INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **26**: 1777–1802 (2006)

(www.interscience.wiley.com) DOI: 10.1002/joc.1338

THE DEVELOPMENT OF A NEW DATASET OF SPANISH DAILY ADJUSTED TEMPERATURE SERIES (SDATS) (1850–2003)

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Received 11 October 2005
Revised 2 March 2006
Accepted 3 March 2006

ABSTRACT

Here we present the development of a new adjusted dataset composed of the 22 longest and most reliable Spanish daily temperature records (maximum and minimum temperatures and derived daily mean temperature) covering the period 1850–2003. The paper describes the approaches followed for compiling, controlling the quality and homogenising these 22 daily Spanish records, leading to the creation of a dataset called 'Spanish Daily Adjusted Temperature Series' (SDATS). An assessment of the sources of data and metadata used is followed by a reliability assessment of the selected network. Data quality control (QC) procedures applied to raw daily maximum ($T_{\max}$) and minimum ($T_{\min}$) temperatures and their results are then considered. For the very first time, an empirical minimisation of the bias related to the impact of changing exposure of thermometers on the records has been undertaken. The application of the Standard Normal Homogeneity Test (SNHT) to check homogeneity of raw $T_{\max}$ and $T_{\min}$ data on a monthly basis is presented, together with a discussion of the causes, magnitudes and timings of the various inhomogeneities. All 22 records contained a number of inhomogeneities (2.6 on average), mainly associated with documented station relocations confirmed by the metadata available. Monthly adjustments calculated for both screen developments and from the SNHT were linearly interpolated to a daily basis following the Vincent *et al.* (2002) scheme. Finally, the procedures adopted for creating the regional average, the Spanish Temperature Series (STS), together with an exploratory analysis of long-term trends of each $T_{\max}$ and $T_{\min}$ records, are provided. The final analysis shows that over mainland Spain highly significant rates of temperature increases have occurred for $T_{\max}$ and $T_{\min}$ (0.12 °C/decade and 0.10 °C/decade, respectively) over 1850–2003. Copyright © 2006 Royal Meteorological Society.

KEY WORDS: daily temperature series; 'screen bias' adjustments; QC; daily data homogeneity; temperature trends; Spain

1. INTRODUCTION

High-quality and long-term homogeneous datasets play a pivotal role in ensuring accuracy of many climatic studies, particularly those dealing with climate variability, climate prediction and climate change. Over the last thirty years, much effort has been expended by different research groups to produce high-quality and homogeneous regional to global temperature datasets on different timescales.

On a global scale and monthly basis, gridded datasets such like the CRUTEM2v (Jones *et al.*, 2001), the HadCRUT2 (Rayner *et al.*, 2003; Jones and Moberg, 2003) or the Global Historical Climatology Network (GHCN, Vose *et al.*, 1992; Peterson and Vose, 1997) have enabled the documentation and analysis of long-term temperature change at the largest spatial scales (e.g. Jones *et al.*, 1999; Jones and Moberg, 2003). On regional and national scales and also monthly timescales, datasets of higher spatial resolution have been compiled over

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different regions of the world: Manley (1974) compiled the Central England Temperature (CET) series; Vincent and Gullet (1999), the Canadian Historical Temperature Dataset; Böhm *et al.* (2001) and Auer *et al.* (2005, 2006), the HISTALP dataset; Brunetti *et al.* (2006), the Italian temperature and precipitation dataset; Aguilar *et al.* (1999) and Brunet *et al.* (2001a), the North-eastern Spain Adjusted Temperature (NESATv2) dataset; and Begert *et al.* (2005), the MeteoSwiss dataset. These and other datasets have enabled an improvement of our knowledge on long-term changes in the mean state of regional to global thermal climate (Folland *et al.*, 2001).

On a daily scale, several global and regional databases have recently been developed and are readily available to the research community: e.g. the GCOS Surface Network (GSN, Peterson *et al.*, 1997) and the Global Daily Climatology Network (GDCNv1.0, NCDC, 2002). Others, like the Australian Daily Adjusted Temperature dataset (Trewin, 1999, 2001), the European Climate Assessment & Dataset (ECA&D; Klein Tank *et al.*, 2002), the Canadian Daily Temperature dataset (Vincent *et al.*, 2002) or the longest daily CET series (Parker *et al.*, 1992) have enabled documentation of changes in temperature extremes on continental, regional and national scales over different periods.

However, the lack of accessible data in many regions has been and is continuing to hinder our further knowledge on long-term changes in the extreme state of climate, as well as our understanding of whether the observed changes in the mean are affecting the variance and the extreme tails of the temperature distribution (Folland *et al.*, 2001). It is worth mentioning here the activities of the joint World Meteorological Organization Commission for Climatology (CCl)/World Climate Research Programme (WCRP) project on Climate Variability and Predictability (CLIVAR), Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI). This group's aims are to fill in the glaring lack of daily data and document changes in the occurrence of climatic extremes over regions with sparse data coverage. Regional workshops have been organised and a set of climate change indices developed, which focus on extremes (see http://ccma/seos.uvic.ca/ETCCDMI and Alexander *et al.*, 2006 and references therein).

Over Spain recent EU-projects like the 'Improved Understanding of Past Climatic Variability from Early European Instrumental Data' (IMPROVE) have enabled reconstruction of one of the longest Spanish records: Cadiz (Barriendos *et al.*, 2002) and analysis of its day-to-day long-term temperature variability (Moberg *et al.*, 2000). The ECA&D project has permitted the recovery of nine Spanish 20th century records (Klein Tank *et al.*, 2002), with five of them used for looking at changes in the extreme behaviour of climate (Klein Tank and Können, 2003). The lack of more daily temperature data still hampers the assessments of long-term extreme temperature changes over this area. Very recently a daily gridded (25 km × 25 km) temperature and precipitation dataset (Luna and Almarza, 2004) has been developed covering the whole Spain, but it just extends from 1961 onwards, and owing to the smoothing procedures employed it is not designed for the analysis of changes in climate extremes (M. Y. Luna, personal communication).

In addition, many problems of data reliability and quality are difficult to deal with, particularly with long records. These are associated with data inhomogeneities caused by temporal changes e.g. in station locations, observational practices or instrumental exposure, all widely recognised in the relevant scientific literature and recently assessed in the WMO's Guidance on Metadata and Homogeneity (Aguilar *et al.*, 2003). At present, only very few approaches to homogenising daily data (Trewin, 1999; Vincent *et al.*, 2002; Brunetti *et al.*, 2004; Maugeri *et al.*, 2004; Della-Marta *et al.*, 2005; Della-Marta and Wanner, 2006) have been developed, as estimating daily adjustments or interpolating monthly correction factors to a daily basis presents a new level of complexity.

With this background in mind, this paper presents a new daily adjusted dataset composed of the longest 22 Spanish daily temperature records (maximum, minimum and the derived mean temperature). In this regard, an assessment of the procedures followed for generating both the SDATS dataset and the corresponding regional timeseries, the Spanish Temperature Series (STS), are presented. The paper is organised as follows: Details of the selected temperature network, data and metadata collection and the sources used are presented in Section 2. Quality controls (QCs) applied to daily maximum and minimum temperature series are discussed in Section 3. The procedures adopted for homogenising the data at the daily timescale are discussed in Section 4. Section 5 gives the approach for creating the STS and provides an initial assessment of long-term trends of daily $T_{\max}$ and $T_{\min}$ timeseries included in the SDATS. Finally, Section 6 summarises procedures and discusses results.

DOI: 10.1002/joc

2. THE SELECTED NETWORK: DATA AND METADATA SOURCES

In the framework of the European Community (EC) funded project EMULATE (**E**uropean and North Atlantic daily to **MUL**tidecadal clim**ATE** variability, 22 long timeseries of raw daily $T_{\max}$ and $T_{\min}$ were collected (see http://www.cru.uea.ac.uk/cru/projects/emulate). One aim was to develop a new daily adjusted temperature dataset over mainland Spain that can confidently be employed when analysing long-term temperature change and variability over this region.

The rationale for selecting the network was based on the following criteria: temporal and spatial coverage, climatic representativeness, long-term continuity of data and potential data quality at highly monitored sites (synoptic stations). First, stations with the longest, continuous and most reliable records were chosen. They had to extend back to the second half of the 19th century or at least to cover the whole 20th century, as one of the objectives of EMULATE is to relate variations and trends in atmospheric circulation patterns to prominent extremes in temperature and precipitation for the period 1850–2003 (http://www.cru.uea.ac.uk/cru/projects/emulate/objectives.pdf). Second, stations had to be at well-spaced locations across mainland Spain. Related to this principle, stations also had to be representative of the different climatic regions of Spain. Also, stations had to be still in use and likely to continue so for the foreseeable future. The last principle that guided the network selection based on potential data quality led us to those stations catalogued at present as the first order (synoptic) stations of the Spanish official meteorological network, which are highly monitored and presumably well-quality controlled by the Servicio de Desarrollos Climatológicos (SDC, Climatological Branch) of the Instituto Nacional de Meteorología (INM, Spanish Meteorological Office).

