Int J Biometeorol (2011) 55:253–263
DOI 10.1007/s00484-010-0331-3

ORIGINAL PAPER

Dynamics of the temperature-humidity index in the Mediterranean basin

**Maria Segnalini · Alessandro Nardone ·
Umberto Bernabucci · Andrea Vitali · Bruno Ronchi ·
Nicola Lacetera**

Received: 28 January 2010 / Revised: 29 March 2010 / Accepted: 5 May 2010 / Published online: 4 June 2010

Abstract The study was aimed at describing the temperature humidity index (THI) dynamics over the Mediterranean basin for the period 1951–2007. The THI combines temperature and humidity into a single value, and may help to predict the effects of environmental warmth in farm animals. In particular, on the basis of THI values, numerous studies have been performed to establish thresholds for heat stress in dairy cows. The THI was calculated by using monthly mean values of temperature and humidity obtained from the National Center for Environmental Prediction/National Center for Atmospheric Research reanalysis project. The analysis demonstrated a high degree of heterogeneity of THI patterns over the Mediterranean basin, a strong north–south gradient, and an overall warming during the study period, which was particularly marked during summer seasons. Results indicated that several areas of the basin present summer THI values which were unfavorable to cow welfare and productivity, and that risk of heat stress for cows is generally greater in the countries of the south coast of the basin. Furthermore, THI data from the summer 2003 revealed that severe positive anomalies may impact areas normally characterized by a favorable climate for animal production. In conclusion, THI dynamics should be taken into careful consideration by farmers and policy makers operating in Mediterranean countries when planning investments in the sector of animal production. The investments should at least partially be directed towards implementation of adaptation measures, which may help to alleviate the impact of hot on farm animals welfare, performance and health.

Keywords Mediterranean basin · Temperature humidity index · Dynamics · Cattle

Introduction

Weather and climate may exert negative effects on farm animal welfare, performance and health (Nardone et al. 2006). Previous studies described the complexity of heat exchanges between animals and the environment, which involve heat production, storage and dissipation, and are dependent on both biological and physical factors (Hahn et al. 2003; Nienaber and Hahn 2007). Evaluation of air temperature alone does not permit an accurate assessment of the effects of the thermal environment on physiology, welfare, health, and productivity in farm animals. For instance, high humidity in combination with high temperatures reduces the potential for evaporative heat loss (West 2003), solar radiation adds heat to that deriving from metabolic processes, and strong winds, especially in combination with precipitation, amplify the adverse effects of cold temperature (Gaughan et al. 2008).

Different approaches have been used to quantify heat stress in farm animals (Hahn et al. 2003). These include utilization of the temperature humidity index (THI), which was originally developed by Thom (1958) as a “discomfort index“ to estimate the levels of discomfort for human beings during summer months. Afterwards, Berry et al. (1964) extended its use to bovine species. Hahn et al. (2003) indicated that, compared to other indexes, the THI is

---

M. Segnalini · A. Nardone · U. Bernabucci · A. Vitali ·
B. Ronchi · N. Lacetera
Dipartimento di Produzioni Animali, Università della Tuscia,
Viterbo, Italy

N. Lacetera (✉)
Via San Camillo De Lellis,
01100 Viterbo, Italy
e-mail: nicgio@unitus.it

a practical tool and a standard for many studies and applications in animal biometeorology. There are a variety of formulas to calculate THI which differ from each other in the weight given to the effects of humidity (Bohmanova et al. 2007). However, in all cases, temperature and humidity are combined in a single value. Several studies suggested that THI values may help to predict the effects of environmental warmth in farm animals. In particular, on the basis of THI values, numerous studies have been performed to establish thresholds for heat stress in dairy cows. Johnson (1980) and Bouraoui et al. (2002) reported that milk production in dairy cows begins to decline when THI reaches the value of 72 or 69, respectively. In a recent study, Vitali et al. (2009) suggested that the risk of death in dairy cows starts to increase when maximum daily THI is above 80.

The Mediterranean basin covers about 10 M km^2 and goes from the Atlantic coast of Portugal to the southern part of the Caspian Sea with a core area that stretches over about 20° latitude and 46° longitude (Nardone 2000). In biogeography, the Mediterranean basin refers to the lands around the Mediterranean sea that have a Mediterranean climate, with mild, rainy winters and hot, dry summers, which support characteristic Mediterranean forests, woodlands, and shrub vegetation (Köppen 1936). However, it is widely accepted that the Mediterranean basin is a highly heterogeneous region, with a climate characterized by a great diversity of features, resulting in a variety of climate types due to its unique geographic location: a transition zone between the hot and dry African climate regime in the south, and the mild and humid European climate in the north (Pinna 1977). Furthermore, the climate of the Mediterranean basin is also very sensitive to meteorological events originating in other parts of the world, such as the North Atlantic Oscillation (NAO), the Indian monsoon and the dust transported from the Sahara to the Atlantic ocean through the Mediterranean basin (Holton 1992). In general terms, the basin is characterized by contrasting variations in temperature and precipitation between winter and summer, stemming from the descending branch of the Hadley circulation in summer while westerlies prevail during the winter season (Bolle 2002).

Climate heterogeneity of the area likely contributes to the differences between the Mediterranean countries in terms of animal production (de Rancourt and Mottet 2006). With regard to bovine species, northern countries, which benefit from a more favorable climate, have larger cattle herds than southern countries where the hot climate and poor grasslands are more suitable to sheep and goat production. However, the ongoing population and urbanization growth in the southern countries of the basin is constantly increasing demand for animal products in urban areas, and thus will certainly strengthen livestock farming, meat and milk industries in these countries.

Previous animal biometeorology studies have utilized THI to characterize the region of Córdoba in central Argentina (De la Casa and Ravelo 2003), and the northeast region of Thailand (Somparn et al. 2004). To the best of our knowledge, the Mediterranean basin has been characterized by focusing the attention on air temperature and precipitation dynamics (Brunetti et al. 2000; Klein Tank and Können 2003; Xoplaki et al. 2004, 2005; Touchan et al. 2005; Scherrer et al. 2006; Pauling and Paeth 2007), whereas no studies have been performed by utilizing THI.

The aim of this study was to describe the THI dynamics over the Mediterranean basin for a period of time comprising the years between 1951 and 2007.

