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

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Abstract

Solar activity (SA) oscillations over the past millennia are analyzed and extrapolated based on reconstructed solar-related records. Here, simple recurrent models of SA signal are applied and tested. The consequent results strongly suggest: (a) the existence of multi-millennial (∼ 9500 years) scale solar oscillations, and (b) their persistence, over at least the last glacial–interglacial cycle. This empirical modelling of solar recurrent oscillations has also provided a consequent multi-millennial-scale experimental forecast, suggesting a solar decreasing trend toward Grand (Super) Minimum conditions for the upcoming period, AD 2050–2250 (AD 3750–4450). Also, a recurrent linear influence of solar variation on continental tropical climate (CTC) has been assessed for the last 20 kyr, and extrapolated for the next centuries. Taking into account the importance of these estimated SA scenarios a comparison is made with other SA forecasts, and their possible associated astronomical forcing and influences on past and future CTC discussed.

1 Introduction

"Long-term solar variability: It is possible that we have missed the forest for the trees. Driven by pragmatic hopes of finding keys to weather prediction, we run the risk of concentrating too much on time scales of practical consequences – of days, months or years. In taking a longer view we see the problem in clearer perspective ..."

Climate and the Role of the Sun (John A. Eddy, 1981)

"... the equatorial and inter-tropical regions can play an important role in the response of the climate system to the astronomical forcing ..."

Equatorial insolation (Berger et al., 2006)

"Throughout the last glacial cycle, reorganizations of deep ocean water masses were coincident with rapid millennial-scale changes in climate. Climate changes have been less severe during the present interglacial ...."

Detecting Holocene changes in thermohaline circulation (Keigwin and Boyle, 2000)

Solar activity (SA) has non-linear characteristics that influence multiple scales in solar processes (Vlahos and Georgoulis, 2004).

For instance, millennia-scale solar oscillations have been recently detected, like those of about 6000 and 2400 years, by Xapsos and Burke (2009) and Charvátová (2000), respectively, with important and interesting influences in the near past and future climate. These millennial-scale patterns of reconstructed SA variability could justify epochs of low activity, such as the Maunder Minimum, as well as epochs of enhanced activity, such as the current Modern Maximum, and the Medieval Maximum in the 12th century.

Although the reason for these SA oscillations is unclear, it has been proposed that they are due to chaotic behavior of non-linear dynamo equations (Ruzmaikin, 1983), or stochastic instabilities forcing the solar dynamo, leading to on-off intermittency (Schmitt et al., 1996), or planetary gravitational forcing with recurrent multi-decadal, multi-centennial and longer patterns (Fairbridge and Sanders, 1987; Fairbridge and Shirley, 1987; Charvátová, 2000; Duhau and Jager, 2010; Perry and Hsu, 2000). It should be noted that all proponents of planetary forcing have forecasted a solar Grand Minimum for the upcoming decades, but one of them has also forecasted a Super Minimum for the next centuries (Perry and Hsu, 2000). In addition, during recent decades, statistical forecasts (with physically-based spectral information of reconstructed records) of solar magnetic activity predict a clear decrease in SA, reaching a minimum around AD 2100 (Steinhilber et al., 2013; S13, hereafter, Velasco et al., 2015).

It should also be noted that several recent studies have been devoted to reconstruct multi-millennial-scale solar/climate related records. In relation to solar records, Steinhilber et al. (2009; S09, hereafter), Steinhilber et al. (2012; S12, hereafter), Solanki et al. (2004; S04, hereafter), and Finkel and Nishiizumi (1997; FN97, hereafter) have investigated isotopic concentrations in ice-cores and tree-rings over the past 9500, 9500, 11 500, and 40 000 years, respectively, in order to estimate SA and/or related isotopic production. Another isotopic reconstruction (Stuverik-Storm et al., 2014; hereafter SS14) has just provided detailed key information over 20 kyr for the past interglacial, or Eemian period, more than 100 000 years ago.

These different cosmogenic radionuclide-based reconstructions of SA present variations for the past millennia, and as Muscheler and Heikkilä (2011) have pointed out, large uncertainties appear in reconstructions of the solar modulation of galactic cosmic rays from different proxies, ^{10}Be and ^{14}C, and of changes in the geomagnetic shielding influence. However, these reconstructed records provide, especially when considered all together, the most objective information as elements for detecting and eventually modelling and extrapolating multi-millennial-scale solar oscillations, trends and absolute levels.

