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HEAT WAVES IN THE MEDITERRANEAN: A LOCAL FEATURE OR A LARGER-SCALE EFFECT?

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ABSTRACT

We analyse the anomalously warm summer months in the Mediterranean region using the 850 hPa temperature, T850, extracted from the ERA-40 reanalysis, in order to find how these anomalies are related to the anomaly of the jet stream over the Euro-Atlantic area. In this region, the westerly jet has two main branches: the Scandinavian jet and the Mediterranean jet, which, in summer, are at a meridional minimum distance.

In addition, we analyse the heat waves in the Central Mediterranean in the last half century using the temperature observations collected at fifty surface stations distributed throughout the Italian peninsula and its two major islands, and we relate these events to the position of the Mediterranean jet.

We find that, when these two jets are almost aligned, there is a streak of the Mediterranean jet over the Alps and, to the south of them, an anticyclonic vorticity aloft, which forces a strong subsidence and an adiabatic warming of the troposphere over the Mediterranean. This configuration is also a characteristic of anomalously warm spells over the basin. While, when the Mediterranean jet resides further south and along the northern rim of Africa, its meridional distance from the Scandinavian jet is relatively large, the vorticity over the Mediterranean is cyclonic and this region is relatively cool. The tropospheric temperature difference between these two configurations (Mediterranean jet over the Alps and jet over North Africa) is of the order of 3 °C.

Since the correlation between the observed temperatures over Italy and the ERA-40 T850 in the Central Mediterranean is more than 90%, and more than 60% in the T850 of the entire Mediterranean basin, we conclude that the heat waves over Italy are representative of exceptionally warm episodes over the Central Mediterranean, and that a warm spell over Italy is a country-scale symptom of warm spells in the Mediterranean basin.

KEY WORDS: climate variation; heat waves; jetstreak; jetstream; Mediterranean; Italy

1. INTRODUCTION

The Mediterranean basin is located in a transitional geographical zone bounded by the Euro-Asian region and by the North African desert, and it is directly under the effect of the Atlantic Ocean (Meteorological Office, 1962). In the longitudinal direction, the basin extends between 10 °W and 35 °E, showing a distinct pressure seesaw pattern between east and west not only at the surface (Maheras *et al*., 1997; Palutikof, 2003), but also at 500 hPa (Piervitali *et al*., 1999). However, during the warm season, the amplitude of this oscillation is at its minimum, and the pressure and temperature fields are almost levelled throughout the entire Mediterranean basin. During this season, the high Alpine mountain range reduces the airflow from the Atlantic into the Central Mediterranean basin. This is when the Western and Central Mediterranean basins are mainly influenced by a western extension of the Azores high (Xoplaki, 2003a), while the Eastern most part of the basin is under the influence of the Asian monsoon (Ziv *et al*., 2004), since a Rossby wave generated by this monsoon enhances the geopotential of the ridge over the East Mediterranean (Rodwell and Hoskins, 1996).

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Heat waves are a familiar feature of the Mediterranean summer (Colacino and Conte, 1995; Giles and Balafoutis, 1990; Matzarakis and Mayer, 1997; Karakostas and Gawith, 1994; Metaxas and Kallos, 1980; Prezerakos, 1978, 1989), and several anomalous warm summers have occurred in the Mediterranean and in southern Europe over the last 50 years, with hot events of different intensities and lengths. These events have a high cost in terms of damage to agriculture, forest-fires, and, also, in terms of human health and death loss (Kovats *et al*., 2004; Meehl *et al*., 2000; World Health Organization, 2003). In this respect, the extremely intense and long hot period places the summer of 2003 (the hottest in 500 years in Europe, Luterbacher *et al*., 2004) on top of all natural disasters of the year with an estimated economic loss of more than US$12.3 Billion (World Health Organization, 2003; Münchener Rückversicherung, 2004), and with an estimated number of heat-related deaths between 22 000 and 35 000 across Europe (Schär and Jendritzky, 2004). Model simulations show that the increased greenhouse gas concentration in the atmosphere has increased the chances of warmer summers, with variability in the central and the eastern basin (Schär *et al*., 2004). This has been viewed as part of the expected signal of global warming (Stott *et al*., 2004). Beniston and Stephenson (2004) show that extreme climatic events in the Mediterranean-European region are due to particular significant changes in the trends of quantiles in the course of the twentieth century, and an increase in the temperature in the course of the twenty-first century is likely to produce an increase in the frequency of severe heat-wave episodes. The time series of surface air temperatures in the Central Mediterranean region show a positive trend during the summer (Maugeri and Nanni, 1998; Brunetti *et al*., 2000, 2004), while precipitation time series show an increase of long dry spells (Brunetti *et al*., 2001, 2002). The spatial distribution of the positive (negative) summer (winter) temperature anomalies has been analysed in terms of mean circulation over the Mediterranean region by several authors (see, among others, Maheras *et al*., 1999; Xoplaki *et al*., 2003a), and by Xoplaki *et al*. (2003b) and Ziv *et al*. (2004) for the Eastern basin. Heat waves result from the combination of different causes, which range from warming of the lower troposphere (Beniston, 2004), to more local factors such as soil moisture deficit (Brabson *et al*., 2005), positive feedback between the summer temperature, and the lack of convective rainfall (Beniston, 2004).