Materials and methods

Study area

The Mediterranean basin we refer to is delimited by the 28° and 48° North parallels and the 10° West and 40° East meridians, and includes, fully or partially, over 20 countries (from the Alpine region in the north to the north African countries in the south, from the Iberian peninsula in the west to the Middle Eastern countries in the east) (Fig. 1).

Data and methods

The THI was calculated by using monthly mean values of temperature and humidity (2.5° x 2.5° latitude–longitude resolution), which were obtained from the National Center for Environmental Prediction (NCEP)/National Center for Atmospheric Research reanalysis project (Kalnay et al. 1996) at the National Oceanic & Atmospheric Administration (NOAA)/Earth System Research Laboratory (ESRL),

Fig. 1 Study area. The Mediterranean basin is delimited by the 28° and 48° North parallels and the 10° West and 40° East meridians

Physical Sciences Division (PSD) for the period 1951–2007. NCEP Reanalysis data were provided by the NOAA/ESRL PSD (Boulder, Colorado, USA) from their Web site at http://www.esrl.noaa.gov/psd/. Briefly, the reanalysis datasets are made available after executing three standard quality control: a "duplicate station check", which eliminates duplicates and key punch errors from reports, a "buddy check", which eliminates extreme values, and a standard deviation check, which compares the daily data against a gridded daily climatology.

Calculation of THI may be carried out by different formulas, which permit the establishment of the water vapour content of the air starting alternatively from wet bulb temperature, dew point temperature, or relative humidity (Bohmanova et al. 2007). Among these variables, the only one available for the study area was the relative humidity. For this reason, we calculated monthly mean values of THI by the following formula, which is based on values of ambient temperature (AT, °C) and relative humidity (RH, %) (NOAA 1976):

$$THI = (1.8 \cdot \mathrm{AT} + 32) - (0.55 - 0.55 \cdot \mathrm{RH}) \cdot [(1.8 \cdot \mathrm{AT} + 32) - 58]$$

With respect to the original one, this formula includes terms (1.8 × AT+32), which convert temperature data from °C to °F. Such a conversion was made because most of literature data reported the THI calculated by measuring ambient temperature in a °F scale. The same formula has been already utilized for THI calculation in Mediterranean countries (Bouraoui et al. 2002; Vitali et al. 2009). Furthermore, Bohmanova et al. (2007) indicated this formula as the one to be preferred for calculation of THI in regions with a subtropical climate, whereas other formulas should be utilized for geographic areas with arid climate. A body of literature has described the Mediterranean climate as subtropical (Troll and Paffen 1964; Griffiths 1976; Trewartha and Horn 1980).

First of all, the Mediterranean basin was characterized on the basis of the mean annual and seasonal THI referred to the 30-year reference period (1961–1990) known as CliNo (Climate Normal). CliNo is the conventional 30-year period utilized for climatologic analysis and confrontation adopted by the World Meteorological Organization (WMO). For the seasonal characterization of the study area, the months of December, January, and February were defined as winter (DJF); March, April, and May, as spring (MAA); June, July, and August, as summer (JJA); and September, October, and November, as fall (SON).

The THI dynamics over the basin were evaluated by comparing mean values of annual and seasonal THI of CliNo and of two 30-year periods (1951–1980 and 1971–2000), and in the light of the known heterogeneity of the area in terms of climate features (Bolle 2002), by plotting maps of THI anomaly isolines for the same three 30-year periods. Furthermore, the THI dynamics were also studied by evaluating mean values of THI and THI anomalies versus CliNo for the decade 1998–2007. This part of the study was carried out to take into due consideration the documented recent extreme climate events, which occurred in the study area (Xoplaki et al. 2005; Goubanova and Li 2006; Luterbacher et al. 2007). Finally, for the summer season of year 2003, which has been widely recognized as one of the hottest of the last century (Xoplaki et al. 2006), and also as a period of time during which European livestock production was dramatically affected by thermal challenge (Vitali et al. 2009; Nardone et al. 2009), a map of THI anomaly isolines was plotted to verify whether the anomalies were uniformly distributed within the study area.

Map of isolines were generated by the geographical software GrADS (Grid Analysis and Display System). GrADS is an interactive desktop tool for visualization and manipulation of earth science data and is freely distributed over the Internet (http://www.iges.org/grads/). It uses a 4-dimensional data environment: longitude, latitude, vertical level, and time. Operations are executed interactively by entering FORTRAN-like expressions at the command line.

Results

Mean values of annual and seasonal THI for CliNo are reported in Table 1. Figures 2 and 3 show the isolines of the mean annual and seasonal THI, respectively, referred to CliNo. Annual THI ranged from 42 to 70, and showed a north–south gradient (Fig. 2), which was similar to that observed by considering air temperature alone (data not

Table 1 Mean values of annual and seasonal temperature humidity index (THI) of the Mediterranean basin calculated for the three periods of reference (1951–1980, 1961–1990 and 1971–2000)

30-year periods	Annual THI	Seasonal THI
1951–1980	61.07	DJF 50.35
		MAM 59.11
		JJA 71.72
		SON 63.12
1961–1990 (CliNo)	61.13	DJF 50.25
		MAM 59.23
		JJA 71.78
		SON 63.28
1971–2000	61.23	DJF 50.32
		MAM 59.33
		JJA 71.99
		SON 63.26

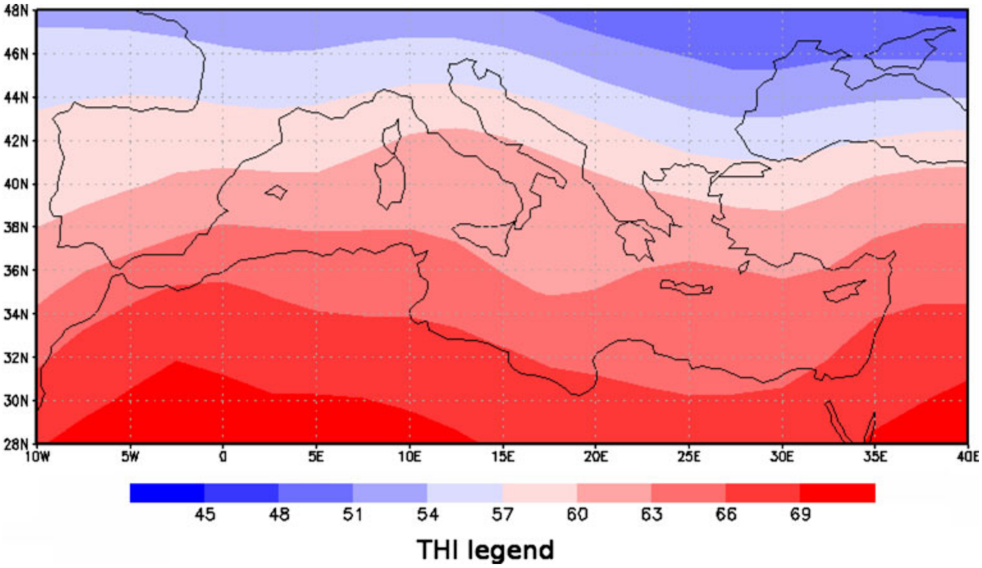

Fig. 2 Regional distribution of mean annual temperature humidity index (THI) for CliNo (Climate Normal). CliNo is the conventional 30-year period (1961–1990) for climatologic analysis and confrontation adopted by the World Meteorological Organization