In terms of climate, and following Haigh (2011), who has pointed out that "it is now possible to identify decadal and centennial signals of solar variability in climate data," we have complementarily analyzed one important tropical climate record: the reconstructed Congo River basin surface air temperature (CRB-SAT) record, because it covers the last 25 kyr (Weijers et al., 2007; W07 hereafter). This tropical climate variable is very important because its location, at the center of tropical Africa, generates isolation from the ocean influences and thus enhances solar influences. This influence is known as continentality.

In addition to solar influences on climate, recent studies have highlighted the importance of human activities, and suggest that anthropogenic global warming (AGW) is currently active, imposing a projected change of $4 \pm 2\,^{\circ}$C by AD 2100 that seems to exceed the maxima values estimated for the past millennia (IPCC, 2013). However, an understanding of climate change remains incomplete because firstly, the main signals of climate long-term forcings have not been well described, neither forecasted, and require further work, with new methods and new data, as is the case for phenomena such as solar and volcanic activity; secondly, paleoclimate studies have begun to

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consider cosmoclimatic approaches (Shaviv et al., 2014); and thirdly, solar influence appears to be modulated by the THC that increased during the present interglacial (Piotrowski et al., 2004).

In this paper, we attempt to advance our knowledge of solar variability by considering reconstructed records of related SA over the last glacial cycle, from isotopic information coming from ice-cores and tree-ring layers, reanalyzing them with a linear modelling of oscillations with recurrent influences. This modelling is achieved through simple analogues and Fourier series models. Tests of the proposed method and the detected low-frequency solar signal, going back in time, are based on independent data. Finally, we discuss the different oscillations detected, the confidence of our forecasts, some alternative forecast methods, and astronomical information that suggests a possible planetary forcing of SA by an unknown mechanism during the last millennia, and its past and future modulated influences on continental tropical climate (CTC).

2 Methodology

2.1 Data

In order to analyze solar/climate recurrent oscillatory patterns, six different reconstructed forcing (five) and climate (one) proxy records of these oscillations are presented.

We have analyzed five different sets of solar-related information. Firstly, total solar irradiance (TSI or S, hereafter) reconstructed by S04, S09 and S12, based on the isotopic information of ^{14}C and ^{10}Be, have recently provided records of SA anomalies for the last millennia. Figure 1a displays S04, S09 and S12 reconstructed and intercalibrated values from 9450 BC to AD 1900, from 7360 BC to AD 2009, and from 7350 BC to AD 1988, respectively. The variance explanation between S04&S09, S04&S12, and S09&S12 for decadal average records are of 52.7, 82.9 and 59.3 %.

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Secondly, there are two interesting and useful solar-related, ^{10}Be isotope concentration records from Greenland ice, one covering the past 40 kyr (FN97) and the other covering only 20 kyr but located at the Eemian (SS14). Figure 1b displays the information of ^{10}Be FN97 and SS14 records.

Thirdly, we will look at a climate record for tropical areas for the last millennia, specifically the Congo River basin surface air temperature (CRB-SAT) record, because it covers the last 25 kyr and it is a continental tropical climate record obtained with a novel and promising molecular technique (W07). This CRB-SAT record (W07), or Tcrb, is relatively more influenced by solar than the rest of the world, because the latitudinal distribution of solar influences shows its maximum in the tropics. Moreover, this record is also relatively less influenced by the ocean, because its signal is coming from the central tropical zone of Africa, which is also isolated by topography. The detrended Tcrb information, is displayed in Fig. 1c.

Although oceanic influences on the Tcrb are minimal, its response to SA should be modulated during the interglacial differently due to the increasing intensity of THC that has been reconstructed by Piotrowski et al. (2004), who pointed out: "From a minimum during the Last Glacial Maximum (LGM), North Atlantic Deep Water (NADW) began to strengthen between 18 and 17 kyr cal BP, approximately 2000–3000 years before the Bølling warming."

2.2 Modelling

To take into account different time-scale recurrences, the solar/climate, SC, variable can be expressed with three models. One model is based on the Fourier Series (FS), another is based on a linear transformation of the proxy variable values, and the last one is based on temporal analogues.

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The FS model can be written by means of:

$$\mathrm{SC}(t) = \sum_{j=1}^{N_{\mathrm{FS}}} \left[a_j \cdot \sin\left(j \frac{2\pi(t)}{T} \right) + b_j \cdot \cos\left(j \frac{2\pi(t)}{T} \right) \right] + e_{\mathrm{FS}}(t), \tag{1}$$

Here, T is the FS base period, N_{FS} represents the number of FS terms or harmonics, j is an index component term, a and b are amplitudes, t is time, and $e_{\mathrm{FS}}(t)$ is the error in this model.

