta_i; i = 1, 2, \ldots, p\}$ coefficients to zero. The complete model and the null model are compared using the log likelihood ratio statistic:

$$L_{Y\to X} = n\left(\log\left|\Omega_{p,\beta_i=0}\right| - \log\left|\Omega_p\right|\right) \tag{2}$$

where $|\Omega_p|$ is the determinant of the covariance matrix of the residual, n is the sample size.

If the statistic $L_{Y\to X}$ in Equation (2) is close to zero, then the null model is as equally good as the full model in predicting the data of X, thus, Y has no causal impact on X. If the statistic is large, then the addition terms of Y help to predict the variability of X and we say that there is Granger causality.

Finally, statistical significance of the test is evaluated by comparing the $L_{Y\to X}$ statistic against the χ^2_p null distribution. If the p-value is smaller than 0.05, then the null hypothesis of no Granger causality is rejected at 5% level of confidence.

Monte Carlo simulation method is used to generate pseudo data of X and Y and repeat the procedure described above to estimate the p-value of no Granger causality. We perform 200 trials to guarantee the convergence of the p-value. It is estimated that the relative error of that p-value is smaller than 1% if more trials were executed. This approach allows us not only to establish the linkage between solar variability and Earth's surface temperature but also to show the statistical significance of the conclusions we will point.

We will report a map of probability of no Granger causality between TSI and TAS in the sense of Granger causality. In order to make multi-model mean of this map, the original result from each model is rescaled to 1° longitude × 1° latitude spatial resolution. Note that, although the rescaled spatial resolution chosen is subjective, the results and conclusions are similar for other rescaled spatial resolutions. We use the area fraction of the Earth surface having significant Granger causality with TSI variations at 5% level of confidence to draw possible consistent conclusions of the Sun-surface temperature relationship.

4. Results and discussions

In this study, we test the null hypothesis of Granger non-causality from TSI to TAS of last millennium as simulated by PMIP3 models. Figure 1 shows the ensemble mean probability map of no Granger causality between TSI variations and TAS (See also Figure S1 for individual models). The uncertainty of Sun-TAS relationship can be seen in mid and high latitude regions of above 30°N (and below 30°S) with large area having inconsistent model responses. However, it's consistent between models that the Sun has Granger causal impact on TAS variability in tropical and subtropical regions. Stippling indicates agreement in more than 70% of models of the ensemble mean probability. In Figure 1, the regions having Granger causality at 5% (10%) of confidence level are marked with red (yellow) contour line.

We have shown that the influence of the Sun on Earth's TAS is not equal for different regions. There are several hypotheses that potentially explain these unequal responses of TAS to solar forcing. Generally, it might be natural and reasonable that the influence of the

Table 1. Last millennium modelling institutes and model IDs and volcanic and solar forcing.

Institute	Model ID	Abbreviation	Volcanic forcing	Solar forcing
BCC	BCC-CSM1-1	BCC	Gao *et al.* (2008)	Vieira *et al.* (2011) and Wang *et al.* (2005)
NASA-GISS	GISS-E2-R	NASA	Crowley *et al.* (2008)	Steinhilber *et al.* (2009)
IPSL	IPSL-CM5A-LR	IPSL	Gao *et al.* (2008)	Vieira *et al.* (2011) and Wang *et al.* (2005)
LASG – IAP	FGOALS-s2	LASG-IAP	Gao *et al.* (2008)	Vieira *et al.* (2011) and Wang *et al.* (2005)
MIROC	MIROC-ESM	MIROC	Crowley *et al.* (2008)	Delaygue and Bard (2011) and Wang *et al.* (2005)
MPI-M	MPI-ESM-P	MPI-M	Crowley *et al.* (2008)	Vieira *et al.* (2011) and Wang *et al.* (2005)
MRI	MRI-CGCM3	MRI	Gao *et al.* (2008)	Delaygue and Bard (2011) and Wang *et al.* (2005)
NCAR	CCSM4	NCAR	Gao *et al.* (2008)	Vieira *et al.* (2011)
UOED	HadCM3	UOED	Crowley *et al.* (2008)	Steinhilber *et al.* (2009) and Wang *et al.* (2005)
UNSW	CSIRO-Mk3L-1-2	UNSW	Crowley *et al.* (2008)	Steinhilber *et al.* (2009)

The forcings of model GISS-E2-R are shown for selected ensemble of r1i1p121.