In this paper, we investigate some regional climate features related to large-scale dynamics. Inspired by the work of Colacino and Conte (1995), who found that, when the subtropical jet is over the Alpine region, the Mediterranean is relatively warmer, and by the work by Ogi *et al*. (2003, 2005) who relate the heat waves to the anomalies in the upper air jets, we analyse the summer climatology in the last half century in order to establish the link between the anomalously warm (cool) events in the Mediterranean with the position of the jet stream in the Euro-Atlantic region.

In section 2 of the paper, we illustrate the dataset and methodology used. In section 3, we examine the anomaly of the jets, of the relative vorticity, and of the geopotential field in relation to the tropospheric monthly temperature anomalies over the Mediterranean. In section 4, we analyse the trends and variability of heat- (cool-) wave events in the Central Mediterranean, and we relate them to the relative position of the Mediterranean and the Scandinavian jet. Finally, conclusions are drafted in section 5.

2. DATA AND METHODOLOGY USED

Elaborating on the pioneering work of Colacino and Conte (1995), who classified heat-wave events as short or long, when the surface air temperature exceeds the normal monthly mean of a given threshold for a given period of time, we adopt an updated definition of warm and cold events based on more recent works. The IPCC (2001) defines an extreme event as follows: '*An extreme weather event is an event that is rare within its statistical reference distribution at a particular place. Definitions of 'rare' vary, but an extreme weather event would normally be as rare as or rarer than the 10th or 90th percentile*'. Therefore, following the definition reported in Klein Tank and Konnen (2003), we define a heat- (cool-) wave when the temperature exceeds the 90th percentile (below the 10th percentile) for 6 or more consecutive days. The values of the percentile thresholds were determined on the basis of the observed temperature series during the climatological base period 1961–90. The base period adopted is consistent with the current World Meteorological Organization (WMO) operational climatology base period (e.g. 1961–90), and with recent studies on the indices of climate extremes developed in the late 1990s (Karl *et al*., 1999).

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In order to enlarge our sample, the 90th percentile was calculated from the 5-day window centered on each calendar day of the daily temperature distribution, i.e. working on a total sample size of 30 years × 5 days = 150 for each calendar day. Using this method, we count the days in runs of 6 or more days in which the temperature is above (below) the percentile threshold of the smoothed annual cycle (Klein Tank and Konnen, 2003).

On the basis of this definition, we extract anomalously warm and cool summer months, and related fields of atmospheric variables (T, wind, geopotential) and derived variables, from the reanalysis of the European Center for Medium-Range Weather Forecast (ECMWF–ERA-40; Simmons and Gibson, 2000).

The analysis of the warm and cool waves and the hot and cold spells in the Central Mediterranean during extended summer (June–September, JJAS) is done using the surface temperature time series (T_{max}, T_{mean}, T_{min}) collected in fifty stations uniformly distributed throughout the Italian peninsula, Sicily and Sardinia, of the National Agrometeorological Network managed by the Ufficio Centrale di Ecologia Agraria (UCEA, Rome-Italy), of the Italian Agriculture Ministry, covering the period 1951–2003 (June to September). The high altitude stations have been discarded from the analysis, as well as those time series with a high number of missing values.

We extracted the heat-wave events that occurred during the period 1951–2003 at each surface station using the definition given by Klein Tank and Konnen (2003), and analysed their trends and the jet position and configuration in relation to these heat-wave events. We also show that the monthly temperatures over Italy monitored at the surface stations are strongly correlated with the T850 over the Central Mediterranean and well correlated with the T850 over the Mediterranean basin extracted from the ECMWF-ERA40 reanalysis.

3. CORRELATION BETWEEN THE SUMMER MEDITERRANEAN MONTHLY TEMPERATURE AND THE 300 HPA ZONAL WIND

Taking into account the discussion of Ogi *et al*. (2003, 2005) relating the warm anomalies in the northern hemisphere to the anomalies of the upper air jets, we examined the position of the jet stream in the Mediterranean and Scandinavian regions in relation to warm (cool) Mediterranean anomalies.

The Euro-African jet, also called the Mediterranean jet, is generated by the thermal contrast between the African warm air and the European cool air. This jet starts near the Atlantic coast of North Africa and weakens in the vicinity of the Himalayas and India, while its meridional position in summer extends from the northern rim of North Africa to the Alpine region. The Scandinavian jet is generated by the thermal contrast between the cool air of the Polar Ocean and the relatively warm air of the North Atlantic. This jet extends from the east coast of North America to the Baltic Sea and Scandinavia. In the cold season, when the thermal contrasts are larger, the western edge of this jet is much further south of the eastern edge, while in the warm season, as the meridional thermal gradient weakens, the Scandinavian and the Mediterranean jets move polewards, assuming an almost zonal configuration (Bryson, 1994)

Accordingly, with the definition by Klein Tank and Konnen (2003), we define as warm (cool) a month when its average temperature is over the 90th percentile (below the 10th percentile) of the entire set of the same month. For instance, an August in the period 1958–2002 is warm if its average temperature is over the 90th percentile of the entire set of the months of August.

