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ANALYSIS AND EVOLUTION OF CLIMATIC DYNAMICS DURING LAST FIFTY YEARS IN SICILY

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ABSTRACT. In the last years the Wavelet Transform has received a lot of attention for the ability to provide a time–frequency representation of analysed signals in the time domain. Such an advanced time-frequency analysis has been effectively applied in various fields, such as, for example, geophysics, astrophysics, telecommunications and climatology. The paper reports the results of the time series of temperature of some Sicilian weather stations. First, different methods have been applied in order to identify cycles and trends present in signals and then, by means of wavelet coherence analysis, a correlation between the cycles present in signals and the solar cycles such as the North Atlantic Oscillation (NAO) and the El Nino Southern Oscillation (ENSO). Finally, the capability of wavelet to highlight the breakdown or discontinuities contained in the signals, has been investigated.

1. Introduction

The Global Warming is currently affecting the whole planet causing a general increasing of temperature and regional modification of the hydrologic regimes. Most of the experiment, performed by Regional Climate Models, indicate that climate change is the results of the sum of naturals and anthropogenic signals. The coastal countries and the islands of the Mediterranean basin, due to their vulnerability to desertification processes, represent an important area to perform analysis and study concerning the climate change. Any climate signal can be interpreted as the result of interactions between physical and dynamic processes that occur on a wide range of spatial and time scales. More precisely, the space scale of the processes involved extends between a few meters and thousands of kilometres while the time scale in a few hours and millions of years (Lau and Weng 1995b). For these reasons, a time series analysis of Sicilian temperature recorded during last 150 years has been performed by means of the Wavelet analysis to extract information regarding the trend, cycle and discontinuities from the original signal. The choice of Wavelet Transform (WT) is very advantageous respect to classical signal analysis techniques such as the Fourier Transform (FT), which only uses a single-window analysis. The focal problem with the fixed window size used in the Windowed Fourier Transform is that it loses the time localization at high frequencies when the window is sliding along the signal because there are too many oscillations captured within the window. Furthermore, it also losses the frequency localization at low frequencies because there are only a few low-frequency oscillations that are included in the window (Santos *et al.* 2001; Nalley *et al.* 2012; Caccamo and Magazù 2018; Colombo *et al.* 2018). The Wavelet transform, that decomposes a one-dimensional signal into two-dimensional time–frequency domains at the same time, is able to handle these issues (Adamowski *et al.* 2009). Wavelets are usually irregular and asymmetric in shape and this property makes them ideal for analysing signals that contain sharp changes and discontinuities (Quiroz *et al.* 2011). Wavelet transforms use also 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). Furthermore, wavelet analysis shows many properties of a time series that may not be revealed by other signal analysis techniques. The results of wavelet analysis can be used to examine the temporal patterns of both a signal's frequency and time domains (Labat 2005; Wang *et al.* 2011). 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 dataset of temperature of Sicily by analysing their monthly and annual time series. Furthermore, a coherence wavelet analysis has also been performed in order to correlate the cycles present in signals with the better-known natural oscillations, like the Solar cycles, the North Atlantic Oscillation (NAO) and the El Nino Southern Oscillation (ENSO).

2. The wavelet analysis

A 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 between a few hours and millions of years (Lau and Weng 1995a). To analyse such a behaviour, powerful mathematics tools are needed. On this purpose, the wavelet analysis represents a powerful method to extract information from a time series. WT 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 allows to extract important information from the signal. In particular, WT, respect to the FT, permits to find not only the value of certain frequencies in a non-stationary serie, but also to identify the time interval in which these frequencies are present and predominant (Caccamo *et al.* 2016, 2017a; Caccamo and A. 2019). From a mathematical point of view, the wavelet is a function that has 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. WT involves shifting forward the wavelet in a number of steps along an entire time series, and generate a wavelet coefficient at each step. One 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 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, the Wavelet transforms analyse trends in time series by separating short, medium, and long-period components (Drago and Boxall 2002). The analysis 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.

