Supplement of Earth Syst. Dynam. Discuss., 6, 1237–1260, 2015
http://www.earth-syst-dynam-discuss.net/6/1237/2015/
doi:10.5194/esdd-6-1237-2015-supplement

Earth System Dynamics
Discussions
Open Access

Supplement of

Multi-millennial-scale solar activity and its influences on continental tropical climate: empirical evidence of recurrent cosmic and terrestrial patterns

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Supplementary Information (SI)

Multi-millennial-scale solar activity and its influences on continental tropical climate: Empirical evidence of recurrent cosmic and terrestrial patterns

By J. Sánchez-Sesma

SI-1. Statistical detrending and demodulation of the solar proxy (10Be) record of FN97

10Be is a proxy of SA. It is produced by the impacts of galactic cosmic rays on Earth (SS14) in a known process of cosmogenic nucleosynthesis. Cosmic rays are highly energetic charged particles that impact Earth's upper atmosphere and terrain surface, that produce 10Be, and that are modulated by the variation in the strength of the geomagnetic field, as well as by solar magnetic shielding (SS14).

In order to homogenize 10Be values, we apply, firstly, a detrending process based on polynomial expressions, and secondly, a demodulation intended to make the variance uniform. Figure S1a shows the polynomial model for detrending, and Figure S1b shows the linear model of the standard deviation for a demodulation. The results are displayed in Figure S4c with two analogue models with lags of 9.6 and 19.2 Kyrs, showing similar variability for the next millennia.

