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Chapter 3

WAVELET ANALYSIS AS A TOOL FOR CHARACTERIZING TRENDS IN CLIMATIC DATA

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Abstract

Wavelet transform is an effective mathematical tool able to provide a time–frequency representation of signals defined in the time domain. So far this innovative multiscale analysis has been successfully applied in various fields of science, such as, for example, geophysics, astrophysics, telecommunications and climatology. In this chapter the wavelet analysis is employed to analyse Sicily temperature data. Sicily represents one of the hot spot for the study of climate change in the Mediterranean area, because of its vulnerability to desertification processes. Precipitations and temperature trends forecasted for the XXI century by Regional Climate Models (RCM) show an increasing temperature trend and a non-clear precipitation trend. To better characterize the temperature trend, the 1865-2016 temperature time series of Palermo and the 1962-2014 time series of four Sicilian localities have been analysed by means of Continue and Discrete Wavelet Transforms. Such analyses allow to identify the fast and slow events contained in the time series and to identify the major features of the Sicilian climate dynamics.

Keywords: wavelet analysis, climatic data, trends, anomalies, temperature

Introduction

The increasing of temperatures and the intensification of the hydrologic cycles are the most evident effects caused by climate change in the Mediterranean basin. One of the most significant consequences of temperature increase and of changes in precipitations is the dramatic modification of hydrologic regimes. During the last 15 years an impressive series of extreme weather events occurred in different places of Sicily, producing damages and, in some cases, even victims.

For example, one can cite the following tragic sequence of severe meteorological events occurred between the years 2007 and 2011:

- 25th October 2007, which took place at Santa Margherita, Giampilieri and Scaletta (Messina), with flash flood and precipitations of 175 mm in 2 hours, against an annual average value of 800-1000 mm;
- 22nd November 2011 at Barcelona and Saponara (Messina) with precipitations of 351 mm in 10 hours (recorded by the Castroreale weather station);
- 01st October 2009 at Giampilieri; this latter was a tragic and disastrous event with 37 victims.

With reference to these three events, the recovery costs of the disaster damages were estimated to be about 900 million euros [1, 2].

These findings are in agreement with the predictions of the Mediterranean Regional Climate Model as shown in the report “The future climate of Italy: analysis of projections of regional models” [3]. The Model predicts that the accumulated yearly precipitations will slightly decrease, while the maximum rain rate is expected to increase in most of Italy, with the exception of Sicily. One more interesting parameter is the forecast of the maximum number of days without rain: it will increase from 5 to 40% respect the average 1971-2000. It is therefore not surprising that many of the arguments concerning both climate variability and climatic change are directly related to the detection of trends in hydro-climatic parameters, such as temperature and precipitation [4]. One way to accomplish trend assessments is through time-series analysis. Wavelet analysis offers several advantages in respect to Fourier Transform or Windowed Fourier Transform analysis, these latter using a single analysis window. The main problem with the fixed window used in the Windowed Fourier Transform is that it loses the time localization at high frequencies when the window is sliding along the time series because there are too many oscillations captured within the window. It also losses the frequency localization at low frequencies because there are only a few low-frequency oscillations included in the window [5-7]. The wavelet transform can handle these issues by decomposing a one-dimensional signal into two-dimensional time–frequency domains at the same time [8-11]. Wavelets are usually irregular and asymmetric in shape and this property makes a wavelet ideal for analysing signals that contain sharp changes and discontinuities [12-15]. Wavelet transforms use different window sizes, which are able to compress and stretch wavelets in different scales used to decompose a time series. Narrow windows are used to track the high-frequency components or rapidly changing events of the analysed signals (which are represented by the lower detail levels), whereas wider window sizes are used to track the signals' low-frequency components including trends (which are represented by the higher detail levels and the approximation component). Moreover, wavelet analysis is able to show many properties of a time series or data (such as trends, discontinuities, change points, and self-similarity) that may not be revealed by other signal analysis techniques. In summary, the wavelet transform is capable of analysing a wider range of signals more accurately when compared to the Fourier analysis [16-19]. The results of wavelet analysis can be used to determine the main components or modes that contribute to producing trends [11, 21, 22].

The main purpose of this study is to combine the use of the Discrete Wavelet Transform (DWT) technique and the Continues Wavelet Transform (CWT) in order to investigate trends, periodicities and singularities present in four datasets concerning the temperature of Sicily by analysing their monthly and annual time series collected from 1962 to 2014.

A Background on Wavelet

Any climate signal can be interpreted as a result of interactions between physical and dynamic processes that occur on a wide range of spatial and temporal scales. The scale of the processes involved extends into the space between a few meters and thousands of kilometres and in time in a few hours and millions of years [23]. To analyse such behaviour we need to use special mathematics tools. The wavelet analysis represents a powerful instrument to extract information from a time series. It can be used to analyse time series that contain non-stationary power at many different frequencies. In the case of meteorological and climatological series, this type of analysis is particularly appreciated because it is able to extract valuable information from the signal [24, 25]. For example, if compared to the simple Fourier transform, the wavelets analysis allows to find not only in the value of certain frequencies in a non-stationary series, but also to identify the time interval in which these frequencies are present and predominant. A wavelet function is a function having a wave shape and a limited but flexible length with a mean value that is equal to zero, and is localized in both time and frequency domains. Let consider a complex-valued function ψ satisfying the following conditions:

$$\int_{-\infty}^{\infty} |\psi(t)|^2 dt < \infty \qquad (1)$$

$$C_\psi = 2\pi \int_{-\infty}^{\infty} \frac{|\Psi(\omega)|^2}{|\omega|} d\omega < \infty \qquad (2)$$

where Ψ is the Fourier transform of ψ. The first condition implies finite energy of the function ψ, and the second condition, the admissibility condition, implies that if $\Psi_{(\omega)}$ is smooth then $\Psi(0) = 0$. The function ψ is the mother wavelet [26].

