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Summer heat waves over western Europe 1880–2003, their relationship to large-scale forcings and predictability

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Abstract We investigate the large-scale forcing and teleconnections between atmospheric circulation (sea level pressure, SLP), sea surface temperatures (SSTs), precipitation and heat wave events over western Europe using a new dataset of 54 daily maximum temperature time series. Forty four of these time series have been homogenised at the daily timescale to ensure that the presence of inhomogeneities has been minimised. The daily data have been used to create a seasonal index of the number of heat waves. Using canonical correlation analysis (CCA), heat waves over western Europe are shown to be related to anomalous high pressure over Scandinavia and central western Europe. Other forcing factors such as Atlantic SSTs and European precipitation, the later as a proxy for soil moisture, a known factor in strengthening land–atmosphere feedback processes, are also important. The strength of the relationship between summer SLP anomalies and heat waves is improved (from 35%) to account for around 46% of its variability when summer Atlantic and Mediterranean SSTs and summer European precipitation anomalies are included as predictors. This indicates that these predictors are not completely collinear rather that they each have some contribution to accounting for summer heat wave variability. However, the simplicity and scale of the statistical analysis masks this complex interaction between variables. There is some useful predictive skill of summer heat waves using multiple lagged predictors. A CCA using preceding winter North Atlantic SSTs and preceding January to May Mediterranean total precipitation results in significant hindcast (1972–2003) Spearman rank correlation skill scores up to 0.55 with an average skill score over the domain equal to 0.28 ± 0.28. In agreement with previous studies focused on mean summer temperature, there appears to be some predictability of heat wave events on the decadal scale from the Atlantic Multidecadal Oscillation (AMO), although the long-term global mean temperature is also well related to western European heat waves. Combining these results with the observed positive trends in summer continental European SLP, North Atlantic SSTs and indications of a decline in European summer precipitation then possibly these long-term changes are also related to increased heat wave occurrence and it is important that the physical processes controlling these changes be more fully understood.

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1 Introduction

Europe has experienced an unprecedented rate of summer warming in recent decades (Klein Tank and Können 2003; Luterbacher et al. 2004; Klein Tank et al. 2005). In the period 1976–1999 the annual number of periods of extreme warmth increased twice as fast as expected from the corresponding reduction in the number of periods of extreme cold temperatures (Klein Tank and Können 2003). Over most of Europe the increase in the mean daily maximum temperature during the summer months has been between 0.1 and 0.8°C per decade in the period 1976–1999 (Klein Tank and Können 2003). The extreme heat wave and drought that hit Europe in summer 2003 had enormous adverse social, economic and environmental effects, such as the death of thousands of elderly people, the destruction of large areas of forests by fire, and effects on water ecosystems and glaciers (Gruber et al. 2004; Koppe et al. 2004; Kovats et al. 2004; Schär and Jendritzky 2004; Kovats and Koppe, 2005). Estimates based on the statistical excess over mean mortality rates amount to between 22,000 and 35,000 heat-related deaths across Europe as a whole (Milligan 2004; Valleron and Boumendil, 2004; Poumadere et al. 2005). Reducing the impacts of future heat waves requires addressing fundamental questions, such as whether heat waves can be predicted, detected and whether their impacts can be mitigated. Heat waves are believed to become more frequent, more intense and longer lasting with climate change (Huth et al. 2000; Beniston 2004; Meehl and Tebaldi 2004; Schär et al. 2004; Stott et al. 2004). The sobering science of Stott et al. (2004) shows that there is a detectable man-made influence on the frequency of extremely warm climatic events and it is very likely that the European heat wave of 2003 was in part attributable to human activities.

Recently, in the meteorological community there have been many studies looking more closely at the 2003 event in the context of past climate variability (e.g., Luterbacher et al. 2004) and future changes in the frequency of heat waves (Beniston 2004; Meehl and Tebaldi 2004; Schär et al. 2004; Stott et al. 2004). Other studies have focused on the interpretation of weather diagnostics of the 2003 heat wave (Black et al. 2004; Fink et al. 2004; Ogi et al. 2005; Trigo et al. 2005).

A growing number of studies have looked at the mechanisms that contribute to the formation and prediction of such extreme warm events such as Sutton and Hodson (2005) who attribute long-term variability of European summer average temperature to a mode of Sea Surface Temperatures (SSTs) called the Atlantic Multidecadal Oscillation (AMO; Enfield et al. 2001). Colman (1997) claims that January and February North Atlantic SST can be used as a predictor of summer, JJA, Central England Temperature (CET) with a correlation skill score of around 0.5. Cassou et al. (2005) demonstrate that there is a significant influence from the tropical Atlantic region on the formation of Rossby wave trains and atmospheric blocking conditions necessary to have anomalous summer heat waves. Vautard et al. (2007) show that deficiencies in Mediterranean winter and spring precipitation lead to an increased frequency of Heat Waves (HWs) through northward transport of latent heat fluxes and land–atmosphere feedback processes. Nakamura et al. (2005) use the Earth simulator forced with daily observed SSTs one month before the 2003 event in three different regions of the North Atlantic. They suggest that vertically propagating high frequency baroclinic wave forcing in the vicinity of the Gulf Stream was an important factor in maintaining blocking over western Europe. Seneviratne et al. (2006) show that land–atmosphere coupling in the form of soil-moisture temperature and soil-moisture precipitation feedbacks are the most important mechanisms contributing to current and future heat wave events.

These studies are part of a global effort to focus climate research on the nature of weather extremes and their impacts on society. Since the Intergovernmental Panel on Climate Change (IPCC 2001) third assessment report there has been a concerted effort by National Meteorological Services to make available long, high-quality climate records in order to assess the changes and variability in daily climate extremes around the world (e.g., Frich et al. 2002; Alexander et al. 2006). Many of these studies on climate extremes have focused on their long-term changes over the maximum possible period for which reliable daily data exist. Another major focus of climate research has been the use of synoptic climatology (Lamb 1972; Hess and Brezowsky 1977; Yarnal 1993) analysis techniques to investigate how the large-scale synoptic weather patterns affect the frequency and trends in extremes (Domonkos et al. 2003; Xoplaki et al. 2003a, b; Haylock and Goodess 2004).

This study has several aims: (1) to build a more complete database of western European high quality daily resolved station temperature in order to quantify the change and variability in heat waves; (2) relate these phenomena with atmospheric circulation, SSTs and other possible forcing factors or covariates. Inherent in our aim is to support mechanisms of European heat wave formation given a more complete, longer and more rigorous observational dataset and (3) to explore the interannual predictability of heat waves using statistical models.

Our definition of a heat wave is similar to other studies such as Collins et al. (2000). We use daily maximum temperature to count the frequency of extended periods of extreme temperature. Extreme temperature is defined as a temperature above a daily percentile threshold to ensure that the heat wave index is applicable to different climatological regions.

This paper starts with a description of the data, including their source and homogeneity as well as the methods used in the study. We discuss Canonical Correlation Analysis (CCA), the main statistical method used in the paper. The results of the analysis are presented, discussed and concluded in the following parts.

2 Data and methods

In this section, we describe the various datasets and indices used in this study. We have split this section into *Predictor* and *Predictand* subsections to help clarify which data have been used for what purpose. The predictor data used in this study is not always strictly a true predictor in the sense that it could be used to forecast in time the occurrence of heat waves. The label is simply used to clarify which data are presumed to be the explanatory and response variables. Table 1 shows a summary of the predictor and predictand variables.

2.1 Predictor data

2.1.1 Sea level pressure (SLP) data

The daily mean SLP dataset used in this study was created as part of a collaborative European project named EMULATE (European and North Atlantic daily to MULtidecadal climATE variability, http://www.cru.uea.ac.uk/cru/projects/emulate/). It is a daily resolution gridded dataset that covers the North Atlantic and European area from 70°W to 50°E and 25°N to 70°N on a 5° × 5° grid from 1850 to 2003. Details of this dataset including the data quantity, quality and methods of reconstruction can be found in Ansell et al. (2006). The dataset combines 82 daily land station series and ship observations. The land station series and ship observations have been corrected for elevation and diurnal pressure variations as well as inhomogeneities caused by instrument changes and/or location. An analysis by Bhend (2005) and a preliminary analysis made in this study indicate that the dataset may contain inhomogeneities due to changing

Table 1 Summary of predictor and predictand variables, their temporal resolution and their domain

Element	Predictor abbreviation	Season/ month	Resolution	Domain	N_{pc} (% exp. var)
Predictand					
Heat wave index	HW	JJA	–	See Fig. 1	4 (69)
Heat wave principle component 1[a]	HWPC1	JJA	–	See Fig. 1	1 (37)
Predictor					
North Atlantic Sea level pressure	SLP	JJA	5° × 5°	70°W–50°E, 25°N–70°N	12 (86)
North Atlantic Sea surface temperature	SSTNA	JJA	2.5° × 2.5°	70°W–50°E, 25°N–70°N	14 (91)
North Atlantic Sea surface temperature	SSTNA	MAM	2.5° × 2.5°	70°W–50°E, 25°N–70°N	13 (87)
North Atlantic Sea surface temperature	SSTNA	DJF	2.5° × 2.5°	70°W–50°E, 25°N–70°N	14 (89)
North Atlantic Sea surface temperature	SSTAT	DJF	2.5° × 2.5°	70°W–50°E, 0°N–70°N	15 (88)
Atlantic multidecadal oscillation[b]	AMO	Annual	2.5° × 2.5°	75°W–7.5°W, 0°N–60°N	–
Western Europe precipitation	PRECWE	JJA	0.5° × 0.5°	15°W–20°E, 35°N–60°N	14 (71)
Mediterranean precipitation	PRECME	JFMAM	0.5° × 0.5°	20°W–50°E, 42°N–46°N	8 (81)
Global mean temperature[c]	GLOBT	Annual	–	Near global	–

All SLP data are taken from Ansell et al. (2006), SST data are described in Smith and Reynolds (2004); and the majority of the precipitation data are from Mitchell and Jones (2005) updated with data from Beck et al. 2005 (see Sect. 2.1 for more detail). The last column shows the number of significant principle components (PC) retained (N_{pc}) and their total accounted variance (see Sect. 2.3 for more information on the method)

[a] The HWPC1 index is the first principle component of JJA HW index

[b] The AMO index was calculated using annually averaged SST in the domain specified in the table (according to the definition in Sutton and Hodson 2005) and then smoothed using a LOESS function with a smoothing parameter of 25 years. This was then de-trended and standardised to have a variance one and mean of zero

[c] The GLOBT series is the annual average global mean temperature (Brohan et al. 2006) that has been smoothed using a LOESS function with a smoothing parameter of 25 years (Cleveland and Devlin 1988), de-trended and standardised to have a variance of one and a mean of zero

density of input data in the earlier years of the dataset (Ansell et al. 2006).

2.1.2 *Sea surface temperature data*

Sea surface temperature (SST) has been shown to have predictive skill in forecasting the boreal winter North Atlantic Oscillation (NAO) (Rodwell et al. 1999) although the effects of this sea–air coupling are more noticeable at decadal timescales (Sutton and Hodson 2005) than at interannual timescales. Since there is evidence that SSTs are indicative of sea-to-air interactions and play a role in modulating atmospheric circulation and climate, the global monthly mean SST dataset of Smith and Reynolds (2004) going back to 1854 (resolution of 2° × 2°) was used as a variable to help account for the variability of heat waves over Europe.

2.1.3 *Precipitation data*

Many authors have cited the importance that low soil moisture played in attributing cause to the 2003 heat wave (Black et al. 2004; Fink et al. 2004; Schär et al. 2004). Others have shown through modelling studies the increased likelihood of extreme temperatures and heat waves associated with drier soil conditions (Schär et al. 1999, 2004; Brabson et al. 2005; Findell and Delworth 2005; Ferranti and Viterbo 2006, Seneviratne et al. 2006). To first order the amount of evapotranspiration is dependant on precipitation (Schär et al. 1999; Ferranti and Viterbo 2006) and since the authors are unaware of any comprehensive soil moisture dataset extending back to 1880 we decided to see if the preceding winter or spring precipitation was a potential predictor of the severity of heat waves (Vautard et al. 2007). Here we have used the global gridded monthly dataset of Mitchell and Jones (2005) called *CRU TS 2.1* (resolution of 0.5° × 0.5°). This dataset currently ends in 2002 so to include 2003 we used data from the Global Precipitation Climatology Center (GPCC, resolution of 1.0° × 1.0°, Beck et al. 2005). Since the climatology's of these two datasets are similar we simply appended the GPCC data to Climatic Research Unit (CRU) data. We used a simple linear interpolation method to transform the 1.0° × 1.0° GPCC data resolution to the 0.5° × 0.5° CRU data resolution.

2.2 Predictand data

2.2.1 *Station based temperature data*

The station based data are a collection of daily resolution long-term time series from around Europe. They are primarily a combination of two datasets, the European Climate Assessment database (Klein Tank 2002; Klein Tank et al. 2002; Wijngaard et al. 2003) and the EMULATE database (Moberg et al. 2006). The database contains daily minimum, mean and maximum temperature and daily total rainfall of varying quality and continuity. However, only daily maximum temperature time series that have met more rigorous continuity, quality control and homogeneity criteria were used in this study. The daily time series needed to have at least 70% complete and non-missing data over the analysis period, 1880–2003 with the additional constraint that no missing values be present in the last five years of the analysis period. The latter criteria helped to minimise the effects of missing data on the trend analysis and helped to reduce possible biases in the Principle Component Analysis (PCA) associated with missing data (see section 4.6 for more details). Time series were carefully screened for inconsistencies including a check for maximum temperature greater than minimum temperature and investigation of outliers (Moberg et al. 2006). We decided to check the homogeneity of these data in more detail and where possible homogenise the daily time series, as explained in the following subsection. Of the 178 station time series in the database only 54 time series met the quality and homogeneity criteria. However, even if a time series was not included in the final dataset (54 time series), the other time series in the database were useful to help assess the homogeneity and in some cases homogenise daily maximum temperature.

