IL NUOVO CIMENTO Vol. 29 C, N. 1 Gennaio-Febbraio 2006
DOI 10.1393/ncc/i2005-10217-y

Statistics of the seasonal cycle of the 1951-2000 temperature records in Italy and in the Mediterranean area(*)

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(ricevuto l'1 Settembre 2005)

Summary. — We present an analysis of the seasonal cycle of the last 50 years of records of surface temperature in Italy, as described by observations of maximum and minimum daily temperature, and of the surface and upper air temperature of the whole Mediterranean area, as described by the 1951-2000 NCEP reanalysis. We compute the best estimate of the seasonal cycle of the variables considered by adopting the cyclograms' technique. In the case of the Italian surface temperature, we observe that in general the minimum temperature cycle lags behind the maximum temperature cycle, and that the cycles of the Southern Italy temperatures records lag behind the corresponding cycles referring to Northern Italy. In the case of the NCEP reanalysis data for the whole Mediterranean area, we observe that at surface the phase and amplitude of the seasonal cycle are strongly characterized by the signature of the underlying surface, while in the upper air large-scale features related to ocean-continent contrast come into play. All seasonal cycles lag considerably behind the solar cycle. In all cases considered, the amplitude and phase of the seasonal cycles do not show any statistically significant trend in the time interval considered. This works supports the idea that climate change studies are much more reliable when upper air data are taken into account.

PACS 92.60.Ry – Climatology.
PACS 92.70.Gt – Climate dynamics.
PACS 92.60.Wc – Weather analysis and prediction.
PACS 01.30.Cc – Conference proceedings.

1. – Introduction

The analysis of the seasonal cycle of temperature records is of the uttermost importance in order to provide a detailed description of the climate of the geographical area under consideration. A correct approach to the evaluation of the seasonal signal allows having a clearer picture of changes in such a signal and at the same time permits a

(*) Paper presented at the Workshop on "Historical Reconstruction of Climate Variability and Change in Mediterranean Regions", Bologna, October 5-6, 2004.
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more precise position of the problem of estimating the statistical properties, in terms of short-time variability, long-term trend, and extremes, of the residual signal [1]. In particular, the possibility of capturing with greater detail the properties of the seasonal signal is especially relevant for the analysis of regions, like the Mediterranean area, that are characterized by relevant intermittence.

In order to provide the statistical description of the seasonal signal of any record, able to quantify the mean seasonal cycle and as well as the properties of its short- and long-term variability, we must have several, well-defined sampled estimates of its fundamental characteristics, namely phase and amplitude.

For each record, we estimate the seasonal component throughout the record by considering the collection of all the local (in time) best estimate of seasonal cycle. Such an approach is along the lines of the statistical technique proposed when introducing the cyclograms [2, 3]. The resulting seasonal signal is not precisely periodic, since the phase and the amplitude of the computed sinuosidal curve are not constant. Therefore it is possible to statistically analyze how the amplitude and phase of the seasonal signal vary with time. Such an approach is viable because our data obey with the narrow-band approximation, *i.e.* in each subset of the data used for the local estimates; the spectrum of the data has a sharp, narrow peak for the frequency component, so that the phase and amplitude of the seasonal 1 y^{-1} cycle are well defined.