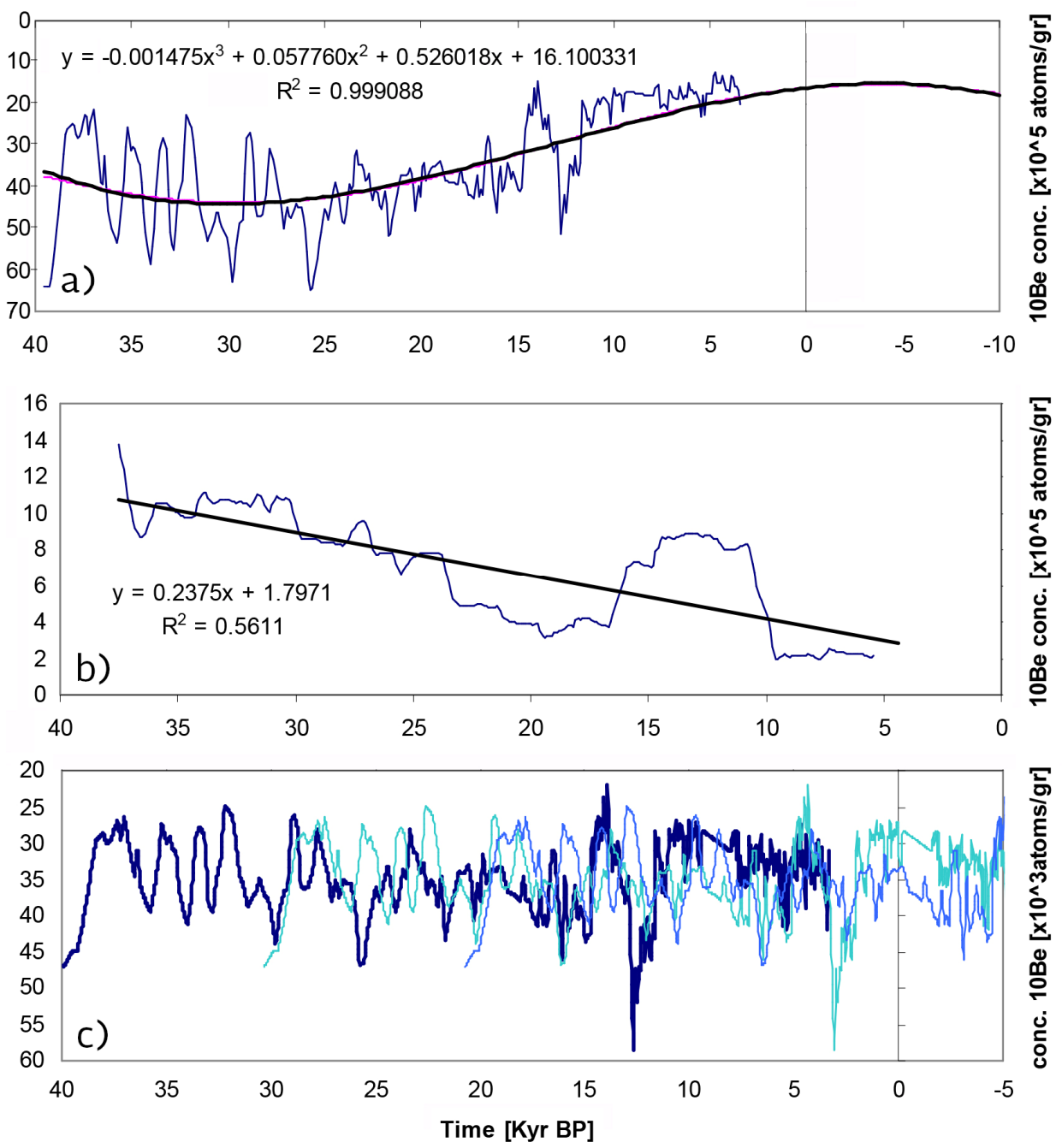

Figure S1. GISP2 icecore analysis. a) 10Be concentration [N97] and a polynomial trend, b). b) Standard deviation and its linear model a). c) Demodulated 10Be [(a)/(linear model of b)], 10Be (DDR), lagged model for 9.6 and 19.2 Kyrs of this DDR of 10Be are also displayed. Please note that in the following figures: as the 10Be concentration varies inversely with solar activity, TSI, the beryllium scale is inverted, and thus upper parts in this scale indicate high TSI levels.

SI-2. Estimation of a temporal adjustment (bias) of the Greenland 10Be record by SS14.

A temporal adjustment for the NEEM 10Be record produced by SS14 is presented. This record is compared with another