2.2.2 *Homogenisation of the daily maximum temperature time series*

Each of the 54 time series used in the analysis can be classified as either *homogenised* or *non-homogenised* and each of the homogenised time series has varying quality of homogeneity depending on the type of homogenisation method applied. In homogenisation studies it is useful to draw a distinction between candidate and reference stations (time series). A candidate station is a time series to which a homogenisation technique is applied whereas a reference station is any other time series which can be used as additional input to the homogenisation technique. Below is an itemised list of the homogenisation categories:

- HOM method ++: The Higher Order Moments (HOM) method of Della-Marta and Wanner (2006) (detailed below) was used with high quality metadata detailing the break points and the magnitude

of adjustments to monthly mean maximum temperature for both the candidate and reference stations.
- HOM method +–: Uses the HOM method with a combination of high quality metadata detailing the break points and the magnitude of adjustments to monthly mean maximum temperature and the results of a Relative Homogeneity Test (RHTest, detailed below) for either the candidate or reference time series.
- HOM method –: Uses the HOM method with limited metadata and only the results of the RHTest to provide information about possible break points.
- RHTest only: Mean adjustments to the daily maximum temperature series were derived from the results of the RHTest applied to monthly and annual maximum temperature data using limited or no metadata.
- Other: The daily maximum series was homogenised by another study. See the references in Appendix for details of the methods used.

The order of the first four items in the list above denotes a natural progression in the level of quality we believe the final homogenised series has. It is difficult to assess the quality of the time series in the ‘‘Other'' category since a direct comparison of methods was not made; however, most of these studies have applied the monthly adjustments calculated from a relative homogeneity test to the daily values. Each station's basic metadata and the level of homogenisation applied to the series are detailed in Appendix.

As a first step in identifying possibly erroneous stations the homogeneity assessment from Wijngaard et al. (2003) were used since many of the stations in the EMULATE database come from the ECA (European Climate Assessment). We also used the results from previous studies to help identify potentially inhomogeneous stations and to gather metadata. See the references contained in Appendix for more information.

Where possible we used the method of Della-Marta and Wanner (2006) to homogenise the daily maximum temperature used in this analysis. This method uses a non-linear model to estimate the relationship between a candidate station and a highly correlated reference station. The model is built in a homogeneous sub-period before an inhomogeneity and is then used to estimate the observations at the candidate station after the inhomogeneity using observations from the reference series. The differences between the predicted and observed values are binned according to which decile the predicted values fit in the candidate station's observed cumulative distribution function defined using homogeneous daily temperatures before the inhomogeneity. In this way, adjustments for each decile were produced. The method presented in this paper can adjust both the mean and the higher order moments (i.e., variance and skewness) of a daily temperature record. The most critical requirement for this method to work is the presence of a highly correlated reference station which has homogeneous sub-periods overlapping the date of the inhomogeneity in the candidate station. Knowing at which time inhomogeneities in the data occur is a difficult task, so we limited our efforts of daily homogenisation to stations where we could either obtain reliable metadata (HOM method ++ or HOM method +–) in collaboration with the data providers listed in the acknowledgements or previous studies listed in Appendix or where we were confident that the RHTest (detailed below) was providing reliable estimates of break points. The countries where this was possible were (some or all stations): Austria, Czech Republic, Germany, The Netherlands, Portugal, Sweden, Switzerland and United Kingdom. We homogenised a total of 25 stations using the HOM method. Detailed results from the application of the HOM method showed (not shown) that many stations needed adjustments not only to their mean but also their variance and skewness characteristics.

Where metadata on the break points (inhomogeneities) in candidate and reference stations were limited we used an RHTest to try and determine their occurrence. A number of different techniques exist to identify inhomogeneities and an overview of the variety of tests is given by Peterson et al. (1998). However, we checked the homogeneity of annual and monthly averaged data using a two-phase regression model used by Easterling and Peterson (1995) among others and then subsequently improved by Lund and Reeves (2002) and modified by Wang (2003). Wang (2003) uses a slightly simplified two-phase regression model compared to Lund and Reeves (2002) which allows the two-phase model to have a common trend parameter instead of two different trend parameters. This model known as the RHTest (Wang 2003), was applied to both the raw anomalies (with respect to the overall mean) of the candidate station and a difference series calculated as the difference between the candidate series and a reference series created from a weighted average of surrounding station series. The method to create the weighted reference series follows Della-Marta et al. (2004) where a weighted reference series is created from stations that have at least ten years of annual average maximum temperature data and have a statistically significant correlation at the 5% level with the candidate series above 0.6 and the inter-station separation is less than six degrees along a great circle. See Della-Marta et al. (2004) for more details.

A comparison of the number of inhomogeneities (not shown) detected using the difference series compared to those detected when using the candidate series only with known dates of potential inhomogeneities (metadata) confirms that the relative or difference test in general produces more reliable results given a suitably reliable reference series (e.g., Della-Marta et al. 2004; Begert et al. 2005).

2.2.3 Heat wave index

Meteorologically, the essential component of a heat wave is a sustained duration of extremely high temperatures. Several approaches can be used to define a heat wave, based on an absolute or a relative threshold of weather variables or as a combination of both. A survey of the meteorological services in Europe (Koppe et al. 2004; Kovats and Koppe 2005) showed that an operational definition of a heat wave has a varying definition but essentially is based on the following elements:

- Air temperature threshold
- Air temperature threshold and a minimum duration
- Indices based on a combination of air temperature and relative humidity

Due to the lack of any long-term humidity database for Europe over the period of investigation, we decided to base our definition of a heat wave on air temperature and a measure of duration. The temperature threshold varies according to each station's Cumulative Distribution Function (CDF) to make the definition of the heat wave relative to the local climate. Generally, the summer (JJA) temperature thresholds used in Europe have a north–south and a west-east gradient. In this study a HW is defined as the number of consecutive 3-day periods in summer (JJA) that exceed the long-term daily 80th percentile of daily maximum temperature. The daily 80th percentile was calculated using a 5-day centered average over the normal period (1906–2003). The 80th percentile was chosen for the HW index so that each seasonal count had a higher chance of not containing zero heat waves, remembering that we need at least three consecutive days above each station's threshold. If the 95th percentile was chosen we could only expect on average around five days above this threshold per season whereas the 80th percentile offers around eighteen days on average. Clearly then, the number of consecutive three day periods being captured using the 80th percentile is higher. A follow on effect of a seasonal HW count being zero often would be that the statistics of the CCA would be possibly unreliable due to a very heavy-tailed and skewed distribution of the seasonal extreme index. We took the cube root of the heat wave index in an attempt to make the index more normally distributed and found no appreciable differences in the CCA patterns or scores series. Primarily this index is aimed at the climatological community for assessment of climate change and long-term variability, and secondly to provide information which is useful to the wider scientific community dealing with the impacts of climate and climate change.

2.3 Canonical correlation analysis

CCA is a statistical technique that relates many predictor variables to many predictand variables in such a way that the correlation between a reduced dataset is maximised (e.g., Wilks 1995; von Storch and Zwiers 1999). It has been used extensively throughout the meteorological and climatological literature (e.g., Nicholls 1987; Xoplaki et al. 2003a, b; Haylock and Goodess 2004). Cherry (1996) highlights the need for caution in interpreting the results of CCA. Importantly he notes that even spatially and temporally uncorrelated data can produce high canonical correlations between variables. The problem of spurious coupled modes is increased when sample sizes are small, when the data is autocorrelated or coupled modes are weak. As with any parametric statistical analysis, there are inherit assumptions that are often neglected as being important. CCA is based on the axioms of correlation analysis. Correlation coefficients between two data sets (and their significance) are affected by non-stationarities in the data such as trends and autocorrelation (Chatfield 1996). Below we summarise the CCA method used in this paper which was designed to avoid the possible pitfalls mentioned above:

1. The long-term linear trend was removed from each predictor and predictand.
2. The predictor and predictand data were standardised by subtracting their long-term mean and divided by their long-term standard deviation (1901–2003 for precipitation data). This had the effect of giving equal weight to all gridpoints and station data points.
3. Following the Preisendorfer (1988) method of CCA the predictor and predictand were dimensionally reduced using Principal Component

Analysis (PCA) retaining a number of selected Principal Components (PCs) using *Rule N* criteria. One thousand synthetic datasets were created and the significant number of PCs assessed at the 5% significance level. Missing predictand data were filled with the long-term mean value before PCA. Both the PCA and CCA calculations were performed using the Singular Value Decomposition (SVD) algorithm, detailed in Preisendorfer (1988) and Haylock and Goodess (2004).

4. If more than one predictor was used, termed Multiple Predictor CCA (MPCCA, e.g., Xoplaki et al. 2003a, b), then a second PCA was performed on the combined selected PCs of each predictor.
5. The significant number of PCs set an the upper limit of PCs used in the CCA, however, like Multiple Linear Regression (MLR) adding more predictors does not often result in more model skill (Chatfield 1996), this is termed 'overfitting' a model. To account for this problem we performed a CCA for every combination of predictor PCs and predictand PCs and performed a one time step cross-validation procedure (e.g., Michaelsen 1987) taking one year out of the CCA at one time and assessing the prediction errors as the mean Spearman rank correlation skill score (Press et al. 1996). Most of the time, this resulted in the number of PCs taken as predictors or predictands in the CCA being less than the upper limit number of significant PCs for the predictor and predictand.
6. In order to assess the statistical significance of the CCA patterns and the canonical correlation coefficients we used a Monte Carlo technique similar to Shabbar and Skinner (2004) where the PCs of the predictand were randomised 5,000 times using a bootstrap with replacement technique (Efron and Gong 1983). The CCAs of each of these synthetic series were used to build an empirical probability distribution for each statistic of the CCA.
7. We tried to minimise the possible over-interpretation of CCA results by also performing a hindcast for each CCA where the model was trained on the first 70% of the detrended data and a validation performed on the remaining years. A number of measures were used to assess the fit of the CCA model to the validation data. These included the Spearman rank correlation, Root Mean Squared Error (RMSE) as well as an Absolute Mean Bias (AMB).

See Haylock and Goodess (2004) for more details on the preprocessing and CCA methodology.

3 Results

In this section we present the results of trend analysis of selected predictor and predictands and CCA analysis between SLP, North Atlantic SSTs and Precipitation from various geographical regions and the frequency of summer HWs at each station. A summary of the predictor and predictand data sets is shown in Table 1. In all references to statistical significance the 5% level has been used. Any use of the word ''significant'' implies statistical significance. Since the data have been standardised (see Sect. 2.3) the CCA loading patterns represent the correlation between the each grid point (or station) data and the canonical score series. Generally, the CCA results including their patterns and score series are only presented below if they are statistically significant according to the methods described in Sect. 2.3 or unless otherwise stated.

3.1 Long-term trends in HW, SLP, SST and PRECWE

Figure 1 shows that all stations used in this analysis have a positive trend in the occurrence of HWs from 1880–2003. Around 80% of the trends are statistically significant. The trend significance (shown by colours) was determined using the non-parametric Kendall Tau test (Press et al. 1996). A non-parametric test was used since the distribution of the HW is usually long-tailed

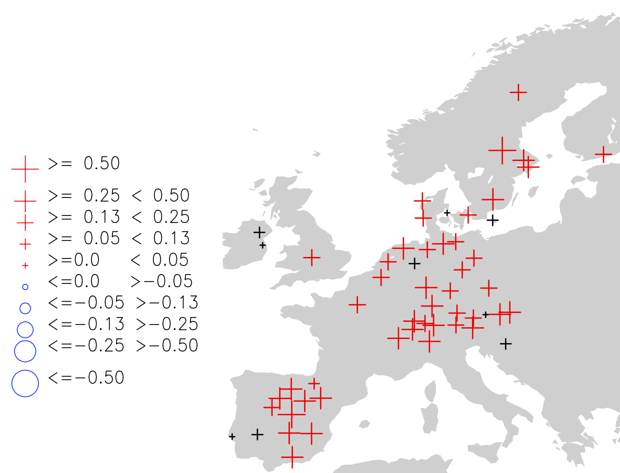

Fig. 1 The long-term linear trend of the HW index in units of frequency per decade calculated over the longest possible period for each station (see Appendix for the details). The sizes of the crosses ('+') and the open circle ('o') denote the magnitude of the positive and negative trends according to the legend on the left side of the figure, respectively. *Symbols that are coloured red* (*blue*) indicate statistically significant positive (negative) trends at the 5% level. *Black symbols* indicate non-significant trends

and not Gaussian. Sometimes the trend shown on the plot has not been calculated over the whole period (see Appendix for details on the starting dates of each record). The largest trends have been found over the Iberian Peninsula and in central western Europe. Incidentally, this is where we also have the most confidence in our data (see Appendix for an overview on the quality and homogeneity of each station series). Averaged over the entire western European domain the frequency of HWs has increased by approximately 0.24 HWs per decade.

Generally, the summer climate of Europe and the Azores region of the North Atlantic has experienced an increase in average JJA mean sea-level pressure from 1901 to 2003 (Fig. 2). The trends from 1880 to 2003 were not shown due to a suspected inhomogeneity in the data over the Azores region around 1900. Approximately 28% of the grid points have experienced statistically significant trends. Significant positive trends of up to 0.15 hPa per decade are shown over northern western Europe whereas significant negative trends of up to 0.35 hPa (0.15 hPa) per decade are shown over North Africa (Icelandic low region).

Summer SSTs in the North Atlantic region (SSTNA) have become significantly warmer over most of the domain. Close to the coastline of western Europe and in the Mediterranean region trends around 0.1°C per decade have been found, whereas SSTs have decreased significantly in the region south of Greenland (Fig. 3). The regions with the highest statistically significant positive trends lie east of Newfoundland and around the North Sea and Baltic Sea.