The model for the lagged and modulated linear contribution of a proxy variable is:

$$\mathrm{SC}(t) = M[\alpha_P P(t + \delta_P) + \beta_P(t - t_1) + \gamma_P] + e_P(t), \tag{2}$$

With $M = 1$ for $0 < t < 10$ kyr BP, $M = 1 + 0.133(t - 10)$ for $10 < t < 17.5$ kyr BP, and $M = 2$ for $17.5 < t < 25$ kyr BP.

Here, $P(t)$ is the proxy variable, α_P is the amplification factor, β_P is the slope, δ_P is the lag, γ_P is the additive constant, t_1 is the initial times for the modeled period, and $e_P(t)$ is the error of this model.

The analogue model is defined as:

$$\mathrm{SC}(t) = \alpha_{\mathrm{A}} \mathrm{SC}(t + \delta_{\mathrm{A}}) + \beta_{\mathrm{A}}(t - t_1) + \gamma_{\mathrm{A}} + e_{\mathrm{A}}(t), \tag{3}$$

Here, α is the amplification factor, β is the slope, δ is the lag, γ is the additive constant, t_1 is the initial times for the modeled period, and $e_{\mathrm{A}}(t)$ is the analogue error of this model.

In all these models, parameters are estimated through iterative or multi-linear regression processes that minimize the RMS values of errors.

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3 Results

3.1 Long-term solar-activity recurrent patterns

In order to detect multi-millennia-scale recurrences and/or persistent oscillations in SA, we need to analyze ^{10}Be information since it is a solar proxy variable and it is available over longer periods than SA records. However, there are several ^{10}Be post-production and fallout processes (i.e. residence time in the atmosphere, scavenging rate, troposphere–stratosphere exchange, precipitation rate, etc.) that may alter the concentration found in the ice archive (FN97; SS14).

Accepting that ^{10}Be concentration variability is influenced by climatic variability through long-term variable trends and modulations, we propose to apply a homogenization process based on statistics to the ^{10}Be (FN97) record. Firstly, a detrending process based on polynomial expressions was applied. And secondly, a demodulation was applied in an attempt to make the variance uniform. The consequent results show the ^{10}Be atmospheric signal of this process with approximated recurrent oscillations with lags of 9.6 and 19.2 kyr, which are shown in the Supplement S1.

The statistically detrended ^{10}Be NF97 record was modeled with a periodic FS function with NF = 10 that employed Eq. (1). After a minimization process, a 9390-year period, P, was found and the corresponding model that explain 49.2 % of variance is displayed in Fig. 2a.

Although this model is based only on the last 40 kyr (see Fig. 2b), it was extrapolated to cover the last 130 kyr, for comparison with other independent information of ^{10}Be. A detailed comparison with the ^{10}Be SS14 record (in 5 parts) coming from Greenland and the Eemian period is displayed in Fig. 2c. The maximum variance explanation, of 18.4 %, corresponds to a temporal adjustment of 2.5 kyr (a temporal bias going back in time) of the SS14 dating. This temporal adjustment is justified because a similar one, of 2.3 kyr, is required by the SS14 18O record when it is compared with another reconstruction from NGRIP Greenland ice-cores by Kindler et al. (2014; K14

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hereafter), which is shown in Supplement S2. This comparison constitutes an important verification and test of the proposed FS model.

In order to verify the detected recurrent patterns of ^{10}Be, we apply different homogenization and extrapolation processes to FN97 data. Specifically, we follow the original calculations made by FN97 and the suggestions provided by Nishiizumi (personal communication, 2014), and we have also calculated the atmospheric signal of ^{10}Be (^{10}Be Atm) based on accumulated snow (Cuffey and Clow, 1997) and the signal of ^{10}Be coming from the GISP2 icecore. Our normalizations, which confirm the previous results for the ~ 9.5 kyr recurrence and a consequent increase (diminish) of the ^{10}Be A(TSI) signal for the following centuries, are also shown in the Supplement S3.

3.2 Application and verification of the ~ 9500-year recurrence of SA

Before extrapolating the ^{10}Be 9.5 kyr recurrences to TSI, we applied a wavelet analysis to the three TSI records. The TSI spectral results (see Supplement S4) show three main, significant periodicities around 9000, 5000, 2400 and 900 years, which confirm the extrapolation of the multi-millennia FS ^{10}Be modelling of 9.5 kyr and its harmonics to the solar activity.