We find that, during summer (JJAS), when the temperature in the given month over the Mediterranean is anomalously warm, the wind aloft is anomalously strong just north of the Alps and it is anomalously weak over North Africa and over Scandinavia, and that, in agreement with the thermal wind equation, the potential temperature shows a strong positive anomaly through the depth of the troposphere between the Alps and North Africa and a cool anomaly between the Alps and Scandinavia.

This analysis has been done for each month of the warm season, JJAS; however, as an example, here we discuss only the results for the month of August. The difference, warm August months minus cold August months, of the zonal wind and of the potential temperature is shown in Figure 1, where the meridional vertical cross section is a zonal average across the Mediterranean basin (10W and 40E).

The excess of the zonal wind speed just above the Alps, in accordance with the thermal wind, is accompanied by warmer temperatures to the south and cooler temperatures to the north of the Alps through the depth of

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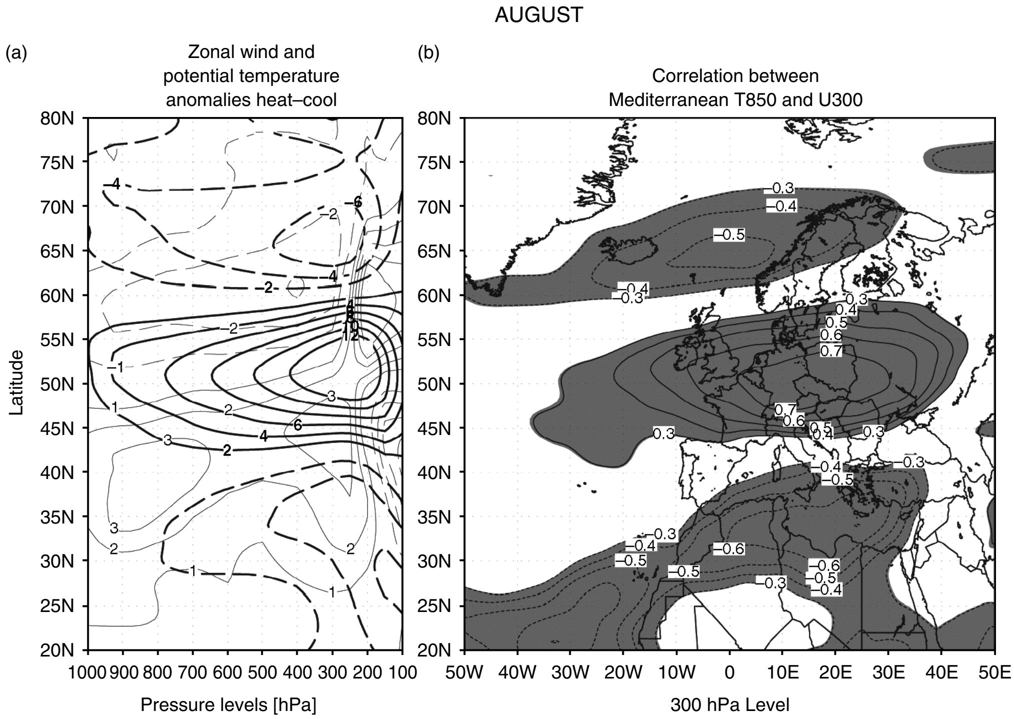

Figure 1. (a) Vertical cross section, averaged trough 10W–40E, of the difference of the zonal wind (bold line) and of the potential temperature (thin line), warm minus cold August. (b) Correlation between the T850 and the zonal wind at 300 hPa over the Mediterranean, shaded area represents a confidence level above 95%

the troposphere. This result is further reinforced by the correlation between the T850 over the Mediterranean and the zonal wind: this correlation is positive over the Alpine region and negative over North Africa and Scandinavia (Figure 1(b)). In addition, Figure 2(a) shows that the difference (warm minus cold in July and August) of the zonal wind at 300 hPa to the north of the Alps is associated with a warm tropospheric anomaly of 2–3 °C over the Mediterranean, and a very high correlation (70–80%) between the T850 and the 300 hPa geopotential. This high geopotential aloft enhances the subsidence which results in an adiabatic warming of the troposphere, Figure 2(b).

4. HEAT AND COOL WAVES IN THE CENTRAL MEDITERRANEAN REGION, TREND AND VARIABILITY, AND RELATED JETSTREAM PATTERNS

In the previous section, we analysed the upper air geopotential and wind field in relation to the T850 anomaly over the Mediterranean; in this section, we relate the position of the Mediterranean jet with the occurrence of heat and cool-wave days in the Central Mediterranean (8°–19 °E, 30°–50 °N).

