IL NUOVO CIMENTO Vol. 27 C, N. 1 Gennaio-Febbraio 2004
DOI 10.1393/ncc/i2004-10009-y

Evolutionary spectral analysis of European climatic series

S. Alessio, A. Longhetto and R. Richiardone
Dipartimento di Fisica Generale, Università di Torino - Torino, Italy

(ricevuto il 3 Maggio 2004; revisionato il 17 Giugno 2004; approvato il 21 Giugno 2004)

Summary. — Five long historical time series of temperature and atmospheric pressure, with lengths from 149 to 279 years, three measured in Northern Italy and two in Sweden, were analyzed from the stationary and evolutionary spectral point of view, by means of the the Wavelet Transform and of the classical Fourier method. The main cyclicities revealed in the series of temperature showed interesting differences between the behaviors of Italian and Scandinavian stations. The time intervals in which each series exhibited in its wavelet spectrum a particularly important contribution by a given scale, or range of scales, were also studied. Opposite behaviors were found in Milan (Italy) and in Scandinavian stations, in the second half of the XXth century, as far as the coupling between temperature and pressure around a scale of 30 years is concerned.

PACS 92.60.Ry – Climatology.
PACS 02.70.Hm – Special methods.

1. – Introduction

The present work deals with the study of a few ultracentennial time series of climatic data recorded in five Italian and North-European sites (Milan, Padua, Genoa, Stockholm and Uppsala). These series (of temperature and atmospheric pressure) were examined with the aim of investigating their time variability, both in the sense of looking for stationary oscillatory modes and in the sense of the evolution of these modes through the years, on interannual and interdecadal scales. The spectral behavior of the series was studied by the Wavelet Transform and by Fourier methods (periodogram).

The range of interesting periods from the geophysic, climatic and atmospheric point of view (range that, at the same time, can be detected by the wavelet and Fourier methods with sequences of the length which is typical of those considered here, that is to say about 150-280 years) goes from 2-2.5 years to—at least—60/70 years (the QBO/ENSO range, 2-7/8 years, partially superimposed to the NAO/AMO range, up to the 60/70 years of the Atlantic Multidecadal Oscillation) [1-7]. Paleoclimatic information from proxy indicators (corals, tree rings for historical epochs) suggests the existence of longer periodicities, up

TABLE I. – *Daily time series examined at the listed measurement stations.*

Site	Variables in °C			Variables in hPA
Milan (Mi)	$t_{\min}$	$t_{\max}$	$\langle t \rangle$	$\langle p \rangle$
Padua (Pd)	$t_{\min}$	$t_{\max}$	$\langle t \rangle$	$\langle p \rangle$
Genoa (Ge)		$t_{\max}$		
Stockholm (St)			$\langle t \rangle$	$\langle p \rangle$
Uppsala (Up)			$\langle t \rangle$	$\langle p \rangle$

to the centennial scales. Unfortunately, these cyclicities cannot be determined precisely by means of data records that in the best case only go back to the first decades of 1700.

Several analyses of historical climatic series of various kinds have been published in recent years. Among these studies, particularly interesting for comparison with the present one are those concerning the Central England Temperature series (CET), examined by means of different spectral methods. Discussing climatic variability at various scales, from the paleoclimatic one to the interseasonal one, Ghil [1] and Plaut *et al.* [2] presented a spectrum of this series, that extends from 1659 to 1993, obtained applying Singular Spectrum Analysis (SSA; Montecarlo SSA [8-10]) to annual averages. The SSA analysis gave 11 significant components. Two of these represented non-linear trends; the other ones represented pseudo-periodicities (spectral peaks but not exactly harmonic components): 5.2 years (ascribed to a remote effect of ENSO low frequency variability), 7.7 years (ascribed to a North Atlantic mode of variability created by the interannual cycle of meandering and intensification of the Gulf Stream), 14.2 years and 25 years (possibly associated to oscillatory modes in the thermohaline circulation of the global ocean).

On the CET data also Baliunas *et al.* [11] published a paper, about a data-adaptive wavelet analysis, finding peaks at 7.5 ± 1 years, 14.4 ± 1 years, 23.5 ± 1 years and 102 ± 15 years, in total agreement with Plaut *et al.* [2], except for 102 years, that had not been put into evidence before.

The series examined in this paper are shorter than the CET, what prevents studying centennial periodicities, but having been measured in different parts of Europe (Northern Italy and Sweden) they should allow characterizing geographically the different influence on the series of climatic variability at interannual and interdecadal scales.

2. – The data

Table I shows (with an obvious notation) the physical quantities that were considered, on a daily basis, in each of the measurement stations, with the corrisponding units.

The sequences recorded in Milan, Padua, Uppsala and Stockholm were previously corrected, validated and homogeneized, together with other series, in the context of the IMPROVE project [12, 13]. The Italian series belong to an extensive climatological archive collected and studied by Italian authors during many years (see, for example, [14-27]). They were chosen for this analysis because no data were missing in them (except Padua series, in which, however, the number of missing data scattered along the series was very little).

Among the physical quantities available for Genoa, that included temperatures measured at various times of the day, the variable "temperature measured at 2 p.m." was

TABLE II. – *Intervals of years covered by monthly data extracted by the various daily series. N=number of monthly data; N_y=number of years.*

Site	t_{min}	t_{max} and $\langle t \rangle$	$\langle p \rangle$
Mi	1763-1998 $N = 2832; N_y = 236$	1763-1998 $N = 2832; N_y = 236$	1763-1998 $N = 2832; N_y = 236$
Pd	1774-1990 $N = 2604; N_y = 217$	1774-1943 $N = 2040; N_y = 170$	1766-1996 $N = 2772; N_y = 231$
Ge	1883-1981 $N = 1788; N_y = 149$	1883-1981 $N = 1788; N_y = 149$	1883-1981 $N = 1788; N_y = 149$
St	1756-2000 $N = 2940; N_y = 245$	1756-2000 $N = 2940; N_y = 245$	1756-2000 $N = 2940; N_y = 245$
Up	1722-2000 $N = 3348; N_y = 279$	1722-2000 $N = 3348; N_y = 279$	1722-2000 $N = 3348; N_y = 279$

chosen, as approximatively representative of t_{max}.

For Padua the time interval examined, and given in table II, originally included 5 single missing data for t_{min} and 6 single missing data, plus one group of four neighbouring missing values, for t_{max}. These "holes" were filled up by simple linear interpolation based on single available data, immediately preceding and following the hole. After that, the mean temperature of the day was computed, as for all the other days, taking the aritmetical mean between minimum and maximum temperature.

For each variable and measurement station, daily data were averaged on a monthly basis, in order to get shorter sequences, better suited for a subsequent evolutionary spectral analysis via discretized Continuous Wavelet Transform (CWT).

Table II shows, for each site and variable, the time interval covered by the data record, the number of monthly data N and the number of years Ny. The temporal intervals shown in table II do not correspond to the original ones given in [12]. This is due to the fact that when a series contained, before or after a certain date, many missing data, the series was simply truncated, thus eliminating the incomplete sections; moreover, for the sake of simplicity, the cut was done in such a way to get series made of whole years of data.

In the present analysis, monthly mean data were trasformed into anomalies, by removing the annual cycle according to the usual procedure, that consists in subtracting from each monthly datum the average, calculated over the whole record, of the proper calendary month. In a few cases, the anomalies still show a residual annual cycle, put into evidence by the frequency domain representation (see sect. **3**). Since the main interest of the present work is centered on interannual and interdecadal variability, the authors of the present work did not attempt to remove the annual cycle in a more refined way. A high power spectral density around a period of 1 year may sometimes be due also to leakage [28] from neighbouring peaks, expecially when, as here, the variance associated to cyclicities with periods around 0.5–2 years is quite high.

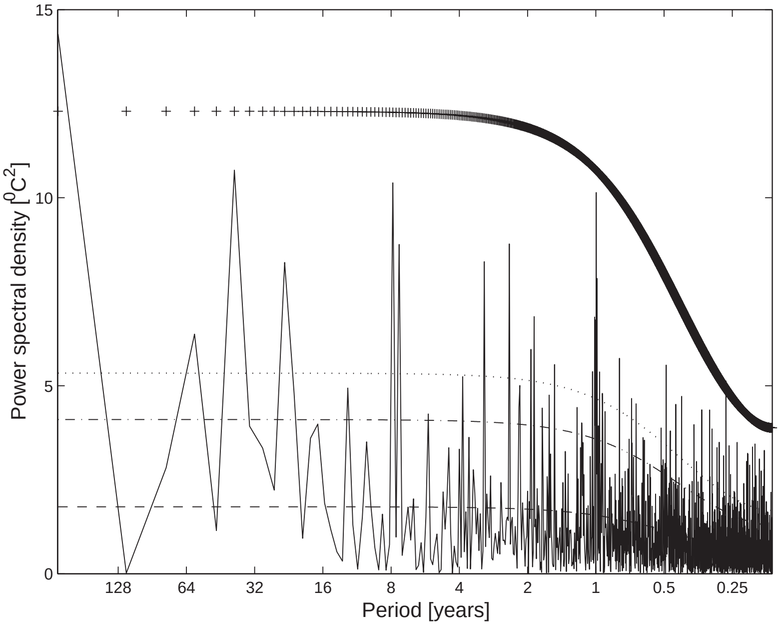

Fig. 1. – Periodogram of monthly anomalies computed from minimum daily temperatures in Milan (continuous line). The figure shows also the red noise background (dashed line), the significance level at 10% (dot-dashed line), at 5% (dotted line) and at 0.1% (crosses).

3. – Stationary spectral analysis

Before investigating the non-stationarity of the series by means of the wavelet transform, for each variable (monthly anomalies) the power spectrum was estimated via periodogram. This raw spectral estimate, giving a first idea of the main cyclicities contained in the sequences, was meant to allow a comparison with the characteristics of the global wavelet spectrum, *gws*, presented in sect. **4**. As examples, two of the periodograms are shown in figs. 1 and 2.