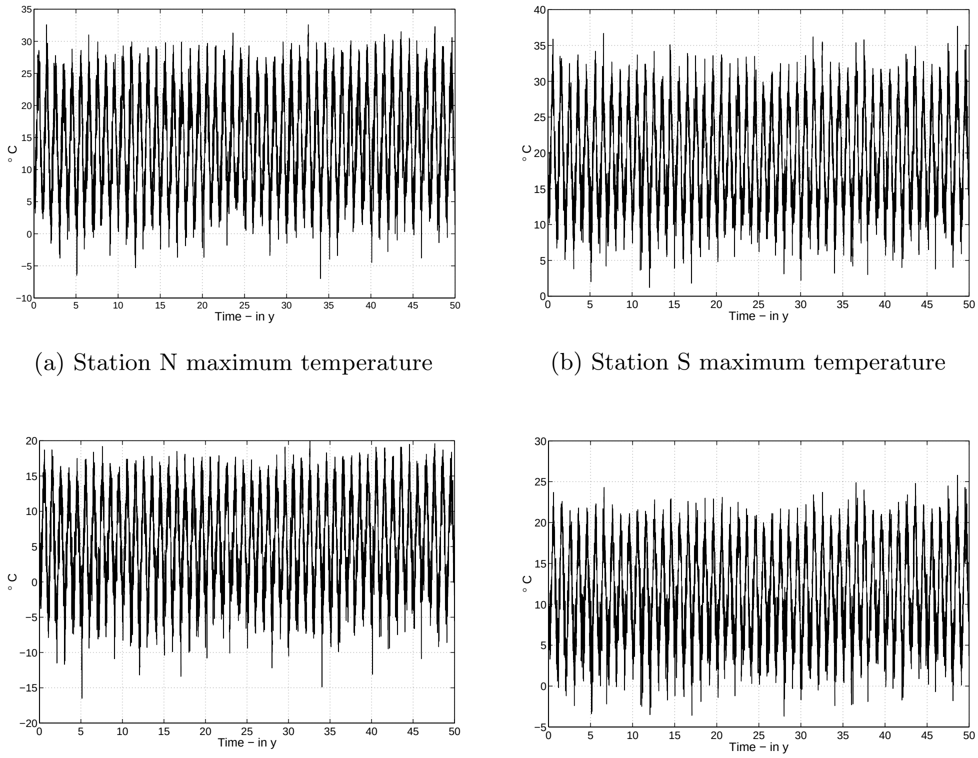
In this study we first consider observational data referring to the surface temperature records of the Italian peninsula. Nevertheless, on one side the surface temperature is a very relevant quantity in terms of influence on the biosphere, including human activities, on the other side it is not the most relevant quantity in terms of representing schematically the thermodynamic properties of the system. As well known, a measure of the average tropospheric temperature is much more relevant in this sense [4]. Therefore, a more physically sensitive approach would be considering the records of the whole vertical temperature profile.

We then also consider the reanalysis data extracted from the National Center for Environmental Protection (NCEP) [5] archive referring to the whole Mediterranean area for the same time frame.

2. – Data description

The data used in this study are derived from a set of station records with daily minimum and maximum temperature observations for a 50-year period (1951-2000). They were extracted from the Italian Air Force (Aeronautica Militare, henceforth AM) climatic data-set, that was recently used for the study of Italian daily precipitation [6, 7]; cloud cover [8] and sea level pressure [9] as well. The AM climatic data-set includes a very large number of stations (164). Some of them, however, cover only rather short periods, other ones have a large number of missing data. Since we are interested in providing information on the Italian climatology, we selected a subset of the stations which give a reasonable coverage of Italy and which are provided with long and reliable records. The result was a subset of 64 stations. The selected records were quality checked and in order to increase the confidence of the results, homogenisation was based, not only on AM records, but also on records derived from other data sources such as Ufficio Centrale di Ecologia Agraria, Servizio Idrografico (SI), and some specific research project that allowed daily series to be recovered for several of the most important Italian observatories.

EOF analysis shows that the daily maximum and minimum temperature data fields can be reduced with a good degree of approximation to two degrees of freedom. In both



(a) Station N maximum temperature

(b) Station S maximum temperature

(c) Station N minimum temperature

(d) Station S minimum temperature

Fig. 1. – Maximum and minimum surface temperature records of station N and station S.

cases, these degrees of freedom contribute to over 90% of the variance of the signal. The two EOFs (not shown) are representative of the two geographically distinct areas of Northern and Southern Italy, with a reasonable boundary given the the 0.7 isolines. Therefore, by suitably averaging the data of the corresponding stations, it has been possible to create two synthetic data sets for northern and southern Italy, which henceforth we refer to as station N and station S temperature records, respectively. Each data set comprises of the records of daily maximum and minimum temperature, which are henceforth indicated as $T_{max}^{N/S}$ and $T_{min}^{N/S}$, with obvious meaning of the indexes. These data are depicted in fig. 1. Qualitatively, the geographic boundary dividing the stations contributing respectively to the station N and S data sets is along the parallel between Firenze (Tuscany) and Bologna (Emilia Romagna).

