North Hemisphere patterns of phase coherence between solar/geomagmetic activity and NCEP/NCAR and ERA40 near-surface air temperature in period 7-8y oscillatory modes

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

Beginning from 1950's, Paluš and Novotná (J. Atmos. Sol.-Terr. Phys. 71, 923–930, 2009) observed statistically significant phase coherence among oscillatory modes with the period of approximately 7–8 years detected in monthly time series of sunspot numbers, geomagnetic activity aa index, NAO index and near-surface air temperature from several mid-latitude European stations. Using again the oscillatory modes with the period 7-8y, here we study North Hemisphere patterns of phase coherence between solar/geomagnetic activity and NCEP/NCAR and ERA40 near-surface air temperature. Both the reanalysis datasets provide consistent patterns of areas with marked, statistically significant coupling between solar/geomagnetic activity and climate variability observed in 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, NCEP/NCAR and ERA40 near-surface air temperature, phase coherence, climate variability

1 Introduction

A renewed interest in the field of Sun-climate relations, namely in detecting and understanding of climate responses to variable solar activity has led to a number of recently published interesting results (see Friis-Christensen (2000); Rind (2002); Haigh (2003); Haigh (2005); Haigh (2007); Kane (2005); De Jager (2005); Lean et al. (2005); Bard and Frank (2006); Tinsley (2008); Lockwood (2009) for reviews). At the present time we are not able to describe the causal chain of events leading to the observed effects, since we lack a comprehensive understanding of the atmospheric processes and their interactions with solar variability (Gleisner et al., 2005). There is a plenty of empirical evidence that the response to solar signal is not homogenously distributed over the atmosphere, but it shows latitudinal, longitudinal and altitudinal dependence. While there is a well-documented influence of the solar signal in the stratosphere, results about tropospheric responses to the solar variability are more ambiguous. Besides the geographical complexity, dynamical coupling between the stratosphere and the troposphere remains purely understood. In this study we are interested in a tropospheric response to variable solar activity, in particular, in measurable influence of the solar variability observed in near-surface air temperature. The strongest solar signal in the tropospheric temperature has been observed in the tropics and in middle latitudes (40°-50°) of both hemispheres (Haigh , 2003; Gleisner and Thejll, 2003; Gleisner et al., 2005; Lu et al., 2007)). Analogous latitudinal dependence was demonstrated in studies of near-surface air temperature (Camp and Tung, 2007; Tung and Camp, 2008; Lean and Rind, 2008).

With the aim to identify responses to solar forcing, relationships between the solar activity, or quantities closely related to the solar activity, and temperature 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). Significance of geomagnetic activity in investigation of climate response to solar

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

Submitted to J. Atmos. Sol.-Terr. Phys.

signal is noticed in several works (Usoskin et al., 2005; De Jager and Usoskin, 2006; Lockwood and Frohlich, 2007). Having available solar/geomagnetic and climate data, a search for dynamical mechanisms of interacting complex processes underlying experimental data in many cases starts with an attempt to identify trends, oscillatory processes and/or other potentially deterministic signals in a noisy environment. Paluš and Novotná (2007) used so-called Enhanced Monte-Carlo Singular System Analysis (EMCSSA) (Paluš and Novotná, 1998, 2004) in order to detect quasiperiodic phenomena in near-surface air temperature from a number of European stations (Paluš and Novotná, 1998, 2004, 2006), in the monthly North Atlantic Oscillation (NAO) index (Paluš and Novotná, 2004, 2006) and, more recently, in the geomagnetic aa index (Paluš and Novotná, 2007) and the sunspot numbers (Paluš and Novotná, 2008). A number of oscillatory modes have been identified in both the solar/geomagnetic data and the climate data, represented by near-surface air temperatures from European stations and the NAO index, some of them with quite similar periods (Paluš and Novotná, 2007, 2008). The existence of oscillatory modes of common frequencies allows for an application of phase-synchronization analysis (Pikovsky et al., 2001; Paluš and Novotná, 2006; Paluš et al., 2007) in order to detect possible interactions in the studied data. Not surprisingly, 11y cycles in the sunspot data and the geomagnetic aa index have been found phase-coherent (Paluš and Novotná, 2009). There was, however, no phase relations found in the 11y cycle between the solar/geomagnetic data and the climate data, neither the 11y cycle have been found significantly present in the near-surface air temperature records in the mid-latitude European stations in the EMCSSA tests. Possible harmonics, i.e. cycles with period 5.5y have been identified in these temperature records, however, the 2:1 synchronization analysis failed to detect any interactions with the solar/geomagnetic data 11y cycle (Paluš and Novotná, 2009). These results are in agreement with those of Moore et al. (2006) who found no consistent phase relationship between the 11y sunspot cycles 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.

On the other hand, the EMCSSA analysis statistically confirmed existence of oscillatory modes with the period 7-8y in both climate (NAO index, near-surface air temperature from mid-latitude European stations) and solar/geomagnetic data analysed by Paluš and Novotná (2007, 2009). Instantaneous phases of the modes underwent synchronization analysis and their statistically significant phase coherence, beginning from 1950's, has been observed. Thus Paluš and Novotná (2009) were able to present the statistical evidence for a coupling between solar/geomagnetic activity and climate variability, obtained from continuous monthly data, independent of the season, however, confined to the temporal scale related to oscillatory periods about 7–8 years.