In abscissae, the figures do not show frequency but the corresponding period, expressed in *years*; the axis is oriented from the right to the left, so that the order of the values of Fourier period is the same that would characterize frequencies in an ordinary spectral plot. If we call T_c the sampling period ($T_c = (1/12)$ y) and indicate with N the number of data in a given series, then we can express the range of Fourier periods as $(2T_c, NT_c)$, the minimum $2T_c$ being the Nyquist period and the maximum NT_c being the length of the record. Of course, the value 0 at the axes origin in fig. 1 and 2 refers to the ordinates. The actual value of Fourier period corresponding to the origin of the abscissae is NT_c.

Each figure also includes the results of a significance test, performed according to the standard criteria explained for example in [3]. As a background spectrum (null hypothesis), a red noise process with model parameter extracted from the data is assumed; the estimate of the significance level I_s is done assuming that each power spectral density value is a random variable distributed as χ^2 with $\nu = 2$ degrees of freedom and computed as $I_\mathrm{s}(P) = S_\mathrm{r}(P) \times \frac{\chi^2_{1-p,\nu}}{\nu}$ where P is Fourier period, S_r indicates the red background

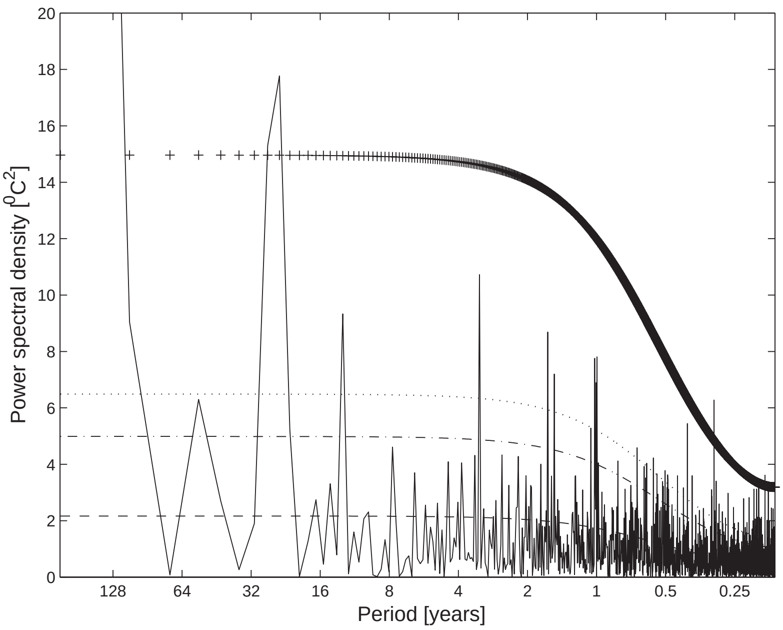

Fig. 2. – Periodogram of monthly anomalies computed from minimum daily temperatures in Padua (continuous line). The figure shows also the red noise background (dashed line), the significance level at 10% (dot-dashed line), at 5% (dotted line) and at 0.1% (crosses).

power spectrum theoretical value, with the given model parameter, p is significance probability and $\nu = 2$ represents the number of degrees of freedom (*e.g.*, 0.05, $\chi^2_{1-p,\nu} = 5.99$, $I_s(P) \simeq 3S_r(P)$). Each figure shows the line of the red noise background spectrum and the lines pertaining to the corresponding levels of spectral significance at 10, 5 and 0.1%.

Similarly to the examples shown here, in the majority of the periodograms there is a remarkable amount of power at the longest periods (that is to say, around periods of the order of the length of the record), what can, at least partially, be attributed to a trend in the series. The series in which this behavior is most evident are those of $t_{\max}$ and $t_{\min}$ in Padua (see fig. 2 for $t_{\min}$). The phenomenon disappears in $\langle t \rangle$, that is to say, in the aritmetical mean between maximum and minimum temperatures: the Padua $\langle t \rangle$ periodogram (not shown) only shows a very large, double peak, more or less in the range between 70 and 20 years (with a knee at 60 years and two maxima, at 33 and 24 years: see the following table IV). This behavior is due to the fact that at Padua $t_{\min}$ has a decreasing trend with time (-1.38°C over 217 years) while $t_{\max}$ has a remarkable increasing trend (+2.27 °C over 170 years). This gives the aritmetical mean, $\langle t \rangle$, a moderate increasing trend (+0.45 °C over 170 years, that is to say about 0.28 °C/100 y). This last value is slightly different from that given by Camuffo *et al.* [12], 0.31 °C/100 y, because Camuffo *et al.* consider the whole series, while here $\langle t \rangle$ series was truncated to 1943, due to missing data. It may be noticed that the decreasing trend of $t_{\min}$ in Padua is peculiar of this series: in Milan all three temperature series have moderate and almost equal increasing trends: over 236 years, 0.64 °C for $\langle t \rangle$, 0.67 °C for $t_{\min}$, 0.60 °C for $t_{\max}$.

This negative trend might depend on the homogeneization procedures that were preliminarly applied to the data. Before the middle of the nineteenth century, no $t_{\min}$ and

TABLE III. – *Periods in years of the main cyclicities found in Milan series ($N_y = 236$) spectra, estimated via periodogram (pdg; first four columns at the left) and via global wavelet spectrum (gws; last four columns at the right). The periods shown in thick character refer to peaks that go beyond the significance level of 5%. The other ones refer to peaks that go beyond the level at* 10%. *An asterisk means that the peak goes beyond the* 0.1% *level.*

From *pdg*				From *gws*			
t_{min}	t_{max}	$\langle t\rangle$	$\langle p\rangle$	t_{min}	t_{max}	$\langle t\rangle$	$\langle p\rangle$
$>$ **128***	$>$ **128***	$>$ **128***	$>$ **128**	$>$ 128	$>$ 128	$>$ 128	
						70	
	60				60		
40	**40**	**40**		40	38–40	40	
24	**24**	**24**		24	24	24	
	12	12	12–**14**				14
8	**8**	**8**		8	8	8	
			5–**6**				
4	4	**4**					
$\sim$ **3**	**3**	**3**	**3**				
2.4	**2.4**	**2.4**	$\leq$ **2.4**				
2	**2**	2					2
	$\leq$ 1.2	1.6					

t_{max} are available: these quantities therefore are to be estimated on the basis of morning or afternoon observations, that must be "corrected" so as to become representative of daily minimum and maximum temperatures. This may be done according to different

TABLE IV. – *Periods in years of the main cyclicities found in Padua series ($N_y = 170$) spectra, estimated via periodogram (pdg; first four columns at the left) and via global wavelet spectrum (gws; last four columns at the right). The periods shown in thick character refer to peaks that go beyond the significance level of* 5%. *The other ones refer to peaks that go beyond the level at* 10%. *An asterisk means that the peak goes beyond the* 0.1% *level.*

From *pdg*				From *gws*			
t_{min}	t_{max}	$\langle t\rangle$	$\langle p\rangle$	t_{min}	t_{max}	$\langle t\rangle$	$\langle p\rangle$
$>$ **100***	$>$ **90***				$>$ 110		
				$>$ 70			
60	**60**	**60**					
	33*	**33**					
24*	**24**	**24***		24	24–64	18–64	
13		13	**13**				
	10						
		8	**8**				
			5.6				
	4	**4**	**4**				
3	$\sim$ 3	3.2–3.4					
		2; 2.4	$\leq$ **2.4**				2
$\sim$ **1.6**		**1.6–1.7**					

TABLE V. – *Periods in years of the main cyclicities found in Genoa series ($N_y = 149$) spectrum, estimated via periodogram (pdg; first four columns at the left) and via global wavelet spectrum (gws; last four columns at the right). The periods shown in thick character refer to peaks that go beyond the significance level of 5%. The other ones refer to peaks that go beyond the level at* 10%. *An asterisk means that the peak goes beyond the* 0.1% *level.*

From *pdg*	From *gws*
t_{max}	t_{max}
	> 128
70*	70
26	26
16	
8	
3.2	
2–2.4	

criteria [29] and there is always some degree of subjectivity in any procedure that may be adopted.

The Padua-$\langle t \rangle$ periodogram described above is similar to the Genoa-t_{max} periodogram (not shown), exhibiting a unique huge peak at low frequency; however, in this case the peak extends from about 50 years to over 128 years and has only one maximum at 70 years.

A visual inspection of all periodograms (for a list of available data recall tables II and I) led to the results shown in the left parts of tables III (for Milan), IV (for Padua), V (for Genoa), VI (for Stockholm) and VII for Uppsala.

For each site and variable, in the leftmost columns of tables III, IV, V, VI and VII, the main periodicities whose peaks, in the periodogram (*pdg*), go beyond the significance level of 5% (sometimes even of 10% only, when useful for the following discussion) are

TABLE VI. – *Periods in years of the main cyclicities found in Stockholm series ($N_y = 245$) spectra, estimated via periodogram (pdg; first four columns at the left) and via global wavelet spectrum (gws; last four columns at the right). The periods shown in thick character refer to peaks that go beyond the significance level of 5%. The other ones refer to peaks that go beyond the level at* 10%. *An asterisk means that the peak goes beyond the* 0.1% *level.*

From *pdg*		From *gws*	
$\langle t \rangle$	$\langle p \rangle$	$\langle t \rangle$	$\langle p \rangle$
> 128		> 128	
40			
20			
14–16		14	
8		8	
4–6	**5–6.5**		5
3.5	**3.6–4.4**		
$\leq$ **2.4**	**2.2**		
	$\leq$ **1.4**		1.3

TABLE VII. – *Periods in years of the main cyclicities found in Uppsala series ($N_y = 279$) spectra, estimated via periodogram (pdg; first four columns at the left) and via global wavelet spectrum (gws; last four columns at the right). The periods shown in thick character refer to peaks that go beyond the significance level of 5%. The other ones refer to peaks that go beyond the level at* 10%. *An asterisk means that the peak goes beyond the* 0.1% *level.*

From *pdg*		From *gws*	
$\langle t \rangle$	$\langle p \rangle$	$\langle t \rangle$	$\langle p \rangle$
> 128*			
70			
30		32	
20			
13		13	
8			
	6.5		
	∼ 4.2		∼ 4
2.4	**2.4**		
2			
1.2	**∼ 1.4***		

listed. The values, expressed in years, are approximated; in particular, the shape of the spectra at low frequency (high period) makes the values appearing in the first row of each table (for example > 128 y) only qualitative. Peaks whose period was very close to one year, or below one year, have not been taken into account.