We applied Eq. (3) with a lag parameter of 9500 years with the TSI records. Results of TSI are displayed in Fig. 3. In this Figure, the three TSI records (S04, S09 and S12) are displayed with their analogue models. Only the S04 model continually covers the next centuries, due to its longest characteristics, and presents an overlapping that explains 16 and 53.4 % of the TSI variance of the last 1000 and 500 years, respectively.

However, in order to test the proposed method, we compare our TSI forecasts with a forecast for the next 500 years based on S12 data and the Fast Fourier Transform (FFT) techniques developed by S13. The TSI(S04) extrapolation explains 61.4 % of the variance of the forecasted TSI(S13) which is based on other data and another technique. This comparison constitutes other important verifications and test of the proposed recurrent model of SA.

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Our model confirms a Grand minimum in the period AD 2050–2200 forecasted by S13 characterized by a sustained deficit of 0.5 $\mathrm{W\,m^{-2}}$.

The same model, shown in Fig. 3a, suggests that the next Super-minimum of SA will ocurr around AD 2100–2600, and will be similar to the period 7500–7000 BP of reduced SA. In Fig. 3, big and small vertical orange arrows indicate Super and Grand solar minima, respectively.

3.3 Influences of the ~ 9500-year recurrence of SA on continental tropical climate

Three models of the CTC temperatures, Tcrb, based on different TSI reconstructions that employed Eq. (2) are displayed in Fig. 4. The modelling required a different modulation for the first ($M = 2.$) and second ($M = 1.$) halves to distinctly consider the decreasing THC deglaciation process until the stabilized Holocene periods (Piotrowski et al., 2004). These models of Tcrb that were based on S04, S09 and S12 records, explain for the 20–10 (10–0) kyr BP 30.0, 23.6 and 31.6 (6.5, 10.9, and 8.5) % of the reconstructed Tcrb record.These three modelling results constitute other tests of our recurrent model of SA. Note that the variance explanation is bigger in the first half of the record when the THC was low and the advected heat from the tropics also was low.

Finally, in another confirmation of not only the recurrent solar modelling, but their influences on climate, we also apply Eq. (3) with a lag parameter of 9600 years to the CTC Tcrb record.

Our model explains most of the variation of the Tcrb during the past centuries. In a comparison, partially depicted in Fig. 5, the Tcrb analogue model explains 7.3, 18.7, 60.8 and 71.7 % of the Tcrb reconstructed record (W07) for the last 10, 5, 2 and 1 kyr, respectively. For the future, our model provides an estimation of a cooling for the 21st century of about 0.5 °C, followed by a slow warming trend with small oscillations during more than 4 centuries. The forecasts comparison also considers two different forecasts of TSI, shown in Fig. 3. With this comparison, we estimated that the Tcrb analogue model also explains in the AD 2050–2500 period 34.3 and 37.1 % of variance of the TSI forecasts, based on S04 and S12 records (S13), respectively.

4 Discussion

Thanks to the recently developed paleoclimate records on solar-related and tropical climate variability, we have found a $\sim$9500-year recurrence of SA and its linear influences on CTC.

Firstly, and in order to confirm this multi-millennial recurrence, we have developed different tests and verifications of the SA and CTC recurrent patterns. The following summarizes the tests and verifications of our findings:

1. Our FS model explains the detrended and modulated ^{10}Be statistically corrected variability over almost the last 40 kyr. However the recurrent patterns based on FN97 when extrapolated backward in time are comparable with independent ^{10}Be information from the Eemian.

2. When this recurrent phenomena detected in the ^{10}Be record was extrapolated to the TSI records, we conducted other tests, establishing the following: (a) the overlapping of the TSI(S04) record explains over 53 % of the variance in the last five centuries, (b) the extrapolated model also based on TSI(S04) presents an important match with different data (S12) and an independent procedure (FFT) employed in the TSI forecast due to S13; and (c) the extrapolated models [TSI(S04), TSI(S09), and TSI(S12)], but backward in time, present an important match with independent CTC Tcrb (W07).

3. When this recurrent phenomena detected in the ^{10}Be record was also extrapolated to the CTC Tcrb record, we conducted another test, establishing that: (a) the overlapping of the Tcrb (W07) record explains over 71 % of the variance in the last millennium, and (b) the analogue model extrapolated forward

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in time presents an important match with, based on different data (S12) and an independent procedure (FFT) employed, the TSI forecast due to S13.

The detected modulation of CTC Tcrb record, occurring during the interglacial, could be linked to the increasing THC that has been reconstructed by Piotrowski et al. (2004): "Neodymium isotope ratios in the authigenic ferromanganese oxide component in a southeastern Atlantic core reveal a history of the global overturning circulation intensity through the last deglaciation ... It exhibits a gradually increasing baseline intensity that plateaus in the early Holocene." This increasing THC implies greater oceanic heat transport from the tropics and a consequent lower thermal response of the CTC.