In our previous analyses (Paluš and Novotná, 1998, 2004, 2006, 2007, 2009) the near-surface temperature data from European stations were used. In this paper we study North Hemisphere geographical patterns of phase coherence between solar/geomagmetic activity and near-surface air temperature from NCEP/NCAR and ERA40 reanalysis data, considering the period 7-8y oscillatory modes. Thus we map a relative strength of the solar/geomagnetic influence on a part of the temperature variability over the North Hemisphere and compare the results with the pattern of coherence between the NAO index and NCEP/NCAR and ERA40 near-surface temperatures.

2 Methods

The phase synchronization analysis (Pikovsky et al., 2001; Paluš and Novotná, 2006; Paluš et al., 2007) is a useful tool for discovering weak dependence in noisy, nonstationary and relatively short data from oscillatory processes. 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 and 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. Considering a system whose evolution is dominated by a (quasi-)oscillatory dynamics, state of such a system can be described by its instantaneous phase ϕ (Pikovsky et al., 2001). For a measured time series, the phase ϕ can be obtained using the analytic signal concept of Gabor (1946). For an arbitrary time series $s(t)$ the analytic signal $\psi(t)$ is a complex function of time defined as

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

The instantaneous phase $\phi(t)$ of the signal $s(t)$ is then

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

There are several ways how to determine the imaginary part $\hat{s}(t)$ of the analytic signal $\psi(t)$. In the standard approach of Gabor (1946), $\hat{s}(t)$ is given by the (discrete) Hilbert transform of $s(t)$ (Paluš, 1997; Pikovsky et al., 2001). When this procedure is applied to a broadband signal, a filtering procedure is required before computing the Hilbert transform.

The approach used in this study is based on the wavelet transform (Torrence and Compo, 1998). Applying a continuous complex wavelet transform (CCWT thereafter) directly to time series $s(t)$, the complex coefficients related to the scale (frequency) of the studied cycles (here the period of 96 months) can directly be used in Eq. (2) for estimation of the phase $\phi(t)$. Thus the CCWT provides both the band-pass filtering of the signal and the phase estimation. In a similar context, 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 and Smirnov (2006) demonstrated that the El Niño-Southern Oscillation drives the North Atlantic Oscillation.

Both the filtering and a possibility of the phase estimation is also given as an output of singular system analysis. Although neither the standard SSA nor our original EMCSSA is applied in the study presented here, we briefly remind this method since the present study is based on our EMCSSA results (Paluš and Novotná, 1998, 2004, 2007, 2009).

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 and Tsonis, 1996; Golyandina et al., 2001; Ghil et al., 2002). Allen and 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 and 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 ϕ. In SSA, each oscillatory mode usually occurs as two orthogonal (shifted in phase by $\pi/2$) realizations that can directly be used as the real and imaginary parts of the analytic signal in Eq. (2) for estimation of the phase $\phi(t)$. 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 and Novotná, 1998, 2004). Therefore, Paluš and Novotná (2007) had used the 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, in particular, for the phase synchronization analysis it is suitable to extract the instantaneous phase of the detected mode by using the CCWT 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 and Novotná, 2006; Paluš et al., 2005).

Using CCWT one could compute a phase for any frequency from the range given by the sampling frequency and recording time. We stress, however, that cycles with the period of 7-8y, analysed here, were not arbitrarily selected, but their existence in the analysed data has been confirmed by previous EMCSSA analyses (Paluš and Novotná, 1998, 2004, 2006, 2007, 2009).

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 phase synchronization analysis (Pikovsky et al., 2001; Paluš and Novotná, 2006; Paluš et al., 2007). 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. A useful quantitative description of behaviour of the instantaneous phase difference $\Delta\phi(t)$ is the mean phase coherence γ defined as

$$\gamma^2 = \langle \cos(\Delta\phi(\mathrm{t})) \rangle^2 + \langle \sin(\Delta\phi(\mathrm{t})) \rangle^2 \tag{3}$$

where $\langle\rangle$ means the temporal average. The mean phase coherence (MPC) tends to zero for $\Delta\phi$ of asynchronous processes and to one for phase locked systems. Considering real, noisy data neither 0 nor 1 is reached. Therefore, possible presence of phase synchronization or phase coherence should be assessed in a statistical test. Paluš and Novotná (2006) describe a statistical testing approach based on surrogate data. In such a test numerically generated surrogate data are used 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 is quantitatively characterized by the mean phase coherence γ. A probability that such γ_o, 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 $\gamma \geq \gamma_o$ is smaller than, say, 5%, we say that the statistical test is significant on the level 95%, or with $p < 0.05$. 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 and 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

In order to remind the previous study (Paluš and Novotná, 2009), we briefly demonstrate some results obtained using monthly mean values of the near-surface air temperature from these stations: Prague–Klementinum (longitude 14° 25'E, latitude 50° 05'N), 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).

