Shifts of seasons at the European mid-latitudes: Natural fluctuations correlated with the North Atlantic Oscillation

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Daily mean near-surface air temperature series from seven European locations were processed in order to obtain reliable estimates of instantaneous phases of the annual cycle as an objective measure of timing of seasons. The recent changes of the latter do not depart from the range of natural phase fluctuations observed in the historical temperature records. Significant, geographically dependent correlations of the phase fluctuations with the North Atlantic Oscillation index, as well as weaker, negative correlations with the El Niño Southern Oscillation index have been observed.

Geophys. Res. Lett. 32 (2005) L12805, doi:10.1029/2005GL022838

PACS numbers:

I. INTRODUCTION

The timing of seasons at mid and higher latitudes has a strong influence on natural ecosystems and human activities such as agriculture, forestry, water management, transportation and tourism. Recently, a number of phenological studies have reported an earlier onset of spring seasons in many European locations [1, 3–5, 13, 14, 16, 17]. Since the changes in timing of seasons has been found correlated with changes in the air temperature [4, 16], some authors have interpreted the advancement of the spring seasons as a direct response to a rise in global temperature, attributed to the CO_2-induced global warming [3, 13]. Other studies have looked for explanations in internal atmospheric circulation processes and significant correlations between phenology dates (the dates of the first leafing or blooming of plants, pollen season starts, etc.) and phases of the North Atlantic Oscillation (NAO) have been detected [5, 16]. Start dates of climatic seasons, determined using daily mean temperatures, have also been found correlated with parameters of atmospheric circulation [10]. Relatively a few studies, however, deal with the annual temperature cycle itself. Using the complex demodulation of the long-term monthly mean near-surface temperature records from Central England and several European stations, Thomson [18] observed that the 20th century changes in the phase of the annual cycle cannot be exclusively explained by insolation variability and argued for an anthropogenic greenhouse signal in the Northern Hemisphere seasonal cycle, especially due to a significant phase deviation starting in the 1940's and continuing till the 1990's. Another work, however, observed in extended European temperature records that the most significant changes in the annual cycle occurred during the 1920's, with a distinct decrease in the annual cycle amplitude [19]. More recently, the observed data have been compared with simulations from general circulation climate models [12, 23]. The observed changes in the amplitude are consistent with the model simulations, yet the phase trends are of opposite signs (i.e., the observed phase advances, but the simulated phase delays). This fact opens the question of a correct estimation of the variability of the annual temperature cycle and of assessing the existence of trends and significance of changes observed in the recent decades in comparison with the historical temperature records.

In this letter we apply four different methods for the estimation of instantaneous phases of the annual cycle from historical records of daily mean near-surface air temperature from seven European locations. The consistency of the estimates is checked by comparing independent methods, their reliability by comparison with actual annual temperature profiles. The recent phase changes are confronted with the historical records and possible relations of the estimated phase fluctuations with atmospheric circulation indices are studied.

II. METHODS

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

$$T(t) = A(t)\cos[\omega t + \phi(t)], \tag{1}$$

where t is time, $A(t)$ is the amplitude, ω is the (constant) frequency given by the tropical (or anomalistic [18]) year. The phase $\phi(t)$ describes the difference from the exact annual cycle, i.e., the fluctuations in the timing of the seasons. There are several different ways how to estimate the phase $\phi(t)$. They can be sorted into two classes of methods: (I.) model based (usually sinusoidal model fitting - SMF) approaches and (II.) analytic signal (complex demodulation) techniques.

(I.) One of the possible SMF techniques assumes a state-space model of the signal such that at each time instant the signal is described by a parameter vector. If the parameter vectors were constant in time, the output signal would be a sinusoid with some amplitude, frequency and phase. The state vectors, however, need not be constant, but may be modelled as a random process, for example as a process with independent identically distributed increments. Such a random walk model for evolution of a frequency of a random signal was described in Ref. [20]. Here we assume that the mean frequency of the signal is a known constant, but the phase $\phi(t)$ of the signal has random increments.