Our experimental multi-millennial-scale analogue forecast of TSI, supported mainly by recurrent oscillations over the last glacial–interglacial cycle, shows a lowering trend toward a minimum for the coming decades. Our forecast also confirms previous efforts by several authors (Fairbridge and Sanders, 1987; Fairbridge and Shirley, 1987; Perry and Hsu, 2000; Duhau and Jager, 2010), who have forecasted a solar Grand Minimum for the upcoming decades. For instance, recent findings linked to periodicities of the solar tachocline and their physical interpretation may permit us to estimate that solar variability is presently entering into a long Grand Minimum, thus consisting of an episode of very low SA (Duhau and Jager, 2010).

Although the complete physical basis of this recurrent process is missing, there are several examples of physical and theoretical evidence that also support our findings. Firstly, it is important to highlight what Mackey (2007) has stated: "In several papers, Rhodes Fairbridge and co-authors described how the turning power of planets is strengthened or weakened by resonant effects between the planets, the sun and the sun's rotation about its axis."

Specifically, there are important works motivated by Rhodes Fairbridge and other researchers, providing a theoretical basis and practical evidences of resonant interactions, for instance:

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1. Abreu et al. (2012) have shown the physical basis of a gravitational forcing of the solar tachocline variations. They developed a gravitational model for describing the time-dependent torque exerted by the planets on a non-spherical tachocline and compared the corresponding power spectrum with the reconstructed SA record. They find an excellent agreement between the long-term cycles in proxies of SA and the periodicities in the planetary torque (with a period from 50 to 504 years).

2. Fairbridge and Sanders (1987) have indicated long-term variations due to planetary forcings. They follow Stacey (1963) who, based on the periodicities of planetary orbits, proposed a ~ 4.45 kyr Outer Planets Restart (OPR) cycle. It is close to half of the ~ 9.5 kyr detected periodic recurrence.

3. Focused on Moon–Earth gravitational links, Keeling and Whorf (2000), based only on the links expressed in tidal astronomical periodicities, have proposed a ~ 1.8 kyr that represents the time for the recurrence of perigean eclipses closely matched with the time of perihelion. This cycle is near the fifth part of the ~ 9.5 kyr detected periodic recurrence. Keeling and Whorf (2000) also detected in their analysis a ~ 4.65 kyr modulation cycle of the 1.8 kyr that is almost half of the ~ 9.5 kyr detected periodic recurrence.

4. Looking for solar-planetary resonances of our detected ~ 9.5 kyr, we compared the "biggest" solar system secular frequencies determined by Laskar (2011) over 20 Ma for the four inner planets, and over 50 Ma for the five outer planets, corresponding to 45.184 and 49.880 kyr, respectively. We found that the mean value of 47.532 kyr is almost five times the solar period detected (47.532 kyr $= 5 \times$ [9.56 kyr]). This means that the solar inner and outer planets show a resonance (5 : 1) with the solar periodicity detected.

5. We also compared the equatorial insolation variability recently evaluated by Berger et al. (2006), who, in line with Milankovitch ideas on astronomical forcing,

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evaluate, using astronomical models and the MTM spectral techniques, significant 95 and 123 kyr periods related to eccentricity periods. The lowest value of 95 000 years is almost ten times the solar period detected. This also means that one of Earth's primary eccentricity periods is in resonance (10 : 1) with the solar periodicity detected.

Finally, we would like to emphasize the social importance of these multi-millennial solar oscillations is clearly shown if we consider that the world population began an almost sustained exponential increase was a lagged response to the past solar Super minimum at ~ 7000 years BP, when a multimillennial period of increasing solar activity provided favorable environments for developing the first civilizations all around the world (Sánchez-Sesma, 2015). Also, in that work a detailed analysis about the detection and empirical modelling of solar and terrestrial variability of ~ 2400-year recurrent patterns and its potential influences on the world population over past and future millennia is presented and discussed.

5 Conclusions

An analysis and test of recurrent solar variability for the last millennia has been presented in this study. It was based on five multi-millennia solar-related reconstructed records from different and valuable proxy information.

The tested existence of the ~ 9.5 kyr period recurrent pattern suggests that SA is characterized by solar dynamics with long-term patterns. Considering that it has been suggested that the modulating oscillations of SA, around 84, 178 and 2400 years, are possibly related to the Sun's rotation rate and impulses of the torque in the Sun's irregular motion (Landscheidt, 1999; Fairbridge and Sanders, 1987; Charvátová, 1995, 2000), our results also suggest that similar mechanisms on the solar dynamo must be proposed for solar oscillations of around 9.5 kyr. This hypothesis should be tested, taking into account the results presented in this paper.

