Comment 4: Model and forecast of Arctic Summer and Central England temperatures and their use for empirical 21st century global temperature forecasts

In order to continue complementing the ESD-2021-84 paper in discussion, with shorter temporal scales, the present comment is mainly associated with the Arctic and central England climate modelling and their influences on global climate.

Part 1. Arctic Summer Temperature (AST)

DATA. The Arctic summer temperature (AST or T) information is based on a recently reconstructed record obtained from several proxies (ice-core, lake sediments and tree-ring), from 23 different local and regional processes (Kaufman et al., 2009). This record and another auxiliar record from Greenland temperatures (Vinther et al., 2009) are depicted in Figure 4.1.1.

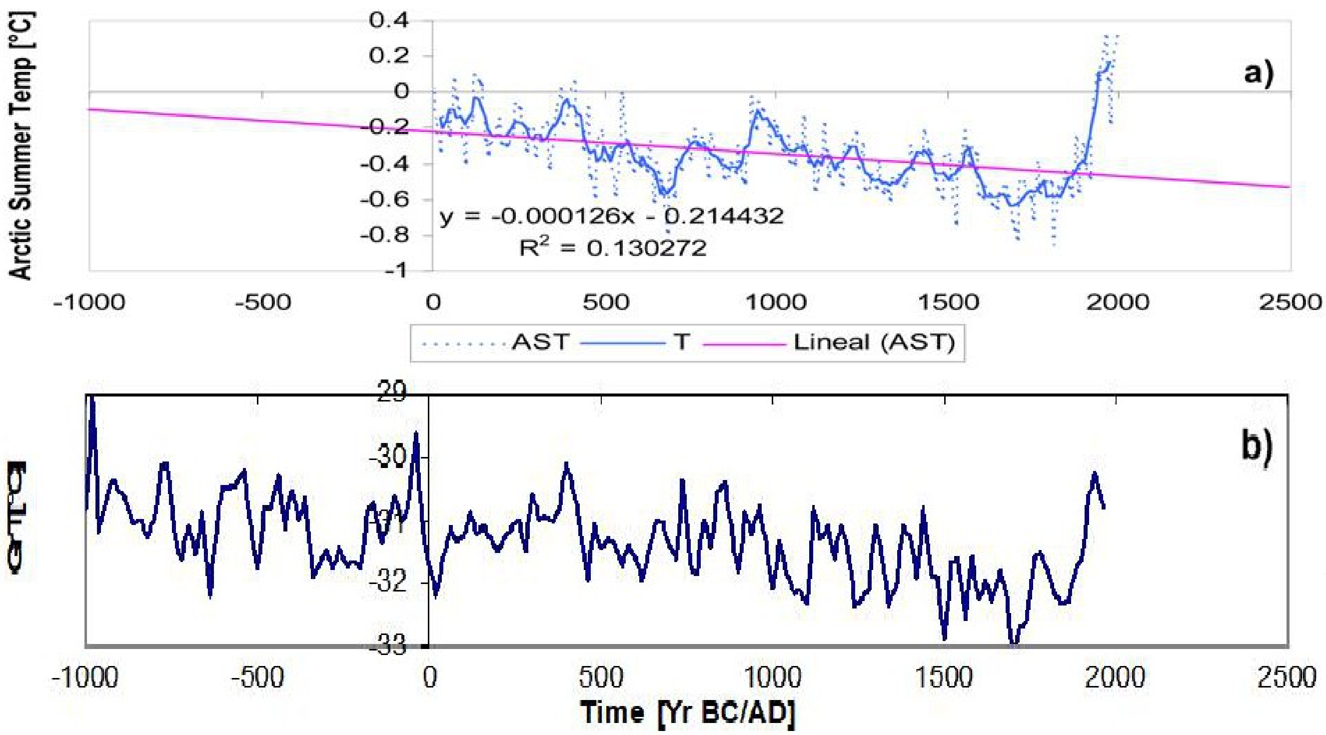


Figure 4.1.1 Millennia-scale reconstructed Arctic and Greenland Temperatures. a) Reconstructed Arctic Summer Temperatures (AST) anomalies [°C], obtained from 23 different proxies for the last 2,000 years (Kaufman et al., 2009), and b) Greenland temperature (GrT) during the late Holocene (Vinther et al., 2009).

MODELS. Tacking into account the recurrent and complex climate environment the AST, or T, is modelled with Fourier Series (FS) and a symetric lagged models. To take into account different contributions, the smoothed climatic variable T may be decomposed into two components of linear and non-linear oscillations, and their calculated error as follows:

$$T(t) = T_{FS}(t) + T_{NL}(t) + e(t) \ , \qquad (1)$$

where $T_{FS}(t)$ is the Fourier series (FS) component due to multi-centennial fluctuations, $T_{NL}(t)$ is the non-linear component based on symmetric self-similarity, and $e(t)$ is the error. The FS component may be written by means of:

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

Here, P is the FS basic period, N_{FS} represents the number of FS terms or harmonics, j is an index component term, *a, b* and *c* are amplitude and bias parameters, and *t* is time.

In addition, to take into account recurrent patterns with symmetric/negative contributions, the *T* non-linear variation may be modeled with the following lagged and symmetric expression:

$$T_{NL}(t) = -\alpha T_{NL}(t-\delta_t) + \delta_T\ , \tag{3}$$

with $\alpha > 0$;

where α is the symmetric amplification factor, δ is the temporal lag, or symmetric period, and δ_T is the bias of this component.