3. Data sets description

The investigated data sets take into account the geographic position of four stations: Palermo, Messina, Cozzo Spadaro and Trapani-Birgi together with their characteristics. All the selected weather stations are located along the seacoast of Sicily, and for this reasons, they can be considered as a good indicator of the Mediterranean climate. In particular, Palermo's temperature time series starts on 1865 and it is the longest temperature record available in Sicily. The geographic position and the characteristics of each station are shown in Figure 1 and in Table 1 respectively.

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

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

TABLE 1. Meteorological stations recording temperature and precipitations data, which were used in this study.

Palermo and Messina weather station are positioned inside the town, Cozzo Spadaro weather station is located inside a lighthouse building in a small fisherman village while Trapani is the military airport weather station located to 12 kilometres from the nearest city. The temperature data sets of the four stations are composed by monthly and annual means. In addition, the temperature data set of Cozzo Spadaro weather station also contains the daily 12 UTC temperatures. All the data sets of temperature have been first decomposed, subtracting the average 1970-2000 monthly values from the row signal in order to obtain the temperature anomalies. This operation let the CWT to be cleaner, due to the deletion of the strong yearly periodicity. To perform the coherence wavelet analysis, the monthly data of Solar sunspot cycles, North Atlantic Oscillation (NAO) index and Southern Oscillation (SOI) index have been also analysed. 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. In this study the Meyer (dmey) mother wavelet has been used since it has 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) (Jones *et al.* 2015; Caccamo *et al.* 2018; Cannuli *et al.* 2018). 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 temperatures, as well as the mother wavelet used. By the decomposition of the signal using specified filters (wavelet and scaling functions) it is possible to produce two types of coefficients: the approximation or residual, and detail vectors (Chou 2007). These coefficients are the results of the convolution between the original signal and a low-pass filter and a high-pass filter. The low-pass filter is the scaling function while the high-pass filter is the wavelet function. The operation of convolution of signals with the low-pass filter produces the approximation coefficients, which represent the large-scale or low frequency components of the original signal; while convolutions with the high-pass filter produces the detail coefficients, which represent the low-scale or high-frequency components (Bruce *et al.* 2002). Furthermore, the data were also analysed by means of the CWT in order to identify discontinuities, singular episode and periodicities contained in the signal. In this case, a Morlet mother wavelet, that results to be one of the most widely used continuous wavelet, has been employed. It consists of a plane wave modified by a Gaussian envelope (Bradshaw and McIntosh 1994):

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

where $\omega_0$is the nondimensional frequency, in this case is equal to 6 to satisfy the admissibility condition [14].

4. Results and discussion

A key concept in traditional time series analysis is the decomposition of a given time series X_t into a trend T_t, a seasonal component S_t and a remainder e_t. To determinate the trend, that are present in the temperature data sets, a nonparametric regression technique has been employed. In order to calculate the seasonal component S_t(and the residual e_t) from the differences $X_t - T_t$, loess regression has been performed. Figures 2, 3, 4 and 5 report the obtained results.

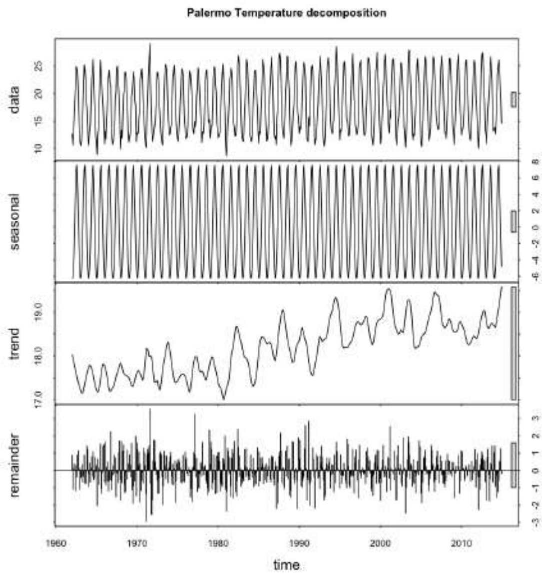

FIGURE 2. Palermo temperature 1962-2015 time series decomposition.