In the case of NCEP reanalysis, we have selected the domain $[10°\text{W} - 40°E] \times [30°\text{N} - 47.5°\text{N}]$ and have considered the surface, 700 hP, 500 hP, and 300 hP geopotential height temperature data for the time frame 1951-2000. The NCEP data have a definition of $2.5° \times 2.5°$, so that each of the four records considered consists of 168 individual time series. The domain of interest is depicted in fig. 2.

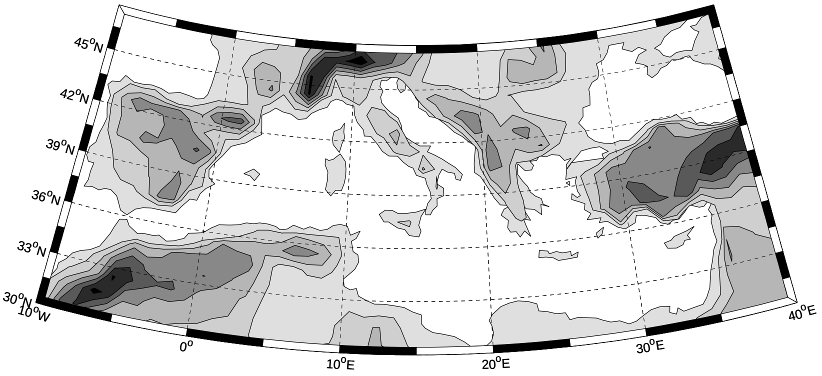


Fig. 2. – Mediterranean area as represented in the NCEP grid.

3. – Local estimate of a given frequency component

We consider the statistical approach related to the technique of cyclograms [2, 3]. Such an approach provides the possibility of capturing the amplitude and phase time-dependent variations of a given frequency sine wave component of the signal under examination.

Given a signal $x\left(t\right)$, $t=1,\ldots,N$, a frequency $2\pi/\tau$ and a time window $2T+1$, we consider the centered moving average over $2T+1$ terms of the series $\{x\left(t\right)\exp\left[\mathrm{i}2\pi t/\tau\right]\}$:

$$a\left(t;\tau,T\right)=\frac{1}{2T+1}\sum_{j=t-T}^{t+T}x\left(j\right)\exp\left[-\mathrm{i}2\pi j/\tau\right], \tag{1}$$

where $T+1\le t\le N-T$ since the signal has N samplings.

If the frequency $2\pi/\tau$ is an integer multiple of $2\pi/N$, we have that $a\left(t;\tau,T\right)$ can be expressed as the DFT of a suitably convolution product:

$$a\left(t;\tau,T\right)=\frac{N}{2T+1}\mathrm{DFT}\left[x*w\right]\left(2\pi/\tau\right)\ , \tag{2}$$

where the first factor is a renormalization constant, $*$ represents the convolution product, and w is the weighting function:

$$w\left(t\right)=\begin{cases}\dfrac{1}{2T+1}, & 1\le t\le T+1\,,\\ 0, & T+2\le t\le N-T\,,\\ \dfrac{1}{2T+1}, & N-T+1\le t\le N\,.\end{cases} \tag{3}$$

Equations (1), (2) imply that, if $2\pi/\tau$ belongs to the discrete spectrum of the signal, and if $2T+1\ge\tau$, $a\left(t;\tau,T\right)$ is related to the best estimate of the $2\pi/\tau$ frequency sine $S\left(t,2\pi/\tau\right)$ and cosine $C\left(t,2\pi/\tau\right)$ wave components of the portion $t-T\le t\le t+T$ of the signal $x(t)$ as follows:

$$C(t, 2\pi/\tau) = \frac{2}{2T+1} \mathrm{Re}\left[a(t;\tau,T)\right] , \tag{4}$$

$$S(t, 2\pi/\tau) = -\frac{2}{2T+1} \mathrm{Im}\left[a(t;\tau,T)\right] , \tag{5}$$

where Re and Im indicate the real and imaginary part, respectively. Therefore, we can construct a *global* best estimate of the $2\pi/\tau$ frequency signal $\Sigma(t, 2\pi/\tau)$ for each value of $T+1 \le t \le N-T$ by considering all the *local* best estimates obtained using the result contained in eq. (4):

$$\begin{aligned} \Sigma(t, 2\pi/\tau) &= C(t, 2\pi/\tau)\cos(2\pi t/\tau) + S(t, 2\pi/\tau)\sin(2\pi t/\tau) \\ &= A(t, 2\pi/\tau)\cos(2\pi t/\tau + \phi(t, 2\pi/\tau)) , \end{aligned} \tag{6}$$

where

$$A(t, 2\pi/\tau) = \sqrt{C(t, 2\pi/\tau)^2 + S(t, 2\pi/\tau)^2}, \tag{7}$$

$$\phi(t, 2\pi/\tau) = -\arctan\left[\frac{S(t, 2\pi/\tau)}{C(t, 2\pi/\tau)}\right] . \tag{8}$$