study with information coming from the NGRIP ice-cores (Kindler et al., 2014) which is located to less than 1000 km from the NEEM site. A temporal bias correction of 2500 yrs going back in time was applied to SS14 data to get the best match with the Kindler et al. (2014) data, and is shown in Figure S6.

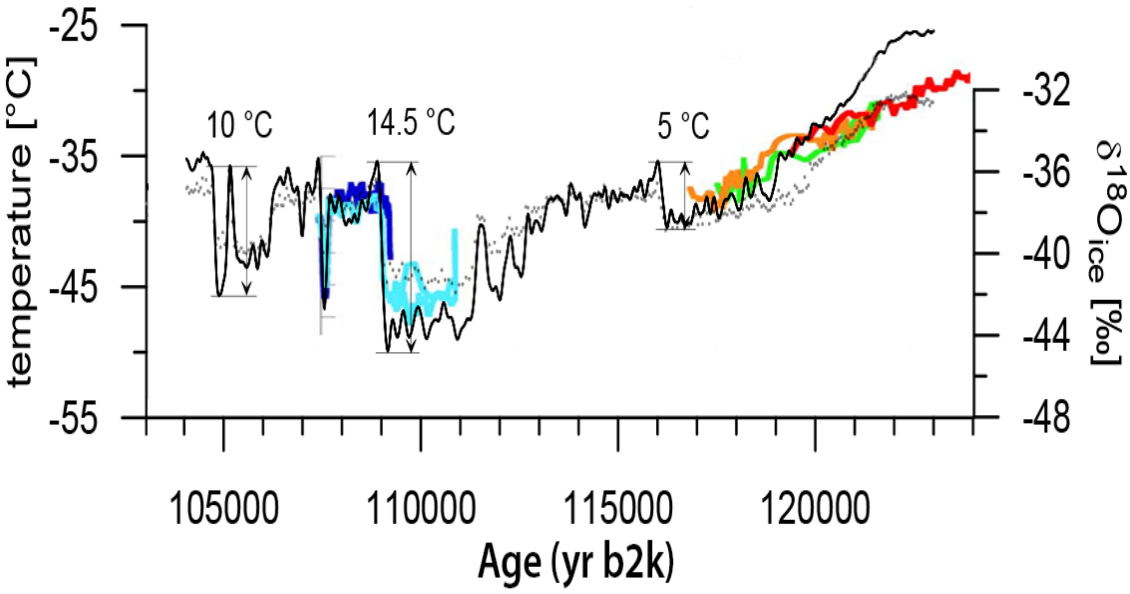

Figure S6. Comparison of NGRIP Greenland ice-core reconstructed isotopic anomalies in two different studies (SS14, K14). The gray points indicate anomalies 18O ice and black line indicates temperature from Kindler et al. (2014). Color lines are anomalies of 18O ice from the SS14 that have been adjusted in time, with a lead of 2500 years to increase the match with K14 results.