According to these principles, the 22 stations depicted in Figure 1 and Table I were selected. In Table I, we provide geographical details of the current locations of the stations and the potential lengths of record for each one. The location map of the Spanish network employed in this study (Figure 1) also provides approximate lengths of records and the elevation of each station. From this plot a reasonably well-spaced

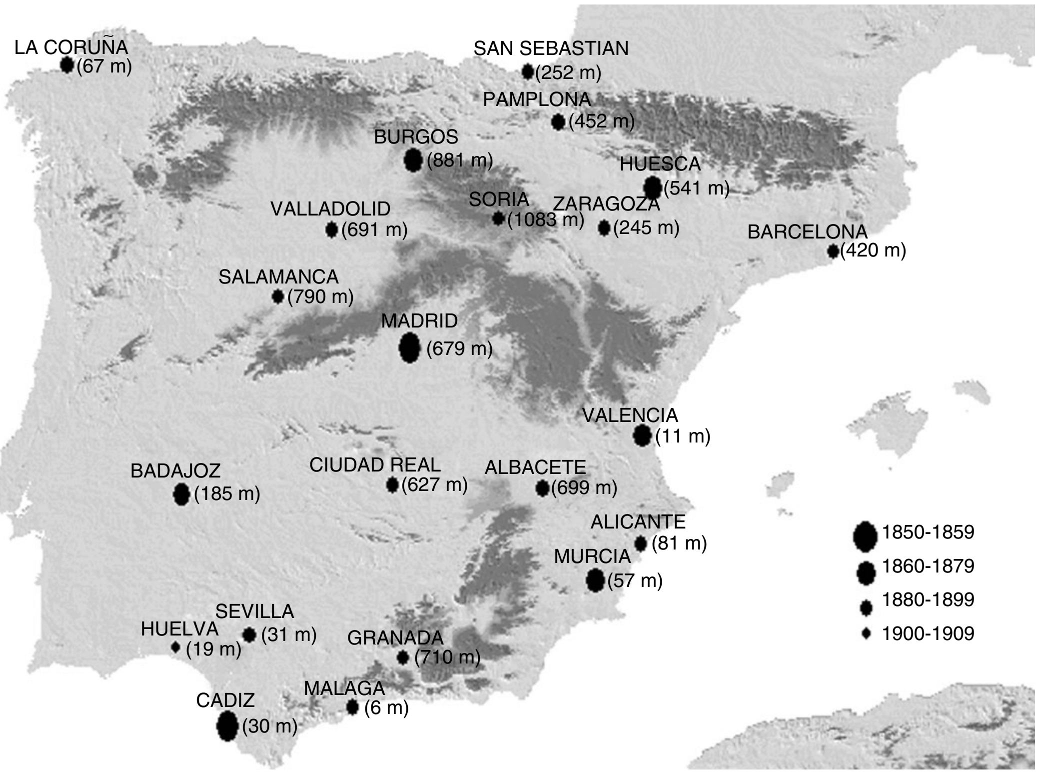

Figure 1. Location map of the 22 Spanish stations used to develop the STS. Names, elevations and approximate lengths of record are shown

DOI: 10.1002/joc

Table I. The selected Spanish temperature network. Name of station, current geographical location (geographical coordinates and elevation) and lengths of record

Location	Long.	Lat.	Alt. (m)	Length
ALBACETE	01°51′47″W	38°57′08″N	698.56	1893–2003
ALICANTE	00°29′40″W	38°22′00″N	81.5	1893–2003
BADAJOZ	06°49′45″W	38°53′00″N	185	1864–2003
BARCELONA	02°10′36″E	41°25′05″N	420.1	1885–2003
BURGOS	03°36′57″W	42°21′22″N	881	1870–2003
CADIZ	06°12′37″W	36°27′55″N	30	1850–2003
CIUDAD REAL	03°55′11″W	38°59′22″N	627	1893–2003
GRANADA	03°37′52″W	37°08′10″N	685	1893–2003
HUELVA	06°54′35″W	37°16′48″N	19	1903–2003
HUESCA	00°19′35″W	42°05′00″N	541	1861–2003
LA CORUÑA	08°25′10″W	43°22′02″N	67	1882–2003
MADRID	03°40′41″W	40°24′40″N	678.9	1853–2003
MALAGA	04°28′57″W	36°39′57″N	6.54	1893–2003
MURCIA	01°07′14″W	37°58′59″N	57	1863–2003
PAMPLONA	01°38′21″W	42°46′06″N	452	1880–2003
SALAMANCA	05°29′41″W	40°56′50″N	789.8	1893–2003
SAN SEBASTIAN	02°02′22″W	43°18′24″N	251.6	1893–2003
SEVILLA	05°53′47″W	37°25′15″N	31	1893–2003
SORIA	02°29′01″W	41°46′29″N	1083	1893–2003
VALENCIA	00°22′52″W	39°28′48″N	11.4	1864–2003
VALLADOLID	04°44′35″W	41°38′40″N	691.4	1893–2003
ZARAGOZA	01°00′29″W	41°39′43″N	245	1887–2003

distribution of stations emerges representing the main physiographic units of Spain. In the coastal lowland sectors there are two stations over the Northern Spanish Atlantic coast, five over the Spanish Mediterranean coast and two over southwestern Atlantic coast. For the Spanish inland plateau there are four stations over the Northern plateau and four over the Southern plateau. The Ebro Valley lowlands have three stations and the Guadalquivir Valley lowlands, two stations. This network essentially covers the entire country and the main Spanish climate types (Oceanic and Mediterranean), sub-types (Atlantic; Mediterranean Continental, Mediterranean Eastern Coast, Mediterranean Southern and Mediterranean Arid or Southeastern) and variants (Atlantic Galician, one station and Atlantic Littoral Basque, one station; Mediterranean Continental of the Northern Plateau, four stations; Mediterranean Continental of Ebro Valley, three stations; Mediterranean Continental of the Southern Plateau, three stations; Mediterranean Catalan, one station; Mediterranean Valencian, one station; Mediterranean Southern Littoral, three stations; Mediterranean Guadalquivir Valley, two stations; Mediterranean Extremaduran, one station; Mediterranean Arid or South-Eastern variant, two stations), according to Martín-Vide and Olcina's (2001) Spanish climate classification. In addition, in order to avoid potentially biased records related to 'urban heat island' influences, more than two-thirds of the meteorological stations selected are situated in non-urban areas from the mid-20th century onwards, with most of them located at airfields and airports.

Raw daily $T_{\max}$ and $T_{\min}$ data were collected from a wide variety of sources, although the bulk of these data (~80%) were obtained in digital (~48%) and hard-copy (~32%) form from INM. The remainder (~20%) were recovered in digital (~14%) and hard-copy (~6%) form from other sources (see legend of Table II and Table III). Table II gives the geographical details and lengths of record for every station, with their principal sources. Table III provides information on the data and metadata holders and documentary sources. INM data mainly cover the 20th century, while the other sources mostly provide data covering the second half of the 19th century. Hence, the authors, besides having to locate and retrieve ancient data kept in hard-copy, faced another time-consuming task, i.e. the digitisation of about 40% of the total data recovered (~2 million daily values).

