Conceptual model for millennial climate variability: a possible combined solar-thermohaline circulation origin for the ~1500-yr cycle

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Abstract

Dansgaard-Oeschger and Heinrich events are the most pronounced climatic changes over the last 120,000 years. Although many of their properties were derived from climate reconstructions, the associated physical mechanisms are not yet fully understood. These events are paced by a ~1500-yr periodicity whose origin remains unclear. In a conceptual model approach, we show that this millennial variability can originate from rectification of an external (solar) forcing, and suggest that the thermohaline circulation, through a threshold response, could be the rectifier. We argue that internal threshold response of the THC to solar forcing is more likely to produce the observed DO cycles than amplification of weak direct ~1500-yr forcing of unknown origin, by THC. One consequence of our concept is that the millennial variability is viewed as a derived mode without physical processes on its characteristic time scale. Rather, the mode results from the linear representation in the Fourier space of nonlinearly transformed fundamental modes.

***Keywords**: rectification, solar forcing, thermohaline circulation, millennial variability, fundamental and derived climate modes*

1. Introduction

The Dansgaard-Oeschger (DO) events are dramatic changes in surface climate which manifest as 6-10^{o}C warming in the North Atlantic over only a few decades (Dansgaard et al. 1993). Massive episodic iceberg discharges and cold conditions in the same region are associated with Heinrich (H) events (Heinrich 1993). Although the two types of fluctuations show different characteristics in the temperature domain, they share common features. Both are associated with the formation of North Atlantic Deep Water, suggesting that the thermohaline circulation (THC) plays an active role. Together with the atmospheric circulation, this can be responsible for the quasi-global impact of the events (Voelker 2002). Additionaly, the temporal distributions of the two types of events are related. Each H fluctuation is followed by a large amplitude DO event which is the first member of a series of progressively cooler fluctuations of the same type (Bond cycle; Rahmstorf 2002), which ends with a H event. The time interval between two consecutive DO fluctuations is around 1500-yr or a multiple of this time scale (Alley et al. 2001, Schulz 2002, Rahmstorf 2003). H events are separated by time intervals of about 10,000 years. Analogue Holocene fluctuations of smaller amplitude appear to be the most recent manifestations of the millennial cycle, which operates independently of the glacial-interglacial climate state (Bond et al. 1997) and whose origin remains unclear.

The concepts proposed to explain the DO events include the thermohaline circulation bistability (Broecker et al. 1985), oscillations in the volume transport of the thermohaline circulation (Broecker et al. 1990), latitudinal shifts of convection in the North Atlantic ocean (Ramstorf 1994), stochastic resonance (Gammaitoni et al. 1998; Ganopolski and Rahmstorf 2002), tropically driven fluctuations (Clement and Cane 1999) and solar forcing mechanisms (Denton and

Karlen 1973; Bond et al. 2001; Braun et al. 2005). The H events are thought to result from the ice sheets growing above a critical height where they become unstable (e.g., MacAyeal 1993). Here we investigate the origin of the 1500-yr cycle using a conceptual model.

2. Solar modes

Sunspots represent concentrations of magnetic flux at the solar surface. They are the longest studied direct tracers of solar activity. A recent reconstruction of decadal solar activity over the 9455 BC-1895 AD period (Solanki et al. 2004) allows to investigate solar-climate links at centennial and millennial time scales. We extended this record to 1995 AD, using decadal averages of the sunspot number (Hoyt and Shatten 1998) (Fig. 1a - thin line). Because the focus of our study is on multi-centennial and millennial time scales, a 25-point running mean filter was applied to the decadal record to obtain the time series shown in Fig. 1a (thick line). One should note that the preliminary filters applied to the time series analysed in this study are used to enhance the signal-to-noise ratio but they have no qualitative influence on the results, which are robust to reasonable variations of the analysing method's parameters. Singular Spectrum Analysis (SSA; Ghil et al. 2002) was applied to this record, using a 500-point window length, in order to identify the quasi-periodic components. The eigenvalue spectrum (Fig. 1b) contains four pairs of components that are above the noise level, which is represented by the flat, quasi-horizontal sequence of eigenvalues. It is thus assumed that the first four pairs of eigenvalues represent the signal while the remaining ones are associated with noise (Ghil et al. 2002). The corresponding pairs of the first four time-EOFs (Fig. 1c,d,e,f) are periodic signals, constantly shifted in time relative to each other, suggesting that the associated components are robust quasi-periodic signals. The associated time-components are shown in Fig. 2a,b,c,d. The MEM Spectrum (Fig. 2f) of a reconstruction based on these four components (Fig.2e) shows that they have periods of ~6500-yr, ~2500-yr, ~950-yr and ~550-yr. Previous studies associated the last three periodicities with solar forcing (O'Brien et al. 1995, Stuiver et al. 1995, Mayewski et al. 1997, Debret 2007).

