Solar signal in climate change: cross wavelet and EMD analysis of time-series

Tatiana V. Barlyaeva and Dmitri I. Ponyavin

Institute of Physics, University of St.Petersburg, 198504, St.Petersburg, Russia

Long-term climatic time series and solar proxies are studied using wavelet transforms and Empirical Mode Decomposition method. Cross wavelet technique is applied to examine coherence and phase relationships between various time-series on interannual scale and to find the solar signal in climatic data. Time-frequency patterns reveal synchronous quasi-periodicities and the global origin of some climatic oscillations. Patterns display also transient correlations and nonlinear impact of solar activity on climate. Geographical regions and historic periods of significant solar impact on climate are allocated. The last 70 years since 1930's demonstrate unusual hypersensitivity of climate response to solar output: this result is discussed in conjunction with the problem of unprecedented high level of sunspot activity and climate warmth in the late 20th century.

1. Purposes

The purposes of this research are:

1) to investigate the change in climate time-series (some instrumental and reconstructed data) on interannual time scale;
2) to find the solar signal in climatic data;
3) if it exists, to find the time periods and regions of climate sensitivity to solar signal.

2. The structure of the poster

1) *Instrumental climate datasets:* wavelet & cross-wavelet (with solar activity) analysis of annual (smoothed by 5 points) data;
2) *reconstructed paleo-climate datasets:* wavelet & cross wavelet (with solar activity) analysis of annual (smoothed by 5 points) data;
3) *reconstructed paleo-climate datasets:* wavelet & cross-wavelet (with solar activity) analysis of modes obtained by Empirical Mode Decomposition method.

3. Methodology

In this research, wavelet analysis, cross wavelet technique (coherence and phase analysis) and Empirical Mode Decomposition (EMD) method were applied to solar and climatic time-series.

Wavelet transform:

This is a well known tool for data analysis since about beginning of 1990's. The mathematical definition of wavelet transform is the following:

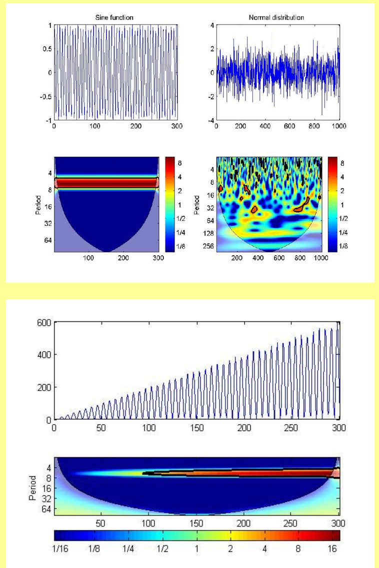
$$W_n(s)=\sum_{n'=0:N-1} x_{n'}\ \psi^*[(n'-n)\partial t/s],$$

where ψ is a localized wavelet, s is a scale parameter and n is a time index.
Here one uses the Morlet wavelet:

$$\Psi_0(\eta)=\pi^{-1/4}\exp(i\omega_0\eta)\exp(-\eta^2/2),$$

where $\omega_0=6$, η is a dimentionless time parameter.

Wavelet pictures for the sine function and the normal distribution (up) and a wavelet picture of the sine function with trend (down) are presented.



Cross wavelet technique:

One can define the wavelet cross spectrum $WCS_i(s)$ as the expectation value of the product of the corresponding $W^x_i(s)$ and $W^y_i(s)$:

$$WCS_i(s)=< W^x_i(s)W^y_i(s)>.$$

WCS is complex valued and can be decomposed into amplitude and phase:

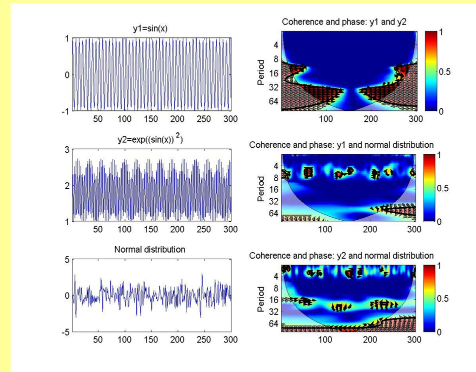
$$WCSi(s)=|WCSi(s)|*\exp(i*\Phi_i(s)).$$

The phase $\Phi_i(s)$ describes the delay between the two signals at time t_i on a scale s.