Table II. List of stations, geographical details and length of records from specific sources

Location	Long.	Lat.	Alt. (m)	Length	Sources
ALBACETE	01°51′17″W	39°00′00″N	686	1893–1900	BMD
ALBACETE	01°51′47″W	38°57′08″N	698.56	1901–2003	INM
ALICANTE	00°29″17″W	38°21′00″N	19	1893–1900	BMD
ALICANTE	00°29′40″W	38°22′00″N	81.5	1901–2003	INM
BADAJOZ	06°49′45″W	38°53′00″N	185	1864–2003	INM
BARCELONA	02°09′E	41°23′N	41.6	1885–1900	MB_ADVICE
BARCELONA	02°10′36″E	41°25′05″N	420.1	1901–2003	INM
BURGOS	03°42′W	42°20′N	860	1870–1893	INM
BURGOS	03°42′W	42°20′N	860	1894–1898	BMD
BURGOS	03°36′57″W	42°21′22″N	881	1899–2003	INM
CADIZ	06°12′17″W	36°27′55″N	30	1850–1996	IMPROVE
CADIZ	06°12′37″W	36°27′55″N	30	1997–2003	ROASF
CIUDAD REAL	03°55′43″W	38°59′21″N	627	1893–1900	BMD
CIUDAD REAL	03°55′11″W	38°59′22″N	627	1901–2003	INM
GRANADA	00°21′W	37°11′N	701	1893–1900	BMD
GRANADA	03°37′52″W	37°08′10″N	685	1901–2003	INM
HUELVA	06°54′35″W	37°16′48″N	19	1903–2003	INM
HUESCA	00°19′35″W	42°05′00″N	541	1861–2003	INM
LA CORUÑA	08°24′23″W	43°22′10″N	9	1882–1900	DWR
LA CORUÑA	08°25′10″W	43°22′02″N	67	1901–2003	INM
MADRID	03°41′15″W	40°24′30″N	655.36	1853–1854	RSP
MADRID	03°41′15″W	40°24′30″N	655.36	1855	RSM
MADRID	03°41′15″W	40°24′30″N	655.36	1856–1859	LG
MADRID	03°41′15″W	40°24′30″N	678.9	1860–1892	ICM/ROAM
MADRID	03°40′41″W	40°24′40″N	678.9	1893–2003	INM
MALAGA	04°25′36″W	36°43′28″N	29	1893–1900	BMD
MALAGA	04°28′57″W	36°39′57″N	6.54	1901–2003	INM
MURCIA	01°07′45″W	37°58′59″N	66	1863–1950	CMTM
MURCIA	01°07′14″W	37°58′59″N	57	1951–2003	INM
PAMPLONA	01°38′21″W	42°46′06″N	452	1880–2003	INM
SALAMANCA	05°40′W	40°58′N	811	1893–1900	BMD
SALAMANCA	05°39′41″W	40°57′23″N	812	1901–1943	INM
SALAMANCA	05°29′41″W	40°56′50″N	789.8	1945–1999	PG
SALAMANCA	05°29′41W	40°56′50″N	789.8	2000–2003	INM
SAN SEBASTIAN	02°00′W	43°19′N	23	1893–1900	BMD
SAN SEBASTIAN	02°02′22″W	43°18′24″N	251.6	1916–2003	INM
SEVILLA	05°59′37″W	37°23′25″N	30	1893–1900	BMD
SEVILLA	05°53′47″W	37°25′15″N	31	1901–2003	INM
SORIA	02°28′W	41°49′10″N	1058.5	1893–1900	BMD
SORIA	02°29′01″W	41°46′29″N	1083	1901–2003	INM
VALENCIA	00°21′W	39°28′N	18	1864–1893	INM
VALENCIA	00°21′W	39°28′N	18	1894–1900	BMD
VALENCIA	00°21′W	39°28′N	18	1901–1935	INM
VALENCIA	00°22′52″W	39°28′48″N	11.4	1937–1999	PG
VALENCIA	00°22′52″W	39°28′48″N	11.4	2000–2003	INM
VALLADOLID	04°43′W	41°39′N	694	1893–1900	BMD
VALLADOLID	04°44′35″W	41°38′40″N	691.4	1901–2003	INM
ZARAGOZA	01°00′29″W	41°39′43″N	245	1887–2003	INM

Sources' acronyms. INM, Instituto Nacional de Meteorología; DWR, Daily Weather Reports; BMD, Boletín Meteorológico Diario; MB-ADVICE, Mariano Barriendos and EU-project Annual to Decadal Variability In Climate in Europe; ICM/ROAM, Instituto Central Meteorologico/Real Observatorio Astronómico de Madrid; RSM, Ricos Sinobas Manuscript; RSP, Rico Sinobas Paper; LG, La Gaceta de Madrid; PG, Pavel Groisman; CMTM, Centro Meteorológico Territorial en Murcia del INM; IMPROVE, EU-project Improved Understanding of Past Climatic Variability from Early European Instrumental Data; ROASF, Real Observatorio de la Armada en San Fernando (Cádiz, España).

Table III. Data and metadata supplied by national and international data holders and external contributors, together with the documentary sources employed for locating and retrieving daily data and metadata for 1850–2003

Data holders and external contributors (EC)	Details on data and metadata recovered and their documentary sources
INM[a], SDC Headquarters, Madrid, Spain	Data: twenty-one series covering the 20th century in digital and hard-copy; gross error checking by SDC
CMTM[a], Murcia, Spain	Data: one digitised record (Murcia), 1863–1950; gross error checking by territorial service of INM in Murcia
EC: IMPROVE[a] project	Data: one digitised record (Cadiz), 1850–1996; gross errors checked (Camuffo and Jones, 2002). Partial metadata on Cadiz's station available in Barriendos *et al.* (2002)
ROASF[a], Cadiz, Spain	Data: Cadiz's updating, 1997–2003. Metadata: Partial metadata on Cadiz's station available in González (1992)
Pavel Groisman, NCDC, Asheville, NC, USA	Data: two digitised records: Valencia 1937–1999 and Salamanca 1945–1999; NCDC (2002)
EC: MB_ADVICE[a] project	Data: one digitised record (Barcelona, 1885–1900)
UK-MO National Library and Archive, Bracknell, UK	Data: daily Weather Reports (DWR): one record (La Coruña, 1882–1900), Boletín Meteorológico Diario (BMD): twelve records, 1893–1900
INM Library & Archive, Madrid, Spain	Data: Madrid station, 1853–1854, in Rico Sinobas (1857); Madrid station, 1860–1889, in ICM (1893); Madrid station, 1890–1892, in ROAM[a] (1892, 1894) Metadata for the entire network available in: Observatorio de Madrid (1866–1880, 1882, 1884, 1886–1887, 1889, 1891–1892, 1895–1896, 1899–1900): *Resumen de las observaciones meteorológicas efectuadas en la Península y algunas de sus islas adyacentes*. Several editorials: Madrid; ICM (Instituto Central Meteorológico) (1907–1949): *Resumen de las observaciones meteorológicas efectuadas en la Península y algunas de sus islas adyacentes*. Est. Tipo-litográfico de I. Barredo: Madrid, and Almarza *et al.* (1996).
Royal Academy of Medicine, Madrid, Spain	Data: Madrid station, 1855, in RSM[a]; Observaciones meteorológicas de Madrid:1800–1857, (23 v.) v. 21, (12–8–M–4–23)
Municipal Newspaper Library, Tarragona, Spain	Data: Madrid station, 1856–1859, in La Gaceta (LG) newspaper.
Library of Sociedad Económica de Amigos del País, Badajoz, Spain	Metadata partially available for Badajoz station from Sánchez Pascua (1985)
CMTG (Centro Meteorológico Territorial de Galicia), Climatological Archive, La Coruña, Spain	Metadata available for La Coruña station in Rios Pardo L. 2000. *El observatorio meteorológico (1)*. CMTG, internal report: La Coruña and in "La Ilustración Gallega y Asturiana' newspaper, n 16, June 8, 1881.

[a] See Table II for meaning of the acronyms employed.

Official meteorological observations in Spain started in 1869, although prior to this date non-official observatories were operating in several Spanish cities. In addition and owing to diverse historical circumstances, the majority of the pre-1900 official instrumental data were lost and hence not archived in the central headquarters of INM. For these reasons and to accomplish EMULATE objectives, the authors undertook exhaustive searches in the meteorological sources held in local, national and international archives and libraries. Different documentary sources were visited in order to locate and retrieve the required 19th century data and their associated metadata, as summarised in Table III.

From these sources, the authors also compiled metadata for the entire network, in order to better guide the detection of homogeneity break points in these records. The metadata recovered is far from complete, but a reasonably well-documented history of the stations and records could be recovered to help build a metadata history for the 22 records employed in this study. In this metadata archive we kept complete information on station identifiers, geographical locational data (geographical coordinates, elevation), climate types, sub-types and variants of each station, dates of station relocations related to the different sites, measurement units, missing data and data sources. Almost complete metadata on thermometric exposures, instruments, observers and historical circumstances covering the observations are also archived in the metadata base. Finally, partial metadata on the micro- and meso-environments around stations were also recovered and kept in the metadata archive.

Figure 2 shows the amount of available data with respect to the potential daily mean temperature data for each year of the period 1850–2003, together with the number of records contributing to each year of the later analysis. Two stations are available from the 1850s onwards, 6 from 1860s, 7 from 1870s, 11 from 1880s, 21 from 1890s and 22 from 1900s.