The right parts of the tables come from the corresponding global wavelet spectra (*gws*, described later), that represent a stabler and smoother spectral estimate: as said before, the periodograms were included in the analysis for comparison with the global wavelet spectral method.

In the tables, there are cases in which several peaks close to one another are represented by a ∼ symbol, or by a ≤ symbol, or even with a range of period values in years (for example, 38–40).

These tables will be discussed in sect. **4**, through the comparison between the columns concerning *pdg* and *gws* for the various stations (see tables VIII and IX).

4. – Evolutionary spectral analysis

The evolution through the years of the dominant frequencies or Fourier periods in a given series requires applying a non-stationary spectral method, like the Wavelet Transform. In this technique, instead of sinusoids of infinite length, a time-limited waveform (real or complex: the so-called mother wavelet) is used and cross-correlated with the series at various positions along the series itself. The duration of the wavelet is expressed through the concept of "scale", which is typical of wavelet analysis. The scale is then varied by stretching the waveform (while leaving its shape unaltered) and the cross-correlation process is repeated at all scales of interest, thus giving a picture of the series behavior in the time-scale plane.

The relation between the concept of scale and the concept of Fourier period or Fourier frequency is particularly well defined in the case of a complex mother wavelet having the shape of a wave packet, as in the case of the Complex Morlet Wavelet (*cmor*). Therefore, the use of *cmor* is typical of time series analyses in the time-frequency or time-period plane, while real wavelets are preferred for revealing different characteristics in a series, like sharp discontinuities or peaks.

The *cmor* wavelet is a wave packet made of a complex sinusoidal oscillation modulated by a gaussian envelope. The number of oscillations under the gaussian is set by the value of a parameter ω_0, that is normally taken equal to 5 or 6. The minimum temporal support of the wavelet corresponds to the minimum scale considered, usually $2T_c$ with *cmor*. The relation between scale and frequency (that is to say, between scale and Fourier period) is different from one wavelet to the other, because it depends on the shape of the wavelet; for *cmor*, scale and Fourier period are more or less equal.

The wave packet at the minimum scale is progressively deplaced along the series (one T_c step at a time, that is in a maximally dense way) and correlated with the series at each position, thus getting a sequence of complex correlation coefficients relative to the minimum scale or period. Later, *cmor* is stretched (scaled) in an autosimilar way, so that its duration changes but the number of oscillations under the Gaussian (set by ω_0) remains constant. In this way, the frequency of the oscillations in the packet changes. The scaled mother wavelet is called the daughter wavelet. The correlation procedure is then repeated, scale by scale, according to a proper rate of scale variation, until the maximum scale of interest (normally order of the record length) is attained. The final result is a two-dimensional array of the complex correlation coefficient, which is a function of time (position along the record) and of frequency, or Fourier period. This array is the wavelet transform; to be precise, it is an arbitrary discretization of the continuous wavelet transform (CWT). The square modulus of the transform is the wavelet spectrum (often called scalogram).

This analysis has a "multiresolution" property [3, 30]:

– at short period (high frequency) the frequency resolution is low and the time resolution is high;

– at long period (low frequency) the time resolution is low and the frequency resolution is high.

In this work, for each time series a wavelet analysis was performed, using a *cmor* wavelet with $\omega_0 = 6$. For this purpose, the authors of this paper adapted to the present case the software, operating in a Matlab environment, freely distributed on the Web by C. and G. Compo [3], University of Colorado (Boulder, Colorado, USA). This software comes with a set of statistical tests, able to make wavelet analysis more quantitative and reliable than in the past. The analysis was performed choosing a significance level of 10%.

The wavelet transform, that like any correlation is a linear convolution in time, is often performed (and this is the case of Torrence and Compo's software) in the frequency domain, by computing the product of the Fourier Transforms of the sequences to be convoluted (data and wave packet) and then taking the inverse Fourier Transform. Direct and inverse transform take place via Fast Fourier Transform: therefore, in order to avoid aliasing in the time domain [28], it is necessary to pad the sequences with zeroes at the edges. The padding causes the presence, at the edges of the scalogram, of an area (cone of influence, *coi* hereafter) which is influenced by the zeroes in the data, that reduce the spectral power with respect to the hypothetical "true" value. The *coi* width increases with scale, that is with Fourier period: as a matter of fact, each scalogram value is influenced by neighbouring values, within a time interval increasing with the temporal width of the daughter wavelet (scale). If then we hypothesize an impulse disturbance at one of the edges of the data sequence, its influence will affect the scalogram up to distances from the edge itself, distances increasing with scale.

In the scalogram, that is usually plotted by means of contour lines in the time-period plane, the most interesting areas are those judged statistically significant, at a given level, according to the test suggested by Torrence and Compo [3]. The test is based on the fact that each "local wavelet spectrum" (a vertical "slice" from the scalogram, pertaining to a given time instant) is distributed (at each period or frequency) like a Fourier spectrum, that is to say, like a χ^2 variable with $\nu = 2$ degrees of freedom. As a background spectrum (null hypothesis), a red noise process with model parameter extracted from the data is assumed (as it is usually done for a Fourier Spectrum). The reliability of this hypothesis was verified by Torrence and Compo by means of Montecarlo numerical simulations.

At last, from the scalogram a "global wavelet spectrum" (*gws*) can be derived, as a time average of all local wavelet spectra. Torrence and Compo build the corresponding significance test from the test for each local spectrum, considering that *gws* is an average of local spectra which are not independent from one another and taking empirically into account the fact that also values included in the *coi* go into the average. Also in this case, numerical simulations allow evaluating proper numerical parameters for the test. The global spectrum represents, for the series, a stationary spectral estimate, comparable with a Fourier spectrum remarkably smoothed, in particular at high frequency, where the wavelet is short in time and therefore is wide in frequency.

In fig. 3 is shown, as a first example, the plot obtained from the wavelet analysis of mean daily temperatures in Milan, previously trasformed into monthly anomalies with respect to the annual cycle (see sect. **2**).

The figure is made up of two separate plots:

– on the left, fig. 3a, there is the scalogram: in abscissae there is time in years, in ordinates there are Fourier periods. At the bottom the longest periods (the lowest frequencies) are shown.

  The wavelet spectral power is represented by thick grayscale isolines: darker shades of gray are associated to relatively high values of power; lighter ones are associated to relatively low values.

  Before computing the transform, the data were standardized to unit variance. As a consequence, a given local value—10 for example—in the scalogram means "power equal to 10 times that pertaining to a white noise process with the same variance of the data", because in this plot, a white noise process would have theoretically unitary power at all times and periods([1]). This normalization is particularly useful for comparing scalograms coming from different variables.

  The contour levels chosen for the plots range from 1 (spectral power equal to the variance of the data) up to a value close to the maximum value of spectral power. Among gray, thick contour lines, other lines appear, which are black solid lines: these enclose the areas of significant spectral power (here at 10%, 90% confidence). The solid, cup-shaped black line, symmetrical with respect to the figure central

([1]) Actually a wavelet analysis of a white noise sample sequence would lead to a scalogram with power maxima distributed at random in the time-period plane. A wavelet analysis of a red noise sample sequence would give an analogous pattern, but with more an more pronounced maxima passing from high to low frequencies, or from low to high periods.

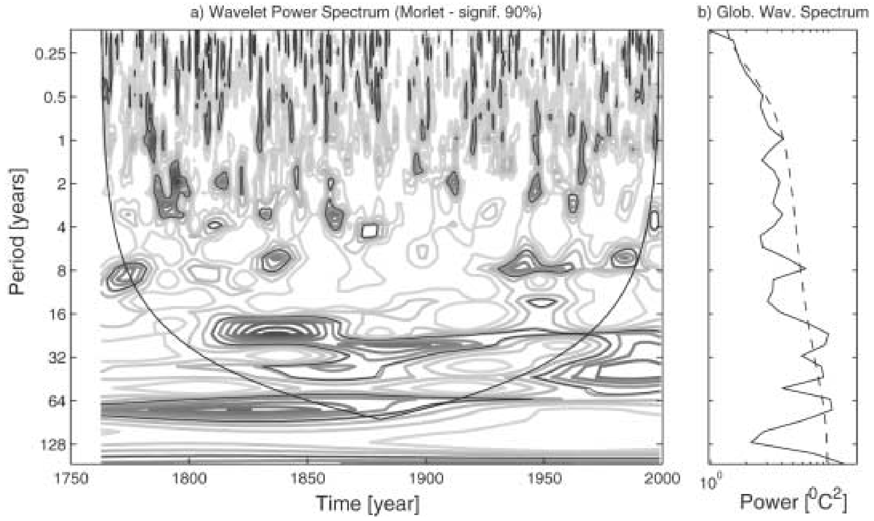

Fig. 3. – Wavelet analysis of Milan mean daily temperatures, reduced to monthly anomalies with respect to the annual cycle and standardized to unit variance. a) Scalogram; the wavelet spectral power is represented by thick grayscale isolines. Darker shades of gray are associated to relatively high values of power; lighter ones are associated to relatively low values. The contour levels range from 1 up to a value close to the maximum value of spectral power. Black solid lines enclose the areas of significant spectral power at 10 per cent (90 per cent confidence). The solid, cup-shaped black line, symmetrical with respect to the figure central axis, represents the edges of the cone of influence. b) Global wavelet spectrum (solid line), together with its 10 per cent significance (dashed) line.

axis, represents the edges of the *coi*. What is external to the cup is affected by zero padding.