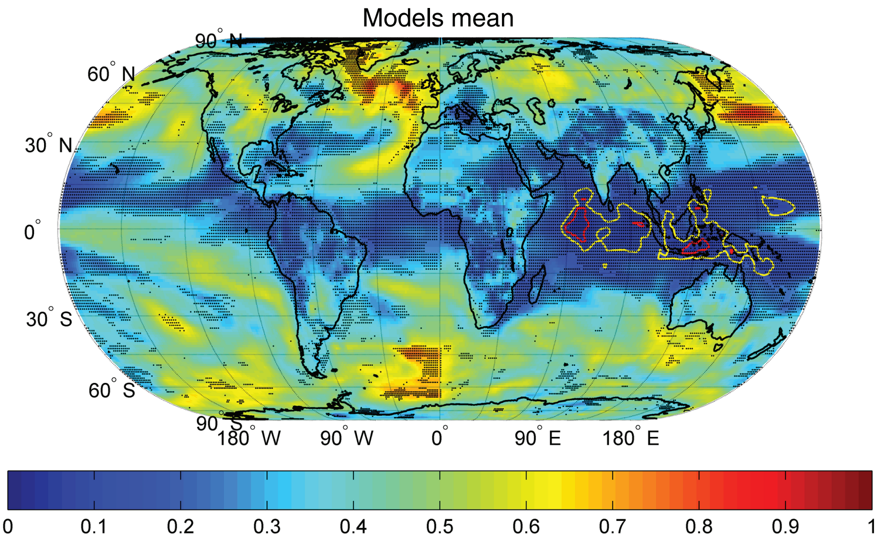

Figure 1. Ensemble mean probability of no Granger causality from TSI to TAS. Stippling indicates agreement in more than 70% of models of the ensemble mean probability. An individual model agreement is defined as the bias of that model's probability from the ensemble mean probability less than one ensemble standard deviation probability. The red (yellow) contour line marks *p*-value =0.05 (0.1). Red shades indicate high probability of no Granger causality.

Sun to Earth's surface is not equal for different regions. This happens because the momentary state of regional climate is controlled by other external and internal forcings (e.g. volcanic forcing, atmospheric circulation, heat advection ...) which might be more significant than solar forcing (Shindell *et al.*, 2003; Solanki *et al.*, 2013). The sensitivity of subtropical regions might be associated with its cloud-free area of the oceans where there is the most incident solar radiation (Meehl *et al.*, 2008; Solanki *et al.*, 2013). Besides, the TAS responses is also related to regional aerosol and cloud properties which might be affected by solar variations (Marsh and Svensmark, 2000; Wang and Dickinson, 2013).

