INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **34**: 49–60 (2014)
Published online 9 February 2013 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.3665

Observed trends and future projections for winter warm events in the Ebro basin, northeast Iberian Peninsula

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ABSTRACT: In this study we analyze the observed trends for the period 1950–2006 in a number of climate indices related to the occurrence of winter warm events in the Ebro basin, northeast Iberian Peninsula. Climatic simulations using 12 regional climate models (RCMs) from the ENSEMBLES database enable calculation of the multi-model means for the projected evolution of these climatic indices for the time periods 2021–2050 and 2051–2080. The results based on observations indicate a significant increase in occurrence of warm and very warm days and nights, melting events at 2000 m a.s.l. and the duration of warm spells across most of the study area. The number of warm spells comprising at least five consecutive warm days or nights also tends to increase, although the trend is not statistically significant for many of the observatories involved in the study. The RCMs project that the trends observed during the observation period will continue, and that the occurrence of warm day and night events and spells are very likely to increase during this century. In some cases the occurrence of warm events is projected to double during the period 2021–2050, and continue increasing for the period 2051–2080. For both the observed and projected periods, most of the indices show a greater increase in the occurrence of these events in the mountain areas of the basin (the Pyrenees and the Iberian mountains).

KEY WORDS winter warm events; climatic indices; trends; regional climate models; Ebro basin; Iberian Peninsula

Received 27 March 2012; Revised 12 November 2012; Accepted 11 January 2013

1. Introduction

It is widely recognized that the global temperature has increased in recent decades, and this trend is expected to accelerate in the future as a consequence of increasing greenhouse gas emissions (Hansen *et al.*, 2010). The focus of concern has increasingly been on changes in temperature extremes and their associated impacts, which influence many aspects of human health, the water cycle and ecosystems (Jungo and Beniston, 2001; Beniston, 2005; García-Herrera *et al.*, 2005; El Kenawy *et al.*, 2011).

Observed temperature changes in the past and the projections for coming decades are subject to marked spatial and seasonal variability (El Kenawy *et al.*, 2011). Spatial variability in the magnitude of warming rates is typically associated with the regional influences of atmospheric circulation, the local effects caused by the topography and the sea surface temperature over particular territories(Black and Sutton, 2007; Fernández-Montes and Rodrigo, in press). These can cause major differences in the significance and even the sign of trends in climatic variables at observatories located very short distances apart (dos Santos *et al.*, 2011; El Kenawy *et al.*, 2011; Vincent *et al.*, 2011). The impacts of temperature change on natural and socioeconomic systems will vary substantially, depending on which seasons are most affected by temperature change, and how the change impacts on the maximum and minimum temperatures (Beniston *et al.*, 2007). Recently there has been increasing interest in investigating changes in temperature extremes, driven particularly by the high spatial and temporal variability of extreme events and the wide-ranging impacts they have in particular geographical areas and seasons (Bonsal *et al.*, 2001; Frich *et al.*, 2002; Moberg and Jones, 2005; Alexander *et al.*, 2006; Moberg *et al.*, 2006; Brown *et al.*, 2008; El Kenawy *et al.*, 2011).

In this study we analyzed the observed trends and projections for coming decades in a set of indices related to the occurrence of winter warm events over the Ebro basin, northeast Iberian Peninsula. Although there are reports of extreme temperature events in the Mediterranean region in general (Della-Marta *et al.*, 2007; Kjellström *et al.*, 2010; Efthymiadis *et al.*, 2011) and the Iberian Peninsula in particular (Brunet *et al.*, 2007; Rodríguez-Puebla *et al.*, 2010; El Kenawy *et al.*, 2011; Fernández-Montes and Rodrigo, in press), this is the first study to focus exclusively on the magnitude and

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persistence of warm events in the Ebro basin during winter (DJFM). Although summer heat waves are normally perceived as being the major negative consequence of climate warming, shifts in the occurrence of warm winter events can have marked consequences for environmental and socioeconomic systems, especially those in regions where snow has a major influence on the economy, ecology and water availability (Beniston, 2005). Thus, relatively mild periods during winter have been shown to cause floods, result in poor skiing conditions and disrupt crop production (Shabbar and Bonsal, 2003; Beniston *et al.*, 2007).

In the Ebro basin, large areas are covered by a winter snow cover (López-Moreno *et al.*, 2007). Winter snow accumulation controls more than 40% of the spring runoff, and determines the capability to fill the Pyrenean reservoirs which supply water for large irrigation areas in the dry Ebro valley (López-Moreno and García-Ruiz, 2004; García-Ruiz *et al.*, 2011). Moreover, ski tourism is currently the main economic activity of the Pyrenees (Lasanta *et al.*, 2007), although snow conditions are highly variable and there are years when the opening of ski resorts is only partial and dependent of snow making devices. Thus, an increase in the frequency and magnitude of winter warm events could have particular importance for the hydrology and economy of the region.

The Ebro basin has a dense network of meteorological stations (observatories). This is necessary to encompass the climatic complexity of the study area (El Kenawy *et al.*, in press), which includes the entire Atlantic–Mediterranean transition and marked gradients in elevation and continentality (López-Moreno *et al.*, 2008b). Consequently, the study area provides a unique opportunity to analyse spatial variability in temperature extremes from observations. Moreover, regional climate simulations allow assessing potential changes in the characteristics of weather and climate extremes at relatively detailed spatial scales (López-Moreno *et al.*, 2008b). The simulation of temperature using 12 regional climate models (RCMs) from the ENSEMBLES dataset enabled assessment of how warm winter events might evolve in the study area during the time periods 2021–2050 and 2051–2080. The possibility to relate observed climate to projections for the future permits to evaluate the feasibility of RCMs to reproduce observed climate in the study region. Moreover, the available data set is useful to assess whether recent warming is consistent with climate change projections in the near future, as it has been previously considered for land areas of Europe (Kjellström *et al.*, 2010), the Mediterranean region and more specifically for Portugal (Ramos *et al.*, 2011).

2. Study area

The Ebro basin study area comprises approximately 83 000 km^2 (Figure 1). In the centre is the Ebro valley, a central depression <400 m a.s.l. in altitude, through which the Ebro River runs. The depression is surrounded by mountain ranges including the Cantabrian Range and the Pyrenees to the north (maximum altitudes >2000 and 3000 m a.s.l., respectively), the Iberian mountains to the south (maximum altitude 2000–2300 m a.s.l.) and the Catalan Coastal Range to the east along the Mediterranean coast (maximum altitude 1000–1200 m a.s.l.). The complex topography and the contrasting influences of the Mediterranean Sea and the Atlantic Ocean lead

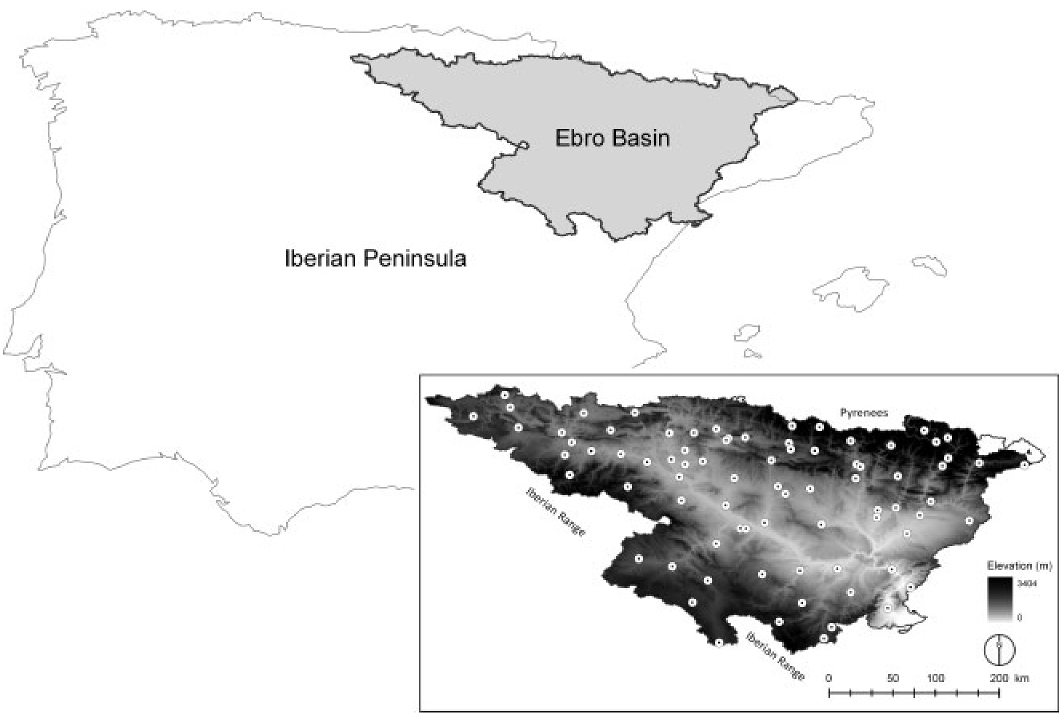

Figure 1. Study area. Black points indicate the location of the meteorological stations involved in the study.