In this study we use monthly mean values of the near-surface air temperature from the NCEP/NCAR (Kalnay et al., 1996) and ERA40 (Simmons and Gibson, 2000) reanalyses. We use the North Hemisphere data in the latitudes from 0 to 70°N in the grid of 2.5°x2.5° in the case of the ERA40 data and 1.875°x1.9° in the case of the NCEP/NCAR data. We evaluate the mean phase coherence for temporal segments of 512 months, starting in January 1958 (see the thick solid line in Fig. 1b). As the only pre-processing of the data, the annual cycle was removed by subtracting the mean values for each month in the year.

The monthly NAO index with its description is available at http://www.cru.uea.ac.uk/cru/data/. The aa-index was obtained from World Data Centre for Solar-Terrestrial Physics, Chilton, http://www.ukssdc.ac.uk/data/wdcc1/wdc_menu.html. The sunspot data 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.

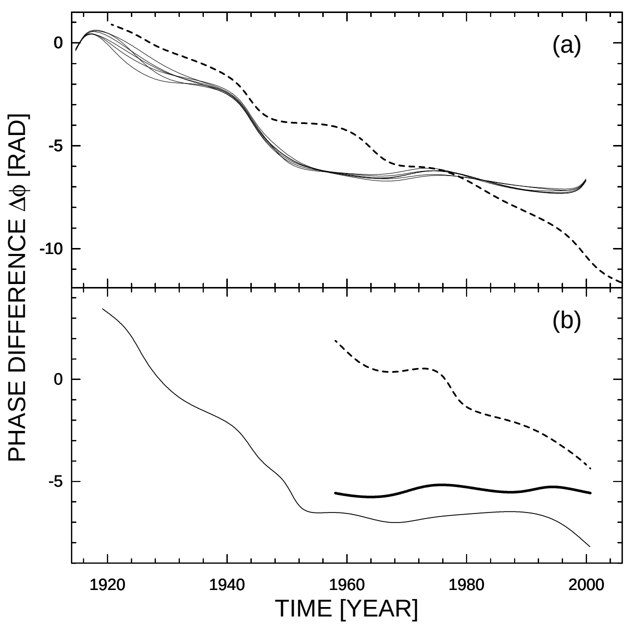

Fig. 1. The instantaneous phase differences of pairs of the oscillatory modes obtained using CCWT with the central wavelet period 96 months from (a) the aa index and the near–surface air temperature from the 6 European stations listed in the Data section (all except of Prague-Klementinum) (thin solid lines); the aa index and the 70 years shifted Prague-Klementinum near-surface air temperature series (dashed line); (b) the aa index and the Prague-Klementinum (14° 25'E, 50° 05'N) near-surface air temperature series (thin solid line); the aa index and the ERA40 near-surface air temperature closest to Prague grid point (15° 00'E, 50° 00'N) (thick solid line); and the aa index and the ERA40 near-surface air temperature from a no-coherence area (0° 00'E, 25° 00'N) (dashed line).

4 Results

In order to remind results of our previous study (Paluš and Novotná, 2009), in Fig. 1 we plot the instantaneous phase difference $\Delta\phi(t)$ between the aa index and several near-surface air temperature series, obtained using the central wavelet frequency related to the period of 96 months. The thin solid lines in Fig. 1a illustrate $\Delta\phi(t)$ between aa index and temperatures from Bamberg, Basel, De Bilt, Potsdam, Vienna and Zurich. The result for the Prague-Klementinum series is plotted in Fig. 1b using the thin solid line. In all cases $\Delta\phi(t)$ decreases at the beginning, however, a plateau occurs from 1950's. The phase coherence in the plateau was quantified using MPC and mutual information (Paluš, 1997) and tested using Fourier transform-based surrogate data (Paluš and Novotná, 2006) with the results strongly supporting the existence of phase synchronization/coherence on the significance levels about 99.5% ($p < 0.005$) (Paluš and Novotná, 2009). For a visual demonstration of the difference between phase coherent and non-coherent modes, we plot $\Delta\phi(t)$ between the aa index and the Prague near-surface air temperature shifted by 70 years (dashed line in Fig. 1a). We can see that in this case $\Delta\phi(t)$ does not plateau but decreases also after 1950's with the same slope as before 1950's.

Now, in order to compare station data with the reanalysis gridded data, in Fig. 1b (thick solid line) we plot the instantaneous phase difference $\Delta\phi(t)$ between the aa index and the near-surface air temperature from the ERA40 grid point 15° 00'E, 50° 00'N (the closest ERA40 grid point to Prague). Apparently, $\Delta\phi(t)$ is confined to the plateau. On the other hand, the decreasing $\Delta\phi(t)$ (dashed line in Fig. 1b) was obtained from the ERA40 grid point 0° 00'E, 25° 00'N which, as we will se below, belongs to one of the areas where no phase coherence between solar/geomagnetic activity and temperature variability was observed. These two $\Delta\phi(t)$ curves also demonstrate the temporal extent of all the following analyses - a segment of 512 months starting in January 1958, ending in August 2000.