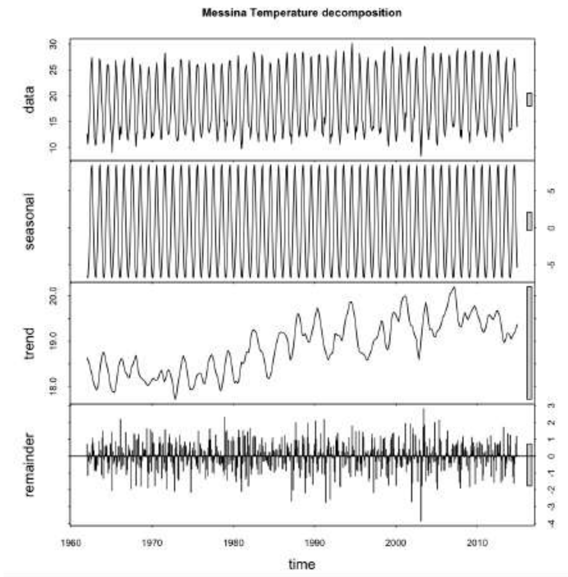

FIGURE 3. Messina temperature 1962-2015 time series decomposition.

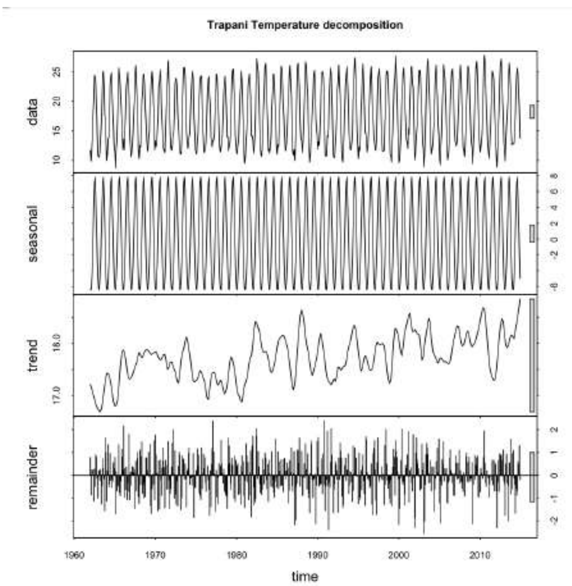

FIGURE 4. Trapani temperature 1962-2015 time series decomposition.

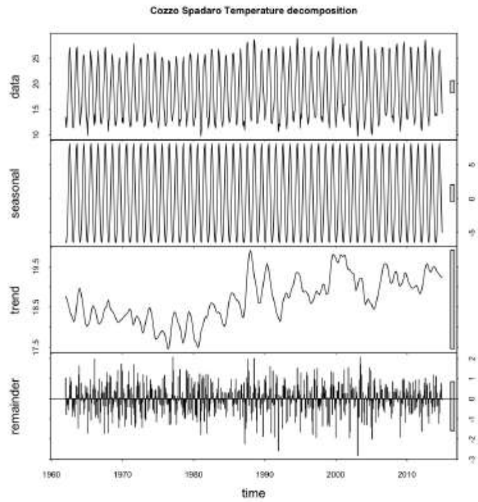

FIGURE 5. Cozzo Spadaro temperature 1962-2015 time series decomposition.

The next step of the analysis consists to perform a CWT to the sunspots, NAO and SOI index data sets, in order to identify the main periodicities contained in these signals and then, compare them with the temperature data sets by means of the wavelet coherence analysis (Pinardi *et al.* 1997; Korres *et al.* 2000; Demirov and Pinardi 2002; Conversi *et al.* 2010; Caccamo *et al.* 2017b; Castorina *et al.* 2018). The CWT analysis of sunspots data set shows a well-defined periodicity of 128 months according with the quasi-eleven years solar cycle. Figure 6 reports on the top the signal of sunspot number from 1962 to 2015, in the middle CWT analysis and on the bottom thea verage wavelet power (bottom-right). In this case the power peak is single and well defined and none secondary peak is present.

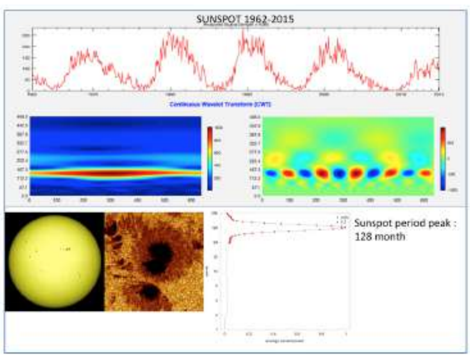

FIGURE 6. Signal of sunspot number 1962-2015 (upper) CWT analysis (middle) and average wavelet power (bottom-right).