– On the right, fig. 3b, there is the global wavelet spectrum and its 10% significance (dashed) line. The ordinate axis is the same as in fig. 3a.

The plots concerning all the series listed in table II were visually inspected; the qualitative results of the analysis will now be presented.

First of all, in the rightmost columns of tables III, IV, V, VI and VII the Fourier periods are shown, for which significant power was found in *gws* of the temperature and pressure series. When computing the *gws* from the wavelet transform, the series variance was re-introduced, so that all *gws* presented in this paper are to be considered as spectra of anomalies (and not standardized anomalies).

We may notice that for *pdg* (leftmost columns of tables III-VII) the 10% significance level is the least stringent among those considered: the levels go down to 0.1%. On the contrary, for *gws*, which is a very smoothed spectral estimate, only the 10% level was considered. Many peaks that are found in the *pdg* of a given series disappear under the significance threshold in *gws*, due to the remarkable smoothing inherent to the *gws* technique.

A visual inspection of tables III, IV, V, VI and VII leads to the comparison among the spectral behaviors of temperatures and pressures in the five sites, shown in Tables VIII and IX. Here we simply speak about "temperatures" because an attempt was made of

TABLE VIII. – *Comparison among the five stations, concerning Fourier periods (in years) of the highest spectral peaks of temperatures (including mean, maximum and minimum temperatures). The values in parentheses are present in pdg only and not in gws. The pairs of values separated by a slash indicate a range of values.*

Mi	70/60	40	24	(12)	8	(4)	(3)	(2.4)	(2)	
Pd	70/60	(33)	24	(13)	(8)	(4)	(3)	(2.4)	(2)	(1.6)
Ge	70		26	(16)			(3.2)	(2.4/2)		
St				16/14	8		(3.5)	($\leq$2.4)		
Up	(70)	30		13	(8)			(2.4)	(2)	(1.2)

summarizing qualitatively the situation, merging the results of the analyses not only of mean temperatures, but also of minumum and maximum temperatures (when present). In fact, an overall similarity was found in Milan among the spectral behaviors of $\langle t \rangle$, $t_{\min}$ and $t_{\max}$, and the same can be said about Padua too. Due to the typical length of the series and to the shapes of the spectra at high period, only periods smaller than 128 years were considered.

In the Italian stations, for temperatures table VIII clearly shows that all stations and both methods of spectral estimate share, a period of 60/70 years and a period of 24/26 years; moreover, but only in *pdg*, for all stations 3, 2.4 and 2 years are found. Milan only has a peak at 40 years (at Padua, in *pdg* only, a period of 33 years is found, that is not so different from 40, provided that all these values are always quite approximated anyway) and a peak at 8 years (that in *pdg* is always a double peak, as in fig. 1). Milan and a Padua, in *pdg* only, also show a 4 years and a 12-13 years peak, that in Genoa becomes a 16 years peak (always in *pdg* only). Genoa series appears, as mentioned before, a little bit anomalous comparing with the other two Italian stations, with a very wide and high peak with maximum around 70 years and for the rest only minor peculiarities.

Scandinavian stations seem different from Italian ones: except for a 70 years periodicity (in *pdg* only) and a 30 years one in Uppsala, they are mainly centered on shorter periods (let us say, about 15 or 13 years and 8 years; 2.4 years in *pdg* only). In Stockholm there is also a 3.5 years peak in *pdg*. In other words, comparing Scandinavia with Italian stations we see that the interdecadal contributions lose importance while the range from 8 to 15 years becomes more important; short periods (below 2.4 years) maintain their role.

Obviously, pressures (table IX) behave differently from temperatures.

Both Milan and Padua suggest periodicities around 13/14 years (and around 5.6/6 years in *pdg* only). In Padua contribution at 8 and 4 years appear in *pdg* only, while in Milan in *pdg* a 3 years peak is found. The only cyclicity shared by both stations and

TABLE IX. – *Comparison among the four stations, for what concerns the Fourier periods (in years) of the main pressure spectral peaks. The values in parentheses are found only in pdg and not in gws. The pairs of values separated by a slash indicate a range of values.*

Mi	14		(6)		(3)	2	
Pd	(13)	(8)	(5.6)	(4)		$\leq$ 2.4	
St			6.5/5	(4.4/3.6)		2.2	$\leq$1.4
Up			(6.5)	4		(2.4)	(1.4)

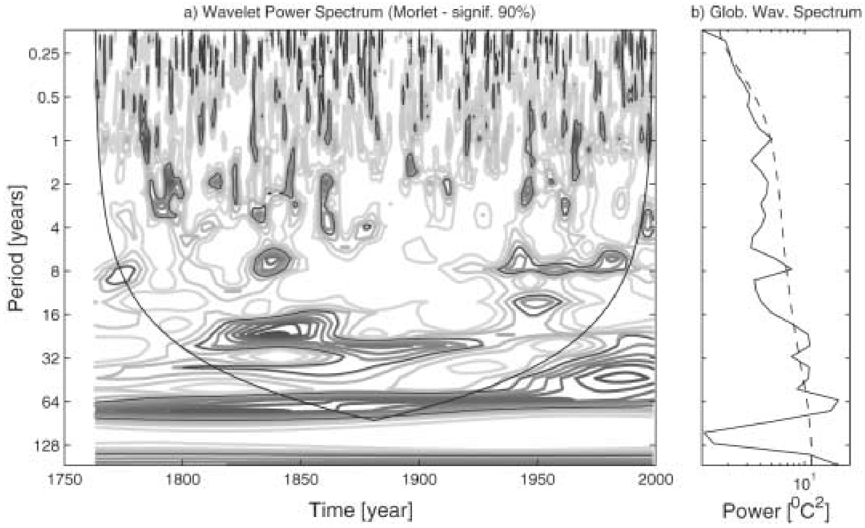

Fig. 4. – Wavelet analysis of daily maximum temperatures in Milan, transformed into monthly anomalies with respect to the mean annual cycle and standardized to unit variance. a) Scalogram; b) global wavelet spectrum. For details, see caption to fig. 3.

both methods of spectral estimate is over periods below 2.4 years.

North European stations give pressure spectra peaked over periods of 6.5 years or smaller: as for the temperatures, periods shorter than in Italy prevail. Typical values are 6.5/5 years, 4 years, 2.2 years, 1.4 years. For Uppsala, in particular, the 1.4 years peak is very pronounced in *pdg*. It may be noticed that the pressure Stockholm spectrum is nearly white.

5. – Non-stationary characteristics

At last, the non-stationarities (evolutionary behavior) pointed out by wavelet analysis will be presented. For each site and variable, the most evident characteristics in the scalogram will be discussed, by examining those Fourier periods around which a concentration of significant power spectral density is found, as well as the corresponding time intervals inside which this concentration (the "episode") takes place. Once more, this is a qualitative description, obtained observing the plots, of which the most interesting examples are shown in figs. 3-9, concerning a few temperature series and the two Italian pressure series.

5·1. *Temperatures.* – The scalograms are remarkably non-stationary: power maxima at the various scales appear and disappear intermittently in time. In the description that follows the terms scale and period will be used interchangeably.

Milan: 1. Mean temperature (fig. 3)

- Scales around 70 years "active" from the beginning and up to about 1940, with a maximum in 1820 (the region is partially in the *coi*. The corresponding peak is significant in *gws*).

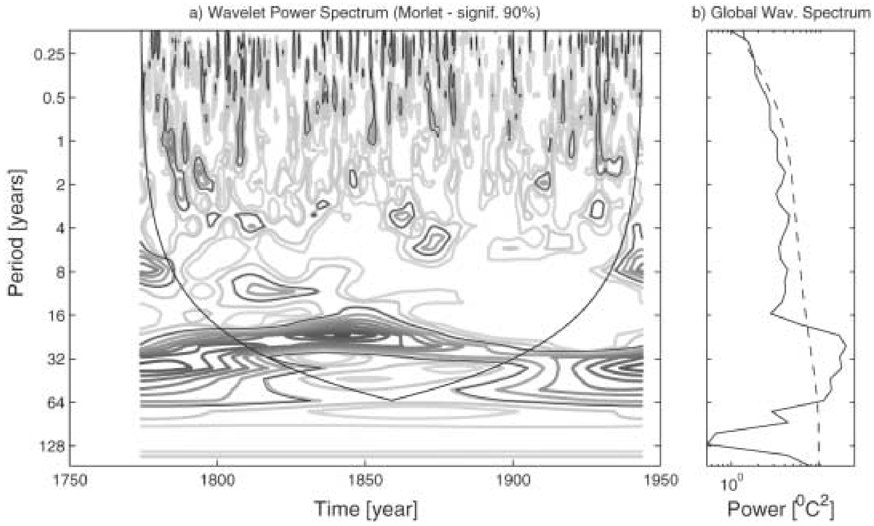

Fig. 5. – Wavelet analysis of daily mean temperatures in Padua, transformed into monthly anomalies with respect to the mean annual cycle and standardized to unit variance. a): scalogram; b) global wavelet spectrum. For details, see caption to fig. 3.