Using the sunspot data with removed modes related to the 11y cycle (Paluš and Novotná, 2008, 2009) and aa index and NAO index without any preprocessing, we have computed the instantaneous phase difference $\Delta\phi(t)$ between each of these three variables and near-surface air temperature data from each grid point of both the reanalysis sets. The instantaneous phases were obtained from the CCWT using the central wavelet frequency related to the period of 96 months. The behaviour of $\Delta\phi(t)$ has been quantified by mean phase coherence γ according to Eq. (3). The MPC values are mapped, using color coding, in Fig. 2 for the ERA40 and in Fig. 3 for the NCEP/NCAR reanalysis data. Tung and Camp (2008) discussed some inconsistency between the ERA40 and NCEP/NCAR reanalysis data related to derivation of the surface temperatures. Gleisner et al. (2005) reported

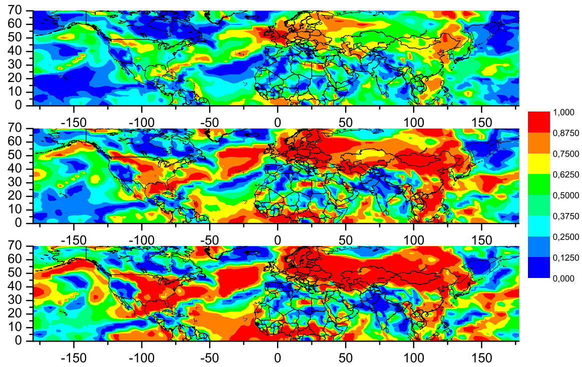

Fig. 2. The mean phase coherence between the sunspot data (top panel), geomagnetic aa index (middle panel), NAO index (bottom panel) and the ERA40 near-surface air temperature for the oscillatory modes obtained using CCWT with the central wavelet period 96 months.

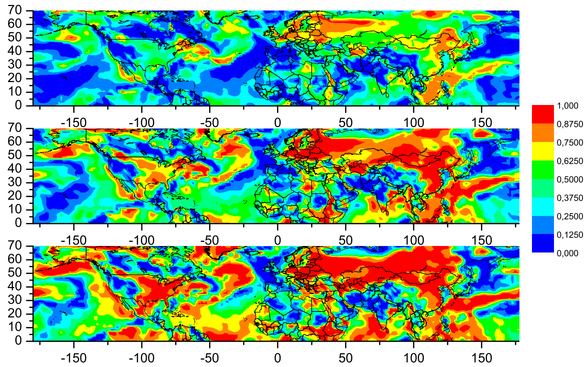

Fig. 3. The mean phase coherence between the sunspot data (top panel), geomagnetic aa index (middle panel), NAO index (bottom panel) and the NCEP/NCAR near-surface air temperature for the oscillatory modes obtained using CCWT with the central wavelet period 96 months.

that Sun-climate relations were substantially weaker in ERA40 data than in the NCEP/NCAR data, especially in upper troposphere thickness. Apparently our results do not confirm such finding; at the first sight it seems that they are even contradictory: The areas of strong phase coherence between the solar data (top panels) and geomagnetic aa index (middle panels) on one side and the temperature data on the other side seem to be more extended in the ERA40 data (Fig. 2) than in the NCEP/NCAR data (Fig. 3). Closer inspection and consideration of the different grid densities used, however, give arguments for a quite good consistency of the obtained results. Moreover, below we will discus the fact that the observed effects are better (more sharply) localized using the NCEP/NCAR data than using the

ERA40 data. It seems that the ERA40 data had to undergo more extended spatial smoothing/averaging than the NCEP/NCAR data, so that the observed effects are more blurred in the ERA40 data.

5 Statistical evaluation

The statistical significance of the observed mean phase coherence has been evaluated using the Fourier transform-based surrogate data. For each grid point 2000 surrogate realizations have been constructed. It is important to establish the statistical significance in each point separately, since the MPC values and their surrogate ranges depend not only on the actual coherence strength, but also on other properties of particular data. Thus it is impossible to establish a universal critical value for the statistical significance. On the other hand, the large number of statistical tests open the question of simultaneous inference. For instance, testing all the 4176 ERA40 grid points, for the total outcome to be significant on the 95% level, a single point test should be significant on the level 99.999%. Such overly conservative approach would diminish or destroy any significance. A more realistic approach would need to estimate the number of actually independent tests which is not a trivial task. Therefore we present significance based on single tests in Fig. 4 for the ERA40 and in Fig. 5 for the NCEP/NCAR reanalysis data. We remind that we were able to perform appropriate tests using the above mentioned station data, so that the statistical evidence for the existence of the discussed phase coherence has been presented in (Paluš and Novotná, 2009). Here, the spatially mapped statistical significance levels should not, at least formally, be considered as a statistical evidence, but rather as orientation information.

