Phase-coherent oscillatory modes in solar and geomagnetic activity and climate variability

Milan Paluš [a,*], Dagmar Novotná [b]

[a] *Institute of Computer Science, Academy of Sciences of the Czech Republic,*
Pod vodárenskou věží 2, 182 07 Prague 8, Czech Republic

[b] *Institute of Atmospheric Physics, Academy of Sciences of the Czech Republic, Boční II/1401, 141 31 Prague 4, Czech Republic*

Abstract

Oscillatory modes with the period of approximately 7–8 years were detected in monthly time series of sunspot numbers, geomagnetic activity aa index, NAO index and near-surface air temperature from several mid-latitude European locations. Instantaneous phases of the modes underwent synchronization analysis and their statistically significant phase coherence, beginning from 1950's, has been observed. Thus the statistical evidence for a coupling between solar/geomagnetic activity and climate variability has been obtained from continuous monthly data, independent of the season, however, confined to the temporal scale related to oscillatory periods about 7–8 years.

Key words: solar activity, geomagnetic activity, NAO, near-surface air temperature, phase coherence, climate variability

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1 Introduction

Possible influences of the solar activity on the terrestrial climate, in particular, possible manifestations of the solar variability in the climate change have been investigated for many years (see Friis-Christensen & Svensmark (1997); Friis-Christensen (2000); Rind (2002); Haigh (2005); Kane (2005); Lean et al. (2005); Bard & Frank (2006); Tinsley (2008) for reviews). Therefore, relationships between the solar activity, or quantities closely related to the solar activity, and climate data have been sought. Besides the well-known sunspot numbers, the aa index characterizing the geomagnetic activity provides the longest data set of solar proxies which goes back to 1868 (Mayaud, 1972). Some relations during the last century and especially during the last sixty years have been observed between the geomagnetic activity and the near-surface air temperature (Cliver et al., 1998; Bucha & Bucha, 1998; Ponyavin, 2004; Le Mouel et al., 2005; Valev, 2006). Possible connections between the Earth's magnetic field and climate were proposed by Courtillot et al. (2007) and critically discussed by Bard & Delaygue (2008). Dependence relations have been sought between the geomagnetic activity and indices describing the dominant pattern of the tropospheric circulation variability in the extratropical Northern Hemisphere, known as the North Atlantic Oscillation (NAO) (Hurrell et al., 2001). Bucha & Bucha (1998) have found correlations between the geomagnetic activity and circulation indices similar to NAO for the period 1970 – 1996. Thejll et al. (2003) observed correlations between the geomagnetic Ap index and the NAO index after 1970, Lukianova & Alekseev (2004) have found a correlated behaviour between the NAO index and the aa index after 1940. The observed correlations are based on the winter NAO index. This seasonal restriction leads to relatively small numbers of data samples (due to the yearly sampling used), making the statistical significance of the observed correlations extremely vulnerable to small changes in the analysed number of samples and to the choice of preprocessing (e.g., filtering or smoothing) parameters. Bard & Delaygue (2008) discuss this kind of problems in relation to analyses presented in (Courtillot et al., 2007). Another example of the problems caused by a limited number of samples and data smoothing is the correlation between the global air temperature and lengths of the solar cycles (Friis-Christensen & Lassen, 1991; Lassen & Friis-Christensen, 1995). Damon & Peristykh (1999) and Laut (2003) assert that the correlated curves of the global temperature and solar cycle durations during last several decades were probably obtained due to

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[*] Corresponding author.
Email address: `mp@cs.cas.cz` (Milan Paluš).
URL: `www.cs.cas.cz/mp` (Milan Paluš).

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a smoothing procedure applied by Friis-Christensen & Lassen (1991) and Lassen & Friis-Christensen (2000) rather than due to an actual dependence.

In this paper we focus on possible scale-dependent relationships between the solar/geomagnetic activity and the climate variability represented by the NAO index and near-surface air temperature. Since several studies (Gleisner & Thejll, 2003; Veretenenko & Pudovkin, 2000; Usoskin et al., 2004) have observed latitudinal dependence of tropospheric responses to the solar/geomagnetic variability, we have focused on temperature records from mid-latitude European stations. Following our previous studies (Paluš & Novotná, 1998, 2004, 2006, 2007), we first identify oscillatory modes on various temporal scales (frequencies) in the monthly solar, geomagnetic and climate data. Then, for the detected oscillatory modes we extract their instantaneous phases and test a possible presence of phase synchronization in pairs of the modes from different source data. We have found statistically significant phase coherence from 1950's for oscillatory modes with the approximate period of 7–8 years.

