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# Paleoclimate forcing by the solar De Vries/Suess cycle

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Received: 8 December 2014 – Accepted: 21 January 2015 – Published: 12 February 2015

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Published by Copernicus Publications on behalf of the European Geosciences Union.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



## Abstract

A large number of investigations of paleoclimate have noted the influence of a  $\sim 200$  year oscillation which has been related to the De Vries/Suess cycle of solar activity. As such studies were concerned mostly with local climate, we have used extensive northern hemispheric proxy data sets of Büntgen and of Christiansen/Ljungqvist together with a southern hemispheric tree-ring set, all with 1 year time resolution, to analyze the climate influence of the solar cycle. As there is increasing interest in temperature rise rates, as opposed to present absolute temperatures, we have analyzed temperature differences over 100 years to shed light on climate dynamics of at least the last 2500 years. Fourier- and Wavelet transforms as well as nonlinear optimization to sine functions show the dominance of the  $\sim 200$  year cycle. The sine wave character of the climate oscillations permits an approximate prediction of the near future climate.

## 1 Introduction

The search for cycles on nearly all time scales in time series of temperatures, precipitations and droughts has a long tradition. The physical mechanisms of these cycles are mostly unknown. As hypotheses, solar modes, auto climate modes (episodic outbursts of big meltwater reservoirs, thermohaline circulation through a threshold response etc.), and cosmic modes governed by big planets are discussed, (Friis-Christensen and Lassen, 1991; Van Geel et al., 2003; Braun et al., 2005; Lohmann and Schöne, 2013; Scafetta, 2012). In the present study we look for dominant climate cycles in the period regime of  $\sim 200$  years and their influence on the recent and near future climate. We found no work on auto oscillations in this period range, by contrast, in all papers solar forcing is considered as the main cycle driver.

The studies begin with De Vries (1958) and Suess (1980) who found variations in the production rates of the cosmic isotopes  $^{14}\text{C}$  and  $^{10}\text{Be}$ . Breitenmoser et al. (2012)

CPD

11, 279–305, 2015

## Forcing of paleoclimate

H.-J. Lüdecke et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Forcing of paleoclimate

H.-J. Lüdecke et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



analyze terrestrial temperature proxies and the De Vries/Suess solar activity and find a good correlation, particularly when incorporating volcanic activity. Cliver et al. (1998) show a precise linear dependence of solar magnetic field (thus solar activity) and Earth temperature and estimate the influence of the Sun on the 20th century Earth climate change up to 100 %. Raspopov et al. (2008) find a clear  $\sim 200$  year cycle and relate it with the solar De Vries/Suess cycle. How closely the Earth temperature is related with the solar De Vries/Suess cycle becomes apparent in the study of Knudsen et al. (2011) who find the characteristic “burst” pattern (1000 years of oscillation, repeating every 2500 years) mirrored in the temperatures derived from stalagmites in subtropical caves of China, Turkey, USA. Novello et al. (2012) find the AMO plus De Vries/Suess cycle the dominant contribution to the northeast Brazilian climate for the last 3000 years, in correspondence with our results (Lüdecke, 2012). Wagner et al. (2001) demonstrate that the De Vries/Suess cycle of  $\sim 205$  years is present in  $^{10}\text{Be}$  data from the GRIP ice core during the last ice age, 20 to 50 kyr BP. Liu et al. (2011) find cycles of 1324, 800, 199, and 110 years in tree-rings of the Tibetan Plateau for the past 2485 years and make a prediction that the temperatures will decrease in the future until  $\sim \text{AD } 2070$  and then increase again. Steinhilber and Beer (2013) find in their analysis of solar isotope data the De Vries/Suess cycle as the strongest spectral component and, additionally, give a prediction of future climate for the next 500 years with cooling until  $\sim \text{AD } 2080$ . Kern et al. (2012) find the influences of 80, 120, 208, 500, 1000 and 1500 year cycles and show that the De Vries/Suess cycle was a dominant factor for the Earth climate. Zhao and Feng (2015) find periodicities of 208, 521, and  $\sim 1000$  years in antarctic ice-core records. Evidences of the dominance of the De Vries/Suess cycle of solar activity on terrestrial climate are given in Seidenglanz et al. (2012); Leal-Silva and Herrera (2012); Costas et al. (2012), and Scafetta (2012) to mention just a few of a long list of papers showing the action of the solar De Vries/Suess cycle on the Earth climate. A possible mechanism of solar modulated cosmic rays on cloud cover and thus on Earth climate is investigated in Svensmark (1998); Marsh and Svensmark (2000); Svensmark et al. (2009); Enghoff et al. (2011). An extensive

survey of papers investigating the influence of the Sun on terrestrial climate cycles is given in Lüning (2014). Dima and Lohmann (2008) and Huybers and Wunsch (2003) discuss a rectification hypothesis based on nonlinearity of the terrestrial system. In view of these various investigations of the influence of solar activity on local climate the question of the effects on the global scale arises.

## 2 Differences vs. absolute temperatures

There is interest in temperature rise rates besides the absolute temperatures, for instance applied in trend analysis (Lennartz and Bunde, 2011) or to detect Dansgaard-Oeschger events (Rahmstorf, 2003). Therefore, we looked in yearly records of 100 year temperature differences for cycles. For this purpose, from a yearly temperature time series  $T(t_1), \dots, T(t_L)$  of the  $L$  years  $t_1, \dots, t_L$  the pertinent  $\Delta T(t)$  record of length  $L - 100$  is derived as follows:  $\Delta T(t_j)$  is the backward temperature difference over 100 years by linear regression  $R$ ,

$$R[T(t_{j-99}), \dots, T(t_j)] = a_j \cdot t + c_j \quad (1)$$

which yields

$$\Delta T(t_j) = a_j \cdot (t_j - t_{j-99}) \quad (2)$$

Note that the  $\Delta T(t)$  record is 100 years shorter than the  $T(t)$  record because the first  $\Delta T(t)$  value belongs to  $t_{100}$ .