Wavelet transforms involve shifting forward the wavelet in a number of steps along an entire time series, and generating a wavelet coefficient at each step. This measures the level of correlation of the wavelet to the signal in each section. The variation in the coefficients indicates the shifting of similarity of the wavelet with the original signal in time and frequency. This process is then repeated for each scaled version of the wavelet, in order to produce sets of wavelet coefficients at the different scales. The lower scales represent the compressed version of the mother wavelet, and correspond to the rapidly changing features or high-frequency components of the signal. The higher scales are the stretched version of a wavelet, and their wavelet coefficients are identified as slowly changing or low frequency components of the signal. Therefore, wavelet transforms analyse trends in time series by separating its short, medium, and long-period components [27]. WT can be performed using two approaches: Continuous Wavelet Transform (CWT) and Discrete Wavelet Transform (DWT). CWT operates on smooth continuous functions and can detect and decompose signals on all scales, while Discrete Wavelet Transform (DWT) operate on scale that have discrete numbers.

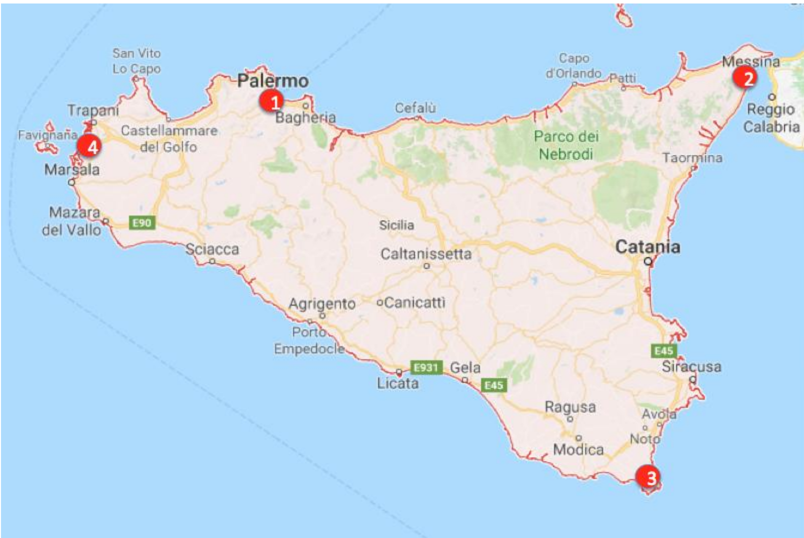

Figure 1. Geographic position of the four analysed weather station.

Site and Data Description

Sicily, being located in the centre of the Mediterranean, represents a privileged point of observation to study climate changes. Its climatic characteristics are able in fact to be considered with a good approximation, as representative of the whole Mediterranean basin. The choice of the data sets used in this work, has been done taking into account the geographic position of each station and its characteristics. All the selected weather stations are in fact very close to the sea coast, with a maximum altitude of 54 metre and, for this reasons, they can be considered as good indicators of the mean Mediterranean climate. The Palermo's temperature time series starts from 1865 and is the longest series available in Sicily. The geographic positions and the characteristics of each station are shown in Figure 1 and in Table 1, respectively.

The Palermo and Messina weather stations are positioned inside the town; the Cozzo Spadaro weather station is located inside a lighthouse building in a small fisherman village, while the Trapani weather station is sited in the military airport located 12 kilometres far from the nearest city. In order to uniform and to compare the time series length for wavelet analysis, we have taken into account the longest common period, i.e., 1962-2014. During this time interval, Sicily had a great economic growth; the populations of the towns of Palermo and Messina increased and several new building have been built, beginning from early seventies. This anthropogenic change could affect the temperature signal, producing a higher increase in respect to the signals of Trapani and Cozzo Spadaro, where minor or no environment changes occurred since 1960. The monthly and annual temperatures of these four weather stations were analysed. The stations used in this study were chosen on the basis of completeness and length of their available record for the period of 1962-2014. This time interval is considered to be long enough to obtain valid statistics mean values in assessing the temperature trend [28]. Furthermore, Partal (2010) [29] considered 40-years data adequate for trend analysis studies. Moreover, although up to three-percent missing data is considered acceptable for meteorological studies [30], we chose only the stations with fully complete records over the chosen time period. This was done in order to avoid possible uncertainties associated with the computation of extrapolation procedures. Therefore, we concluded that having 53 years data is sufficient for the purpose of trend detection.

Table 1. Meteorological stations employed to record temperature and precipitation data

WMO ID	Station Name	Latitude (°)	Longitude (°)	Elevation (m a.s.l.)	Observation Period
16405	Palermo	38°07’00”	13°18’44”	36	1865-2015
16420	Messina	38°12’02”	15°33’11”	54	1962-2014
16480	Cozzo Spadaro	36°41’10”	15°07’57”	44	1952-2015
16429	Trapani-Birgi	37°54’50”	12°29’28”	4	1962-2014