2 Methods

The singular system analysis (SSA) is a well-known method for the detection and extraction of trends and oscillatory modes from noisy time series such as long-term records of meteorological variables or measurements from other complex geophysical processes (Vautard et al., 1992; Elsner & Tsonis, 1996; Golyandina et al., 2001; Ghil et al., 2002). Allen & Smith (1996) introduced the Monte Carlo SSA (MCSSA), a statistical approach in which eigenvalues (variance) of the SSA modes are tested using so-called surrogate data. The latter are considered as the null hypothesis of pure red noise and are constructed as realizations of an autoregressive process of order 1 (AR1) which reflects the $1/f^\alpha$ character of the spectrum of the analyzed data, but cannot support oscillations. Then oscillatory modes, if they exist, can in principle be distinguished from a red-noise background. Paluš & Novotná (1998, 2004) proposed to test regularity and predictability in dynamics of the SSA modes, in addition to the test based on the eigenvalues. Using such enhanced MCSSA (EMCSSA), we can distinguish weak dynamical modes with a higher regularity or dynamical memory from false oscillatory modes given by band-pass SSA-filtered noise. Having detected oscillatory modes, the next step is an evaluation of their instantaneous phases (Pikovsky et al., 2001; Paluš, 1997). There are several ways to obtain the latter (Paluš et al., 2005). In SSA, each oscillatory mode usually occurs as two orthogonal (shifted in phase by $\pi/2$) realizations, which allow a direct evaluation of the instantaneous phase. The SSA-extracted modes and their phases, however, suffer from some uncertainty in their temporal localization given by the embedding window used in the univariate SSA (Paluš & Novotná, 1998, 2004). Therefore, we use EMCSSA for the detection of the oscillatory modes in the analyzed data. Once the existence of a particular mode is confirmed in the EMCSSA test, for further processing we extract the instantaneous phase of the detected mode by using the complex continuous wavelet transform (CCWT) (Torrence and Compo, 1998) which gives the instantaneous phases correctly localized in time. The instantaneous phases extracted by using SSA and CCWT are not exactly the same, however, their evaluation gives equivalent results (Paluš & Novotná, 2006; Paluš et al., 2005). The processing of the instantaneous phases becomes a useful tool for assessing relationships in geophysical data on different temporal scales. Moore et al. (2006) use the wavelet extracted phases to search for relations between the sunspot cycle and various meteorological records. Using the same type of phases, Mokhov & Smirnov (2006) demonstrated that the El Niño-Southern Oscillation drives the North Atlantic Oscillation.

Having extracted the instantaneous phases $\phi_1(t)$ and $\phi_2(t)$ of two oscillatory processes, we can study possible relationships between the two processes by the recently developed method of synchronization analysis (Pikovsky et al., 2001; Paluš & Novotná, 2006; Paluš et al., 2007). The synchronization analysis is a useful tool for discovering weak dependence in noisy, nonstationary and relatively short data. It has many successful applications in physiology (Schäfer et al., 1998) and other sciences (Pikovsky et al., 2001). In analysis of climate related data, Maraun & Kurths (2005) have found epochs of phase coherence between the El Niño-Southern Oscillation and the Indian monsoon. Tatli (2007) presents phase synchronization between the North Sea–Caspian pattern index and near-surface air temperature over large territories of the extratropical Northern Hemisphere.

In the classical case of periodic self-sustained oscillators, existence of their coupling (dependence) can lead to phase synchronization, defined as a phase locking, i.e., the phase difference $\Delta\phi(t) = \phi_1(t) - \phi_2(t)$ is constant. If the studied oscillators have different frequencies, they can synchronize for rational frequency ratio n:m (n, m are natural numbers). For such a case we can define the generalized phase difference $\Delta\phi(t) = m\phi_1(t) - n\phi_2(t)$. Again, the synchronization, or the phase locking is given by $\Delta\phi(t)$ =const.

In the case of phase-synchronized chaotic or other complex and noisy systems, fluctuations of the phase difference typically occur. Therefore, the criterion for phase synchronization is that the absolute values of $\Delta\phi$ are bounded (Rosenblum et al., 1996). It is important to note that the instantaneous phases are not represented as cyclic functions in the interval $[0, 2\pi)$ or $[-\pi, \pi)$, 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 (independent) systems, while epochs of phase synchronization (or coherence) appear as plateaus in $\Delta\phi(t)$ vs. time plots. However, the occurrence of a plateau in the $\Delta\phi(t)$ vs. time plot is just a visual indication of a possible phase synchrony. In order to prove that the phase synchronization (coherence) indeed exists in the analyzed data, it must be assessed in a quantitative way. Paluš & Novotná (2006) describe a statistical testing approach using numerically generated surrogate data that have the same frequency spectra (amplitudes of Fourier coefficients) as the original data, but their Fourier phases are randomized independently for each time series. Thus any dependence between the series, present in the original tested data, is removed in the surrogate data. However, the autocorrelations (serial correlations) of individual series are preserved. Ebisuzaki (1997) advocates an equivalent approach to test crosscorrelations in serially correlated data. The phase differences $\Delta\phi(t)$ are then computed from the surrogate data in the same way as from the original tested data. The character of the phase difference can be quantitatively characterized by several different ways and consequently, a probability that such a $\Delta\phi$ plateau, as observed in the analyzed data, can occur by chance without any real dependence, is evaluated using a large number of surrogate data realizations. If the probability of a random occurrence of an equivalent plateau is smaller than, say, 5%, we say that the statistical test is significant on the level $p < 0.05$. Such a result is usually considered as the statistical evidence for the existence of phase synchronization in the studied pair of time series. Strictly speaking, however, such statistical testing provides the evidence for dependence of the phases, but not necessarily for the specific physical mechanism of phase synchronization. Therefore we will use the broader term "phase coherence" instead of the more specific "phase synchronization". Paluš & Novotná (2006) give a detailed description of this testing approach, as well present the results in the case of the phase coherence between the oscillatory modes with a period in the range of the quasi-biennial oscillation (QBO, 27 months in this case) in time series of the North Atlantic Oscillation index and the near-surface air temperature from several mid-latitude European locations. Here we apply the same testing procedure for the phase coherence described below. Paluš (2007) presents a more general discussion regarding the hypothesis testing procedures using the surrogate data techniques.