shown). The analysis of humidity values (data not shown) did not reveal any significant trend, but indicated the strong influence of the Mediterranean sea, in that the proximity to large bodies of water and the prevalence of moisture-bearing winds favors high humidity. Values of THI ranged from 30 to 60 in DJF, from 50 to 70 in MAM, from 60 to 79 in JJA, and from 50 to 71 in SON (Fig. 3). Also, in this case, a north–south gradient was observed.

Mean values of annual and seasonal THI for the periods 1951–1980 and 1971–2000 are reported in Table 1. Table 2 reports results of the comparison carried out among mean values of annual and seasonal THI calculated for the three 30-year periods considered in the study. Briefly, the comparison pointed out an overall warming in the study area, and that the THI increase was particularly marked during summer (+0.27 units). Further-

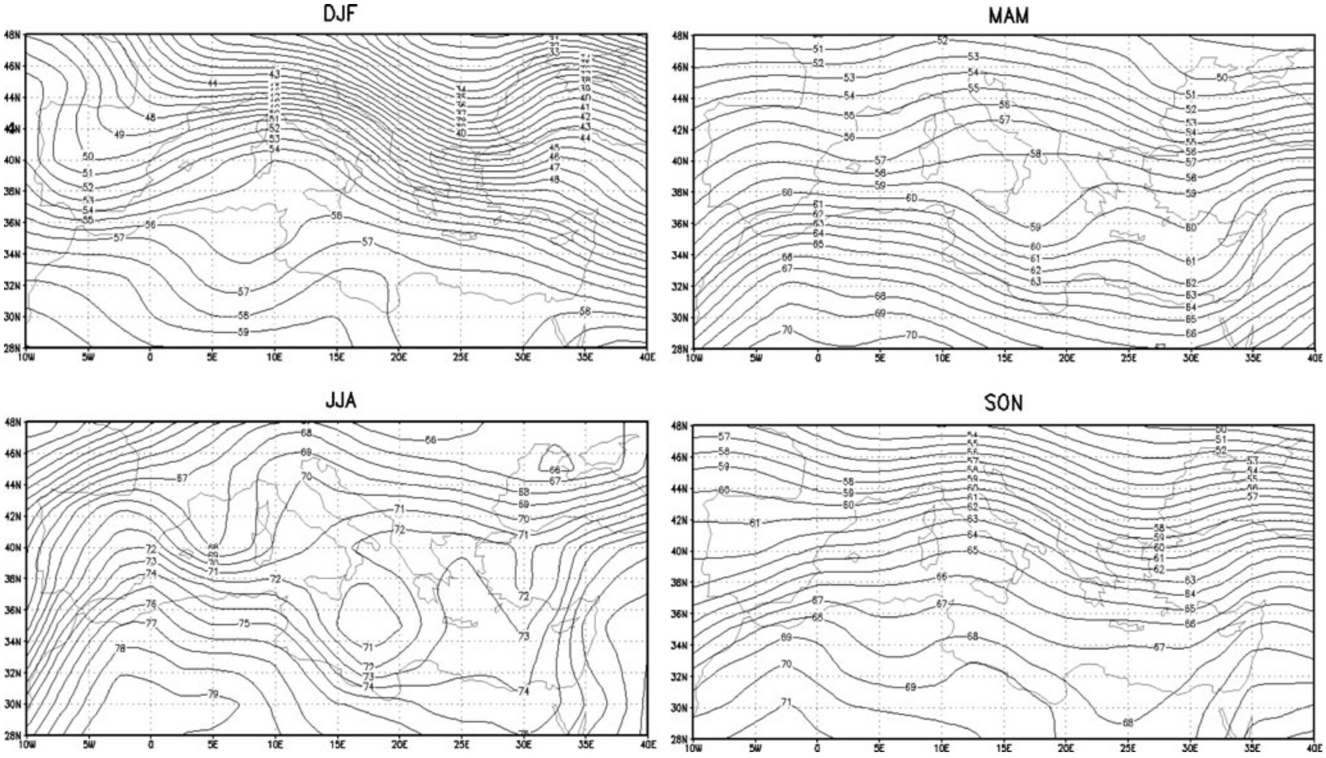

Fig. 3 Regional distribution of seasonal temperature humidity index (THI) for CliNo (Climate Normal, 1961–1990 period). The months of December, January, and February were defined as winter (*DJF*), March, April, and May as spring (*MAM*), June, July, and August as summer (*JJA*), and September, October, and November as fall (*SON*). Values of THI range from 30 to 60 in *DJF*, from 50 to 70 in *MAM*, from 60 to 79 in *JJA*, and from 50 to 71 in *SON*

Table 2 Results of the comparison carried out among mean annual and seasonal temperature humidity index (THI) calculated for the three periods of reference (1951–1980, 1961–1990 and 1971–2000)

Periods compared	Annual	Seasonal
1951–1980 vs 1961–1990 (CliNo)	−0.06	DJF+0.10 MAM −0.12 JJA −0.06 SON −0.16
1971–2000 vs 1961–1990 (CliNo)	+ 0.10	DJF+0.07 MAM+0.10 JJA+0.21 SON −0.02
1971–2000 vs 1951–1980	+ 0.16	DJF −0.03 MAM+0.22 JJA+0.27 SON+0.14

more, the analysis also indicated that, comparing the winter seasons, the THI in the basin slightly decreased during the study period (−0.03 units).