Differences by linear regression  $\Delta T(t)$  are better suited to reveal temperature periodicities in a certain frequency range than temperatures  $T(t)$  themselves, because frequency components outside the range are weakened, the differencing acting as a spectral filter. The Fourier spectra of the  $T(t)$  and the  $\Delta T(t)$  records show the same frequencies but different peak powers. This is plausible since the derivative of a sine function has the same spectrum as the sine function itself, and the  $\Delta T(t)$  data are rather similar to a sine function.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



### 3 The data

For sufficient resolution in the Fourier analysis and to avoid possible distortions by interpolations,  $T(t)$  records of 1 year time resolution are desirable. A length of at least  $\sim 2000$  years is further desirable to avoid Fourier artifacts within the multi centennial region of interest. Recently two appropriate Northern Hemisphere temperature proxy stacks are available extending back to a maximum of  $-2500$  yr BP. One stack (0 to AD 1973) contains 91 temperature proxy series evaluated from tree rings, stalagmites, ice cores, sediments etc. (Christiansen and Ljungqvist, 2012). The other ( $-499$  BP to AD 1993) was evaluated from 7284 tree ring samples, a total of 1546 ring width series, from high elevation conifers from the Austrian Alps (Büntgen et al., 2011). For the Southern Hemisphere a Tasmanian tree ring record of 3592 years exists (Cook et al., 2000). Figure 1 shows the geographic locations of the proxies used in this study. Apart from these records no other publicly available data meet the requirements for the analysis. For a relation with solar activity, we analyzed the production rate record  $P(t)$  of the solar isotope abundances of  $^{10}\text{Be}$  and  $^{14}\text{C}$  (Steinilber et al., 2012), which has a time resolution of 22 years. This  $P(t)$  series extends back to  $-7404$  BP. Fourier and wavelet analyses were given (Steinilber et al., 2012). Table 1 gives the main characteristics of the records used. Figure 2 shows the data together with their  $\Delta T(t)$  resp.  $\Delta P(t)$  graphs, constructed according to Eqs. (1) and (2). Since the  $P(t)$  record has 22 year time steps we have used 110 years instead of 100 years for the differences.

### 4 Spectral analysis

For the discrete Fourier transform (DFT) the records were padded with 25 000 zeros, yielding optimum interpolation of the DFT spectra. The data were converted to anomalies around the mean and normalized to the SD. The confidence curves with respect to background noise were generated by MC-simulation for which 10 000 random time series are applied with the same lengths and Hurst exponents  $H$  as the

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



pertinent records, in the form of anomalies and normalized to the SD.  $H$  was obtained by detrended fluctuation analysis (DFA) (Kantelhardt et al., 2001; Kantelhardt, 2004). With MC-simulation the calculation of the confidence curves is not restricted to red AR1 noise.

5 Table 2 gives the record lengths, record resolutions, Hurst exponents, DFT periods for the strongest peak in the  $\sim 200$  year period band, and confidence levels. Figure 3 shows the DFT spectra. The  $\sim 200$  year peaks in the NH series B $\ddot{u}$  and Chr/Lju, as well as the pertinent peak in the Stei/Beer isotope record have powers giving 99% confidence level against noise, in the SH series of Cook only 95%.

10 We note that the spectrum of the  $P(t)$  record shows 3 distinct peaks at  $\sim 200$  years. It would seem that this reflects the amplitude modulation AM of the De Vries oscillation (Knudsen et al., 2011) known as the “Suess bursts” (1000 years of strong oscillation amplitude followed by weaker oscillation, repeating every 2500 years. Spectrum of an AM being a central carrier with two sidebands).

15 Figure 4 shows the wavelet analysis (Torrence and Compo, 1998) of the  $T(t)$  resp.  $P(t)$  records, Fig. 6 the cross wavelets (Grinsted et al., 2004). Because the Stei/Beer record with 22 year steps and its 1 year step interpolated version show no difference in DFT, the interpolated version was applied for the wavelet analysis. All wavelet spectra exhibit variations in power and frequency over the time. We mention that the NH records B $\ddot{u}$  and Chr/Lju have a disruption of the cycle regularity around the years  $\sim$  AD 700 whereas in the SH (Cook) similar disruptions are centered around  $\sim$  AD 500 and  $\sim$  AD 1500. Contrasting to the NH records, the periodicity of the Cook record is weak for the years  $>$  AD 1400.