While it is challenging to identify the true regional impacts of solar forcing to TAS (i.e. the regions that are Granger caused by solar variability) since details of the related mechanisms are still not fully proven (Solanki *et al.*, 2013), it is possible to estimate how much of the Earth surface are influenced by solar forcing. The area of the Earth surface where there is no Granger causality from TSI to TAS at 5% level of confidence is depicted in Figure 2 for each model. Whereas the models BCC-CSM1-1, MIROC-ESM and CCSM4 have low area fraction of less than 10%, the model FGOALS-s2 has highest area fraction of around 60%. The rest models have area fraction from 15% to 30%. It is interesting to note that 'low area fraction' models exhibit low sensitivity of TAS in tropical and subtropical areas to TSI variations. Also, these models might not show the convergence in simulating TSI-TAS relationship compared to other models. Thus, if we assume that the sensitivity of tropical and subtropical TAS to TSI is true, it might be reasonable and interesting to take the ensemble mean of probability of no Granger causality with removal of 'low area fraction' models in the computation. In fact, this computation is against conclusions of previous studies (e.g. Knutti *et al.* (2010)) which suggest the approach 'one model, one vote' while investigating the multi-model mean effect. However, if we remove 'low area fraction' models from ensemble mean computation for a sensitivity analysis, the probability map of no Granger causality between TSI variations and TAS can be obtained in Figure 3. This Figure show a more clearly result compared to Figure 2 with the extension of the regions where there is Granger causality from TSI to TAS at 5% of confidence level. A large

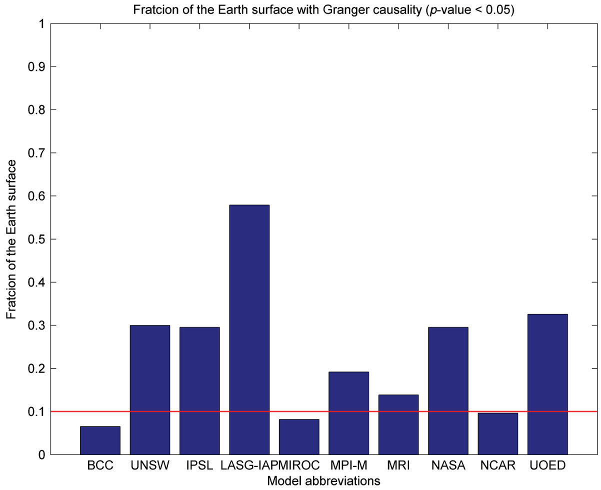

Figure 2. Fraction of Earth surface with Granger causality from TSI to TAS (p-value <0.05). Fraction is shown for individual model. 'Low area fraction' models include BCC, MIROC and NCAR. Horizontal red line marks area fraction of 0.1. See also Table 1 for model abbreviations.

part of these regions are in Indian Ocean and tropical Pacific. Besides, large areas of Northern high latitude are found to have Granger causality in several models (See Figure S1), although the ensemble mean probability of no causality is higher than 10%. Moreover, the consistency between these models is shown to be high in most regions of Earth surface, not only in the tropical and subtropical regions as seen in Figure 2. Though other groups of models can be made (e.g. the model LASG-IAP which is negatively biased is also excluded from the ensemble mean), the final conclusion about the causal impact of solar forcing to tropical and subtropical TAS does not change significantly (not shown). In other words, this conclusion is robust and independent from the selection of models. The impacts of solar maximum and minimum to Earth's surface climate are not considered in this study. Several studies show that solar maximum and minimum might abruptly alter atmospheric circulation and TAS in different regions (Woollings *et al.,* 2010; Martin-Puertas *et al.,* 2012).

The results presented here are models dependent. However, most models (excluding MPI-ESM-P and MRI-CGCM3) only include prescribed non-evolving ozone and tropospheric aerosols in their simulations. The solar-related ozone change is one factor that potentially explains the unequal responses of TAS to solar forcing. For example, the sensitivity of tropical temperature to solar forcing might be explained from the sensitivity of stratospheric tropical ozone to the Sun as shown in (Austin *et al.,* 2008). Another factor that might affect the responses of TAS to solar forcing is the representation of the stratosphere in each model. The changes of the Sun-TAS relationship in different regions might be explained from the various effect of the Sun to the stratosphere which in turn alters the climate of lower troposphere through dynamical coupling (Haigh and Blackburn, 2006; Simpson *et al.,* 2009; Solanki *et al.,* 2013). Therefore, the next generation of models with full solar-related ozone changes and well-resolved stratosphere might help better understanding of solar signal responses in TAS. Also, they might adjust the significance of the causal impact of solar forcing to tropical and subtropical TAS as stated in this study. In further studies, the comparison between model results and observation or reconstruction record of TAS is necessary. This analysis helps to identify the quality of considered models in given regions and might increase the robustness of the results. Besides, it can then be used to shed lights on mechanism.