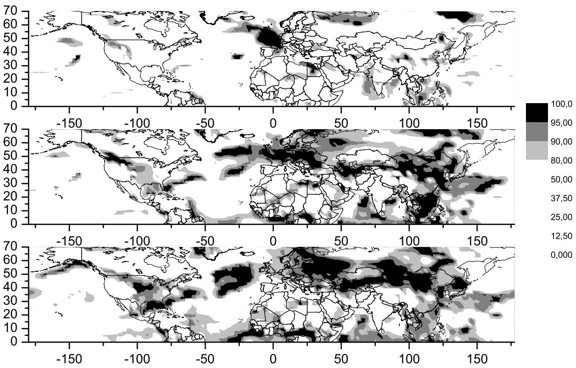

Fig. 4. The significance levels for the mean phase coherence between the sunspot data (top panel), geomagnetic aa index (middle panel), NAO index (bottom panel) and the ERA40 near-surface air temperature for the oscillatory modes obtained using CCWT with the central wavelet period 96 months. The shadowed levels are 80% ($p < 0.2$, light grey), 90% ($p < 0.1$, dark grey), and 95% ($p < 0.05$, black).

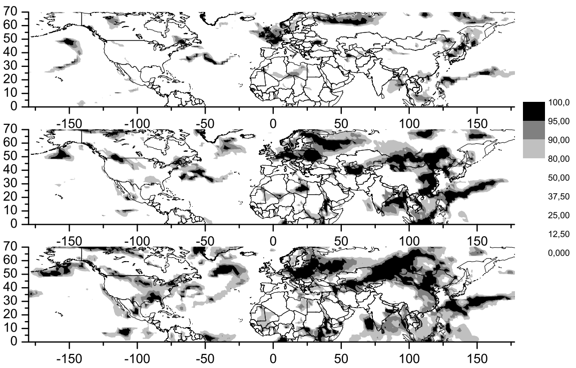

Fig. 5. The significance levels for the mean phase coherence between the sunspot data (top panel), geomagnetic aa index (middle panel), NAO index (bottom panel) and the NCEP/NCAR near-surface air temperature for the oscillatory modes obtained using CCWT with the central wavelet period 96 months. The shadowed levels are 80% ($p < 0.2$, light grey), 90% ($p < 0.1$, dark grey), and 95% ($p < 0.05$, black).

6 Discussion of the results

A quick comparison of the top and middle panels in Figs. 2–5 remind the results from the station data (Paluš and Novotná, 2009) where the coherence of temperature with the sunspot data has been weaker than that with the geomagnetic data, however, all the results were statistically significant. Here not only the areas of coherence between temperature and the sunspot data are less extended than those of coherence between temperature and the aa index, but even the results are not significant in the areas where the station data gave the significant results (e.g. Czech Republic, Germany). This discrepancy between the station and reanalysis data can evokes a suspicion that the solar signal is partially attenuated in the reanalysis data. This problem should be clarified in future studies using other solar data.

The areas of strong phase coherence between the temperature and the geomagnetic aa index (middle panels in Figs. 2–5) are quite more extended and statistically significant consistently with the station data. If we focus on the Eastern Hemisphere with latitude extent 30-70°N we can observe that the high coherence areas are confined to land areas. Here we can see the high spatial resolution of the NCEP/NCAR data (Fig. 3) – the Baltic Sea is clearly distinguished by low coherence from high coherence over the surrounding land, while this distinction is totally blurred in the ERA40 data (Fig. 2). Therefore it would be more useful to discuss the NCEP/NCAR data results due to the more precise localization of the observed coherence phenomena. We can see that the high coherence region extents over Northern, Western and Central Europe further to the East, leaving out most of the Southern European areas. Then it spreads eastward over Asia, extending more to the South in the far East. Looking back to Scandinavia and continuing eastward toward Russia, the coherence area is squeezed a bit to the South, probably due to influence of the Arctic Ocean. The return of the high coherence back to the North at the far East is apparently due to the land extended more to the North – the north-most maximum between 100 and 125°E is apparently due to Tajmyr peninsula followed northward by the Severnaja Zemlja archipelago. The north-most high coherence spot around 150°E is probably due to area of Cape Svjatoj Nos followed northward by Ljahovskie and Novosibirskie archipelagos. This spot is bounded from the South and East, probably due to the influence of the Okhotsk Sea from the South and the East Siberian Sea from the East. This correspondence of the high coherence with the land is clear only in the considered strip between 30-70°N on the Eastern Hemisphere, possibly including Great Britain and Ireland on the West, if we consider also the sunspot data. In other parts of the world high coherence areas cover parts of the land as well as parts of seas and oceans and these patterns require further study.

Considering again the suspicion that the smaller extent of the areas of high coherence of temperature with the sunspot data is due to lower quality of the data could imply that these areas should be subsets of the coherence areas of temperature with the aa index. This seems to be the case, with the one exception – Great Britain and Ireland, the areas with quite high and statistically significant phase coherence between temperature and the sunspot data, but with low and insignificant coherence with the aa index.

Since Paluš and Novotná (2009) observed mutual coherence of temperature, the sunspot data, the aa index and the NAO index, it might be useful to study also the coherence patterns between temperature and the NAO index (bottom panels in Fig. 2–5). These areas are the most extended and include consistently the areas of phase coherence of temperature with the geomagnetic aa index and consequently also the areas of coherence with the sunspot data, however, with the exception of Great Britain and Ireland, as noted above. These findings could open the debate about the role of the NAO in possible transmission of the solar signal from the stratosphere to the troposphere.