From Table I, summarizing the monthly distribution of the heat- (cool-) wave days and their relative percentages (1951–2003), it emerges not only that they are a recurrent feature of the Mediterranean summer, but also that more than half of the heat-wave days are in June and August (152 and 187 days, respectively), accounting for 66% of the total. In July and September, the number is relatively small (107 and 67, respectively). The monthly distribution of the number of heat-wave days changes from decade to decade as shown in Figure 3, where the shift towards warmer Augusts is mainly in the last decade. The total number of summer-time days affected by a heat (cool)-wave is 513 (156), which is 8% of the total number of days in the last half century in the extended summer season JJAS.

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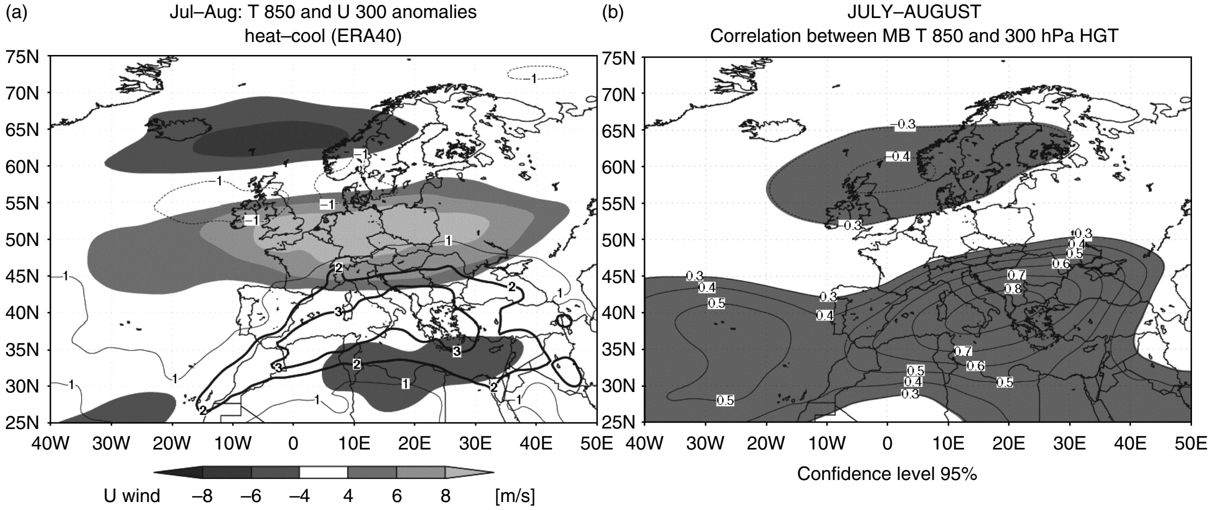

Figure 2. (a) Anomalies (hot minus cool July and August) of the T850 (contour) and of the zonal wind at 300hPa (shaded). (b) Correlation between the T850 in July and August and the geopotential at 300 hPa, shaded area represent a confidence level above 95%

Table I. Summary of the heat waves (left) and of the cool waves (right) in the period 1951–2003

Month	Heat waves		Cool waves	
	Number of days	% days	Number of days	% days
JUNE	152	30	37	24
JULY	107	21	36	23
AUG	187	36	39	25
SEPT	67	13	44	28
Total	513	100	156	100

In Table II, the decadal distribution of the number of heat and cool waves is reported, showing the cooling of the 70s and an impressive warming in the last decade of the twentieth century, when 187 heat-wave days account for the 46% of the total number of heat-wave days in the last half century.

A more detailed analysis of station data over Italy shows that the number of days classified as heat-wave days is greater in June and August than in July and September (Figure 3(a), left panels). The cool-wave statistics, for the same period, show a maximum in the 70s in all the summer months, and a substantial

Table II. Decadal distribution of the summer (JJAS) heat-wave days (left) and of the cool-wave days (right)

Decadal distribution				
Decade	Heat waves		Cool waves	
	Number of days	Number of days	% days	% days
1951–60	66	16	18	12
1961–70	38	9	35	22
1971–80	18	4	89	57
1981–90	98	24	8	5
1991–00	187	46	6	4
Total	407	100	156	100