3. The rectification hypothesis

The ~1500-yr variability of the DO events has neither been detected in solar reconstructions (Stuiver and Braziunas 1993) nor was it found by our SSA. Consequently, if its origin were related to the sun, then its relation with the solar forcing would not be linear (Braun et al. 2005). As a complex system, the climate could respond nonlinearly to external forcing. One particular type of nonlinearity is related to thresholds: a climate components only responds significantly to forcing if this has values above a certain threshold. Such a transformation of the forcing signal by a climate component is known as "rectification" (Huybers and Wunsch 2003). For example, the local effects produced in a specific month (e.g. in temperature field) by a seasonal shift of atmospheric circulation over a specific area, represent a rectification of the forcing causing the atmospheric change. Many other physical processes can generate such transformations in the climate system (Kim et al. 1998; Clement et al. 2000; Rial 2004). Previous studies emphasized the role of thresholds (McManus et al. 1999, Paillard 2001) and rectification (Schulz et al. 1999) in past climate variations.

Assuming a DO-sun connection (Braun et al. 2005) a rectification is applied to the solar activity reconstruction (Fig. 1a). This is equivalent with the hypothesis that a part of the climate system responds to external (sun related) forcing only if this has values above a given threshold. Consequently, the decadal sunspot number record is rectified by resetting all values smaller than 30 to 30. Visually this transformation is represented by a straight horizontal line which cuts the time series shown in Fig. 1a. Because our focus is on millennial variability, a 25-point running mean filter is then applied to the resulting signal to obtain the time series shown in Fig. 3a.

Additionaly, a preliminary SSA is performed in order to remove the ~6500-yr component. Through this analysis the ~6500-yr signal is separated and then subtracted from the initial time series. The residual record is shown in Fig. 3b. The quasi-periodic components contained in this time series are identified using the SSA method (Fig. 3c). Among the dominant components, aside from the periodicities identified in the initial record, the analysis reveals a quasi-periodic signal (Fig. 3e) characterized by a period of ~1400-yr (Fig. 3f). One observes that the maxima in the solar forcing are separated by ~1400-yr cycles or a multiple of it (Fig. 3e), which is a key property of the recurrence time of millennial climate variability (Schulz 2002). The fluctuating spacing time between maxima, as multiples of the ~1400-yr periodicity, appears to be related to the longer ~6500-yr period component, which modulates the higher frequency signals.

4. Toy model

The effect of rectification on the spectral properties of a signal resulting from a linear combination of quasi-periodic components is further investigated through idealized numerical experiments. A time series is generated from the superposition of three harmonic functions with periods of 2500-yr, 950-yr and 550-yr. These correspond to the fundamental modes contained in the solar activity reconstruction. The generated signal is rectified so that all values in the time series which are smaller than 0.2 are reset to 0.2, resulting in the time series shown in

Fig. 4a. One should note that the rectified signal includes much more abrupt variations than the initial one. An SSA applied to this rectified time series emphasizes two groups of modes, which explain comparable amounts of variance. The first group includes the three fundamental modes contained in the initial, non-rectified signal (Fig. 4c,e,g for their time-EOFs and Fig. 5a,c,e for their time series). The second group contains new quasi-periodic components with periods of ~700-yr, ~1400-yr and ~450-yr (Fig. 4d,f,h for their time-EOFs and Fig. 5b,d,f for their time series). Therefore, derived modes can result from rectification of the signal generated through superposition of the fundamental modes (Dima and Lohmann 2004).