Data Analysis

The temperature data sets of the four stations are composed by monthly and annual mean values. In addition, the temperature data set of Cozzo Spadaro weather station also contains the daily 12 UTC temperatures. In order to identify the trends, the conventional discrete wavelet analysis of signals was performed on each time series using the multilevel 1-D wavelet decomposition function in MATLAB. This produces the wavelet transform of the input data at all dyadic scales. The Mayer (dmey) wavelet was used in this study because the Meyer mother wavelet has two features that make them very useful in analysing temperature records: first, they are fairly smooth and second, they have limited frequency bands. The smoothness feature makes them more capable of detecting the smooth component of the signal. Moreover, smoother wavelets are preferred here because the trends are supposed to be gradual and represent slowly changing processes. Smoother wavelets should be better at detecting long-term time-varying behaviour (good frequency-localization properties) [31]. The finite frequency bandwidth enables them to detect and isolate the various periodic components of the record. For each monthly dataset, seven levels of decomposition were used. This number is based upon the number of data point, equal to 636 average monthly temperature, as well as the mother wavelet used. Decomposing the signals using specified filters (wavelet and scaling functions) produces two types of coefficients: the approximation or residual, and detail vectors [32, 33]. These coefficients resulted from the convolution of the original signal with a low-pass filter and a high-pass filter. The low-pass filter is the scaling function and the high-pass filter is the wavelet function. The convolutions of signals with the low-pass filter produced the approximation coefficients, which represent the large-scale or low frequency components of the original signal. Convolutions with the high-pass filter produced the detail coefficients, which represent the low-scale or high-frequency components [34, 35]. The data were also analysed by using the CWT in order to identify discontinuities, singular episode and periodicities contained in the signal. In this case, one of the most widely used continuous wavelet, a Morlet mother wavelet, was used. It consists of a plane wave modified by a Gaussian envelope [36]:

$$\psi_0(\eta) = \pi^{-1/4} e^{i\omega_0\eta} e^{-\eta^2/2} \tag{3}$$

where ω_0 is the nondimensional frequency, here taken to be 6 to satisfy the admissibility condition [37].

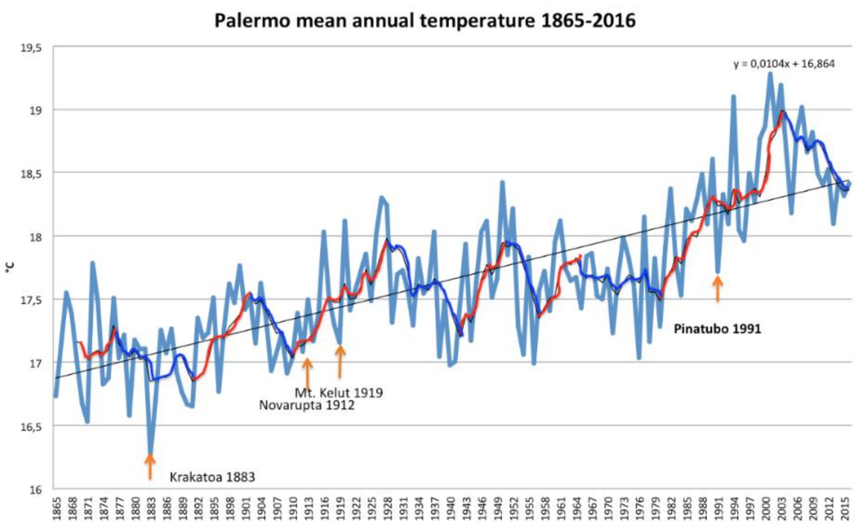

Figure 2. Palermo mean annual temperature data (blue curve); 5 years mean values (red and dark blue curves) and linear trend (black line). The orange arrows show the correspondence of negative peaks with the major volcanic eruptions occurred during the last 150 years.

Results and Discussion

The analysis of Palermo's annual mean temperature 1865-2016 graph (Figure 2) allow us to make some general considerations regarding the influence of the world biggest volcanic eruption on the temperature signal. Volcanic eruptions can inject into the stratosphere a huge volume of chemically and micro physically active gases and solid aerosol particles, which affect the Earth's radiative balance and climate and disturb the stratospheric chemical equilibrium. The resulting disturbance to the Earth's radiation balance affect surface temperatures trough directs radiative effect as well as trough indirect effects on the atmospheric circulation. In the analysed signal we found in fact the footprint of the Hearth's major volcanic eruptions occurred during the last 150 years. They are all remarked in the figure with an orange arrow in correspondence of the year of the eruption. The linear trend of temperature was also calculated and it was equal to 0,0104°C/years that means a total temperature increase of 1,58°C for the whole period. The first analysis performed on Palermo longer time series of monthly temperature was a Discrete Wavelet Transform. The detail of reconstruction at level 9 is shown on Figure 3. It shows a positive trend of temperature with 2 main slopes: the first starts on 1870 and continue till 1910. A range of about 40 years in which the temperature stay about stationary before stating to increase again becoming from 1960 and continuing till 2010 follows it. The total amount of temperature increasing was about + 1,55°C on line with the value obtained using the linear regression.

After this result obtained for Palermo, we started to analyse the 53 years long temperature series for Messina, Palermo, Trapani and Cozzo Spadaro, respectively. For each data set a Discrete Wavelet Transform decomposition at level 7 and a Continuous Wavelet Transform was performed. For the DWT we used the temperature data sets, while for CWT, in order to eliminate the strong yearly periodicity, the temperature anomalies were calculated and used.