Figure 4 shows the isolines of annual THI anomalies versus CliNo for the two 30-year periods different from CliNo considered in the study (1951–1980 and 1971–2000). Anomalies referred to the period 1951–1980 ranged from −0.5 to +0.7 units of THI (Fig. 4a). In detail, the period 1951–1980 was colder than CliNo in the central and west countries of the basin (−0.5 THI units), whereas countries in the east (especially those in the Balkan area) were hotter (+0.7 THI units). Anomalies referred to the period 1971–2000 ranged from −0.8 to +0.8 units of THI (Fig. 4b). The greatest negative anomaly (−0.8 THI units) was observed in the south-west part of the area and over eastern Turkey, whereas the greatest positive anomaly (+0.8 THI units) characterized the central and north-east area of the basin.

Figure 5 shows the isolines of seasonal THI anomalies versus CliNo for the two 30-year periods different from CliNo considered in the study (1951–1980 and 1971–2000). The analysis referred to the period 1951–1980 (Fig. 5a) demonstrated that for the winter season the anomalies ranged from −0.6 (Iberian Peninsula) to +1.8 units of THI (eastern Turkey); for spring, they ranged from −0.9 (north-east of the basin) to +0.6 (eastern and north-western France); for summer, they ranged from −0.6 (central basin, Sicily, and north-western Spain) to +0.6 (Balkan area); and for fall, they ranged from −0.9 (western and central basin) to +0.6 (Balkan area).

The analysis of seasonal anomalies referred to the period 1971–2000 (Fig. 5b) pointed out that for the winter season the anomalies ranged from −1.8 (eastern Turkey) to +1.5 units of THI (north-east of the basin); for the spring, the range was −0.9 to +0.9 (eastern Turkey and north-east of the Black Sea, respectively); for summer, the anomalies ranged from −0.6 (Spain, Morocco, Algeria, and Libya) to +0.9 (north-east of the Black Sea); and for fall, the range was −0.9 to +0.6 (northern and Balkan areas, and eastern part of the basin and Black Sea, respectively).

Table 3 reports the mean values of annual and seasonal THI for the whole period 1998–2007, and for each single year of the decade.

Figure 6 shows the THI anomalies calculated for the decade 1998–2007 versus CliNo. Value of annual THI anomaly over the decade indicated a general warming in the area with a positive anomaly respect to CliNo of +0.73 (Fig. 6a). On the other hand, a positive annual anomaly was recorded for each single year of the decade with the lowest value referring to year 2005 (+0.27) and the highest to year 2007 (+1.12). The analysis of seasonal anomalies (Fig. 6b) showed that in the winter season the anomalies recorded have been either positive (years 1998, 2001, 2002, 2004, 2007) or negative (years 1999, 2000, 2003, 2005, 2006); in the spring season, only a negative anomaly was recorded (year 2004, −0.22), whereas for the remaining 9 years of

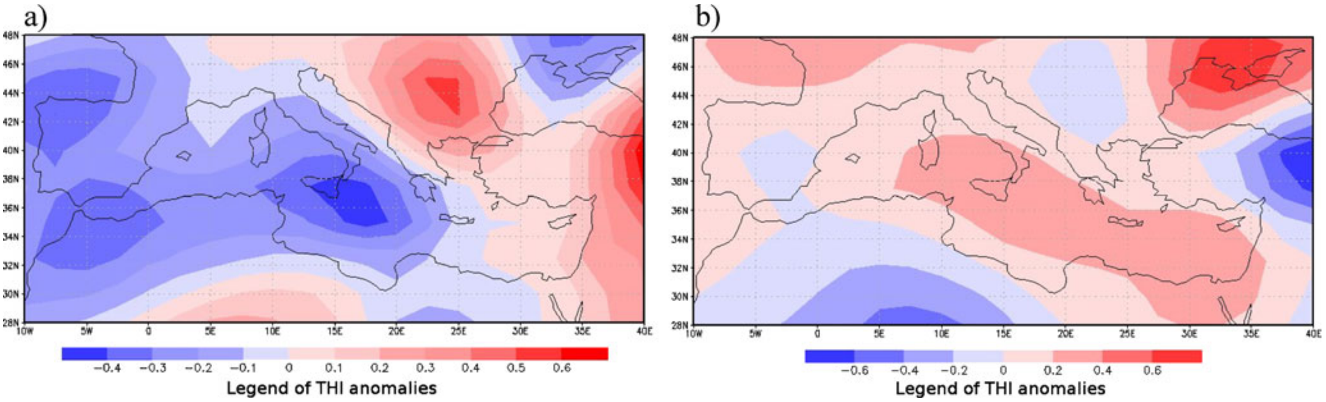

Fig. 4 Isolines of annual temperature humidity index (THI) anomalies versus CliNo (Climate Normal, 1961–1990 period) for the two 30-year periods different from CliNo considered in the study (1951–1980, **a**, and 1971–2000, **b**)