We can reasonably extend the function $\Sigma(t, 2\pi/\tau)$ to the whole range $t = 1, \ldots, N$ in the following way:

$$\overline{\Sigma}(t, 2\pi/\tau) = \begin{cases} A(T+1, 2\pi/\tau)\cos(2\pi t/\tau + \phi(T+1, 2\pi/\tau)) , & t < T+1 , \\ \Sigma(t, 2\pi/\tau) , & T+1 \le t \le N-T , \\ A(N-T, 2\pi/\tau)\cos(2\pi t/\tau + \phi(N-T, 2\pi/\tau)) , & t > N-T . \end{cases} \tag{9}$$

Since the coefficients of the sine and cosine waves change with t, the signal $\overline{\Sigma}(t, 2\pi/\tau)$ is not purely periodic, *i.e.* its DFT does not have $2\pi/\tau$ as only nonzero component. Obviously, the more persistent with t are the phase and amplitude of the local estimates of the $2\pi/\tau$ signal, the more monochromatic is $\overline{\Sigma}(t, 2\pi/\tau)$.

4. – Seasonal cycles

In order to simplify the data handling we have neglected the February 29th entries of the bissextile years in all of our records, the 4 datasets of the Italian surface temperature and the 168×4 datasets of the NCEP reanalysis. Since these corrections regard in each case less than 0.1% of the total record, we are confident that this procedure does not alter relevantly the results later presented.

Since we are interested in evaluating the seasonal cycle, we consider in eq. (6) $\tau = 365$. The most natural time window suitable for having a local estimate of the seasonal cycle is clearly one year as well. Therefore, we select $2T + 1 = \tau = 365$. It is important to underline that such an approach is reasonable only if the signal obeys the narrow-band approximation, *i.e.* the spectrum of the signal has a strong, narrow peak for the annual cyclic component. If, on the contrary, the signal were characterized by a broad spectral feature comprising the 1 y^{-1} frequency component, it would be a mathematical

TABLE I. – *Statistics of the amplitude of the seasonal signal for the Italian surface temperature records.*

Variable	μ	2σ	σ/μ
$A\left\{T^N_{max}\right\}$	10.19 °C	1.34 °C	0.07
$A\left\{T^S_{max}\right\}$	8.79 °C	1.27 °C	0.09
$A\left\{T^N_{min}\right\}$	8.65 °C	1.30 °C	0.09
$A\left\{T^S_{min}\right\}$	7.33 °C	1.28 °C	0.11

nonsense to investigate whether the seasonal cycle is changing. In such a case the seasonal cycle is just not defined, because several contiguous spectral components having different frequencies and shifting phase differences give contributions of comparable importance.

4·1. *Italian surface temperature.* – The results we obtain for the amplitude signals are summarized in table I. The results referring to the phase signals are reported in table II. Note that instead of the actual phase delay expressed in radiants, we report the relative delay with respect to the solar forcing expressed in calendar days. In fig. 3 we present the results obtained for the function $\overline{\Sigma}\,(t, 2\pi/365)$ for the four records considered.