to marked spatial variations in weather extremes, even over very short distances. While continental conditions dominate the Ebro depression, the climatic conditions shift progressively from those influenced by the Atlantic Ocean in the west toward Mediterranean conditions in the east. The spatial distribution of mean annual temperature ranges from 0.8 to 16.2 °C, which is largely explained by the abrupt altitudinal gradient and the transitions from oceanic to continental conditions in the central part of the basin (López-Moreno *et al.*, 2011).

3. Data and methods

3.1. Database of observed temperature and selected temperature indices

Changes in observed winter warm events were analyzed using the database of maximum and minimum temperatures developed for the northeastern Iberian Peninsula (see El Kenawy *et al.*, , for a complete description of the methodology). Data from a large number of observatories (1583) were processed to create a new quality controlled and homogeneity-tested dataset. Quality control focused on detecting typographical errors and resolving problems of consistency among nearby stations (Stepanek *et al.*, 2009). Inhomogeneous series were detected and eliminated using three tests: the Standard Homogeneity test (Alexanderson, 1986), the Easterling and Peterson two-phase regression technique (Easterling and Peterson, 1995) and the Vincent method (Vincent, 1998). When a statistically significant breakpoint was identified at the 95% confidence level, a monthly correction was applied and then interpolated to daily data (Sheng and Zwiers, 1998). We selected 60 observatories having complete records for the period December 1959 to March 2006. This was important because analyses of extreme events are often sensitive to the occurrence of missing records in the time series. In addition, this 47-year period was selected as it provided the best balance between the length of the series and the availability of an adequate number of observatories having an appropriate spatial distribution. The dataset used was tested for the presence of serial correlations, cross-correlations and exceedance effects at the boundaries of the series, which may have affected the calculation of extreme events reported in previous studies (El Kenawy *et al.*, 2011). Figure 1 shows the spatial distribution of the 60 observatories within the Ebro basin.

Based on the daily series from the selected observatories, we calculated 11 indices related to the annual occurrence and persistence of winter warm events during the study period. We considered the months from December to March (DJFM), as this is the period when snow accumulation dominates melting in these mountain areas (López-Moreno *et al.*, 2007). As our annual winter period (from December to March) spanned two calendar years, our analysis included the winters from 1959 to 2005.

Table 1 provides a detailed description of the 11 calculated indices. The first four indices are based on annual exceedances of the long-term (1959–2005) 90th and 99th percentiles in maximum and minimum daily temperatures. Thus, it was possible to quantify the occurrence of warm and very warm days and nights. To assess the persistence of warm events, we counted the number of events and their duration for warm periods of at least five consecutive warm days and nights (>90th percentile of the daily maximum and minimum temperatures, respectively). To assess the occurrence of melt days (MDs) in mountain areas, we used daily linear regressions between temperature and the altitude of each observatory and computed the regional maximum and minimum daily temperature at 2000 m a.s.l. At this elevation, continuous snow cover is expected in the Pyrenees even during snow poor years (López-Moreno *et al.*, 2007). From these estimates we counted the number of melt nights (MN, $T_{\min} > 0$ °C) at this elevation, and the number of days when the maximum temperature exceeded 0 °C and 10 °C, which were defined as MDs and intense melt days (IMDs), respectively.

The linear trend in the derived temperature indices for each observatory was obtained using the ordinary least squares (OLS) regression between the series of years and the various temperature indices. From the linear models of each index, we calculated the corresponding values for the first (1959) and last (2005) years of the base period, which provided the magnitude of the observed change during the study period. The significance of the trends was assessed using the Spearman's rank correlation test at the 95% significance level (p value < 0.05). The use of

Table 1. Climate indices used in the study to characterize extreme temperature events.

Abbreviation	Name	Description
WD	Warm days	Days with maximum temperature higher than the 90th percentile
VWD	Very warm days	Days with maximum temperature higher than the 99th percentile
WN	Warm nights	Days with minimum temperature higher than the 90th percentile
VWN	Very warm nights	Days with minimum temperature higher than the 99th percentile
NSD	Number of spells with warm days	Number of spells with at least five consecutive warm days
NSN	Number of spells with warm nights	Number of spells with at least five consecutive warm nights
DSD	Duration of spells with warm days	Mean duration of spells with at least five consecutive warm days
DSN	Duration of spells with warm nights	Mean duration of spells with at least five consecutive warm nights
MN	Melting nights	Minimum temperature at 2000 m a.s.l. higher than 0 °C
MD	Melting days	Maximum temperature at 2000 m a.s.l. higher than 0 °C
IMD	Intense melting days	Maximum temperature at 2000 m a.s.l. higher than 10 °C

Table 2. RCMs from the ENSEMBLES database used in this study.

Institute	Driving GCM	Model	Acronym
C4I	HadCM3Q16	RCA3	C4IRCA3
CNRM	ARPEGE	Aladin	CNRM-RM4.5
DMI	ECHAM5-r3	DMI-HIRHAM5	DMI-HIRHAM5
ETHZ	HadCM3Q0	CLM	ETHZ-CLM
GKSS	IPSL	CLM	GKSS-CCLM4.8
HC	HadCM3Q0	HadCM3Q0	METO-HC_HadRM3Q0
ICTP	ECHAM5-r3	RegCM	ICTP-REGCM3
KNMI	ECHAM5-r3	RACMO	KNMI-RACMO2
METNO	HadCM3Q0	HIRHAM	METNOHIRHAM
MPI	ECHAM5-r3	REMO	MPI-M-REMO
SMHI	HadCM3Q3	RCA	SMHIRCA
VMGO	HadCM3Q0	RRCM	VMGO-RRCM

a non-parametric test for this purpose provides an advantage over linear procedures, as it does not assume a Gaussian distribution of the data time series, and is not affected by the presence of outliers (Moberg and Jones, 2005).

3.2. The use of RCMs for the prediction of extreme temperature events in coming decades

Temperatures simulated by the RCMs for a control period (1961–1990) and two future time periods (2021–2050 and 2051–2080) were obtained from the ENSEMBLES project database (http://www.ensembles-eu.org/, Hewitt and Griggs, 2004). This comprises a number of transient simulations of climate from 1950 to 2100 at high spatial resolution (25 km^2 grid size, approximately 0.2 °) for the A1B scenario of moderate greenhouse gases emissions (Nakicenovic *et al.*, 1998). Table 2 lists the 12 RCMs used in this study and their driving global circulation models (GCMs).

From the daily maximum and minimum temperatures simulated by each RCM, we calculated the same 11 temperature indices that were analyzed using station data for the 1961–1990 control period. The magnitudes of the 90th and 99th percentiles of maximum and minimum temperature in the control period were used as thresholds to calculate the number of exceedances during the 2021–2050 and 2051–2080 time periods. The number of MDs and nights at sites at altitudes >2000 m a.s.l. was also obtained for the two periods.

To assess the reliability of the RCMs, we made a direct comparison between observed and simulated warm events during the 1961–1990 control period. Thus, the magnitude of the 90th and 99th percentiles for T_{max} and T_{min}, and the occurrence and duration of warm spells and melt events simulated by the RCMs for the control period (multi-model mean) were extracted for those grid points where an observatory was located, and compared with the observed data for the same period. The mean simulated and observed values of each index for the entire basin were compared to assess whether the models accurately simulated the magnitude of the observed variables. The coefficient of correlation between the 60 observatories and their corresponding simulated grids facilitated assessment of the ability of the RCMs to reproduce spatial climate variability in the Ebro basin.