A normalized time and scale resolved measure for the relationship between two time series $x(t_i)$ and $y(t_i)$ is the wavelet coherency (*WCO*), which is defined as the amplitude of the *WCS* normalized to the two single *WPS*:

$$WCO_i(s)=|WCS_i(s)|/(WPS^x_i(s)WPS^y_i(s))^{1/2},$$

where $WPS_i(s)$ is the wavelet power spectrum: $WPS_i(s)=<W_i(s)W_i(s)^*>$.



The coherence and phase analysis illustration: periodic functions and normal distribution.

Empirical Mode Decomposition (EMD):

For a given signal $x(t)$ we look for a decomposition into simpler signals (modes):

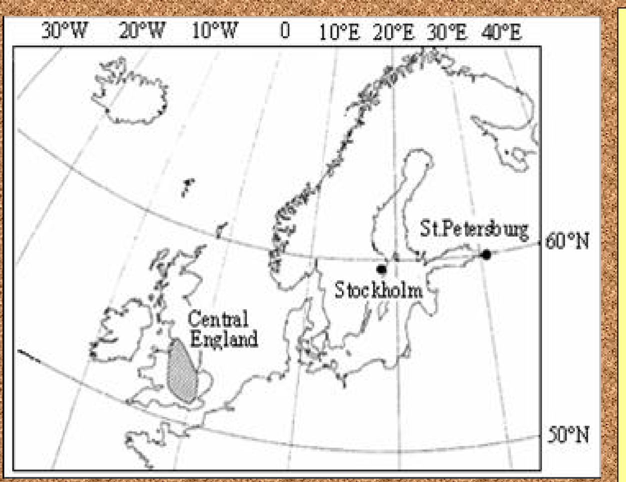
$$x(t)=m_K[x](t)+\sum_{k=1:K}d_k\ [x](t),$$

where $d_k(t)$ is the amplitude of the k-th component. Each of the components has to have a physical and mathematical meaning.

The effective algorithm of EMD can be summarized as follows:

1) identify the extrema of $x(t)$;
2) interpolate between minima (resp. maxima), ending up with some envelope $e_{min}(t)$ (resp. $e_{max}(t)$);
3) compute the mean $m(t)=(e_{min}(t)+e_{max}(t))/2$;
4) extract the detail $d(t)=x(t)-m(t)$;
5) iterate on the residual $m(t)$.

4. Experimental data



The map of the instrumental datasets under consideration.

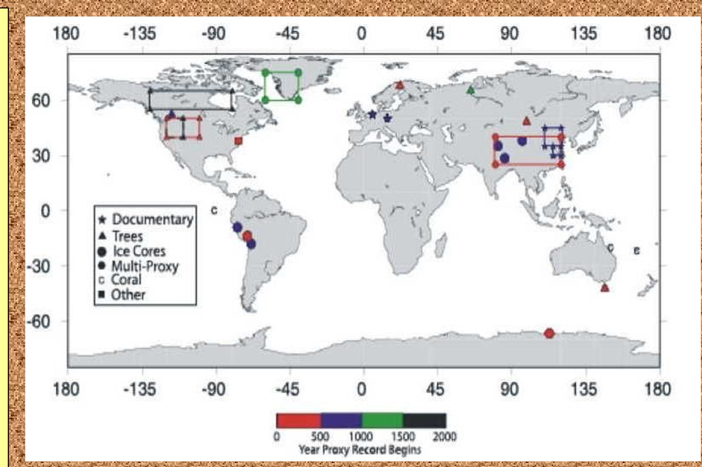
In this research the instrumental air temperature datasets for Stockholm, St.Petersburg and Central England were studied.

Also the climate proxies (T, NAO, SOI) discussed in the paper of Jones & Mann (2004) are used. The length of data sets varies from 300 to 2000 years.

Paleo data were reconstructed by different methods based on the information kept in corals, trees, ice cores and documentary.

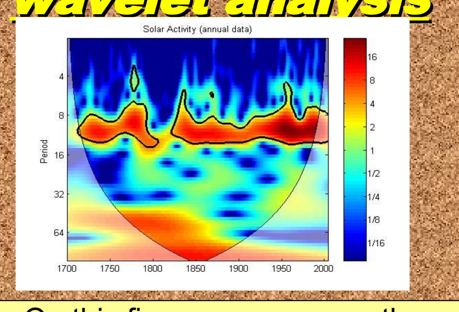
Here we investigate the annual climate data smoothed by Moving Average Smoothing (MAS) method by 5 points as well as non-smoothed ones.