Repeated numerical experiments show that the characteristic time scales of the derived modes depend on the periods of the fundamental components contained in the initial signal, but not on reasonable variations of the rectification level and on the weights with which the fundamental modes are included in the initial time series. For example, qualitatively the same results are obtained if the rectification level is changed in a range of 50% of the signal amplitude, and if the weights are changes by 30% of their typical values of 0.33. These last two parameters affect only the amplitudes of the derived components relative to that of the fundamental modes. Such a wide range of values for the rectification level and weights suggests that many physical processes have the potential to rectify the solar signal, and that the rectification of the solar forcing represents a robust method to generate derived modes.

These fundamental and derived cycles revealed by numerical experiments were identified in Holocene records alkenone SST and ice core data, consistent with the rectification hypothesis. The alkenone SST data contain periodicities of ~2300-yr, 1000-yr and ~800-yr (Rimbu et al. 2004) and the glaciochemical records from Greenland include cycles with periods of ~2500-yr, ~1400-yr and ~980-yr (Witt and Schumann 2005).

5. Thermohaline circulation as potential rectifier

The North Atlantic Deep Water formation and THC represent important components of both, DO and H events. Theoretical and numerical studies show that THC can suffer abrupt transitions between distinct circulation modes in association with different states of North Atlantic Deep Water formation (Broecker et al. 1985; Ganopolski and Ramstorf 2001) and with shifts in the location of convection (Ramstorf 1994). Such transitions are forced, for example, when the fresh water forcing exceeds a certain threshold (Manabe and Stouffer 1988). Thus, due to its strong nonlinearity (Stommel 1961), the THC has the potential to rectify an external forcing.

The dominant periodicities associated with THC variations over the Holocene were investigated in a record of the Iceland-Scotland Overflow Water, which is an important component of the thermohaline circulation (Bianchi and McCave 1999) (Fig. 6a). The first two most robust quasi-periodic components identified by SSA have periods of ~1400-yr (Bianchi and McCave 1999) and ~700-yr, which are derived modes predicted by our concept (Fig. 6c,d,e,f). The fact that the ~1400-yr and ~700-yr derived periodicities, generated through rectification in the idealized experiments (Fig. 4b), dominate the spectrum of the THC proxy record (Fig. 6b), supports the idea that THC is involved in rectification. However, this does not exclude the possibility that other climate components, like the atmosphere or the Greenland Ice Sheet (GIS), also cause the rectification and/or generate the millennial mode (Rial 2004).

In order to further investigate this possibility one must consider the effects of rectification on the forcing signal. As is observed in Fig. 4a, the variation contained in the forcing signal (dashed line), corresponding to the fundamental modes, is partly reproduced in the rectified signal. In the spectral domain the forcing and the rectified signals have different projections. The forcing contains only the fundamental modes but the rectified signal includes both, the fundamental and the derived cycles. Let assume that the solar forcing is transferred through the atmosphere without any significant change of his form and then reaches the ocean surface, where is rectified by the THC. For example, in Fig. 4a the dashed line corresponds to the atmospheric (solar) forcing and the solid line to the THC signal (rectified response). According to previous considerations, in this case the atmosphere includes only the fundamental cycles. For the ocean however, both, the fundamental and derived modes can be identified in the spectrum (Debret et al. 2007). Consequently, coherent ocean atmosphere variations could only be associated with the fundamental modes, as only these are present in the spectra of both climate components. The derived cycles are observed only in the THC spectrum. This feature has been emphasized in previous studies showing that the ocean and the atmosphere over Greenland show coherent variations for the fundamental modes (~1000-yr and ~550-yr), but not for the derived cycles (Chapman and Shackleton 2000). Furthermore, Holocene oxygen isotope data from Greenland (GISP2 ice core) contain only fundamental modes (Schulz and Paul 2002). The considerations presented above indicate that the THC is involved in rectifying the signal, and not the atmosphere or the GIS.