There has been a weak drying trend in summer precipitation across western Europe (Fig. 4) in agreement with Pal et al. (2004). However, only a few isolated areas of statistically significant trends are shown. The British Isles, the western Alps and central Italy show the strongest declines in precipitation of between 1.5 and 5.0 mm per decade. As only 1.5% of grid points show a statistically significant decline in precipitation no strong conclusion can be made about these trends.

3.2 Simultaneous SLP as a predictor of heat waves

We find that there are two major modes of SLP variability associated with HWs [in agreement with the cluster analysis derived patterns of Cassou et al. (2005) called *Blocking* and *Atlantic Low* and CCA derived patterns of Xoplaki et al. (2003b)]. The first CCA mode (Fig. 5a, stippled area) shows that strong positive anomalies of SLP over the Scandinavian region are associated with anomalously high frequency of HWs

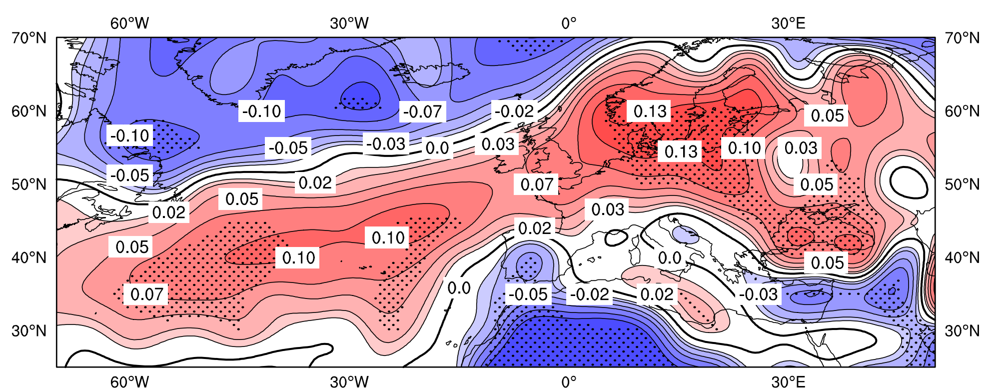

Fig. 2 The long-term linear trend in JJA averaged SLP in hPa per decade calculated over the 1901–2003 period. *Stippled areas* show statistically significant trends at the 5% level

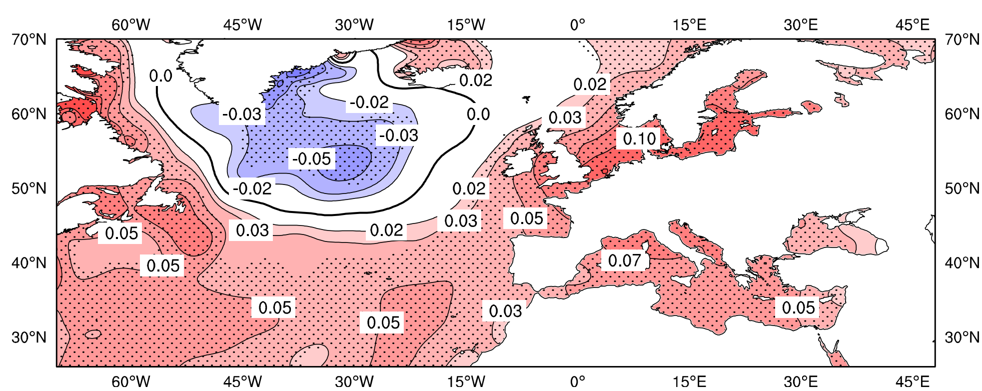

Fig. 3 The long-term linear trend in JJA averaged SSTNA in °C per decade calculated over the 1880–2003 period. *Stippled areas* show statistically significant trends at the 5% level

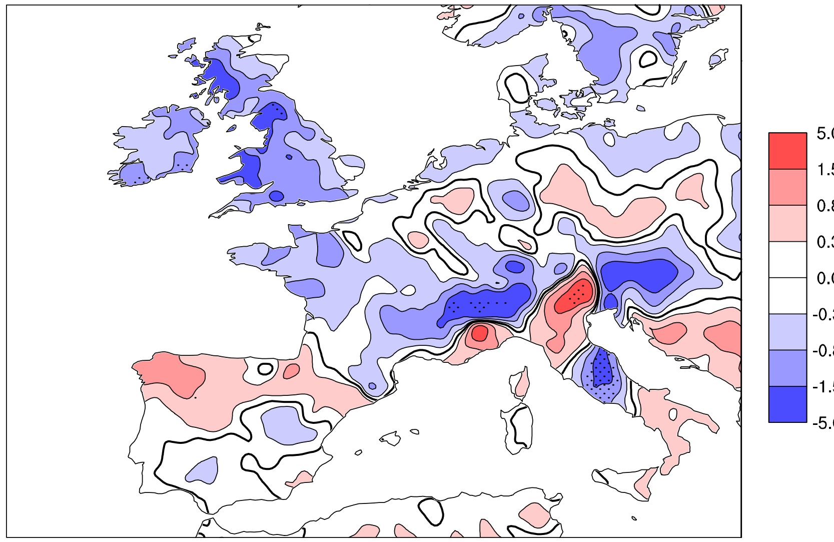

Fig. 4 The long-term linear trend in JJA averaged PRECWE in mm per decade according to the legend in the right of the figure calculated over the 1901–2003 period. *Stippled areas* show statistically significant trends at the 5% level

(Fig. 5b, coloured red crosses) over northern and central western Europe and weak negative HW anomalies over the Iberian Peninsula. This pattern also resembles the summer NAO (Barnston and Livezey 1987) described in Hurrell and Folland (2002) who showed that the SLP in the northeast Atlantic was anomalously high from the mid-1960s to the mid-1980s. The canonical score series (Fig. 5c) show the time evolution of the CCA loadings. The dashed line indicates the canonical score associated with HWs and the solid line shows the canonical score associated with the SLP. The correlation between the two score series of the first CCA is 0.8 (significant at the 5% level, Table 2). Notably the summers of 1997, 1976, 1959, 1947 and 1911 show a high score on this CCA mode (dashed line in Fig. 5c). There tends to be a higher frequency of higher and lower CCA scores in the latter half of the century compared with the earlier years. The 1976 event was at the time thought to be unprecedented by Ratcliffe (1976) in the previous 250 years. A detailed overview of the event affecting the British Isles can be found in Shaw (1977). As we will discuss below this was also a very dry summer. The first CCA accounts for 17% of HW variability (Fig. 5; Table 2).

The second CCA SLP loading pattern shown in Fig. 6a (stippled areas) resembles a stationary wave pattern with anomalously low SLP over central North Atlantic, positive anomalies over western Europe and negative anomalies over eastern Europe. This CCA accounts for 8% of the total HW variability over the domain and is associated with heat waves over the Iberian Peninsula (Fig. 6b, coloured red crosses). This CCA mode has a high HW score value associated with the 2003 heat wave (Fig. 6c, black curve) indicating that this pattern (Fig. 6a, b) was important in the development of the 2003 event. Notice, however, that there is a large difference between the solid and the dashed curve in Fig. 6c which indicates that the CCA predictor (SLP) underestimated the observed within CCA HW variability. Black et al. (2004) and Luterbacher et al. (2004) showed the importance of persistent anticyclonic conditions over Europe contributing to the 2003 heat wave. These conditions are mainly visible in the middle layers of the atmosphere. A plot of JJA SLP over western Europe and the North Atlantic does not show (not shown) the signature of strong anomalously anticyclonic circulation over western Europe but hints towards the formation of a large heat low extending from the Iberian Peninsula to parts of western Europe. The dominant feature of the 2003 event in terms of SLP was the strong anomalous low pressure found in the middle North Atlantic. Combined, the first four CCAs account for around a third (Table 2) of HW variability. This indicates that there are either missing explanatory variables or that the large-scale seasonally averaged patterns presented here are not able to resolve the regional scale state of atmospheric circulation and heat wave variability.

3.3 Simultaneous and lagged SST as a predictor of heat waves

Primarily there are two modes of JJA SSTNA variability that are associated with summer HWs which for the sake of brevity are not shown but are described below. The first shows that anomalous warm (cold) SSTs around the North and Baltic seas extending southward along the Bay of Biscay and the western coast of the Iberian Peninsula and westward to the Azores are linked with anomalously high (low) fre-

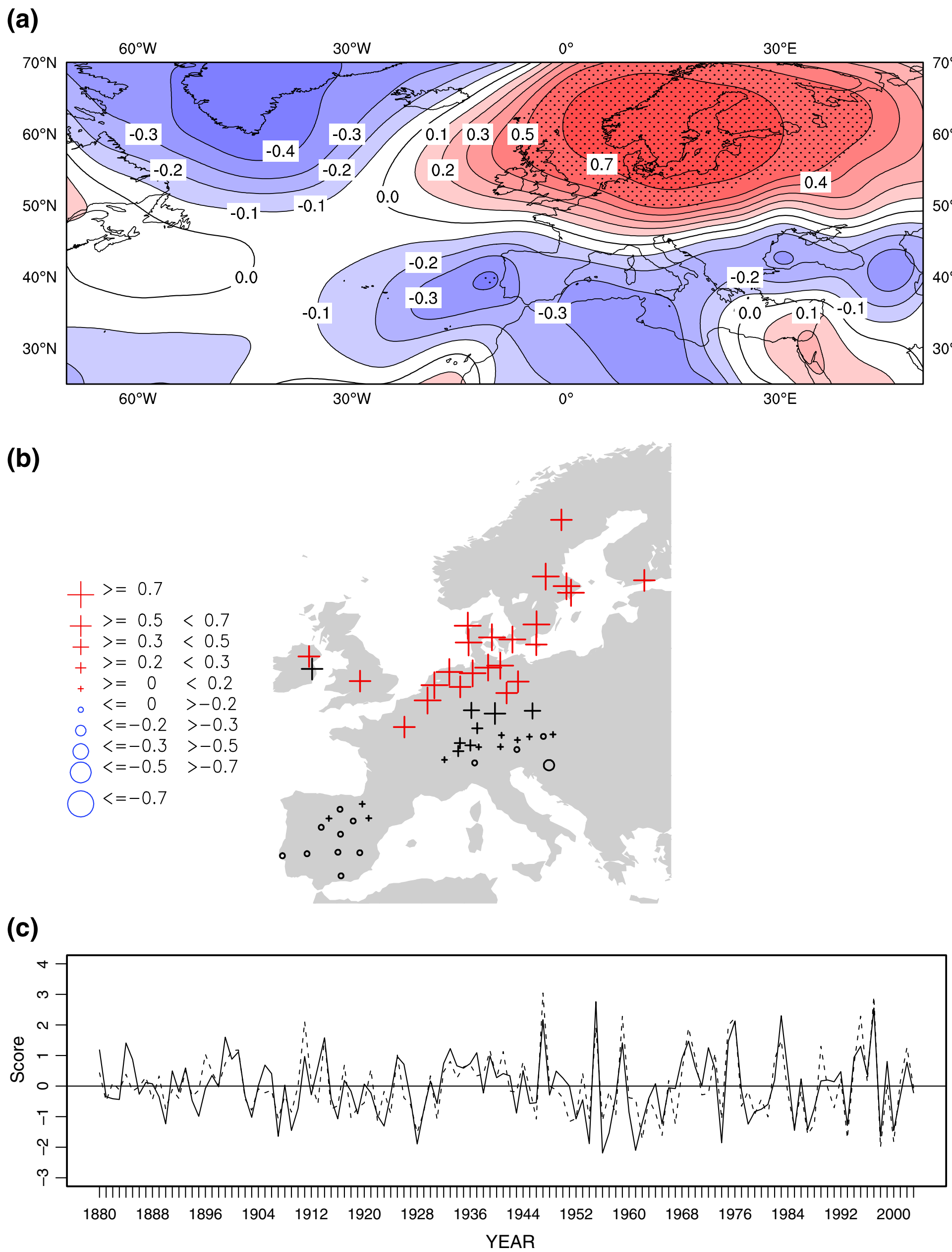

Fig. 5 The first CCA between JJA averaged SLP and the JJA HW index which accounts for approximately 16.6% of JJA HW variability. **a** The SLP canonical pattern, **b** the HW canonical pattern and **c** the canonical score series from 1880 to 2003. *Red* (*blue*) *areas* in **a** indicate positive (negative) correlations above (below) 0.1. Stippled areas in **a** show statistically significant correlations at the 5% level. In **b** the sizes of the crosses ('+') and open circles ('o'), respectively, show the magnitude of canonical loadings according to the legend on the left of the figure. Both CCA loadings in **a** and **b** are expressed as a correlation coefficient between each grid point (or station) data (standardised and de-trended according to section 2.3) and the canonical score series for each grid point (station). *Symbols that are coloured red* (*blue*) indicate statistically significant positive (negative) correlations at the 5% level, whereas *black symbol* indicate lower than the 5% level significance correlations. In **c** the *solid and dashed lines* are the SLP and HW canonical score series, respectively, which have a significant (5% level) correlation coefficient of 0.81

quency of HWs across western Europe with highest loadings in central western Europe. The second SSTNA CCA shows (not shown) a dipole structure with warm Baltic and North Seas with a cool western Mediterranean which is related to anomalously lower number of heatwaves in the Iberian Peninsula. A summary of the total accounted variance of the SSTNA/HW CCA can be found in Table 2. Notice that the accounted variance is similar (34%) to using JJA SLP as a single predictor of HWs.