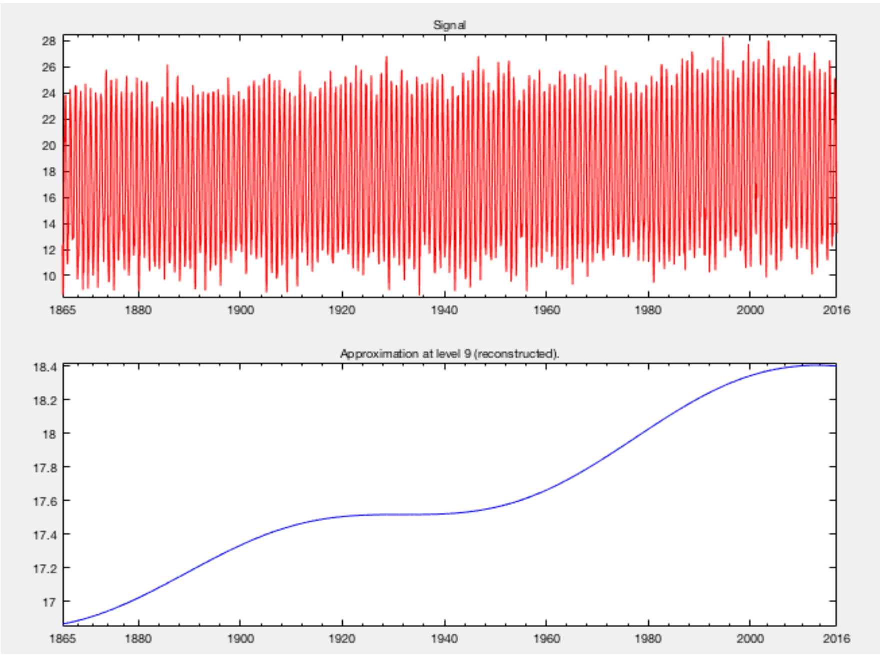

Figure 3. Palermo DWT signal (on the top) and approximation at level 9 (on the bottom) of the 1865-2016 mean monthly temperature values.

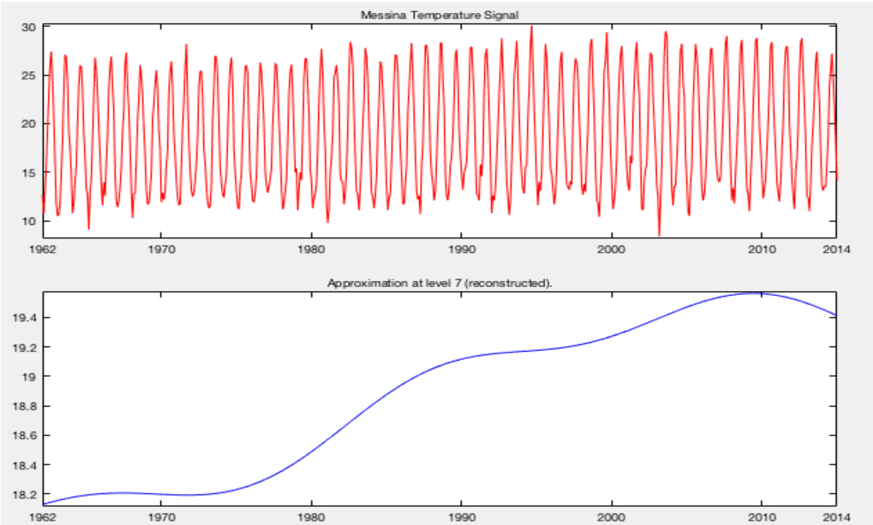

Figure 4. Messina DWT (on the top) and approximation at level 7 (on the bottom) of the 1962-2014 mean monthly temperature values.

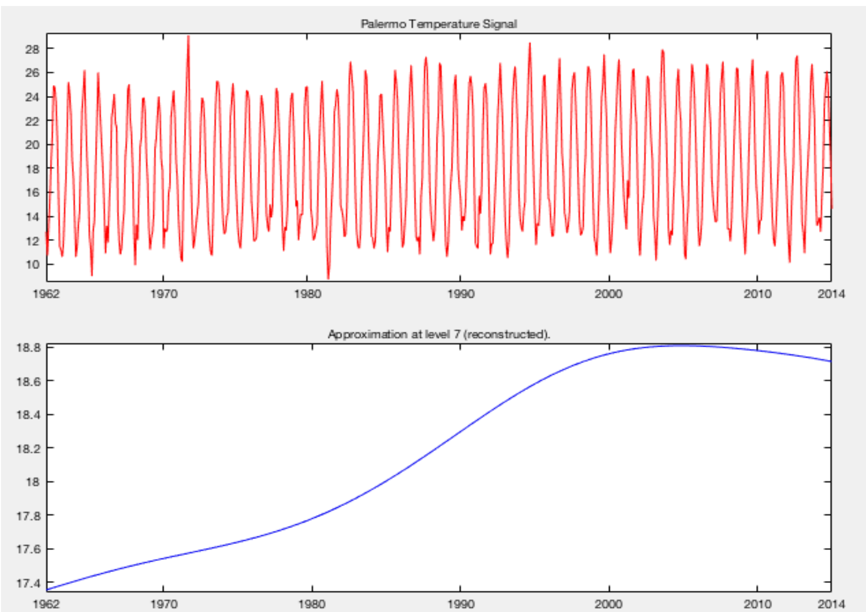

Figure 5. Palermo DWT data (on the top) and approximation at level 7 (on the bottom) of the 1962-2014 mean monthly temperature values.

Each signal shows some differences and some common trend characteristics. Messina, Palermo and Trapani show, for example, a decreasing trend during the last years. Palermo seems to reach the maximum temperature in 2005 while Messina and Trapani reach the maximum value in 2010, before that the temperature starts to decrease. Messina shows also an almost flat trend during the 1962-1975 time range and then a rapid up-slope till 1990, while Palermo and Trapani show a more regular trend. The Cozzo Spadaro trend is quite different; it is the only one that shows a negative trend from 1962 to 1978; moreover, it shows a continue temperature increase till the end of the signal. In Table 2 the minimum and maximum values reached, the difference and the increasing of temperature obtained subtracting the value of 2014 to the values of 1962, are shown.