4. Results

4.1. Observed changes in winter warm events

Figure 2 shows the observed changes in the occurrence and persistence of winter warm and very warm days and nights in the study area for the period 1959–2006. The duration and frequency of warm spells lasting at least five consecutive days are shown in Figure 3. Table 3 summarizes the observed trends for the number of stations classified according to the sign (i.e. positive or negative) and significance of the Spearman's rank test (significance level set at $p < 0.05$).

Our results for the computed indices suggested a major trend of increasing occurrence of winter warm events in the Ebro basin. There was a positive evolution in the annual occurrence of warm days (WDs) at the majority of cases (statistically significant for 92% of observatories). Figure 2 shows that the annual number of WDs increased from 3–8 days per winter at the beginning of the study period to 14–22 at the end of the period, although there were considerable spatial differences across the basin. Thus, the increase in the number of WDs in the Ebro basin varied between 6 and 18 days per winter. There was no clear spatial pattern in the magnitude of change across the study area, although positive differences dominate across the entire Ebro basin.

The occurrence of very warm days (VWDs) increased at all observatories with the exception of one observatory, where the trend was negative but not statistically significant. Figure 2 shows that the number of VWDs per winter occurred in the beginning of the study period ranged from 0.5 to 2, but ranged from 3 to 5 days at the end of the study period. The largest increase occurred in the northern and eastern parts of the Ebro basin. At 57% of the observatories the positive trend was statistically significant ($p < 0.05$).

Only at a few observatories a decrease in the occurrence of warm or very warm nights (WN or VWN) was observed, with the majority showing a statistically

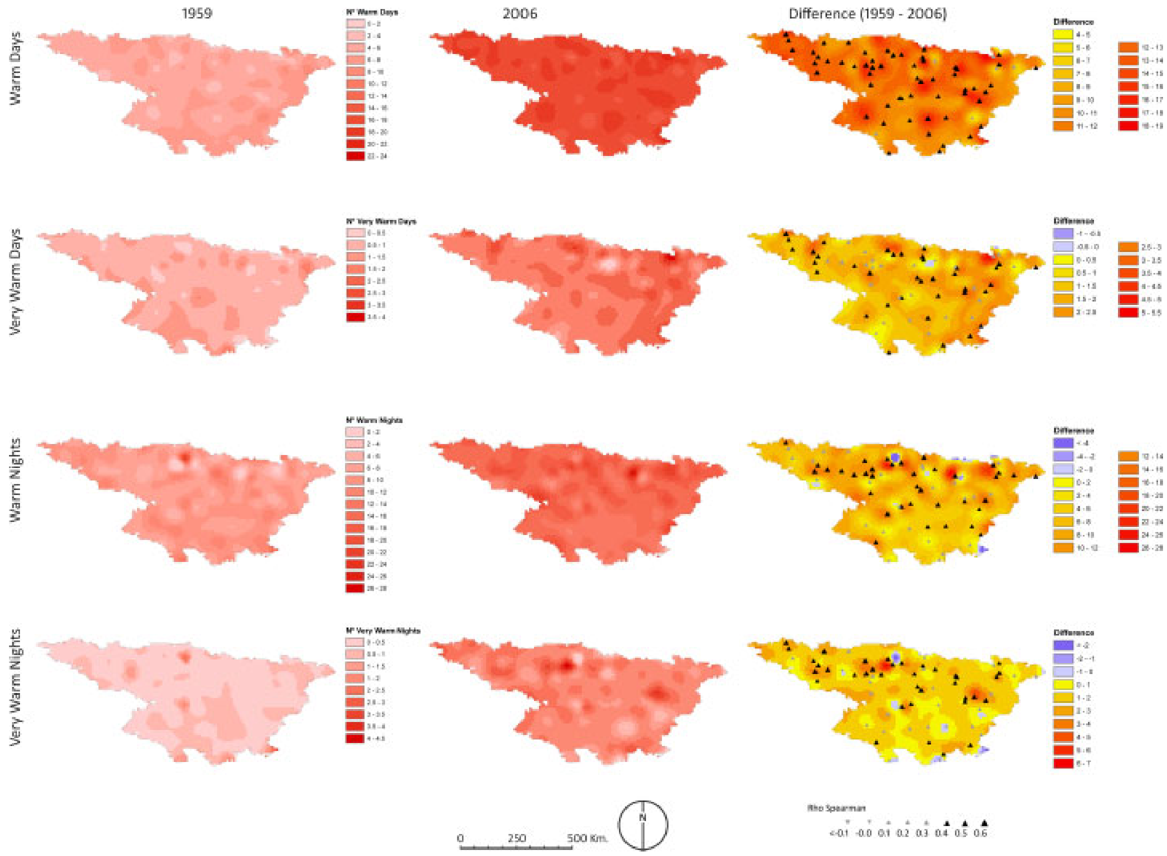

Figure 2. Number of warm and very warm days and nights per winter estimated for 1959 and 2006 using linear regression. The panels on the right indicate the magnitude of change and the statistical significance (black triangles = statistically significant; grey triangles = non-significant), based on the Spearman's rank test. Interpolation was done after the trend analyses in each observatory.

significant increase, 55% and 60%, respectively. Figure 2 shows that the greatest increase in the occurrence of warm and very warm nights occurred in the northernmost parts of the basin, which is an area where a very low occurrence of these types of events characterized the beginning of the study period. Thus, the number of warm (very warm) nights per winter at the beginning of the study period ranged from 2 to 14 (0.5 to 3), but ranged from 15 to 25 (1 to 4.5) nights at the end of the study period.

The number of warm days and nights involving at least five consecutive days increased, but in most cases the increase was not statistically significant. Thus, there were only 8% and 20% observatories with statistically significant increases in the number of spells for maximum and minimum temperature, respectively. In 35% and 10% of the cases, respectively, the number of spells decreased but in any case the change was statistically significant. The duration of the spells (NSD and NSN) increased in all cases, and was statistically significant at most of the observatories (78% and 62% for the maximum and minimum temperatures, respectively). No spatial pattern in the occurrence and duration of day and night warm spells (DSD and DSN) was evident among the observed changes (Figure 3).

Figure 4 shows that there was a marked and statistically significant increase in the number of melt events at altitudes >2000 m a.s.l. during recent decades. The increase was particularly evident in the number of MN and IMDs. Thus, the linear regressions indicated that between 1959 and 2005 the number of MDs increased from 72.2 to 82.5, which was a smaller relative increase than that detected for the number of IMD (0.9–14.6 days) and MN (6.1–13.6 days).

4.2. RCM simulations for the twenty-first century

Figure 5 shows a comparison of the observed and simulated occurrences of warm and very warm days and nights for the control period (1961–1990), and the frequency and duration of warm spells. Overall, the RCMs adequately reproduced the occurrences of winter warm events during the control period, although differences were observed among the various indices. In general, the RCMs accurately simulated the spatial distribution of the 90th and 99th percentiles of maximum temperature for the period 1961–1990. Data from most of the observatories showed a high degree of consistency with the simulated values; the relatively low coefficients of determination ($r^2 = 0.24$ and 0.21, respectively) can be explained by the presence of a small number of observatories with large deviations from the fitted line.