We wish to emphasize that the amplitude of the seasonal signal is significantly larger for maximum than for minimum temperature, and that is significantly larger for variables referring to northern Italy. Moreover, the two effects roughly sum up linearly, *i.e.*

$$\left\langle A\left\{T^N_{max}\right\}\right\rangle - \left\langle A\left\{T^S_{max}\right\}\right\rangle \approx \left\langle A\left\{T^N_{min}\right\}\right\rangle - \left\langle A\left\{T^S_{min}\right\}\right\rangle, \tag{10}$$

where we have dropped the t- and τ-dependences of A for sake of simplicity and where the notation $\langle\rangle$ indicates the mean value. Another interesting result is that for both N and S stations the seasonal signal of minimum temperature has a phase delay with respect to the seasonal signal of the maximum temperature. Moreover, the seasonal cycle of the temperature records of station has a delay with respect to the seasonal cycle of the corresponding temperature records of station N. Also in this case the two effects roughly sum up linearly:

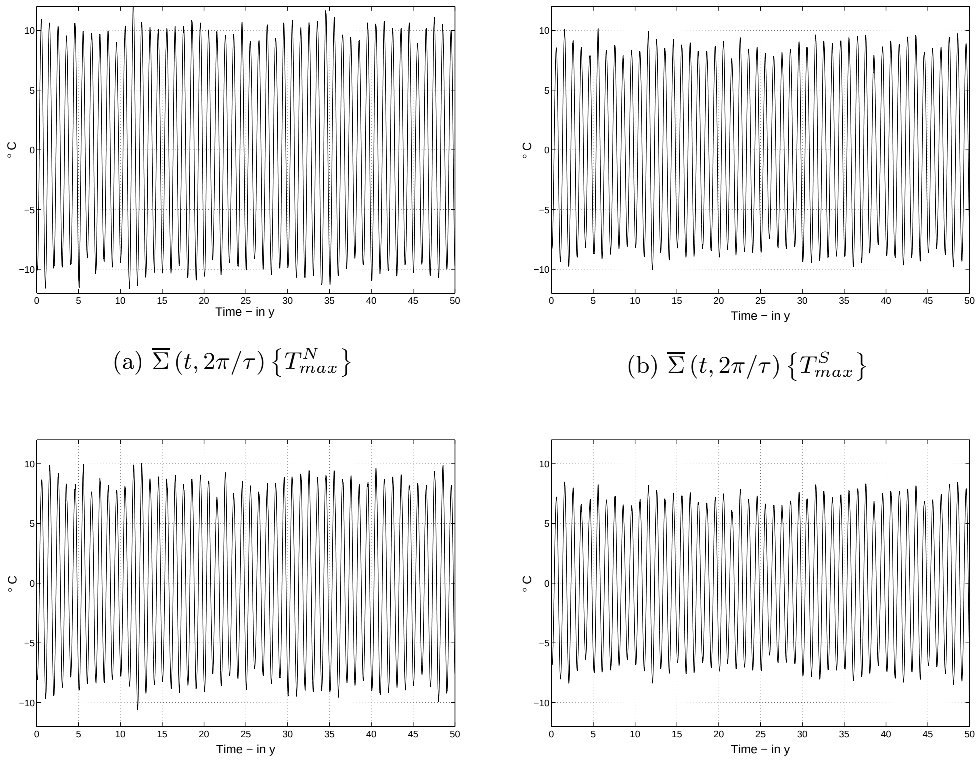
$$\left\langle \phi\left\{T^N_{max}\right\}\right\rangle - \left\langle \phi\left\{T^S_{max}\right\}\right\rangle \approx \left\langle \phi\left\{T^N_{min}\right\}\right\rangle - \left\langle \phi\left\{T^S_{min}\right\}\right\rangle \approx 9\text{d}, \tag{11}$$

$$\left\langle \phi\left\{T^N_{max}\right\}\right\rangle - \left\langle \phi\left\{T^N_{min}\right\}\right\rangle \approx \left\langle \phi\left\{T^S_{max}\right\}\right\rangle - \left\langle \phi\left\{T^S_{min}\right\}\right\rangle \approx 4\text{d}, \tag{12}$$

where we have expressed the phase differences in terms of calendar days "d". The maximum temperature record of station N is the closest in terms of phase delay to

TABLE II. – *Statistics of the phase delay of the seasonal signal with respect to the solar forcing for the Italian surface temperature records.*

Variable	μ	2σ	σ/μ
$\phi\left\{T^N_{max}\right\}$	28 d	8 d	0.13
$\phi\left\{T^S_{max}\right\}$	32 d	7 d	0.09
$\phi\left\{T^N_{min}\right\}$	38 d	6 d	0.08
$\phi\left\{T^S_{min}\right\}$	42 d	6 d	0.07