**Forcing of paleoclimate**

H.-J. Lüdecke et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## 5 Sine wave fit by nonlinear optimization

The appearance of Fig. 2 suggests that the  $\Delta T(t)$  and  $\Delta P(t)$  records can be reasonably represented by single sine functions

$$\Delta T_{\text{sin}e} \text{ (resp. } \Delta P_{\text{sin}e}) = \sin(2\pi\nu \cdot t + \varphi) \quad (3)$$

- 5 The parameters of the sine function  $\nu$  and  $\varphi$  could in principle be taken from the DFT. However, DFT has uncertainty margins and treats the data as infinite recurrences, which is equivalent to compulsory boundary conditions

$$\sin(2\pi\nu \cdot t_{\text{start}} + \varphi) = \sin(2\pi\nu \cdot t_{\text{end}} + \varphi) \quad (4)$$

- 10 To avoid this restrictions and associated possible artifacts, the frequency  $\nu$  and the phases  $\varphi$  of the sine representations  $\Delta T_{\text{sin}e}$  and  $\Delta P_{\text{sin}e}$  were determined by nonlinear optimization (Nelder and Mead, 1965). The objective function  $F(\nu, \varphi)$  to be minimized is the negative Pearson correlation between  $X = \Delta T_{\text{sin}e}$  and  $Y = \Delta T(t)$  resp.  $X = \Delta P_{\text{sin}e}$  and  $Y = \Delta P(t)$

$$F(\nu, \varphi) = -\rho_{XY} = -\frac{\text{cov}(X, Y)}{\sigma_X \sigma_Y} \quad (5)$$

- 15 As the result, we find nearly the same frequencies for all records as in DFT (see Table 2). Table 3 shows parameters and results of the nonlinear optimization. Figure 6 shows the difference records  $\Delta T(t)$  and  $\Delta P(t)$  together with the pertinent sine representations. The running correlations for a 200 year window are given in Fig. 7, showing a notable common gap of correlation around  $\sim$  AD 700 for the B $\ddot{u}$  and Chr/Lju series. The disruption of the climate cycle which occurs for the two NH temperature stacks B $\ddot{u}$  and Chr/Lju around  $\sim$  AD 700 (see Fig. 6) is visible also in the wavelets (see Fig. 4) and in the cross wavelets (see Fig. 5, left middle, right upper, and right middle panel). The corresponding is valid for the SH Cook series at  $\sim$  500 and  $\sim$  AD 1500. In these perturbation zones the phases appear to be reversing.

We note that the 20th century  $\Delta T(t)$  maximum is comparable in magnitude with the past maxima. Thus, the proxies used in this paper show that the warming rate during the 20th century lies within the natural rates of change.

The correlation of the  $\Delta T(t)$  records B $\ddot{u}$  and Chr/Lju (AD 99–1973) is 0.45. The higher correlation of these records with sine functions  $\Delta T_{\text{sine}}$  indicates that the essential content of the two records is their periodic character.

The sine representation over the 9307 years of the Stei/Beer difference record yields a correlation of only 0.21, apparently due to phase noise during the long time. For a test, we divided the record into subsections of  $\sim 2330$  years and find higher correlations with periods and phases given in the rows 4.0–4.3 of Table 3. According to this, the  $\sim 200$  year cycle varies between 185 and 230 years in period length. In a corresponding wavelet diagram (Knudsen et al., 2011) the period is found to shift up to  $\sim 240$  years in 5000 yr BP, in agreement with our finding given in Table 3 and in the left upper panel of Fig. 4.

## 6 Phase noise of the climate cycle

To identify reasonably maxima and minima in Fig. 6 as real extrema, we must define an objective criterion. Since each record is represented by a single sine function, we define the following criterion for a cycle maximum: it must lie within less than half of the sine period to a sine maximum and exceed  $1/2$  of the data SD. If more than one maximum satisfies this condition, we choose the strongest one. Admissible maxima which only fail the “standard-deviation-condition” are still counted if the Pearson correlation of the data with the sine representation exceeds 0.4 during the time interval between two neighboring sine minima. The corresponding criterion applies with the minima. Figure 8 shows the time deviations of the maxima and minima from the sine wave extrema (Fig. 6) demonstrating a good cycle stability over the whole duration of  $\sim 2500$  years.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





## 7 Confidence levels

In order to ascertain a statistical confidence level of the correlation between the data and the sine-representations (see Fig. 6), we assumed the Null hypothesis that the correlation is caused by chance. We tested the Null hypothesis by Monte Carlo simulations, in each case with 10 000 random surrogate records of the same length and the same Hurst exponent  $H$  as the pertinent time series  $T(t)$  resp.  $P(t)$  given in Table 2. The surrogate time series were converted into difference records  $\Delta T(t)$  resp.  $\Delta P(t)$  according to Eqs. (1) and (2). Next, the Pearson correlations of these surrogates with the pertinent sine representations  $\Delta T_{\text{sine}}$  resp.  $\Delta P_{\text{sine}}$  given in Table 3 were calculated. The following numbers of surrogates out of 10 000 had better or equal correlations with the pertinent sines: 6 for Bü, 3 for Chr/Lju, 42 for Cook, and 0 for Stei/Beer. As a consequence, the Null hypothesis can be rejected with a confidence level of 99.9 % for Chr/Lju, Bü, and Stei/Beer and of 95 % for Cook.

Besides 100 year linear regression length, we tested also the lengths 50 and 150 years for all temperature records. However, the sine representation by nonlinear optimization becomes more difficult for the 50 year length because the algorithm tends to be trapped in local minima. With 50 year length, the values of the correlations for all records are distinctly worse than for 100 year length. With 150 year length, again neither significant differences to 100 year length in the optimum period arise, however, the correlations with the pertinent sine representations become somewhat better. In order to verify that in the period-phase plane no better correlations than those with the sine representations cited in Table 3 exist, we optimized the difference records through all sine periods from 50 years until 200 years in 0.1 year steps evaluating in every step only the sine phases by nonlinear optimization. As a result, no better correlations than those belonging to the “De Vries/Suess” periods, cited in Table 3, are found. Thus, choice of a 100 year linear regression length appears not to cause systematics.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## 8 Tentative prediction of the climate future