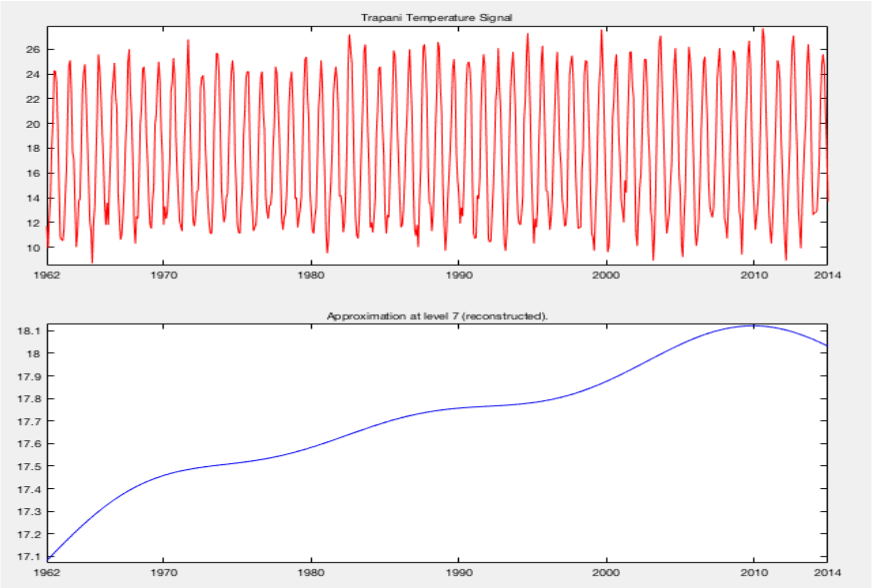

Figure 6. Trapani DWT data (on the top) and approximation at level 7 (on the bottom) of the 1962-2014 mean monthly temperature values.

A Continuous Wavelet Transform has also been performed on the mean monthly temperature anomaly of four time series using a Morlet mother wavelet. The anomaly was first calculated subtracting from the monthly mean temperature, the average monthly temperature of the 30 years 1971-2000. This operation cleans the signal of the strong annual frequency, making the CWT graph more readable.

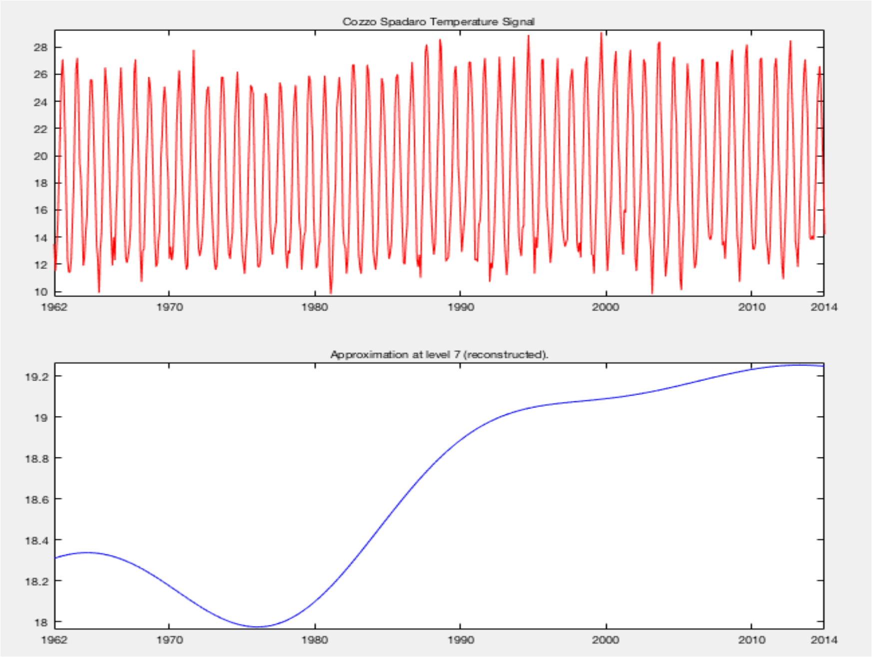

Figure 7. Cozzo Spadaro DWT data (on the top) and approximation at level 7 (on the bottom) of the 1962-2014 mean monthly temperature values.

Table 2. Minimum, Maximum, Max difference and temperature increase of each weather station

Weather Station	Minimum	Maximum	Max difference	Temperature increasing 1962-2014
Messina	18,13	19,56	1,435	+1,27°C
Palermo	17,35	18,81	1,453	+1,37°C
Trapani	17,08	18,12	1,041	+0,94°C
Cozzo Spadaro	17,98	19,25	1,278	+0,95°

Messina CWT shows the presence of periodicities longer than 2 years from 1980, when a 24-36 months signal started. It disappears around 1990. During these 10 years, an abrupt episode is present in 1987. At the same time, a periodicity of about 60 month appears and continues till 2008, overlapped to a 36-month periodicity that finishes in 2010. A second strong singular episode is presents in 2003 (Figure 8). Palermo CWT graph also shows the absence of longer than 2 years periodicities from 1962 to 1980. Starting from these years a periodicity of 24 to 36 month appears and continues to be present until 2008. Two singular episodes are again visible in the graph in 1987 and in 2003. A longer periodicity of about 60 months appears in the graph in correspondence of the singular episode of 1987 and continues until 2012 (Figure 9).