3 Data

The monthly mean values of the near-surface air temperature from the Czech stations of Prague–Klementinum (longitude 14° 25'E, latitude 50° 05'N, the measurement period 1775–2006) and Milešovka (13° 55'E, 50° 33'N, 1905–2005), as well as from several other European stations: Bamberg (10° 53'E, 49° 53'N), Basel (07° 35'E, 47° 33'N), De Bilt (05° 11'E, 52° 06'N), Potsdam (13° 04'E, 52° 23'N), Vienna (16° 21'E, 48° 14'N), and Zurich (08° 34'E, 47° 23'N), from the period 1901–1999 (Klein-Tank et al., 2002) were used. The annual cycle was removed by subtracting the mean values for each month in the year, averaged over the whole record. The monthly NAO index (1824–2005) with its description is available at http://www.cru.uea.ac.uk/cru/data/. The aa-index spanning the period 1868–2005 was obtained from World Data Centre for Solar-Terrestrial Physics, Chilton,
http://www.ukssdc.ac.uk/data/wdcc1/wdc_menu.html. The sunspot data spanning the period 1749–2006 was obtained from the SIDC-team, Royal Observatory of Belgium, Ringlaan 4, 1180 Brussels, Belgium,
http://sidc.oma.be/DATA/monthssn.dat.

The time series with the monthly sampling obtained as the monthly mean values are used in all cases of the analysed data.

4 Results of EMCSSA

A number of oscillatory modes have been detected in the analyzed data. Paluš & Novotná (2004, 2006) give a detailed description of EMCSSA of the atmospheric data (near-surface air temperature, NAO index). Paluš & Novotná (2007) and Paluš & Novotná (2008) extend EMCSSA to the aa index and the sunspot data.

The common occurrence of the oscillatory modes with the periods of approximately 11, 5.5, and 2.2 years and in the range 7 – 8 years in the sunspot numbers, the aa index, the near-surface air temperature and the NAO index is summarized in Tab. 1.

Let us focus on the modes with the approximate period of 8 years detected in the near-surface air temperature, the NAO index and in the aa index. Figure 1 compares the shapes of these modes when extracted either by SSA or CCWT. Due to the temporal uncertainty, the SSA mode is shifted relatively to the CCWT mode in the case of the near-surface air temperature (Fig. 1a). In the case of the NAO index (Fig. 1b), the timings are consistent, however, CCWT performs stronger smoothing than SSA. Some shift and stronger wavelet smoothing is also apparent in the case of the aa index (Fig. 1c.)

Considering the raw sunspot data, Paluš & Novotná (2007) detected only the mode given by the 11yr solar cycle. After removal of modes related to the 11yr cycle, however, Paluš & Novotná (2008) were able to identify also other oscillatory modes, in particular, the modes with the period of approximately 7.4yr and 2.2yr.

Again, we can compare the mode extracted by SSA in the natural empirical orthogonal function (EOF) base (Fig. 2a) with the modes obtained by CCWT with the

Source	Period [years]			
data	≈ 11	7 – 8	≈ 5.5	≈ 2.2
sunspots	+	+	−	+
aa	+	+	+	−
T	−	+	+	+
NAO	−	+	−	+

Table 1
Occurrence of the most significant oscillatory modes with periods of approximately 11, 7 – 8, 5.5 and 2.2 years in the sunspot numbers, the aa index, the near-surface air temperature and the NAO index. All data are used with the monthly sampling (monthly mean values).

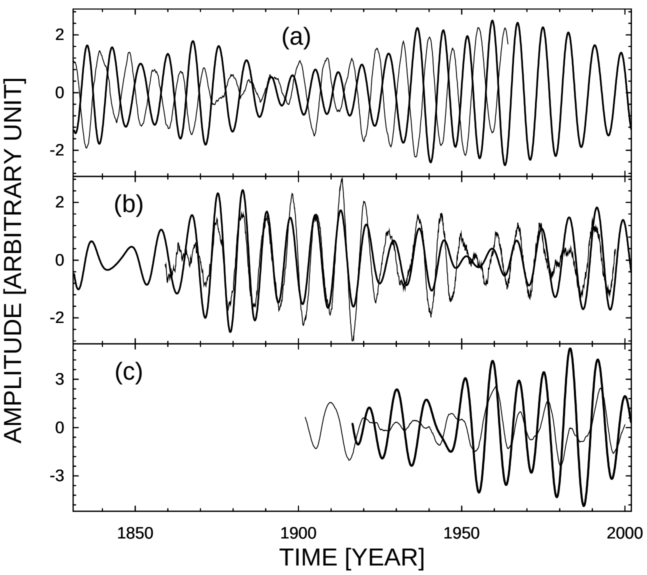

Fig. 1. Oscillatory modes with the approximately 8yr period, extracted by the means of SSA (thin lines) and by the means of CCWT (thick lines), from (a) the monthly Prague near-surface air temperature, (b) the monthly NAO index, and (c) the monthly geomagnetic aa index.