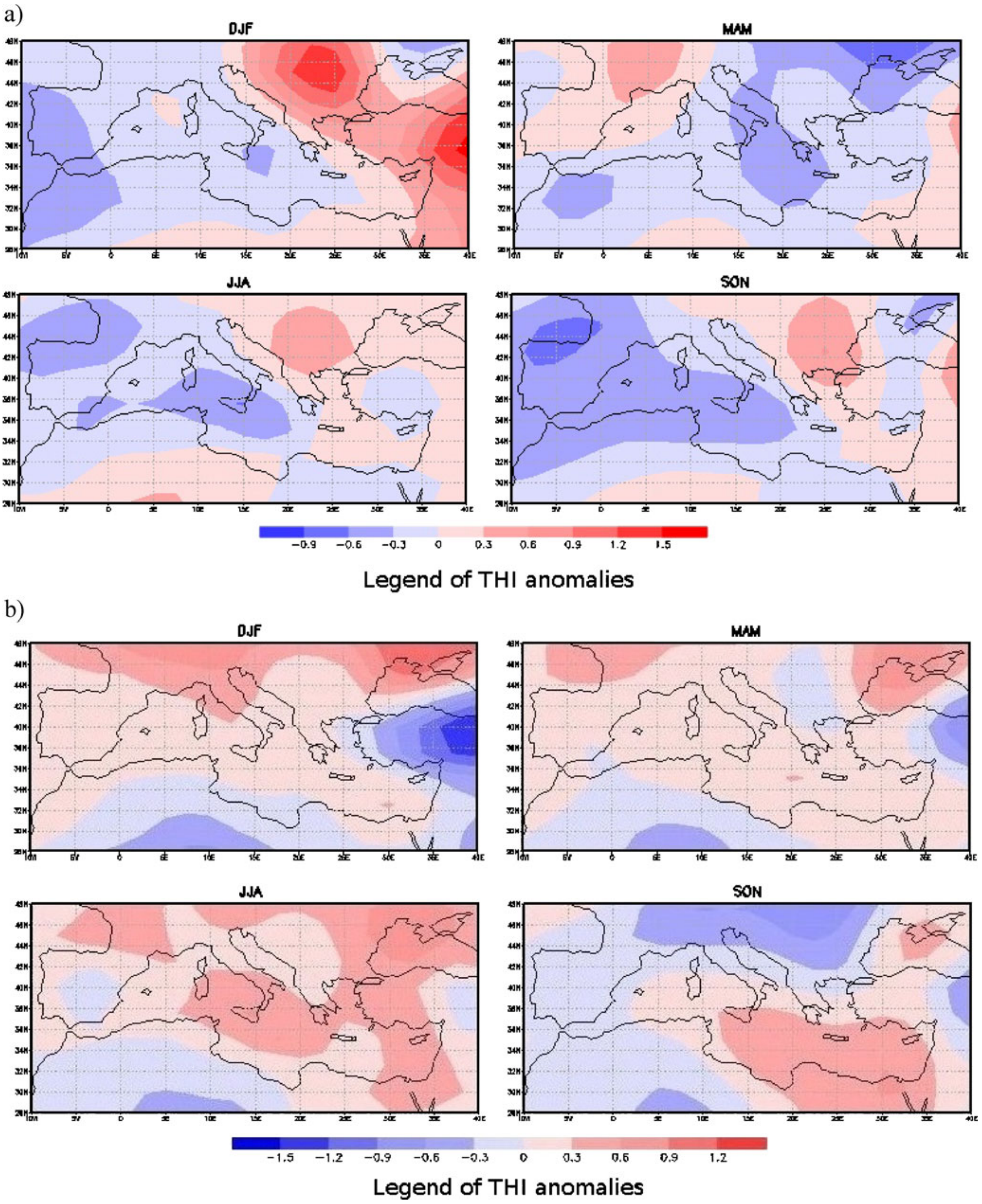

Fig. 5 Isolines of seasonal temperature humidity index (THI) anomalies versus CliNo (Climate Normal, 1961–1990 period) for the two 30-year periods different from CliNo considered in the study (1951–1980, **a**, and 1971–2000, **b**)

Table 3 Mean values of annual and seasonal temperature humidity index (THI) of the Mediterranean basin calculated for the decade 1998–2007

Years	Annual THI	Seasonal THI
1998–2007	61.86	DJF 50.49
		MAM 60.10
		JJA 72.89
		SON 63.95
1998	61.73	DJF 51.80
		MAM 59.66
		JJA 72.83
		SON 63.46
1999	62.04	DJF 50.05
		MAM 60.32
		JJA 73.08
		SON 63.90
2000	61.69	DJF 49.83
		MAM 60.20
		JJA 72.40
		SON 63.86
2001	62.10	DJF 52.18
		MAM 61.13
		JJA 72.74
		SON 63.90
2002	62.12	DJF 50.48
		MAM 60.26
		JJA 72.57
		SON 64.46
2003	61.75	DJF 49.59
		MAM 59.46
		JJA 73.92
		SON 63.98
2004	61.58	DJF 50.83
		MAM 59.01
		JJA 72.36
		SON 64.16
2005	61.40	DJF 49.62
		MAM 59.81
		JJA 72.73
		SON 63.41
2006	61.91	DJF 49.16
		MAM 60.50
		JJA 73.04
		SON 64.89
2007	62.25	DJF 52.10
		MAM 60.59
		JJA 73.24
		SON 63.45

the decade, the anomalies were positive with the maximum value recorded in 2001 (+1.9); in the summer season, only positive anomalies were recorded and the highest value was relative to summer 2003 (+2.14); also, in the fall season, the anomalies were all positive and ranged from +0.13 (year 2005) to +1.61 (year 2006).

Figure 7 shows the isolines of summer THI anomalies of year 2003 versus CliNo. Also, in this case, the study area revealed a strong heterogeneity: a single negative anomaly (−1) was detected in eastern Turkey, whereas the positive anomalies showed a very wide range (from +0.5 to +5.5) and a south–north gradient.

Discussion

Results reported herein are in line with those obtained from previous studies, which on the basis of climate features different from THI indicated that the geographical Mediterranean domain does not share the Mediterranean climate according to its commonly adopted definition (Köppen 1936; Bolle 2002). Furthermore, still in agreement with previous findings referring to temperatures (Klein Tank and Können 2003; Xoplaki et al. 2005, 2006; Luterbacher et al. 2007), the present study pointed out an overall THI increase in the Mediterranean basin in the period 1951–2007, and also that the THI dynamics in the study area were not spatially and temporally homogeneous.

First of all, we wish to remark that the general agreement between our results with those from previous analysis referred to temperature is not surprising, because in the THI formulas the weight of temperature is higher than that of relative humidity and this happens regardless the formula chosen for calculation (Bohmanova et al. 2007). However, as already explained, characterization of a geographic area in terms of THI permits a more accurate prediction of the effects of environmental warmth in cattle because this index takes into account the role of humidity in affecting the potential for evaporative heat loss from the body.

On the basis of previous observations, climate heterogeneity of the Mediterranean basin would reflect the presence of strong mesoscale features, which determine large climatic gradients within a region, which would, otherwise, have a much more homogeneous climate. The climatic heterogeneity of the area is likely due to physical and physico-geographical factors such as the atmospheric circulation, which in turn alters the storm track, air temperature, precipitation and pressure distribution, to the Atlantic and Mediterranean sea surface temperatures (SSTs) pattern and distribution, to the land–sea interactions, and also to the latitude, altitude and orography (Frei and Schär 1998). The response of the Mediterranean basin to large-scale climate forcing is very complicated, with strong