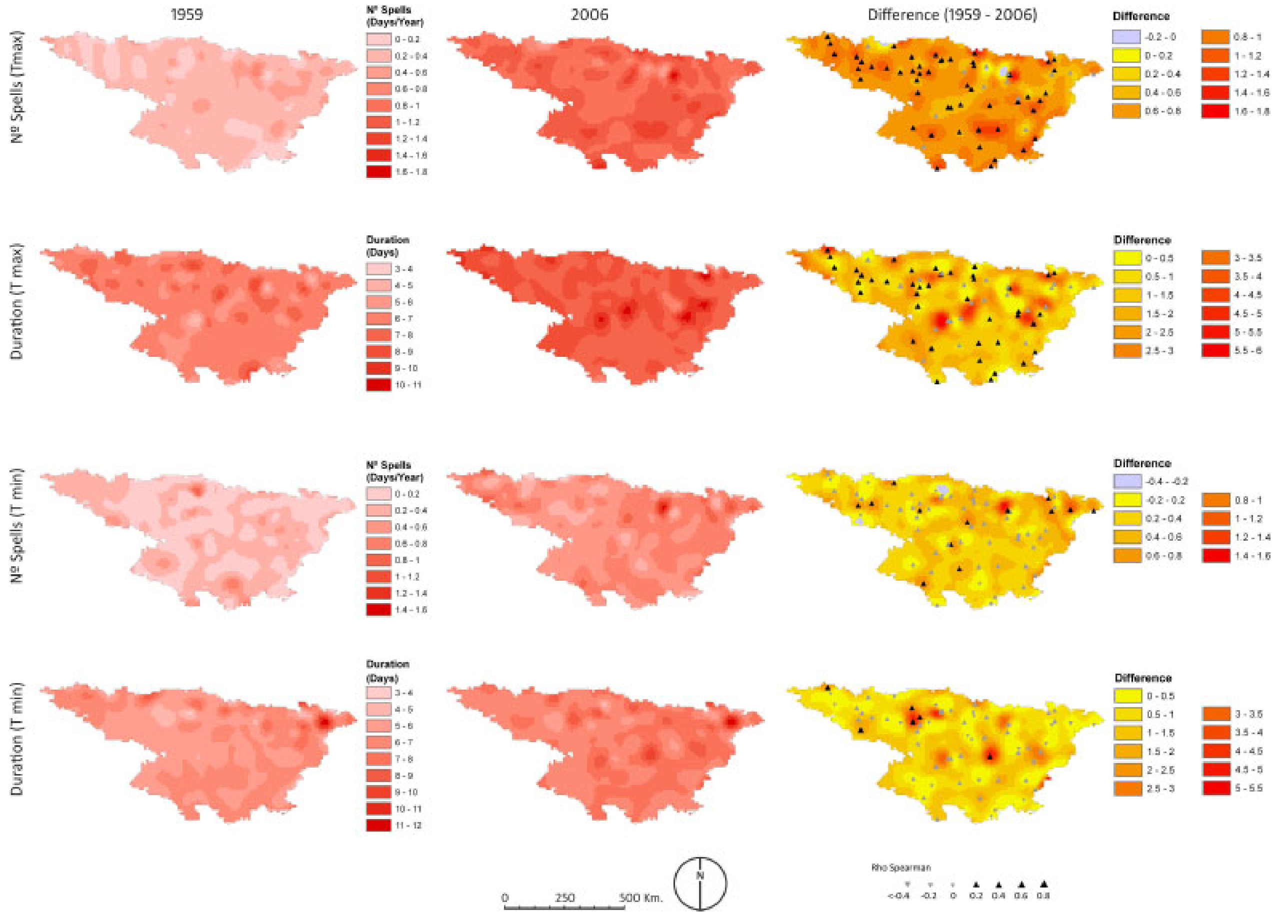

Figure 3. Number per winter and duration of spells of at least five consecutive warm days and nights, estimated for 1959 and 2006 using linear regression. The panels on the right indicate the magnitude of change and the statistical significance (black triangles = statistically significant; grey triangles = nonsignificant), based on the Spearman's rank test. Interpolation was done after the trend analyses in each observatory.

Table 3. Number of stations with different sign and significance of the Spearman's rank test for the various climatic indices.

	WD	VWD	WN	VWN	NSD	DSD	NSN	DSN
Positive ($\alpha < 0.05$)	55 (92%)	34 (57%)	33 (55%)	36 (60%)	5 (8%)	47 (78%)	12 (20%)	37 (62%)
Positive ($\alpha > 0.05$)	5 (8%)	25 (42%)	23 (38%)	21 (35%)	34 (56%)	13 (22%)	42 (70%)	23 (38%)
Negative ($\alpha < 0.05$)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0(0%)	0 (0%)	0 (0%)	0 (0%)
Negative ($\alpha > 0.05$)	0 (0%)	1 (1%)	4 (7%)	3 (5%)	21 (35%)	0 (0%)	6 (10%)	0 (0%)

Numbers between brackets indicate the percentage calculated from the overall number of stations (60).

However, the RCMs underestimated the daily maximum temperature by 1–2 °C at the majority of observatories. The high percentiles of minimum temperature were better simulated than was maximum temperature with respect to both the magnitude across the entire basin and its spatial distribution, as evidenced by the error estimates and the coefficients of determination. The mean duration of day and night warm spells for the whole study area was accurately simulated by the RCMs for the entire basin, as indicated by the agreement between the mean observed and simulated values, and the low mean bias error (MBE) and mean absolute error (MAE) values. However, the coefficients of determination were low in both cases, suggesting that the RCMs were unable to accurately reproduce the spatial variability of this variable. As evident in the plots, this can be explained by the low variance of the simulated values compared with the observed values. The accuracy in reproducing the number of day and night warm spells was intermediate, with coefficients of determination of approximately 0.25 and a slight tendency to overestimate the observed number of spells (MAE = 3.8 and 2.9 for day and night warm spells, respectively).

A winter mean of 75.6 melting days (MDs) and 5.2 intense melting days (IMDs) was observed during the period 1961–1990, but the RCMs simulations underestimated the winter occurrences of these events (means of 57.7 MD and 2.9 IMD). The observed and simulated melting nights (MNs) were 8.5 and 10.7, respectively, suggesting better agreement for this index.

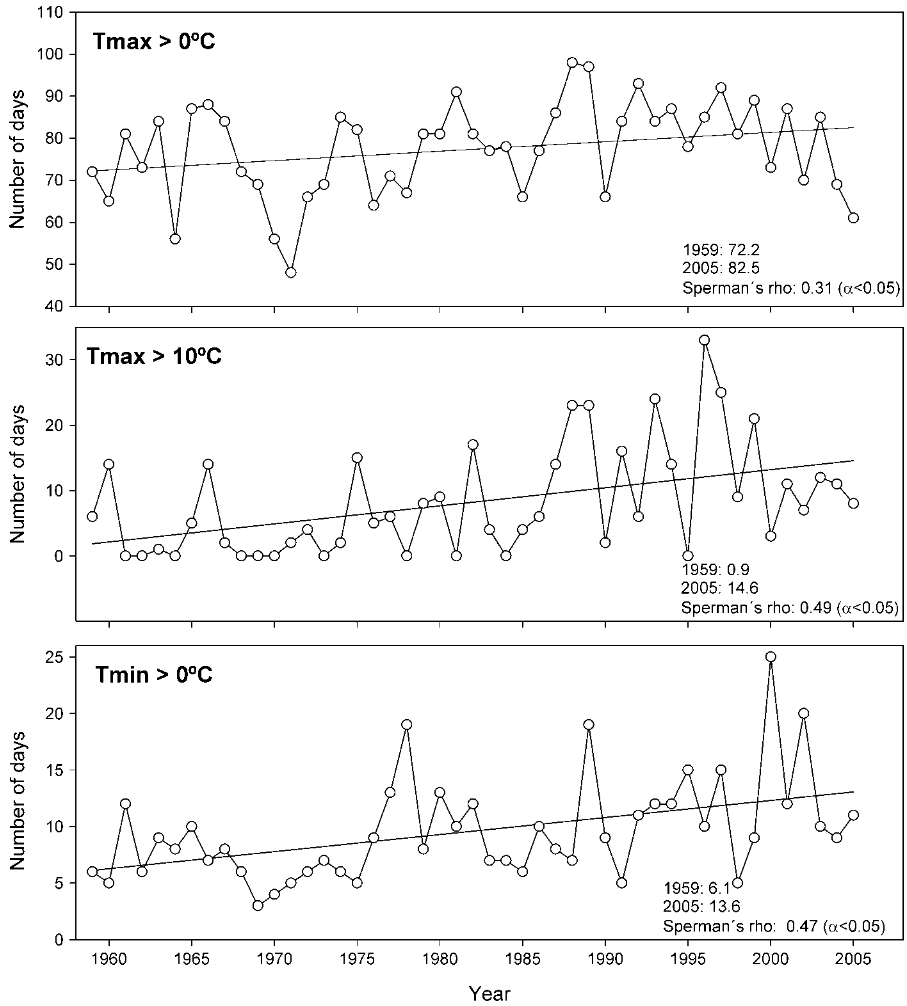

Figure 4. Evolution of MDs (T_{max} > 0 °C), very IMDs (T_{max} > 10 °C) and MNs (T_{min} > 0 °C) at 2000 m a.s.l. These indices were derived from a regional series for all observatories at altitudes >2000 m a.s.l.