– Within the *coi*, a wide range of scales between 24 and 60 years is active after 1940. The corresponding peak (40 years) is significant in *gws*.
– There is activity around 35-45 years from 1830 to 1880; also this contributes to the 40 years peak in *gws*. From 1880 to 1950-60 an apparent

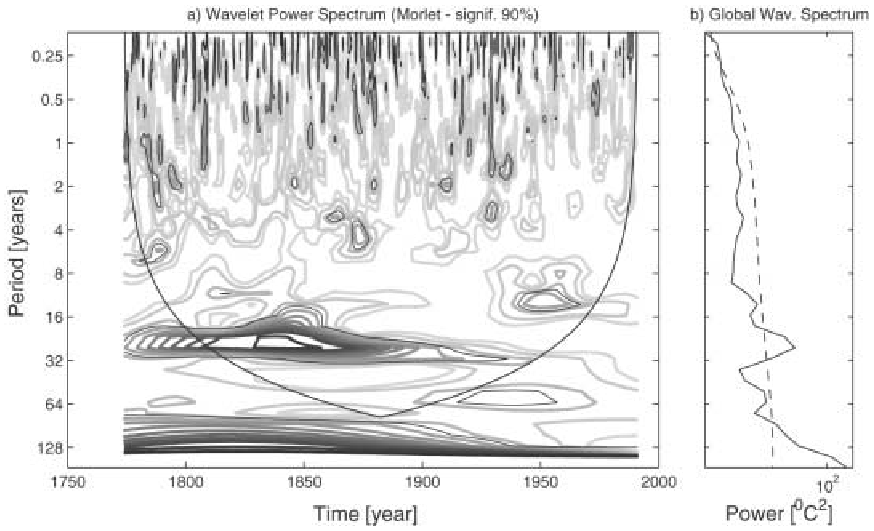

Fig. 6. – Wavelet analysis of daily minimum temperatures in Padua, transformed into monthly anomalies with respect to the mean annual cycle and standardized to unit variance. a) Scalogram; b) global wavelet spectrum. For details, see caption to fig. 3.

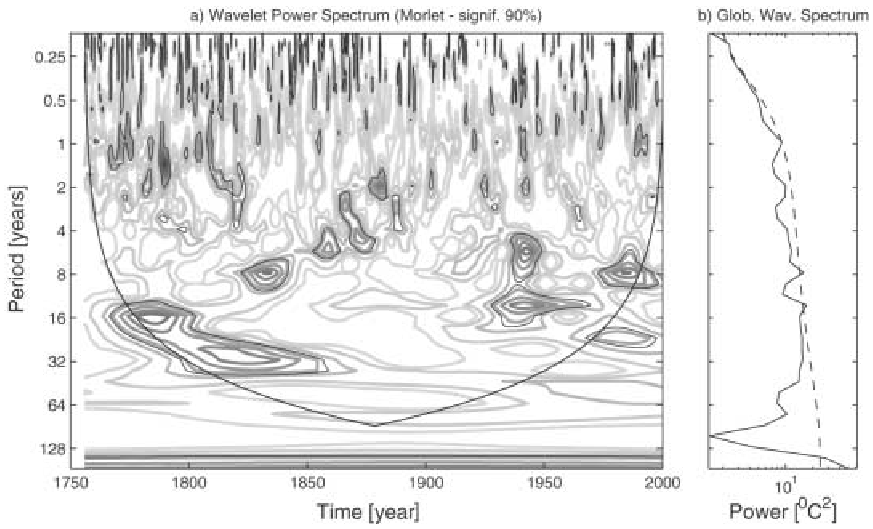

Fig. 7. – Wavelet analysis of daily mean temperatures in Stockholm, transformed into monthly anomalies with respect to the mean annual cycle and standardized to unit variance. a) Scalogram; b) global wavelet spectrum. For details, see caption to fig. 3.

shift from 35-45 to 24 years can be noticed.

– Scales around 24 years active between 1810 and 1860,with a maximum in 1840. The corresponding peak is significant in *gws*.
– Scales around 6-8 years active around 1840, in 1930-60 and in 1985; scales

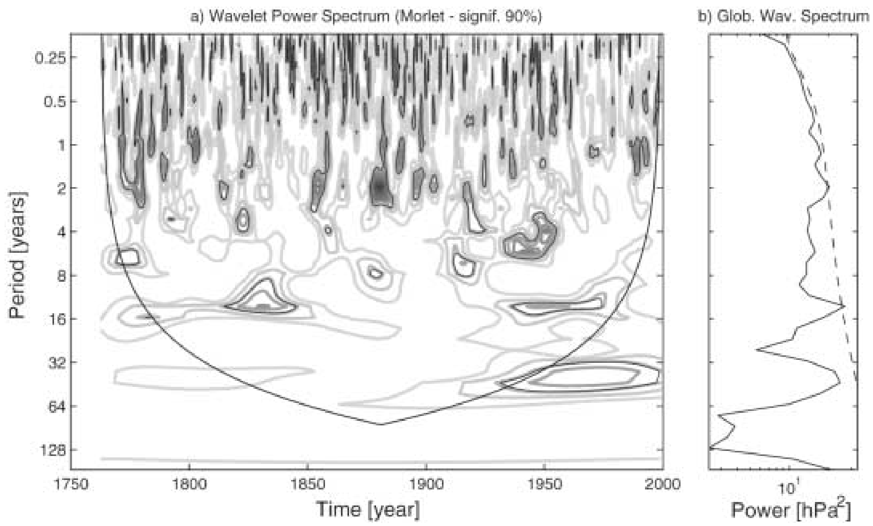

Fig. 8. – Wavelet analysis of daily mean pressures in Milan, transformed into monthly anomalies with respect to the mean annual cycle and standardized to unit variance. a) Scalogram; b) global wavelet spectrum. For details, see caption to fig. 3.

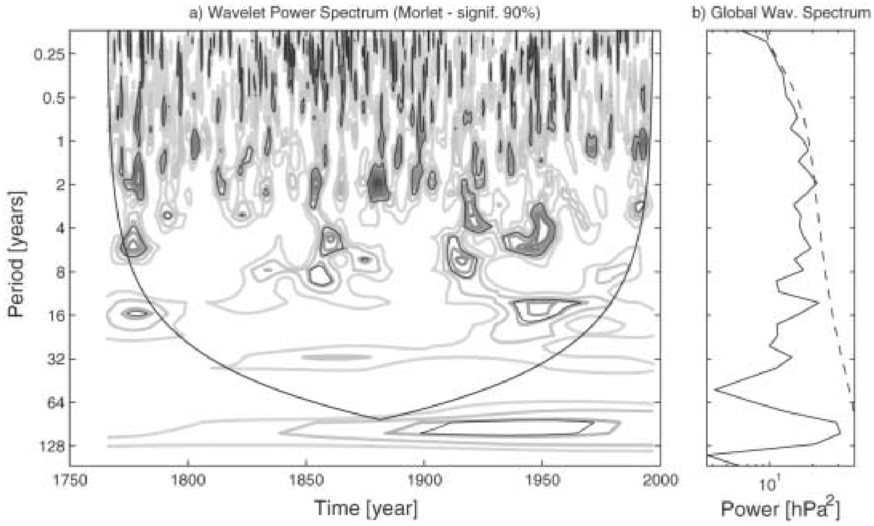

Fig. 9. – Wavelet analysis of daily mean pressures in Padua, transformed into monthly anomalies with respect to the mean annual cycle and standardized to unit variance. a) Scalogram; b) global wavelet spectrum. For details, see caption to fig. 3.

around 8-10 years active in 1770. Obviously, 1770 and 1985 are inside the *coi*. All this creates in *gws* a 8 years significant peak.

– At shorter periods, several significant, temporally narrow "episodes"([2]) can be seen, apparently scattered at random. However around 1790-1800 activity around 2 years comes into evidence (also in $t_{\min}$, whose scalogram is not shown, and in $t_{\max}$, see fig. 4) and, to a lesser extent, activity around 3-4 years is visible in 1860-80 (this is evident mainly in $t_{\min}$, whose scalogram is not shown).

2. Minimum temperature

   Its scalogram, not shown, is similar to the previous one. However in particular it may be noticed that:

   – the peak at 70 years is inside the *coi* and lasts up to about 1880. It is less extended than the peak observed for $\langle t \rangle$.

   – Around 8 years of period the greatest contributions come from about 1775 (inside the *coi*), from about 1810 (with a drift toward 6 years in 1840) and from the interval 1930-1960.

   – In 1860-80 some activity around a period of 4 years is evident.

   – In 1790-1800 the contribution at 2 years, already seen in the mean temperature, is present.

3. Maximum temperature (fig. 4)

([2]) It must be recalled that temporal resolution is poor at large scales and elevated at small scales, so that the scalogram peaks are very large in time in the bottom part of the figure and very localized in the upper part

Also this scalogram is similar to the previous ones. However it may be noticed that:

- the contributions to the scales around 60/70 years are distributed along the whole record length.
- There is a remarkable local activity between 32 and 64 years of period, with a maximum around 40 years, between 1950 and 2000, within the *coi* (as for $\langle t \rangle$ but more evident). As a consequence, the 38-40 years peak in *gws* is mainly due to the second half of the XXth century.
- In 1940-60 a local contribution to the power around 12-14 years can be seen (it can be recognized also in $\langle t \rangle$, but there it is by far less evident). This contribution, so temporally local, is enough to give in *pdg* a 90% significant peak.
- The role of the scales around 8 years appears emphasized, expecially around 1840 and in the interval 1930/85.

Padua: these temperature series after the removal of missing data are definitely shorter than those recorded in Milan. As a consequence, the largest scales are studied less accurately. The scalograms are quite different from those of Milan; moreover, with respect to Milan, the scalograms concerning $\langle t \rangle$, $t_{\min}$ and $t_{\max}$ are more different from one another (a fact that is evident also observing the corresponding *gws*).