Lagged SSTNA in the months of DJF and MAM preceding JJA HWs do not show particularly promising lead skill (see Table 2). Generally, anomalously warm SSTs in MAM and DJF over the whole SSTNA domain except a cooler area east of Newfoundland, or anomalously warm SSTs in the Baltic and North Seas are associated with higher HW occurrence in summer. Only around 4–5% of HW variability can be accounted for by SSTNA in MAM or DJF and the combined statistically significant areas in the CCA patterns is small. However, the hindcast Spearman rank skill score shows statistically significant positive correlations over the Iberian Peninsula and over central western Europe using DJF and MAM SSTNA, respectively. Skill scores as high as 0.5 indicate that up to 25% of HW occurrence can be predicted by preceding SSTNA (not

Table 2 Summary of the CCAs between various predictors (see Table 1 for details) and JJA HW

Predictor(s)	Season	N_{CCA}	CCA	r	% variance accounted	$\mu_{hindcast}$	Model skill description
SLP	JJA	12	1	**0.81**	16.6	0.47 ± 0.42	Good skill over the entire domain, except the Alps
			2	**0.72**	8.4		
			3	**0.63**	2.5		
			4	**0.46**	4.4		
			Total	–	32.0		
SSTNA	JJA	14	1	**0.76**	20.2	0.54 ± 0.25	Good skill over the entire domain
			2	**0.73**	5.9		
			3	**0.64**	6.5		
			4	**0.48**	1.7		
			Total	–	34.3		
SSTNA	DJF	6	1	**0.38**	1.6	0.12 ± 0.35	Generally poor skill over the entire domain. Iberian Peninsula skill score around 0.5
			2	**0.29**	1.6		
			3	**0.20**	0.5		
			4	**0.19**	1.2		
			Total	–	4.9		
SSTNA	MAM	2	1	**0.33**	3.9	0.21 ± 0.38	Generally poor skill over the entire domain. Highest values over central western Europe (0.5)
			2	0.03	0.0		
			Total	–	3.9		
PRECWE	JJA	5	1	**0.76**	13.4	0.49 ± 0.30	Good skill over the entire domain
			2	**0.71**	11.5		
			3	**0.54**	2.7		
			4	**0.37**	2.2		
			Total	–	29.8		
PRECME	JFMAM	2	1	**0.42**	6.2	0.23 ± 0.48	Generally moderate to poor skill over the domain. However, central Europe between 0.3 and 0.5 (see Fig. 8d)
			2	0.03	0.0		
			Total	–	6.2		
SLP	JJA	12	1	**0.86**	14.2	0.60 ± 0.29	Good skill over the domain, up to 0.84
SSTNA	JJA		2	**0.83**	19.6		
PRECWE	JJA		3	**0.72**	6.7		
			4	**0.64**	4.5		
			Total	–	45.0		
SSTAT	DJF	8	1	**0.56**	10.1	0.28 ± 0.28	Generally moderate to poor skill over the domain. Skill up to 0.55 in central western Europe (see Fig. 11e)
PRECME	JFMAM		2	**0.43**	1.4		
			3	0.22	0.3		
			4	0.16	0.6		
			Total	–	12.4		

The first three columns show the predictor(s) abbreviation, the season the predictor was averaged over and the number of PCs retained to build the CCA (N_{CCA}) after cross-validation, respectively. The column titled CCA shows the number of predictand PCs retained after cross-validation, r is the canonical correlation between the CCA score series, where bold figures represent statistically significant correlations at the 5% level (calculated using the bootstrap technique), % variance accounted refers to the variance of JJA HWs accounted for by each CCA, $\mu_{hindcast}$ is the average hindcast Spearman rank correlation skill score of all stations with an approximate 95% confidence interval to show the spread of results using the 1880–1965 period to build the model and 1966–2003 to validate the model (in the case where a precipitation predictor was used the period 1901–1971 was used to build the model and remaining period used to validate the model). The last column gives a brief description of the hindcast skill. See Sect. 2.3 for details on the CCA model selection method

shown). These results agree with those of Colman and Davey (1999) who found predictability of western European summer mean temperature with correlation skills scores also in the order of 0.5. In summary we find a weak but significant signal of winter SSTs affecting the frequency of HWs and summer average temperature over western European.

3.3.1 The Atlantic multidecadal oscillation

We find evidence supporting the analysis of Sutton and Hodson (2005) that the occurrence of warmer than average temperatures over Europe are related to long-term changes in the Atlantic Multidecadal Oscillation (AMO) (Enfield et al. 2001). The AMO, essentially a monopole structure of SSTs over the North Atlantic, is believed to be caused by the North Atlantic thermohaline circulation (Knight et al. 2005). The correlation between the locally weighted regression (LOESS) smoothed (Cleveland and Devlin 1988) HWPC1 score series and the AMO (see Table 1 for the definitions) shown in Fig. 7a is 0.8. The significance is difficult to determine since the effective number of degrees of freedom is around 2. Figure 7b shows the loading

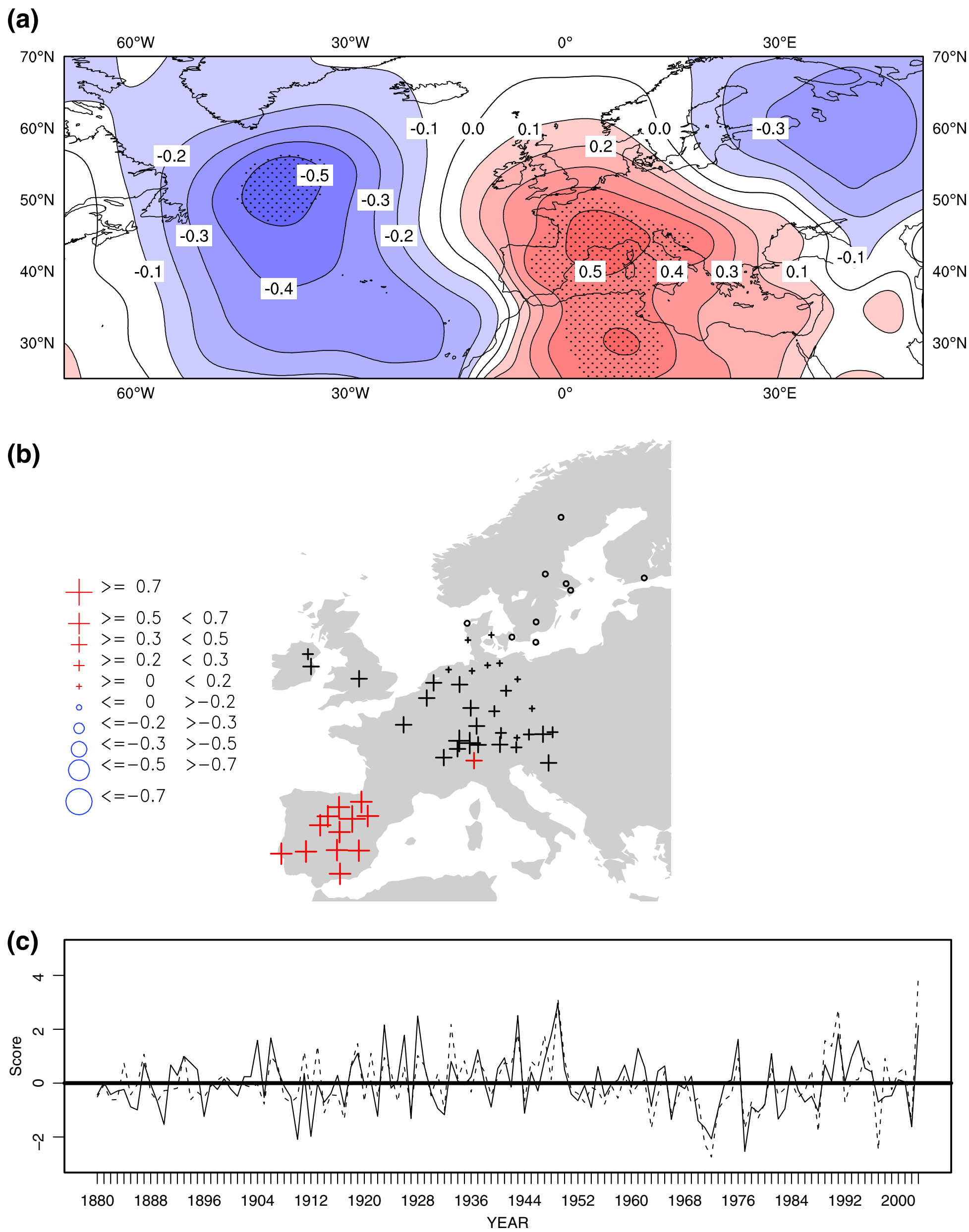

Fig. 6 The second CCA between JJA averaged SLP and the JJA HW index which accounts for approximately 8.4% of JJA HW variability. **a** The SLP canonical pattern, **b** the HW canonical pattern and **c** the canonical score series from 1880 to 2003. The *colours*, *symbols* and *stippling* are the same as for Fig. 5. In **c** the *solid and dashed lines* are the SLP and HW canonical score series, respectively, which have a significant (5% level) correlation coefficient of 0.72

pattern associated with HWPC1. According to this PC the western European domain is under the influence of anomalously high or low frequency of HWs. High occurrence of HWs between 1880 and 1905, 1925 and 1950 and 1990 and 2003 periods is coincident with anomalously high SSTs in the region defined by the AMO. Although this analysis does not provide a causal link between the long-term variations in North Atlantic SSTs it is interesting to compare them since for the first time such a long-term analysis of European HWs has been performed. We also correlated the HWPC1 series with the global mean temperature (GLOBT) series (see Table 1 for details; Fig. 7a, dotted curve) and noted that it also has a correlation of approximately 0.8. Naturally the question that arises is whether extreme hot temperatures in western Europe are modulated by GLOBT or by the AMO. It is tempting to extrapolate from Fig. 7a that there is a phase lag between the AMO series and the HWPC1 since the peaks (troughs) of the HWPC1 series tend to lag the AMO peaks (troughs) by approximately five years. Could the atmosphere retain and react to an ocean forcing from five years earlier that is either AMO or GLOBT induced? It is certainly an interesting question that can only be answered by many forced and unforced complex model simulations.

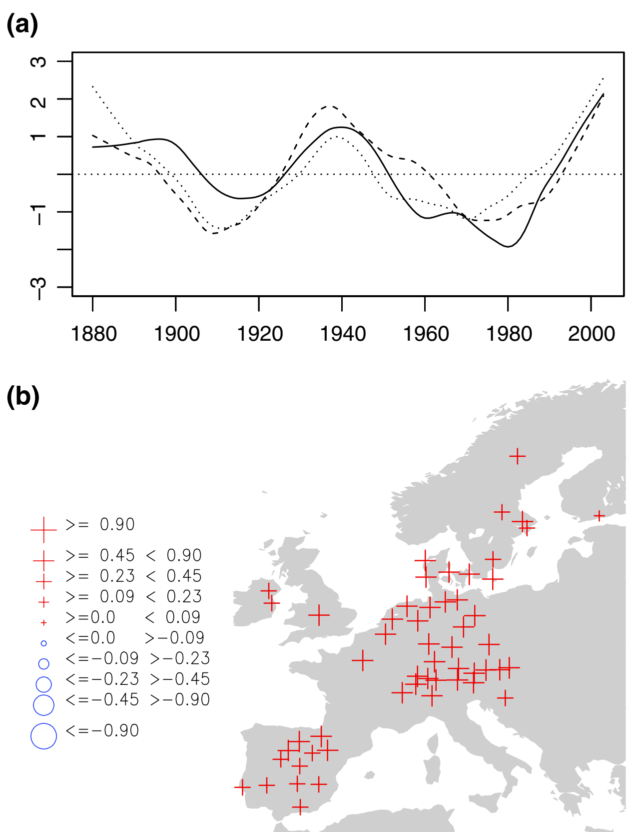

Fig. 7 **a** A time series plot, showing the smoothed Atlantic Multidecadal Oscillation (AMO, *dashed line*) index, the smoothed first principle component of JJA HWs (HWPC1, *solid line*) and the smoothed Global mean temperature (GLOBT, Brohan et al. 2006, dotted line), from 1880 to 2003 and **b** the loading patterns associated with the raw (unsmoothed) first principle component (PC). In **b** the sizes of the crosses ('+') and the open circles ('o') denote the magnitude of the positive and negative PCA loadings according to the legend on the left side of the figure. The correlation between the three time series is approximately 0.8, however, it is hard to determine the statistical significance due to the limited number of degrees of freedom. The first PC of the HW index accounts for 37% of HW variability. The time series have been smoothed using a LOESS smoother with a period set approximately to 25 years. See Table 1 for more details on each index

3.4 Simultaneous and lagged precipitation as a predictor of heat waves

Schär et al. (1999) show the importance of summertime (JJA) precipitation and soil moisture feedback processes as an important factor in the probability of severe and long lasting rainfall deficiencies over Europe. Ratcliffe (1977) suggested that this mechanism was partly responsible for the severity of the 1975/1976 drought affecting western Europe and the British Isles. Heat waves are also related to soil moisture deficiencies (Brabson et al. 2005; Ferranti and Viterbo 2006; Vautard et al. 2007) thus we investigated the role of PRECWE (see Table 1) summer precipitation (JJA) on the occurrence of HWs.

In the first CCA (not shown), statistically significant correlations reveal that anomalously dry western central and northern European summers are associated with a higher frequency of HWs in those areas. Whereas there is no statistically significant correlation over the Alps and anomalously higher summer precipitation over the Iberian Peninsula is associated with fewer HWs. The second CCA shows (not shown) that significant (negative) correlations exist between PRECWE anomalies over most of central western Europe and the frequency of HWs. Other notable extremes in the CCA score series are the summer of 1911 where widespread HWs were accompanied by drought conditions (see Burt 2004 for an overview of the event in the UK) and 1947 and 1949. Again the accounted variance of these two modes is only a modest 13% and 12% each and a total of 30% accounted variance (Table 2).