Assuming N_{FS}, the constants *a*, *b* and *c*, and period *P* may be jointly evaluated after a multi-linear regression that looks for a basic FS period that minimizes the RMS values of *e(t).* The second component of the *T* signal is evaluated, based on the symmetric self-similarity of this component and another minimization of errors.

RESULTS. To estimate climate oscillations in the reconstructed record *T*, or smoothed AST, firstly a wavelet analysis was applied using the online resource by Torrence and Compo (1998). The spectral analysis results of the AST, based on wavelets and displayed in Figure 4.1.2, show three main and significant (10% significance level) periodicities around 2000, 1000 and 500 years. Two secondary oscillatory contributions were also detected at periods around 180 and 63 years.

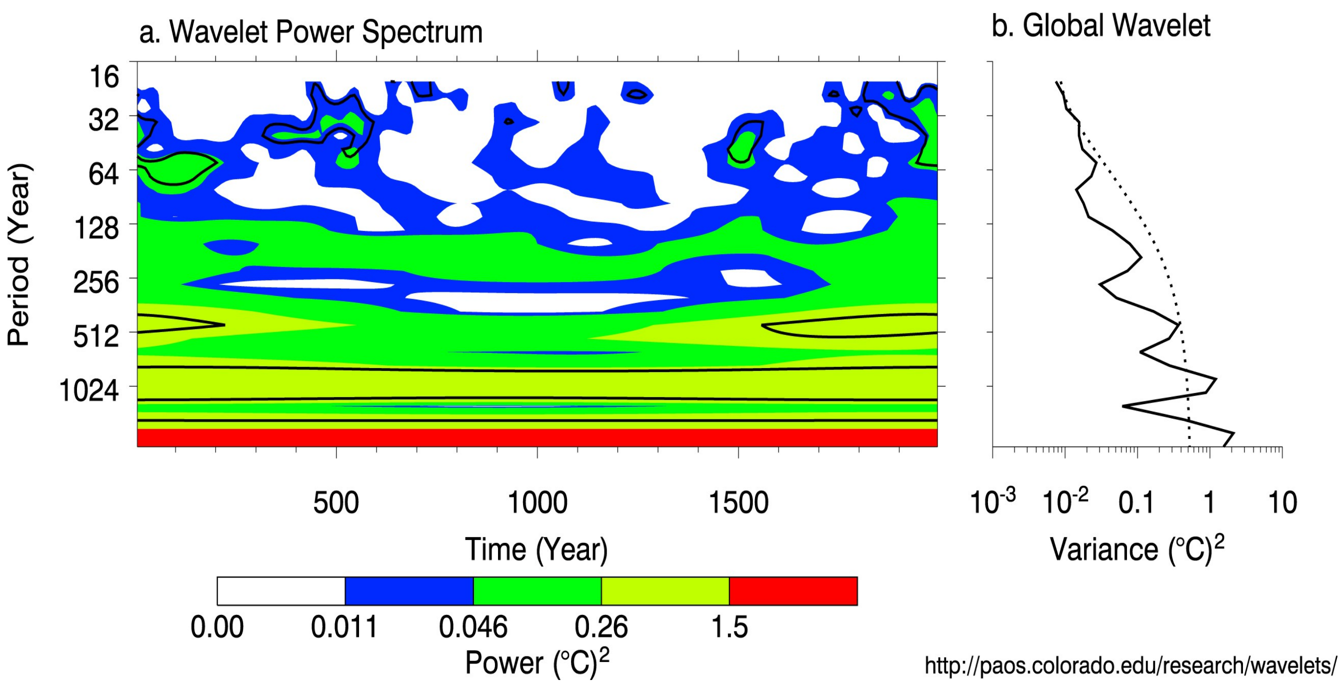


Figure 4.1.2 Wavelet analysis of the AST smoothed signal, Ts. a) The wavelet power spectrum. The contour levels are chosen so that 75%, 50%, 25%, and 5% of the wavelet power is above each level, respectively. Black contour is the 10% significance level, using a red-noise (autoregressive lag1) background spectrum. b) 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) (Torrence and Compo, 1998).