1. Mean temperature (fig. 5)
   - A contribution of all scales between 16 and 64 years is evident: before 1825 (inside the *coi*), with center on 36/40 years and maximum evidence before 1790; then between 1820 and 1890, with center at 24 years and maximum evidence around 1840; at last after 1880 the area of significant power is centered again around 40 years. All these characteristics give a single, very wide peak in *gws* (18/64 years).
   - Around 1815 there is a contribution to 12 years (the interval 1940-60, in which the same thing happened for maximum temperature in Milan, cannot be seen here because the data end in 1943).
   - Around 1860-70 scales of 4-6 years are active;
   - between 1780 and 1800 contributions of smaller periods (below 2/3 years) are found.
2. Minimum temperature (fig. 6)
   - There is remarkable power at the largest scales (> 70 years), but completely inside the *coi*. Also a contribution around 64 years, from 1910 to 1950, is inside the *coi*.
   - The power in the range 16-32 years has a maximum in the interval 1830-1840 and is present from the beginning of the record up to more or less 1930. From this power, the 24 years significant peak in *gws* is originated.
   - The scalogram confirms a contribution around a period of 12 years in 1815-20 (to be compared with the case of $\langle t \rangle$) and moreover shows another one (12/14 years) in 1940-60 (as already seen for Milan, $t_{\max}$ in the same time interval): recall that $t_{\min}$ record is longer than $t_{\max}$ and $\langle t \rangle$: it extends up to 1990.
   - A contribution at 4 years is visible in 1860-1880;

- a contribution at about 2 years (let's say between 1 and 3 years) is visible between 1780 and 1800.

3. Maximum temperature

   The scalogram, not shown, is similar to that of mean temperature, except for the fact of showing relatively more power at the longest periods.

Genoa: this scalogram, not shown, has a less definite structure than the previous ones.

- It shows high power levels at periods ≥ 26 years up to 1950; between 1830 and 1870 (partially in the *coi*) the maximum power also covers the range 16-24 years. In *gws* all this gives a big peak, with maximum at about 70 years, plus a minor peak around 26 years.
- Between 1940 and 1960 significant power is found between 8 and 16 years (maximum at 12 years): this is to be compared with the analogous contribution seen for Milan, $t_{\max}$ and Padua, $t_{\min}$.

Stockholm: its scalogram, visible in fig. 7, is different from Italian ones, in particular from those of Milan and Padua.

- There is more activity in the period range below 16 years, except for a contribution in the range 16-40 years between 1770 and 1860, with a shift from 16 to 32-40 years with time, and a contribution at 24 years after 1970 (but inside the *coi*).
- In 1770-1800 and in 1925-70 the most evident contribution is centered on 12/18 years.
- In 1820-45, around 1940 and 1980 a 8 years contribution is well marked.
- Around 1940 also the 6 years scale gives a contribution, as well as in 1980-90.
- In the interval 1850-1900 a 4 years contribution is present.
- Between 1770 and 1830 1-2 years periods are also active.

It is interesting to notice a few apparent regular scale shifts, as the following (see fig. 7):

- from 1 to 3 years between 1770 and 1830;
- from 8 to 2 years between 1820 and 1890;
- from 16 to 32 years from 1770 to 1860.

Uppsala: This temperature scalogram (not shown) is very similar to the one of Stockholm, except for the fact that before 1760 and after 1940 relatively more power is found in the period band around 64 years.

It may be noted marginally here that Uppsala series starts in 1722, but before 1739 measurements were performed in interiors, not heated and well ventilated, according to the standard of the epoch; therefore the mean temperatures of this first interval are artificially high due to the measurement method, that affects minima more than maxima [31]. Re-computing the spectra with post-1740 data only, in the periodogram the contribution of the longest periods diminishes and the 70 years peak, as well as the 20 years peak, disappear, while the importance of the 30 years peak and of the peaks in the range of periods below 5/6 years are

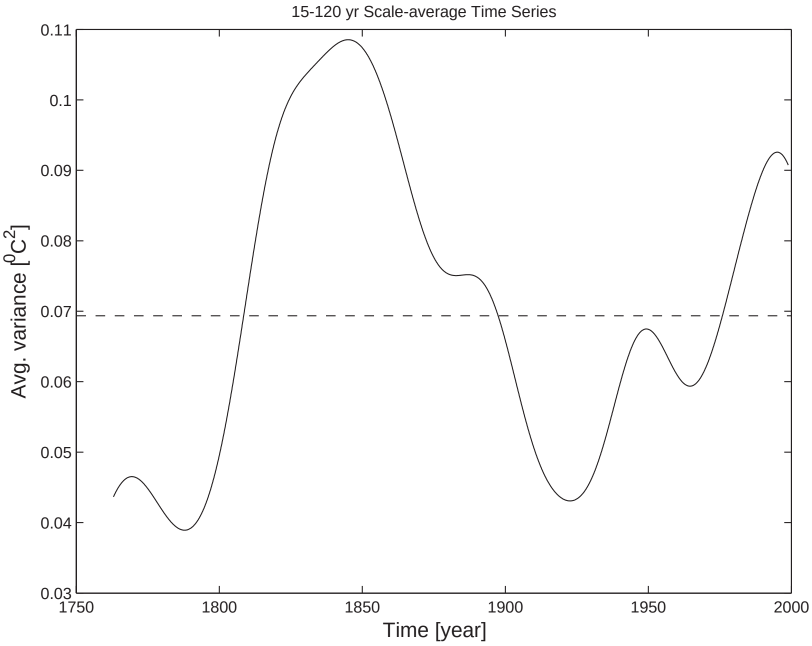

Fig. 10. – Time series of average variance of $\langle t \rangle$ in Milan, in the scale band 15-120 years. The dashed line represents the significance value at the 10% level.

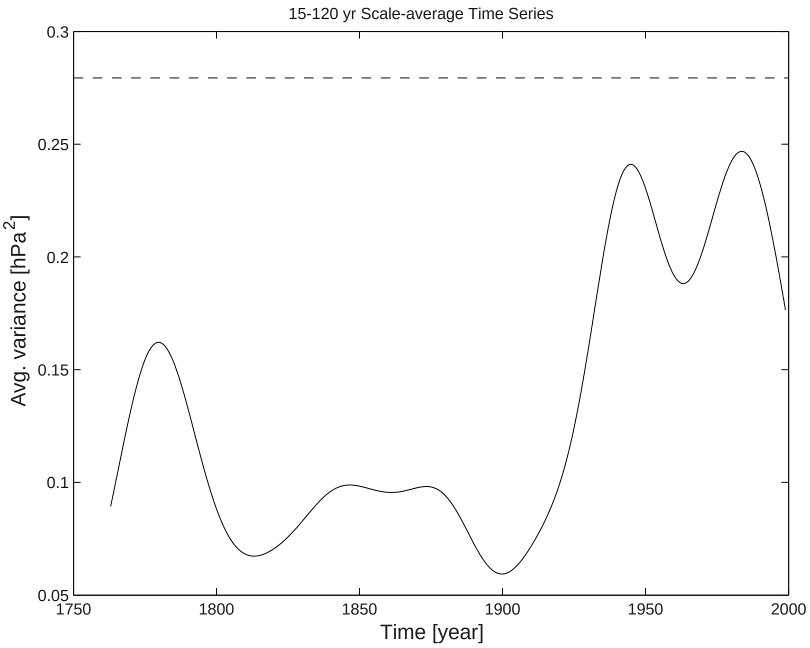

Fig. 11. – Time series of average variance of $\langle p \rangle$ in Milan, in the scale band 15-120 years. The dashed line represents the significance value at the 10% level.

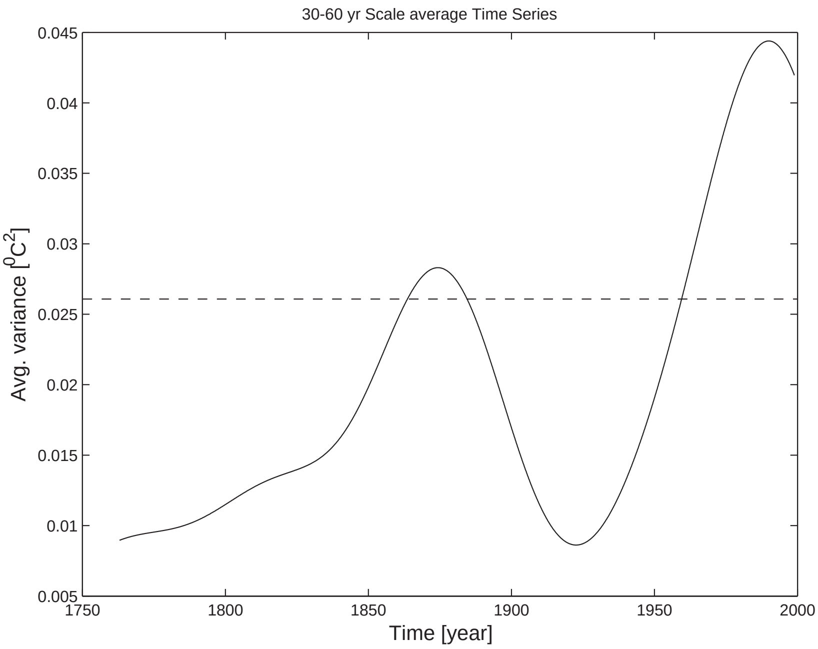

Fig. 12. – Time series of average variance of $\langle t \rangle$ in Milan, in the scale band 30-60 years. The dashed line represents the significance value at the 10% level.