The CWT of North Atlantic Oscillation Index shows a main peak in the high frequencies domain, with a maximum at about 3 months and a series of minor peaks at 12 and 30 months. Figure 7 shows on the top the signal NAO from 1962 to 2015, in the middle CWT analysis and on the bottom the average wavelet power. Finally, the CWT of the Southern Oscillation Index has been done and it shows 2 main periodicities. The first and stronger one is comprised between 28 to 60 months, while a secondary peak shows a periodicity of about 135 months. Figure 8 reports on the top the signal SOI Index from1962 to 2015, in the middle the CWT analysis and on the bottom the average wavelet power.

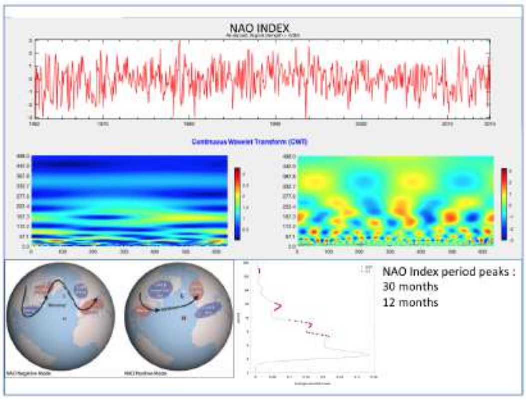

FIGURE 7. Signal NAO 1962-2015 (upper) CWT analysis (middle) and average wavelet power (bottom-right).

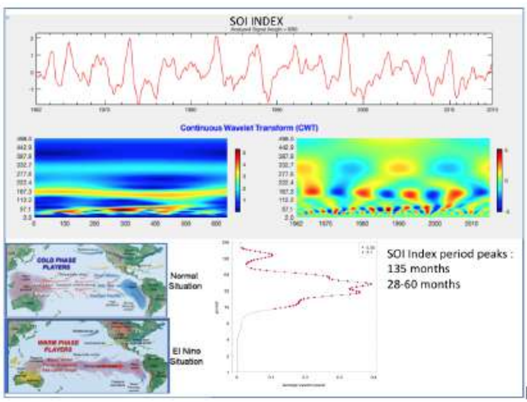

FIGURE 8. Signal SOI 1962-2015 (upper) CWT analysis (middle) and average wavelet power (bottom-right).

At the same way the CWT of the temperature anomaly of Palermo, Messina, Trapani and Cozzo Spadaro have been performed and the obtained results are shown respectively on Figures 9, 10, 11 and 12. For each CWT, in order to highlight the main periodicities, a dashed line is overlapped and a triangle is over imposed to the singularities founded in the signal. In Figure 9, the CWT of Palermo's temperature shows a periodicity of about 130 months become on 1965 and finish to about 2000 (line A on figure); a periodicity of about 60 months (line B) is present starting from middle 80' and continues until 2015. The lines C and D in figure highlight the shorter periodicities of about 30 months which start on 1980 and continue until 2008. Moreover, a couple of singularities are present on 1987 and 2003 focused by triangle 1 and triangle 2 in figure.

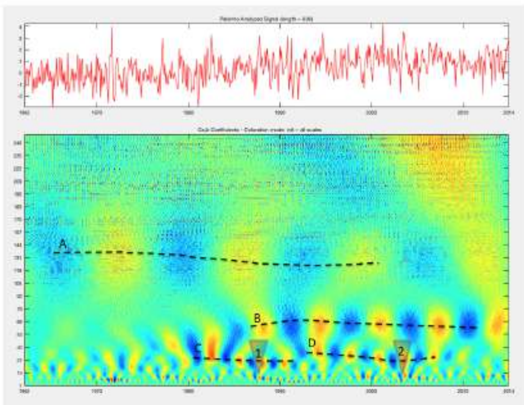

FIGURE 9. Palermo CWT of temperature anomaly 1962-2015.