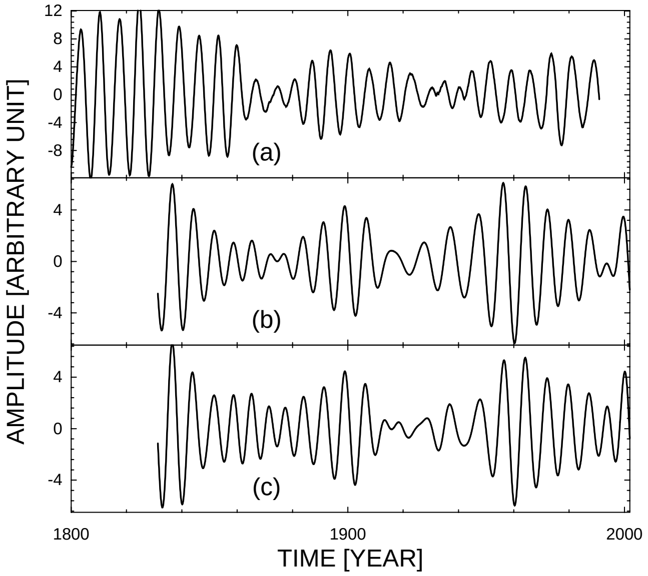

Fig. 2. The oscillatory mode with the approximately 7.4 yr period obtained from the sunspot data residuals after previously removed modes related to the 11 yr cycle, extracted by using SSA (a) and CCWT with the central wavelet frequency corresponding to the periods 8 yr (b) and 7.4 yr (c).

Morlet basis (Torrence and Compo, 1998), using two close central wavelet frequencies corresponding to the periods 8 yr (Fig. 2b) and 7.4 yr (Fig. 2c). We can see that the wavelet extracted modes have a more limited frequency range and the wavelets with different central frequencies are able to better fit the mode shapes in different temporal segments apparently dominated by different frequencies.

It is important to note that the frequency or period accuracy of the SSA approach is limited by the number of frequency bins given by the embedding dimension (Paluš & Novotná, 1998, 2004). The accuracy of the frequency or the period of a particular mode can be increased after the extraction of this mode from the original data and its subsequent spectral or autocorrelation analysis, as Paluš & Novotná (1998, 2004) have done for the temperature mode and found the average period of 7.8yr. On the other hand, oscillatory modes from natural processes are never strictly periodic and their frequency is variable. We illustrate this variability by presenting histograms of instantaneous frequencies of the two close modes – the mode with the period 7.8yr from the Prague temperature (Fig. 3a), and the period 7.4yr mode obtained from the sunspot data residuals after previously removed modes related to the 11 yr cycle (Fig. 3b). The instantaneous frequencies were obtained by differentiation of the instantaneous phases (Paluš & Novotná, 1999; Paluš et al., 2007). The latter were computed by applying the analytic signal approach to the two orthogonal (shifted by $\pi/2$) components of each oscillatory mode, as explained above (see Paluš & Novotná (2006); Paluš et al. (2005) for details). Thus the presented histograms are not nec-

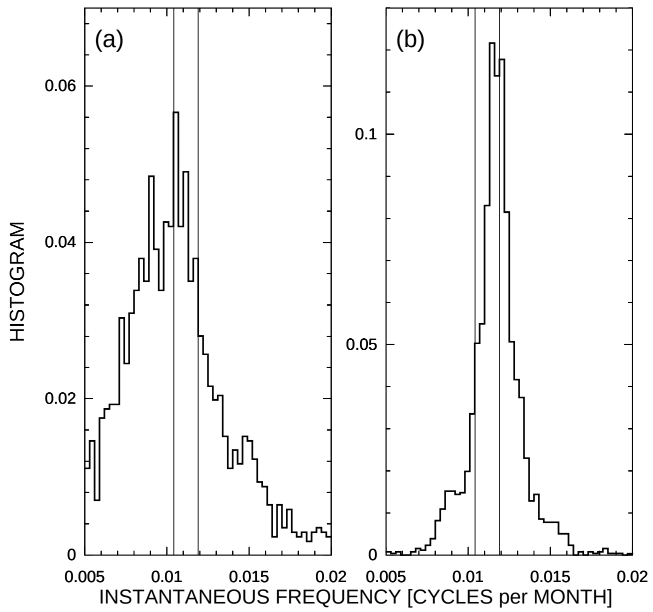

Fig. 3. Histograms of the instantaneous frequencies of the 7.8 yr temperature mode (a) and the 7.4 yr sunspot mode (b). The thin vertical lines mark the frequencies corresponding to the period of 8 and 7 years, reading from the left to the right side.