3.4.1 *Lagged and simultaneous Mediterranean precipitation*

Recently Vautard et al. (2007) documented the link between preceding winter and spring precipitation (JFMA) in the Mediterranean region as a possible useful predictor of the occurrence of HWs in Europe. However, since their composite analysis is restricted to the last 50 years, we decided to perform this analysis over a longer period which our data affords us and using the CCA model framework. Figure 8 shows the first canonical patterns and scores between PRECME (JFMAM) and HWs. The first canonical pattern shows that strong negative anomalies (canonical correlation between –0.5 and –0.7, only significant in the east of the PRECME domain, Fig. 8a) of precipitation over the PRECME area are linked to a significantly higher frequency of HWs over central western Europe and the Iberian Peninsula. However, the overall canonical correlation is weak (0.42) and overall this CCA only accounts for 6% of HW variability. Interestingly the hindcast (Fig. 8d) results reveals significant skill in central and western Europe with correlation skill scores in the order of 0.3 and up to 0.5 indicating that around 10–20% of HW occurrence can be accounted for using this region's lagged precipitation. Our CCA 1 spatial patterns (Fig. 8a, b) are very similar to the station based composite figures presented in Vautard et al. (2007).

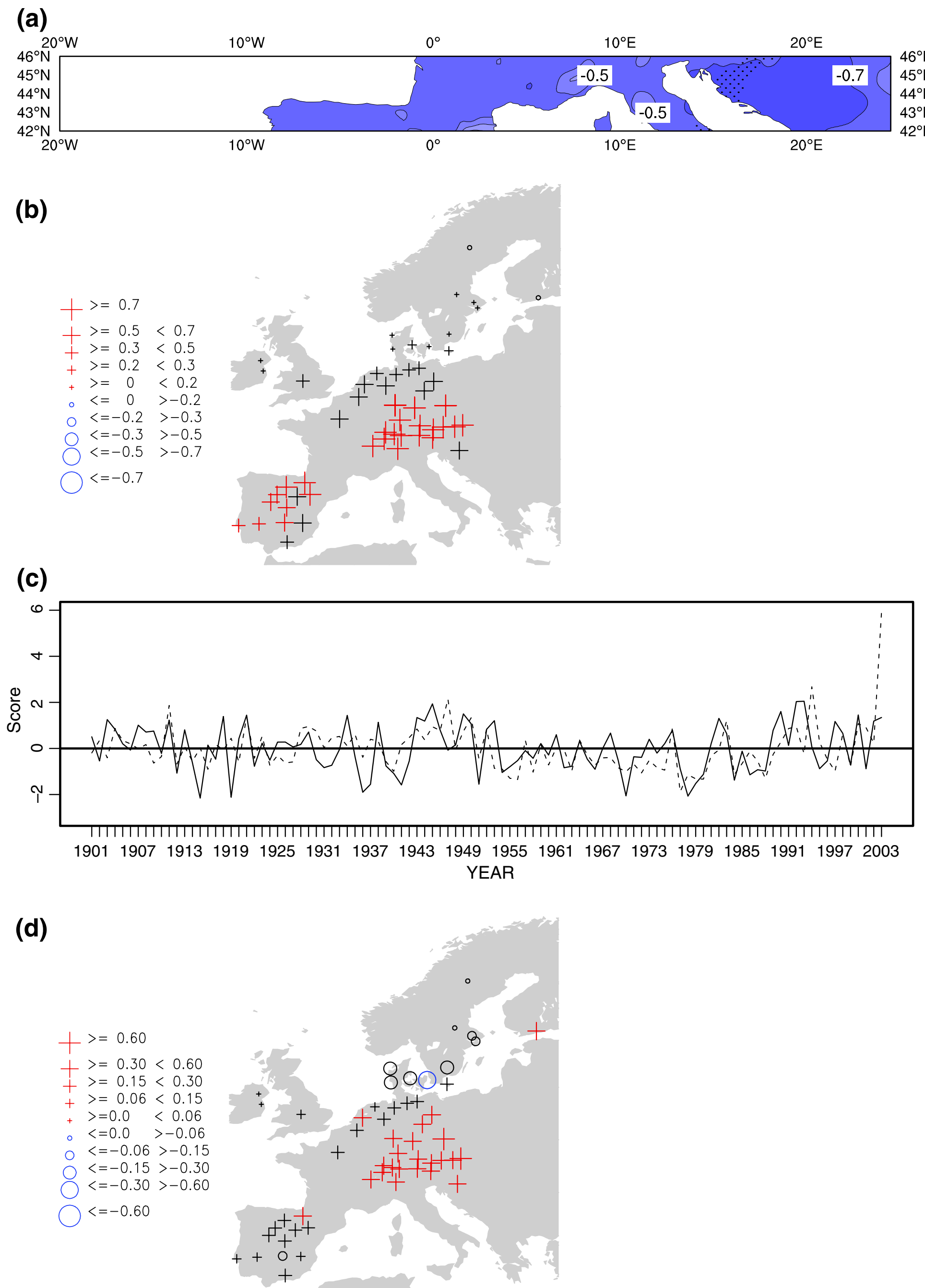

Fig. 8 The first CCA between JFMAM averaged PRECME and the JJA HW index which accounts for approximately 6.2% of JJA HW variability. **a** The canonical PRECME pattern, **b** the HW canonical pattern and **c** the canonical score series from 1901 to 2003. In **b** the sizes of the crosses ('+') and open circles ('o') show the canonical loadings expressed as a correlation coefficient for each station according to the legend on the left of the figure. In **c** the *solid and dashed lines* are the PRECME and HW canonical score series, respectively, with a significant (5% level) canonical correlation of 0.42. **d** The Spearman rank hindcast skill score of the CCA between JFMAM averaged PRECME and the JJA HW index. The model was built in the period 1901–1971 and the model hindcast in the remaining, 1972–2003 period. The sizes of the crosses ('+') and open circles ('o') show the magnitude of the skill score according to the legend on the left of the figure. *Coloured symbols* in **b** and **d** and *stippling* in **a** indicate statistical significance (5% level)

3.5 Multiple simultaneous predictors of heat waves

In the experiments presented earlier between simultaneous SLP, SSTNA and PRECWE, the predictors were all highly correlated with HWs (based on the results in Table 2 and accounting for around 33% of the total variance based on the canonical correlations). However, are each of the predictors, SLP, SSTNA and PRECWE all simply collinear? To try and answer this we have combined the predictors using the methodology described in Sect 2.3 to see if more variance of HWs can be accounted for by a combination of predictors (e.g., Xoplaki et al. 2003a, b). Figure 9 shows the combined CCA 1 loadings and score series. The CCA loadings for each predictor are similar to the single predictor CCA loadings shown in Fig. 5a for SLP, and SSTNA and PRECWE (not shown). Statistically significant correlations indicate that higher frequency of HWs in the north of the domain are associated with anomalously high SLP

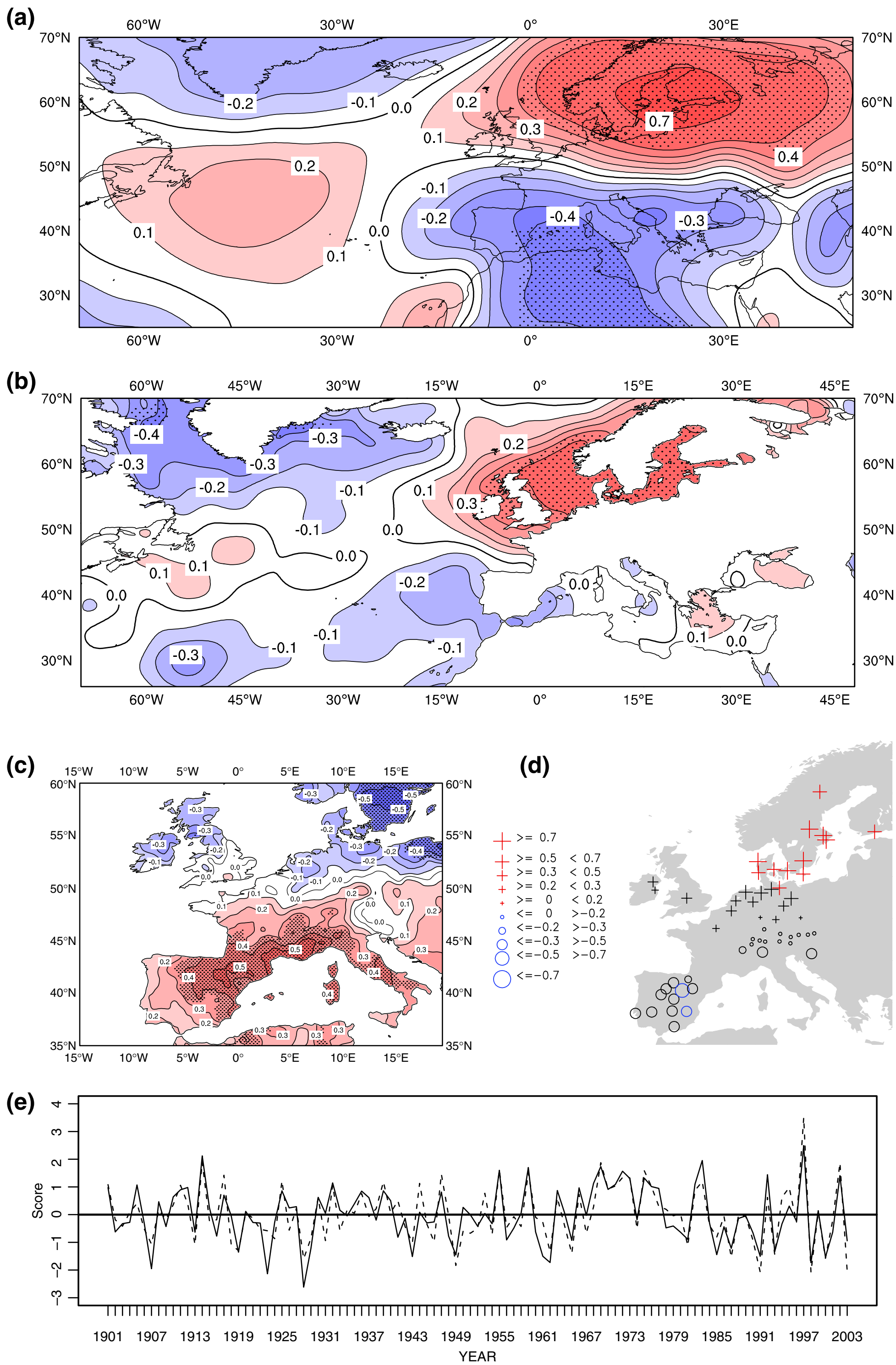

Fig. 9 The first multiple predictor CCA between JJA averaged SLP, SSTNA, PRECWE and the JJA HW index which accounts for approximately 14.2% of JJA HW variability. **a** The SLP canonical pattern, **b** the SSTNA canonical pattern, **c** the PRECWE canonical pattern, **d** the HW canonical pattern and **e** the canonical score series from 1901 to 2003. In **d** the sizes of the crosses (‘+’) and open circles (‘o’) show the canonical loadings expressed as a correlation coefficient for each station according to the legend in the left of the figure. In **e** the *solid and dashed lines* are the multiple predictor and HW canonical score series, respectively, with a significant (5% level) canonical correlation of 0.86. Coloured symbols in **d** and stippling in **a**–**c** indicate statistical significance (5% level)

over Scandinavia, significantly warmer SSTNA in the North sea and Baltic regions and precipitation deficiencies in northern Europe. The second multiple CCA (Fig. 10) patterns also resemble the loading patterns identified in Fig. 6a for SLP and SSTNA and PRECWE (not shown). Higher frequency of HWs over the western half of the domain are associated with anomalous high pressure over central western Europe (similar to the pattern identified in the 300 hPa level in Xoplaki et al. 2003), warm SSTs in the Mediterranean and westward to the Azores and the east coast of North America and precipitation

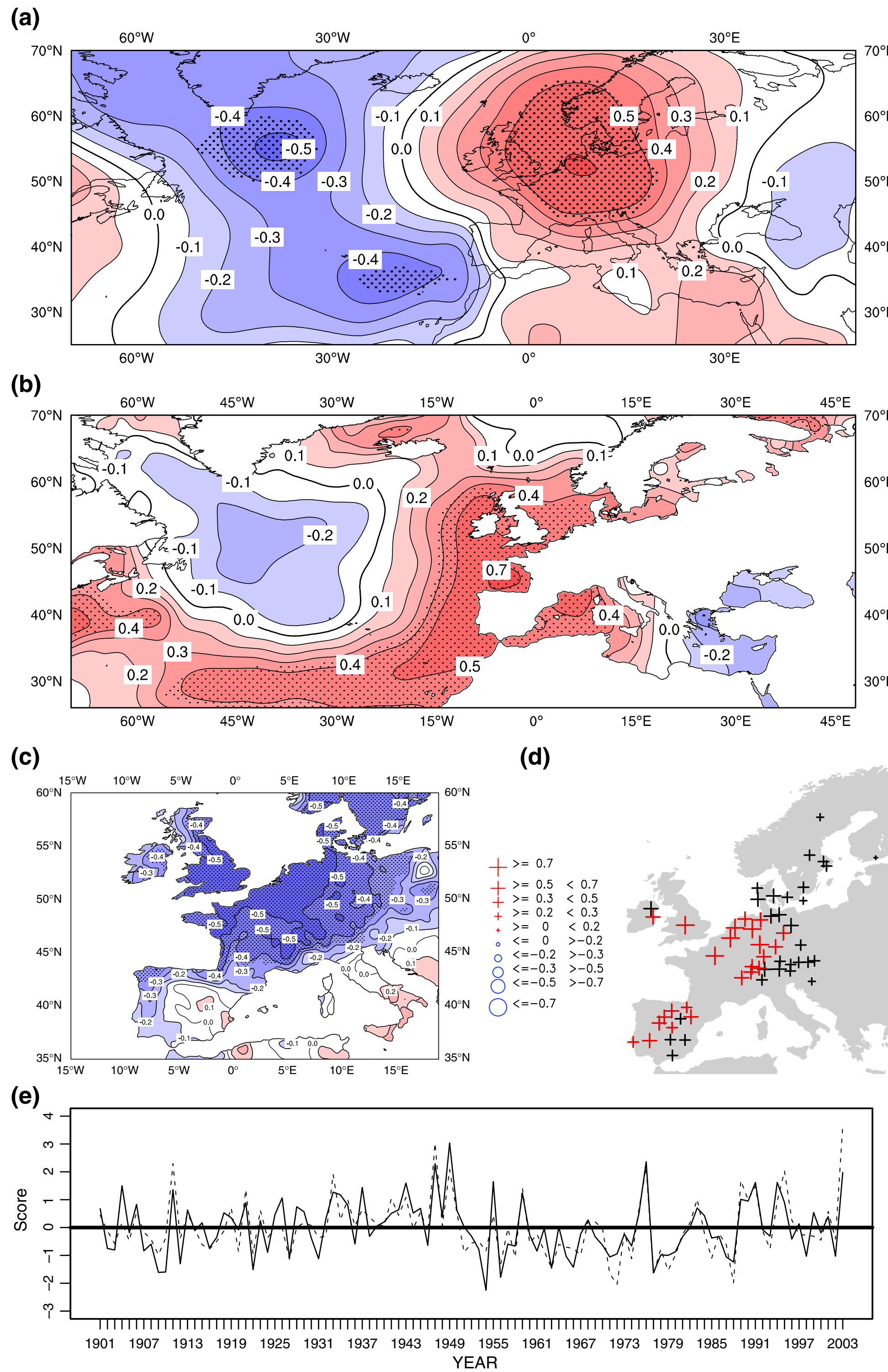

Fig. 10 The second multiple predictor CCA between JJA averaged SLP, SSTNA, PRECWE and the JJA HW index which accounts for approximately 19.6% of JJA HW variability. **a** The SLP canonical pattern, **b** the SSTNA canonical pattern, **c** the PRECWE canonical pattern, **d** the HW canonical pattern and **e** the canonical score series from 1901 to 2003. In **d** the sizes of the crosses ('+') and open circles ('o') show the canonical loadings expressed as a correlation coefficient for each station according to the legend in the left of the figure. In **e** the solid and dashed lines are the multiple predictor and HW canonical score series, respectively, with a significant (5% level) canonical correlation of 0.83. *Coloured symbols* in **d** and *stippling* in **a**, **b** and **c** indicate statistical significance (5% level)

