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Interactive comment on "Characterizing ecosystem-atmosphere interactions from short to interannual time scales" *by* M. D. Mahecha et al.

M. Palus (Referee)

mp@cs.cas.cz

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1 General comment

The authors use the singular system (or singular spectrum) analysis (SSA) to uncover modes of variability in the dynamics of time series of ecosystem and some meteorological variables. Using the detected (quasi)oscillatory modes, mutual relations of

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various variables are studied in order to characterize ecosystem-atmosphere interactions. The topic is relevant for the scope of the Biogeosciences Discussions and I find the manuscript very interesting and worth for publication, however, I have several comments and/or suggestions which, in my opinion, could improve the manuscript and make the authors' conclusions better supported by the results of data analysis.

2 Towards specific comments

I use the fact that two referees already posted their comments with many remarks on errors and omissions and I will focus on more general questions which I consider interesting. I add just a remark to already mentioned confusions with T and N for the total length. On the top of p. 1410 (l. 5) N is used, while in eq. (6) T is used.

Another small remark: p. 1420, l. 21-24: [Paluš & Dvořák(1992)] showed that SSA cannot be reliably used for estimating the dimension of nonlinear systems.

3 Interannual variability in atmospheric temperature T

P. 1415, l. 15–19. Not only the length of the record plays its role, but also the position in both time and space – the presence of some oscillatory modes in the T record changes with the geographical location [Paluš & Novotná(1998)] and the relative variance of a particular mode changes in time. So it is hard to say what is the reason of the absence of slower (than 1 year) modes in the analysed record. The presence of the strong annual cycle in the T data can influence the test. Therefore, searching for slower oscillatory modes, deseasonalised data can be used. I.e., instead of the raw T data, "anomalies" or differences from the seasonal means can bring different results. Note

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Figure 1: The annual mode extracted from the the monthly Prague near-surface air temperature series (T) plotted against the annual mode extracted from the the monthly Prague humidity series (H).

also that [Paluš & Novotná(2006)] did not detect the QBO mode using the standard SSA, but using their enhancement based on the test of regularity of the SSA modes.

4 Relations of oscillatory modes: nonlinear?

The plots of the annual (annual + other) modes of T vs. NEE, resp. NEE vs. other variables are used to characterize the studied relations as nonlinear, showing hysteresis. Already one of the other referees expressed doubt whether this behaviour cannot be just a consequence of the seasonal pattern (annual cycle) in the studied variables. In order to better understand relations of oscillatory modes from data with different levels of dependence, I did the following analysis using the data I have available: the monthly atmospheric temperature T and humidity H from the Prague-Klementinum station. The "pure" annual mode, i.e. the SSA mode with the largest eigenvalue from T against the same mode from H are plotted in Fig. 1. We can see similar nontrivial behaviour as in the examples shown in the discussed manuscript.

In order to see relations of oscillatory modes from data with the same frequency spectra but known dynamics and dependence, instead of the temperature and humidity data I used so-called isospectral surrogate data [Theiler et al.(1992),Paluš(1995)]. In order to preserve the possible existence of cycles we need to preserve the whole spectrum of the signal, but to randomize phases of such cycles in order to destroy any dependence

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Figure 2: The annual mode extracted from surrT plotted against the annual mode extracted from surrH series, independently randomized.

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Figure 3: The annual mode extracted from surrT plotted against the annual mode extracted from surrH series, randomized together as the bivariate surrogate data preserving the original T-H cross-correlations.

which existed between T and H. The isospectral surrogate data are constructed from the real temperature and humidity data by the means of the Fast Fourier Transform (FFT): The FFT is computed, the magnitude of the FFT coefficients (i.e. the power spectrum) is preserved, but the Fourier phases are randomized. After inverse FFT we obtain signals with the same power spectra as the original series but, due to independent randomization in each case, surrogate data of T and H, surrT and surrH, respectively, are mutually independent. The relation of the annual modes from such surrogate data is illustrated in Fig. 2. Before characterizing the results, I add another example, but instead of (independent) surrogate data which preserved spectral properties of individual series, now I construct the bivariate surrogate data [Prichard & Theiler(1994), Paluš(1996)] preserving also the cross-correlations of the original (temperature and humidity) series. The relation of the annual modes from the bivariate surrogate data is illustrated in Fig. 3.

Comparing Fig. 1 with Fig. 3 we can observe that reproducing only the linear relationships the fine structure of Fig. 1 is lost and Fig. 3 resembles more or less filled ellipsoid. This distinction is possible due to a relatively long time series. On the other hand, selection of a suitable subset from the picture of the independent annual cycles in Fig. 2

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Figure 4: An 8-year subset of Fig. 2, i.e., the annual mode extracted from surrT plotted against the annual mode extracted from surrH series, independently randomized.

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Figure 5: Another 8-year subset of Fig. 2, i.e., the annual mode extracted from surrT plotted against the annual mode extracted from surrH series, independently randomized.

one can obtain a figure more resembling the possibly nonlinear/hysteretic behaviour of the real data in Fig. 1 or in figures 3,4 of the discussed manuscript – see Fig. 4 and Fig. 5. Any visual assessment is usually unreliable and subjective, especially having only a short record available. Searching evidence for nonlinear relations, a quantitative test would be necessary [Paluš(1996)]. Studying relations of oscillatory processes, however, synchronization analysis would be interesting.