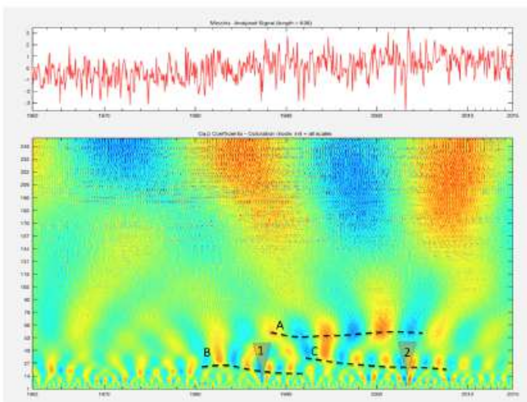

FIGURE 10. Messina CWT of temperature anomaly 1962-2015.

The CWT of Messina is quite different respect to the Palermo CWT, due to the missing of the periodicity of about 130 months. Figure 10 shows essentially how from 1962 to 1980 none periodicity longer than 24 months is present in the signal. Starting from 1980, a periodicity of about 30 months appears (line B) and continues until 1992 when a little longer signal starts (line C) and continue until 2008. Finally, a periodicity of about 60 months starts on 1987 and continue until 2006. The two discontinuities we found on Palermo CWT are again visible in the same position (1987 and 2003).

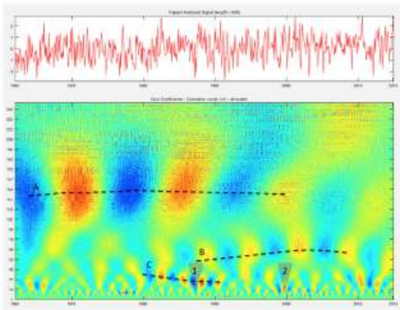

FIGURE 11. Trapani CWT of temperature anomaly 1962-2015.

The CWT of Trapani reproduces some feature of the CWT of Palermo such as the presence during the same years of the periodicity of about 130 months (line A). Moreover, a periodicity of about 60 months is present starting from 1987, in correspondence of the main singularity, and continues until 2010 (line B). Finally, a periodicity of about 30 months appears on 1980 and finish on 1991. A second singularity is present around the 1999. Cozzo Spadaro is the last weather station analysed be means of CWT. The main feature visible in Figure 12 is the strong signal associated to the singularity occurred on 1987 (triangle 1). The longer periodicity present is the one of about 130 months starts on 1987 and continues until 2015. A second periodicity of about 60 months is present in the same period of time.

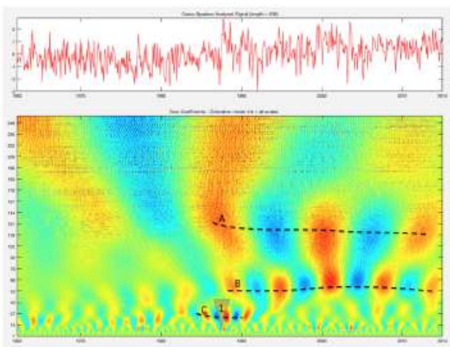

FIGURE 12. CWT of Cozzo Spadaro temperature anomaly 1962-2015.

So far, wavelet analysis has been applied to a single data set only. But it is also possible to calculate cross wavelet spectra from two data sets, thus extending the idea of a cross correlation to the time-frequency representation. The normalised version of the cross wavelet spectrum is called coherence (Farge 1992; Liu 1994). The Wavelet coherence spectrum obtained crossing the SOI and the NAO index versus the temperature anomaly of the four weather stations has been plotted and the results are shown respectively in Figure 13 and 14.

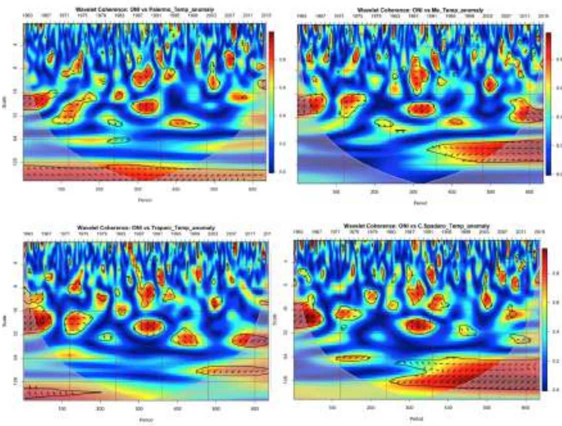

FIGURE 13. Wavelet coherence SOI versus Palermo (upper left), Messina (upper right), Trapani (lower left) and Cozzo Spadaro (lower right) temperature anomalies.