deficiencies in western European. This pattern also clearly shows that atmospheric blocking of the westerlies is occurring since negatively anomalous SLP occurs in the central North Atlantic and is associated with anomalously cool SSTs in the same area (Fig. 10, stippled areas).

The total accounted variance of this multiple CCA is 46% (Table 2) which is substantially higher than the other CCAs involving only one of the predictors. This indicates that the variability between SLP, SSTNA and PRECWE is not entirely collinear and that it is necessary to consider more than just one of these meteorological parameters to account for the occurrence of summer HWs. These results suggest that it will be important to consider the physical processes that lead to the observed variability in all four of these parameters and their feedback processes.

3.6 Multiple lagged predictors of heat waves

In this section we explore the use of a CCA model with lagged SSTs and lagged Mediterranean precipitation as predictors of summer HW since in the previous subsections and as suggested by earlier studies they show the most promise of predictability. We used DJF SSTAT and JFMAM PRECWE as predictors of JJA HWs. The first CCA (Fig. 11a) shows a classic tripole pattern with anomalously cool SSTs east of Newfoundland, warm SSTs over most of central northern Atlantic and cool SSTs in the tropical North Atlantic. The extent of the stippled area is small and so the statistical significance of this SST pattern is low. This pattern is also associated with an anomalously dry northern Mediterranean region over the extended season JFMAM (Fig. 11b, stippled areas) and results in more HWs over the central Europe and the Iberian Peninsula (Fig. 11c, red coloured crosses). Of all the models summarised in Table 2 which are capable of being used to predict the occurrence of HWs in time this model has the highest overall hindcast skill (Fig. 11e). The model $\mu_{\text{hindcast}} = 0.28 \pm 0.28$ correlation skill score indicates that the model accounts for between approximately 0 and 35% of HW variability with significant hindcast skill in central western Europe and the Iberian Peninsula (Fig. 11e).

4 Discussion

4.1 Heat wave changes

Summer HWs have significantly increased in frequency at most stations since 1880 and are likely to continue to increase (e.g., Huth et al. 2000; Beniston 2004, Meehl and Tebaldi 2004; Schär et al. 2004) due to anthropogenic influences on climate. We have observed increases in the average frequency of HWs of 0.24 per decade since 1880 over western Europe.

4.2 Circulation influence

Our results demonstrate evidence that the summer Azores high has increased in strength, that average SLP over some parts of Europe has increased significantly and the summer Icelandic low has deepened (Fig. 2). This analysis is supported by Hurrell and Folland (2002) who document an increase in the summer NAO. We have found two patterns of atmospheric circulation that are important for the formation of heat waves similar to those obtained by Cassou et al. (2005). One with anomalously high SLP centered over Scandinavia and low SLP south of Greenland, the Mediterranean and North Africa. Resulting in anomalously high frequency of HWs in northern western Europe. The other pattern shows a distinct wave pattern with anomalously low SLP in the central North Atlantic, high SLP over central western Europe and low SLP over northeast Europe. Findell and Delworth (2005) show a strengthening of this wave pattern in doubled CO_2 experiments. Philipp et al. (2007) classified the daily SLP dataset of Ansell et al. (2006) (as used in this paper) using a cluster analysis technique based on simulated annealing. They show that on the daily time scale the seasonal cluster frequency JJA cluster number 1 is increasing in frequency. The spatial pattern of this cluster centroid is similar to the anomalous SLP pattern shown in Fig. 6a. Using only SLP as a predictor resulted in around 32% of HW occurrence being accounted for which is probably due to missing covariates and/or that the large-scale seasonally averaged SLP data used are not able to resolve the regional scale state of atmospheric circulation. Improved simultaneous skill of the CCA may be found by combining upper-level circulation data with the SLP data as is the case in Xoplaki et al. (2003b), however, we did not consider this due to the lack of systematic upper-air observations before the 1950s. However, there may be some promise in using reconstructed upper-air data such as those described in Schmutz et al. (2001).

4.3 SST and regional precipitation influence

SSTs have become significantly warmer over the central North Atlantic; however, there is also a pronounced cooling south of Greenland. North Atlantic SSTs are an important factor in the decadal modulation of HWs as illustrated in Fig. 7. There is some evidence (Fig. 7) that the AMO index leads the occurrence of western European HWs. However, since we only have observed approximately two cycles of this phenomenon the deduction of phase relationships is speculative. We also show that global warming, as measured by the global mean temperature series, could also be modulating the occurrence of HWs in western Europe.

The influence of winter and spring SSTs on European summer temperature has been discussed by Col-

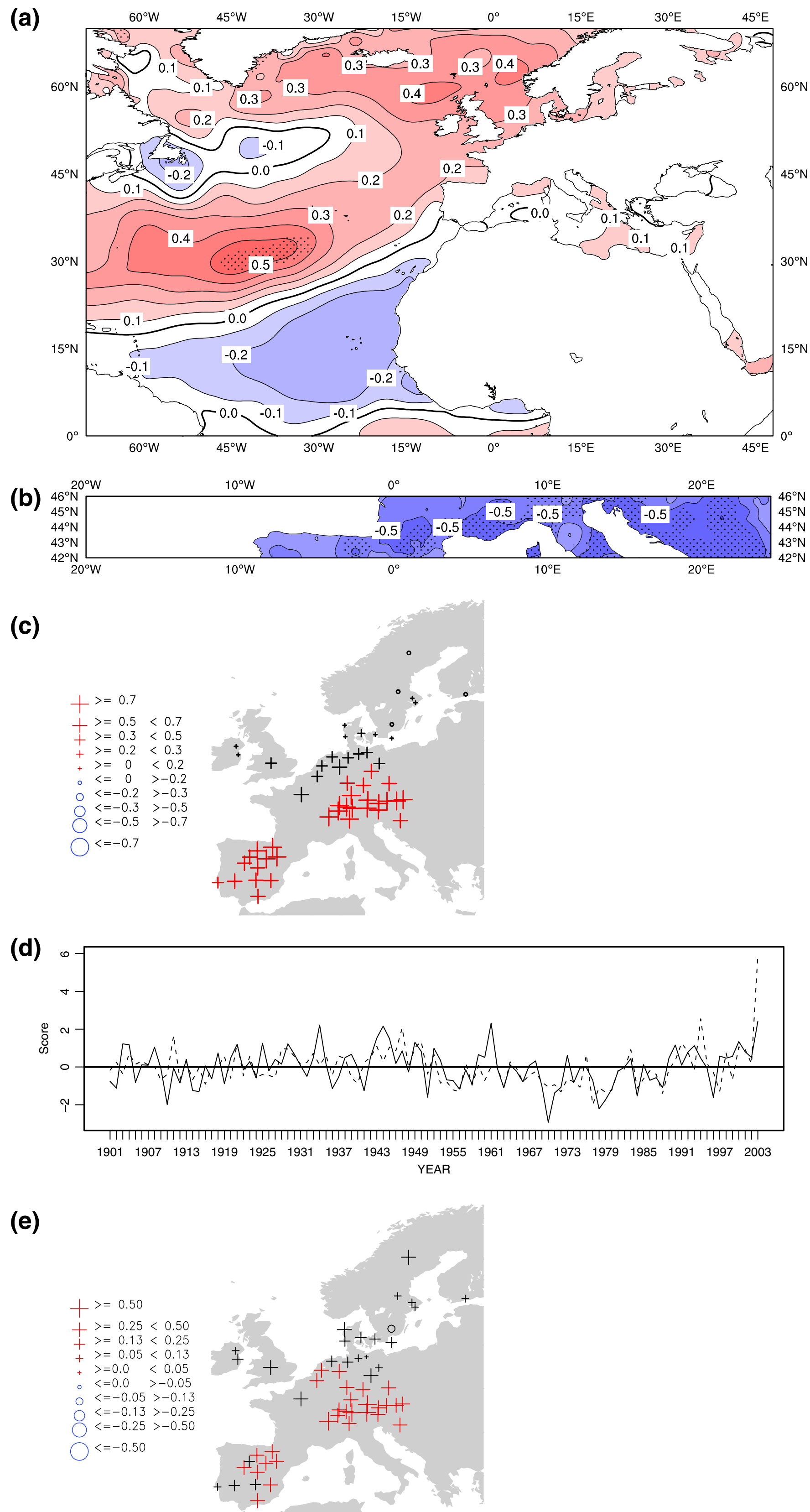

Fig. 11 The first multiple predictor CCA between DJF averaged SSTAT, JFMAM PRECME and the JJA HW index which accounts for approximately 10.1% of JJA HW variability. **a** The SSTNA canonical pattern, **b** the PRECWE canonical pattern, **c** the HW canonical pattern and **d** the canonical score series and **e** the hindcast (1982–2003) Spearman rank correlation skill score. In **c** and **e** the sizes of the crosses ('+') and open circles ('o') show the canonical loadings expressed as a correlation coefficient and the Spearman rank correlation skill score, respectively, for each station. In **d** the *solid and dashed lines* are the multiple predictor and HW canonical score series, respectively, with a significant (5% level) canonical correlation of 0.56. *Coloured symbols* in **c** and **e** and *stippling* in **a** and **b** indicate statistical significance (5% level)

man and Davey (1999). In this study it was suggested that the warm SSTs noticeable in JJA (see Fig. 10b) close to the European coast and extending in Azores region are likely to be the result air-to-sea interaction and the westward advection of heat. The excess heat was suggested to be gained by a sea-to-air interaction from previous (winter and spring) North Atlantic SSTs. We believe another plausible explanation for higher JJA SSTs associated with a higher number of HWs (see Figs. 11a, b) is due simply to the presumed increased insolation as a result of anomalously high pressure over the same region(s). However, as shown in Figs. 10, 11 and Table 2, SLP, SSTNA and PRECWE are not collinear, but increase the skill of the CCA model and hence represent a complex chain of regional and large-scale feedback processes. We have not investigated this complex chain of causality since it is beyond the scope of this paper. One way to tackle this problem would be to perform sensitivity experiments with a Regional Climate Model (RCM).

European summer precipitation shows some evidence that it has decreased in isolated areas although not significantly over the western Europe area. Some studies show that it is likely to decrease in the future (Pal et al. 2004) which will affect the soil moisture content (Findell and Delworth 2005) and increase the likelihood of hot extreme temperatures (Brabson et al. 2005). A preceding dry winter and spring Mediterranean initiates a regional soil moisture feedback process between regional temperature and precipitation (Schär et al. 1999; Seneviratne et al. 2006; Vautard et al. 2007) that is capable of amplifying the affects of anomalous large-scale circulation patterns.

On the interannual timescale we have shown that winter North Atlantic SSTs and the extended season, JFMAM Mediterranean precipitation can be used to predict around 15–25% of summer western European HW variability (Colman 1997; Colman and Davey 1999; Vautard et al. 2007), however, possibly other important predictors we have not explored such as the Eurasian winter snow cover extent (Qian and Saunders 2003). We experimented with other time periods of PRECME as possible predictors of JJA HWs and found that if only JFMA PRECME is used (i.e., giving one month lead in the forecast) then the hindcast skill was only marginally weaker. We also tested MAM PRECME and May PRECME to measure the influence of spring precipitation on the prediction of JJA HW and found that the hindcast skill scores were reduced substantially. This indicates that winter precipitation is more important than spring precipitation in the prediction of summer HWs.

4.4 Tropical influence

The work of Cassou et al. (2005) demonstrates that there is a significant influence from the tropical Atlantic region on the formation of Rossby wave trains and atmospheric blocking conditions necessary to have anomalous summer heat waves. When Cassou et al. (2005) force their model with anomalously high tropical Atlantic diabatic heating there is an increased occurrence of two modes of atmospheric circulation they call *Blocking* and *Atlantic Low*. Both of these modes are associated with higher than average frequency of warm summer days in France and are very similar in appearance to the two CCA circulation modes shown in Figs. 5a and 6a, respectively.