As an indicator of solar activity variations the Wolf number index (from NGDC database http://ngdc.noaa.gov/ngdc.html) is used. As above, we study smoothed and non-smoothed annual data.



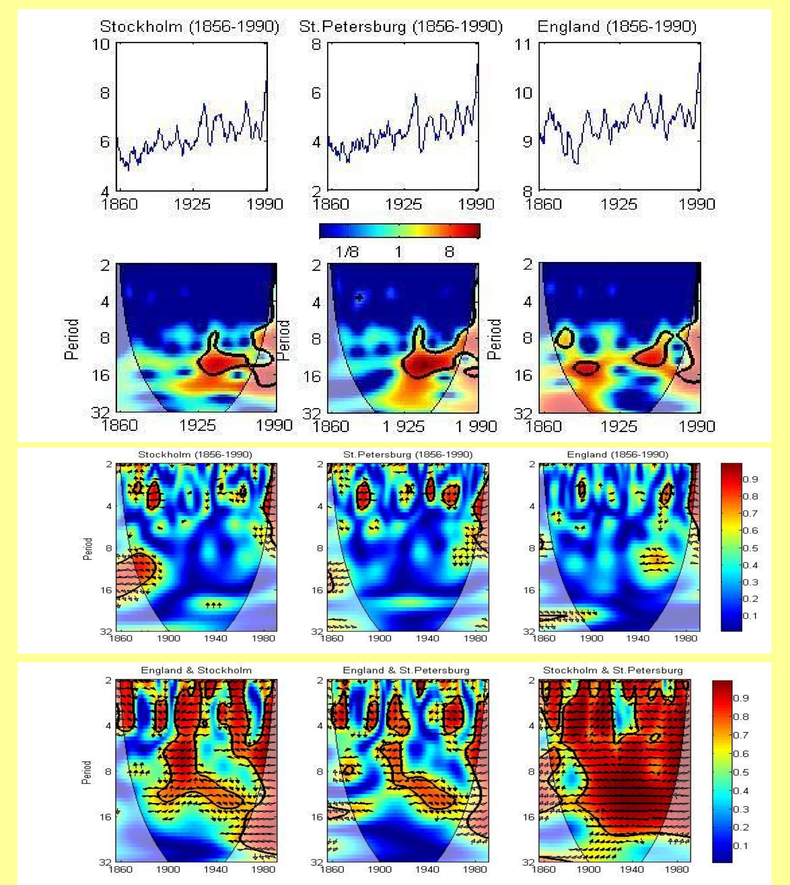
The map of available high-resolution (annual or decadal) proxy indicators with a verifiable temperature signal available over much of the past two millennia (Jones and Mann, 2004).

5. Solar activity: wavelet analysis



On this figure one can see the wavelet spectrum of annual Wolf numbers. The well known 11-year periodicity can be seen. Some peculiarity in 1800-1820 is observed. ***One can see the increasing of the wavelet amplitude around 11-year period since 1930.***

6. Air Temperature (instrumental data)

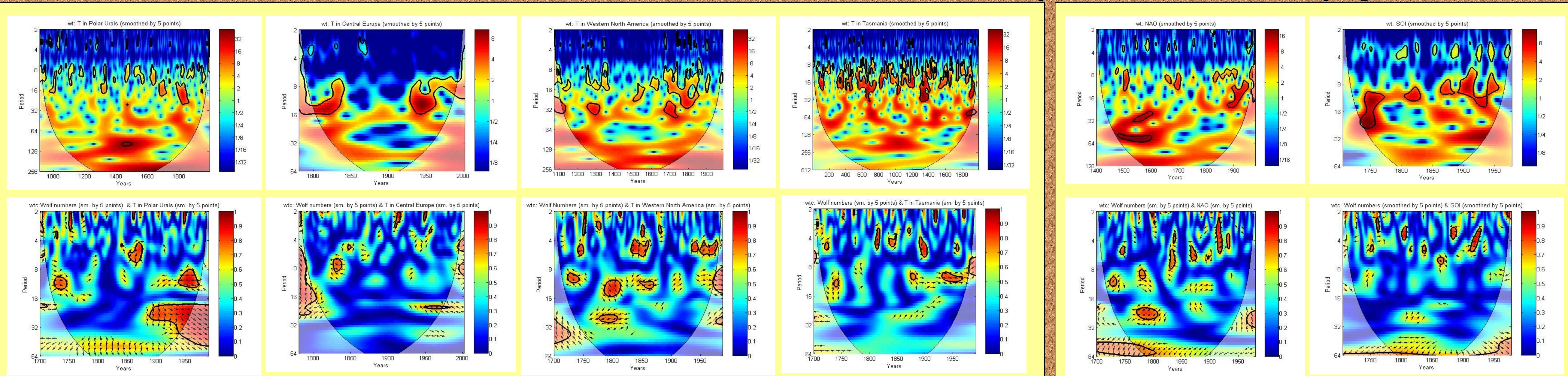


The result of wavelet analysis of the instrumental air temperature data (5-year smoothed) are presented.