6. Extrapolation to the last glacial period

Considering the limited precision of the sunspot reconstruction (Solanki et al. 2004), it is reasonable to consider that the Holocene ~1400-yr mode and the ~1500-yr periodicity, which is connected to abrupt climate changes over the last glacial period (Bond et al. 1997), correspond to the same mode. One can assume that the fundamental solar cycles provide the forcing for the climate over the last glacial period also, and that the THC acts as a rectifier during this time interval. A first order validation of the assumption that our concept applies also to the last glacial period would come from the identification in various proxy records for this period of both, the solar fundamental modes and the derived cycles resulting through rectification. The GISP2 and GRIP $\delta^{18}O$ records include both, fundamental and derived components (Grootes and Stuiver 1997, Hinnov et al. 2002, Ditlevsen et al. 2005). As an example, we show the spectrum of a GISP2 glaciochemical (Potassium) record for the 10.000 -100.000 BP period (Fig. 7a) (Mayewski et al. 1997) which highlight all the solar fundamental modes identified for the Holocene (~2500-yr, ~950-yr, ~550-yr) but also the three derived modes which are predicted by our concept (~1500-yr, ~700-yr and ~450-yr) (Fig. 7b). Furthermore, in the initial analysis of abrupt climate changes (Dansgaard et al. 1984), the DO events were associated with the ~2500-yr fundamental periodicity.

7. Physical relevance of the millennial mode

An intriguing consequence of our concept is that the ~1500-yr time scale of abrupt climate changes, appears as a derived mode, but not as a fundamental one. It is therefore important to understand the physical significance of this cycle in particular and of the derived modes in general. Is the ~1500-yr cycle generated by physical processes with characteristic millennial time scales? While a signal constructed as a superposition of three harmonic signals is optimally decomposed into these functions, supplementary harmonics (derived modes) are required to decompose the non-harmonic rectified signal (Fig. 5). This is because the form of the base functions (harmonic) is not optimal in representing the rectified non-harmonic signal. It also implies that the derived modes, which exist only in the Fourier domain, are not associated with physical processes characterized by their time scale. The derived modes are a consequence of rectification (which physically can correspond to a threshold response of the THC to solar forcing) due to the nonlinearity of this climate component. For example, variable solar forcing can modify the atmospheric circulation patterns which can further change the hydrological cycle. For values above a specific threshold, the freshwater forcing can induce transitions between different THC equilibrium states (Ramstorf 1995, Paillard 2001).

However, although such a threshold response (rectification) results in the non-harmonic form of the climatic signal and generates the derived modes in the Fourier space, it is not characterized by a millennial time scale. From this perspective, the ~1500-yr cycle is a derived mode whose period is not a result of physical processes that are characterized by millennial time scales. It appears as the pacemaker of the abrupt climate changes because the Fourier method is used to identify periodic components in a non-harmonic signal. If possible erroneous chronologies of GISP2 and GRIP cores are not considered, then the fact that the maxima and minima of the ~1500-yr cycle do not always correspond to the observed extremes of DO and H events (Alley et al. 2001) can have a simple interpretation. It supports the lack of a physical mechanism based on processes characterized by millennial time scale, which would generate the ~1500-yr mode. For example, the key physical mechanism generating the millennial cycle in the spectrum seems to be a threshold response. It could physically correspond to a significant THC response to solar forcing, which extends over only several decades and therefore it is not associated with physical processes characterized by millennial time scales.

8. Why are the derived modes prominent in the spectra ?

One important property related to the ~1500-yr mode is that it is prominent in the spectra of records in which DO events are observed (Grootes and Stuiver 1997, Hinnov et al. 2002, Ditlevsen et al. 2005), although it is most likely a derived cycle. In order to explain this feature it is necessary to analyse how the Fourier method identifies harmonic signals in rectified time series (Fig. 8).