7 General discussion and conclusion

Paluš and Novotná (2007, 2008) proved existence of common oscillatory modes (i.e., the modes with the same average period) in the solar/geomagnetic and climate data. Therefore they were able to apply the synchronization analysis (Pikovsky et al., 2001; Paluš, 1997; Paluš and Novotná, 2006) in order to find a possible dependence between the phases of the observed oscillatory modes, and thus to find possible relationships of the solar, geomagnetic and climate variability. 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 from several European stations, 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 and Alekseev (2004) claim that their correlation is significant since the end of 1940's. Paluš and Novotná (2009) 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, and without any special preprocessing such as removal of El Niño and volcanic signals, however, confined to the temporal scale related to the oscillations with the period of about 7–8 years. Here we study the North Hemisphere patterns of phase coherence between solar/geomagmetic activity and NCEP/NCAR and ERA40 near-surface air temperature in period 7-8y oscillatory modes, again in the continuous monthly records independent of the season, and without any special data preprocessing. The temporal scale related to the oscillatory period 7-8y has not been chosen arbitrarily, but based on our previous results proving the existence of the period 7-8y oscillatory modes in the solar/geomagnetic and climate data (Paluš and Novotná, 1998, 2004, 2007, 2008).

It is important to note that our results (Paluš and Novotná, 1998, 2004, 2007, 2008) are not isolated in the scientific literature. Plaut et al. (1995) detected an oscillatory component with the period 7.7y in 335y long central England temperature record. 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 and Moore (2001). Applying MCSAA on the winter NAO index, Gámiz-Fortis et al. (2002) detected oscillations with the period 7.7 years. Unal and Ghil (1995) and Jevrejeva et al. (2006) observed oscillations with periods of 7 – 8.5 years in a number of sea level records. Feliks and 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 and 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 7–8y 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 and 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. Thus the oscillatory phenomena with the period 7-8y present an important part of climate variability. We have shown the North Hemisphere patterns of phase coherence between the period 7-8y oscillatory modes in near-surface air temperature and solar/geomagnetic activity. While other studies (Gleisner et al., 2005; Tung and Camp, 2008) point to inconsistencies in solar responses, or even inconsistencies in occurrence of approximate 8y periodicities (Pišoft et al., 2009) when comparing the ERA40 and NCEP/NCAR reanalysis datasets, using the temporal scale of naturally existing oscillatory phenomena we have found consistent results using both the ERA40 and NCEP/NCAR reanalysis data. We have pointed out to a possible role of the NAO in the transmission of the solar influence from the stratosphere to the troposphere. Most of the results, however, require further study and understanding. The future aims range from technical tasks (analysis of different solar data, inclusion of the Southern Hemisphere), through theoretical challenges related to the origin of the observed oscillatory modes and their interactions (Does NAO play a role in the solar signal transition mechanism from the stratosphere to the troposphere? Is there other mechanism influencing Great Britain and Ireland? Or, is NAO the instigator of the observed phase coherence and other synchronization phenomena which can lead to climate shifts, as recently proposed by Wang et al. (2009)?) to the quite critical question about the role of this part of climate variability in the present climate change.

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 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.

Acknowledgement

This study was supported by the Grant Agency of the Academy of Sciences of the Czech Republic project No. IAA300420805, and in part by the Institutional Research Plans AV0Z10300504 and AV0Z30420517.

References

Allen, M.R., Smith, L.A., 1996. Monte Carlo SSA: Detecting irregular oscillation in the presence of colored noise. J. Climate 9(12), 3373–3404.

Bard, E., Frank, M., 2006. Climate change and Solar variability: What's new under the sun? Earth Planet. Sci. Lett. 248(1-2), 1–14.

Camp, Ch. D., Tung, K. K., 2007. Surface warming by the solar cycle as revealed by the composite mean difference projection. Geophys. Res. Lett. 34, L14703.

Da Costa, E.D., de Verdiere, A.C., 2002. The 7.7-year North Atlantic Oscillation. Q.J.R. Meteorol. Soc. 128, 797–817.

Gabor, D., 1946. Theory of Communication. J. IEE London 93(3), 429–457.

De Jager C., 2005. Solar forcing of climate. 1: Solar variability. Space Science Reviews 120, 197–241.

De Jager, C., Usoskin, I.G., 2006. On possible drivers of Sun-induced climate changes. J. Atmos. Sol.-Terr. Phys. 68, 2053-2060.

Ebisuzaki, W., 1997. A method to estimate the statistical significance of a correlation when data are serially correlated. J. Clim. 10, 2147–2153.

Elsner, J.B., Tsonis, A.A., 1996. Singular Spectrum Analysis. A New Tool in Time Series Analysis. Springer, Berlin.

Feliks, Y., Ghil, M., 2007. Interannual, synchronized oscillations over the North Atlantic, Eastern Mediterranean and Ethiopian Plateau. Geophys. Res. Abs. 9, 05600.