Figure 6 shows the mean number of winter warm and very warm days and nights simulated for the time periods 2021–2050 and 2051–2080 by the 12 RCMs. The results show that the RCMs predicted a marked increase in the occurrence of warm and very warm days and nights in the Ebro basin for the twenty-first century. Thus, Figure 6 shows that for the 2021–2050 time period the multi-model mean was >20 events for the entire basin, whereas the corresponding number of events for the control period was 12.1 (i.e. 10% of the 121 days that comprise the period from December to March). In some areas of the Pyrenees (north), the Iberian system (southwest) and some sectors in the east of the basin, the number of events was expected to reach 28. For the time period 2051–2080 the predicted number of warm events was >28 in all cases and exceeded 38 in the Pyrenees.

Similar results were obtained for the occurrence of very warm events. Thus, the multi-model mean was 2–3 events for the basin, while the number of events corresponding to the control period was 1.2. A greater increase in winter warm events was predicted to occur in the Pyrenees, some sectors of the Iberian mountains and the most eastern part of the basin. A similar spatial pattern was predicted for the 2051–2080 time period, but the magnitude of the increase was almost double that in the earlier time period. Thus, the mean predicted occurrence was six VWDs per year, but was ten per year in the most affected areas in the Pyrenees and the Iberian mountains.

The change in the predicted occurrence of warm and very warm nights was very similar to that for warm and very warm days, in both magnitude and spatial distribution. The mountain areas showed the greatest increase in the predicted occurrence of warm and very warm nights in the basin.

Figure 7 shows the mean change (multi-model estimation) in the number and duration of events of at least five consecutive warm days and nights projected for the time periods 2021–2050 and 2051–2080, relative to the control period. For the number of spells of WDs, the RCMs simulated a mean of 0.4–0.7 events per winter during the control period. These spells were predicted to occur more frequently in the Iberian mountains and the north-eastern part of the Ebro basin (including the Pyrenees) and, depending on the sector of the basin, to increase by 0.6–1.2 and 0.9–1.95 events per year for the time

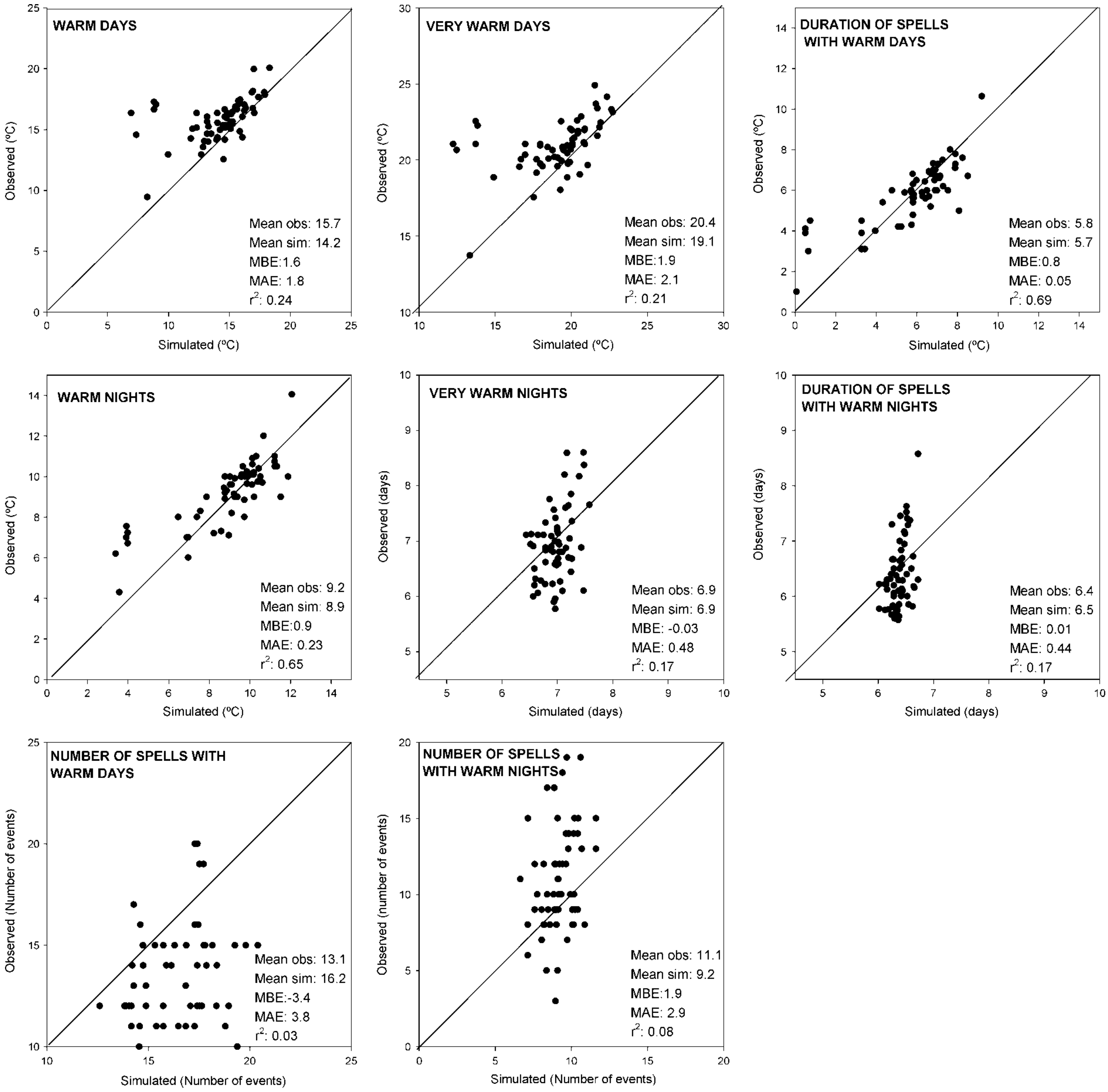

Figure 5. Observed versus simulated (by RCMs) occurrence of warm and very warm days and nights, and the frequency and duration of warm spells during the control period (1961–1990).

periods 2021–2050 and 2051–2080, respectively. Thus, the Pyrenees and the Iberian mountains are the sectors of the Ebro basin where the increase is projected to be more extreme. The simulated duration of warm spells lasting at least 5 days ranged from 6.4 to 7.6 days for the control period. The longest duration was found in the northeastern part of the Ebro basin (including the Pyrenees) and the Iberian mountains. The RCM simulations indicated that the duration of warm spells will increase by 0–0.9 days for the 2021–2050 time period, and 0.9–2.7 days for the 2051–2080 time period. In contrast to the observed frequency of spells of WDs which are expected to increase more in the mountain areas, their duration is expected to increase more in the Ebro Depression, especially in those areas close to the Mediterranean coast.

The spatial pattern of the annual number of spells of warm nights lasting more than 5 days was very similar to that observed for spells of WDs, although the occurrence was lower (0.25–0.4 days year^{-1}). The RCMs also simulated an increase in spells of warm nights for the time periods 2021–2050 (0.5–0.9) and 2051–2080 (0.6–1.95). The simulated duration of spells of warm nights for the control period ranged from 6 to 7 days within the study area. The duration of such spells was projected to increase markedly in coming decades, particularly in the northeastern part of the Ebro basin, where an increase of up to 0.9 days was predicted for the 2021–2050 time period, and an increase of >2 days was predicted for the 2051–2080 time period.