essarily equivalent to the power (Fourier) spectra, but they better reflect possibly nonstationary fluctuations of the frequencies of the modes. We can see that the most probable period of the sunspot mode is 7.4 years, with the slight tendency to higher frequencies (Fig. 3b); while in the case of the temperature mode the most probable period is 7.8 years, with considerable weight on slower frequencies (Fig. 3a). There is, however, a great deal of common frequencies of the two modes, giving thus a possibility of interactions during some time intervals.

5 Results of synchronization analysis

In order to assure the precise temporal localization of the modes and their phases, in the following we study the instantaneous phases $\phi_i(t)$ and phase differences $\Delta\phi(t)$ obtained by using CCWT.

Figure 4 demonstrates the initial steps of the synchronization analysis. The oscillatory mode with the approximately 8yr period is obtained from the sunspot data residuals (after previously removed modes related to the 11 yr cycle), by using CCWT with the central wavelet frequency giving the period 96 months. The complex continuous wavelet transform gives the complex analytic signal consisting of the real part $s(t)$ and the imaginary (shifted by $\pi/2$) part $\hat{s}(t)$ (Fig. 4a). The instantaneous phase $\phi(t)$ of the extracted signal (mode) $s(t)$ is

$$\phi(t) = \arctan \frac{\hat{s}(t)}{s(t)}. \qquad (1)$$

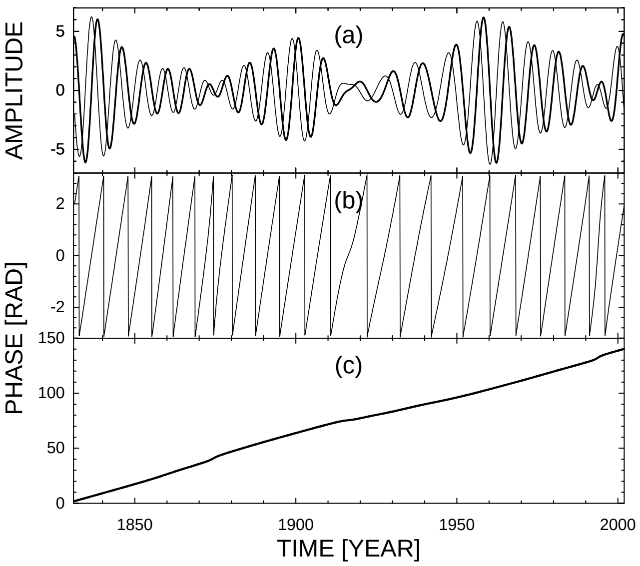

Fig. 4. Two orthogonal ($\pi/2$-lagged) versions of the oscillatory mode with the approximately 8yr period obtained from the sunspot data residuals after previously removed modes related to the 11 yr cycle, extracted by using CCWT (a); the wrapped instantaneous phase of this mode (b); and the unwrapped instantaneous phase of this mode (c).

This is so-called wrapped phase, confined in the interval $[-\pi, \pi)$ (Fig. 4b). Adding 2π after each cycle we obtain so-called unwrapped (monotonously increasing) phase (Fig. 4c), used in the following synchronization analysis.

Using the central wavelet frequency related to the period of 96 months, the obtained instantaneous phase difference $\Delta\phi(t)$ between the aa index and the Prague near-surface air temperature (Fig. 5a, thick line) and between the aa index and the NAO index (Fig. 5a, thin line) decrease at the beginning, however, a plateau occurs from 1950's. Not surprisingly, $\Delta\phi(t)$ between the NAO index and the near-surface air temperature (Fig. 5a, dashed line) is bounded to the plateau, too. The statistical testing for phase synchronization, described by Paluš & Novotná (2006), was applied and confirmed the phase coherence with the high statistical significance $p < 0.004$ and $p < 0.006$ in the case of the aa–NAO index relation and the aa–near-surface air temperature relation, respectively. As a "visual test", in Fig. 5b we compare $\Delta\phi(t)$ between the aa index and the Prague near-surface air temperature (thick line) with $\Delta\phi(t)$ between the aa index and the Prague near-surface air temperature delayed by 70 years (dashed line) and $\Delta\phi(t)$ between the aa index and the Prague near-surface air temperature from the same time as the aa index, but reversed in time (thin line). We can see that in the latter two cases no plateau occurs. Considering also the statistical evaluation we can conclude that the observed plateau reflects a specific relations among the phases of the 7–8yr mode in the aa index, in the near-surface air temperature and in the NAO index, starting in 1950's. The result is also