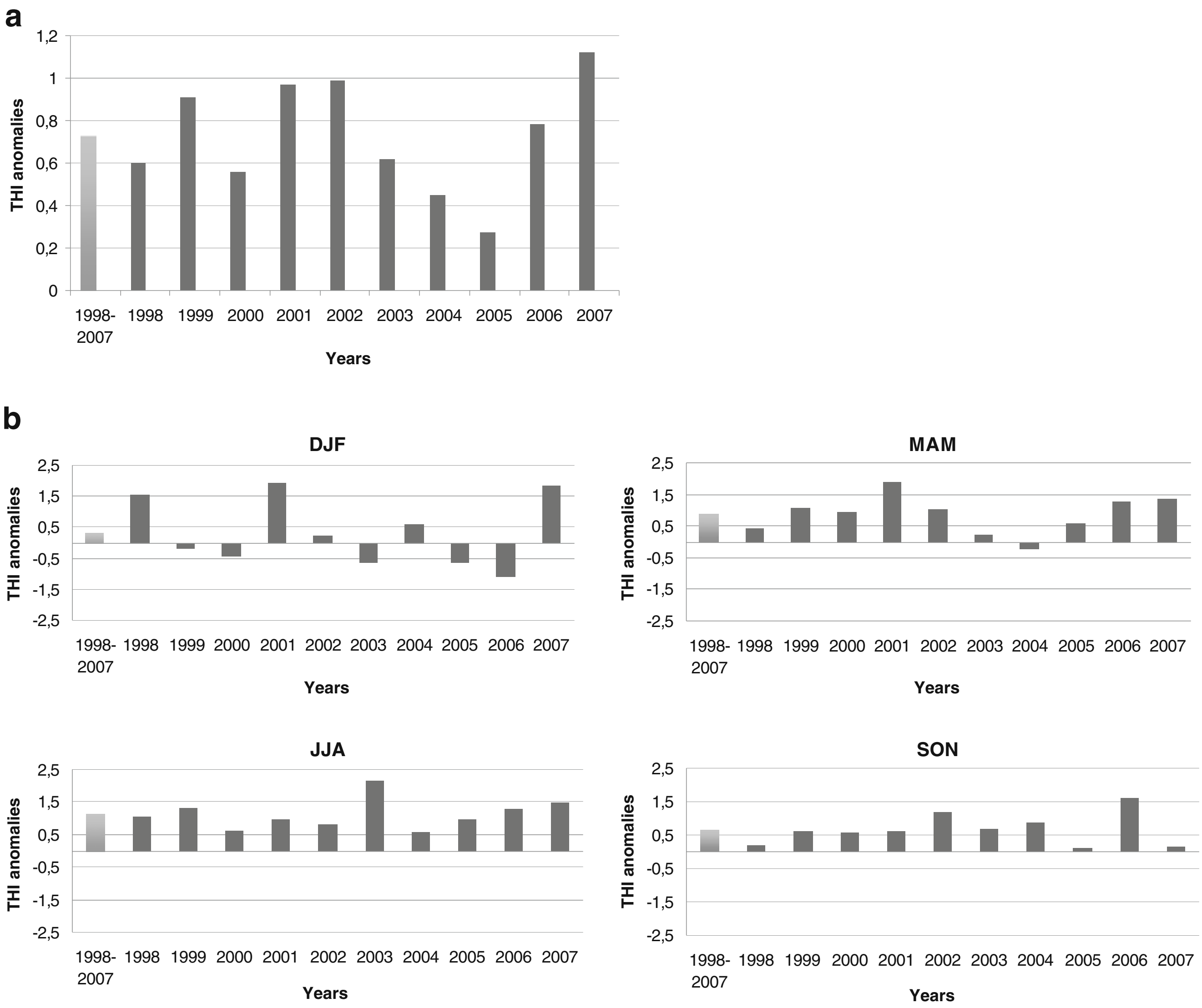

Fig. 6 Annual (**a**) and seasonal (**b**) temperature humidity index (THI) anomalies calculated for the decade 1998–2007 versus CliNo (Climate Normal, 1961–1990 period)

spatial and temporal variability. Surface meteorological forcing over the Mediterranean is associated with the NAO, whose impact on climate and ecosystem parameters in northern and southern Europe is well documented. The growing interest in the NAO is partially explained by the fact that the spatial signature of the observed climate warming over the last century resembles the surface temperature anomalies associated with this index (Pokrovsky 2009). The positive phase of the summer NAO (SNAO) is associated with warm, dry and relatively cloud-free conditions over north-western Europe, and, less strongly, with cooler, wetter and cloudier conditions over southern Europe and the Mediterranean, especially in the eastern part (Folland et al. 2009). Linderholm et al. (2009) reported that, since approximately the 1960s, the positive trend in the SNAO, associated with increased drought in northern Europe, coincides with a trend towards increased drought in the Mediterranean region, indicating that the recent temperature increase has caused drier conditions in both southern and northern Europe during summer.

Our analysis on seasonal THI dynamics in the period 1951–2000 pointed out an increase of summer and a slight decrease of winter values, and also differences in the THI dynamics between the west-central and eastern parts of the basin. These results are in line with those reported by Klein Tank and Können (2003) who indicated that the overall warming registered in Europe in the period 1976–1999 was likely associated with an increase in warm extremes rather than with a decrease in cold extremes. Furthermore, results reported herein are also concordant with those from Xoplaki et al. (2006), who indicated that in the period 1950–1999 there was a significant increase of summer