SI-3. Detrending and demodulating the solar proxy (10Be) record of FN97, following Alley et al. (1995)

Alley et al. (1995) have proposed a method for interpolating between the end-members cases of 10Be wet and dry deposition. They argued that, on average, under conditions of global constant global 10Be production rate and constant dry deposition rate and scavenging ration for precipitation, a linear relation should be expected between 10Be flux and snow flux at GISP2. Then, deviation of measured 10Be from the correlation line can be attributed to changes in the atmospheric concentration of 10Be.

Figures S2 and S3 show these processes to obtain the Atmospheric 10Be. Figure S2 shows: the 10Be concentration [N97], ice accumulation rate [Alley, 2000], and their linear correlation. And Figure S3 shows: deviations from the linear interpolation (see S2c), its standard deviation, and the demodulated deviations (S3a) with a precessional sinusoidal model.

The final atmospheric signal of 10Be without orbital influences is displayed in Figure S4 with a simple analogue model with a lag of 9.4 Kyrs, showing a potential decrease of TSI for the next centuries and lower values for the next millennia.

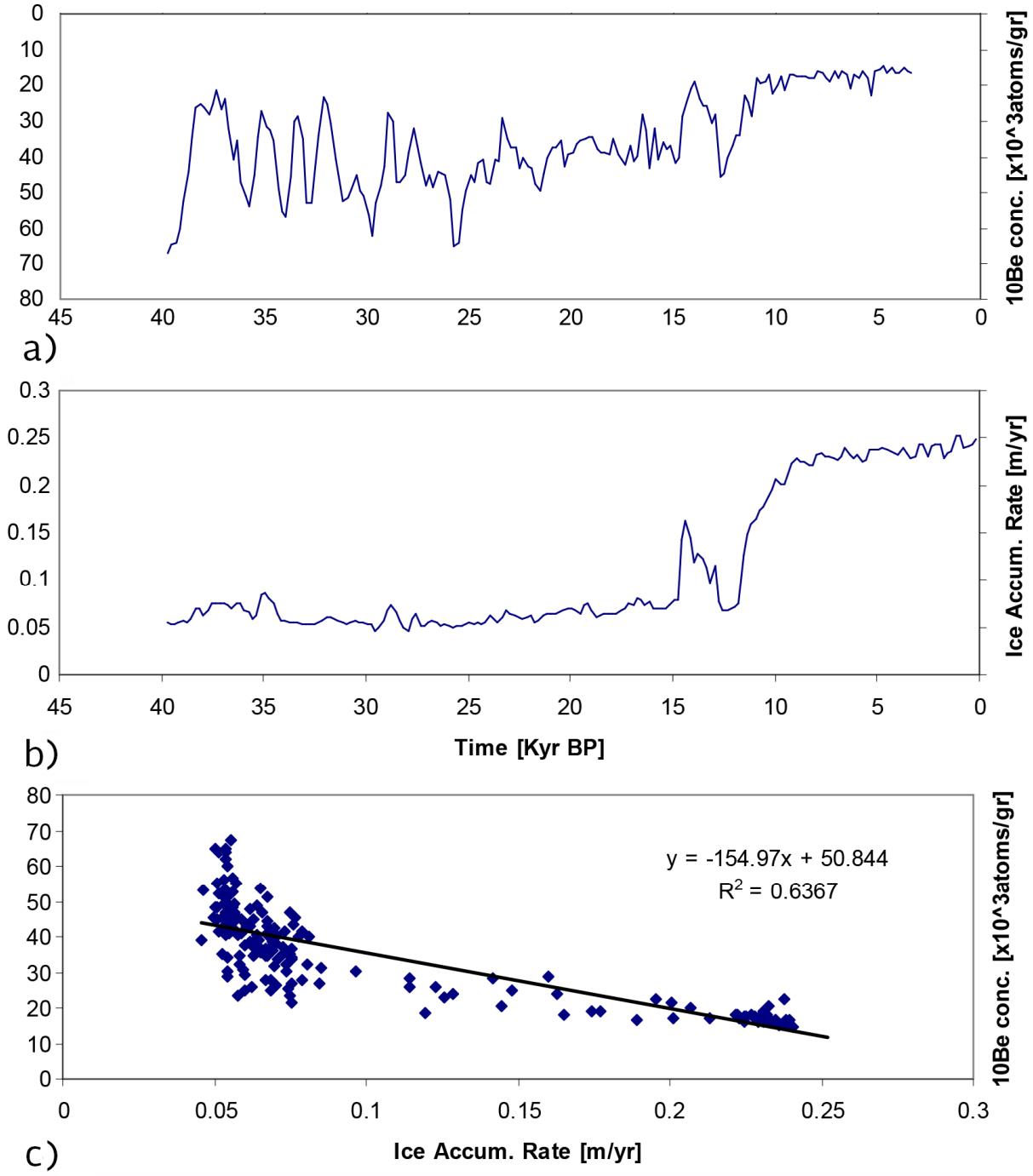

Figure S2. GISP2 icecore analysis. a) 10Be concentration [N97], b) ice accumulation rate [Alley, 2000], c) linear correlation between 10Be concentration and ice accumulation shown in a) and b).