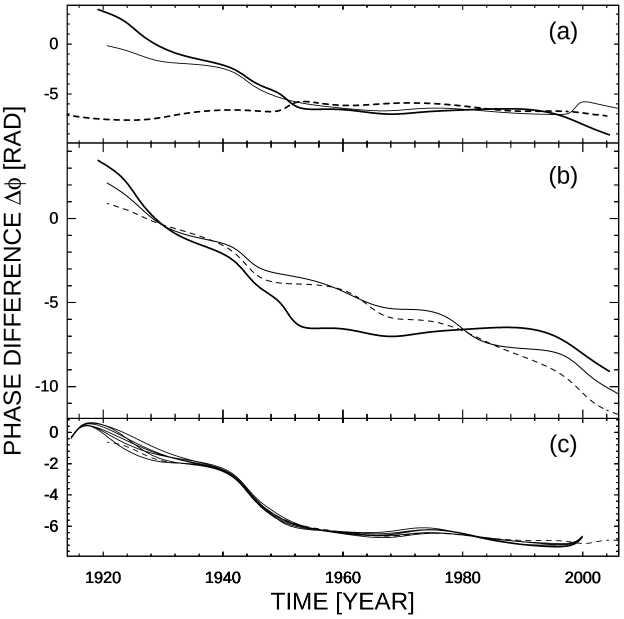

Fig. 5. The instantaneous phase differences of pairs of the oscillatory modes obtained using CCWT with the central wavelet period 96 from (a) the aa index and the Prague near–surface air temperature (thick solid line), the aa index and the NAO index (thin line), the NAO index and the Prague near-surface air temperature (thick dashed line) ; (b) the aa index and the Prague near-surface air temperature (thick solid line), the aa index and the time-reversed Prague near–surface air temperature series (thin solid line), the aa index and the 70 years delayed Prague near-surface air temperature series (thin dashed line); (c) the aa index and the near–surface air temperature from the Milešovka station (dashed line), the aa index and the near-surface air temperature from the 6 European stations (thin solid lines). The monthly sampling, or the monthly mean values are used in all the cases.

confirmed using the monthly means of the near-surface air temperature from other European cities as well as from the Czech mountain station Milešovka (Fig. 5c). Considering the scale specificity of the observed phase coherence, the results are equivalent using the central wavelet frequencies corresponding to the periods 92 – 98 months. For the periods of 90 and 100 – 102 months, the coherent period is shorter (starting in 1960's), while for shorter and longer periods the phase coherence is lost.

While the 7–8yr mode in the temperature, in the NAO index and in the aa index have the dominant period about 7.8 - 8 yr, the related mode in the sunspot data is dominated by the period of 7.4yr with a considerable weight about 7yr (Fig. 3b). Therefore we performed the synchronization analysis between the sunspot 7–8yr mode and the related modes in the other three variables (temperature, NAO, aa index) using the central wavelet periods 96 and 87 months (Fig. 6). From 1950's the results are rather consistent and especially in the relation sunspots-temperature (Fig. 6a) the phase coherence is comparable with the previous case (Fig. 5). In the relations sunspots-NAO and sunspots-aa index the coherence seems to be weaker (the plateaus are "less flat", i.e. some trend is apparent – Fig. 6b, c), however, this behaviour is still significantly different from the temporal evolution of the phase difference of asynchronous processes. In other words, the phases of the studied oscillatory modes are not independent.

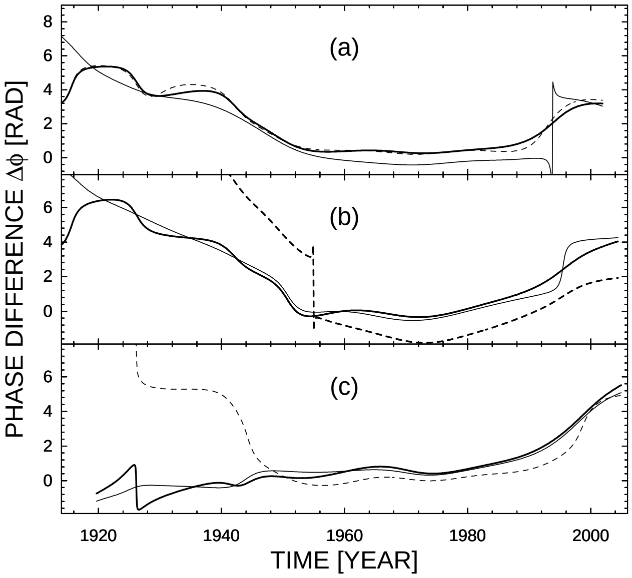

Fig. 6. The instantaneous phase differences of pairs of the oscillatory modes with the approximately 7–8yr period obtained using CCWT from the monthly sunspot data residuals (after previously removed modes related to the 11 yr cycle) and (a) the Prague near-surface air temperature; (b) the NAO index; and (c) the aa index. Different line types mark using different combinations of the central wavelet frequency used: solid thick line is used for the period 87 months for the sunspots and 96 months for the other variable, solid thin line denotes the period 96 months, and the thin dashed line denotes the period 87 months for both the variables.