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With all of these recurrent phenomena, we have presented, tested and verified an experimental multi-millennial forecast technique for SA. The consequent forecasted trend toward these Grand (Super)-minima of TSI conditions is very important from a paleoclimatic perspective, because information from different reconstructions and models indicates a potential continental tropical temperature cooling of around 0.5 °C for the rest of the 21st century, a warming of around 0.3 °C from the end of the 21st century to the end of the 23th century, a cooling of around 0.3 °C from the end of the 23rd century to the middle of the 24th century, and a warming of around 0.65 °C from the middle of the 24th century to the end of the 25th century without taking into account volcanic and anthropogenic forcing.

The recurrence in solar activity was verified through its influence on CTC. Three models of the CTC temperatures, Tcrb, based on different SA reconstructions were evaluated. The modelling required a different modulation considering the increasing THC process. These three modelling results constitute other tests of our recurrent model of SA.

The assessed connection between TSI and CTC is also supported by previous studies, such as those by Berger et al. (2006), who pointed out that "the equatorial and inter-tropical regions can play an important role in the response of the climate system to the astronomical forcing." The modulated connection between TSI and CTC helps us to confirm the previous studies on THC, such as those by Piotrowski et al. (2004), who pointed out that "The gradually increasing baseline through the deglaciation indicates that THC does not switch between distinct glacial and interglacial modes of circulation but rather that varies as a continuum."

However, more research is needed to better understand the solar recurrent patterns and their influences not only in the tropical climate but also in the global climate, because, as Peeters et al. (2004) have suggested, the Mozambique and Agulhas currents in the western Indian Ocean could be an efficient carrier of the CTC signal (influenced by SA) to the global scale.

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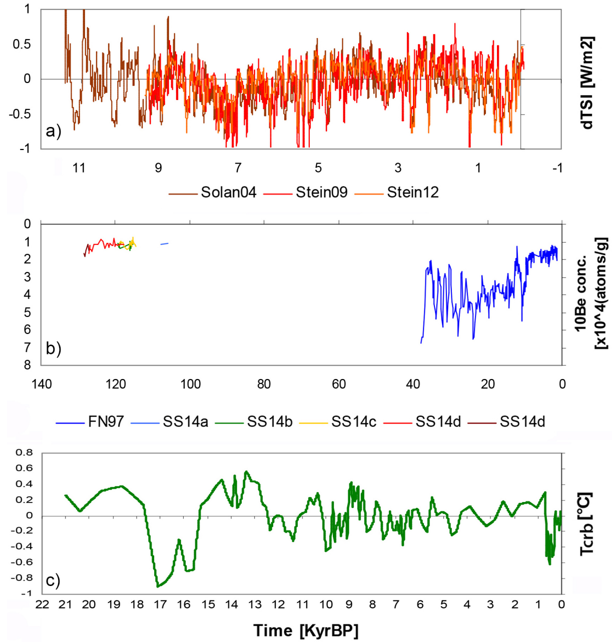

Figure 1. Solar-related and climate signals. **(a)** Solar activity, TSI, reconstructed by S04, S09 and S12, after an intercalibration using the S09 record as a base. **(b)** ^{10}Be isotope concentration in polar ice cores during the past 130 kyr (Finkel and Nishiizumi, 1997; Stuverik-Storm et al., 2014). **(c)** The continental tropical Congo River basin (CRB) mean annual surface air temperature record for the last 21 000 years, based on lipids (W07). Please note that in all figures: as the ^{10}Be concentration varies inversely with Solar activity, TSI, the beryllium scale is inverted, and thus upper parts in this scale indicate high TSI levels.