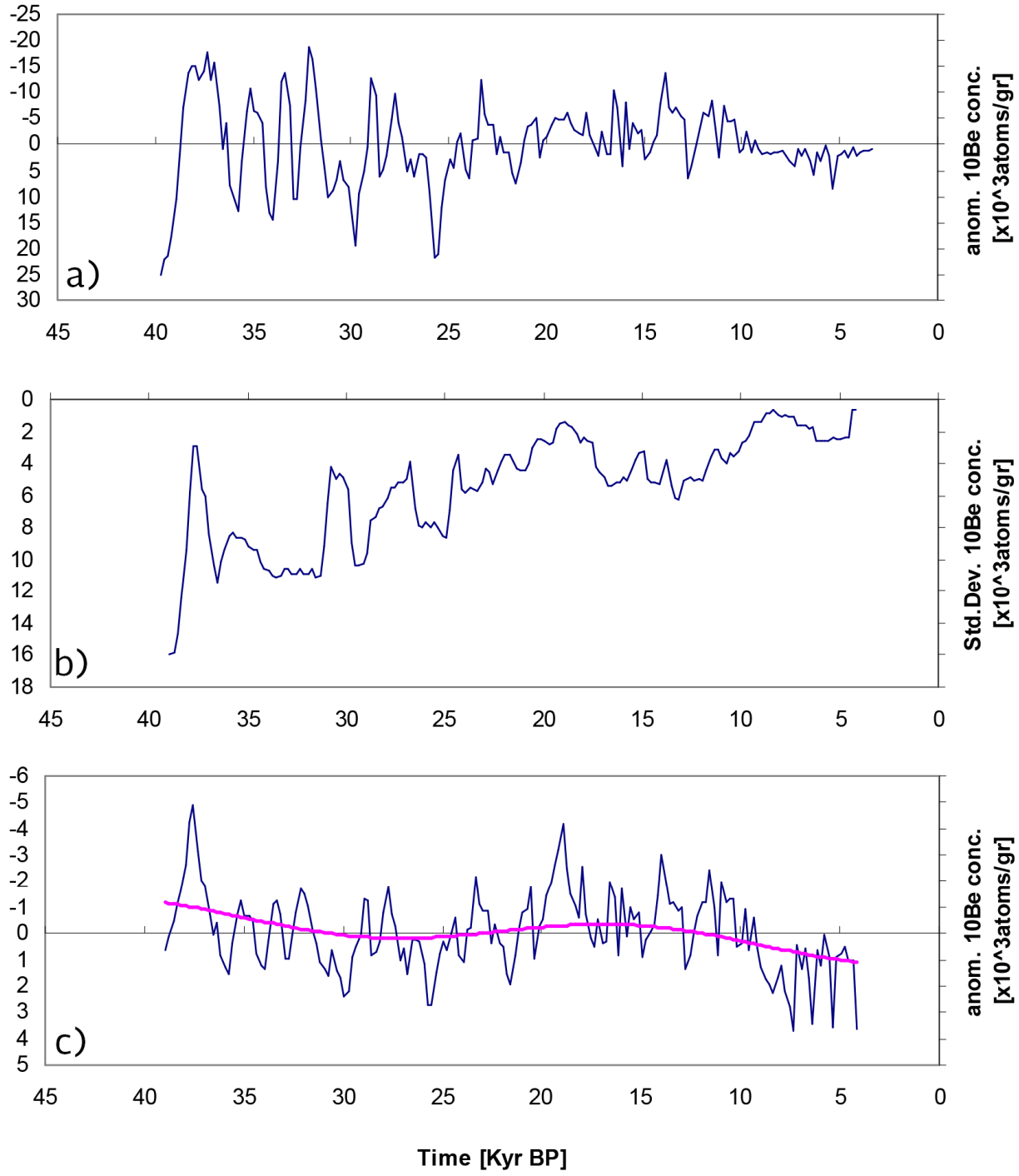

Figure S3. GISP2 icecore analysis. a) 10Be residual concentration after to eliminate ice accumulation linear contributions (Fig S4c), b) Standard deviation of a), c) Demodulated 10Be [(a)/(b)] with a precession simple model with linear and sinusoidal variation for detrending.

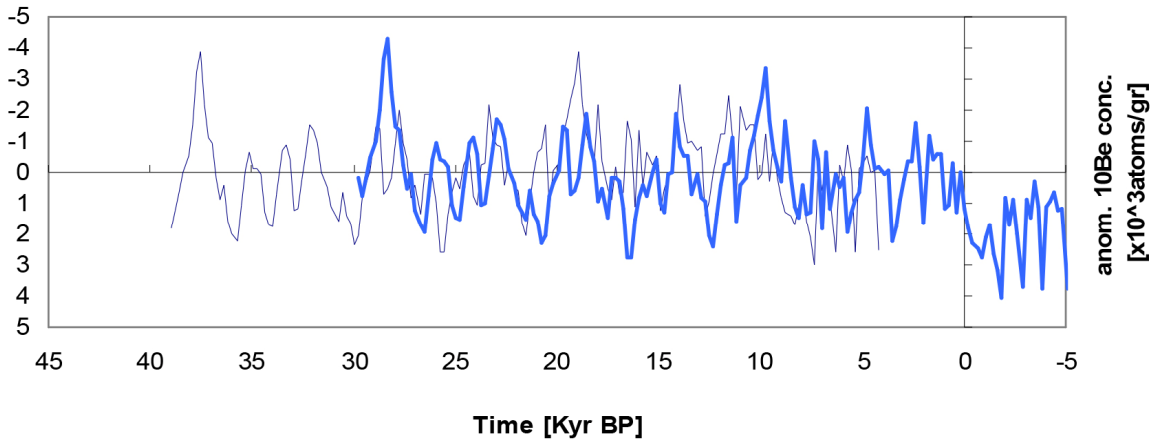

Figure S4. GISP2 icecore analysis. 10Be detrended and demodulated residual concentration (DDR) after to: a) sustract ice accumulation linear contributions (Fig S4c), b) divide by standard deviation (Fig. S5b), c) substract linear and sinusoidal variation (Fig S5c). A lagged model (9.4 Kyr) of this DDR of 10Be is also displayed.

SI-4. Spectral analysis of solar activity

In order to verify the multi-millennia scale solar oscillation of ~9500 yrs detected in 10Be records, a wavelet analysis was applied to the reconstructed records of TSI, using the online resource by Torrence and Compo (1998).

TSI spectral results, displayed in Figure S1, show three main, significant (~10% level) periodicities around 9000, 5000, and 2400 years. It should be noted that the *S09* record also shows relatively high-frequency significant variability with periods around 200 years.