The Earth's climate shows a rather regular oscillation of  $\sim 200$  year period during the last millennia. However, frequency, phase, and strength of the oscillation are found to vary in different time series of temperatures and for different times (see Figs. 4–6, and 8). Nonetheless, the relative historic stability of the cycle suggests that the periodic nature of the climate will persist also for the foreseeable future. Disregarding other conceivable forcings e.g. anthropogenic influences, an approximate prediction of the climate for the next 100 years suggests itself. Figure 9 shows the  $T_{\text{sine}}$  representation from AD 1800 to AD 2100 derived from the  $\Delta T_{\text{sine}}$  representation by a  $\pi/2$  phase shift. It gives correctly the 1850–1900 temperature minimum and shows a temperature drop from present to  $\sim$  AD 2080, the latter comparable with the minimum of 1870, as already predicted in the studies (Steinhilber and Beer, 2013; Liu et al., 2011) on the grounds of solar activity data alone.

## 9 Summary and discussion

We have analyzed the differences of temperatures resp. isotope production rates of the most extensive paleoclimate temperature proxy sets for the NH and the SH (Christiansen and Ljungqvist, 2012; Büntgen et al., 2011; Cook et al., 2000) and an isotopes production time series (Steinhilber and Beer, 2013). The methods are spectral, including wavelet analyses and nonlinear optimization fitting of single sine functions to the records. The global picture emerges of a  $\sim 200$  year period climate oscillation which correlates highly with the De Vries/Suess oscillation of solar activity. This would indicate that the dominant forcing of the paleoclimate is the solar activity.

For different records and different times, however, we find frequencies differing slightly from the main  $\sim 200$  year periodicity. The solar influence is modified by the response of the Earth system and its inherent forcings such as volcanic activity. Such a response can cause time delays to which the phase delays between the climate time-

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Forcing of paleoclimate

H.-J. Lüdecke et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



series  $\Delta T(t)$  may be attributed. The terrestrial activities may dominate the solar activity temporarily, e.g. disrupting the sine-like oscillations. Such disruptions are clearly visible in Figs. 4–7. They can affect the oscillation amplitude as well as the phase. For longer term changes in phase and amplitude one may keep in mind a modulation of the higher frequency oscillations (e.g. the  $\sim 200$  year period De Vries/Suess cycle) by lower frequency –, i. e. millennial period cycles. Zhao and Feng (2015) showed that the millennial cycles exhibit high phase stability compared to the centennial cycles. This could show such a modulation, which is by all means to be expected in view of the nonlinearities of the terrestrial system, and even for the sun system itself, as the different frequencies in the rows 4.0–4.4 of Table 3 show. By such modulation, continuous phase changes over a long time can occur, equivalent to frequency shifts as mentioned above, such as we and also Zhao/Feng find them in different proxies and for different times. We observe that the unequal strength of the sidebands of the  $\sim 200$  year period oscillation of the solar activity (Fig. 3 left upper panel) is consistent with a simultaneous modulation of amplitude and phase. Evidently with the proxies available of only 10 to 12 De Vries/Suess cycles such cross modulation between cycles cannot be unambiguously proven, but nonetheless is a possible explanation for the differing frequencies.

*Acknowledgements.* We thank Sebastian Lüning for helpful discussions and providing us with additional references to the interdependence of solar activity and climate change.

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## Forcing of paleoclimate

H.-J. Lüdecke et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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## Forcing of paleoclimate

H.-J. Lüdecke et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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**Forcing of  
paleoclimate**

H.-J. Lüdecke et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

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**Forcing of paleoclimate**

H.-J. Lüdecke et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Forcing of paleoclimate

H.-J. Lüdecke et al.

**Table 1.** Characteristics of the records used: Bü (Büntgen et al., 2011), Chr/Lju (Christiansen and Ljungqvist, 2012), Cook (Cook et al., 2000), and Stei/Beer (Steinilber and Beer, 2013).

Record	Data	Method	Season	Resolution [years]	Time span BC/AD
Bü	proxy-temperatures	tree rings	summer	1	–499 until 2003
Chr/Lju	proxy-temperatures	multi	all	1	0 until 1973
Cook	proxy-temperatures	tree rings	summer	1	–1600 until 1991
Stei/Beer	isotopes production rates	$^{10}\text{Be}$ , $^{14}\text{C}$	all	22	–7404 until 2012

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





## Forcing of paleoclimate

H.-J. Lüdecke et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



**Table 2.** Parameters and results of DFT.

$T(t)$ resp. $P(t)$ record	Length [years]	Resolution [years]	Hurst exponent	$\sim 200$ year peak period [years]	Peak confidence level [%]
Bü	2503	1	1	186.0	99
Chr/Lju	1974	1	1.1	189.4	99
Cook	3592	1	0.9	200.8	95
Stei/Beer	9417	22	0.6	202.2	> 99

## Forcing of paleoclimate

H.-J. Lüdecke et al.

**Table 3.** Single sine representations of the difference records  $\Delta T(t)$  resp.  $\Delta P(t)$  by nonlinear optimization (phases given in radians). The piecewise optimizations for the Steinhilber/Beer data (No. 4.1–4.3) and the total length optimizations for the records Stei/Beer (No. 4.4 compared with No. 4.0) and Cook (No. 3.0 compared with No. 3.1) demonstrate the variations of periods and phases over the time. We mention that the  $\Delta T(t)$  resp.  $\Delta P(t)$  records start 100 resp. 110 years later than the  $T(t)$  resp.  $P(t)$  records (see Table 1).