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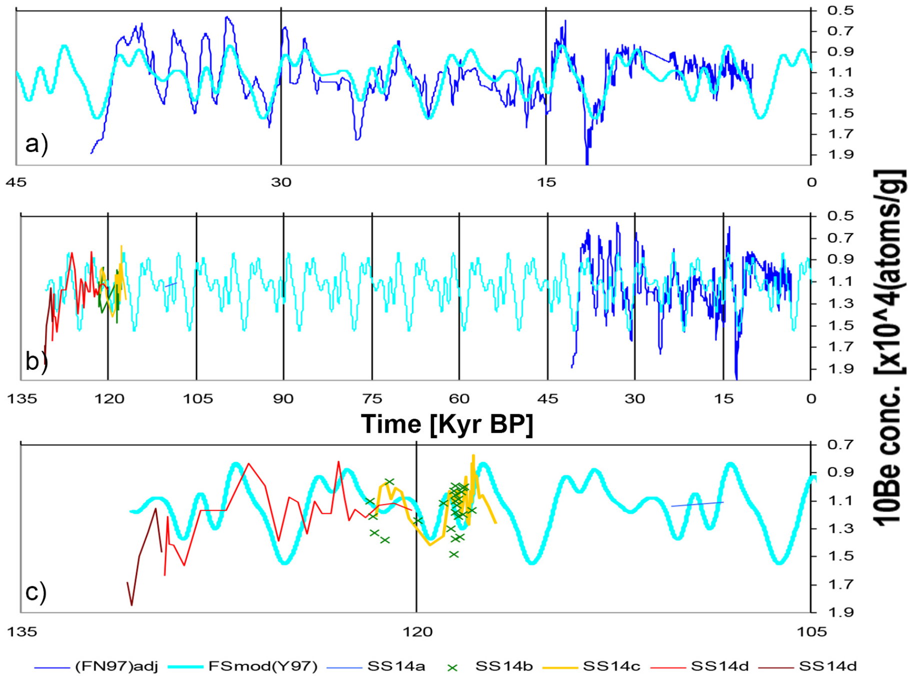

Figure 2. Data and modelling of ^{10}Be isotope concentration in Greenland ice cores. **(a)** Data and a FS model of ^{10}Be isotope for the past 40 kyr provided by FN97 (Finkel and Nishiizumi, 1997) after detrended and demodulated. **(b)** The model, shown in **(a)**, is extrapolated covering the last 135 kyr, and the SS14 (Stuverik-Storm et al., 2014) data is included for comparison. **(c)** A zoom of **(b)** for a detailed comparison of the extrapolated FS model and the SS14 data. Please note that a maximum match implies a SS14 temporal adjustment, or time bias, of 2.3 kyr going back in time.

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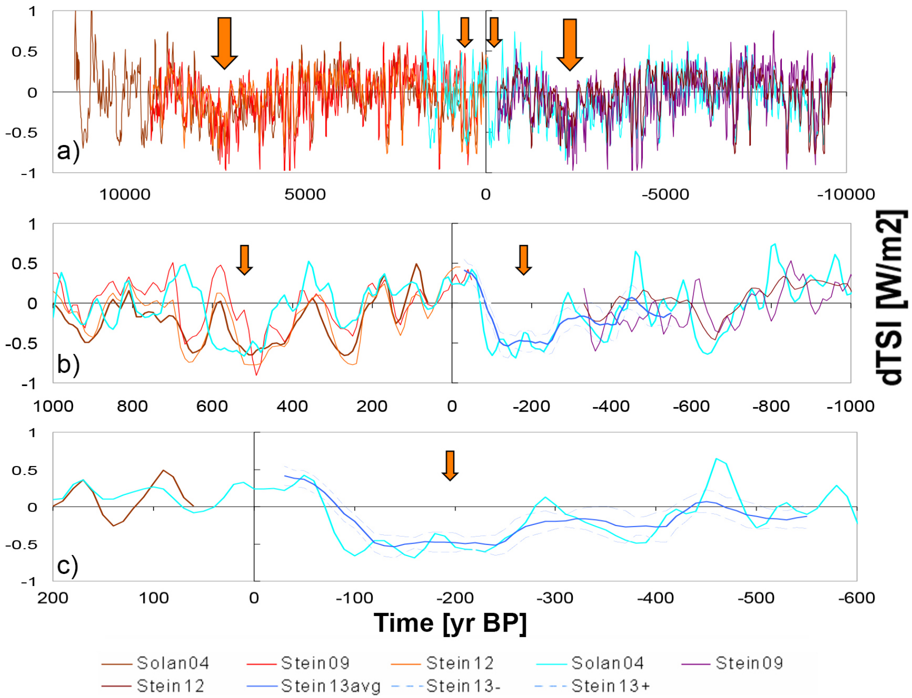

Figure 3. Solar activity signals reconstructed and modelled records. **(a)** Solar activity, TSI, reconstructed by S04, S09 and S12, shown in Fig. 1a, and their analogue models. **(b)** A zoom of **(a)** that covers only 2kyr. **(c)** Another greater zoom of **(a)** that covers only 0.85kyr including the independent TSI forecast by S13. **(d)** The CTC Tcrb signal and its simple model including the independent TSI forecast by S13. Big and small vertical arrows indicate Super and Grand solar minima.