5. Summary and conclusions

The Granger causality of solar forcing to near-surface air temperature (TAS) is analyzed using past millennium simulations of PMIP3 models. To our knowledge, this is the first causal analysis of solar forcing to regional TAS for this period.

We show that there is Granger cause from the Sun to Earth's TAS field during past millennium as simulated by PMIP3 models, indicating that there is contemporaneous year-to-year up to several lagged years effect of TSI variations to TAS. It is interesting to note that previous studies have shown weak evidence of causal impact between solar irradiance and global temperature in recent periods of industrial times (Attanasio *et al.,* 2012; Pasini *et al.,* 2012; Stern and Kaufmann, 2013). Here, we have shown that there is evidence of Granger causality between TSI variations and TAS in state-of-the-art modelling simulations covering the period 850–1850 AD, especially in tropical and subtropical regions. The fraction of Earth surface where there is Granger causality from TSI to TAS at 5% level of confidence ranges from less than 10% to around 60% between models. Whereas the models CSIRO-Mk3L-1-2, IPSL-CM5A-LR, FGOALS-s2, MPI-ESM-P, GISS-E2-R and HadCM3 show clear solar signal of tropical and subtropical TAS responses as similar to the ensemble mean, the models BCC-CSM1-1, MIROC-ESM and CCSM4 have large deviation compared to the ensemble mean. There is no agreement between models in simulating TSI-TAS relationship in mid and high latitude regions. However, the low probability of no Granger causality between TSI and Northern high latitude TAS as seen in several models is noted.

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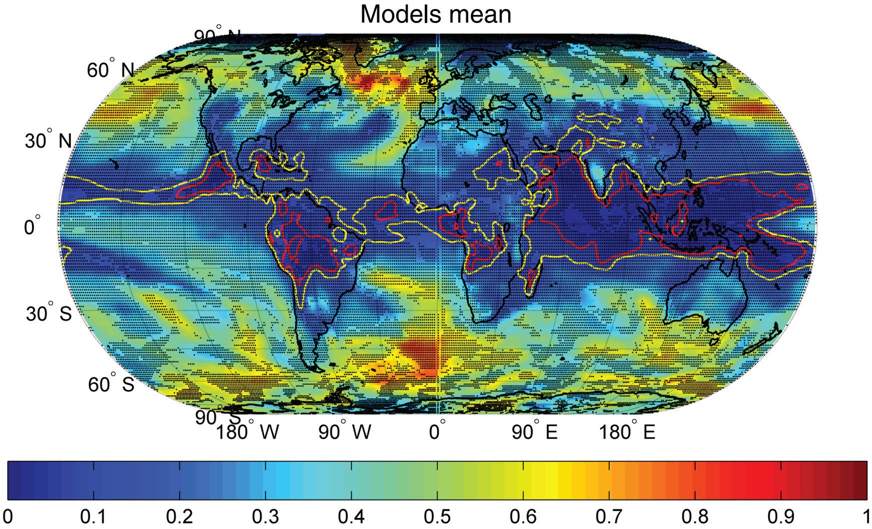

Figure 3. As in Figure 1 but with removal of 'low area fraction' models (see also Figure 2) in ensemble mean computation. There is stronger Granger causality in the tropical and subtropical regions between TSI and TAS compared to Figure 1. High consistency in most regions between models is also found.

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Supporting information

The following supporting information is available:

Figure S1. Probability of no Granger causality from TSI to TAS for individual models. The name of each model is shown on each small figure. The red (yellow) contour line marks p-value = 0.05 (0.1). Red shades indicate high probability of no Granger causality.

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