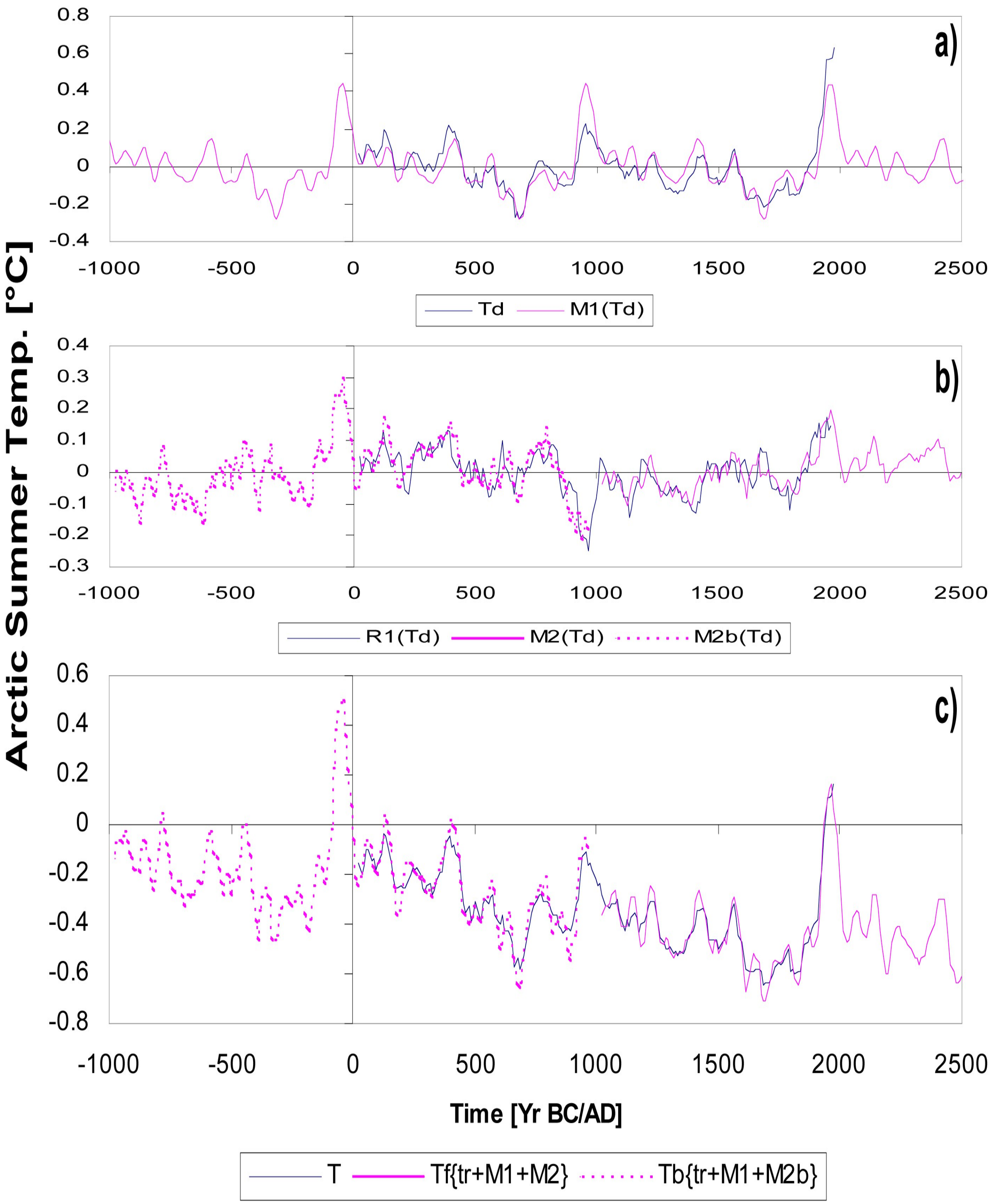


Figure 4.1.3 A comparison of reconstructed AST for the last 20 centuries, and its millennium-scale modeling components, with experimental extrapolations for both the next five centuries and also the previous millennium; a) comparison of the AST with a linear Fourier series model M1, b) comparison of the residue of AST with a non-linear self-similar symmetric model M2, and c) the sum of the trend (see Figure 1) and two models M1 and M2 in forward and backward versions, for test and experimental forecast purposes, respectively. See a comparison with instrumental record in the SI.

Secondly, we evaluated the detrended and smoothed AST record. To do so, it was necessary to take into account its linear trend, *tr*, shown in Figure 4.1.1a, as follows: *Td=T-tr*. A linear oscillation model was evaluated with the Fourier series (see eq. 2) with N_{FS} =14, adjusted to the *Td* record. This function (*M1*), which implies an estimation of 29 parameters, explains 72.5% of the *Td* variance during last 2000 years, and is also depicted in Figure 4.1.3a. The period of 1002 years was obtained after an iterative multi-linear regression that seeks, from 800 to 1200 years, the best FS period that minimizes the RMS values of the *Td*'s error.

Thirdly, the residue of *Td*, after the linear FS component was eliminated (Figure 4.1.3b), indicates centennial-scale oscillations with millennium-scale lagged symmetry. This residue demonstrates symmetrical self-similar oscillations, in which the first ten centuries, 1th-10th (years 0 – 1000), are a symmetrical analogue of the last ten centuries, 11th-20th (years 1000 – 1999) and *vice-versa*. Then, by applying the non-linear model to the residue (see Eq. 3, with α =0.8, and δ_t=1000 yr), model 2 arises (*M2*), which is explaining 54.6% of the variance of the same residue, during the last ten centuries. Also applying the non-linear model to the residue going backward (see Eq. 3 with α =1./0.8, and δ_t=-1000 yr), model 2b arises (*M2b*), explaining 54.6% of the variance of the same residue, during the first ten centuries. A justification of the symetric part of the AST modelling could be given considering geomagnetic results over Europe and Asia over the last 4000 years (Burakov et al., 1998), This study detects in three different places that geomagnetic intensity grows and diminish in the first and second AD millennia (See Figs 1 and 4 of this paper). Then, approximated anti-symmetric values for geomagnetic changes can be otained 1000 years before (or after).

The integrated, trend, linear and non-linear models *Tf*{*tr+M1+M2*} and *Tb*{*tr+M1+M2b*} were extrapolated going forward to 2500 AD and going backward to 1000 BC, respectively (see Figure 4.1.3c). The joint, *Tf* and *Tb,* models explains 85.7 and 92.2% of the *T* variance for the last two millennia and last millennium, respectively.