(a) $\overline{\Sigma}\,(t, 2\pi/\tau)\,\{T^N_{max}\}$

(b) $\overline{\Sigma}\,(t, 2\pi/\tau)\,\{T^S_{max}\}$

(c) $\overline{\Sigma}\,(t, 2\pi/\tau)\,\{T^N_{min}\}$

(d) $\overline{\Sigma}\,(t, 2\pi/\tau)\,\{T^S_{min}\}$

Fig. 3. – Seasonal cycle of the maximum and minimum temperature records of the two stations.

the solar cycle, which constitutes a fundamental forcing to the system. Such delay corresponds to ≈ 28 d; at the same time such record is characterized by the maximum average amplitude, which ranges $\approx 10.2°$ C.

We can interpret these results in physical terms as follows. On the one side, the lag and different amplitudes of the cycles of maximum and minimum temperatures can be related to the different impacts of changes of the two well-distinct processes of day solar SW heating and night LW cooling on the local thermodynamic systems where measurements are taken, in terms of relations to the thermal intertia. On the other side, larger-scale thermal intertia effects related to the different thermal properties of sea and land provide a qualitative argument for the differences in amplitude and phase of the station N and S cycles, the main reason being that northern Italy is more continental than southern Italy.

We also want to point out is that there is no statistically significant linear trend in either the amplitude of the phase of the seasonal signal. In other terms, our analysis suggests that in Italy in the time frame 1951-2000 *seasons have not changed* in their annual evolution. The statistical analysis of the trend of the signals has been assessed by optimally fitting the signals with linear autoregressive models AR(N) [10, 11] and then performing Montecarlo experiments using the deduced parameters. We underline that

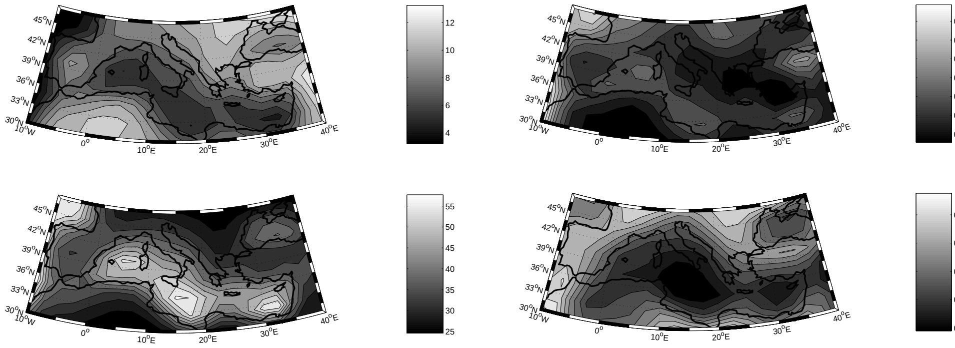


Fig. 4. – Seasonal cycle of the surface daily temperature for the NCEP reanalysis of the Mediterranean area. Left: from top to bottom, mean amplitude (in °C), and mean phase delay (in d) with respect to the solar cycle of the seasonal signal. Right: corresponding noise-to-signal ratio.

in general it is sensible to perform the analysis of the time dependence of the seasonal signal properties only if the record comprises several seasonal cycles. In our case such condition is obeyed, since we have $N \gg 2T + 1$. Futher details can be found in [12].

4˙2. *NCEP reanalysis for the Mediterranean area.* – We extend our analysis by considering the NCEP reanalysis temperature data for the Mediterranean area. In fig. 4 we report the average amplitude and phase delay of the seasonal signal and the corresponding signal-to-noise ratio for the surface data. We observe that the phase and amplitude of the seasonal cycle are strongly characterized by the signature of the underlying surface: over the Mediterranean Sea the amplitude is smaller and the phase delay is larger than over land. On the far western portion of the domain, we also observe the strong signature of the Atlantic Ocean. The amplitude and phase signals are strongly negatively