Different periods of missing data are also evident from the inspection of Figure 2. The fraction of missing data for the whole period (1850–2003) is about 7% of the potential daily data; however, a higher percentage is evident for the period 1863–1940, in which the percentage of available to potential data is ~7%. Moreover, for the two shorter sub-periods of 1899–1905 and 1932–1939, missing data percentages are higher at 22% and 15%, respectively. This marked reduction in the available data in both intervals is mainly related to the political instabilities that Spain experienced between the end of the 19th century and in the early 1940s, associated among others with events like losing the last overseas Spanish Colonies (Cuba and Philippines) in 1898 and the Spanish Civil War. Owing to these severe political and socio-economic crises, meteorological operational services in Spain were dramatically disturbed during these times. Finally, the lack of data drops down to 1.5% during 1940–2003. Although data gaps are filled in some studies (Eischeid *et al.*, 2000; Feng *et al.*, 2004), no attempt to fill in gaps has been performed in the present study.

3. RAW DATA QC

Although some gross error checks were undertaken by the SDC on the fraction of the digitised daily records obtained from INM, or by Barriendos *et al.* (2002) in a simpler data verification with the Cadiz record, a more complete data quality assessment on the entire network was undertaken here to identify and label the suspicious, errant values and outliers that could remain both in the supplied readily available digitised records and in the data recovered and digitised by the authors.

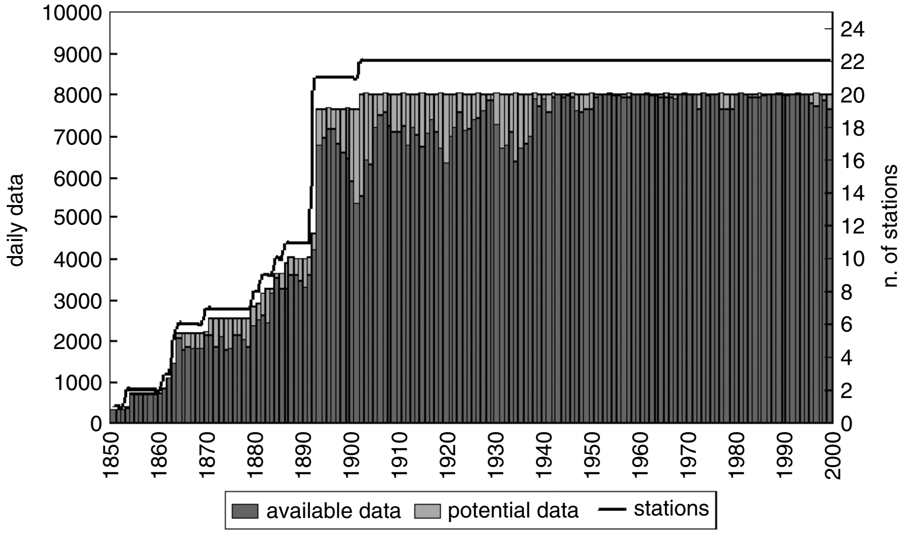

Figure 2. Available *versus* potential daily mean temperature data in relation to the number of meteorological stations

DOI: 10.1002/joc

Careful analysis of data quality, particularly of daily data, is a key and essential task before undertaking any homogeneity assessment or any long-term climate change analysis with these data. A well-performed data QC can avoid any potential errors that could compromise the adjustments obtained from any homogeneity tests carried out with the data. It is also essential for improving any assessment with respect to changes in climatic extremes. Moreover, data quality tests largely enable improvement not only of the quality of the raw data but also the completeness of the dataset, as some fraction of flagged values can be filled after examining the original sources.

For these reasons, the 22 Spanish raw $T_{\max}$ and $T_{\min}$ timeseries were subjected to different QC tests, in order to identify and flag potentially errant values introduced when recording, manipulating, formatting, transmitting or archiving the data, as well as for ensuring internal consistency and temporal and spatial coherence of the data. In this regard, the following recommended (Aguilar *et al.*, 2003) set of data quality tests were undertaken with the raw data:

(1) Gross error checks:
  - Aberrant values ($T_{\max}$ and $T_{\min}$ values $>50\,^{\circ}\mathrm{C}$ and $< -50\,^{\circ}\mathrm{C}$)
  - Consistency of calendar dates: no. of days per year and no. of days per month
  - Comparison of monthly averages between those calculated from the digitised daily data and those registered in the available original sources

(2) Tolerance tests:
  - Four or more consecutive identical values
  - Values exceeding ± 4 standard deviation (σ)

(3) Internal consistency: ($T_{\max} < T_{\min}$)

(4) Temporal coherency: (values exceeding a $25\,^{\circ}\mathrm{C}$ difference between consecutive observations)

(5) Spatial coherency:
  - Values exceeding $\pm 4\sigma$ threshold for the difference between the candidate record and its group of reference stations
  - Visual comparisons among neighbouring stations

During the long period of the recovered temperature records, the majority of the meteorological stations had been relocated at least once during their operational history, according to the available metadata for each station. For this reason, quality tests were undertaken separately for each record to distinguish those time intervals belonging to the different station locations. This enabled the use of more realistic thresholds for detecting/labelling suspicious values. Table IV gives details of the various periods tested for the entire network.

A summary of the results of the QC is given in Table V, and Table VI shows the results according to the different tests applied. From the total number of daily values only a very small fraction (0.58%) was flagged as potentially erroneous values.

In a second step, these values were scrutinised one-by-one in the original sources, when available. As stated, about 62% of daily data were obtained in digital form, so we did not have access to the original sources. This fact constrained the possibility of retrieving a larger fraction of the flagged values, as the original sources could not be directly examined. However, as most of the records obtained in digital form came from the second half of the 20th century they had been previously checked for gross errors by SDC.

Available original sources were checked to ensure that no digitisation or data manipulation errors were introduced in the dataset. When this happened, the true value recovered from its source was corrected in the dataset. About 70% of the total flagged values could be corrected by examining the original sources (Table V), which made the QC of raw data a worthwhile exercise. In the cases when the flagged values could not be scrutinised, expert judgment guided the comparison of these values, leaving them unchanged or making them missing values. This was done by comparing adjacent values in the same timeseries, by using other climate elements (pressure and precipitation) and by considering simultaneous observations for well-correlated stations. When these checks supported the hypothesis of a wrong value, it was set as missing and excluded from any further analysis. In this study, only 30% of the flagged values were set to missing values.

DOI: 10.1002/joc

Table IV. Time intervals for each station, together with the INM local code, for which the QC procedures described have been applied

NAME	INM CODE	PERIOD	NAME	INM CODE	PERIOD
ALBACETE	8178	1893–1936	CADIZ	5972	1850–2003
ALBACETE	8175	1939–2003	MURCIA	7182C	1863–1950
ALICANTE	8025E	1894–1920	MURCIA	7182A	1951–1974
ALICANTE	8025G	1921–1938	MURCIA	7182	1976–2003
ALICANTE	8025	1939–2003	PAMPLONA	9262	1880–1974
BADAJOZ	4478	1864–1954	PAMPLONA	9263D	1975–2003
BADAJOZ	4452	1955–2003	SALAMANCA	2870D	1893–1944
BARCELONA	0201E	1885–1925	SALAMANCA	2867	1945–2003
BARCELONA	0200E	1926–2003	S. SEBASTIAN	1024D	1893–1900
BURGOS	2327	1870–1943	S. SEBASTIAN	1024E	1916–2003
BURGOS	2331	1944–2003	SEVILLA	5787D	1893–1932
CIUDAD REAL	4121C	1893–1970	SEVILLA	5790	1933–1950
CIUDAD REAL	4121	1971–2003	SEVILLA	5783	1951–2003
GRANADA	5515A	1893–1937	SORIA	2030	1893–2003
GRANADA	5514	1938–2003	VALENCIA	8416A	1863–1932
HUELVA	4605	1903–1984	VALENCIA	8416	1935–2003
HUELVA	4642E	1984–2003	VALLADOLID	2422C	1893–1923
HUESCA	9901F	1861–1943	VALLADOLID	2422F	1924–1940
HUESCA	9898	1944–2003	VALLADOLID	2422C	1942–1969
LA CORUÑA	1387	1882–2003	VALLADOLID	2422G	1970–1973
MADRID	3195	1853–2003	VALLADOLID	2422	1974–2003
MALAGA	6171	1893–1942	ZARAGOZA	9443D	1887–1950
MALAGA	6155A	1943–2003	ZARAGOZA	9434	1951–2003

Table V. Summary of QC results for raw daily data as absolute counts and percentages with respect to the total amount of data examined

Total amount of tested values	1 981 192	
Flagged values	11 505	0.58%
Recovered values	8 090	0.41%
Not recoverable values	3 415	0.17%

The most frequent type of errors found were associated with mistyped values when digitising from available original sources. Most were highlighted when running the 1. iii test (Table VI) and could be recovered, corrected and incorporated into the dataset. The tolerance tests applied also provided a remarkable number of potentially errant values, mainly related to four successive and identical values, but after examining the sources the bulk of them were validated and retained in the dataset to be considered as true values. The rest of the quality checks were passed with very few cases of potential errors in comparison with the other two tests, and most of them could be easily corrected. QC procedures were repeated several times to account for the effect of an outlier's removal on the statistical distribution of data.