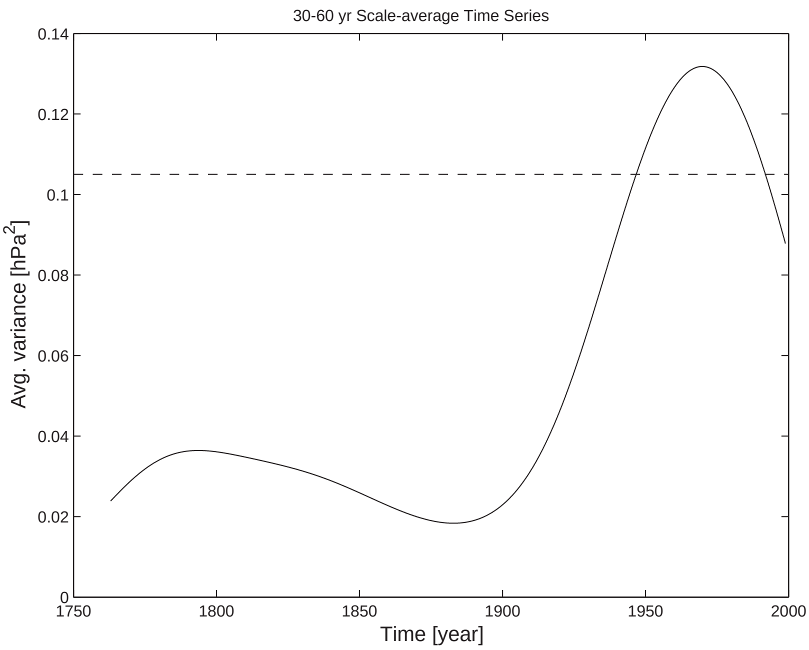

Fig. 13. – Time series of average variance of $\langle p \rangle$ in Milan, in the scale band 30-60 years. The dashed line represents the significance value at the 10% level.

emphasized. In *gws* the 13 years peak and the circa-trentennial peak significances are reduced (the last one also moves its maximum to a period of about 26 years). On the other hand, the 8 years peak becomes significant. The power at the largest scales increases, in contrast with what happens in *pdg*. In summary, the effect on *gws* of removing the interval 1722-1739 seems to be particularly intense and clear in the range of periods around 60/70 years, that lose their importance (while in *pdg* the contrary takes place!).

5˙2. *Pressures*. – Generally speaking, pressure scalograms are definitely less structured than the temperature ones, and the corresponding *gws* have a reduced number of significant peaks.

Milan: the most evident contributions (fig. 8) are the following.

- Periodicity around 40 years, post-1930 (inside the *coi*);
- around 12 years in 1810-40 and in 1940-70;
- around 4 years in 1930-55;
- 1-2 years everywhere, but mainly around 1780 and in the second half of the nineteenth century (around 1880: power maximum at 2 years of period).

Padua: the most important contributions are (fig. 9) the following.

- 70-100 years from 1900 to 1975 (inside the *coi*);
- about 16 years in 1940-50;
- about 6 years in 1775 and in 1855-60;
- between 2 and 8 years in 1910-60; in particular in 1930-55 the contribution to the 4 years period, already seen in Milan pressure, appears again, with exactly the same shape;
- many "episodes" scattered here and there at short scales, incuding the evident maximum at 2 years in 1880, already seen in Milan.

Stockholm: the scalogram (not shown) is almost lacking of any peculiarity and similar to that of a white noise process. Only the details that follow can be clearly recognized.

- A contribution at 6 years around 1820;
- a contribution at 4 years around 1950-60;
- small-scale contributions (below 2 years) mainly in 1820-50.

Uppsala: as in the case of Stockholm, the following remarks may be done (figure not shown).

- There is a contribution at 4-8 years around 1820;
- a contribution at 4 years around 1730, 1760 and 1960;
- a contribution to scales less or equal to 2 years, particularly in the first half of the nineteenth century.

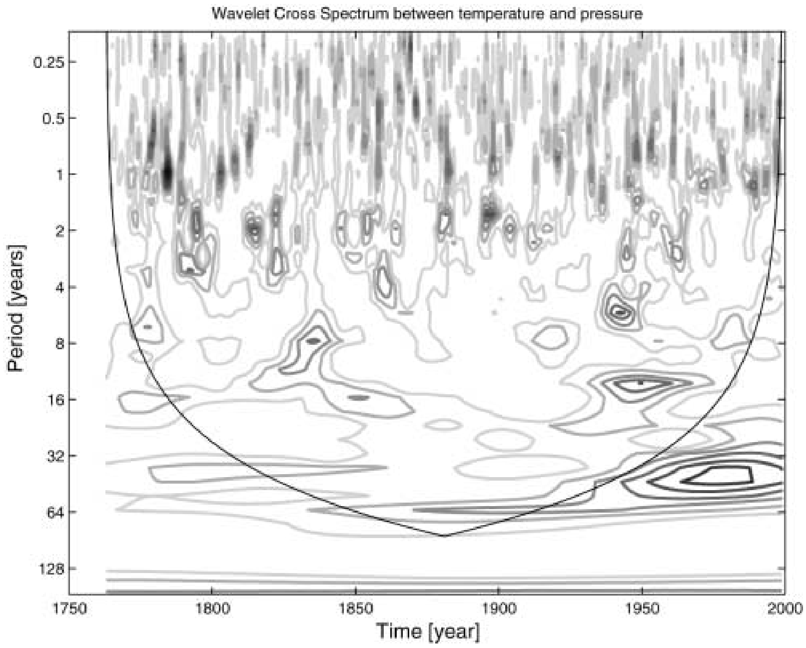

Fig. 14. – Cross-scalogram between $\langle t \rangle$ and $\langle p \rangle$ in Milan. Thick, dark gray isolines correspond to high power values; lighter shades of gray are associated to low power values. The solid black cup-shaped line represents the edge of the cone of influence.

5˙3. *Relation between temperature and pressure in the interdecadal range of periods.* – Observing figs. 3 and 8 it may be noticed that in Milan while $\langle t \rangle$ shows activity at all scales > 16 y, though variously modulated in time, $\langle p \rangle$ only shows activity in the range 32–64 y from about 1950 on (inside the *coi*).

In order to further investigate this point, first of all the Milan scalograms of $\langle t \rangle$ and $\langle p \rangle$ were averaged over the ranges of scales 15–120 years (fig. 10 and fig. 11) and 30–60 years (fig. 12 and fig. 13).

In these sequences, the variance of the original series was re-introduced, so that they are time series of average variance in a given period band. The dashed line in each figure represents a significance value at the 10% level, computed according to a procedure suggested by and Compo [3].

The figures show that while $\langle t \rangle$ has significant variance in the band 15-120 years from 1810 to 1890 and from 1970 to 2000, $\langle p \rangle$ never attains it. But if the range of scales is reduced to 30-60 years, in the interval from about 1950 to 2000 the average variance becomes significant for both variables.

This is confirmed by the cross-scalogram (Wavelet Cross Spectrum, described by and Compo [3]) between $\langle t \rangle$ and $\langle p \rangle$ in Milan, that in the interdecadal scale shows (fig. 14) only a maximum in the region 30–60 years, 1950-2000([3]) (inside the *coi*). The same turns out to be true if one couples $\langle p \rangle$ with $t_{\min}$ or $t_{\max}$ in Milan (cross-scalograms not shown).

([3]) Since only a qualitative information was seeked in this case, for the cross scalogram no significance test was introduced.

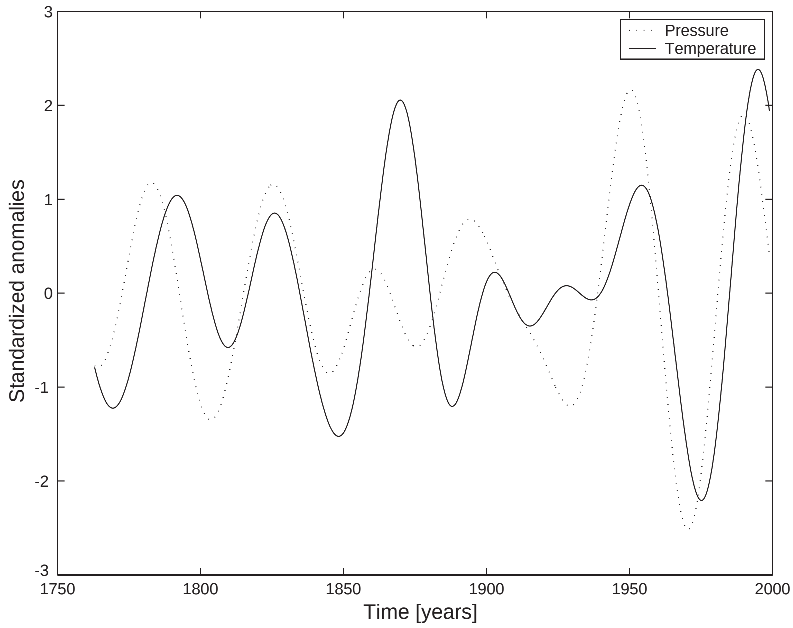

Fig. 15. – Reconstruction of $\langle t \rangle$ and $\langle p \rangle$ non-dimensional standardized anomalies in Milan, on the basis of the scales 30–60 years only.

This however does not tell if the pressure signal leads or lags the temperature signal in this "episode" characterizing the second half of the XXth century in Northern Italy. If then from the wavelet transform one reconstructs the anomalies of $\langle t \rangle$ and $\langle p \rangle$ (by Inverse Wavelet Trasform) selecting only the contributions due to the periodicities in the range 30-60 years (fig. 15), one sees that in general the pressure signal tends to leading the temperature signal, but only from 1950 both variables show a synchronous oscillation of remarkable amplitude. It must be noted here that the quantities plotted in this figure were made comparable by standardizing them to unit variance, and therefore making then non-dimensional.

Repeating the analysis with the pair ($t_{\min}$, $\langle p \rangle$) in Padua (the only possible case, see table II), the phenomeon does not show, possibly obscured by the power associated with the remarkable time trend of $t_{\min}$ that has already been described.

As for the North-European stations, nothing similar is found. Therefore this strong coupling between temperature and pressure in the second half of the XXth century should be the signature of a relatively local phenomenon.

6. – Conclusions

In the present study, the properties of stationary and evolutionary spectra of temperature and pressure time series recorded in Northern Italy (Milan, Padua, Genoa) and Scandinavia (Stockholm, Uppsala), obtained applying the wavelet technique, were examined.