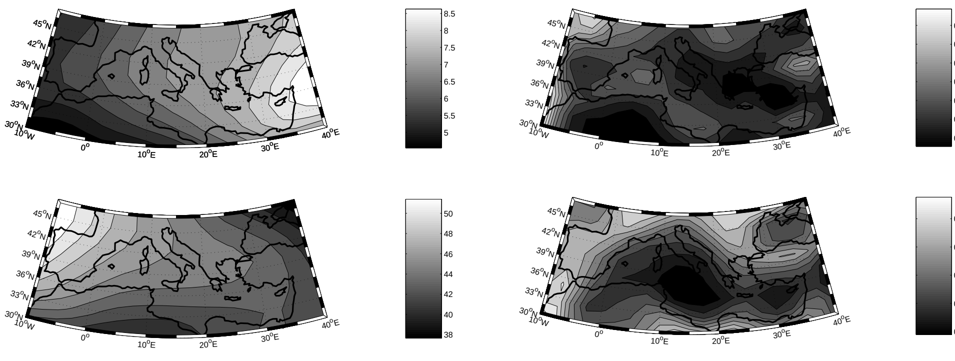


Fig. 5. – Seasonal cycle of the 500 hP geopotential daily temperature for the NCEP reanalysis of the Mediterranean area. Left: from top to bottom, mean amplitude (in °C), and mean phase delay (in d) with respect to the solar cycle of the seasonal signal. Right: corresponding noise-to-signal ratio.

TABLE III. – *Mean* ± 2 *standard deviations of the spatial correlation between the fields descriptive of the amplitude of the seasonal cycle. The statistics is computed over the* $49\times365+1$ *realizations of the fields.*

Variable	$A\{T_{SURF}\}$	$A\{T_{Z700}\}$	$A\{T_{Z500}\}$	$A\{T_{Z300}\}$
$A\{T_{SURF}\}$	1	0.53 ± 0.24	0.32 ± 0.27	0.32 ± 0.23
$A\{T_{Z700}\}$	0.53 ± 0.24	1	0.65 ± 0.34	0.70 ± 0.30
$A\{T_{Z500}\}$	0.32 ± 0.27	0.65 ± 0.34	1	0.86 ± 0.14
$A\{T_{Z300}\}$	0.32 ± 0.23	0.70 ± 0.30	0.86 ± 0.14	1

correlated: we obtain a value for the spatial correlation of $\langle A[t],\phi[t]\rangle = -0.79\pm0.18$, where the mean and the variance have been calculated over the $49\times365+1$ realization of the fields. We have that in general the signal-to-noise ratio is around 0.1 and tends to be smaller over the marine regions. This result confirms and projects in a wider picture what obtained from the surface observational data from the Italian peninsula discussed above.

When considering upper air data, the picture changes dramatically. In fig. 5 we report the average amplitude and phase delay of the seasonal signal and the corresponding signal-to-noise ratio for the 500 hP geopotential height data. These fields are representative also of the 700 hP and 300 hP geopotential height fields, not shown here.

The most notable feature of the time-averaged fields represented in fig. 5 is that the signature of the Mediterranean Sea is almost lost, while large scales features, representative of the ocean-continent contrasts, come into play. Such contrast can be traced to the presence of a marked zonal gradient in the two fields. This implies that the local land-sea contrast picture, which is very effective for the surface data, is not adequate for the upper air data. We also notice that the amplitude of the seasonal signal is generically lower than for surface data, while for the phase delay the bias does not seem to be as large. Moreover, the phase delay and amplitude fields do not show a relevant correlation; statistical inspection shows that the spatial correlation of the two fields is not statistically significant. The noise-to-signal ratio is on the average quite similar to the surface data case, even though the minimum is shifted eastward.

For the upper air data, there is no statistically relevant spatial correlation between the amplitude and the phased delay signals, as opposed to the surface data, where such correlation is very strong. In table III we present the statistics of the spatial correlation between the amplitude signals at various levels. We observe that all the signals show statistically significant correlation, and that usually the correlation is higher for nearby

TABLE IV. – *Mean* ± 2 *standard deviations of the spatial correlation between the fields descriptive of the phase delay of the seasonal cycle. The statistics is computed over the* $49\times365+1$ *realizations of the fields. NS stands for statistically non-significant.*