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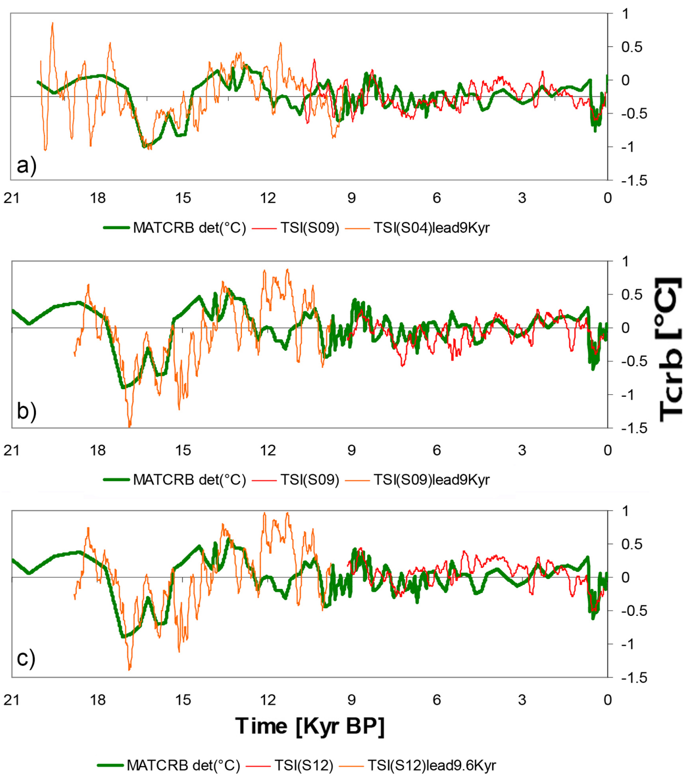

Figure 4. Tropical climate (CRB) T reconstructed and detrended signal and its solar-based models. The CRB T models, extrapolated backward in time, were based on: **(a)** TSI (S04), **(b)** TSI (S09) and **(c)** TSI (S12), applying Eq. (2) with greater modulated amplitudes before 10 kyr BP.

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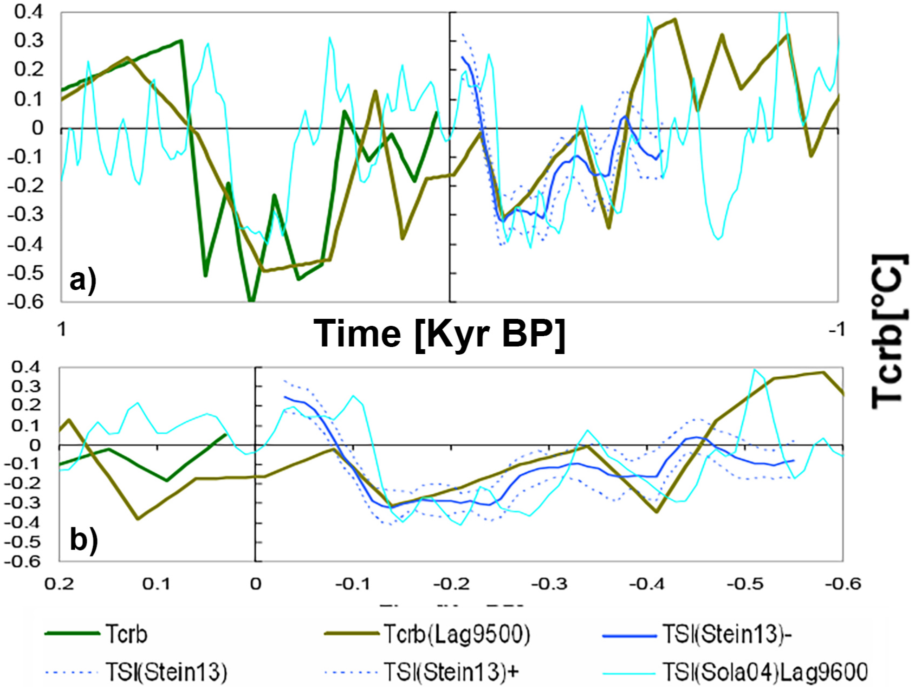

Figure 5. Continental tropical climate, Tcrb reconstructed and its analogue model with a lag of 9.6 kyr but including two forecasts of TSI, provided by our analogue model TSI (S04) and the TSI forecast by S13. **(a)** The CRB T signal and its model, during the last 1 and future 1 kyr, and **(b)** a zoom of **(a)** during the last 0.3 and future 0.6 kyr.

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