4. HOMOGENISATION OF DAILY MAXIMUM AND MINIMUM TEMPERATURES

As has been widely recognised in the relevant literature for many years (e.g. Mitchell, 1953; Jones *et al.*, 1986), the majority of long-term meteorological observations have been affected by non-climatic factors, principally

Table VI. QC results distributed according to the type of test applied as absolute counts with percentages in parenthesis

	Gross error checks	Tolerance tests	Internal consistency test	Temporal coherency test	Spatial coherency tests
Total of flagged values	4941 (0.25)	5995 (0.3)	161 (0.008)	192 (0.01)	216 (0.01)

related to changes in station locations, local environments, instrumental exposures and instrumentation, observing practices or data processing. All these factors can introduce and have introduced gradual or abrupt breaks in data series. As widely recognised, to estimate adjustments for these problems is another key pre-requisite before undertaking any climatic analysis, especially regarding any long-term climate variability and change assessment.

In this section, the homogenisation procedures applied to the 22 Spanish daily temperature records are discussed. Firstly, we describe the empirical approach employed, for the very first time, for minimising the so-called 'screen bias' affecting the earliest temperature records, which is related to changes over time to thermometric exposures. Secondly, we show the application of the Standard Normal Homogeneity Test (SNHT) developed by Alexandersson and Moberg (1997). And thirdly, we address the scheme adopted for interpolating the estimated monthly adjustment factors to the daily timescale.

4.1. The minimisation of 'screen bias' in the Spanish network

Prior to the generalised use of Stevenson screen, different types of exposures and stands were used for protecting thermometers (i.e. north walls, Glaisher and Montsouris' open stands, Wild metallic cylindrical screen, etc.). Exposures varied on a country-by-country basis over the globe, as documented by Parker (1994). According to this study, temperature readings taken under ancient stands are likely biased to a higher or lower degree depending on latitude, observation time during the day and year, and hence this bias has had a different impact on daily extreme (maximum or minimum) temperatures. Several studies have shown and estimated the sign and magnitude of this bias on thermometric records over different areas of the world: Andersson and Mattisson (1991) over Sweden; Nicholls *et al.* (1996) over southwestern Australia; Nordli *et al.* (1997) over European Nordic countries; Böhm *et al.* (2001) over the Greater Alpine Region; Brunet *et al.* (2004) over Spain. These studies outline varied impacts on the records associated with the thermometer shelters and exposures employed in the past. Furthermore, it has been shown for Mediterranean climates, by Nicholls *et al.* (1996) and Brunet *et al.* (2004), that pre-sheltered temperatures tended to have a strong warm-bias in $T_{\max}$ records compared to current observing practices, while $T_{\min}$ readings had a small cold-bias compared to those of the modern period. In this regard, Brunetti *et al.* (2006) show for Italy the errors due to the effect of screen height and the impact of buildings on thermometric exposures (see Figure 1 in Brunetti *et al.*, 2006). These seem to produce an error with a time evolution that is similar to the one evident in Spain owing to the screen effect. Therefore, the use of the original data in estimating long-term temperature evolution gives negatively biased results in terms of trend. This result is also in agreement with the findings of Böhm *et al.* (2001) and Begert *et al.* (2005).

For the Spanish meteorological network during the 19th century and early decades of the 20th century, it was common to protect thermometers under open stands. These were mostly the Montsouris or French stand and to a lesser extent the Glaisher stand (Rico Sinobas, 1857; ICM, 1891; AAOAM, 1992). These types of open stands were more sensitive to radiation effects than the currently employed Stevenson screen. Therefore, pre-screened observations mainly show unreliable high maximum temperatures in the early parts of the longest Spanish records (Brunet *et al.*, 2004). The main problem with dealing with the bias is that relative homogenisation procedures will not work as all stations are similarly affected.

In this regard and within the framework of the Spanish-funded SCREEN ('Assessment and minimisation of 'screen bias' incorporated into the longest Spanish air temperature records by time-changing thermometric exposures throughout dual temperature observation (SCREEN)') research project, paired temperature observations were taken using the old Montsouris stand and modern Stevenson screens in the meteorological gardens of La Coruña and Murcia, representative of the Oceanic climate and the Mediterranean Arid or southeastern climate subtype and of high and low cloud cover levels, respectively. In this project, the 19th century Montsouris stands were built and operated according to details given in publications from the period (Angot, 1903). Figure 3 shows a replica of the ancient Montsouris stand assembled and installed at the meteorological garden of Murcia station in the framework of the SCREEN project, illustrating the exposures employed in the ancient Spanish meteorological network. In Table VII we show the monthly median differences estimated from daily $T_{\max}$ and $T_{\min}$ timeseries recorded under both exposures at the two experimental sites, together with the corresponding 95% confidence intervals. These difference timeseries (Stevenson minus Montsouris) were calculated from the paired observations for 1 year (Jun 2003 to May 2004). As can be clearly seen, daily maximum temperatures taken under ancient stands are more sensitive to radiation effects than daily minimum temperatures. On an annual basis, $T_{\max}$ is 1.5 °C (1.2 °C) higher for Montsouris readings at Murcia (La Coruña) than for Stevenson ones, while $T_{\min}$ is only 0.3 °C (0.2 °C) lower for Montsouris compared to Stevenson readings.

Because of this common 'warm-bias' ('cold-bias') of daily maximum (minimum) temperatures, we have undertaken a very preliminary empirical minimisation of the 'screen bias', by employing the monthly median difference values provided in Table VII as monthly adjustments, before undertaking a normal homogeneity assessment of the entire dataset. The experimental dual observation of temperatures is still ongoing and will last through the foreseeable future at both sites, as the main aim of the SCREEN project is to obtain more robust adjustments by estimating transfer functions from other well-correlated meteorological variables. Table VIII gives information on the group of stations to which the calculated adjustments were applied, as well as the dates of the introduction of the Stevenson screens for the Spanish network. In bold (italic) we show stations adjusted with the Murcia (La Coruña) empirical factors. Owing to both the brief period of paired thermometric observations (one year) and the highest impact of the open stand on daily maximum temperatures compared to minimum temperatures, we decided to apply the monthly adjustments estimated to only the maximum temperature records and not to the minimum temperature series. Adjustments of minimum temperatures will be done later when longer pair-wise timeseries become available. The adjustments of maximum temperatures were undertaken by directly subtracting the monthly estimated screen bias from the monthly averages calculated from the raw $T_{\max}$ time series, prior to moving to the monthly homogeneity assessment. The screen bias adjustment was applied to the 20 $T_{\max}$ records shown in Table VIII for the periods with pre-Stevenson thermometric exposures. For Cadiz and Malaga no screen adjustments were applied to their respective raw $T_{\max}$ time series, as our fragmentary metadata for both stations indicated that

Figure 3. Picture showing both the old Montsouris stand and the new Stevenson screen as replicated in the Meteorological Garden of Murcia (Courtesy of the project SCREEN). This figure is available in colour online at www.interscience.wiley.com/ijoc

Table VII. Monthly median difference time series (Stevenson minus Montsouris) in °C with the 95% confidence interval in brackets, estimated from daily maximum and minimum temperatures recorded using the ancient and new exposures at the two Spanish meteorological gardens at La Coruña and Murcia. The paired observations were simultaneously recorded between Jun 2003 and May 2004 for minimising 'screen bias' of the pre-Stevenson records

	La Coruña		Murcia	
	T_{max}	T_{min}	T_{max}	T_{min}
Jan	−0.85 (±0.26)	0.20 (±0.07)	−1.16 (±0.21)	0.50 (±0.12)
Feb	−1.23 (±0.27)	0.24 (±0.11)	−1.38 (±0.31)	0.37 (±0.11)
Mar	−1.58 (±0.29)	0.18 (±0.04)	−1.46 (±0.16)	0.26 (±0.09)
Apr	−1.36 (±0.18)	0.16 (±0.07)	−1.70 (±0.18)	0.36 (±0.11)
May	−1.68 (±0.26)	0.20 (±0.07)	−1.80 (±0.17)	0.31 (±0.10)
Jun	−1.62 (±0.19)	0.22 (±0.04)	−1.71 (±0.07)	0.39 (±0.06)
Jul	−1.61 (±0.19)	0.26 (±0.04)	−1.76 (±0.08)	0.28 (±0.05)
Aug	−1.51 (±0.23)	0.37 (±0.12)	−1.59 (±0.12)	0.32 (±0.13)
Sep	−1.20 (±0.24)	0.21 (±0.07)	−1.50 (±0.09)	0.17 (±0.09)
Oct	−0.90 (±0.25)	0.23 (±0.05)	−1.40 (±0.26)	0.30 (±0.07)
Nov	−0.80 (±0.2)	0.20 (±0.17)	−1.12 (±0.26)	0.25 (±0.07)
Dec	−0.71 (±0.22)	0.24 (±0.15)	−1.24 (±0.20)	0.44 (±0.09)