Most of the RCM also projected a marked increase in melt events. Table 4 shows that the mean number of predicted MDs ($T_{max} > 0$ °C) per winter during the control period was 57.6. These events were projected to increase in frequency to 75.5 and 85.3 days winter^{-1}

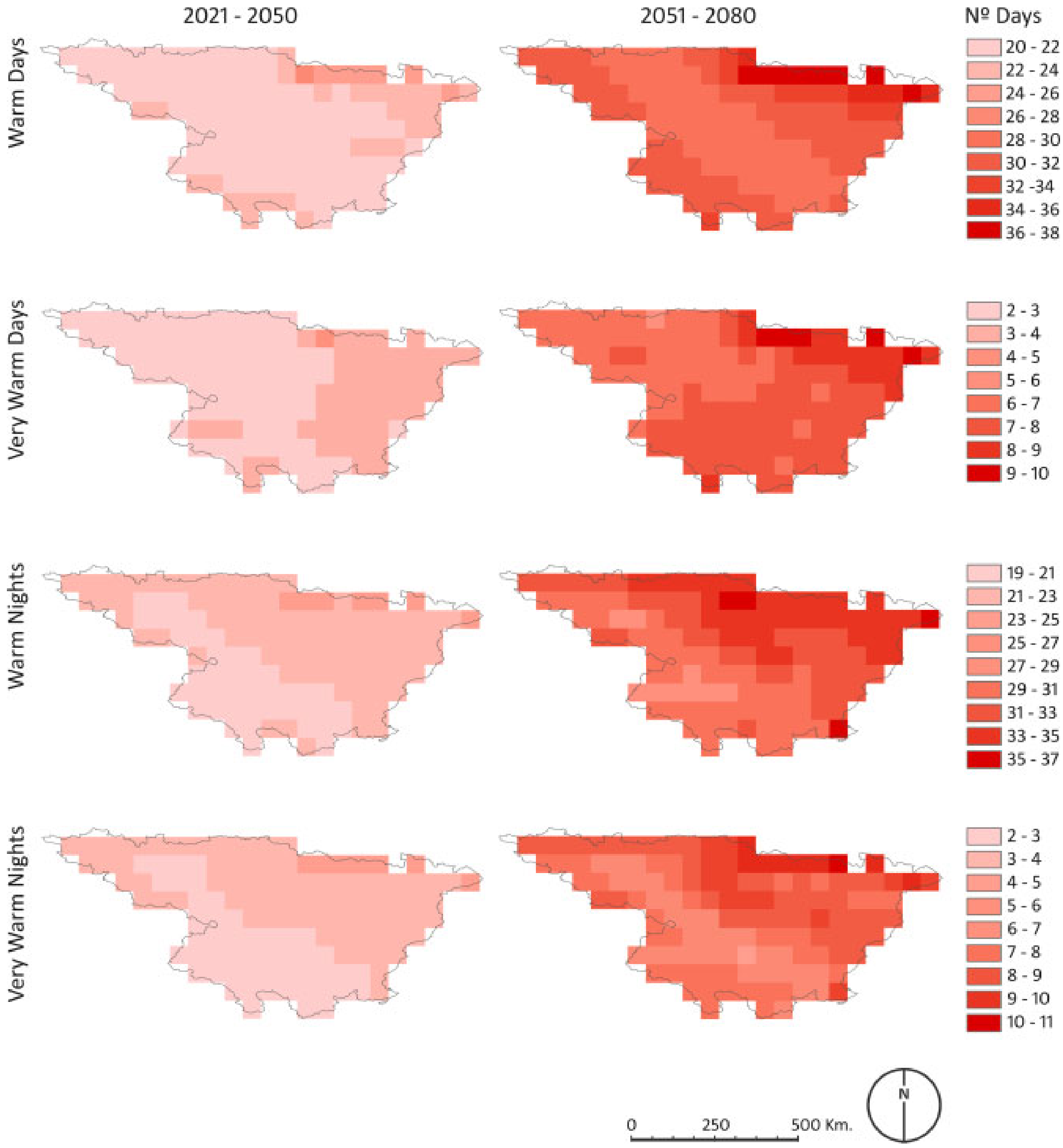

Figure 6. Mean number of winter warm and very warm days and nights for the time periods 2021–2050 and 2051–2080 simulated by the 12 RCMs used in this study. The number of events corresponding to the control period was 12.1 and 1.21 for warm and very warm events (the 10% and 1%) of the 121 days comprising the period from December to March.

for the 2021–2050 and 2051–2080 time periods, respectively. Intense snow MD events ($T_{max} > 10$ °C) were predicted to increase from a multi-model mean of three events in the control period to 6.2 and 9.5 events for the 2021–2050 and 2051–2080 time periods, respectively. Night melt events ($T_{min} > 0$ °C) were also predicted to increase from a mean of 10.7 events per winter to 20.5 and 33.1 for the 2021–2050 and 2051–2080 time periods, respectively.

5. Discussion and conclusions

Our results provide clear evidence of an increase in the occurrence of warm events in the study area during the 1961–2006 period. The occurrence of WDs increased most, and the trend was statistically significant at 92% of observatories. Most of the observatories also showed a trend of increase in VWDs, warm and very warm nights (VWD, WN and VWN), but the percentage of observatories for which these trends were statistically significant was less (55–60%). While the magnitude of change in WD did not show a particular spatial pattern, the increases in VWD, WN and VWN were greater in mountainous areas in the north and east of the basin. The number of spells with at least five consecutive WD or WN generally increased, but in most cases the increase was not statistically significant, and several observatories showed negative but non-significant trends. However, the duration of the spells tended to be significantly longer at the majority of observatories (78% and 62% for spells of WD and WN, respectively). The trend of increase in winter temperature extremes explains why the frequency of MDs, very IMDs and MNs has increased during

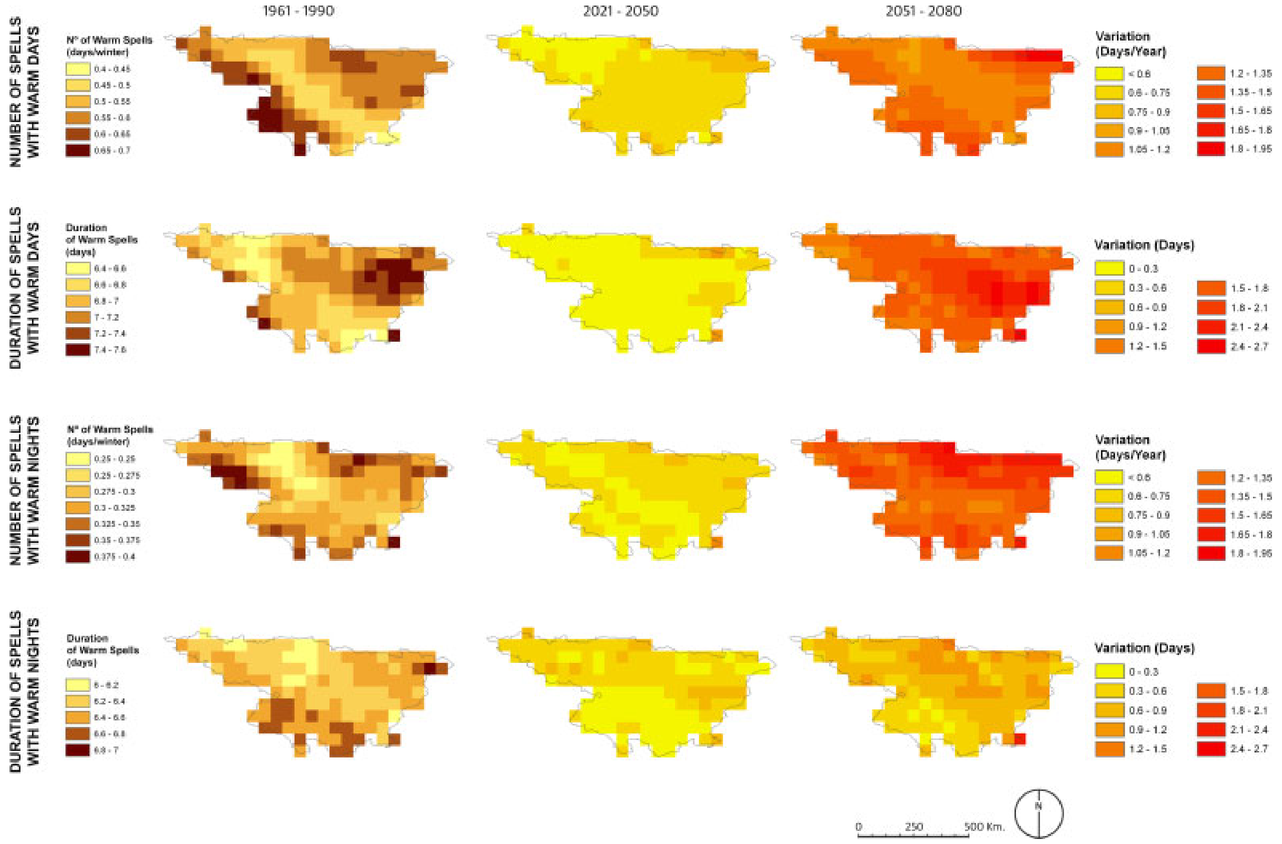

Figure 7. Mean change in the number and duration of events of five consecutive warm days and nights projected for the time periods 2021–2050 and 2051–2080, relative to the control period.