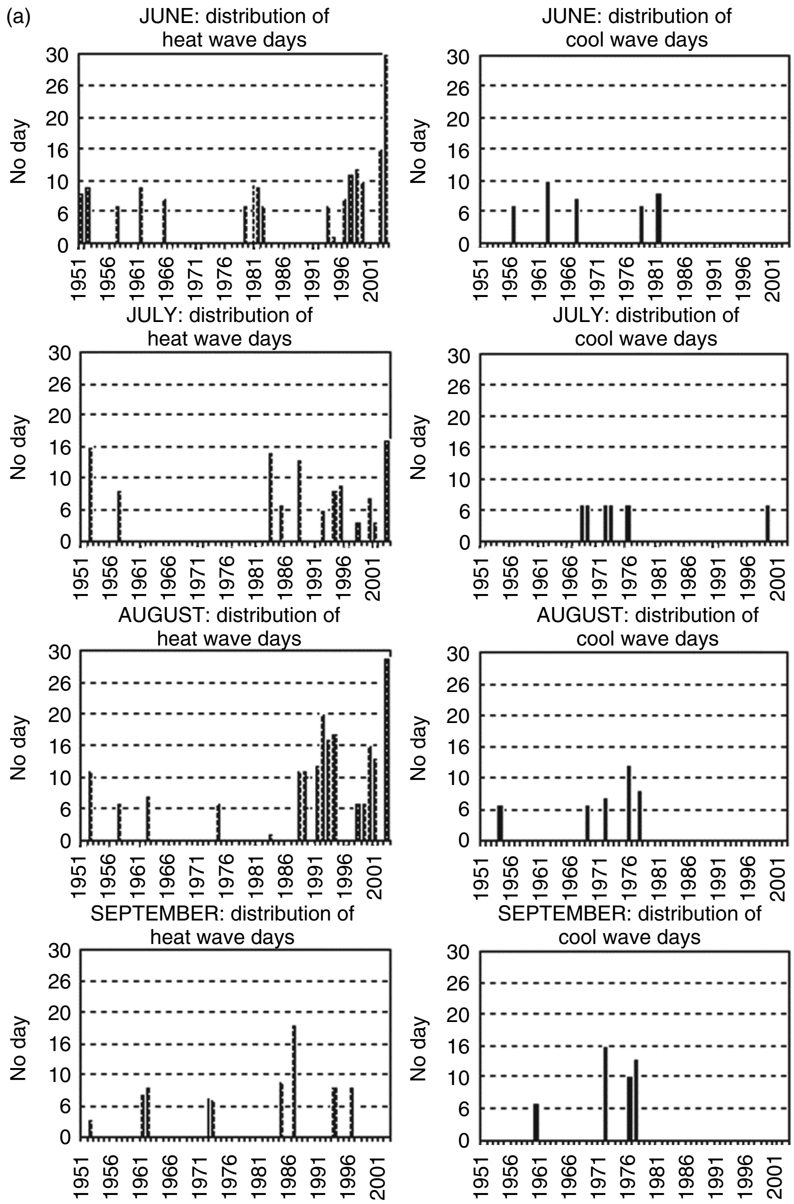

Figure 3. (a) Yearly number of heat (left) and cool (right) wave days in the period 1951–2003 in JJAS. (b) Monthly distribution of hot (left) and cool (right) days, and monthly distribution of the heat (left) and cool (right) wave events in the five decades of the last half century. (c) Percentage of hot days in a month for JJAS in the five decades of the last half century

decrease afterwards (Figure 3(a), right panels). Moreover, a significant positive change in the frequency of occurrence of hot summer episodes and an increase of the total number of hot days is evident in Figure 3(b) (left panels), showing the number of hot days per month in the period 1951–2003, for each decade. The heat waves are almost absent in the 70s, when we had a large number of cool-wave events. From the 70s till the present, the number of cool waves have decreased and almost disappeared in the last decade (Figure 3(b) – right panels). While the last two decades were characterized by a large number of heat waves, with a very hot month of July in the 1981–1990 decade, and a very hot June and August in the last decade when 30% of the days were classified as heat-wave days (Figure 3(c)).