Trapani CWT, as also seen for Messina and Palermo, maintains the same characteristics: absence of periodicities longer than 2 years till 1980 when a 24 to 36 months periodicity appears and continues until 1990. The point at 1987 shows a well-defined singularity, while a second one appears in 1999. Starting from this point a new periodicity of about 60 months appears and continues till 2010 (Figure 10). The CWT of Trapani contains also another important feature: the presence of a well-defined periodicity of about 128 months from 1962 to the middle of 1980s. This periodicity is typical of solar cycles and is more or less present also in the others CWT.

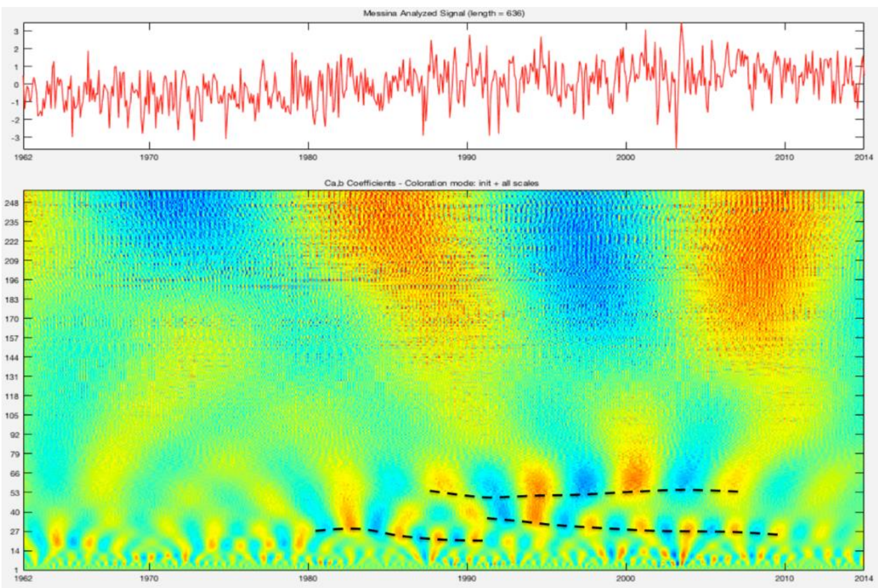

Figure 8. CWT of Messina 1962-2014 mean monthly temperature anomaly.

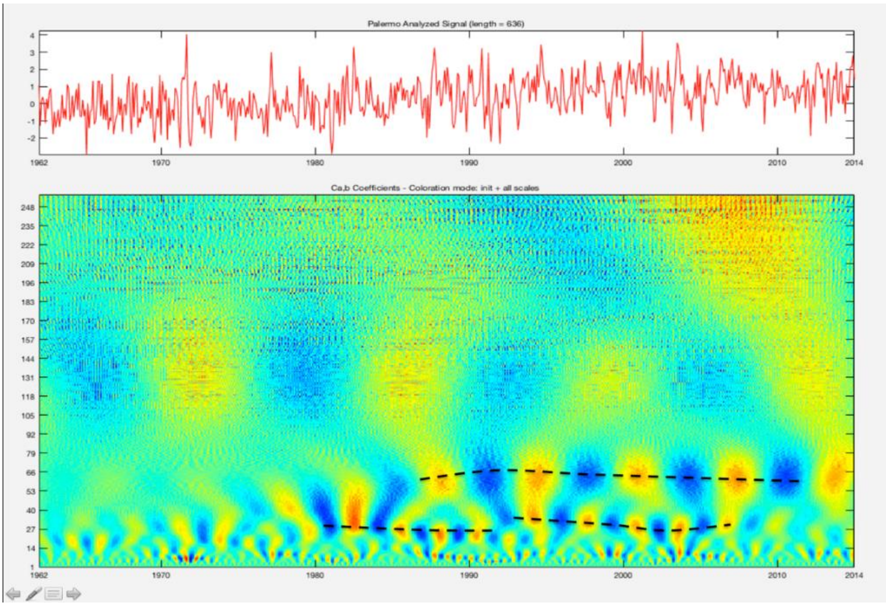

Figure 9. CWT of Palermo 1962-2014 mean monthly temperature anomaly.

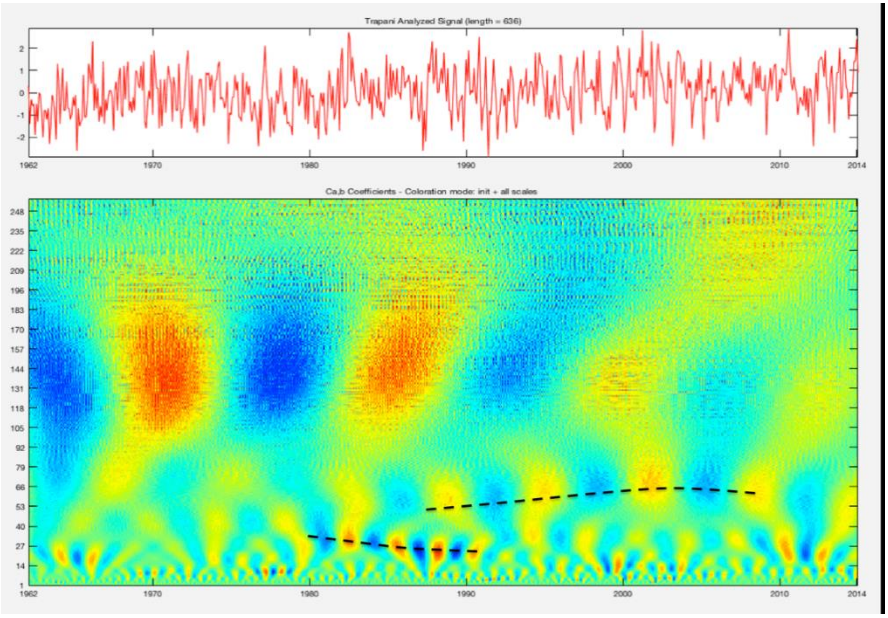

Figure 10. CWT of Trapani 1962-2014 mean monthly temperature anomaly.