In most cases (Figs. 5, 6) the plateaus end shortly before the right end of the record, i.e. before or after the year 2000. Due to the available data it is not possible to conclude whether the epoch of the phase coherence ends, or we observe edge effects of the wavelet transform. On the other hand, there are enough data available on the left side from the coherent epoch, so that, considering the 8yr modes, we can conclude that before 1950's there was no phase coherence between the solar and geomagnetic activity on one side and the climate variability on the other side. The 8yr modes from the temperature and NAO, however, are phase coherent all the time (Fig. 5a). The same can be claimed about the 8yr modes from the sunspots and the aa index, considering the central wavelet period of 96 months (Fig. 6c).

In the following we study the instantaneous phase difference $\Delta\phi(t)$ using other modes from Tab. 1. Considering the limited accuracy of the period estimates, for the

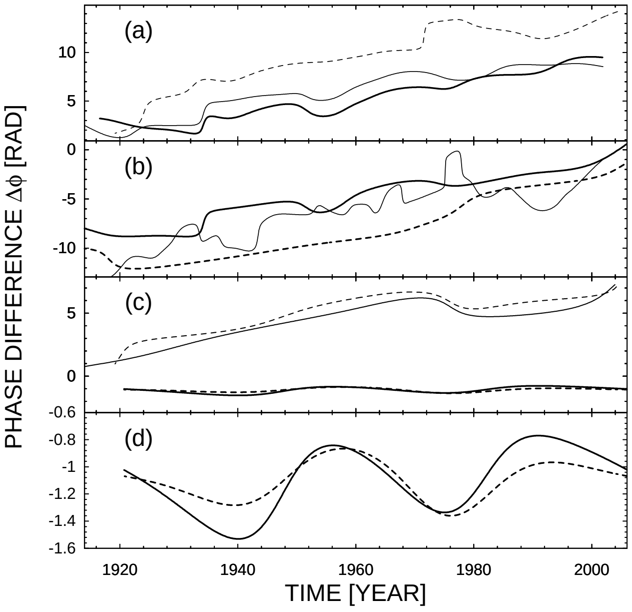

Fig. 7. The CCWT-obtained instantaneous phase differences of (a) period 5.5yr modes extracted from the sunspot numbers and the Prague near-surface air temperature (solid thin line), the aa-index and the NAO index (dashed thin line) and the aa-index and the Prague near-surface air temperature (solid thick line); (b) period 2.2yr modes extracted from the sunspot numbers and from the Prague near-surface air temperature (solid thin line), period 136-month modes extracted from the sunspot numbers and from the Prague near–surface air temperature (dashed thick line), and the period 128-month mode from the sunspot numbers vs. the period 64-month mode from the Prague near-surface air temperature (solid thick line); (c) period 136-month modes extracted from the sunspot numbers and the NAO index (solid thin line), period 136-month modes extracted from the aa-index and the NAO index (dashed thin line), period 136-month modes extracted from the sunspot numbers and the aa-index (solid thick lines) and period 128-month modes extracted from the sunspot numbers and the aa-index (dashed thick lines); (d) period 136-month modes extracted from the sunspot numbers and the aa-index (solid thick lines) and period 128-month modes extracted from the sunspot numbers and the aa-index (dashed thick lines) in their individual scale.

11-year cycle we used modes with the central wavelet periods of 128 and 136 months. The results, however, do not substantially differ. In Fig. 7 we can see a number of increasing or decreasing $\Delta\phi(t)$ curves indicating no phase relations in the studied cases. While Paluš & Novotná (2006) report the phase coherence of the QBO (27 month) modes from the near-surface air temperature and from the NAO index, the related 2.2yr mode from the sunspot data is not coherent either with the temperature (Fig. 5b, solid thin line), nor with the NAO mode in the QBO range. The only phase coherence, indicated by the bounded $\Delta\phi(t)$, is observed in the period 11yr modes from the aa index and the sunspot numbers (thick lines in Fig. 7c). A more detailed view (Fig. 7d) shows that $\Delta\phi(t)$ between the sunspots and the aa index is neither constant nor fluctuating, but changing in a cyclic manner with a period about 36 years.

6 Discussion and conclusion

We used the enhanced Monte Carlo singular system analysis (Paluš & Novotná, 1998, 2004) in order to identify oscillatory modes in the solar (the sunspot numbers) geomagnetic (the aa index) and climate (the NAO index, the near-surface air temperature) variability. Existence of some common oscillatory modes (i.e., the modes with the same average period) gives the possibility to apply the synchronization analysis (Pikovsky et al., 2001; Paluš, 1997; Paluš & Novotná, 2006) in order to find a possible dependence between the phases of the studied oscillatory modes, and thus to find possible relationships of the solar, geomagnetic and climate variability. Using the modes with the approximate period of 11 years, the phase coherence has been found between the solar and geomagnetic activity. The phase difference of the related modes from the sunspot numbers and from the aa index is bounded, however, changing in a periodic manner with the approximate period of 36 years. On the other hand, no direct phase relation has been found between the 11yr mode in the solar and geomagnetic activity on the one side and in the climate variability on the other side. Neither the possible 1:2 synchrony between the solar 11yr mode and the period 5.5 year mode in the near-surface air temperature was observed. These results are in agreement with those of Moore et al. (2006) who found no consistent phase relationship between the sunspot numbers and the sea ice extent or the spring ice break-up in seas and ports, sea surface temperatures, sea level pressure, and various long meteorological records from cities in Europe.