(II.) The second class of the techniques are based on the analytic signal concept of Gabor [7]. For an arbitrary signal $s(t)$ the analytic signal $\psi(t)$ is a complex function of time defined as

$$\psi(t) = s(t) + j\hat{s}(t) = A(t)e^{j\Phi(t)}. \tag{2}$$

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

$$\Phi(t) = \arctan\frac{\hat{s}(t)}{s(t)}. \tag{3}$$

The amplitude is

$$A(t) = \sqrt{s(t)^2 + \hat{s}(t)^2}. \tag{4}$$

Now, there are several ways how to determine the imaginary part $\hat{s}(t)$ of the analytic signal $\psi(t)$:

(II.1. – HT) Using the standard approach of Gabor [7], $\hat{s}(t)$ is given by the (discrete) Hilbert transform of $s(t)$ [15].

(II.2. – SSA) The second approach is based on singular system analysis: Take the analyzed time series $\{y(i)\}$, $i = 1, \ldots, N_0$, and construct a map into a space of n-dimensional vectors $\mathbf{x}(i)$ with components $x^k(i)$, where $k = 1, \ldots, n$, given as

$$x^k(i) = y(i + k - 1). \tag{5}$$

Construct a symmetric $n \times n$ matrix $\mathbf{C} = \mathbf{X}^T\mathbf{X}$, with elements:

$$c_{kl} = (1/N)\sum_{i=1}^{N} x^k(i)x^l(i), \tag{6}$$

where $1/N$ is the proper normalization and the components $x^k(i)$, $i = 1, \ldots, N$, are supposed to have a zero mean. The symmetric matrix $\mathbf{C}$ can be decomposed as

$$\mathbf{C} = \mathbf{V}\Sigma\mathbf{V}^T, \tag{7}$$

where the $n \times n$ matrix $\mathbf{V} = \{v_{ij}\}$ gives an orthonormal basis in the space of vectors $\mathbf{x}(i)$, Σ=diag$(\sigma_1, \sigma_2, \ldots, \sigma_n)$,

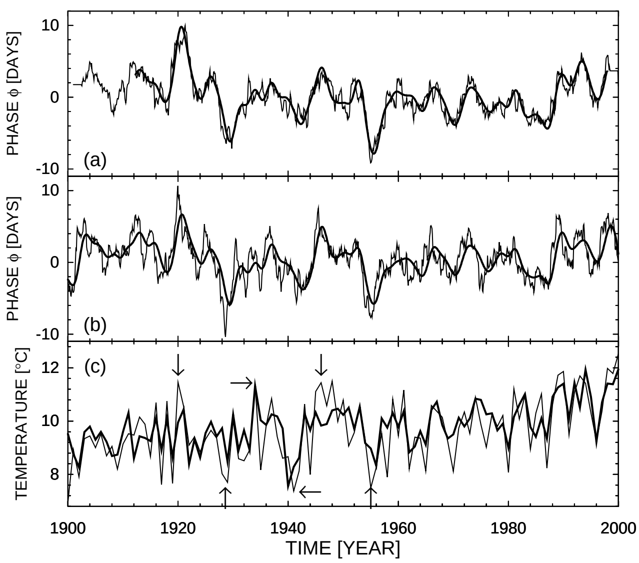

FIG. 1: (a,b) The instantaneous phase (difference) $\phi(t)$ of the annual cycle obtained from the daily mean near-surface air temperature record from (a) Potsdam, extracted using the wavelet (thick line) and the sine fitting method (thin line); and (b) from Prague, extracted using the wavelet (thick line) and the SSA method (thin line). (c) Annual (thick line) and March – May (thin line) mean near-surface air temperatures, Prague record.

σ_i are non-negative eigenvalues giving the variance of orthogonal modes

$$\xi_i^k = \sum_{l=1}^{n} v_{lk}x_i^l, \tag{8}$$

into which the original series can be decomposed. For more details see, e.g., [22].

The temperature time series are dominated by the annual cycle and the two largest eigenvalues are related to the following two modes: the extracted annual cycle and 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. (3).

(II.3. – WV) The final approach is based on the wavelet transform [21]. Applying a continuous complex wavelet transform to the temperature series, the complex coefficients related to the scale (frequency) of the annual cycle can be directly used in Eq. (3) for estimation of the phase $\Phi(t)$.