To verify the complete models, foreward and backward, they are compared with the reconstructed GrT(V09) record, in the Figure 4.1.4.

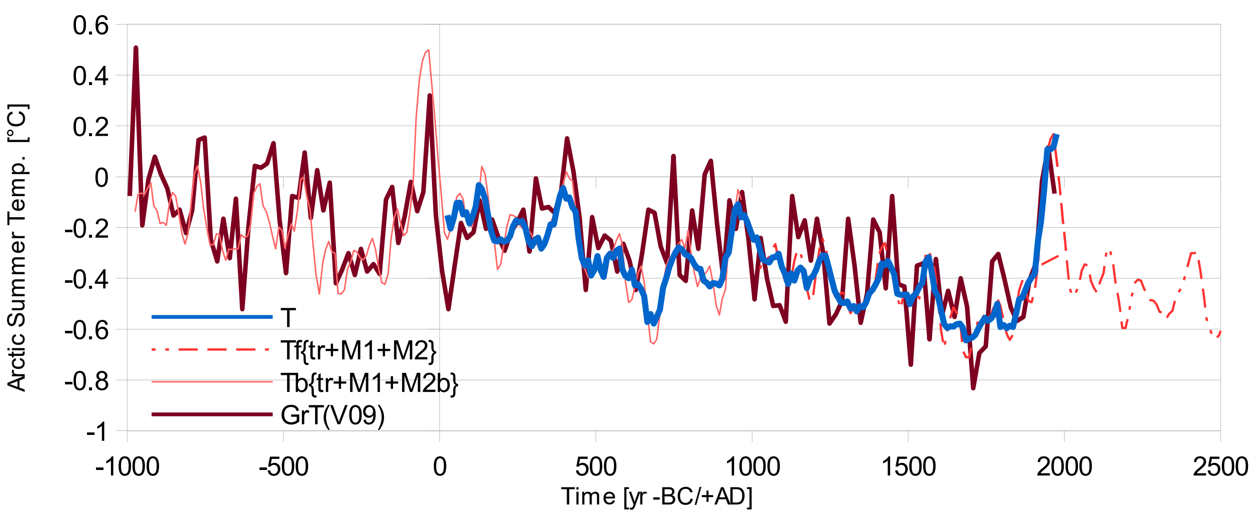
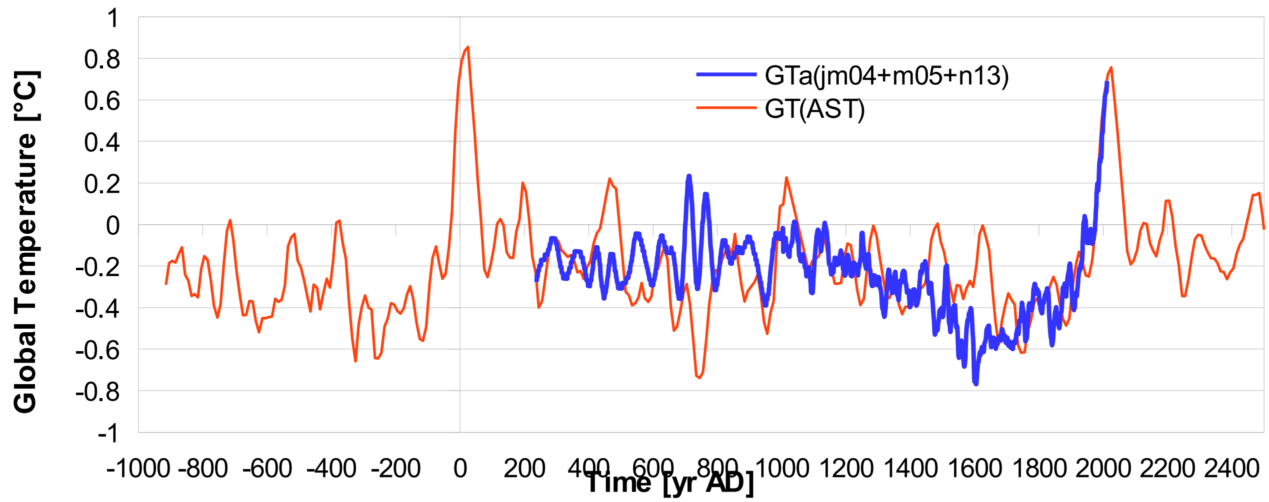