Table VIII. Dates of Stevenson screen introduction in the Spanish meteorological network defining periods of application of the monthly adjustment factors for maximum temperature given in Table VII. In bold (italic) adjusted stations using Murcia (La Coruña) estimated monthly factors

Albacete	4/1915	**Alicante**	1/1909	**Badajoz**	1/1909	**Barcelona**	1/1901
Burgos	1/1905	**Ciudad Real**	1/1908	**Granada**	1/1909	**Huelva**	1/1909
Huesca	4/1912	*La Coruña*	6/1912	**Madrid**	1/1894	**Murcia**	1/1913
Pamplona	1/1916	**Salamanca**	1/1909	*S. Sebastian*	1/1901	**Sevilla**	5/1912
Soria	1/1914	**Valencia**	1/1901	*Valladolid*	10/1912	**Zaragoza**	4/1913

the thermometers were exposed for an undefined period between the last decades of the 19th century and early 20th century inside a louvred rectangular hut of 2m × 3m × 2m with a door opening to the north. Ideally the screen adjustments should be calculated for each site, but resources limited the parallel measurements to two sites, even though future empirical adjustments will be able to more confidently adjust stations located in climatic domains similar to those characterising La Coruña and Murcia.

4.2. The application of the SNHT on a monthly basis and results

For assessing homogeneity of the T_{max} and T_{min} monthly records, once the screen bias adjustments had been applied to the T_{max} time series, the SNHT relative homogeneity approach developed by Alexandersson and Moberg (1997) was used with the entire network. Detection and correction of inhomogeneities of monthly temperature records were undertaken following the SNHT application scheme described in Aguilar *et al.* (2002).

Here we discuss both the application and results obtained after using the SNHT on a monthly basis. First, we describe the selection of sets of reference stations for each one of the candidate stations. Second, we present the scheme adopted to detect inhomogeneous periods on an annual and a seasonal scale. And third, we show the correction pattern applied to monthly averages of daily maximum and minimum temperatures within SDATS.

4.2.1. The selection of the groups of reference stations. The selection of the reference stations for undertaking the relative homogeneity assessment of each candidate station was made according to three complementary criteria: first, highly correlated stations; second, geographical and climatic proximity/affinity; and third, the availability of a sufficient number of reference series for any time slice of the candidate record.

Pearson product-moment correlations were estimated among all stations for annual, seasonal and monthly averages of daily mean temperature (T_{mean}) calculated from monthly averages of daily T_{max} and T_{min} time series $[(T_{\mathrm{max}} + T_{\mathrm{min}})/2]$. Coefficients were obtained from the first difference series, to avoid the impact of inhomogeneities. A maximum set of eight to nine stations were found to be highly correlated with nearby stations, across the 20th century. However, as the number of available records decreased during the second half of the 19th century, the set of reference stations had to be reduced for that period depending on the candidate station. A minimum of three available reference stations was set for the homogeneity assessment with the SNHT. Because the number of potential reference stations dramatically reduced during the earliest decades of the second half of the 19th century, and owing to the geographical proximity and climatic affinity among stations, the SNHT could not be undertaken for the following stations and initial sub-periods: Badajoz between 1864–1875; Burgos 1870–1883; Cadiz 1850–1862; Huesca 1861–1882; La Coruña 1882–1885; Madrid 1853–1862; and Valencia 1864–1887. For these stations and periods the monthly correction factors that were obtained from the SNHT for the subsequent period of each record were used.

Table IX shows the correlation coefficients of annually averaged T_{mean} records between each candidate station (right column) and their potential reference stations (columns 2 to 10), calculated using the first difference approach, as recommended by Peterson and Easterling (1994). As is evident from this table, correlation coefficients (r) mainly reach values of 0.8 and 0.9 and in some cases exceed 0.9, although in a few cases they are lower than 0.75, corresponding to distant 19th century reference stations, but necessary for making the relative homogeneity assessment with the SNHT.

4.2.2. The detection method's pattern of inhomogeneities. After having identified the reference stations, the SNHT was applied to T_{max}, T_{min} and the derived T_{mean} annual and seasonal averages of the 22 meteorological stations, in order to detect potential inhomogeneities in all three variables. At this stage, the objective was not homogenizing the records but just detecting breakpoints in the timeseries, which potentially indicated inhomogeneities. The correction pattern emerges from both the inspection of the statistically obtained breakpoints, the analysis of the Q-series (the difference between the candidate series and a weighted average of the reference series) provided by the implementation of the SNHT and also from the available metadata.

Before the SNHT application, all 22 stations were considered as potentially non-homogeneous. A total of 57 inhomogeneities were detected (2.6 per station on average) on an annual basis. These breakpoints in the records' homogeneity were validated by scrutinising the annual and seasonal T_{mean}, T_{max} and T_{min} Q-series. Therefore, for validating a breakpoint provided by the SNHT and not documented in the available metadata, it had to at least appear in the annual and two seasonal timeseries of the inspected record, as well as having to be picked by the T_{mean} series and at least by one of the T_{max} or T_{min} series.

Figure 4 shows the number of breakpoints detected per year and the number of stations (left panel) and also the number of breakpoints in relation to the available number of records for each year over 1850–2003 (right

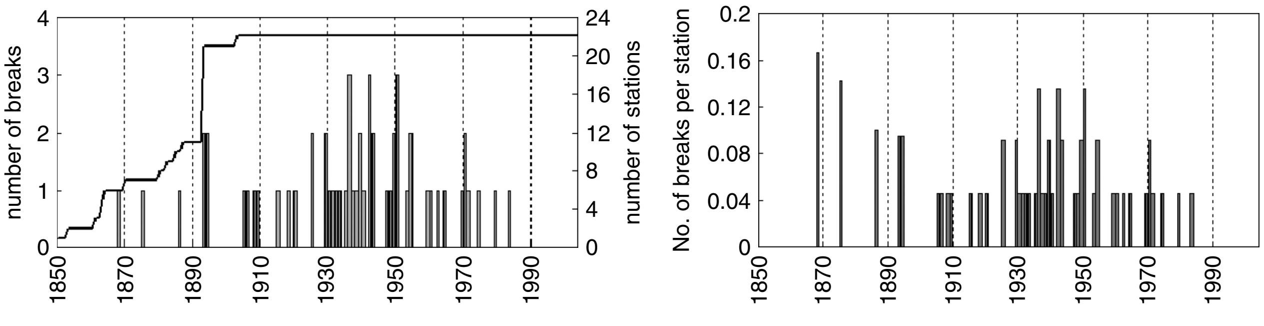

Figure 4. Number of breaks detected per year according to the SNHT applied to annual and seasonal averages of daily T_{mean}, T_{max} and T_{min} time series of SDATS over the 1850–2003 period. Left panel: breaks per year and number of stations contributing per year (black line). Right panel: breaks per year in relation to the number of records available

DOI: 10.1002/joc

Table IX. Pearson product-moment correlations (r in brackets) among annual averages of daily mean temperatures of each candidate station and its group of reference stations (RS)