4.1 Synchronization analysis

Based on the concept of phase synchronization of chaotic oscillators [Rosenblum et al.(1996), Pikovsky et al.(2001)], a novel technique has been developed to analyze complex, even non-stationary, bivariate data [Rosenblum et al.(1996), Paluš(1997), Pikovsky et al.(2001)]. First, we calculate the instantaneous phases $\phi_1(t)$ and $\phi_2(t)$ of analyzed signals, in our example of the annual modes extracted from the temperature and humidity data. The instantaneous phase and amplitude of a signal $s(t)$ can be determined by using the analytic signal concept of [Gabor(1946)], recently introduced into the field of nonlinear dynamics within the context of chaotic synchronization

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[Rosenblum et al.(1996)]. The analytic signal $\psi(t)$ is a complex function of time defined as

$$\psi(t) = s(t) + j\hat{s}(t) = A(t)e^{j\phi(t)}. \tag{1}$$

$A(t)$ is the instantaneous amplitude and the instantaneous phase $\phi(t)$ of the signal $s(t)$ is

$$\phi(t) = \arctan\frac{\hat{s}(t)}{s(t)}. \tag{2}$$

Having the analyzed signals extracted as the SSA modes, each oscillatory mode usually exists together with its orthogonal ($\pi/2$-delayed or advanced) version. These two modes can be considered as the real and imaginary parts of the analytic signal and the phase $\phi(t)$ can be obtained according to Eq. (2). Having the instantaneous phases $\phi_1(t)$ and $\phi_2(t)$ of the temperature and humidity annual modes, respectively, we define the instantaneous phase difference

$$\Delta\phi(t) = \phi_1(t) - \phi_2(t). \tag{3}$$

In the classical case of periodic self-sustained oscillators phase synchronization is defined as phase locking, i.e., the phase difference is constant. In the case of phase-synchronized chaotic or other complex, noisy systems fluctuations of phase difference typically occur. Therefore, the criterion for phase synchronization is that the absolute values of $\Delta\phi$ must be bounded [Rosenblum et al.(1996)]. When the instantaneous phases are not represented as cyclic functions in the interval $[0, 2\pi)$ but as monotonously increasing functions on the whole real line, then also the instantaneous phase difference $\Delta\phi(t)$ is defined on the real line and is an unbounded (increasing or decreasing) function of time for asynchronous states of systems, while epochs of phase synchronization appear as plateaus in the $\Delta\phi(t)$ vs. time plots. The instantaneous phase difference $\Delta\phi(t)$ of the annual modes extracted from T and H (thick solid line in Fig. 6) is not constant, but its fluctuations are confined within a limited range. We cannot unambiguously speak about phase synchronization, however, some level

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Figure 6: The instantaneous phase difference $\Delta\phi(t)$ of the annual modes extracted from T and H (thick solid line), bivariate surrogate data of T and H (thin solid line) and independent surrogate data of T and H (thick dashed line).

of phase coherence is definitively present. The $\Delta\phi(t)$ for the bivariate surrogate data is also limited, however, an increasing trend is apparent (thin solid line in Fig. 6). [Paluš & Novotná(2006)] show how such a difference can be quantitatively characterized and statistically evaluated. The phase difference $\Delta\phi(t)$ for the independent surrogate data (thick dashed line in Fig. 6) is clearly changing in a large range, showing no phase locking behaviour.

In general, the phase coherence between the annual modes in T and H cannot be satisfactorily explained by the linear cross-correlation in the related bivariate surrogate data. Before declaring that the T–H relationship is nonlinear, there is another problem to consider. The uni- bi- or multi-variate FFT surrogate data destroy nonlinearity also in the internal dynamics of each variable. Many discussions about the inherent dynamics of the atmospheric temperature and other meteorological variables occurred in literature, with conclusions ranging from low-dimensional chaos to linear stochastic processes. [Paluš & Novotná(1994)] demonstrated that after removal of the annual cycle, the residual dynamics of T (Prague–Klementinum record of the length over 200 years) was not distinguishable from the surrogate linear stochastic process. Possible nonlinearity seems to be connected with the annual cycle.

Consider the dominant component of the annual temperature cycle can be written, apart from a noise term, as

$$T(t) = A(t)\cos[\omega t + \psi(t)], \tag{4}$$

where t is time, $A(t)$ is the amplitude, ω is the (constant) frequency given by the tropical (or anomalistic) year. The phase difference $\psi(t)$ describes the difference from the exact harmonic annual cycle, i.e., the fluctuations in the phase of the annual cycle. (Note that in statistical modelling the term phase is used for $\psi(t)$, I use the terminology of the synchronization analysis, where the instantaneous phase is $\phi(t) = \omega t + \psi(t)$.) In a linear stochastic representation $\psi(t)$ would be a randomly fluctuating quantity. We know that the annual cycle is not a simple harmonic, $\psi(t)$ fluctuates, however, these fluctuations are not simply a random process, but a process reflecting atmospheric processes, in particular, $\psi(t)$ of T records from European stations correlates with the North Atlantic Oscillation [Paluš et al.(2005)]. Thus we can see the annual cycle phase fluctuations as the nonlinear response of the atmosphere to the driving due to the Earth movement. (On the centennial scale the fluctuations $\psi(t)$ are much larger than the phase shift due to the precession.) In order to make a statement about nonlinearity in the ecosystem variables, it is necessary to show that the fluctuations of the related annual cycle is not just a linear transformation of the temperature annual cycle. A different type of analysis, however, also applicable in this case, have been used by [Paluš et al.(2004)] who removed the influence of the temperature annual cycle from studied geological data by a multiple linear regression and analysed the residuals in order to characterize the inherent dynamics under interest.

In summary, in order to characterize the ecosystem behaviour as highly nonlinear (p. 1417, l. 22), the authors should provide results of more detailed analysis and quantitative/statistical testing. I tried to point out some possibilities using the above examples. Of course, the authors are not obliged to use any of the above mentioned approaches, but can find inspiration in extended literature on nonlinear dynamics and nonlinearity detection in physical or statistical literature.

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