Then, in analogy with (1) we put:

$$\Phi(t) = \omega t + \phi(t), \tag{9}$$

where ω is the constant annual frequency and $\phi(t)$ is the instantaneous phase (difference) giving the fluctuations in the timing of the seasons.

III. DATA AND RESULTS

The described methods have been applied to daily mean near-surface air temperature series recorded in Bamberg, Basel, DeBilt, Potsdam, Vienna and Zuerich during the period of 1901–1999 [11] and Prague - Klementinum during 1775–2001. The WV and SMF estimates of $\phi(t)$ for the Potsdam data are compared in Fig. 1a), and the WV and SSA estimates for the Prague record in Fig. 1b). The WV estimates from the all seven European locations are presented in Fig. 2c) using the thin smooth lines.

The WV method provides smooth, robust with respect to noise estimates of $\phi(t)$ which could, however, neglect local extrema. The SMF, SSA and HT methods are more sensitive to relatively fast fluctuations, but also more vulnerable to noise. The overall agreement of all the methods is very good, i.e., our estimates measure a real physical phenomenon and are not significantly affected by statistical biases or numerical artifacts potentially inherent to a particular method. In order to understand consequences of the $\phi(t)$ fluctuations, in Fig. 1c) we plot the annual mean temperature and the mean temperature over March, April and May (M-A-M) in Prague. Comparing Fig. 1c) with 1b) one could infer that the extrema in the M-A-M temperature are caused either by the extrema in the annual means such as in 1934 (warm months M-A-M during a warm year, marked by the right arrow in Fig. 1c) and in 1941 (left arrow) when the cold year 1940 is followed by the cold months M-A-M in 1941; or, more frequently, the whole year mean temperature is not extremal but the M-A-M temperature reaches its local extremum due to an extremal fluctuation in the phase $\phi(t)$ of the annual cycle: The peaks in the M-A-M temperature, distant from the annual mean temperature (Fig. 1c), coincide with the peaks in $\phi(t)$ (Fig. 1b), e.g., in 1920 and 1946 (the down arrows), or in 1928 and 1955 (the up arrows in Fig. 1c). Fig. 2.: The annual profiles of the daily temperatures in the years with the most distant $\phi(t)$ extrema are illustrated in Fig. 2a): The 1929 annual cycle (full lines) is apparently delayed relatively to the 1920 annual cycle (dashed lines). The temperature of March 21, 1920, is attained in 1929 on April 14, i.e., with a delay of 24 days (given by the smoothed data, illustrated by the thick lines; the delay is marked by the full straight lines in Fig. 2a). The difference of the $\phi(t)$ peaks in 1920 and 1929 in the SSA estimate (Fig. 1b, thin line) is 21 days. This is a good agreement, considering the variance of the raw daily temperature (thin lines in Fig. 2a). Further in the year, the delay is attenuated – the temperature of May 1, 1920 is attained in 1929 with the delay of 15 days. The summer maxima of the 1920 and 1929 cycles are shifted by approximately 10 days, which agrees with the difference in the $\phi(t)$ extrema in the WV estimate (Fig. 1b, thick line). The combination of the estimation methods gives us robust (WV) and sensitive (SSA or SMF) estimates of the fluctuations in the phase $\phi(t)$ of the annual cycle from both the qualitative (positions of extrema) and quantitative (the agreement of the $\phi(t)$ estimates with the actual seasonal shifts given by the smoothed temperature) points of view. Unlike Thomson [18], we did not confirm any significant deviations of $\phi(t)$ from 1940's. The annual temperature cycles in the 1990's are generally advanced in comparison with the period of the mid-1950's to the 1980's, so we can confirm the 4–6 day spring advancement observed in the phenological events [13]. This season shift, however, does not depart from the range of $\phi(t)$ fluctuations observed in historical records (Fig. 2b,c). Instead of disputing a cause of the particular $\phi(t)$ digression observed in the 1990's, it is more desirable to understand mechanisms underlying the process of the fluctuations of the phase $\phi(t)$ of the annual temperature cycle. The first step of research in this direction is a comparison of the $\phi(t)$ fluctuations with circulation indices. (The NAO and SOI data, used below, and their descriptions are available at http://www.cru.uea.ac.uk/cru/data/.) The strongest effect of the North Atlantic Oscillation [8, 9] on $\phi(t)$ occurs in its January – March period, similarly as in the case of the phenology dates [5]. The related correlation coefficients range from 0.32 and 0.33 for Basel and Zuerich, to 0.47 and 0.51 for Prague and Potsdam,