Candidate	RS 1	RS 2	RS 3	RS 4	RS 5	RS 6	RS 7	RS 8	RS 9
Albacete (Alb)	Ali (0.89)	Bad (0.83)	Cre (0.92)	Gra (0.85)	Mad (0.86)	Mur (0.80)	Sev (0.91)	Val (0.78)	–
Alicante (Ali)	Alb (0.89)	Bar (0.86)	Gra (0.80)	Huel (0.80)	Mal (0.88)	Mur (0.84)	Sev (0.89)	Val (0.86)	–
Badajoz (Bad)	Alb (0.83)	Bur (0.86)	Cad (0.86)	Cre (0.82)	Huel (0.88)	Mad (0.89)	Mur (0.76)	Sal (0.84)	Sev (0.91)
Barcelona (Bar)	Alb (0.78)	Ali (0.86)	Hue (0.85)	Mad (0.82)	Mal (0.82)	Mur (0.78)	Vale (0.93)	Zar (0.92)	–
Burgos (Bur)	Cre (0.83)	Hue (0.87)	Mad (0.85)	Pam (0.89)	Sal (0.79)	Sor (0.91)	Vall (0.92)	Zar (0.90)	–
Cádiz (Cad)	Ali (0.74)	Bad (0.86)	Huel (0.85)	Hue (0.71)	Mad (0.82)	Mal (0.73)	Mur (0.67)	Sev (0.78)	Val (0.70)
Ciudad Real (Cre)	Alb (0.92)	Bad (0.82)	Gra (0.81)	Mad (0.81)	Mur (0.77)	Sal (0.78)	Sev (0.87)	Sor (0.85)	–
Granada (Gra)	Alb (0.85)	Bad (0.84)	Cad (0.81)	Cre (0.81)	Mad (0.84)	Mal (0.81)	Mur (0.75)	Sev (0.84)	–
Huelva (Huel)	Ali (0.80)	Bad (0.88)	Cad (0.85)	Cre (0.78)	Gra (0.84)	Mal (0.79)	Mur (0.66)	Sev (0.85)	–
Huesca (Hue)	Bar (0.85)	Cad (0.71)	Mad (0.81)	Mur (0.74)	Pam (0.92)	Seb (0.78)	Val (0.71)	Zar (0.90)	–
La Coruña (Cor)	Bur (0.90)	Cad (0.81)	Hue (0.89)	Mad (0.89)	Pam (0.89)	Sal (0.81)	Seb (0.87)	Vall (0.92)	–
Madrid (Mad)	Bur (0.85)	Cad (0.82)	Hue (0.81)	Mur (0.75)	Sal (0.75)	Sor (0.87)	Val (0.82)	Vall (0.86)	–
Málaga (Mal)	Alb (0.91)	Ali (0.88)	Bad (0.83)	Cad (0.73)	Cre (0.84)	Gra (0.81)	Huel (0.79)	Mur (0.83)	–
Murcia (Mur)	Alb (0.80)	Ali (0.84)	Cad (0.67)	Gra (0.75)	Mad (0.75)	Mal (0.83)	Sev (0.79)	Vale (0.81)	–
Pamplona (Pam)	Bar (0.88)	Bur (0.89)	Hue (0.92)	Mad (0.90)	Seb (0.89)	Sor (0.89)	Vall (0.89)	Zar (0.91)	–
Salamanca (Sal)	Bad (0.84)	Bur (0.79)	Cre (0.78)	Hue (0.78)	Mad (0.75)	Sor (0.79)	Vall (0.84)	Zar (0.78)	–
San Sebastián (Seb)	Bar (0.84)	Bur (0.86)	Hue (0.78)	Cor (0.87)	Pam (0.89)	Sor (0.82)	Vall (0.85)	Zar (0.85)	–
Sevilla (Sev)	Alb (0.91)	Bad (0.91)	Cad (0.78)	Cre (0.87)	Gra (0.84)	Huel (0.85)	Mal (0.86)	Mur (0.79)	–
Soria (Sor)	Bur (0.91)	Hue (0.90)	Mad (0.87)	Pam (0.89)	Sal (0.79)	Seb (0.82)	Vall (0.89)	Zar (0.90)	–
Valencia (Val)	Alb (0.78)	Ali (0.86)	Bar (0.93)	Cre (0.71)	Gra (0.75)	Mal (0.82)	Mur (0.81)	Zar (0.87)	–
Valladolid (Vall)	Bad (0.86)	Bur (0.92)	Cre (0.87)	Mad (0.86)	Pam (0.89)	Sal (0.84)	Seb (0.85)	Sor (0.89)	–
Zaragoza (Zar)	Bar (0.92)	Bur (0.90)	Hue (0.90)	Mad (0.86)	Pam (0.91)	Sor (0.90)	Val (0.87)	Vall (0.88)	–

panel). About 25% of the breakpoints identified are located during the politically problematic times in the 1930s due to the Spanish Civil War, when political instability severely disrupted the Spanish meteorological services. The largest number of breakpoints was detected during the second half of the 19th century (right panel) related to the low network density, while during the 20th century no tendency in the number of breakpoints towards a higher/lower frequency of breaks is evident.

Table X shows both the dates of breakpoints in homogeneity (gradual and abrupt) and their causes over the entire network. Individual years indicate a single shift found in the data, while periods in brackets show a trend. From the 57 breaks detected over the entire network, 52 are related to abrupt shifts and only 5 to gradual trends.

Figure 5 illustrates the causes of the 57 break points in homogeneity for the entire network (top graph) and the distribution of inhomogeneities found for each station (bottom graph). Changes in location and setting are

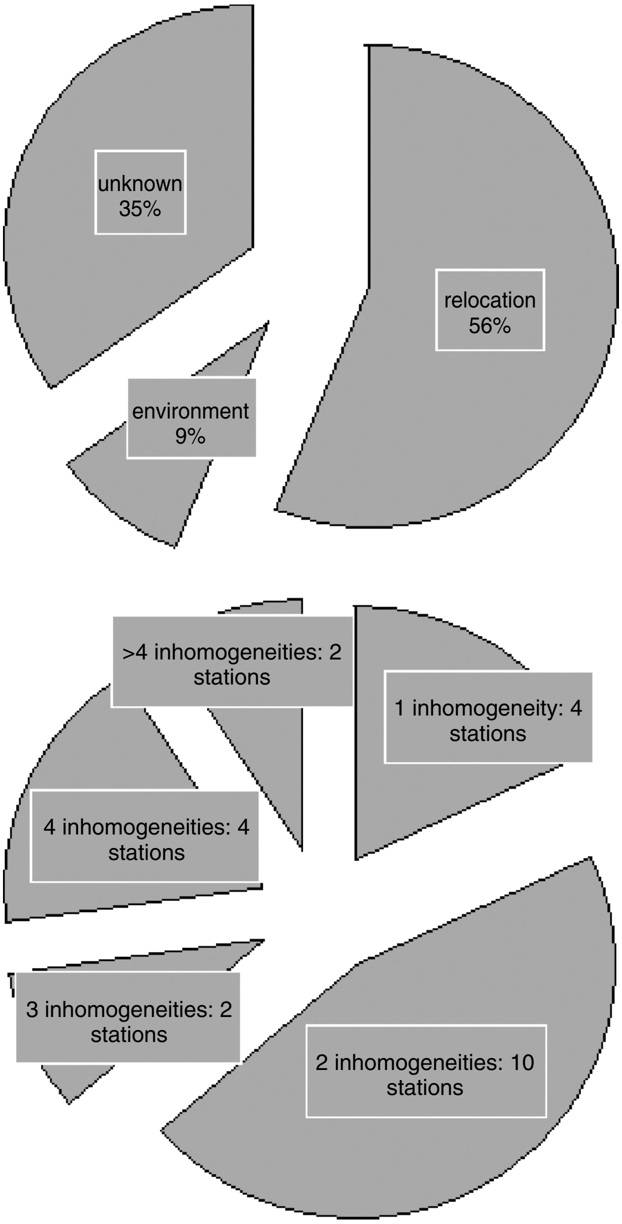

Figure 5. Causes of the inhomogeneities found (top graph) and frequency distribution of the number of estimated inhomogeneities (bottom graph) found using SNHT

Table X. The break points (abrupt and gradual) detected by SNHT on an annual basis and their causes for the 22 stations of SDATS

Station	Break	Cause	Break	Cause	Station	Break	Cause	Break	Cause
Albacete	1936	Relocation	–	–	La Coruña	1893	Unknown	1915	Relocation
Alicante	1920	Relocation	1933	Relocation		1929	Relocation	(1930–2003)	Environment
	1939	Relocation	1950	Unknown	Madrid	1893	Relocation	(1894–1960)	Environment
	1970	Unknown	–	–	Malaga	1925	Unknown	1931	Unknown
Badajoz	(1909–1954)	Environment	1954	Relocation		1942	Relocation	1971	Unknown
Barcelona	1925	Relocation	–		Murcia	1939	Unknown	1953	Relocation
Burgos	(1905–1943)	Environment	1943	Relocation	Pamplona	1949	Relocation	1961	Unknown
Cadiz	1875	Unknown	1964	Unknown		1974	Relocation	–	–
Ciudad Real	1938	Unknown	1948	Unknown	Salamanca	1929	Relocation	1936	Relocation
	1954	Unknown	1962	Unknown		1943	Relocation	–	–
	1970	Relocation	1979	Unknown	S. Sebastian	1918	Relocation	–	–
Granada	1908	Unknown	1937	Relocation	Sevilla	1932	Relocation	1950	Relocation
Huelva	1936	Relocation	1950	Relocation	Soria	1942	Relocation	–	–
	1959	Unknown	1983	Relocation	Valencia	1935	Relocation	1947	Relocation
Huesca	1868	Unknown	1886	Unknown	Valladolid	1940	Relocation	1969	Relocation
	1894	Unknown	1942	Relocation	Zaragoza	(1906–1949)	Environment	1949	Relocation

the main cause of inhomogeneities (about 56% of stations). Station relocations have been common during the longest Spanish temperature records. Stations were moved from one place to another within the same city/town (i.e. from the city centre to outskirts in the distant past and, more recently, from outskirts to airfields and airports far away from urban influence) and from one setting (roofs) to another (courtyards). These facts obviously induced homogeneity breaks in the analysed records that have to be corrected. The topoclimate influence exerted by urban development had negative effects on 5 out of the 22 stations, as gradual trends were detected (Table X and Figure 5 top graph). Finally, the rest of the inhomogeneities identified by SNHT had no explanation in the available metadata archives, which illustrated the incompleteness of the metadata recovered. Summarising Figure 5 (bottom graph), for about the half of the network (10 stations) two homogeneity breakpoints were found, while one was detected at four stations, three at two stations, four at another four stations and more than four inhomogeneities at two stations.

