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Interactive comment on “Orbital forcings of the Earth’s climate in wavelet domain” *by* A. V. Glushkov et al.

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Comment on: Orbital forcings of the Earth’s climate
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Abstract

Glushkov and his coauthors have utilized non-decimated wavelet analysis to discuss the variability on Milankovitch scales for several biochemical parameters in antarctic ice cores and marine sediment cores. In this comment, we argue that uncertainties in the age-depth models may cause problems when applying non-decimated wavelet analysis to palaeoclimatic time series. Further, we discuss the significance of the presented results with respect to both the method and data sets.

1 Introduction

Wavelet analysis is a suitable tool for investigating periodic components, which occur temporarily or with non-constant amplitudes. In particular, when studying the dynamics of the Earth's climate on large time scales, wavelet analysis of palaeoclimatic proxy data provides age intervals that are dominated by certain periodicities. Glushkov *et al.* have utilized a particular version of discrete wavelet transform (DWT), the non-decimated wavelet transform (NWT), for analyzing exemplary data sets from this field of research. In Sect. 2 of this comment, we summarize potential problems caused by uncertainties in the age models and the astronomical tuning of the time-scales. Alternative wavelet approaches that are adapted to unevenly sampled data are discussed in Sect. 3. Finally, in Sect. 4, we re-analyze the Vostok deuterium record in terms of the weighted wavelet Z-transform method and discuss the statistical significance of wavelet filtered components, which are supposed to represent the impact of orbital cycles.

2 Age uncertainty and time-scale tuning

The uncertainty of age models of palaeoclimatic records (see, e.g., [Telford *et al.*(2004)]) is the major source of problems and errors in spectral analysis. Since observational evidence of Milankovitch theory has been found, records are frequently tuned to the variability curve of solar irradiation. This means that between isolated points with directly measured (but usually uncertain) age values, timescales

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are obtained by graphical adjustment of large-scale variability patterns in the data with respect to their apparent representations in the reference. It is questionable if such records can be used to study variations on Milankovitch scales because they are implicitly used to generate these records. Variations on Milankovitch scales of a record can be analyzed if the corresponding age model is based on a suitably large amount (or equivalently, a small spacing) of directly measured age values, and (realistic) confidence intervals of all estimated ages that are significantly smaller than the considered period.

Vostok age models. For the Vostok ice core various age models based on different approaches have been published (see, e.g., [Ruddiman and Raymo(2003)]). As Glushkov *et al.* have examined the deuterium-based relative temperature data, we assume that the GT4 timescale (also known as the extended glaciological timescale EGT 20) according to [Petit *et al.*(1999)] has been applied. GT4 gives estimates for the age of the ice which is appropriate for analyzing the Deuterium signal. However, the estimated uncertainty of the corresponding age values ranges between 5 and 15 kyr where at least the latter value (for the older part of the record) leads to severe problems for reconstructing variability signals on the 20 kyr band. Alternatively, there are more recent age models that adjust the atmospheric δ^{18}O to a synthetic orbital signal ([Shackleton(2000)]) or use CH_4 measurements ([Ruddiman and Raymo(2003)]). Both models are based on the chemical characteristics of the gas that is confined in bubbles of the ice cores and, therefore, the gas age may differ from the ice age significantly.

Marine composite core age models. Following a proposal of [Shackleton(1995)], the records of the marine cores V19-30 (replacing the originally used SPECMAP stack for the upper 620 kyr of the composite sequence), ODP 677 and ODP 846 have been combined to one marine sequence (sometimes referred to as the S95 composite ([Lisiecki and Raymo(2005)])) covering the last approx. 6 Myr of climate history. The corresponding timescale has been obtained by combining the age models of the respective components.

Recently, several groups have considered benthic δ^{18}O records from various marine cores to construct more sophisticated composites with improved age models (e.g., [Karner *et al.*(2002)]). Correlating data sets with certain age measurements yields more reliable timescales due to the larger amount of references. The resulting age models are based on different approaches. Very promising for this type of data analysis is the depth-derived, minimally tuned HW04 timescale of [Huybers and Wunsch(2004)] spanning the last 780 kyr. In contrast, the (most recent) LR04 age model by [Lisiecki and Raymo(2005)] is essentially aligned to the orbital forcing. By choosing either one or the other timescale, significant differences in the spectral domain may be expected. A fair analysis should involve different age models and discuss their effects on the spectral properties of the records.