The phase coherence has been found and statistically confirmed in relationships of the oscillatory modes with the period of approximately 7–8 years detected in the sunspot data, the aa index, the NAO index and the near-surface air temperature, starting in 1950's. Thejll et al. (2003) observed correlations between the geomagnetic Ap index and the winter NAO, increasing from 1950's, although statistically significant from 1970's. Using filtered data of the yearly aa index and the winter NAO index, Lukianova & Alekseev (2004) claim that their correlation is significant since the end of 1940's. We have observed a dependence between the solar activity represented by the sunspot numbers and the geomagnetic aa index, and the climate variability, represented by the NAO index and the near-surface air temperature, statistically significant from 1950's in the continuous monthly records independent of the season, however, confined to the temporal scale related to the oscillations with the period of about 7–8 years. It is interesting to note that the oscillatory mode with the period of 7.8 years has been detected in the NAO, in the Arctic Oscillation, in the Uppsala winter near-surface air temperature, as well as in the Baltic Sea ice annual maximum extent by Jevrejeva & Moore (2001). Applying MCSAA on the winter NAO index, Gámiz-Fortis et al. (2002) detected oscillations with the period 7.7 years. Unal & Ghil (1995) and Jevrejeva et al. (2006) observed oscillations with periods of 7 − 8.5 years in a number of sea level records. Feliks & Ghil (2007) report the significant oscillatory mode with the 7.8 year period in the Nile River record, the Jerusalem precipitation, tree rings and in the NAO index. Da Costa & Colin de Verdiere (2002) have detected oscillations with the period 7.7 years in interactions of the sea surface temperature and the sea level pressure. Using global sea-surface temperature fields, Moron et al. (1998) observed 7–8yr oscillations involving the entire double-gyre circulation of the North Atlantic. In an analysis of the mechanisms responsible for interannual variability in the Greenland Iceland-Norwegian Seas, Gámiz-Fortis & Sutton (2007) obtained a quasi-periodic, similar to 7-year signal in sea surface temperature and sea surface salinity using a control integration of the HadCM3 coupled climate model.

Our first application of EMCSSA (Paluš & Novotná, 1998) yielded the observation of the mode with the period of 7.8 years in the near-surface air temperature from several mid-latitude European locations. The observations of the period 7–8yr modes have recently been extended to the NAO index (Paluš & Novotná, 2004), to the geomagnetic activity aa index (Paluš & Novotná, 2007), and to the sunspot data (Paluš & Novotná, 2008). Here we describe our new finding that the instantaneous phases of these modes are not independent. We have already admitted above that the used testing procedures give the statistical evidence for the dependence of the phases, not necessarily for the specific physical mechanism of phase synchronization (Rosenblum et al., 1996). Thus, for the sake of exactness, we use the broader term "phase coherence." Reminding necessary conditions for occurrence of the phenomenon of phase synchronization, however, can help to better understand our results. One can ask why we observe coupling between the solar/geomagnetic activity and climate variability in the 7–8yr modes, when the 11yr cycle is much stronger in both the solar and geomagnetic activity. This would be a relevant question if the observed coupling is due to a direct driving, linear transfer or some resonance mechanism in which the solar forcing is the sole cause of the observed cycles in the climate variability. The phase synchronization, however, is physically different mechanism from the linear transfer, driving or resonance. For the occurrence of phase synchronization, two (or more) cyclic phenomena should exist as self-sustained oscillatory processes. Then, due to even a weak coupling, such oscillatory processes can synchronize (Pikovsky et al., 2001). This is exactly what we have observed: the 7-8yr oscillations have been confirmed in the whole studied time series by using the EMCSSA tests. Before 1950's, these cycles in the climate data – NAO and temperature – are mutually synchronized/coherent, but evolve independently of the 7-8yr cycles in the solar/geomagnetic activity. From 1950's the 7-8yr oscillations in the climate become phase synchronized with the 7-8yr oscillations in the solar/geomagnetic activity. (The solar and geomagnetic activities themselves are always coherent in both 7-8yr and 11yr scales. No 11yr cycles have been found in the NAO and near-surface temperature data.)

The atmospheric processes are nonlinear and thus we cannot expect full understanding of weather and climate evolution within the framework of linear theory. Nonlinear phenomena such as phase synchronization can help to understand cooperative behaviour and coupling within atmospheric phenomena and with possible external influences. We have demonstrated a possibility of coupling between the solar/geomagnetic activity and climate in a part of their variability related to the temporal scale of 7–8 years, starting in 1950's. Actual physical mechanisms of such coupling, however, are still to be proposed. We believe that the presented results will foster relevant discussions and the research in this direction can contribute to understanding of the role of the solar and geomagnetic activity in the climate change.

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