- One can see the 11-year signal in their wavelet spectra since ~1930. It is similar for Stockholm and St.Petersburg (they have similar climate) and different – more complicated – for Central England (the climate of England is affected by Gulf stream). See the figures at the bottom.
- The cross wavelet spectra of the Wolf numbers (5-year smoothed) and the climate data under consideration demonstrate some coherence/phase relationship between the time-series. But this effect is not very strong and explicit.
- The last three figures demonstrate the relationship between the temperature data sets.

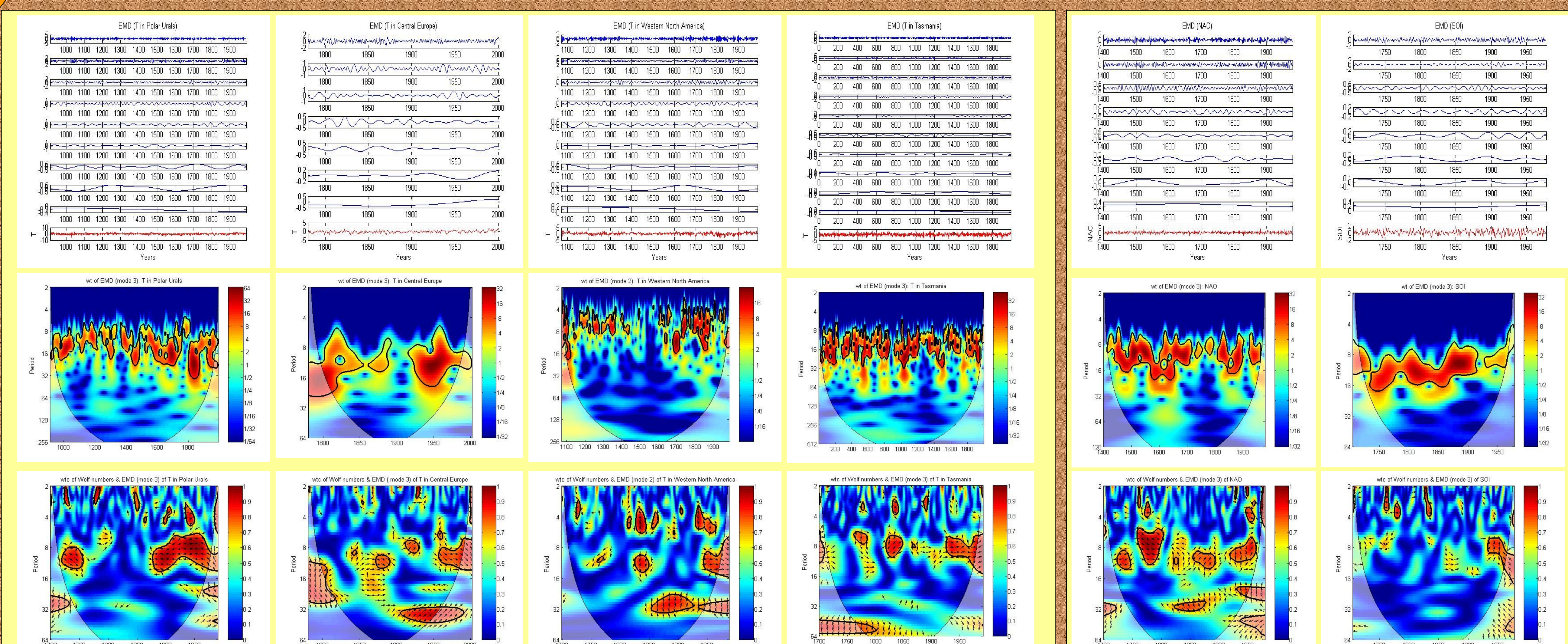
Thus, it is seems that the climate is exceptional during last ~70 years. It would be interesting to investigate whether such 11-year signal in climate time-series can be observed in earlier time intervals.