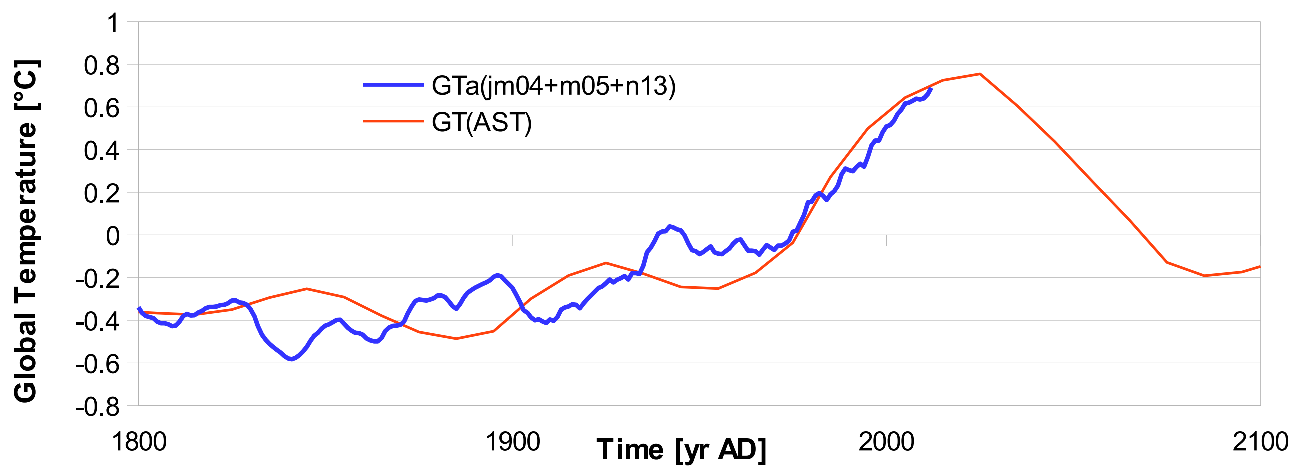
Figure 4.1.4 A verification of reconstructed AST with smoothing and its models. The verification is basedon the GrT byVinther et al., 2009 (V09).

One important aspect of the backward extrapolation is a warming, that occurred during 300-50 BC. This warming, known as the Roman Warm Period (RWP; Lamb, 1977), is part of an interval of general warmth and dryness in Europe from ~200 B.C. to A.D. 400, is re-produced with the modeling variability of the AST signal. This warming, is around 12% bigger than the recent warming.

The T (from AST) record modelling is used to extrapolate global temperatures. The T model is lagged (50 years) and linearly adjusted to the annual values to the global temperature (GT) integrated record 238-2010 (see appendices of the main part of this work). The resulting extrapolation is depitec in Figure 4.1.5



a)



b)

Figure 4.1.5 Global temperatures and its empirical forecast 2010-2100. a) Linearly adjusted SAT record in annual values to the GT integrated record 238-2010; b) a zoom of a) for the last two and next centuries.

Part 2. Central England Temperature (CET)

DATA. The Central England temperature (CET) series is the longest instrumental time series of temperature in the world (Parker et al 1992), with monthly values that extends back to 1659 (MetOffice, 2022). Its annual anomaly values (respect 9.5 °C) are depicted in Figure 4.2.1

MODEL. Although during last decades there has been a rapid warming in the CET that appears to be an anthropogenic influence on the climate, here an analog model is proposed and applied.

RESULTS. The modelling analog results of the CET are also displayed in Figure 4.2.1 and provides an empirical forecast for annual CET values. The initial record is “lagged” around 270 years and reproduce tha most recent part of the CET record and provides information for an experimental forecast.

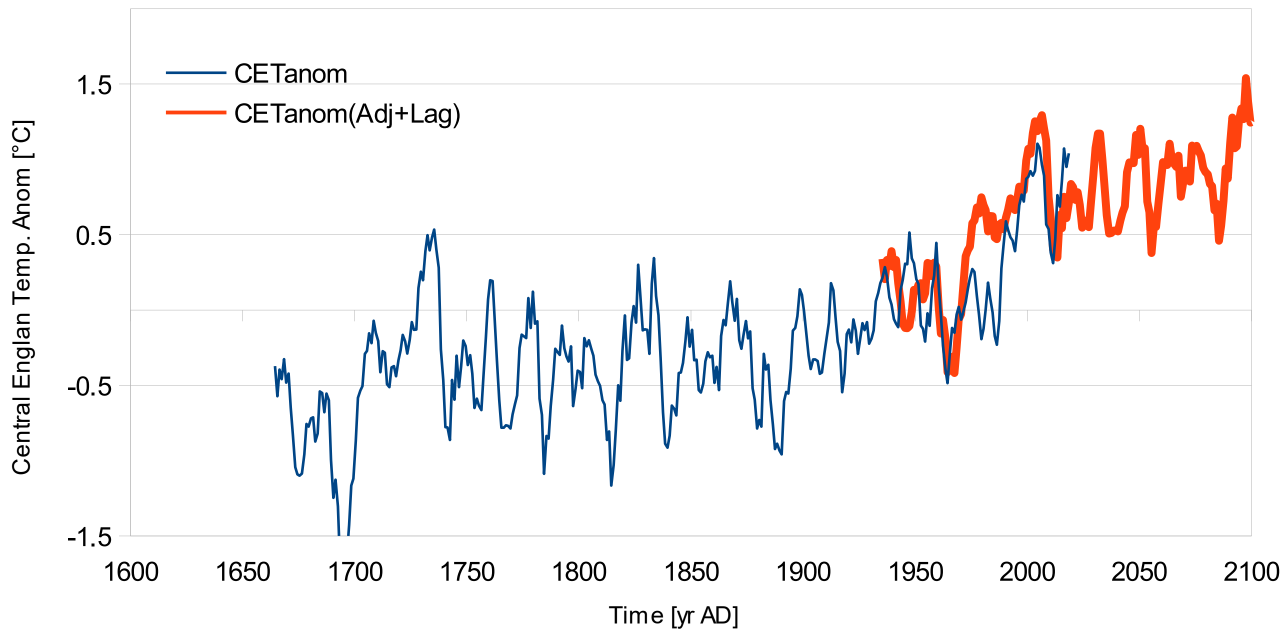
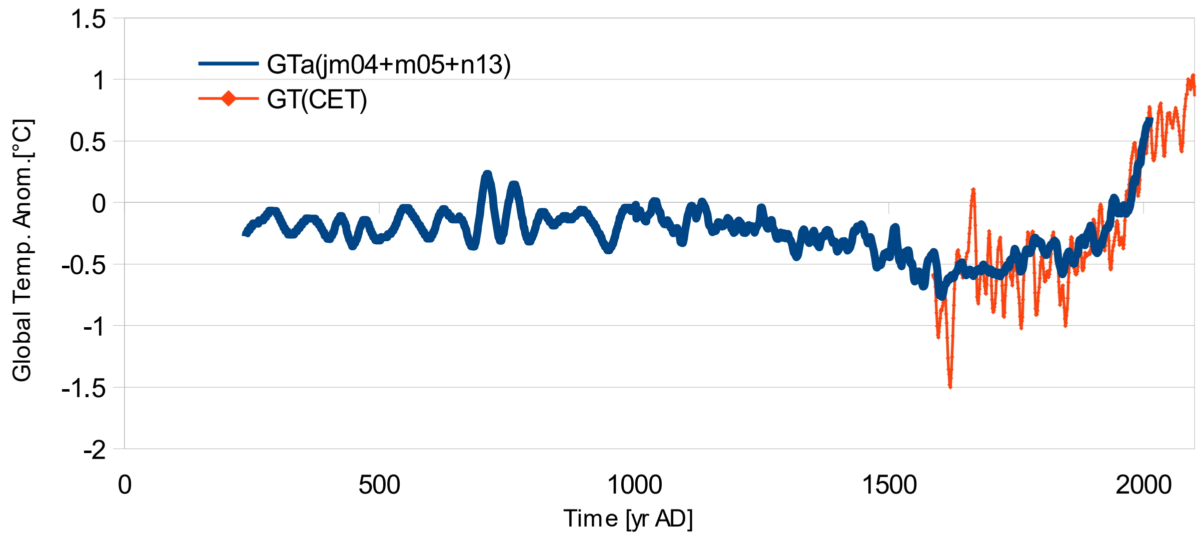