No.	Record	from	to	duration	sine period	sine phase	cor
		[BC/AD]					
1.0	Bü	–400	2003	2404	184.0	4.483	0.49
2.0	Chr/Lju	99	1973	1875	189.9	0.046	0.58
3.0	Cook	–401	1991	2393	199.7	2.481	0.41
3.1	Cook	–1501	1991	3493	204.8	3.056	0.36
4.0	Stei/Beer	–408	2012	2421	203.0	1.775	0.68
4.1	Stei/Beer	–7294	–4962	2332	228.1	3.788	0.47
4.2	Stei/Beer	–4962	–2630	2332	230.9	6.202	0.34
4.3	Stei/Beer	–2630	–320	2310	215.5	0.919	0.45
4.4	Stei/Beer	–7294	2012	9417	232.1	0.236	0.21

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

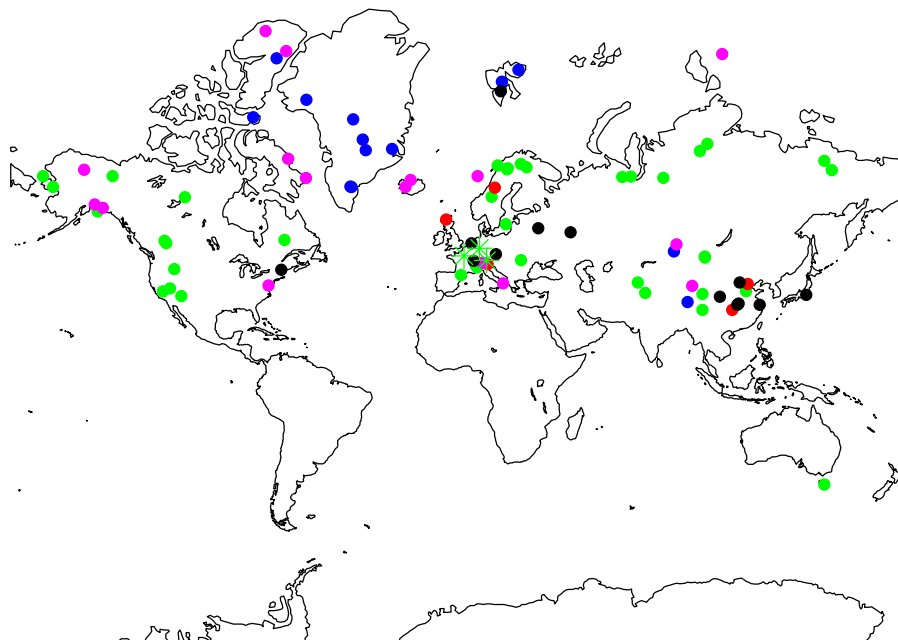
Printer-friendly Version

Interactive Discussion



## Forcing of paleoclimate

H.-J. Lüdecke et al.



**Figure 1.** (Color online) Global overview of the temperature proxies used in this study. Green color: tree-rings, red color: speleothems, blue color: ice-cores, magenta color: sediments, black color: other as pollen, multi-proxy, documentary, and ice melt layers. 91 sites (Christiansen and Ljungqvist, 2012 and Cook et al., 2000) are depicted, the several thousand tree-ring sites of Büntgen et al. (2011), concentrated in central Europe, are represented by green crosses.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

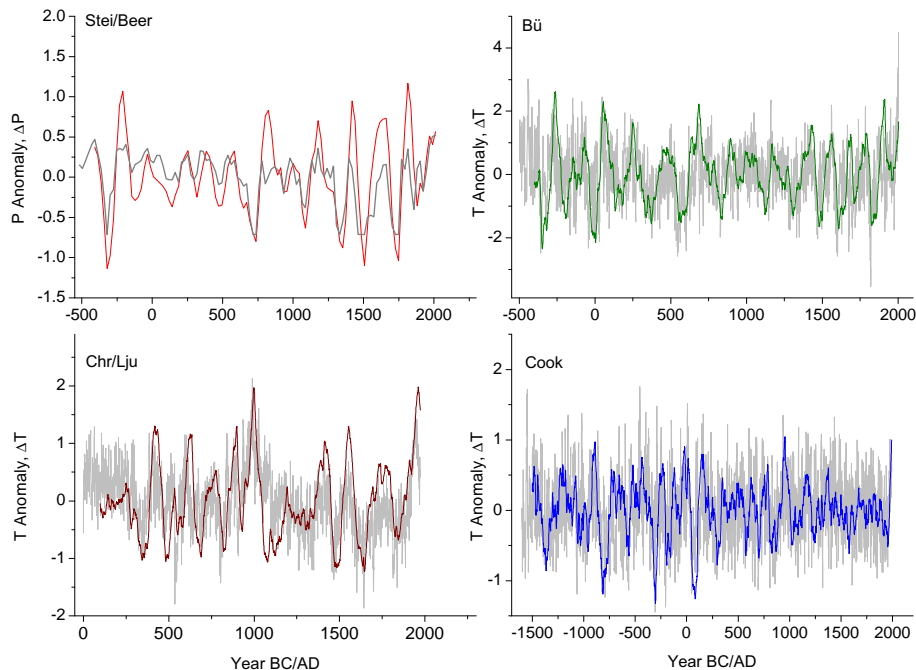
Printer-friendly Version

Interactive Discussion



Forcing of  
paleoclimate

H.-J. Lüdecke et al.