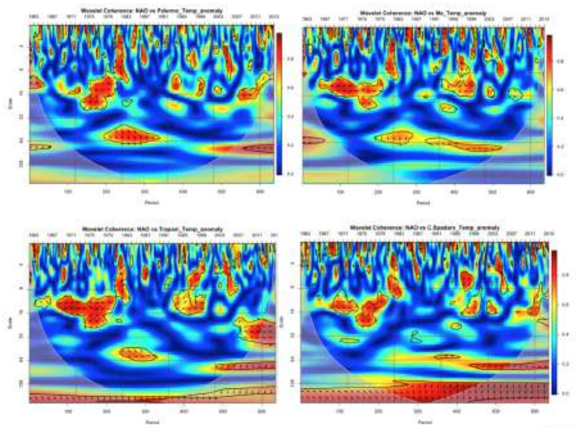

FIGURE 14. Wavelet coherence NAO versus Palermo (upper left), Messina (upper right), Trapani (lower left) and Cozzo Spadaro (lower right) temperature anomalies.

5. Conclusions

The nonparametric regression technique, the CWT and the wavelet coherence analysis were applied on the Sicilian temperature time series, in order to analyse their trends, determine the main periodicities present in the signals and try to find the correlations between the temperature pattern and some of the main climatic oscillations can affect the Mediterranean basin. The multidisciplinary analysis performed on Sicilian temperature time series from 1962 to 2015, has highlighted that:

- The temperatures have everywhere rise with small difference due mainly to the position of the weather stations. The increase of temperature is contained between 0,97°C and 1,39°C;
- Before 1980 the main periodicity present on the signal is correlate only with the 120 months cycle of sunspots;
- After 1980 two high frequency oscillations with period 30 and 60 months affect the temperature signals and amplify the warming trend. The Wavelet Coherence analysis can't solve which one – NAO or SOI – is better correlated with temperature.
- On 1987 a strong discontinuity is visible in all the four CWT followed by a new one on 2003. The very high temperature recorded during the summer seasons and the length of the warm season (that includes also the number of days between the first and the last day of the year with temperature >30°C) lasted more than 100 days, probably caused such discontinuities.

Regarding this last point, a deeper analysis of mean daily temperature performed for Cozzo Spadaro, showed that 1987 and 2003 have been the warmest years in Sicily. Moreover, by Figure 15 reports the number of days comprises from the first and the last day of the year in which temperature have reached 30°C, the average length has passed from about 58 days on the 1950s to about 74 days on the 2010s with an average increasing of 16 summer days (15).

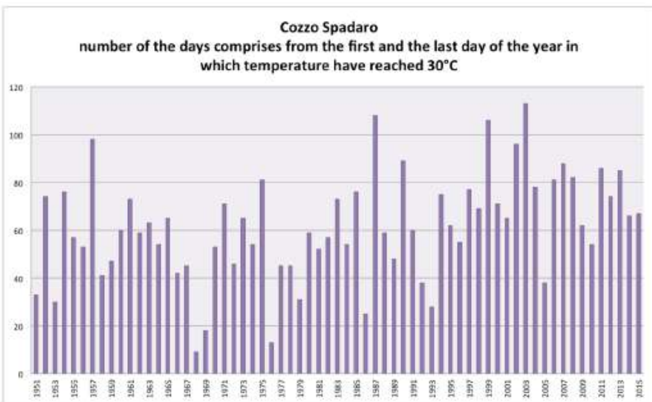

FIGURE 15. Cozzo Spadaro number of days comprises from the first and the last day of the year in which temperature have reached 30°C (Summer days). The graph shows that on 1987, 1999 and 2003 the number of summer days exceed 100 days.

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