3 Wavelet analysis for unevenly sampled data

A typical approach to cope with unevenly sampled data is an appropriate interpolation of the observed time series to a given, uniformly spaced grid. Glushkov *et al.* have presented a variant of this method by interpolating with cubic Hermite polynomials. However, as spline interpolation has been found to fail in their application, the appropriate choice of the local polynomials seems to play a crucial role for the data sets considered.

Observational records do not provide information about the behaviour on time scales shorter than the temporal resolution. The interpolation approach implicitely assumes that the observable is well-behaved in time. This assumption is problematic for palaeoclimatic proxy data which frequently show large differences (e.g., of temperatures) within small time windows. If a signal consisting of temporary averages of a particular parameter (being the typical case in palaeoclimatology) is interpolated again, the corresponding reconstruction of the variability may remarkably differ from the actual one which influences the results of the wavelet analysis. Even if the NWT approach performs well for analyzing data with regular sampling, its outcome must be treated with special care in the discussed application.

There are several approaches to overcome the problem of being dependent on information distributed on a regular grid. The simplest idea is based on an application of the Haar wavelet, a piecewise continuous function ([Scargle(1997)]). A more realistic decomposition is provided by using differentiable functions as mother wavelets (e.g., the Morlet wavelet). [Frick *et al.*(1998)] proposed appropriate corrections of the wavelet transform for gapped data records (GWM). [Foster(1996)] introduced the weighted wavelet Z-transform (WWZ), a projection method reorthogonalizing the three basic functions (real and imaginary part of the Morlet wavelet and a constant) by rotating the matrix of their scalar products. He furthermore introduces appropriate statistical tests to distinguish between periodic components and a noisy background signal for unevenly sampled data. [Andronov(1998)] suggested a further improvement of WWZ by introducing additional weighting factors. Recently, WWZ was successfully applied to palaeoclimatic records by [Witt and Schumann(2005)]. Because GWN and WWZ consider only the information directly measured along the cores, they are not affected by additional uncertainties caused by interpolation. From this point of view, the corresponding approaches are more suitable for the analysis of unevenly sampled data.

4 Vostok deuterium record

Apart from problems with interpolating data, wavelet analysis cannot be applied as a black-box method because different choices for the mother wavelets, i.e., their shapes and spectral representations are possible. Moreover, in case of a continuous wavelet transform, the scale parameter that represents the spectral bandwidth must be fixed. It has to be statistically tested if the wavelet coefficients indicate a signal that is significantly different from a white or red noise climatic background. Only if such a test fails and the variability beyond the noisy background signal is related to Milankovitch cycles, the reconstruction of the original signal as a superposition of wavelet filtered components on Milankovitch scales is justified.

To illustrate the dependence on the wavelet basis, we have performed a continuous wavelet analysis (as in [Witt and Schumann(2005)]) for the Vostok deuterium record (we use this data set rather than the temperature reconstruction for a better consistency to the marine δ^{18}O records analyzed by Glushkov *et al.*). Considering the wavelet amplitude map as presented in Fig. 1, we find that this record has a rather complex variation structure. Obviously, it is a very rough approximation to model the variations of the Vostok deuterium record by a superposition of variations on the three Milankovitch scales and a red noise background. In particular, an additional period of about 60 kys (eventually caused by a superposition of higher frequencies) occurs for the last 150 kys and has to be taken into consideration.

Even if we ignore the problems mentioned in the previous paragraph and reconstruct the variations on Milankovitch scales as done in Fig. 2, these reconstructions are far from being identical to those of Glushkov *et al.* Remarkable differences are visible in the signal that corresponds to eccentricity (please see the reversed age scale on the related figures). This difference is caused on the one hand by the broader spectral bandwidth of the Daubechies wavelet compared to the abbreviated Morlet wavelet. On the other hand, the discrete wavelet transform reconstructs the entire signal, whilst the continuous wavelet transform only its variability. We do not discuss here if either of the reconstructions is correct, but we want to make clear that the choice of the wavelet basis and the wavelet scale parameters matter and have to be discussed in great detail.

5 Conclusions

Wavelet analysis is a promising approach to identify features of climatic variability in palaeoclimatic proxy data in both time and frequency domain. Due to the irregular sampling of the data in time, the use of especially adapted implementations is recommended whereas interpolation approaches provide an additional source of error. The choice of an appropriate mother wavelet and statistical tests for testing the significance of the periodic fluctuations are of particular interest. Unfortunately, in the Glushkov *et al.* paper, a discussion of these crucial issues is missing.