**Figure 2.** (Color online) Proxy temperatures  $T(t)$  and cosmic isotopes rate  $P(t)$  (grey). Differences  $\Delta T(t)$  ( $\Delta t = 100$  years) and  $\Delta P(t)$  ( $\Delta t = 110$  years) by linear regression (Eqs. 1 and 2) (blue color). Left upper panel:  $P(t)$  and  $\Delta P(t)$  (Steinilber and Beer, 2013) with a linear regression length of 110 years enforced by the 22 year steps of the original  $P(t)$  record. Left lower panel: northern hemispheric  $T(t)$  and  $\Delta T(t)$  from stalagmites, tree rings, sediments, ice cores, pollen etc. (Christiansen and Ljungqvist, 2012). Right upper panel: northern hemispheric  $T(t)$  and  $\Delta T(t)$  from tree rings (Büntgen et al., 2011). Right lower panel: southern hemispheric  $T(t)$  and  $\Delta T(t)$  from tree rings (Cook et al., 2000).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

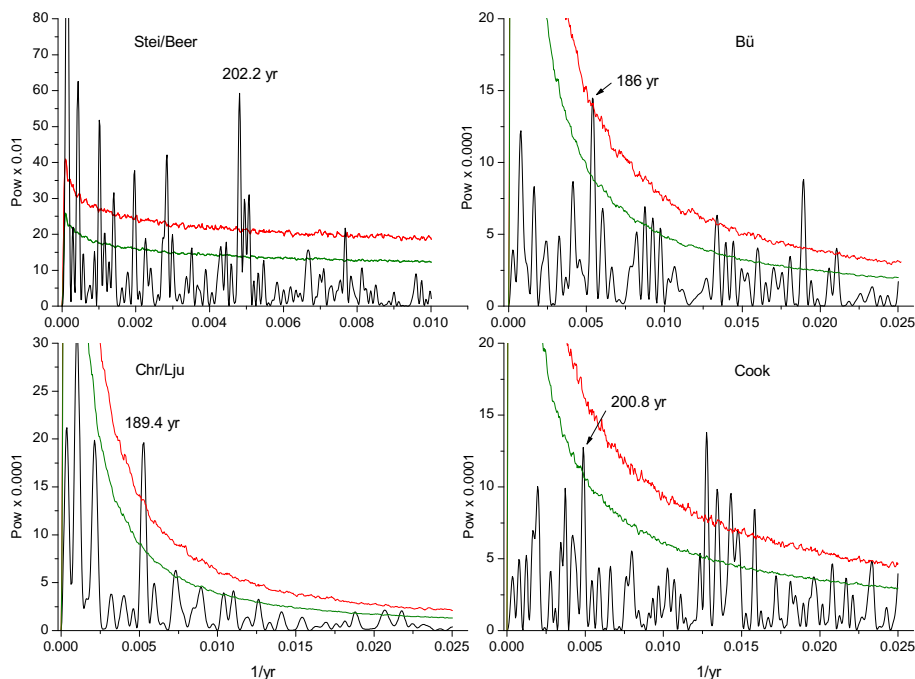
Printer-friendly Version

Interactive Discussion



Forcing of  
paleoclimate

H.-J. Lüdecke et al.



**Figure 3.** (Color online) Fourier analysis (DFT) together with 99% (red) and 95% (green) confidence lines of the  $T(t)$  resp.  $P(t)$  time series. Left upper panel:  $P(t)$  record of Steinhilber and Beer (2013). Right upper panel:  $T(t)$  record of Büntgen et al. (2011). Left lower panel:  $T(t)$  record of Christiansen and Ljungqvist (2012). Right lower panel:  $T(t)$  record of Cook et al. (2000).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

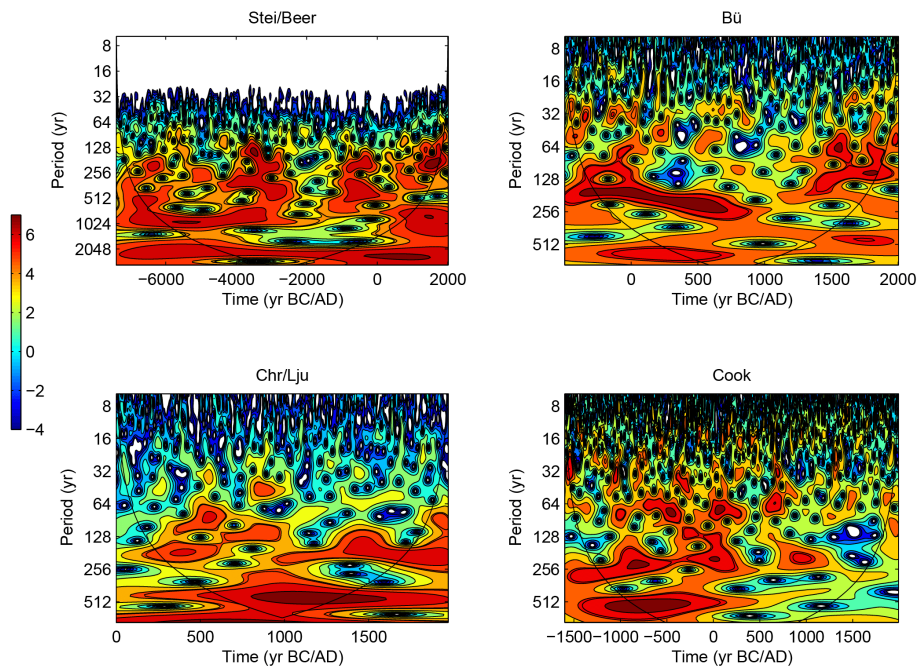
Printer-friendly Version

Interactive Discussion



Forcing of  
paleoclimate

H.-J. Lüdecke et al.