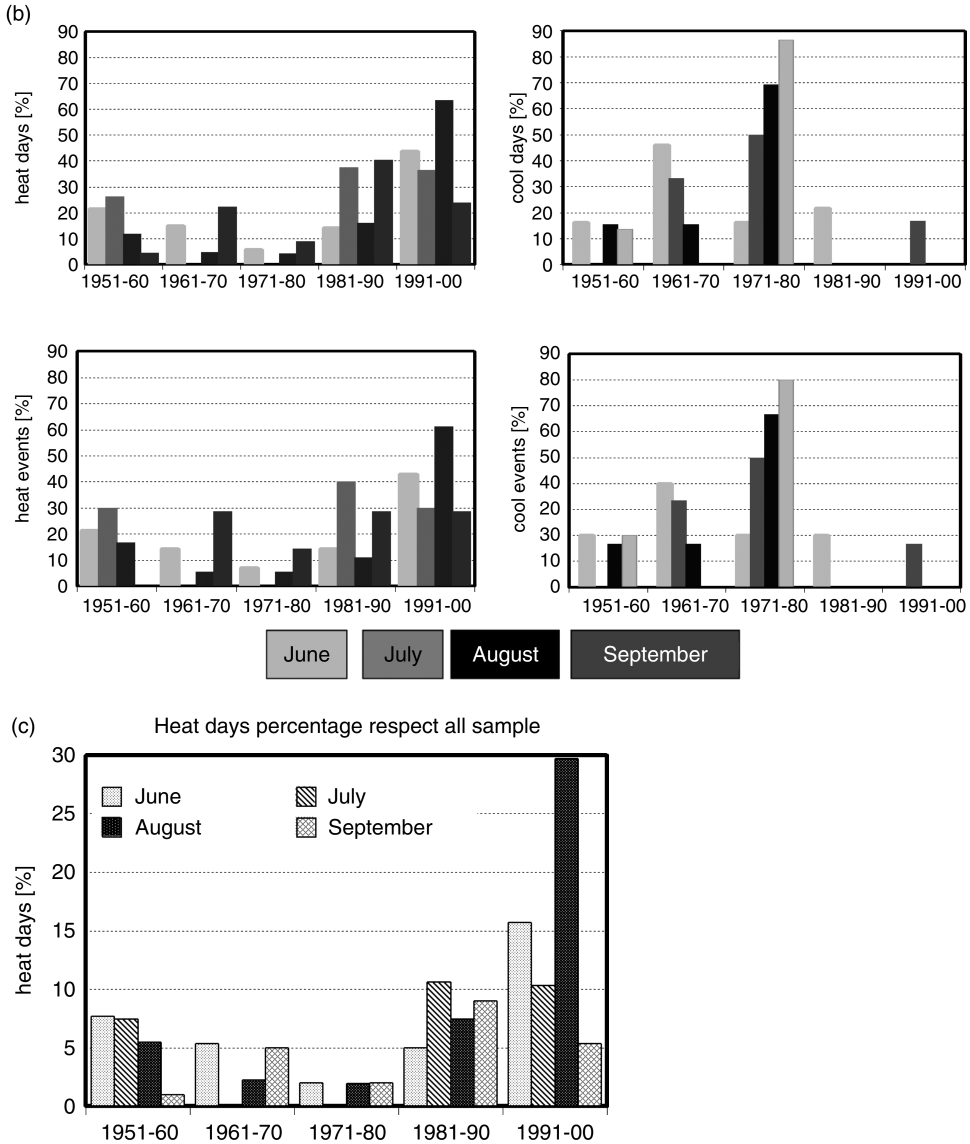

Figure 3. (*Continued*)

We find that during these heat-wave days, the meridional scale of the Scandinavian and Mediterranean jet system is at its minimum, i.e. the eastern edge of the Scandinavian jet and the western edge of the Mediterranean jet are almost aligned (Figure 4(a)) and that the Mediterranean jet splits into two sub-branches, the main southeastern branch starts in the Eastern Mediterranean and weakens when it reaches Central Asia, while a minor branch resides north of the Alpine region. With this configuration, which has a persistency from 1 to 3 weeks, there is a ridge to the south of the Alpine jet, which covers most of the Mediterranean area (Figure 4(a)). The associated anticyclonic vorticity, Figure 5(a), induces a tropospheric subsidence with an adiabatic warming which displaces the warm isothermals northwards from North Africa into the Mediterranean (Figure 6(a)).

When the eastern edge of the Scandinavian jet deflects northwards towards the Scandinavian peninsula, the Mediterranean jet is in a single streak with the western edge over the Atlantic Ocean off Gibraltar, and the eastern edge in the south part of European Russia, while the core of the jet lies in the southern part of the

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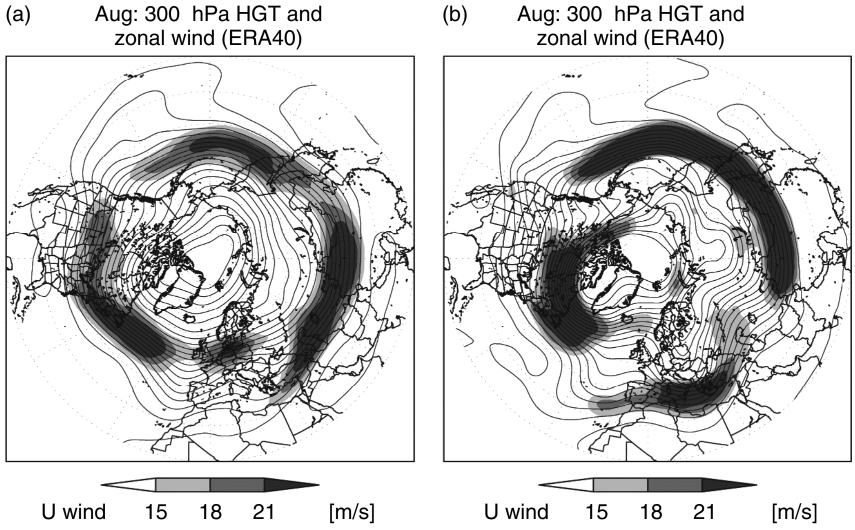

Figure 4. Geopotential (40-m contour) and intensity of zonal wind (shade) at 300 hPa. (a) Pattern during heat-wave days of August in the warm decade 1991–2000; (b) Pattern during cool-wave days of August in the cool decade 1971–1980