Preliminary analysis into the teleconnections between tropical Atlantic precipitation (as a proxy for tropical diabatic heating) and European summer HWs from 1880 using CCA seems to confirm that there is a tropical influence. However, we have not pursued these investigations in the present paper since the statistical significance of the CCA between JJA tropical African precipitation and JJA HWs indicate that these connections are weak. Possible factors confounding the CCA analysis could be intraseasonal differences in the tropical forcing shown by Cassou et al. (2005) to be important.

4.5 Predictability of HWs and non-linear effects

From the discussion above it is clear that many different factors are affecting the occurrence of European HWs. Our best statistical prediction model on the interannual timescale utilises lagged SSTs and lagged Mediterranean precipitation with skill scores at best around 0.5. We have used linear methods based on anomalies and as Campbell (2005) suggests these types of models may not be the best to use when non-linear processes are involved. We have noticed that the CCA models in Figs. 6c, 8c, 10e and 11d have systematically underestimated the 2003 heat wave and it has been suggested that this may be due to a soil moisture feedback threshold being exceeded (Ferranti and Viterbo 2006) that drastically alters the linearity between predictor variables. We should therefore investigate the use of other statistical techniques to compliment the efforts being made by seasonal dynamical models in the prediction of these events. Predictability at the decadal and interdecadal timescales appears to be modulated by the AMO. With a forecast of multidecadal weakening of the AMO in the next 50 years (Knight et al. 2005) the increase in

HWs expected from anthropogenic influences (Schär et al. 2004; Stott et al. 2004) could be partially offset making the summer climate of Europe less extreme than it otherwise would be.

4.6 CCA issues

At the beginning of the analysis period (1880) approximately half of the stations have data. This number increases almost to the maximum number of stations by 1900. The missing values were filled with the long-term mean HW occurence at each station; this could have had an effect on the results of the PCA analysis (Sect. 2.3). Since this action could of subsequently biased all CCAs we repeated all analyses with a subset of only the longest and most complete stations in the database (27 in total). A comparison of the results shows (not shown) that the number of stations included in the CCAs has a small effect on their patterns and scores series but does not affect the overall conclusions stated above. Our conclusions are also robust to excluding the year 2003 from our analysis.

Most CCA models which could be used for climate prediction showed weak canonical correlations indicating that the statistical relationships were weak and that the overall accounted for variance of HWs was low. However, careful Monte Carlo, cross-validation and hindcast experiments indicated that indeed these CCA models have some practical skill and are not being overfitted. Simple experiments increasing the number of predictor PCs in any of the CCAs shown, increased the accounted variance of the CCA and usually decreased the hindcast skill of the model.

5 Conclusions

We have created a new homogenised daily maximum temperature data set to document the long-term trends of HWs over western Europe since 1880 and their relationship to large-scale forcing variables. This dataset is part of an ongoing effort to improve the homogeneity of long-term daily temperature time series over Europe. For the first time, temperature data have been homogenised at the daily timescale using a new method that is capable of homogenising the higher order moments of the probability distribution. Previous methods of homogenising daily temperature records only explicitly homogenise the mean of the probability distribution.

Using a statistical approach we confirm that atmospheric circulation, North Atlantic SSTs and precipitation over western Europe are related to western European HWs. This analysis has been performed over a longer period and over a larger domain than earlier studies. The CCA analyses document the important large-scale modes associated with HW events over the last 124 years. Previous studies looking at large-scale relationships with temperature have used mean temperature, however, this study uses an extreme index (HW) that combines a measure of the extremity of warm temperatures and a measure of persistence. However, generally the same large-scale modes of circulation, SST and precipitation are related to mean temperature and HWs.

We have shown that on multidecadal timescales summer HWs are related to the AMO which was previously only shown for mean summer temperature (Sutton and Hodson 2005). However, we cannot confirm whether the global mean temperature or the AMO are driving multidecadal variability in western European HWs.

We have extended previous interannual summer temperature predictability analyses in both temporal and spatial domain. Using winter SSTs as well as winter and spring precipitation as a proxy for soil moisture results in useful interannual predictive skill of HWs over central and southern western Europe.

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6 Appendix

Table 3.

Table 3 A list of high quality daily maximum temperature time series used in this study

Station name	Country	Data availability	Latitude	Longitude	Elevation	Daily homogenisation	Number of breakpoints	HOM method	Metadata and/or previous study
Graz-University	Austria	01/01/1894–31/12/2003	48°05′N	15°27′E	366	Yes	3	++	Auer et al. (2001)
Innsbruck-University	Austria	01/01/1880–31/12/2003	47°16′N	11°24′E	577	Yes	2		Auer et al. (2001)
Kremsmünster	Austria	01/01/1880–31/12/2003	48°03′N	14°08′E	383	Yes	8	++	Auer et al. (2001)
Salzburg	Austria	01/01/1880–31/12/2003	47°48′N	13°00′E	437	Yes	8		Auer et al. (2001)
Sonnblick	Austria	01/01/1886–31/12/2003	47°03′N	12°57′E	3,106	No	0		Auer et al. (2001)
Vienna	Austria	01/01/1880–31/12/2003	48°14′N	16°21′E	198	Yes	5		Auer et al. (2001)
Brussels-Uccle	Belgium	01/01/1880–31/12/2003	50°54′N	4°32′E	55	Yes	0		Demarée et al. (2002)
Zagreb	Croatia	01/01/1881–31/12/2003	45°49′N	15°59′E	157	No	?		
Prag	Czech Republic	01/01/1880–31/12/2003	50°05′N	14°25′E	191	Yes	4	–+	RHTest
Hammer-Odde-Fyr	Denmark	01/01/1880–31/12/2003	55°17′N	14°47′E	12	No	?		
Köbenhavn	Denmark	01/01/1880–31/12/2003	55°41′N	12°32′E	9	Yes	3		RHTest
Nordby	Denmark	01/01/1880–31/12/2003	55°27′N	8°24′E	4	No	?		
Tranebjerg	Denmark	01/01/1880–31/12/2003	55°51′N	10°36′E	11	Yes	3	–	RHTest
Vestervig	Denmark	01/01/1880–31/12/2003	56°46′N	8°19′E	18	No	?		
Helsinki	Finland	01/01/1880–31/12/2003	60°19′N	24°58′E	51	No	?		
Paris-Parcmontsouris	France	01/01/1880–31/12/2003	48°49′N	2°20′E	75	Yes	5	++	Caussinus and Mestre (2004)
Bamberg	Germany	01/01/1880–31/12/2003	49°53′N	10°53′E	282	Yes	3	++	Herzog and Müller-Westermeier (1998)
Bremen	Germany	01/01/1890–31/12/2003	53°02′N	8°47′E	5	Yes	3	++	Herzog and Müller-Westermeier (1998)
Frankfurt	Germany	01/01/1880–31/12/2003	50°07′N	8°40′E	103	Yes	1	++	Herzog and Müller-Westermeier (1998)
Halle	Germany	01/01/1900–31/12/2003	51°29′N	11°59′E	104	Yes	1	++	Herzog and Müller-Westermeier (1998)
Hamburg-Bergedorf	Germany	01/01/1891–31/12/2003	53°29′N	10°15′E	35	Yes	1	++	Herzog and Müller-Westermeier (1998)
München	Germany	01/01/1880–31/12/2003	48°10′N	11°30′E	515	Yes	2	–+	Herzog and Müller-Westermeier (1998)
Münster	Germany	01/01/1891–31/12/2003	51°58′N	7°36′E	63	Yes	5	++	Herzog and Müller-Westermeier (1998)
Potsdam	Germany	01/01/1893–31/12/2003	52°23′N	13°04′E	81	No	0		Herzog and Müller-Westermeier (1998)
Schwerin	Germany	01/01/1890–31/12/2003	53°38′N	11°23′E	59	Yes	2	++	Herzog and Müller-Westermeier (1998)
Stuttgart	Germany	01/01/1900–31/12/2003	48°43′N	9°13′E	401	Yes	3	–+	Herzog and Müller-Westermeier (1998)
Dublin	Ireland	01/01/1881–31/12/2003	53°22′N	6°21′W	68	No	?		
De-Bilt	Netherlands	01/01/1901–31/12/2003	52°06′N	5°11′E	2	Yes	3	++	Pers. comms Albert Klein Tank
Eelde	Netherlands	01/03/1906–31/12/2003	53°08′N	6°35′E	4	Yes	3	++	Pers. comms Albert Klein Tank
Lisboa-Geofisica	Portugal	01/01/1901–31/12/2003	38°43′N	9°09′W	77	Yes	4	–+	
Albacete	Spain	14/11/1893–31/12/2003	38°57′N	1°52′W	704	Yes	1		Brunet et al. (2006)
Badajoz	Spain	01/01/1880–31/12/2003	38°53′N	6°50′W	185	Yes	2		Brunet et al. (2006)
Burgos	Spain	01/12/1880–31/12/2003	42°22′N	3°43′W	881	Yes	2		Brunet et al. (2006)
Ciudad Real	Spain	01/12/1893–31/12/2003	38°59′N	3°55′W	627	Yes	6		Brunet et al. (2006)

Table 3 continued

Station name	Country	Data availability	Latitude	Longitude	Elevation	Daily homogenisation	Number of breakpoints	HOM method	Metadata and/or previous study
Granada	Spain	01/11/1893–31/12/2003	37°08′N	3°38′W	680	Yes	2		Brunet et al. (2006)
Madrid	Spain	01/01/1880–31/12/2003	40°25′N	3°41′E	667	Yes	2		Brunet et al. (2006)
Pamplona	Spain	01/04/1880–31/12/2003	42°46′N	1°38′W	459	Yes	3		Brunet et al. (2006)
Salamanca	Spain	01/11/1893–31/12/2003	40°57′N	5°29′W	618	Yes	3		Brunet et al. (2006)
Soria	Spain	18/11/1893–31/12/2003	41°26′N	2°29′E	1,082	Yes	1		Brunet et al. (2006)
Valladolid	Spain	12/12/1893–31/12/2003	41°38′N	4°46′W	735	Yes	2		Brunet et al. (2006)
Zaragoza	Spain	01/09/1887–31/12/2003	41°40′N	1°01′W	247	Yes	2		Brunet et al. (2006)
Falun	Sweden	01/10/1902–31/12/2003	60°37′N	15°40′E	157	Yes	2	–+	RHTest
Stensele	Sweden	01/01/1891–31/12/2003	65°04′N	17°09′E	325	No	?		
Stockholm	Sweden	01/01/1880–31/12/2003	59°21′N	18°03′E	44	Yes	1	++	Moberg et al. (2002)
Uppsala	Sweden	01/01/1880–31/12/2003	59°52′N	17°38′E	13	Yes	3	++	Bergström and Moberg (2002)
Växjö	Sweden	01/01/1891–31/12/2003	56°52′N	14°48′E	166	No	?		
Basel	Switzerland	01/01/1901–31/12/2003	47°33′N	7°35′E	316	Yes	6	++	Begert et al. (2005)
Bern	Switzerland	01/01/1880–31/12/2003	46°56′N	7°25′E	570	Yes	8	++	Begert et al. (2005)
Geneva	Switzerland	01/01/1880–31/12/2003	46°15′N	6°08′E	420	Yes	2	++	Begert et al. (2005)
Lugano	Switzerland	01/07/1880–31/12/2003	46°00′N	8°58′E	273	Yes	4		Begert et al. (2005)
Säntis	Switzerland	01/01/1901–31/12/2003	47°15′N	9°21′E	2,490	Yes	5		Begert et al. (2005)
Zürich	Switzerland	01/01/1882–31/12/2003	47°23′N	8°34′E	556	Yes	6	++	Begert et al. (2005)
Armagh	United Kingdom	01/01/1880–31/12/2003	54°21′N	6°65′W	62	Yes	3	++	Butler et al. (2005)
CET	United Kingdom	01/01/1880–31/01/2003	52°25′N	1°50′W	78	Yes	3		Parker and Horton (2005); Parker et al. (1992)

The first six columns show the basic metadata of the station series. Column seven shows whether or not the series has explicitly been homogenised at the daily timescale either by the methods described in this paper or others listed in column ten. Column eight shows the number of inhomogeneities (break points) identified and corrected in each series. A question mark in this column indicates that there are an unknown number of break points in the series. The ninth column indicates the whether the Higher Order Moments method of Della-Marta and Wanner (2006) has been used to homogenise the daily temperature time series. HOM Method ++ means that the Higher Order Moments Method has been applied with reliable metadata for the candidate and the reference series, for HOM Method +– (–+) the candidate (reference) record has reliable metadata and the reference (candidate) has metadata only from the RHTest. The last column of the table either lists the source of reliable metadata or the label 'RHTest' shows that the relative homogeneity test by Wang (2003) was used to obtain information about inhomogeneities in the record on a monthly and annual timescale

Reference

Alexander LV, et al (2006) Global observed changes in daily climate extremes of temperature and precipitation. J Geophys Res 111:D05109

Ansell TJ, et al (2006) Daily mean sea level pressure reconstructions for the European–North Atlantic region for the period 1850–2003. J Climate 19:2717–2742

Auer I, Böhm R, Schöner W (2001) Austrian long-term climate 1767–2000 multiple instrumental climate time series from central Europe. Techn. Ber., Zentralanstalt für Meteorologie und Geodynamik, Wien

Barnston AG, Livezey RL (1987) Classification, seasonality and persistence of low frequency atmospheric circulation patterns. Mon Wea Rev 117:1083–1123

Beck C, Grieser J, Rudolf B (2005) A new monthly precipitation climatology for 2005 the global land areas for the period 1951 to 2000. DWD, Klimastatusbericht KSB 2004, ISBN 3-88148-402-7:181–190

Begert M, Schlegel T, Kirchhofer W (2005) Homogeneous temperature and precipitation series of Switzerland from 1864 to 2000. Int J Climatol 25:65–80

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 31:2202–2202

Bergström H, Moberg A (2002) Daily air temperature and pressure series for Uppsala (1722–1998). Clim Change 53:213–252