Figure 4.2.1 Central England temperatures (CET) 1660-2100 in annual values. The observed anomalies are modelled considering an analog located 270 yrs before. The analog model is adjusted with a linear transformation and a forced slope.

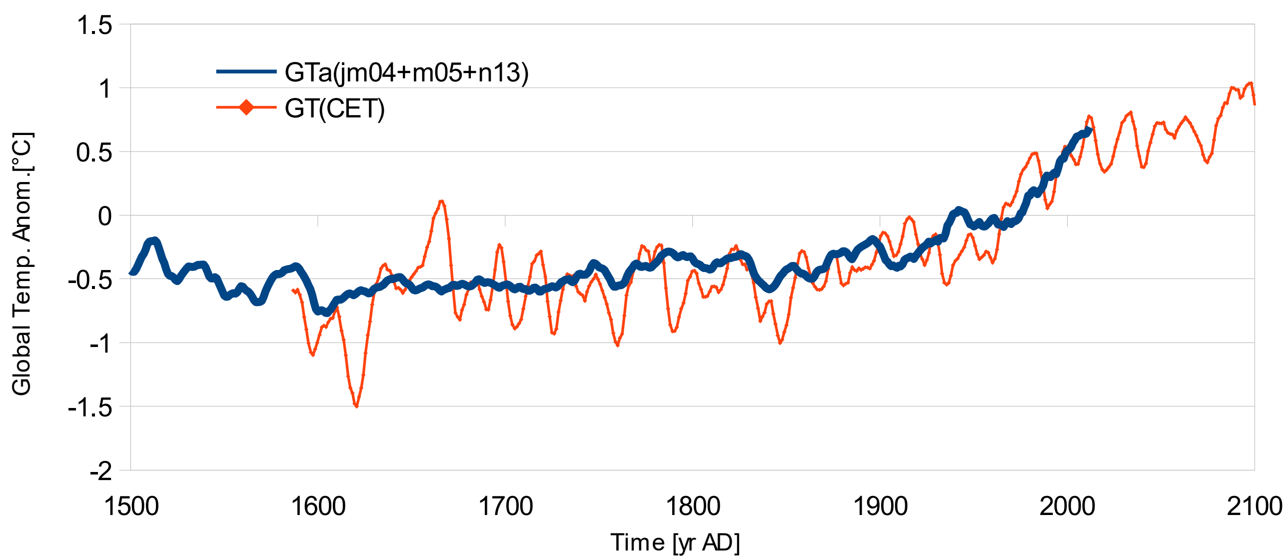
This CET analog model with a lag/recurrency of 270 years, can be justified considering previous results. For instance, based on 14C information coming from tree-rings, Sonett (1990), has pointed out: “ The inventory of atmospheric radiocarbon exhibits quasi-periodic variations of mean period of (269 years) over the entire 9000 year record.” Although the period is inconstant and subject to random variability (with an standard deviation of around 119 years) it corresponds to the quasiperiodic extension of the Maunder minimum throughout the Holocene. Sonett also have pointed out: “The radiocarbon maxima are amplitude modulated by the 2300 year period and thus vary significantly in peak value.”