Let us consider a harmonic function of period T (Fig. 8a) which is represented in the spectrum (Fourier space) as a narrow peak. We assume that this signal is rectified at a given positive level (Fig. 8a). The residual signal (Fig. 8b-solid line) has a non-harmonic shape and consists of a series of relatively narrow pulses separated by time intervals of constant length. A Fourier analysis identifies those harmonic functions which represent the best fit to the analysed signal. A harmonic of period T fits relatively well to the residual signal because its maxima are synchronized with the positive consecutive extremes of the analysed time series (Fig. 8b-dash-dot line). Note that a harmonic function of period T/2 (Fig. 8b-dashed line) also fits the residual signal well because the maxima of the two time series are synchronized as well. A key question is: which harmonic function fits better, that of period T or that of period T/2? In the interval between the two peaks (Fig. 8, BC segment), the climate response is quasi-independent of the forcing. Therefore none of the two signals fit this part of the record. However, in the AB and CD intervals the T/2 period curve (Fig. 8b-dashed line) is closer to the rectified signal than the T period curve (Fig. 8B-dash-dot). This means that the former signal fits better to the rectified non-harmonic time series than the latter. Consequently, in the spectrum the T/2 period signal corresponding to a derived mode is more prominent than the T period signal, which is associated with the fundamental cycle. In summary, the derived modes can be more prominent in spectra than the fundamental modes, because the former fit better to the non-harmonic signal. Therefore, the 1500-yr cycle, being a derived mode, can be more prominent in the climate spectra than the fundamental cycles. This is consistent with the combined solar origin and THC rectification hypotheses. The above considerations imply that the maxima of the derived modes are synchronized with the maxima of the fundamental modes. This is in agreement with the synchronization between maxima of the ~1500-yr mode and of the rectified sunspot number time series (Fig. 3e).

9. Summary and conclusions

The results can be synthesized as follows:

1. In the context of our study the ~1500-yr mode can result from rectification of external (solar) forcing. The spectrum derived through rectification of the solar modes is similar to that of climate records for the last glacial period.
2. We suggest that the THC is involved in the rectification, although other components of the climate system could also induce such a transformation. This is supported by the dominance of the derived modes in a THC proxy record and by the coherent variations between ocean and atmosphere over Greenland associated only to the fundamental modes, but not to the derive ones (Chapman and Shackleton 2000).
3. According to our concept, the ~1500-yr cycle is a derived mode without associated physical processes of the same time scale; the prominence of

the ~1500-yr peak in the spectra might be a consequence of applying the Fourier analysis to non-harmonic signals.

Based on proxy records we presented support that the ~1500-yr mode appears in the Fourier space through rectification of solar forcing, and suggested that the THC could be the rectifier. Both, solar forcing and the THC as rectifier are elements required for the generation of the ~1500-yr cycle. Therefore this millennial mode has a dual, solar-internal climate origin. Unlike previous suggestions about a combined solar-THC origin of this cycle (Braun et al. 2005), the time scale of the millennial mode does not result from the synchronization of two cycles, but from rectification and analysis in the Fourier space. This transformation modifies the form of the initially harmonic signal, resulting in a relatively wide millennial peak in the Fourier spectrum (Wunsch 2000).

As a consequence of our concept, spectral analyses can be used to estimate major forcing factors in specific locations, given knowledge of the fundamental modes. For example, in regions where the THC, as a potential rectifier, has no influence, the solar modes dominate. Accordingly, the spectra of the records in such regions are only emphasizing the solar fundamental modes. Conversely, the derived modes would have maximum amplitudes in regions where the rectifier has maximum influence. For example, the fact that the spectra of Greenland records for the last glacial period include prominent derived modes (~1500-yr period component) suggests that the THC, as a rectifier, had a significant influence over this area. The different amplitudes of the ~1500-yr variability in the last glacial and interglacial periods can be related to the stronger effect on Greenland climate of the THC during glacial times relative to the Holocene.

As we show, nonlinear physical processes affecting the fundamental modes, such as threshold response, are reflected in Fourier space as derived modes. These latter cycles can also be generated in proxy records by the nonlinear processes which are specific to the recording system (Crowley et al. 1992; Huybers and Wunsch 2003). Therefore the existence of the derived modes can depend on a) nonlinear physical processes, b) on the recording system and c) on the analysing method. Due to its specific properties, limitations and advantages, the Fourier analysing technique can provide a modified perception of the physical processes, as is shown in Fig. 9. The physical process represented by rectification is reflected in the Fourier space as three derived modes. Since these are not associated with processes with their time scales, they may generate a perturbed view about the physical processes.