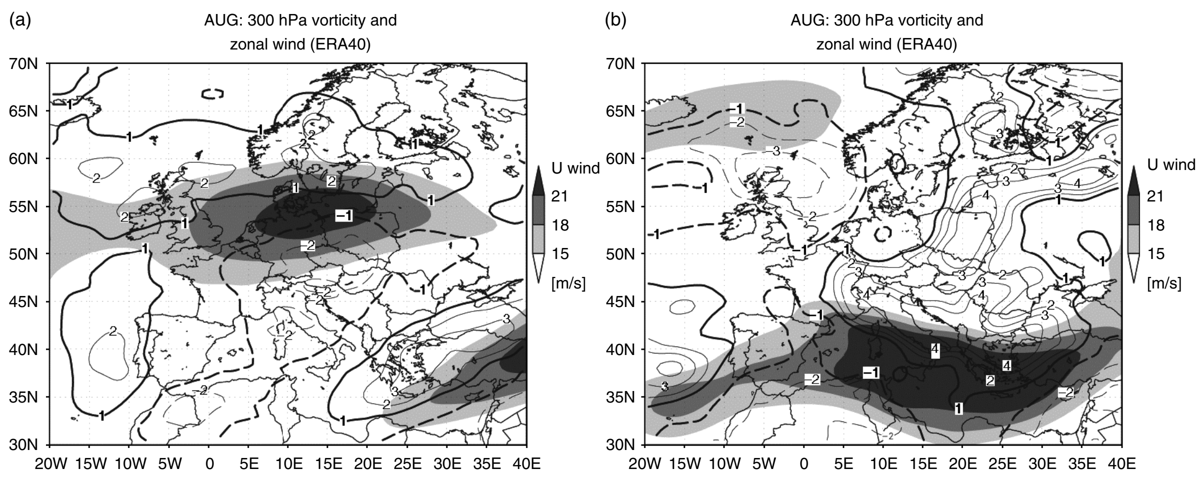

Figure 5. The relative vorticity ($1 \times 10^{-5}\,1/s$ contour) and zonal wind (shade) at 300 hPa fields. Where (a) and (b) are as in Figure 4

Mediterranean Sea (Figure 4(b)). With this configuration, there is a ridge over the British islands and a trough over the Mediterranean (Figure 4(b)). The vorticity over the Mediterranean Sea is cyclonic (Figure 5(b)), while a tropospheric strong subsidence occurs over the coastal region of North Africa, which displaces the warm isotherms southward back to the Sahara (Figure 6(b)).

Furthermore, our analyses show that the monthly surface temperature, obtained averaging surface observations over Italy, in June, July, August, and September is 90% correlated with the T850 over the Central Mediterranean (not shown), and more than 60% correlated with the T850 over the entire Mediterranean basin. This correlation is 67% in June, falls to 60% in July, and is 77% in August and 76% in September (Figure 7); therefore the temperature anomalies over Italy represent the Country-scale signal of larger-scale (regional) signal. This argument is further substantiated by the relation of the monthly T850 over the Central Mediterranean with dynamical features on the Mediterranean basin scale.

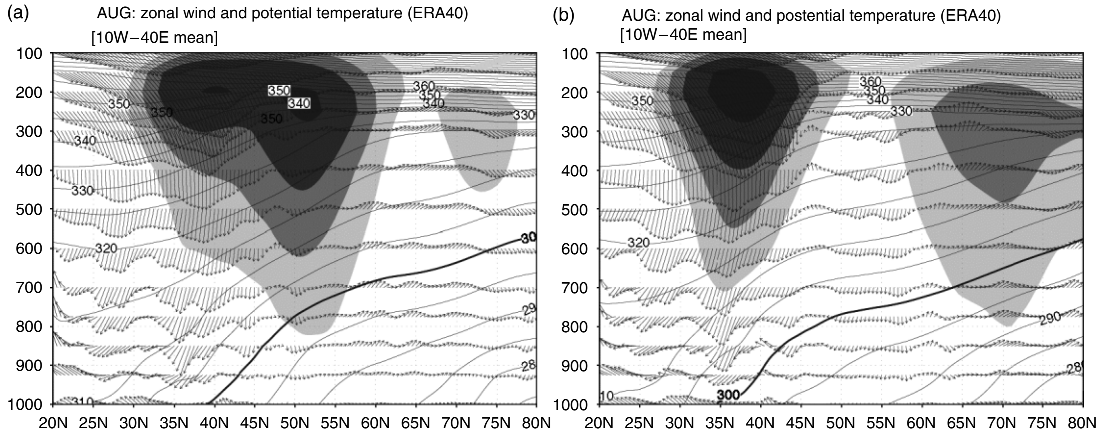

Figure 6. The vertical cross section, averaged trough 10W-40E, of the zonal wind (shaded), of the isentropes, and of the vector (v,w) in *m/s* and *mm/s* respectively. Where (a) and (b) are as in Figure 4

5. CONCLUSIONS

Through a statistical analysis of temperature observed at the surface in Italy during the period 1951–2003, we find that the highest number of heat waves occur in June and August, and that, from the 70s there has been a monotonic increase of their number, with about half of the events in the last decade of the twentieth century, and the longest and warmest in the summer of 2003. On the other hand, the number of cool waves reached a maximum in the 70s; then it monotonically decreased and summer cool waves almost disappeared in the last decade of the century. This tendency towards an increase of heat-wave events both in number and intensity has been attributed to the larger-scale warming by several authors (Schär *et al*., 2004; Stott *et al*., 2004).

We have shown that the warm episodes in the Mediterranean are associated with the presence of a jet streak located in the north of the Alps and an anticyclonic vortex over the Mediterranean: with this configuration, there is a strong subsidence and an adiabatic warming of the troposphere. When the Mediterranean jet resides along the northern rim of Africa, the vorticity over the Mediterranean is positive (cyclonic), and this region is relatively cool.