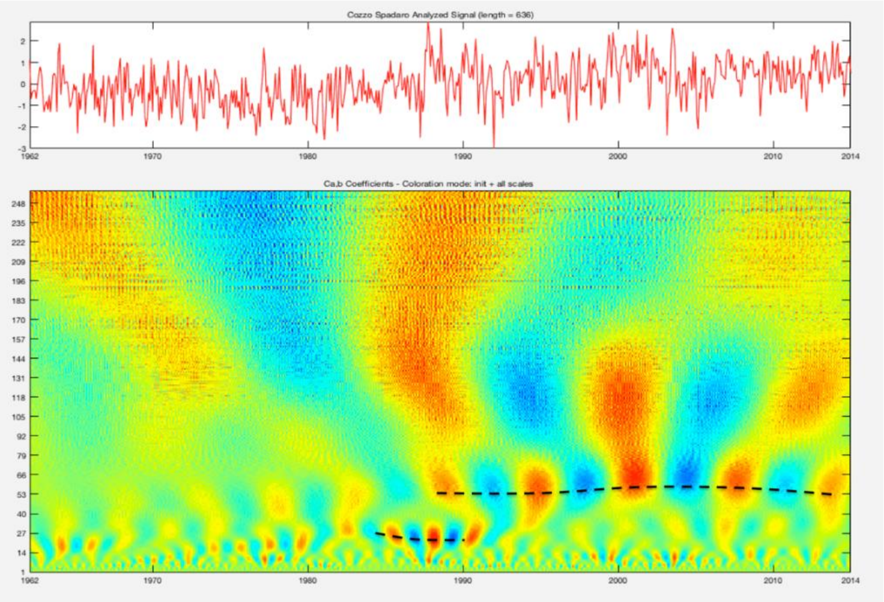

Figure 11. CWT of Cozzo Spadaro 1962-2014 mean monthly temperature anomaly.

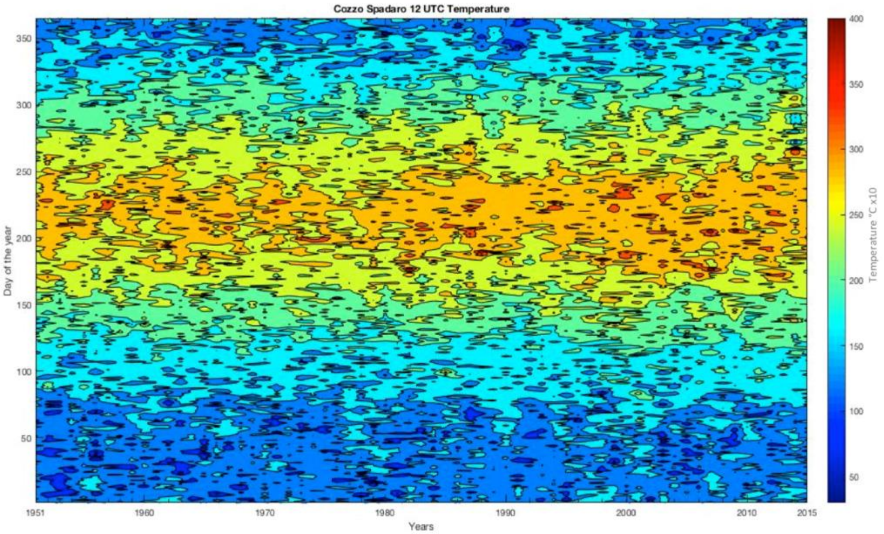

Figure 12. Cozzo Spadaro daily 12 UTC temperature surface plot.

Finally, concerning the Cozzo Spadaro CWT, the graph shows the absence of periodicities until 1985. A periodicity of about 30 months appears and continues till 1990. The singular episode of 1987 is here well marked as the beginning of the 60 months periodicity that continues till the end (Figure 11). The availability of Cozzo Spadaro daily 12 UTC temperatures from 1951 to 2015, let us allow to further explore it in order to understand how the temperature is changing. For this reason, the data have been arranged in a matrix of 365 rows per 65 columns, where the rows represent the days of each year from January 1st (on the bottom) to December 31st (on the top) and the columns (from left to right) the years from 1951 to 2015. To better visualize the temperature changes, a colour scale has been used to represent the temperature. The obtained plot is showed in Figure 12.

Conclusion

The aim of this chapter was to use the Wavelet analysis on a 53 years long temperature time series of four localities of Sicily, in order to detect the temperature trends and to identify the climate dynamics that drives the process of global warming in Sicily and in general in the Mediterranean area. The first step of this work was to compare the annual mean temperatures of Palermo (the longest available time series), with the big world volcanic eruption calendar. It soon appears a strong correlation between the occurrences of an eruption, which is immediately followed by decreasing temperature. As second step, we performed a Discrete Wavelet Transform on the temperature signal, in order to identify the trends present in the signal. For Palermo, the DWT performed on the 150 years temperature time series, identifies a total positive trend of 1,55°C, with two periods of more intense warming during 1880-1910 and 1960-2000, together with a range in which the temperature values have been stationary or decreased. This is about the same trend recorded for the global temperature trend of the Northern Hemisphere. In order to make comparable the four data series, only the common years 1962-2014 have been analysed during the next step. The DWT of the four time series, show that during these years, all the four weather stations have registered a temperature increase. The amplitude of this warming, oscillates from less than 1°C to about 1,4°C, depending on the position and on the characteristics of each weather stations. Both the weather stations positioned inside the town of Palermo and Messina, showed for example, the major increasing of temperature, respectively of 1,37°C and 1,27°C. This is due to the major anthropogenic impact occurred in the two cities and to the urban heat island effect. The places where the anthropogenic impact was negligible registered a temperature increase of about 1°C during last 53 years.