Table 4. Mean number of simulated MDs, IMDs and MNs per winter during the control period (1961–1990) and the 2021–2051 and 2051–2080 time slices.

	1961–1990	2021–2051	2051–2080
$T_{min} > 0\ ^{\circ}C$	10.6	20.5	33.1
$T_{max} > 0\ ^{\circ}C$	57.6	75.5	85.2
$T_{max} > 10\ ^{\circ}C$	3.0	6.2	9.5

recent decades. Despite some evident biases, the RCMs relatively accurately reproduced the observed occurrence of winter warm events in the region; the projections of the climate models were consistent with the observed trends. Increases in the 11 indices considered in this study are expected to continue for the 2021–2050 and 2051–2080 time periods.

Most previous studies that have analyzed recent trends in extreme temperatures at various spatial scales have also indicated a warming trend of temperature extremes. For example, Guirguis *et al.* (2011) detected a generalized increase in recent winter temperature extremes that could not be entirely explained by the evolution of the North Atlantic Oscillation (NAO) or other major climate modes. According to Moberg *et al.* (2006), winter temperature extremes in Europe increased over the period 1900–2000, but with marked regional differences. A number of indicators have suggested an increase in winter temperature extremes in the western Mediterranean (Efthymiadis *et al.*, 2011; Hertig *et al.*, 2010) and the Iberian Peninsula in particular (Brunet *et al.*, 2007; Rodríguez-Puebla *et al.*, 2010; El Kenawy *et al.*, 2011). These trends have usually been related to the evolution of the NAO and the East Atlantic (EA) pattern (Fernández-Montes and Rodrigo, in press).

The statistically significant increase in the annual number of melt days and melt nights (MD, $T_{max} > 0\ ^{\circ}C$; MN, $T_{min} > 0\ ^{\circ}C$) and the annual number of intense melt days (IMD, $T_{max} > 10\ ^{\circ}C$) found in this study explain the change in snow accumulation (López-Moreno, 2005) and in the river regimes of mountain headwaters in the Ebro basin, where winter runoff has increased in importance relative to spring flows (López-Moreno and García-Ruiz, 2004). This trend has been also reported in many mountain areas of the world (De Jong *et al.*, 2009), and more specifically in the Mediterranean region (García-Ruiz *et al.*, 2011).

The application of climate simulations to the observational control period (1961–1990) showed that in general the RCMs relatively accurately reproduced the observed magnitudes and spatial distributions indicated by the indices used, especially for extremes in minimum temperature. This result agree with those found by Kjellström *et al.* (2010), who indicated that most of ENSEMBLES simulations reproduced adequately winter minimum temperature in Southern Europe. However, discrepancies were seen between observed and simulated indices, which in some cases were significant. This was the case in the systematic 1–2 °C underestimation of the 90th and 99th percentiles of daily maximum temperature (T_{max}), and the poor ability of the RCMs to represent the spatial variability of the mean duration of day and night warm spells. Ramos *et al.* (2011) also found that RCMs were less able to simulate extreme maximum temperatures in Portugal relative to extreme minimum temperatures, which were well simulated.

The RCMs projected a marked increase in the occurrence of WD, VWD and VWN, which is consistent with the observed trends. Other studies have also reported consistency between observed trends and RCMs simulations with respect to temperature extremes, including the Mediterranean region (Barkhordarian *et al.*, 2011) and Portugal (Ramos *et al.*, 2011). Consistent with the stronger overall warming for the period 2051–2080, the predicted increase was greater for the 2051–2080 period than for the 2021–2050 period. The magnitude of the change projected for coming decades was almost the same for day and night temperatures.

As in the analysis of many of the observed variables for the 1959–2006 period, the simulation predicted more extreme changes in the mountain areas of the Ebro basin. A similar finding with respect to the mean winter maximum and minimum temperatures in the study region was reported by López-Moreno *et al.* (2008b). In these mountain areas the number of MN, MD and IMD was projected to double, and in some cases triple, relative to the control period. Projected temperature conditions will significantly impact on snowpack as a consequence of changes in snowfall/precipitation ratio and an earlier snowmelt. Moreover, the possibility to produce artificial snow in ski runs is expected to be severely reduced. These changes impact on the economic feasibility of ski resorts and threat the water supply for agriculture and domestic use (López-Moreno *et al.*, 2008a). An increase of winter runoff and a decrease of spring runoff could force to change the reservoirs' management strategies (López-Moreno and García-Ruiz, 2004), with an earlier filling that reduces the possibility to control floods (López-Moreno *et al.*, 2002). Such reduction is problematic because temperature increases may result in more frequent winter floods in rivers of the snow dominated headwaters (Beniston, 2005). Moreover, a higher frequency of warm events during winter may lead to earlier blooms and growth of trees and crops in the region (e.g. almonds and wheat), which could increase their vulnerability to the frost events that are likely to occur in the future, even under greenhouse climate conditions (Beniston, 2011). All these potential impacts are very important for the ecology and economy of the region. For this reason, results provided in this study should feed into the more detailed assessment of the different related fields, with specific simulations of the hydrology, snow energy balance, vegetation dynamics and crop productions under the temperature changes identified for the next decades.

Acknowledgments

We thank the Agencia Estatal de Meteorología for providing the temperature data used in this study. This work was supported by the research projects CGL2011-27574-CO2-02 and CGL2011-27536, financed by the Spanish Commission of Science and Technology and FEDER; and ACQWA (FP7-ENV-2007-1-212250), financed by the VII Framework Programme of the European Commission; Efecto de los escenarios de cambio climatico sobre la hidrología superficial y la gestión de embalses del PirineoAragonés, financed by Obra Social La Caixa and the Aragón Government and Influencia del cambioclimático en el turismo de nieve CTTP01/10, financed by the *Comunidad de Trabajo de los Pirineos*.

References

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein-Tank AMG, Haylock M, Vazquez-Aguirre JL. 2006. Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research D: Atmosphere* **111**(5): D05109.

Alexanderson H. 1986. A homogeneity test applied to precipitation data. *International Journal of Climatology* **6**: 661–675.

Barkhordarian A, Bhend J, vonStorch H. 2011. Consistency of observed near surface temperature trends with climate change projections over the Mediterranean region. *Climate Dynamics*. DOI: 10.1007/s00382-011-1060-y

Beniston M. 2005. Warm winter spells in the Swiss Alps: strong heat waves in a cold season? *Geophysical Research Letters* **32**: L01812.

Beniston M. 2011. Warm Winter spells in the Swiss Alps: strong heat waves in a cold season? A study focusing on climate observations at the Saentis high mountain site. *Geophysical Research Letters* **34**: L16710.

Beniston M, Stephenson DB, Christensen OB, Ferro CAT, Frei C, Goyette S, Halsnaes K, Holt T, Jylhä K, Koffi B, Palitikof J, Scöll R, Semmler T, Woth K. 2007. Future extreme events in European climate: an exploration of regional climate model projections. *Climatic Change* **81**: 71–95.

Black E, Sutton R. 2007. The influence of oceanic conditions on the hot European summer of 2003. *Climate Dynamics* **28**: 53–66.