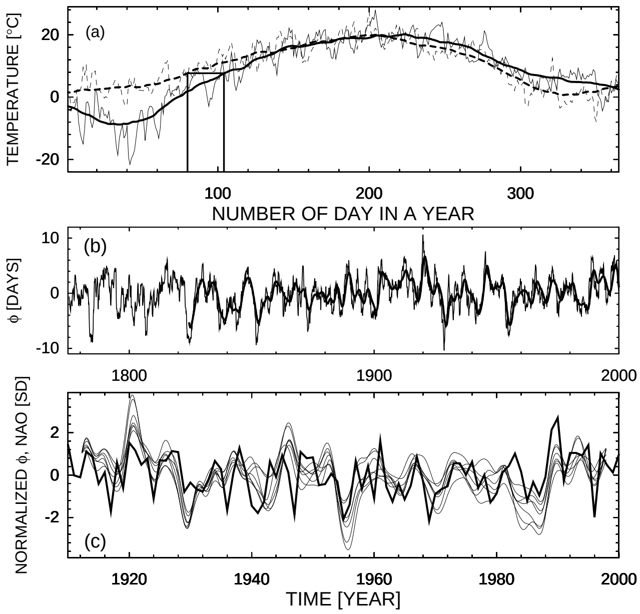

FIG. 2: (a) The daily mean near-surface air temperature in Prague in 1920 (dashed lines) and in 1929 (full lines), raw data (thin lines) and smoothed data (thick lines). The full straight lines show that the temperature of March 21, 1920; was reached with a delay of 24 days in 1929. (b) The phase $\phi(t)$ of the annual cycle obtained from the full 1775 – 2001 Prague record (thin line – SSA, thick line – the wavelet method). (c) The phase $\phi(t)$ of the annual cycle obtained from the seven European stations using the wavelet method (thin smooth lines) and the NAO index averaged over the January-March period (thick line). All data normalized to the zero mean and the unit variance.

respectively, considering the 20th century records. The correlations are geographically dependent and statistically significant. Considering the Southern Oscillation Index (SOI), we obtain weaker, negative correlations, e.g., -0.14 for Prague, or -0.16 for Potsdam. This is an interesting result, considering that the crosscorrelation of the related SOI and NAO indices is 0.004. (Obtained using the annual SOI averages against the January – March NAO averages, used above. The correlation between the monthly SOI and NAO indices is 0.06, see http://www.cdc.noaa.gov/Correlation/table.html.)

IV. CONCLUSION

In this study we compared four methods for estimating the phase $\phi(t)$ of the annual temperature cycle at mid-latitudes using daily mean near-surface temperature records from seven European locations. The estimates have been found robust, mutually consistent and correctly capturing shifts in the temperature cycles of different years, i.e., the shifts in the onsets of seasons. The latter can be estimated in an objective and robust way, without any subjective definitions of the seasons, just by computing relative differences of $\phi(t)$ of different years for the date(s) of interest. Using this approach we have confirmed the advancement of the spring seasons in the 1990's, observed in the phenological records. Without further evidence, however, this season shift cannot be regarded as a systematic trend or tendency due to recent anthropogenic influences, since fluctuations of $\phi(t)$ of comparable amplitudes occurred throughout the historical temperature records ranging back to the end of the 18th century. Moreover, no significant trends were detected using the wavelet and SSA decompositions of the phases $\phi(t)$. The $\phi(t)$ fluctuations (the fluctuations of the timing of seasons) can be regarded as a natural dynamical phenomenon which should be accounted for in deseasonalization and related processing of temperature data. The process of $\phi(t)$ fluctuations is probably connected with global atmospheric circulation processes, as suggested by the correlations with the circulation indices, esp. with the NAO index. Considering the recently growing interest in quantifying possible limits of predictability of the NAO phenomenon and the ability of the climate numerical models of simulating it [2, 6], such a significant correlation is potentially very important. Since the NAO does not fully explain the $\phi(t)$ fluctuations, further research of the $\phi(t)$ dynamics and factors influencing it, is desirable. Potential skills in prediction of onsets of seasons could have significant socio-economic impacts, while an unpredictable phase in the climate may be a more serious problem to society than changes in the amplitude of the annual cycle or even of the mean temperature [18].