Results shown here are a major starting point for a better understanding of the physical mechanisms yielding to such severe events, and will give some hints for the improvement of the forecast of these phenomena, which are expected to occur more frequently in the course of the twenty-first century, as suggested by regional climate scenarios (Beniston, 2004).

Moreover, authors are now investigating, using both data analysis and numerical modelling, the role played by two other major physical processes: (1) the large soil moisture deficits, which, accrued in the region owing to exceptionally early and warm spring, may intensify most of the subsequent summer heat waves, as in 2003 (Beniston, 2004); (2) the anomalous summer monsoons in West Africa and/or Asia, and associated tropical Sea Surface Temperature Anomalies (SSTAs) (Baldi *et al*., 2004; Raicich *et al*., 2001), which may lead to a lower tropospheric warming and a change in the atmospheric circulation over the Mediterranean basin (Brunetti *et al*., 2004).

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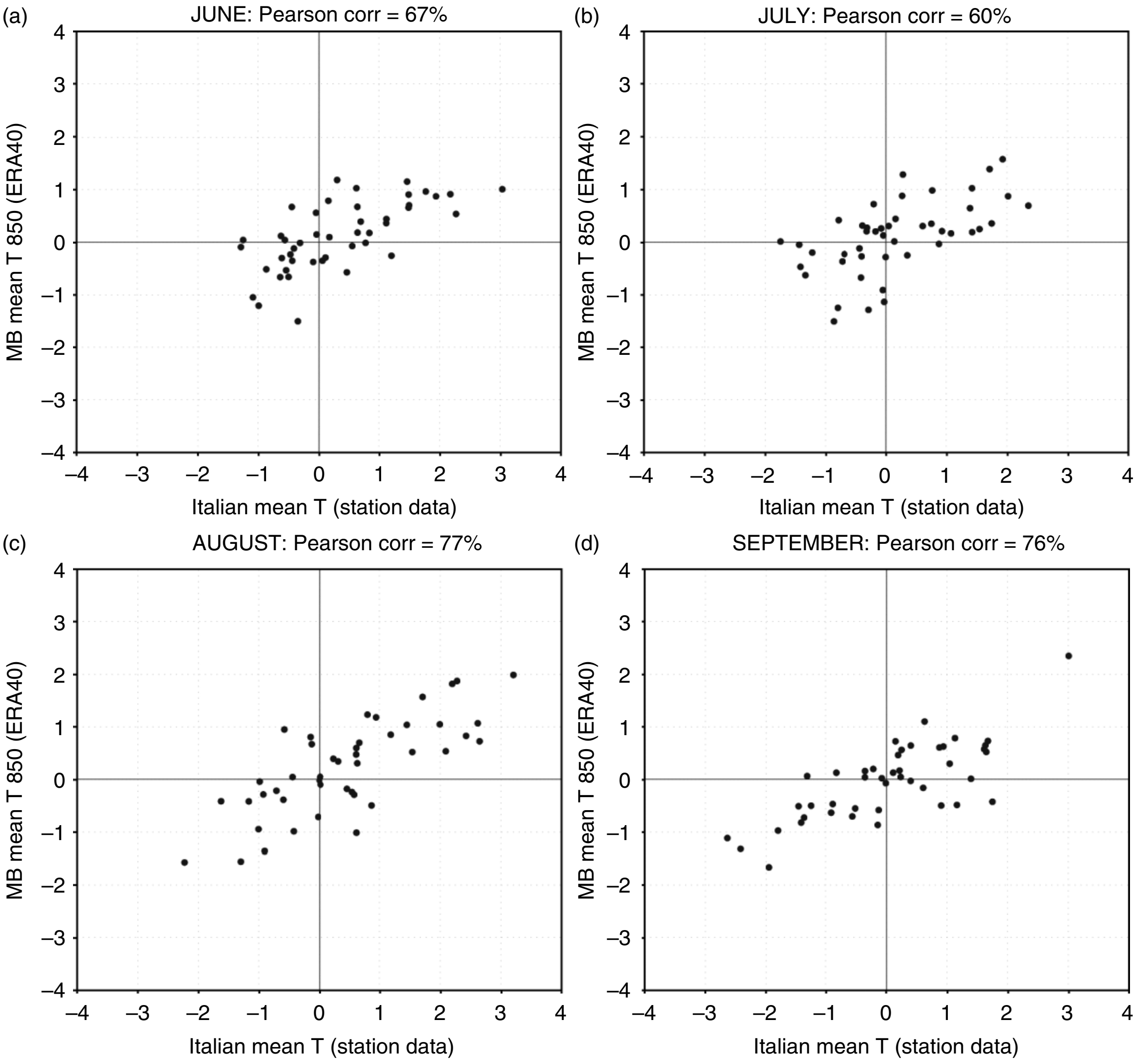

Figure 7. Scatter plot between the 850 hPa temperature, T850, computed averaging the ERA-40 data over the Mediterranean and the surface temperature, T_{surf}, obtained averaging surface observations over Italy, in June, July, August, and September (panel a,b,c,d respectively)

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