In addition, lacustrine sediments from the Estancia Basin of central New Mexico reveal decadal to millennial oscillations during Last Glacial Maximum (LGM) time (Menking, 2015). LGM sediments reflect changes in hydrologic balance, and with radiocarbon dates, provide time series for the interval ~23,600 to ~18,300 ka. Spectral analysis using REDFIT (Schulz and Mudelsee, 2002) show dominant periods of ~900,~375, and ~265 yr. In this work, Menkig (2015) has pointed out : “Lake Estancia sediments record variations in solar activity during LGM time.”

In order to get another independent climate scenario, the extended CET record, was non-linearly adjusted to the GT integrated record (the CET temporal scale was amplified 15%). This integrated record considers several proxy records and the HadCRUT5 (2022) instrumental record over the period 245-2021 AD (See details in the main part of this work). Results are shown in Figure 4.2.2



a)



b)

Figure 4.2.2 Global temperatures and its empirical forecast 2010-2100. a) Non-linearly adjusted CET record in annual values to the GT integrated record 238-2010, a temporal expansion of 15% was applied; b) a zoom of a) for the last 5 and next centuries.

Part 3. Global temperature scenarios based on AST and CET.

A comparison of scenarios estimated in this study (main part of ESD-2021-84 paper in discusion and its four comments) are shown in Figure 4.3.1

The initial scenario (or scenario 0) was considering solar, lunar and other shorter recurrent contributions (See datails in the main part of ESD-2021-84 paper).

The complementary scenario 1 was obtained from the isotopic record from calcites of a Northern Sweden cave over the last 4000 years lagged 270 years. This scenario, thanks to the lagged provides a similar forcast for the next two centuries. (See datails in the comment 1 of the ESD-2021-84 paper).

The complementary scenario 2 was obtained from an extended version of SSTepac (adding Niño 12 recent data) adjusted to Global temperature instrumental record coming from HadCRUT5 (2022) over the period 1856-2021. This scenario, thanks to the extended SSTepac record (See Figure 3.6) and the lagged SST of 23 years imposed to the model [GT(SSTepac)] provide a similar forcast for more than 20 years. (See datails in the comment 2 of the ESD-2021-84 paper).

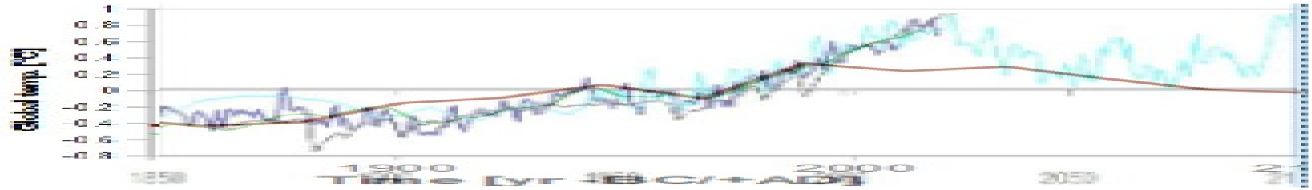
The complementary scenario 3 was obtained with a linear "extrapolation" of IPCC scenarios. It was evaluated an averaged version of the rcp2.6, rcp4.5 and rcp8.5 scenarios to estimate the rcp0.0 scenario. This scenario correspond to "zero GHG emissions" at the end of the 21st century. (See datails in the comment 3 of the ESD-2021-84 paper).

The complementary scenario 4 was obtained from a forcasted version (with a validated forecast of more than 500 years) of Arctic temperature (AT) adjusted to an integrated Global temperature record that integrates several proxy records and the HadCRUT5 (2022) instrumental record over the period 245-2021 AD (See datails in this comment of the ESD-2021-84 paper).

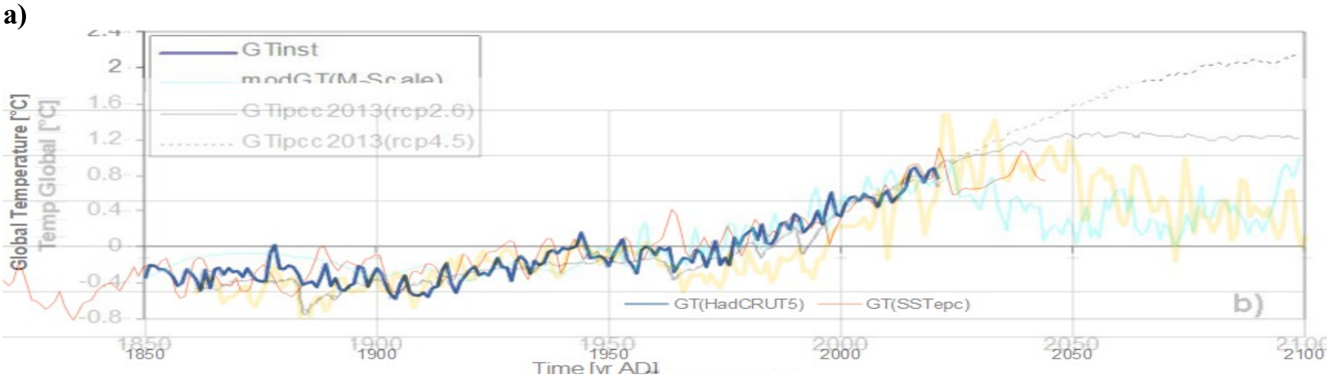
The complementary scenario 5 was obtained from a forcasted version (with a forecast of more than 200 years) of Central England Temperature (CET) adjusted to an integrated Global temperature record that integrates several proxy records and the HadCRUT5 (2022) instrumental record over the period 245-2021 AD (See datails in this comment of the ESD-2021-84 paper).