**Figure 4.** (Color online) Wavelet analyses of the  $T(t)$  resp.  $P(t)$  time series. Left upper panel (Steinhilber and Beer, 2013). Left lower panel (Christiansen and Ljungqvist, 2012). Right upper panel (Büntgen et al., 2011). Right lower panel (Cook et al., 2000).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

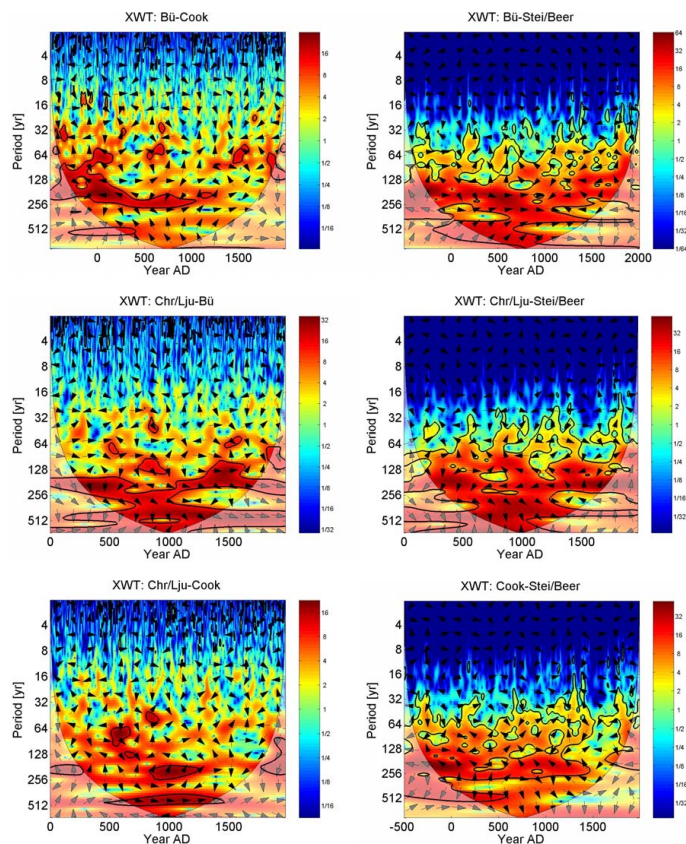
Printer-friendly Version

Interactive Discussion



## Forcing of paleoclimate

H.-J. Lüdecke et al.



**Figure 5.** (Color online) Cross wavelets of the  $T(t)$  resp.  $P(t)$  records, results reliable inside the cone of influence. The arrows give the phase relation with in-phase pointing right, anti-phase pointing left and the first record leading the second one by  $\pi/2$  pointing straight down (Grinsted et al., 2004).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

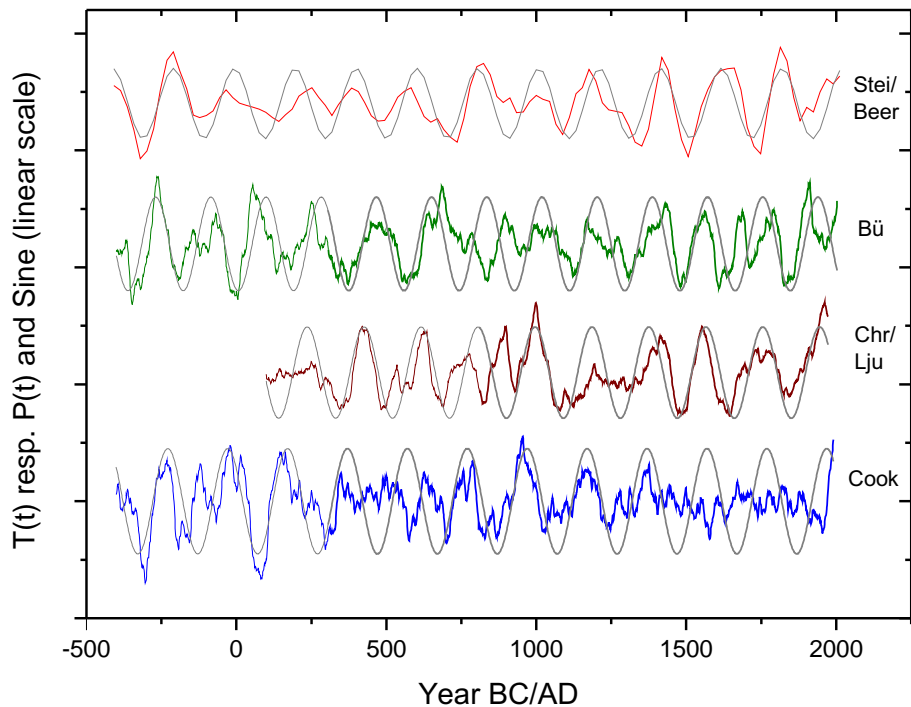
Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





**Figure 6.** (Color online) Representations of the difference records  $\Delta T(t)$  resp.  $\Delta P(t)$  by a single sine each (grey color) as an outcome of nonlinear optimization, numerical results given in Table 3. The records are normalized to the SD, sine amplitudes arbitrary (not relevant for correlation).