The next step was to analyse the four time series using the CWT. The obtained results show some common features:

- Two strong singularities that appear in the signal in correspondence of the year 1987 and 2003;
- A 60 months periodicity starting in 1987 and continuing at least until 2010.
- A 128 months periodicity starting in 1962 and continuing to about middle 1980s.

This means that in 1987 something occurred in the climate dynamics of Sicily and requires further analysis. An interesting and intriguing hypothesis is described in different literature papers and regards the sea-atmosphere interaction. Conversi et al. 2010 [38] states “1987 appears to be a year of change for the entire Mediterranean basin surface circulation.” Furthermore Demirov and Pinardi’s [39] simulations of the interannual surface Mediterranean circulation from 1979 to 1993 identify two periods, 1981–87 and 1988–93, which differ in precipitation and winter wind regimes. Pinardi et al. [40] and Korres et al. [41], using data-validated simulations describe the dramatic reversal of the Ionian gyre in the summer of 1987 from its “usual” cyclonic state to an anticyclonic pattern. In particular, they show a reversal in the surface current directions in the Ionian sea, with the Atlantic/Ionian stream (and associated nutrients and hydrographical properties), branching further northward, at 35.5°N, and linked it to the surface circulation changes to the previous winter anomalies in the winds and heat fluxes. The alteration lasted approximately 10 years, until 1997, when the gyre re-reversed.

The presence of the 128 months periodicity in the CWT, let us to make the hypothesis that before 1985 was the Sun to mainly drive the temperature trends, while starting from the middle 1980s, other cyclic oscillations like ENSO or NAO or others unknown, become most significant in the determination of the increasing temperature.

Finally, the Cozzo Spadaro 12 UTC daily temperature analysis allows to understand the way in which the temperature is changing. Starting from the beginning of the ’1980s, a long sequence of red spot is visible in Figure 12. Each red spot could be assimilated to a heat wave with temperature higher of

35°C. This means than the temperature pattern is changing, showing an increasing number of summer hot days and heat waves. Another distinguishing feature is expressed by the colours in the plot where the expansion of the orange area corresponding to an increasing length of the summer season is registered. Counting the number of the days comprised from the first and the last day of the year in which temperature reached 30°C (summer days), the average length passed from about 58 days in 1950s to about 74 days in 2010s, with an average increase of 16 summer days (Figure 13).

Moreover the graph shows that in 1987, 1999 and 2003, the number of summer days exceeded 100 days. This result is coherent with the presence of the singularities we have found in the CWT of the four Sicilian weather stations. These new evidences let us to state that the year 1987 is confirmed to represent an important year for climate change in Sicily because for the first time the number of summer days reached the record value of 100 days. This so high number, was reached again only 12 years later in 1999 and then again in 2003; both years were characterized by a sequence of very long heat wave, one of which is still remembered as "killer heat wave" because during the summer 2003 caused a record high temperature across the whole Europe with at least 30.000 deaths (more than 14.000 in France alone).

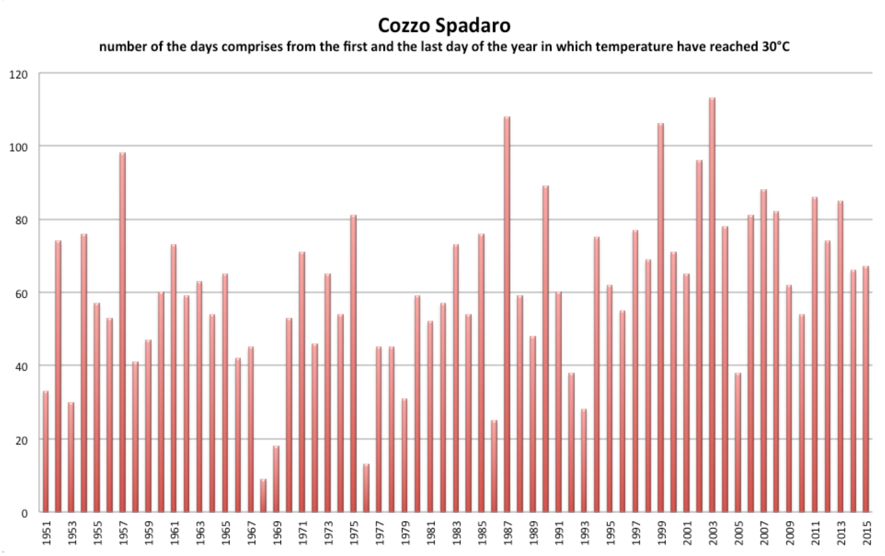

Figure 13. Cozzo Spadaro number of days comprised from the first and the last day of the year in which temperature have reached 30°C (Summer days).

In conclusion, the use of discrete and continuous wavelet analysis coupled with other graphics tools such as the matrix temperature arrangement and the surface graph visualization, reveals to be very powerful tools capable to extract additional and very useful information on the climate dynamics contained in a simple data set of temperature.

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