This comparison is enhancing two different aspects of the complementary scenarios:
a) Complementary scenarios 1, 2, 3 and 4 present a decaying values for the end of 21st century.
b) Complementary scenario 5 present gentle increasing values for the rest of 21st century.

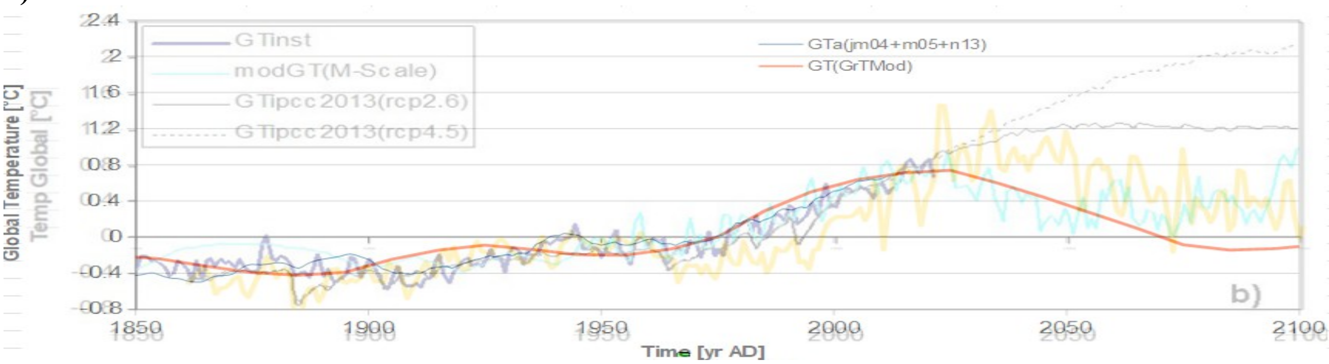
This difference can be justified because the scenario 5, based on CET record, only covers the last 360 years with increasing temperature trends over all this period. Then, the scenario 5 could be considered not only the upper limit-values, but also one that provides a conservative scenario of GT values.



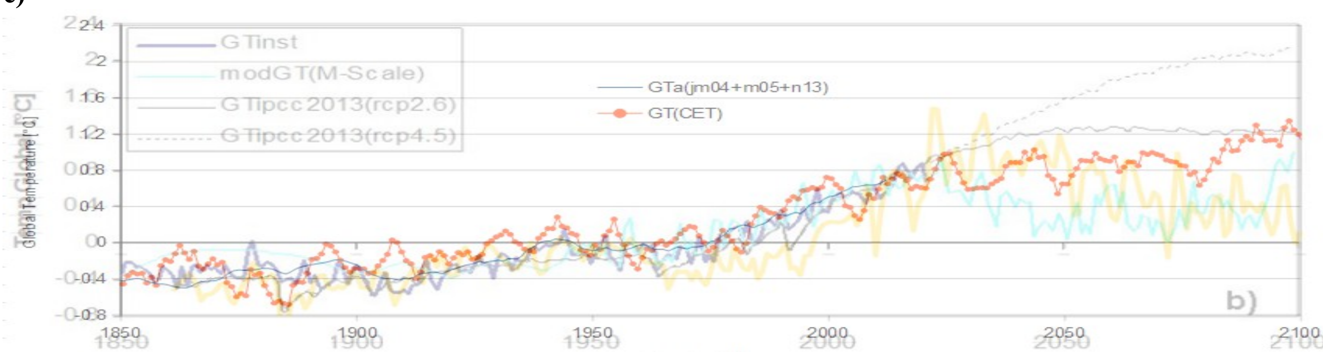
a)



b)



c)



d)

Figure 4.3.1 Comparison of six global temperature scenarios 1850-2100. An adapted Figure 11b from the paper ESD-2021-84 in discussion with the first scenario estimated (Scenario 0, with cyan line) and the Average rcp0.0 values (Scenario 3 in yellow line) and the ajusted and lagged forecast based on: a) information coming from a Sweden cave (Scenario 1, in brown thin line); b) the eastern equatorial Pacific SST (Scenario 2, in red thin line), c) the modelling of Arctic temperatures (T) (Scenario 4, in red wide line); d) the modelling of central England temperatures (CET) (Scenario 5, in red dotted line)

Part 4. Preliminary conclusions (of this and previous coments)

These detected non-linear recurrent patterns and oscillations in the Arctic and Central England climates, after to be further verified and replicated with independent data and models, will contribute with some of scenarios of future global climate. Our findings strongly suggest that past variability may play, as recurrences, an active role in natural climate change during the coming centuries. Our results also support that, non-linearity is required for accurate modeling and forecasting of climate-related issues. However, further multi-scale modeling efforts are still required.

Our results have placed low-frequency (with multi-millenial and multi-centennial processes), long-term and delayed influences on climate variability in an important place for climate modeling and analysis, and of course, for climate forecasting. Also, our results have clearly shown how important are climate reconstructions, their analysis and extrapolations considering astronomical lagged influences with ocean-atmospheric mechanisms in different temporal scales.

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