Acknowledgments

This study is supported by the Institutional Research Plans AV0Z10300504, AV0Z30420517 and AV0Z10750506.

[1] Ahas, R., et al. (2002), Changes in European spring phenology, *Int. J. Climatology*, *22(14)*, 1727–1738.

[2] Bojariu, R. and L. Gimeno (2003), Predictability and numerical modelling of the North Atlantic Oscillation, *Earth-Science Reviews*, *63(1-2)* 145–168.

[3] McCarty, J.P. (2001), Ecological consequence of recent climate change, *Conservation Biology*, *15(2)*, 320–331.

[4] Chmielewski, F.M., and T. Rotzer (2002), Annual and spatial variability of the beginning of growing season in Europe in relation to air temperature changes, *Climate Research*, *19(3)*, 257–264.

[5] D'Odorico, P., J. Yoo, and S. Jaeger (2002), Changing seasons: An effect of the North Atlantic Oscillation?, *J. Climate*, *15(4)*, 435–445.

[6] Eden, C., R.J. Greatbatch, and J. Lu (2002), Prospects for decadal prediction of the North Atlantic Oscillation (NAO), *Geophys. Res. Lett.*, *29(10)*, 1466–1469.

[7] Gabor, D. (1946), Theory of communication, *J. IEE London*, *93(3)*, 429–457.

[8] Hurrell, J.W., and H. VanLoon (1997), Decadal variations in climate associated with the North Atlantic Oscillation, *Climatic Change*, *36(3-4)*, 301–326.

[9] Hurrell, J.W., Y. Kushnir, and M. Visbeck (2001), Climate - The North Atlantic oscillation, *Science 291(5504)*, 603.

[10] Jaagus, J., J. Truu, R. Ahas, and A. Aasa (2003), Spatial and temporal variability of climatic seasons on the East European Plain in relation to large-scale atmospheric circulation, *Climate Research*, *23 (2)*, 111–129.

[11] 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.

[12] Mann, M.E., and J. Park (1996), Greenhouse warming and changes in the seasonal cycle of temperature: model versus observations, *Geophys. Res. Lett.*, *23*, 1111–1114.

[13] Menzel, A., (2000), Trends in phenological phases in Europe between 1951 and 1996, *Int. J. Biometeorology*, *44(2)*, 76–81.

[14] Menzel, A., and P. Fabian (1999), Growing season extended in Europe, *Nature*, *397*, 659.

[15] Paluš, M. (1997), Detecting phase synchronization in noisy systems, *Phys. Lett. A*, *235*, 341–351.

[16] Scheifinger, H., et al. (2002), Atmospheric mechanisms governing the spatial and temporal variability of phenological phases in Central Europe, *Int. J. Climatology*, *22(14)*, 1739–1755.

[17] Sparks, T.H., and A. Menzel (2002), Observed changes in seasons: An overview, *Int. J. Climatology*, *22(14)*, 1715–1725.

[18] Thomson, D.J. (1995), The seasons, global temperature, and precession, *Science*, *268*, 59–68.

[19] Thompson, R. (1995), Complex demodulation and the estimation of the changing continentality of European climate, *Int. J. Climatology*, *15*, 115–185.

[20] Tichavský, P., and P. Händel (1995), Two algorithms for adaptive retrieval of slowly varying multiple cisoids in noise, *IEEE Trans. Signal Processing*, *43(5)*, 1116–1127.

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

[22] Vautard, R., P. Yiou, and M. Ghil (1992), Singular spectrum analysis: a toolkit for short noisy chaotic signals, *Physica D*, *58*, 95–126.

[23] Wallace, C.J., and T.J. Osborn (2002), Recent and future modulation of the annual cycle, *Climate Res.*, *22*, 1–11.