Bhend J (2005) North Atlantic and European cyclones: their variability and change from 1881 to 2003. Master Thesis, Institute of Geography, University of Bern, Switzerland

Black E, Blackburn M, Harison G, Hoskins B, Methven J (2004) Factors contributing to the summer 2003 European heatwave. Weather 59:217–223

Brabson BB, Lister DH, Jones PD, Palutikof JP (2005) Soil moisture and predicted spells of extreme temperatures in Britain. J Geophys Res 110:D05104. doi:10.1029/2004JD005156

Brohan P, Kennedy JJ, Haris I, Tett SFB, Jones PD (2006) Uncertainty estimates in regional and global observed temperature changes: a new dataset from 1850. J Geophys Res 111:D12106. doi:10.1029/2005JD006548

Brunet M, Saladié O, Jones PD, Sigró J, Aguilar E, Moberg A, Lister D, Walther A, López (2006) The development of a new dataset of Spanish daily adjusted temperature series (SDATS) (1850-2003). Int J Climatol 26:1777–1802

Burt S (2004) The August 2003 heatwave in the United Kingdom: Part 1—Maximum temperatures and historical precedents. Weather 59:199–208

Butler CJ, Suarez AMG, Coughlin ADS, Morrell C (2005) Air temperatures at Armagh observatory, northern Ireland, from 1796 to 2002. Int J Climatol 25:1055–1079

Campbell EP (2005) Statistical modeling in nonlinear systems. J Climate 18:3388–3399

Cassou C, Terray L, Phillips AS (2005) Tropical Atlantic influence on European heat waves. J Climate 18:2805–2811

Caussinus H, Mestre O (2004) Detection and correction of artificial shifts in climate series. J Roy Stat Soc C-App 53:405–425

Chatfield C (1996) The analysis of time series, an introduction. Chapman and Hall. 5. Aufl

Cherry S (1996) Singular value decomposition analysis and canonical correlation analysis. J Climate 9:2003–2009

Cleveland WS, Devlin SJ (1988) Locally-weighted fitting: an approach to fitting analysis by local fitting. J Am Stat Assoc 83:596–610

Collins D, Della-Marta P, Plummer N, Trewin B (2000) Trends in annual frequencies of extreme temperature events in Australia. Aust Met Mag 49:277–292

Colman A (1997) Prediction of summer central England temperature from preceding North Atlantic winter sea surface temperature. Int J Climatol 17:1285–1300

Colman A, Davey M (1999) Prediction of summer temperature, rainfall and pressure in Europe from preceding winter North Atlantic ocean temperature. Int J Climatol 19:513–536

Della-Marta P, Collins D, Braganza K (2004) Updating Australia's high quality annual temperature dataset. Aust Met Mag 53:75–93

Della-Marta PM, Wanner H (2006) A method of homogenising the extremes and mean of daily temperature measurements. J Climate 19:4179–4197

Demarée G, Lachaert P, Verhoeve T, Thoen E (2002) The long-term daily Central Belgium Temperature (CBT) series (1767–1998) and early instrumental meteorological observations in Belgium. Clim Change 53:269–293

Domonkos P, Kysely J, Piotrowicz K, Petrovic P, Likso T (2003) Variability of extreme temperature events in South-Central Europe during the 20th century and its relationship with large-scale circulation. Int J Climatol 23:987–1010

Easterling D, Peterson T (1995) A new method for detecting undocumented discontinuities in climatological time series. Int J Climatol 15:369–377

Efron B, Gong G (1983) A leisurely look at the bootstrap, the jackknife, and cross-validation. Am Stat 37:36–48

Enfield DB, Mestas-Nunez AM, Trimble PJ (2001) The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental US. Geophys Res Lett 28:2077–2080

Ferranti L, Viterbo P (2006) The European summer of 2003: sensitivity to soil water initial conditions. J Climate 19:3659–3680

Findell KL, Delworth TL (2005) A modeling study of dynamic and thermodynamic mechanisms for summer drying in response to global warming. Geophys Res Lett 32:L16702

Fink A, Brucher T, Kruger A, Leckebush G, Pinto J, Ulbrich U (2004) The 2003 European summer heatwaves and drought—synoptic diagnosis and impacts. Weather 59:209–216

Frich P, Alexander L, Della-Marta P, Gleason B, Haylock M, Klein Tank A, Peterson T (2002) Observed coherent changes in climatic extremes during the second half of the twentieth century. Clim Res 19:193–212

Gruber S, Hoelzle M, Haeberli W (2004) Permafrost thaw and destabilization of Alpine rock walls in the hot summer of 2003. Geophys Res Lett 31:L13504

Haylock M, Goodess C (2004) Interannual variability of European extreme winter rainfall and links with mean large-scale circulation. Int J Climatol 24:759–776

Herzog J, Müller-Westermeier G (1998) Homogenitätsprüfung und Homogenisierung klimatologischer Messreihen im Deutschen Wetterdienst. Techn. Ber. 202, Deutscher Wetterdienst

Hess P, Brezowsky H (1977) Katalog der Großwetterlagen Europas 1881–1976. Techn. Ber. 3. Auflg., Ber. d. 113, Deutscher Wetterdienst, Offenbach

Hurrell JW, Folland CK (2002) A change in the summer atmospheric circulation over the North Atlantic. CLIVAR Exchanges 7:52–54

Huth R, Kysely J, Pokorna L (2000) A GCM simulation of heat waves, dry spells, and their relationships to circulation. Clim Change 46:29–60

IPCC (2001) Climate Change 2001: the scientific basis contribution of working group I to the third assessment report of the intergovernmental panel on climate change (IPCC). Cambridge University Press, Cambridge

Klein Tank A (2002) Climate of Europe: assessment of observed daily temperature extremes and precipitation events. De Bilt, KNMI., Techn. Ber., KNMI, De Bilt, The Netherlands

Klein Tank A, et al (2002) Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment. Int J Climatol 22:1441–1453

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

Klein Tank AMG, Können GP, Selten FM (2005) Signals of anthropogenic influence on European warming as seen in the trend patterns of daily temperature variance. Int J Climatol 25:1–16

Knight JR, Allan RJ, Folland CK, Vellinga M, Mann ME (2005) A signature of persistent natural thermohaline circulation cycles in observed climate. Geophys Res Lett 32:L20708. doi:10.1029/2005GL024233

Koppe C, Kovats R, Jendritzky G, Menne B (2004) Heat-waves: impacts and responses. Techn. Ber., Word Health Organisation Regional Office for Europe, Copenhagen, Sweden. In: Health and Global Environmental Change Series, no. 2

Kovats R, Hajat S, Wilkinson P (2004) Contrasting patterns of mortality and hospital admissions during hot weather and heat waves in Greater London, United Kingdom. Occupat Environ Med 61:893–898

Kovats R, Koppe C (2005) Integration of public health with adaptation to climate change: lessons learned and new directions. Kap. Heatwaves: past and future impacts. Lisse, Swets & Zeitlinger

Lamb H (1972) British Isles weather types and a register of daily sequence of circulation patterns, 1861-1971. Bd. 116 von *HMSO*. London

Lund R, Reeves J (2002) Detection of undocumented changepoints: a revision of the two-phase regression model. J Climate 15:2547–2554

Luterbacher J, Dietrich D, Xoplaki E, Grosjean M, Wanner H (2004) European seasonal and annual temperature variability, trends, and extremes since 1500. Science 303:1499–1503

Meehl G, Tebaldi C (2004) More intense, more frequent, and longer lasting heat waves in the 21st century. Science 305:994–997

Michaelsen J (1987) Cross-validation in statistical climate forecast models. J Climate Appl Meteor 26:1589–1600

Miles MK (1977) Atmospheric circulation during the severe drought of 1975/76. Meteorol Mag 106:154–164

Milligan J (2004) Heatwaves: the developed world's hidden disaster, Techn Ber, International Federation of Red Cross and Red Crescent, World Disasters Report

Mitchell T, Jones P (2005) An improved method of constructing a database of monthly climate observations and associated high-resolution grids. Int J Climatol 25:693–712

Moberg A, Bergström H (1997) Homogenization of Swedish temperature data. Part III: The long temperature records from Stockholm and Uppsala. Int J Climatol 17:667–699

Moberg A, Bergstrom H, Krigsman J, Svanered O (2002) Daily air temperature and pressure series for Stockholm (1756–1998). Climatic Change 53:171–212

Moberg A, et al (2006) Indices for daily temperature and precipitation extremes in Europe analysed for the period 1901-2000. J Geophys Res 111:D22106. doi:10.1029/2006JD007103

Nakamura M, Enomoto T, Yamane S (2005) A simulation study of the 2003 heatwave in Europe. J Earth Simul 2:55–69

Nicholls N (1987) The use of canonical correlation to study teleconnections. Monthly Weather Rev 115:393–399

Ogi M, Yamazaki K, Tachibana Y (2005) The summer northern annular mode and abnormal summer weather in 2003. Geophys Res Lett 32:L04706. doi:10.1029/2004GL021528

Pal JS, Giorgi F, Bi XQ (2004) Consistency of recent European summer precipitation trends and extremes with future regional climate projections. Geophys Res Lett 31:L13202. doi:10.1029/2004GL019836

Parker D, Horton B (2005) Uncertainties in central England temperature 1878–2003 and some improvements to the maximum and minimum series. Int J Climatol 25:1173–1188

Parker DE, Legg TP, Folland CK (1992) A new daily central England temperature series, 1772–1991. Int J Climatol 12:317–342

Peterson T, et al (1998) Homogeneity adjustments of in situ atmospheric climate data: a review. Int J Climatol 18:1493–1517

Philipp A, Della-Marta PM, Jacobeit J, Fereday DR, Jones PD, Moberg A, Wanner, H (2007) Long term variability of daily North Atlantic–European pressure patterns since 1850 classified by simulated annealing clustering. J Climate (in press)

Poumadère M, Mays C, Le Mer S, Blong R (2005) The 2003 heat wave in France: dangerous climate change here and now. Risk Anal 25:1483–1494

Preisendorfer R (1988) Principal component analysis in meteorology and oceanography. Elsevier, Amsterdam

Press W, Teukolsky S, Vetterling W, Flannery B (1996) Numerical recipies in FORTRAN 77: the art of scientific programming. Cambridge University Press, Cambridge

Qian BD, Saunders MA (2003) Summer UK temperature and its links to preceding Eurasian snow cover, North Atlantic SSTs, and the NAO. J Climate 16:4108–4120

Ratcliffe RAS (1976) The hot spell of late June–early July 1976. Weather 31:355–357

Ratcliffe RAS (1977) A synoptic climatologists viewpoint of the 1975/76 drought. Meteorol Mag 106:145–154

Rodwell M, Rowell D, Folland C (1999) Oceanic forcing of the wintertime North Atlantic oscillation and European climate. Nature 398:320–323

Schär C, Luthi D, Beyerle U, Heise E (1999) The soil-precipitation feedback: a process study with a regional climate model. J Climate 12:722–741

Schär C, Jendritzky G (2004) Climate change: hot news from summer 2003. Nature 432:559–560

Schär C, Vidale P, Luthi D, Frei C, Haberli C, Liniger M, Appenzeller C (2004) The role of increasing temperature variability in European summer heatwaves. Nature 427:332–336

Schmutz C, Gyalistras D, Luterbacher J, Wanner H (2001) Reconstruction of monthly 700, 500 and 300 hPa geopotential height fields in the European and Eastern North Atlantic region for the period 1901–1947. Clim Res 18:181–193

Seneviratne S, Lüthi D, Litschi M, Schär C (2006) Land-atmosphere coupling and climate change in Europe. Nature 443:203–206

Shabbar A, Skinner W (2004) Summer drought patterns in Canada and the relationship to global seas surface temperatures. J Climate 17:2866–2880

Shaw MS (1977) The exceptional heat-wave of 23 June to 8 July 1976. Meteorol Mag 106:329–346

Smith TM, Reynolds RW (2004) Improved extended reconstruction of SST (1854–1997). J Climate 17:2466–2477

von Storch H, Zwiers W (1999) Statistical analysis in climate research. Cambridge University Press, Cambridge

Stott P, Stone D, Allen M (2004) Human contribution to the European heatwave of 2003. Nature 432:610–614

Sutton RT, Hodson DLR (2005) Atlantic Ocean forcing of North American and European summer climate. Science 309:115–118

Trigo RM, Garcia-Herrera R, Diaz J, Trigo IF, Valente MA (2005) How exceptional was the early August 2003 heat-wave in France? Geophys Res Lett 32:L10701. doi:10.1029/2005GL022410

Valleron AJ, Boumendil A (2004) Epidemiology and heat waves: analysis of the 2003 episode in France. C R Biol 327:1125–1141

Vautard R, Yiou P, D'Andrea F, de Noblet N, Viovy N, Cassou C, Polcher J, Ciais P, Kageyama M, Fan Y (2007) Winter Mediterranean trigger of summer heat and drought waves in Europe. Geophys Res Lett (in press)

Wang X (2003) Comments on ''Detection of undocumented changepoints: a revision of the two-phase regression model''. J Climate 16:3383–3385

Wijngaard J, Klein Tank A, Können G (2003) Homogeneity of 20th century European daily temperature and precipitation series. Int J Climatol 23:679–692

Wilks D (1995) Statistical methods in the atmospheric sciences. Academic, New York

Xoplaki E, González-Rouco FJ, Gyalistras D, Luterbacher J, Rickli R, Wanner H (2003a) Interannual summer air temperature variability over Greece and its connection to the large-scale atmospheric circulation and Mediterranean SSTs 1950–1999. Clim Dyn 20:523–536

Xoplaki E, Gonzalez-Rouco J, Luterbacher J, Wanner H (2003b) Mediterranean summer air temperature variability and its connection to the large-scale atmospheric circulation and SSTs. Clim Dyn 20:723–739

Yarnal B (1993) Synoptic climatology in environmental analysis: a primer. Belhaven Press, London