In their paper, Glushkov *et al.* discussed periodicities in geological archives whose

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frequencies are close (but not necessarily equal) to those of dominant orbital cycles. As there are nonlinear feedback mechanisms between solar irradiation and surface temperature (see, e.g., [Paillard(2001)]), wavelet analysis of climatic proxies yields a study of the (nonlinear) response of the Earth's climate rather than of the forcings themselves. The orbital parameters can be investigated directly, e.g., by analyzing the models of [Berger(1978)] (see, e.g., [Lin and Chao(1998)] and [Mélice *et al.*(2001)]).

Finally, as the age model has been graphically tuned to orbital cycles at least for the marine composite core, the choice of the corresponding data set for studying the temporal evolution of the climate response to orbital forcing must be subjected to some additional criticism. For the Vostok ice core, there are several competing age models as well which should be appropriately discussed.

Given that the understanding of nonlinear dependences of the Earth's climate on solar irradiation is critical issue, we would like to encourage further work using non-traditional methods of data analysis that contributes to the solution of this problem.

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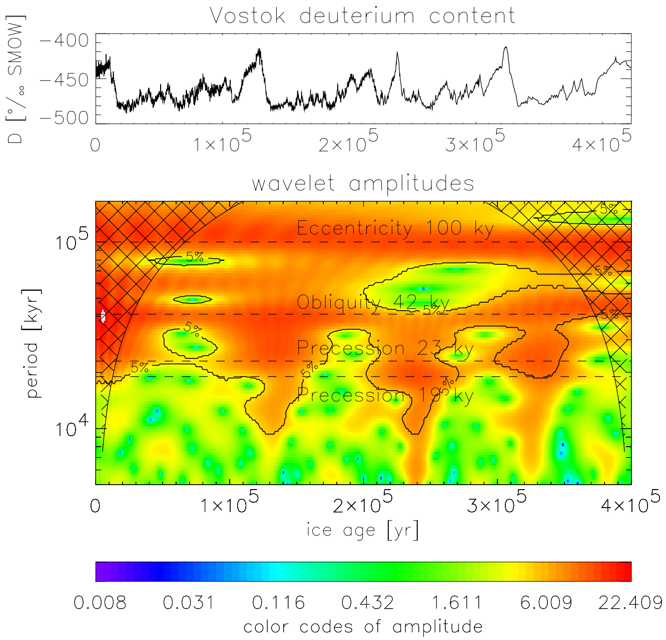

Figure 1: Original time series of the Vostok deuterium record (upper panel) and the corresponding wavelet amplitudes (lower panel) depending on the localization (age) and the period length. For calculations, the WWZ method and an abbreviated Morlet wavelet have been used. Cross hatched regions indicate the cone of influence, where the wavelet analysis is affected by edge effects. Contour lines mark periodic shares (red colors indicating the strongest periodicities) that are significantly different from a red noise background assuming an error of 5% (see [Witt and Schumann(2005)] for details). The periods of the major Milankovitch cycles are displayed by dashed lines. The bottom panel displays the color codes.

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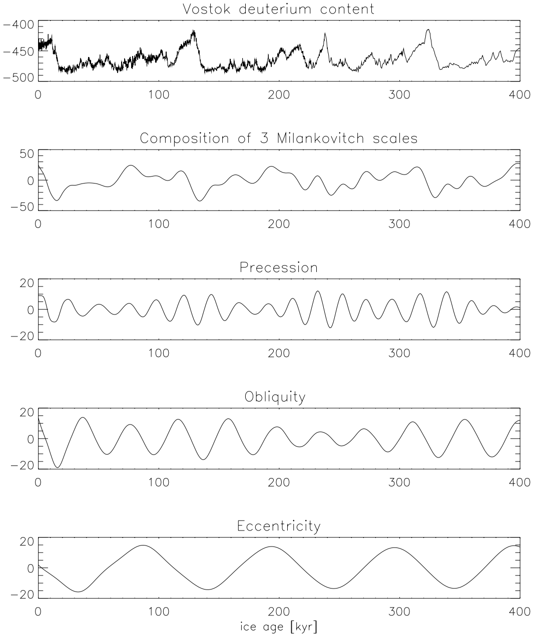

Figure 2: Wavelet amplitudes at the major Milankovitch scales of 20, 42, and 100 kyr, and the resulting reconstruction of the long-term variability of the original time series (from bottom to top).