Variable	$\phi\{T_{SURF}\}$	$\phi\{T_{Z700}\}$	$\phi\{T_{Z500}\}$	$\phi\{T_{Z300}\}$
$\phi\{T_{SURF}\}$	1	0.37 ± 0.36	NS	NS
$\phi\{T_{Z700}\}$	0.37 ± 0.36	1	0.55 ± 0.45	NS
$\phi\{T_{Z500}\}$	NS	0.55 ± 0.45	1	0.71 ± 0.29
$\phi\{T_{Z300}\}$	NS	NS	0.71 ± 0.29	1

levels, as to be expected. In particular, it is to be noted the very high average correlation between the 300 and 500hP geopotential height amplitude fields and the low uncertainty on such correlation. We observe that the correlation is higher for nearby levels of the upper air than for surface data and 700hP geopotential height data, suggesting that the surface data are qualitatively different from the upper air data, because of the obvious strong influence of the surface-air processes. In table IV we show the corresponding results for the phase delay signals. Similar conclusions apply, apart from the fact that in this case the statistical significance is restricted to the nearby levels only.

Also in the case of NCEP reanalysis data, we find no statistically significant trends for both amplitude and phase delay in any grid point considered. Such significance has been assessed with the same methodology applied for the observational data set.

5. – Conclusions

This work is composed by the analysis of data sets covering the last 50 years of daily maximum and minimum temperature which are representative of the Northern and of the Southern Italy temperature fields and by the analysis of the 1951-2000 NCEP reanalysis of the surface and upper air daily temperature data of the Mediterranean region. The use of reanalyses is related to the fact that the tropospheric temperature is a much more relevant climatic state variable than surface temperature.

We have analyzed the seasonal cycle with the technique of cyclograms, which allows finding at each time the quasi-instantaneous best estimate of the annual component of the record. The resulting seasonal signal is not strictly periodic, since at each time the estimates of phase and amplitude change slightly. It is important to underline that such an approach is viable because our signal obeys the narrow-band approximation, *i.e.* the spectrum of the signal has a strong, narrow peak for the annual cyclic component. If, on the contrary, the signal is characterized by a broad spectral feature comprising the 1y-1 frequency component, it is a mathematical nonsense to investigate whether the seasonal cycle is changing. In such a case the seasonal cycle is just not defined, because several contiguous spectral components having different frequencies and shifting phase differences give contributions of comparable importance.

In the case of the Italian surface data, we have that in general, the amplitude of the maximum temperature seasonal cycle is larger than that of the minimum temperature, and seasonal cycles of station N are larger than those of station S. In terms of phase, we observe that in general the minimum temperature seasonal cycle lags behind the maximum temperature seasonal cycle, and that the seasonal cycles of the station S lag behind the corresponding cycles of the station N. All seasonal cycles lag considerably behind the solar cycle. On the one side, thermal inertia effects related to the day/night cycle explain the lag and different amplitudes of the cycles of maximum and minimum temperatures. On the other side, larger scale thermal inertia effects related to the different thermal properties of sea and land provide a qualitative argument for the differences in amplitude and phase of the station N and S cycles.

When analyzing the NCEP reanalyses, we have that the surface data essentially confirm the results obtained with the observational data. In particular, the signature of the Mediterranean Sea is very evident in determining the spatial pattern of the fields of the average amplitude and phase delay of the seasonal cycle. When considering the upper air data, the picture is very different. The spatial pattern are in this case weakly related to the local land-sea contrast as described by the Mediterranean sea borders, while larger scale features resembling the ocean-continent contrast can be observed. Therefore, we can generally observe a pattern of westward increasing amplitude and decreasing phase delay. Another difference with the surface data is that in the upper air the phase and the amplitude of the seasonal cycle of a given level are not statistically cross-correlated. On the contrary, we have that the corresponding average fields of nearby pressure levels are highly spatially cross-correlated, suggesting the vertical coherence of the seasonal signal. The differences between the statistical properties of the seasonal signal of the surface and upper air support the importance of considering upper air data when assessing the relevance of climate change signals.

In all datasets analyzed, the time-dependent estimates of amplitude and phase of the seasonal cycles do not show any statistically significant trend in the time frame considered. Succinctly, seasons seem to have not changed in their annual evolution within the Mediterranean area.

It is important to note that, when considering a limited area, the direct solar forcing is not the only relevant forcing, since air advection at all levels from nearby areas plays a fundamental role in determining the state of the system under consideration. Therefore, it would be important to consider in future analyses the estimates of the convergence of thermal fluxes.

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We wish to thank for technical and scientific help M. Felici and M. Brunetti.

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