Friis-Christensen, E., 2000. Solar variability and climate - A summary. J. Space Sci. Rev. 94(1-2), 411-421.

Gámiz-Fortis, S.R., Pozo-Vázques, D., Esteban-Parra, M.J., Castro-Díez, Y., 2002. Spectral characteristics and predictability of the NAO assessed through Singular Spectral Analysis. J. Geophys. Res. 107(D23), 4685.

Gámiz-Fortis, S.R., Sutton, R.T., 2007. Quasi-periodic fluctuations in the Greenland-Iceland-Norwegian Seas region in a coupled climate model. Ocean Dyn. 57(6), 541–557.

Ghil, M.R., Allen, M., Dettinger, M.D., Ide, K., Kondrashov, D., Mann, M.E., Robertson, A.W., Saunders, A., Tian, Y., Varadi, F., Yiou, P., 2002. Advanced spectral methods for climatic time series. Rev. Geophys., 40, 1003.

Gleisner, H., Thejll, P., 2003. Patterns of tropospheric response to solar variability. Geophys. Res. Lett., 30(13), 1711.

Gleisner, H., Thejll, P., Stendel, M., Kaas, E., Machenhauer, B., 2005. Solar signals in tropospheric reanalysis data: Comparing NCEP/NCAR and ERA40. J. Atmos. Sol.-Terr. Phys. 67, 785-791.

Golyandina N., Nekrutkin, V., Zhigljavsky, A., 2001. Analysis of Time Series Structure. SSA and Related Techniques. Chapman and Hall/CRC, Boca Raton.

Haigh, J.D., 2003. The effects of solar variability on the Earth‘s climate. Phil. Trans. R. Soc. Lond. A 361, 95-

111.
Haigh, J.D., 2005. Solar variability and climate. Astrophysics and Space Science Library 344, 65–81.
Haigh, J.D., 2007. The Sun and Earth‘s Climate. Living Rev. Solar Phys. 4, lrsp-2007-2. http://solarphysics.livingreviews.org/Articles/lrsp-2007-2/
Hurrell, J.W., Kushnir, Y., Visbeck, M., 2001. Climate - The North Atlantic oscillation. Science 291(5504), 603–605.
Jevrejeva, S., Moore, J.C., 2001. Singular Spectrum Analysis of Baltic Sea ice conditions and large-scale atmospheric patterns since 1708. Geophys. Res. Lett. 28(23), 4503–4506.
Jevrejeva, S., Grinsted, A., Moore, J.C., Holgate, S., 2006. Nonlinear trends and multiyear cycles in sea level records. J. Geophys. Res., 111, C09012.
Kane, R.P., 2005. Sun-Earth relation: Historical development and present status - A brief review. Adv. Space Res., 35(5), 866–881.
Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., Joseph, D., 1996. The NCEP/ NCAR 40-year reanalysis project. Bulletin of the American Meteorological Society 77, 437471.
Klein-Tank, A.M.G. et al., 2002. Daily dataset of 20th century surface air temperature and precipitation series for the European Climate Assessment. Int. J. Climatology 22, 1441–1453.
Lean J., Wang, Y.M., Sheeley, N.R., 2005. SORCE contribution to new understanding of global change and solar variability. Solar Physics 230, 27–53.
Lean, J. L., Rind, D. H., 2008. How natural and anthropogenic influences alter global and regional surface temperatures: 1889 to 2006. Geophys. Res. Lett. 35, L18701.
Lockwood, M., 2009. Recent changes in solar outputs and the global mean surface temperature. III. Analysis of contributions to global mean air surface temperature rise. Proc. R. Soc. A 464, 1387-1404.
Lockwood, M., Frohlich, C., 2007: Recent oppositely-directed trends in solar climate forcing and the global mean surface air temperature. Proc. R. Soc. A 463, 2447-2460.
Lu H., Jarvis M.J., Graf H.-F., Young P.C., Horne R.B., 2007. Atmospheric temperature response to solar irradiance and geomagnetic activity. J. Geophys. Res. 112, D11109.
Lukianova, R., Alekseev, G., 2004. Long-term correlation between the NAO and solar activity. Solar Phys. 224, 445–454.
Maraun, D., Kurths, J., 2005. Epochs of phase coherence between El Niño/Southern Oscillation and Indian monsoon. Geophys. Res. Lett. 32(15), L15709.
Mayaud, P.N., 1972. The aa indices: a 100year series characterizing the magnetic activity. J. Geophys. Res. 77(34), 6870–6874.
Mokhov I.I., Smirnov, D.A., 2006. El Niño-Southern Oscillation drives North Atlantic Oscillation as revealed with nonlinear techniques from climatic indices. Geophys. Res. Lett. 33(3), L03708.
Moore, J., Grinsted, A., Jevrejeva, S., 2006. Is there evidence for sunspot forcing of climate at multi-year and decadal periods? Gephys. Res. Lett. 33, L17705.
Moron V., Vautard R., Ghil, M., 1989. Trends, interdecadal and interannual oscillations in global sea-surface temperatures. Climate Dyn. 14(7–8), 545–569.
Paluš, M., 1997. Detecting phase synchronization in noisy systems. Phys. Lett. A 235, 341–351.
Paluš, M., 2007. From Nonlinearity to Causality: Statistical testing and inference of physical mechanisms underlying complex dynamics. Contemp. Phys. 48(6), 307–348.
Paluš, M., Novotná, D., 1998. Detecting modes with nontrivial dynamics embedded in colored noise: Enhanced Monte Carlo SSA and the case of climate oscillations. Phys. Lett. A 248, 191–202.
Paluš, M., Novotná, D., 2004. Enhanced Monte Carlo Singular System Analysis and detection of period 7.8 years oscillatory modes in the monthly NAO index and temperature records. Nonlin. Proc. Geophys. 11, 721–729.
Paluš, M., Novotná, D., Tichavský, P., 2005. Shifts of seasons at the European mid-latitudes: Natural fluctuations correlated with the North Atlantic Oscillation. Geophys. Res. Lett. 32, L12805.
Paluš, M., Novotná, D., 2006. Quasi-Biennial Oscillations extracted from the monthly NAO index and temperature records are phase-synchronized. Nonlin. Proc. Geophys. 13, 287–296.
Paluš, M., Novotná, D., 2007. Common oscillatory modes in geomagnetic activity, NAO index and surface air temperature records. J. Atmos. Sol.-Terr. Phys. 69, 2405–2415.
Paluš, M., Kurths, J., Schwarz, U., Seehafer, N., Novotná, D., Charvátová, I., 2007. The solar activity cycle is weakly synchronized with the solar inertial motion. Phys. Lett. A 365 412–428.
Paluš, M., Novotná, D., 2008. Detecting Oscillations Hidden in Noise: Common Cycles in Atmospheric, Geomagnetic and Solar Data. In: Donner, R., Barbosa, S. (eds.): Nonlinear Time Series Analysis in the Geosciences – Applications in Climatology, Geodynamics, and Solar-Terrestrial Physics. Lecture Notes in Earth Sciences 112. Springer, Berlin, 327–354.
Paluš, M., Novotná, D., 2009. Phase-coherent oscillatory modes in solar and geomagnetic activity and climate variability. J. Atmos. Sol.-Terr. Phys. 71, 923–930.
Pikovsky, A., Rosenblum, M., Kurths, J., 2001. Synchronization. A Universal Concept in Nonlinear Sciences. Cambridge University Press, Cambridge.
Pišoft, P., Mikšovský, J., Žák, M., 2009. An analysis of the spatial distribution of approximate 8 years periodicity in NCEP/NCAR and ERA-40 temperature fields. Eur. Phys. J. Special Topics 174, 147–155.