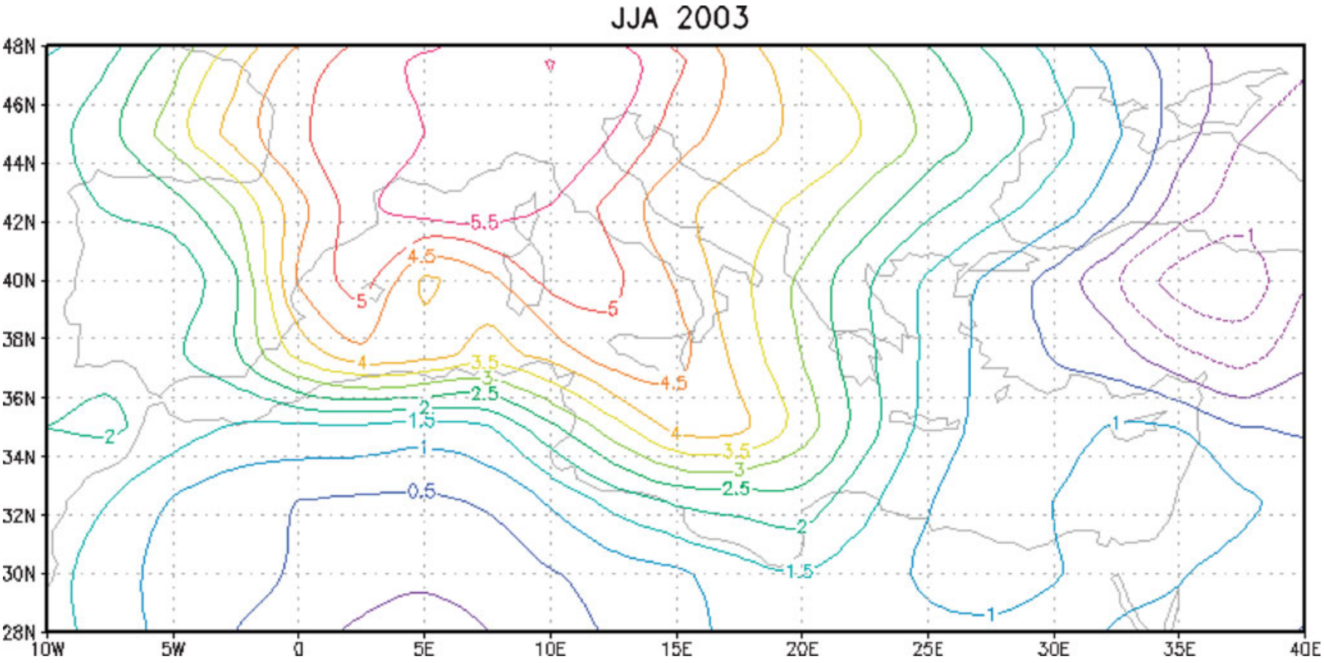

Fig. 7 Isolines of summer temperature humidity index (THI) anomalies for the year 2003 versus CliNo (Climate Normal, 1961–1990 period)

temperatures in western and central Mediterranean, but not in the eastern areas of the basin. Investigating the difference between western and eastern Mediterranean pressures, Brunetti et al. (2002) hypothesized a higher frequency of anticyclones over the central-western part of the basin. It follows that the different temperature trends in western and eastern areas may be caused by the complex relationships between the Mediterranean climate, the general atmospheric circulation and the SSTs. In practice, the western parts of the basin are in a maritime regime, whereas the eastern parts are highly continental.

The present study also testified that warming of the Mediterranean basin in terms of THI was particularly marked in the decade 1998–2007, and that summer 2003, autumn 2006 and winter 2007 were the periods during which the positive anomaly values were higher with respect to CliNo. Xoplaki et al. (2005) reported that the decade 1995–2004 was the warmest in the last half millennium, and Luterbacher et al. (2007) indicated that autumn 2006 and winter 2007 were also the warmest in more than 500 years. Finally, several studies have documented that the summer of 2003 was the warmest summer ever recorded over western and central Europe, and was characterized by serious health problems in human beings and farm animals (Beniston 2004; Fink et al. 2004; Díaz Jiménez et al. 2005; Vitali et al. 2009). In summer 2003, an anticyclone stationed above western Europe prevented precipitation that usually enters the continent from the Atlantic Ocean. Extreme maximum temperatures of 35–40°C were repeatedly recorded in July and to a greater extent in August. Both results from the present study and data provided by the European Centre for Medium-Range Weather Forecasts (www.ecmwf.int) indicated that the anomalous summer was centered over Switzerland, southern Germany, northern Italy, and south-eastern France. Furthermore, results reported herein also testify that the anomalies showed a south–north gradient. Previous studies documented that these kind of anomalies are caused by the spatial and temporal dominance of subtropical high pressure cells on cyclonic storms (Bolle 2002).

As already reported above, the THI has been widely utilized to predict the effects of environmental warmth in dairy cows. In a recent study carried out in Tunisia, Bouraoui et al. (2002) indicated that exposure of dairy cattle to mean daily THI higher than 69 is responsible for negative effects on milk yield, and that the extent of these effects is proportional to the number of units the THI is above the threshold. The present study indicated that, in several regions of the Mediterranean basin, summer THI values represent a major challenge for livestock industry, and made available a series of bioclimatic maps, which individuate the areas at a greater risk for cattle. In particular, the strong north–south gradient indicates that dairy cows reared in the countries of the central and south regions of the basin are likely to experience conditions of severe heat stress during summer months, which may severely compromise their performance, health and survival. Furthermore, data referring to summer 2003 testify that severe positive THI anomalies may also interest geographic areas with a favorable climate for animal production, and that therefore may be characterized by a reduced capacity to cope with this kind of extreme climate events.

In conclusion, findings from this study suggest that THI dynamics should be taken into careful consideration by farmers and policy makers operating in Mediterranean countries when planning investments in the sector of animal production. In particular, in the areas of the basin where the THI increase was more pronounced or which were shown to be subjected to extreme climate events, the investments should at least partially be directed to implementation of adaptation measures, which may help to alleviate the impact of hot extremes on animal welfare, performance and health.

Acknowledgements This study was financially supported by EU (CIRCE Integrated Project # 036961), and Università degli Studi della Tuscia.

References

Beniston M (2004) The 2003 heat wave in Europe: A shape of things to come? An analysis based on Swiss climatological data and model simulations. Geophys Res Lett 31 L02202. doi:10.1029/2003GL018857

Berry IL, Shanklin MD, Johnson HD (1964) Dairy shelter design based on milk production decline as affected by temperature and humidity. Trans Am Soc Agric Eng 7:329–331

Bohmanova J, Misztal I, Cole JB (2007) Temperature-Humidity Indices as indicator of milk production losses due to heat stress. J Dairy Sci 90:1947–1956. doi:10.3168/jds.2006–513

Bolle HJ (2002) Mediterranean climate: Variability and trends. Springer, New York

Bouraoui R, Lahmar M, Majdoub A, Djemali M, Belyea R (2002) The relationship of temperature-humidity index with milk production of dairy cows in a Mediterranean climate. Anim Res 51:479–491. doi:10.1051/animres:200236

Brunetti M, Maugeri M, Nanni T (2000) Variations of temperature and precipitation in Italy from 1866 to 1995. Theor Appl Climatol 65:165–174

Brunetti M, Maugeri M, Nanni T (2002) Atmospheric circulation and precipitation in Italy for the last 50 years. Int J Climatol 22:1455–1471. doi:10.1002/joc.805

De la Casa AC, Ravelo AC (2003) Assessing temperature and humidity conditions for dairy cattle in Córdoba, Argentina. Int J Biometeorol 48:6–9. doi:10.1007/s00484-003-0179-x