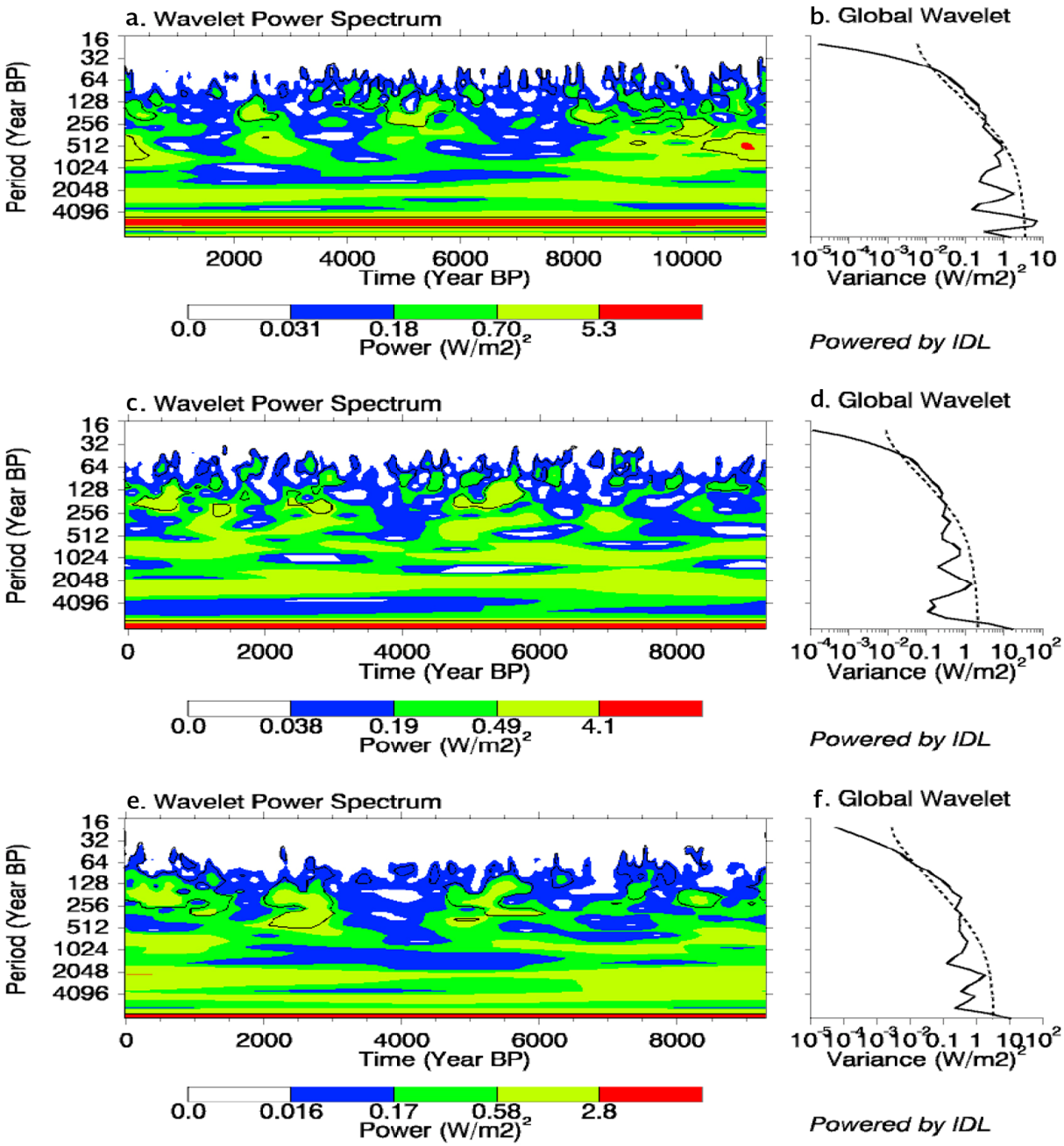

Fig. S5: (a, c, and e.) The wavelet power spectrum of TSI(S04), TSI(S09), and TSI(S12), respectively. The contour levels are chosen so that 75%, 50%, 25%, and 5% of the wavelet power is above each level, respectively. Black contour is the 10% significance level, using a red-noise (autoregressive lag1) background spectrum. (b, d, and f.) The global wavelet power spectrum (black line). The dashed line is the significance for the global wavelet spectrum, assuming the same significance level and background spectrum as in (a, c, and e,, respectively). Reference: Torrence, C. and G. P. Compo, 1998: A Practical Guide to Wavelet Analysis. Bull. Amer. Meteor. Soc., 79, 61-78.