In general, through nonlinear transformations of fundamental cycles several derived modes can be generated. Given the large number of nonlinear processes and recording systems which are active in the climate system, many of the quasi-periodic components identified in climate records might be derived modes. Since these have no specific physical mechanisms that act on the time scales of the derived cycles, the identification of fundamental modes appears to be of central importance.

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Figure captions

Figure 1 Singular Spectrum Analysis (SSA) of the reconstruction of decadal sunspots number for the 9455 BC - 2000 AD period. Since the focus of our study is on multi-centennial and millennial time scales, a 25-point running mean filter was applied to the initial record (panel a - thin line) to obtain the time series in panel a (thick line). The SSA was then performed using a 500-point window length. The eigenvalue spectrum (panel b) contains four pairs which are above the noise level. Pairs of Time-EOFs corresponding to the components with periods of 6500 yr (c), 2500 yr (d), 950 yr (e) and 550 yr (f).

Figure 2 Time components identified with SSA on the sunspot number reconstruction. a) the ~6500-yr period component; b) the ~2500-yr period component; c) the ~950-yr period component; d) the ~550-yr period component; e) the reconstruction based on these four components and its MEM spectrum, derived using the parameters: MEM order=160, No. of sample frequencies=1024 (f).

Figure 3 Singular Spectrum Analysis of the rectified solar activity reconstruction for the last 11.400-yr. The rectification level is indicated by the horizontal line in Fig. 1a. The decadal sunspot number record is rectified by replacing the values smaller than 30 with this value. Then a 25-yr point running mean filter is applied to obtain the time series shown in panel a). Through a preliminary SSA, the 6500-yr component is removed, resulting in the residual record shown in panel b); c) The eigenvalue spectrum derived from SSA applied to this time series; d) Time-EOFs 5 and 6; projecting them on the initial time series on obtains the corresponding principal components (PCs); based on these T-EOFs and PCs, the corresponding quasi-periodic component is reconstructed (e); the MEM spectrum of the quasi-periodic components shown in panel e), derived using the parameters: MEM order=40, No. of sample frequencies=256 (f).

Figure 4 Toy model representing climate forcing as a superposition of three harmonic functions with periods of ~2500-yr, ~950-yr and ~550-yr (dashed line), which is rectified at the 0.2 level, to obtain the response signal (solid line) (a). b) SSA derived eigenvalue spectrum. Time-EOFs of the fundamental components with periods of ~2500-yr (c), ~950-yr (e) and ~550-yr (g). Time-EOFs of the derived components with periods of ~700-yr (d), ~1400-yr (f) and ~450-yr (h) identified in the rectified signal.

F**igure 5** Fundamental and derived components derived through SSA on the rectified signal. The ~2500-yr (a), ~950-yr (c) and ~550-yr (e) period time components. The ~700-yr (b), ~1400-yr (d) and ~450-yr (f) period components identified in the rectified signal.

Figure 6 Sortable silt mean size (a), a proxy for near-bottom paleocurrent speed, from Iceland-Scotland Overflow Water which is an important component of the thermohaline circulation. SSA of the THC proxy record; b) the eigenvalue spectrum; c) the Time-EOFs associated to the ~1400-yr component; d) the ~1400-yr component; e) the Time-EOFs associated to the ~700-yr component; f) the ~700-yr component.

Figure 7 Spectral content of a proxy record for the last glacial period. Decadal GISP2 Potassium concentration for the last 100.000 years (a). MTM spectrum of the potassium record, computed using the parameters: Resolution = 2, Number of Tapers = 3 (b); The 99% (thick dashed line) and 95% (thin dashed line) confidence levels against the null hypothesis of a red noise spectrum are also shown. The fundamental (derived) modes are indicated by continuous (dashed) arrows.

Figure 8 Schematic representation of a Fourier analysis applied to a rectified signal. a) The initial harmonic function of period T. The rectification level is represented by the horizontal line; b) the rectified signal and the two harmonics of periods T and T/2; on the AB and CD segments the T/2 period harmonic fits better to the rectified signal than the T period harmonic.

Figure 9 Conceptual representation in the Fourier space of a system described by three fundamental modes and a nonlinear transformation (rectification).