From a stationary point of view, the main cyclicities found in Norther Italy stations for temperatures are 60/70 years, 33/40 years, 24/26 years and 8 years. Scandinavian stations show a smaller contribution of the highest periods: the main cyclicities are 30, 13/16 and 8 years. Pressure spectra are centered on smaller periods: in Northern Italy the main contributions come from 13/14 years and from periods below 2.4 years.

From the evolutionary point of view, it may be stated that in all scalograms a remarkable intermittence is observed, but certain "episodes" appear in several variables and sites: to give only a few examples, one may quote the contribution around 12 years of period in 1940-1960 ($t_{\max}$ in Milan and Genoa, $t_{\min}$ in Padua, $\langle t \rangle$ in Stockholm and Uppsala; $\langle p \rangle$ in Milan); the contribution around 24 years of period in 1820-1860 for Italian temperatures; the contribution around 30 years in Milan for $\langle t \rangle$ and $\langle p \rangle$ in the second half of the XXth century. On the other hand, it is evident that certain spectral peaks (expecially as far as *pdg* is concerned) are mainly due to temporally localized episodes.

The scalograms of Northern Italy are, for each physical quantity, generally similar among themselves, and the same may be said about Scandinavian stations, what reveals a comforting internal coherence in the analysis. Wavelet analysis proves once again to be a good tool for studying the temporal evolution of spectral characteristics in climatological data series. As expected, it proves to be endowed by the necessary time and frequency resolution qualities, by a satisfactory spectral estimate stability and to be able to give, when associated to proper statistical tests, not only qualitative but also quantitative results.

A strong coupling between $\langle t \rangle$ and $\langle p \rangle$ around 30 years of period was found in Milan in the second half of the XXth century, with the pressure signal leading the temperature one, while in North-European stations nothing similar is found. Therefore this strong coupling between temperature and pressure is probably due to a relatively local phenomenon.

Comparing analyses of the CET series, performed by other authors, with the present one, one may state that for Italian stations there is total agreement with [2] and [11] about the cyclicity at 24-25 years; this periodicity is, on the contrary, absent in Scandinavian stations. Values not too distant from 14 years, as well as 8 years, are present everywhere, except in Genoa. On the contrary, the about 5 years periodicity of Plaut *et al.* are not found in the present analysis, maybe due to a reduced ENSO effect on the examined sites. At last, the centennial periodicity seen by Baliunas *et al.* might be present also in our data, but the frequency resolution of this analysis, performed on series that are shorter than the CET one, does not allow identifying it. On the other hand, in the present case a cyclicity of about 60/70 years, typical of the AMO, was revealed in all stations except Stockholm. Moreover, periodicities in the range 30/40 years were revealed in some of the series. It may be noted that for interdecadal scales several dynamical interpretations are put forward, and listed, for example, by Wanner *et al.* [7]. The same author in another paper [32] states that a 64 years cycle is visible also in Alpine precipitation series.

As a final remark, it may be mentioned that data homogeneization may influence the search for periodicities in climatic series.

Homogeneization of long historical records is nowadays a key subject in the field of climatic variability research. Many open questions remain about these procedures: what is clear is that no homogeneization method exists, that can be applied to any series. Rather, the procedure must be designed case by case, taking into account the problems that need to be solved. In the IMPROVE project [12, 13], in which the series used in the present study were homogeneized, the homogeneization was performed mainly with the aim of revealing long-term trends and in many cases supposed inhomogeneities were corrected by means of step functions, which for sure can introduce spurious components of high frequency in the spectra of the series. In general, applying correction functions may affect in an unknown way the results of stationary and non-stationary spectral analysis.

* * *

The authors are grateful to Dr. M. Maugeri and Dr. T. Nanni for kindly granting the use of the time series analyzed in this work. Wavelet software was provided by C. and G. Compo, and is available at URL: http://paos.colorado.edu/research/wavelets.

REFERENCES

[1] Ghil M., *Natural Climate Variability* in *Encyclopedia of Global Environmental Change*, Vol. **1**, edited by T. Munn (Wiley, Chichester) 2002, pp. 544-549.

[2] Plaut G., Ghil M. and Vautard R., *Interannual and Interdecadal Variability in 335 Years of Central England Temperatures*, in *Science*, **268** (1995) 710.

[3] Torrence C. and Compo G. P., *A Practical Guide to Wavelet Analysis*, in *Bull. Am. Meteorol. Soc.*, **79** (1998) 61.

[4] Saravanan R., *A Multiwave Model of the Quasi-Biennial Oscillation*, in *J. Atm. Sci.*, **57** (1990) 2465.

[5] Perlwitz J. and Graf H. F., *The Statistical Connection between Tropospheric and Stratospheric Circulation of the Northern Hemisphere in Winter*, in *J. Climate*, **8** (1995) 2281.

[6] Philander S. G. H., *El Niño, La Niña and the Southern Oscillation* (Academic Press, San Diego, CA) 1990.

[7] Wanner H. *et al.*, *North Atlantic Oscillation - Concepts and Studies*, in *Surveys in Geophysics*, **22** (2001) 321.

[8] Ghil M. *et al.*, *Advanced Spectral Methods for Climatic Time Series*, in *Rev. Geophys.*, **40-1** (2002) 1.

[9] Dettinger M. D. *et al.*, *Software Expedites Singular - Spectrum Analysis of Noisy Time Series*, in *EOS, Trans. Am. Geophys. Union*, **76-2** (1995) 12,14,21.

[10] Mann M. E. and Lees J. M., *Robust Estimation of Background Noise and Signal Detection in Climatic Time Series*, in *Clim. Change*, **33** (1996) 409.

[11] Baliunas S. *et al.*, *Time Scales and Trends in the Central England Temperature Data (1659-1990): A Wavelet Analysis*, in *Geophys. Res. Lett.*, **24** (1997) 1351.

[12] Camuffo D. and Jones P., *Improved Understanding of Past Climatic Variability from Early Daily European Instrumental Sources* (Kluwer Academic Publishers, Dordrecht) 2002.

[13] Moberg A. and Bergström H., *Homogeneization of Swedish Temperature Data. Part III: The Long Temperature Records from Uppsala and Stockholm*, in *Int. J. Climatol.*, **17** (1997) 667.

[14] Brunetti M., Maugeri M. and Nanni T., *Variations of Temperature and Precipitation in Italy from 1866 to 1995*, in *Theor. Appl. Climatol.*, **65** (2000) 165.

[15] Brunetti M., Mangianti F., Maugeri M. and Nanni T., *Climate Variation in Italy from 1866 to 1995*, in *World Resource Review*, **12** (2000) 31.

[16] Brunetti M., Buffoni L., Maugeri M. and Nanni T., *Trend of Minimum and Maximum Daily Temperature in Italy from 1865 to 1996*, in *Theor. Appl. Climatol.*, **66** (2000) 49.

[17] Brunetti M., Buffoni L., Maugeri M. and Nanni T., *Precipitation Intensity Trends in Northern Italy.* in *Int. J. Climatol.*, **20** (2000) 1017.

[18] Brunetti M., Buffoni L., Maugeri M. and Nanni T., *Urban heat island bias in Italian air temperature series.* in *Nuovo Cimento C*, **23** (2000) 423.

[19] Brunetti M., Buffoni L., Maugeri M. and Nanni T., *Trends in the Daily Intensity of Precipitation in Italy from 1951 to 1996*, in *Int. J. Climatol.*, **21** (2001) 299.

[20] Brunetti M., Maugeri M. and Nanni T., *Changes in total precipitation, rainy days and extreme events in northeastern Italy*, in *Int. J. Climatol.*, **21** (2001) 861.

[21] Boehm R., Auer I., Brunetti M., Maugeri M., Nanni T. and Scoehner W., *Regional Temperature Variability in the European Alps 1760-1998 from Homogenised Instrumental Time Series*, in *Int. J. Climatol.*, **21** (2001) 1779.
[22] Maugeri M., Bagnati Z. Brunetti M. and Nanni T., *Trends in Italian total cloud amount, 1951-1996*, in *Geophys. Res. Lett.*, **28** (2001) 4551.
[23] Brunetti M., Maugeri M., Navarra A. and Nanni T., *Droughts and Extreme Events in Regional Daily Italian Precipitation Series*, in *Int. J. Climatol.*, **22** (2002) 543.
[24] Brunetti M., Maugeri M. and Nanni T., *Atmospheric Circulation and Precipitation in Italy for the Last 50 Years*, in *Int. J. Climatol.*, **22** (2002) 1455.
[25] Brunetti M., Maugeri M. and Nanni T., *Study of the Solar Signal in Mean Central Europe Temperature Series from 1760 to 1998*, in *Nuovo Cimento C*, **26** (2003) 287.
[26] Maugeri M., Brunetti M., Monti F. and Nanni T., *The Italian Air Force Sea Level Pressure Data Set (1951-2000)*, in *Nuovo Cimento C*, **26** (2003) 453.
[27] Brunetti M., Buffoni L., Mangianti F., Maugeri M. and Nanni T., *Temperature, Precipitation and Extreme Events During the Last Century in Italy*, in *Global and Planetary Change*, **40** (2004) 141.
[28] Oppenheim A. W. and Schafer R. W., *Discrete-Time Signal Processing* (Prentice Hall, London) 1989.
[29] Maugeri M. *et al.*, *Sea Level Pressure Variability in the Po Plain (1765-2000) from Homogeneized Daily Secular Records*, in *Int. J. Climatol.*, **24** (2004) 437.
[30] Lau K. M. and Weng H., *Climate Signal Detection Using Wavelet Transform: How to Make a Time Series Sing*, in *Bull. Am. Meteorol. Soc.*, **76** (1995) 2391.
[31] Moberg A. *et al.*, *Day-to-Day Temperature Variability Trends in 160 to 175 Year - Long European Instrumental Records*, in *J. Geophys. Res.*, **105**, N. D18 (2000) 22849.
[32] Wanner H. *et al.*, *Interannual to century scale climate variability in the European Alps*, in *Erdkunde (Earth Science)*, **54** (2000) 62.