7. Reconstructed climatic time-series: wavelet and cross wavelet (with Wolf numbers) spectra



The results of wavelet and cross wavelet (with Wolf numbers, 5-year smoothed data) analysis for such climate proxies (also 5-year smoothed data) as air temperature, NAO and SOI are presented. Here one can see the temperature figures for four different regions: Polar Urals, Central Europe, Western North America and Tasmania. One can see the 11-year signal which appears differently in the different regions. From the comparison with the corresponding cross wavelet spectra one can suggest that the signal can be seen better in the polar and coast-ocean regions. From the comparison with the wavelet spectra of Wolf numbers one can remark that the 11-year signal is stronger during the periods of the high level solar activity. The signal in Central Europe (continental zone), where the coherence between the temperature and Wolf numbers is weak, can nevertheless be seen during the same periods (for example, ~1830-1870). ***So, the 11-year signal can be observed in the second half of the XX-th century and sometimes in the past – probably it is related to the high level of solar activity. It is suggested to filter the original unsmoothed data by Empirical Mode Decomposition (EMD) method and to investigate the wavelet and the cross wavelet (with the unsmoothed data set of Wolf numbers) spectra of EMD-components.***

8. Reconstructed climatic time-series: cross wavelet spectra of EMD-modes



The results of EMD applied to the reconstructed temperature, NAO and SOI time-series (unsmoothed values) one can see on the top figures. The 3-rd (sometimes 2-nd) mode (from top to bottom) corresponds to ~11-year periodicity. Using the wavelet and the cross wavelet techniques one can better study the evolution of the mode corresponding to this signal and its relationship with Wolf numbers (unsmoothed data). The results are presented. ***One can see the relatively strong 11-year signal since about 1930-th year.***

9. Conclusions

As a result of the investigation the following conclusions can be made:

4. **The ~11-year signal in instrumental and reconstructed data;**
6. **The signal is nonlinear: it can be observed in different regions in different periods;**
8. **The signal is more stable in north regions;**
10. **The response to the signal can be observed not only in north or oceanic regions, but also on the continents in the periods of the high level solar activity;**
12. **In the considered instrumental temperature data the 11-year signal is observed to be more explicit since 1925-1930-th years.**

References

[1] A. Grinsted, J.C. Moore, and S. Jevrejeva, Application of the cross wavelet transform and wavelet coherence to geophysical time series, Nonlinear Processes in Geophysics, 11, 561-566, 2004.
[2] N.E. Huang, Z. Shen, S.R. Long, M.C. Wu, E.H. Shih, Q. Zheng, C.C. Tung, and H.H. Liu, The Empirical Mode Decomposition and the Hilbert Spectrum for Nonlinear and Nonstationary Time Series Analysis, Proceedings of the Royal Society of London, Ser. A, 454, 903-995, 1998.
[3] S. Jevrejeva, J.C. Moore, and A. Grinsted, Influence of the Arctic Oscillation and El Niño-Southern Oscillation (ENSO) on ice conditions in the Baltic Sea: The wavelet approach, J. Geophys. Res., 108 (D21), 4677, 2003.
[4] P.D.Jones and M.E. Mann, Climate over past millennia, Reviews of Geophysics, 42, 1-42, 2004.
[5] D.Maraun and J.Kurthz, Cross wavelet analysis: significance testing and pitfalls, Nonlinear Processes in Geophysics (2004) 11: 505–514.
[6] N.R. Rigozo, D.J.R. Nordemann, E. Echer, A. Zanandrea, and W.D. Gonzalez, Solar Variability Effects Studied by Tree-Ring Data Wavelet Analysis. Advances in Space Research, 29, 1985-1988, 2002.
[7] G. Rilling, P. Flandrin, and P. Goncalves, Empirical mode decomposition, fractional gaussian noise and Hurst exponent estimation, G. R., P. F. and P. G. IEEE-ICASSP, March 19-23, Philadelphia, USA 2005.
[8] C. Torrence and G.P. Compo, A Practical Guide to Wavelet Analysis, Bull. Amer. Meteor. Soc., 79, 61-78, 2002.
[9] Usoskin, I. G., Millennium-scale sunspot number reconstruction: evidence for an unusually active sun since the 1940s, Physical Review Letters, vol. 91, no. 21, November 21, 2003.

Acknowledgements

This work is supported by Ministery of Education of Russian Federation, grant No. 37852.