Bonsal BR, Zhang X, Vincent LA, Hogg WD. 2001. Characteristics of daily and extreme temperatures over Canada. *Journal of Climate* **14**(9): 1959–1976.

Brown SJ, Caesar J, Ferro CAT. 2008. Global changes in extreme daily temperature since 1950. *Journal of Geophysical Research-Atmospheres* **113**: D05115. DOI: 10.1029/2006JD008091

Brunet M, Jones PD, Sigro J, Saladie O, Aguilar E, Moberg A. 2007. Temporal and spatial temperature variability and change over Spain during 1850–2005. *Journal of Geophysical Research* **112**: D12117. DOI: 10.1029/2006JD008249

De Jong C, Lowler D, Essery R. 2009. Mountain hydroclimatology and snow seasonality: Perspectives on climate impacts, snow seasonality and hydrological change in mountain environments. *Hydrological Processes* **23**: 955–961.

Della-Marta PM, Haylock MR, Lutterbacher J, Wanner H. 2007. Doubled length of western European summer heat waves since 1880. *Journal of Geophysical Research* **112**: D15103.

Easterling DR, Peterson TC. 1995. A new method for detecting undocumented discontinuities in climatological time series. *International Journal of Climatology* **15**: 369–377.

Efthymiadis D, Goodess CM, Jones PD. 2011. Trends in Mediterranean gridded temperature extremes and large-scale circulation influences. *Natural Hazards and Earth System Sciences* **11**: 2199–2214.

El Kenawy A, López-Moreno JI, Vicente-Serrano SM. 2011. Recent changes in daily temperature extremes in Northeastern Spain: 1961–2006. *Natural Hazards and Earth System* **11**: 1–21.

El Kenawy A, López-Moreno JI, Stepanek P, Vicente-Serrano S. in press. An assessment of the role of homogenization protocols in the performance of daily temperature series and trends: application to Northeastern Spain. *International Journal of Climatology*. DOI: 10.1002/JOC.3410

Fernández-Montes S, Rodrigo FS. in press. Trends in seasonal indices of daily temperature extremes in the Iberian Peninsula, 1929–2005. *International Journal of Climatology* . DOI: 10.1002/joc.3399

Frich P, Alexander LV, Della-Marta P, Gleason B, Haylock M, Klein-Tank AMG, Peterson T. 2002. Observed coherent changes in climatic extremes during the second half of the twentieth century. *Climate Research* **19**: 193–212.

García-Herrera R, Diaz J, Trigo RM, Hernández E. 2005. Extreme summer temperatures in Iberia: health impacts and associated synoptic conditions. *Annales Geophysicae* **23**: 239–251.

García-Ruiz JM, López-Moreno JI, Serrano-Vicente SM, Beguería S, Lasanta T. 2011. Mediterranean water resources in a global change scenario. *Earth-Science Reviews* **105**(3–4): 121–139.

Guirguis K, Gershunov A, Schwartz R, Bennett S. 2011. Recent warm and cold daily winter temperature extremes in the Northern Hemisphere. *Geophysical Research Letters* **38**: L17701.

Hansen J, Ruedy R, Sato M, Lo K. 2010. Global surface temperature change. *Reviews of Geophysics* **48**(4): RG 4004 DOI: 10.1029/2010RG000345.

Hertig E, Seubert S, Jacobeit J. 2010. Temperature extremes in the Mediterranean area: trends in the past and assessments for the future. *Natural Hazards and Earth System Sciences* **10**: 2039–2050.

Hewitt CD, Griggs DJ. 2004. Ensembles-based predictions of climate changes and their impacts. *Eos* **85**: 566.

Jungo P, Beniston M. 2001. Changes in the anomalies of extreme temperature anomalies in the 20th century at Swiss climatological stations located at different latitudes and altitudes. *Theoretical and Applied Climatology* **69**: 1–12.

Kjellström E, Boberg F, Castro M, Christensen JH, Nikulin G, Sánchez E. 2010. Daily and monthly temperature and precipitation statistics as performance indicators for regional climate models. *Climate Research* **44**(2–3): 135–150.

Lasanta T, Laguna M, Vicente-Serrano SM. 2007. Do tourism-based ski resorts contribute to the homogeneous development of the Mediterranean mountains? A case study in the central Spanish Pyrenees. *Tourism Management* **28**: 1326–1339.

López-Moreno JI. 2005. Recent variations of snowpack depth in the Central Spanish Pyrenees. *Arctic, Antartic, and Alpine Research* **37**(2): 253–260.

López-Moreno JI, García-Ruiz JM. 2004. Influence of snow accumulation and snowmelt on streamflow in the Central Spanish Pyrenees. *International Journal of Hydrological Sciences* **49**(5): 787–802.

López-Moreno JI, Beguería S, García-Ruiz JM. 2002. Influence of the Yesa reservoir on floods of the Aragón River, central Spanish Pyrenees. *Hydrology and Earth System Sciences* **6**(4): 753–762.

López-Moreno JI, Vicente-Serrano SM, Lanjeri S. 2007. Mapping of snowpack distribution over large areas using GIS and interpolation techniques. *Climate Research* **33**: 257–270.

López-Moreno JI, García-Ruiz JM, Beniston M. 2008a. Environmental Change and water management in the Pyrenees. Facts and future perspectives for Mediterranean mountains. *Global and Planetary Change* **66**(3–4): 300–312.

López-Moreno JI, Goyette S, Beniston M. 2008b. Climate change prediction over complex areas: spatial variability of uncertainties and expected changes over the Pyrenees from a set of regional climate models. *International Journal of Climatology* **28**(11): 1535–1550.

López-Moreno JI, Vicente-Serrano SM, Moran-Tejeda E, Zabalza J, Lorenzo-Lacruz J, García-Ruiz JM. 2011. Impact of climate evolution and land use changes on water yield in the Ebro basin. *Hydrology and Earth System Sciences* **15**: 311–322.

Moberg A, Jones PD. 2005. Trends in indices for extremes in daily temperature and precipitation in Central and Western Europe. *International Journal of Climatology* **25**: 1173–1188.

Moberg A, Jones PD, Lister D, Walther A, Brunet M, Jacobeit J, Alexander LV, Xoplaki E. 2006. Indices for daily temperature and precipitation extremes in Europe analyzed for the period 1901–2000. *Journal of Geophysical Research D: Atmosphere* **111**(22): D22106.

Nakicenovic N, Grübler A, McDonalds A. 1998. *Global Energy Perspectives*. Cambridge University Press: Cambridge; 299.

Ramos AM, Trigo RM, Santo FE. 2011. Evolution of extreme temperatures over Portugal: recent changes and future scenarios. *Climate Research* **48**: 177–192.

Rodríguez-Puebla C, Encinas AH, García-Casado LA, Nieto S. 2010. Trends in warm days and cold nights over the Iberian Peninsula: relationships to large-scale variables. *Climatic Change* **100**: 667–684.

dos Santos CAC, Neale CMU, Rao TVR, da Silva BB. 2011. Trends in indices for extremes in daily temperature and precipitation over Utah, USA. *International Journal of Climatology* **31**(12): 1813–1822.

Shabbar A, Bonsal B. 2003. An assessment of changes in winter cold and warm spells over Canada. *Natural Hazards* **29**: 173–188.

Sheng J, Zwiers F. 1998. An improved scheme for time dependent boundary conditions in atmospheric circulation models. *Climate Dynamics* **14**: 609–613.

Stepanek P, Zahradnı́éek P, Skalák P. 2009. Data quality control and homogenization of the air temperature and precipitation series in the Czech Republic in the period 1961–2007. *Advances in Science and Research* **3**: 23–26.

Vincent LA. 1998. A technique for the identification of inhomogeneities in Canadian temperature series. *Journal of Climate* **11**: 1094–1104.

Vincent LA, Aguilar E, Saindou M, Hassane AF, Jumaux G, Roy D, Booneeady P, Montfraix B. 2011. Observed trends in indices of daily and extreme temperature and precipitation for the countries of the western Indian Ocean, 1961–2008. *Journal of Geophysical Research D: Atmosphere* **116**(10): D10108.