**Forcing of paleoclimate**

H.-J. Lüdecke et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

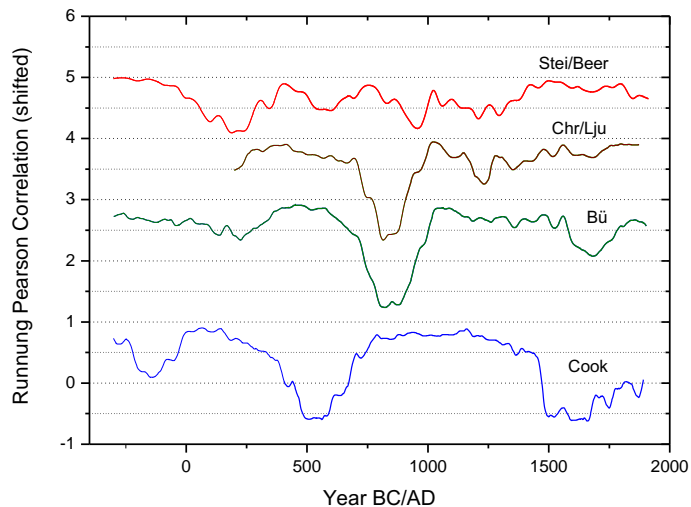
Interactive Discussion





## Forcing of paleoclimate

H.-J. Lüdecke et al.



**Figure 7.** (Color online) Running Pearson correlation of  $\Delta T(t)$  with  $\Delta T_{\text{sine}}$  resp.  $\Delta P(t)$  with  $\Delta P_{\text{sine}}$ , window length 200 years. The curves are shifted for clarity, Bü + 2, Chr/Lju + 3, and Stei/Beer + 4.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

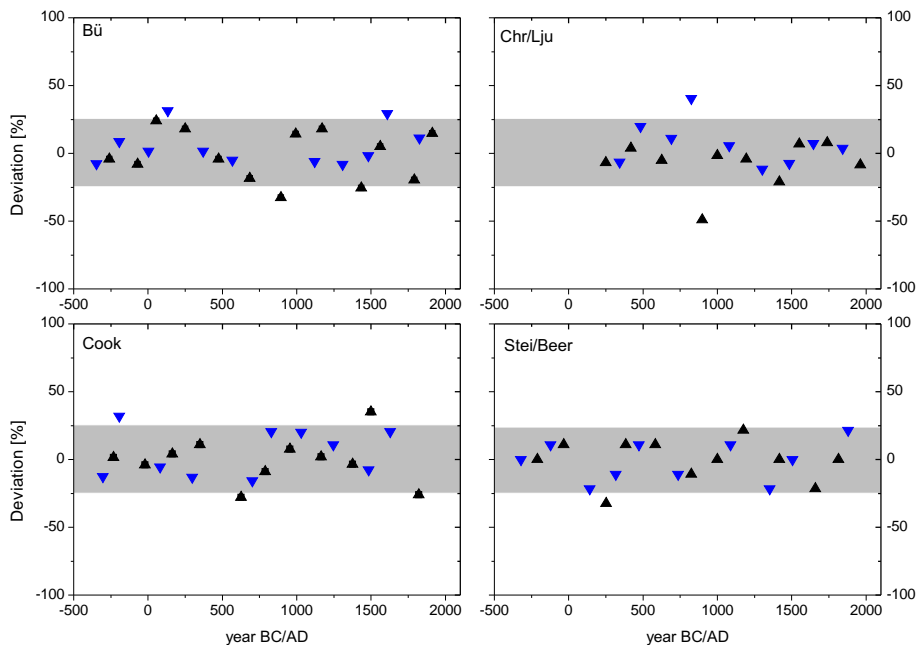
Printer-friendly Version

Interactive Discussion



## Forcing of paleoclimate

H.-J. Lüdecke et al.



**Figure 8.** (Color online) Deviations of the maxima (black triangles) and minima (blue triangles) from the pertinent sine extrema in % of period length. All records have 1 year time resolution except for Steinhilber/Beer (22 years). Grey shaded areas indicate the  $\pm 25\%$  deviation zone. The minima of the sine representations for Bü at AD 743 and 927, for Cook at AD 470, and for Stei/Beer at AD 912 have no valid analog in the time series (see also Fig. 6).

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

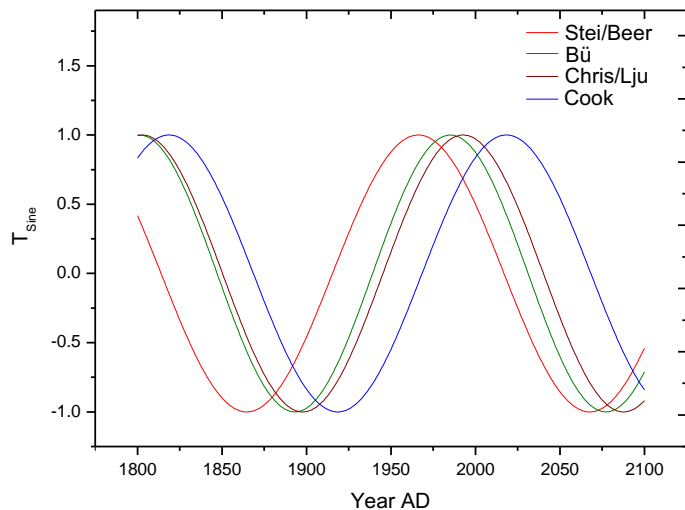
Printer-friendly Version

Interactive Discussion



## Forcing of paleoclimate

H.-J. Lüdecke et al.



**Figure 9.** (Color online) Sine representations of recent and future climate  $T(t)$  according to the  $\sim 200$  year period for the data sets of No. 1.0, 2.0, 3.0, and 4.0 of Table 3. Please note that this is the  $T_{\text{sine}}$  representation, which differs from the  $\Delta T_{\text{sine}}$  representation shown in Fig. 6 only by  $\pi/2$  in phase.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