Díaz Jiménez J, Linares Gil C, García Herrera R (2005) Impact of extreme temperatures on public health. Rev Esp Salud Pública 79:145–157

Fink AH, Brücher T, Krüger A, Leckebusch GC, Pinto JG, Ulbrich U (2004) The 2003 European summer heatwaves and drought-synoptic diagnosis and impacts. Weather 59:209–216

Folland CK, Knight J, Linderholm HW, Fereday D, Ineson S, Hurrell JW (2009) The summer North Atlantic oscillation: past, present, and future. J Clim 22:1082–1103

Frei C, Schär C (1998) A precipitation climatology of the Alps from high-resolution rain-gauge observations. Int J Climatol 18:873–900

Gaughan JB, Mader TL, Holt SM, Lisle A (2008) A new heat load index for feedlot cattle. J Anim Sci 86:226–234. doi:10.2527/jas.2007-0305

Goubanova K, Li L (2006) Extremes in temperature and precipitation around the Mediterranean basin in an ensembles of future climate scenario simulations. Glob Planet Chang 57:27–42. doi:10.1016/j.gloplacha.2006.11.012

Griffiths JF (1976) Applied climatology. Oxford University Press, London

Hahn GL, Mader TL, Eigenberg RA (2003) Perspective on development of thermal indices for animal studies and management. EAAP Technic Ser 7:31–44

Holton JR (1992) An Introduction to dynamic meteorology. Academic, San Diego

Johnson HD (1980) Environmental management of cattle to minimize the stress of climatic change. Int J Biometeorol 24:65–78

Klein Tank AMG, Können GP (2003) Trends in indices of daily temperature and precipitation extremes in Europe, 1946–99. J Clim 16:3665–3680

Kalnay et al (1996) The NCEP/NCAR 40-year reanalysis project. Bull Am Meteorol Soc 77:437–470

Köppen W (1936) Das geographische aystem der klimate. In: Köppen W, Geiger R (eds) Handbuch der Klimatologie, Bd 1. Gebr Borntröger, Berlin, pp C1-C44

Linderholm HW, Folland CK, Walther A (2009) A multicentury perspective on the summer North Atlantic oscillation (SNAO) and drought in the Eastern Atlantic region. J Quat Sci 24:415–425. doi:10.1002/jqs.1261

Luterbacher J, Liniger MA, Menzel A, Estrella N, Della-Marta PM, Pfister C, Rutishauser T, Xoplaki E (2007) Exceptional European warmth of autumn 2006 and winter 2007: Historical context, the underlying dynamics, and its phonological impacts. Geophys Res Lett 34 L12704. doi:10.1029/2007GL029951

Nardone A, (2000) Weather condition and genetics of breeding systems in the Mediterranean area. Proc XXXV Int Symp It Soc Progr Zootec. Ragusa, Italy, pp 67–91

Nardone A, Ronchi B, Lacetera N, Bernabucci U (2006) Climate effects on productive traits in livestock. Vet Res Commun 30 (1):75–81. doi:10.1007/s11259-006-0016-x

Nardone A, Ronchi B, Lacetera N, Ranieri MS, Bernabucci U (2009) Effects of climate change on animal production and sustainability of livestock system. Livestock Sci 130:57–69

Nienaber JA, Hahn GL (2007) Livestock production system management responses to thermal challenges. Int J Biometeorol 52:149–157. doi:10.1007/s00484-007-0103-x

NOAA (1976) Livestock hot weather stress. Oper Man Lett C-31-76, Kansas City, MO

Pauling A, Paeth H (2007) On the variability of return periods of European winter precipitation extremes over the last three centuries. Clim Past 3:65–76

Pinna M (1977) Climatologia. UTET, Torino

Pokrovsky OM (2009) European rain rate modulation enhanced by changes in the NAO and atmospheric circulation regimes. Comput Geosci 35:897–906. doi:10.1016/j.cageo.2007.12.005

de Rancourt M, Mottet A (2006) Mediterranean animal production: development or decline? Options Méditerr 78:13–22

Scherrer SC, Appenzeller C, Liniger MA (2006) Temperature trend in Switzerland and Europe: implication for Climate Normal. Int J Climatol 26:565–580. doi:10.1002/joc.1270

Somparn P, Gibb MJ, Markvichitr K, Chaiyabutr N, Thummabood S, Vajrabukka C (2004) Analysis of climatic risk for cattle and buffalo production in northeast Thailand. Int J Biometeorol 49:59–64. doi:10.1007/s00484-004-0206-6

Thom EC (1958) Cooling degrees: day air-conditioning, heating and ventilating. Trans Am Soc Heat 55:65–69

Touchan R, Xoplaki E, Funkhouser G, Luterbacher J, Hughes MK, Erkan N, Akkemik Ü, Stephan J (2005) Reconstructions of spring/summer precipitation for the Eastern Mediterranean from tree-ring widths and its connection to large-scale atmospheric circulation. Clim Dyn 25:75–98

Trewartha GT, Horn LH (1980) An Introduction to climate. McGraw-Hill, New York

Troll C, Paffen KH (1964) Karte der Jahreszeiten klimate der Erde. Erdkunde 18:5–28

Vitali A, Segnalini M, Bertocchi L, Bernabucci U, Nardone A, Lacetera N (2009) Seasonal pattern of mortality and relationships between mortality and temperature humidity index in dairy cows. J Dairy Sci 92:3781–3790. doi:10.3168/jds.2009.2127

West JW (2003) Effects of heat-stress on production in dairy cattle. J Dairy Sci 86:2131–2144

Xoplaki E, González-Rouco JF, Luterbacher J, Wanner H (2004) Wet season Mediterranean precipitation variability: influence of large-scale dynamics and trends. Clim Dyn 23:63–78. doi:10.1007/s00382-004-0422-0

Xoplaki E, Luterbacher J, Paeth H, Dietrich D, Steiner N, Grosjean M, Wanner H (2005) European spring and autumn temperature variability and change of extremes over the last half millennium. Geophys Res Lett 32:15713. doi:10.1029/2005GL023424

Xoplaki E, Luterbacher J, González-Rouco JF (2006) Mediterranean summer temperature and winter precipitation, large-scale dynamics, trends. Il Nuovo Cimento C 29(1):45–54. doi:10.1393/ncc/i2005-10220-4