Plaut, G., Ghil, M., Vautard, R., 1995. Interannual nad interdecadal variability in 335 years of central England temperatures. Science 268, 710–713.

Rind, D., 2002. The Sun's Role in Climate Variations. Science 296, 673–677.

Rosenblum, M.G., Pikovsky, A.S., Kurths, J., 1996. Phase synchronization of chaotic oscillators. Phys. Rev. Lett. 76, 1804–1807.

Schäfer, C., Rosenblum, M.G., Kurths, J., Abel, H.-H., 1998. Heartbeat synchronized with ventilation. Nature 392, 239.

Simmons, A.J., Gibson, J.K. (Eds.), 2000. The ECMWF Project Plan, ECMWF Project Report Series, 1, ECMWF, Reading, UK.

Tatli, H., 2007. Synchronization between the North Sea–Caspian pattern (NCP) and surface air temperatures in NCEP. Int. J. Climatol. 27, 1171–1187.

Thejll, P., Christiansen, B., Gleisner, H., 2003. On correlation between the North Atlantic Oscillation, geopotential heights, and geomagnetic activity. Geophys. Res. Lett. 30(6), 1347.

Tinsley, B.A., 2008. The global atmospheric electric circuit and its effects on cloud microphysics. Reports on Progress in Physics 71, 066801.

Torrence, C., Compo, G.P., 1998. A practical guide to wavelet analysis. Bull. Amer. Meteorological Society 79(1), 61–78.

Tung, K. K., Camp, Ch. D., 2008. Solar cycle warming at the Earth surface in NCEP and ERA40 data: A linear diskriminant analysis. J. Geophys. Res. 113, D05114.

Unal, Y.S., Ghil, M., 1995. Interannual and interdecadal oscillation patterns in sea level. Clim. Dyn. 11, 255–278.

Usoskin, I.G., Schussler, M., Solanki, S.K., Mursula, K., 2005. Solar activity, cosmic rays, and Earth's temperature. A millenium-scale comparison. J. Geophys. Res. 110, A10102.

Vautard, R., Yiou, P., Ghil, M., 1992. Singular spectrum analysis: a toolkit for short noisy chaotic signals. Physica D 58, 95–126.

Wang, G., Swanson, K.L., Tsonis, A.A., (2009). The pacemaker of major climate shifts. Geophys. Res. Lett. 36, L07708.