4.2.3. The estimation of monthly adjustment factors. The detection pattern identified after undertaking the SNHT exercise for annual and seasonal T_{mean}, T_{max} and T_{min} timeseries was applied to the monthly quality-controlled T_{mean} and T_{min} values and to the monthly T_{max} pre-adjusted for screen bias data, in order to estimate the required monthly adjustments. The selected approach follows the 'guided application' of SNHT (Aguilar *et al.*, 2002). The same breakpoints detected on an annual and a seasonal basis, as documented in Table X, have been transferred to the 12 months of each record for obtaining for each month and variable the monthly adjustment factor estimated from SNHT.

The frequency distribution of the size of the inhomogeneities for both T_{max} and T_{min} timeseries is shown in Figure 6 (top and bottom graphs, respectively). In both cases, moderate correction factors (positive and negative) have been estimated more frequently. About two-thirds of the inhomogeneities (66.6%) found for the T_{min} records are distributed between the −1 and +1 °C intervals. This concentration is even more evident for T_{max}, as more than a half of the inhomogeneities (55.5%) have a smaller size (−0.5 to +0.5 °C).

Figure 6 also makes clear the differences between T_{max} and T_{min} timeseries taking into account the sign of the inhomogeneities. In the first case, there is a slight predominance of positive values (346) with respect to negative ones (338), although exactly the same value is obtained on average (0.63 °C). For T_{min} records, however, there is a clear difference between positive and negative adjustments. There is a preponderance of negatives values (389) with respect to positive ones (295), which is also evident in the average value calculated (−0.86 °C and +0.80 °C). As a summary for the entire network and period, T_{min} records require larger and more frequent negative adjustments than T_{max} data.

These results can be partially explained by the available metadata. As stated, station relocations from urban to rural areas have been a common feature for the most of stations. These relocations have affected T_{min} more than T_{max}, as usually lower minimum temperatures and slightly higher maximum temperatures are recorded at the new rural sites (Karl *et al.*, 1988; Jones *et al.*, 1990; Portman, 1993). In addition, the tendency to change thermometer exposures from courtyard-level to roof-level and vice versa could also be another cause of this warm-bias present in the minimum temperature data throughout the entire period, as stated by Brunetti *et al.* (2006) in their analysis on long-term temperature variability over Italy.

Annual, summer and winter half-year average adjustments, including the systematic error due to the old screens and expressed as the difference between monthly raw and adjusted values, for the 22 T_{max} and T_{min} records are shown in Figure 7 (top and bottom panel, respectively). Several differences between the estimated T_{max} and T_{min} monthly adjustments averaged over all single series can be seen. Pre-1910 adjustments for T_{max} require reduction of the original data by about 1 °C on average, while the pre-1900 T_{min} records needed smaller increases of the raw data (about 0.5 °C in average). The larger reductions for T_{max} compared to the T_{min} increases during the second half of the 19th century are strongly related to the screen bias minimisation scheme, which was applied only to T_{max} records. Seasonal differences in adjustments (warm half-year *vs* cold half-year) can also be appreciated during that period. The summer half-year required larger reductions than the winter half-year, as the old thermometric stands introduced a higher overestimation of T_{max} readings during this part of the year (Brunet *et al.*, 2004). Another difference between T_{max} and T_{min} averaged adjustments across the 20th century is the slightly higher correction factors estimated for T_{min}, as monthly adjustments for T_{max} remain close to zero but for T_{min} they oscillate from −0.5 to +0.5 °C.

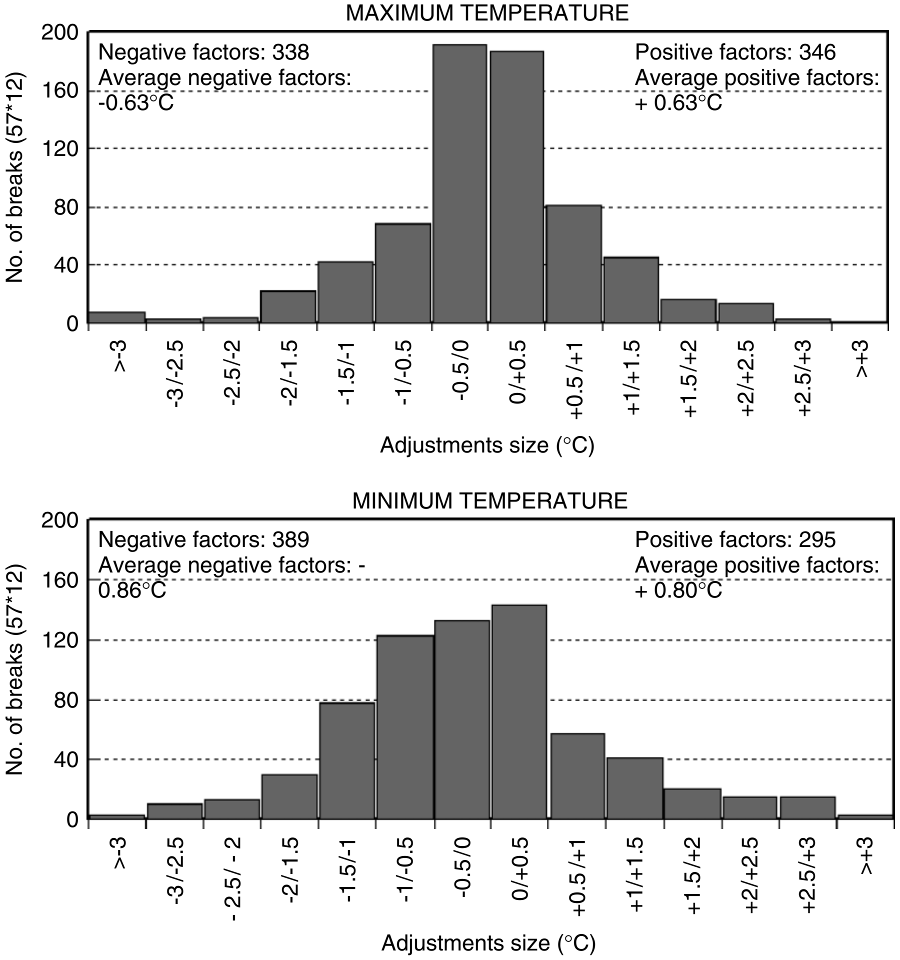

Figure 6. Frequency distribution of break magnitudes referred to the 57 detected and adjusted breaks after using SNHT for homogeneity testing of annual and seasonal averages of daily $T_{\max}$ (top plot) and $T_{\min}$ (bottom plot) timeseries for the 1850–2003 period. The figure shows the corresponding breaks as calculated from monthly data

4.3. The interpolation of monthly adjustment factors on a daily scale

The monthly correction factors estimated using SNHT, together with the screen-bias adjustments, have been linearly interpolated to a daily basis following the Vincent *et al.* (2002) weighting interpolation procedure, based on the scheme developed by Sheng and Zwiers (1998).

As stated in the introduction, homogenising daily data directly is a complicated task due to the high variability of the daily records in contrast to the more stable monthly, seasonal or annual averaged data. Despite this, the adjustment of daily data are necessary before undertaking any reliable analysis dealing with, for instance, changes in extreme events. From the different and still scarce methodological approaches available to adjust daily data, we have chosen the scheme developed by Vincent *et al.* (2002) for Canadian daily temperature data. This approach attempts to provide a better time-interpolation procedure that preserves monthly averages and does not introduce artificial discontinuities at the beginning and ends of calendar months. This scheme derives daily adjustments from the estimated monthly correction factors by means of a linear interpolation between mid-month 'target' values, which are chosen so that the average of the daily adjustments over a given month equals the monthly correction factors. The 'target' values are related to the monthly adjustments by means of a matrix relationship:

$$\mathbf{T} = \mathbf{A}^{-1}\mathbf{M}$$

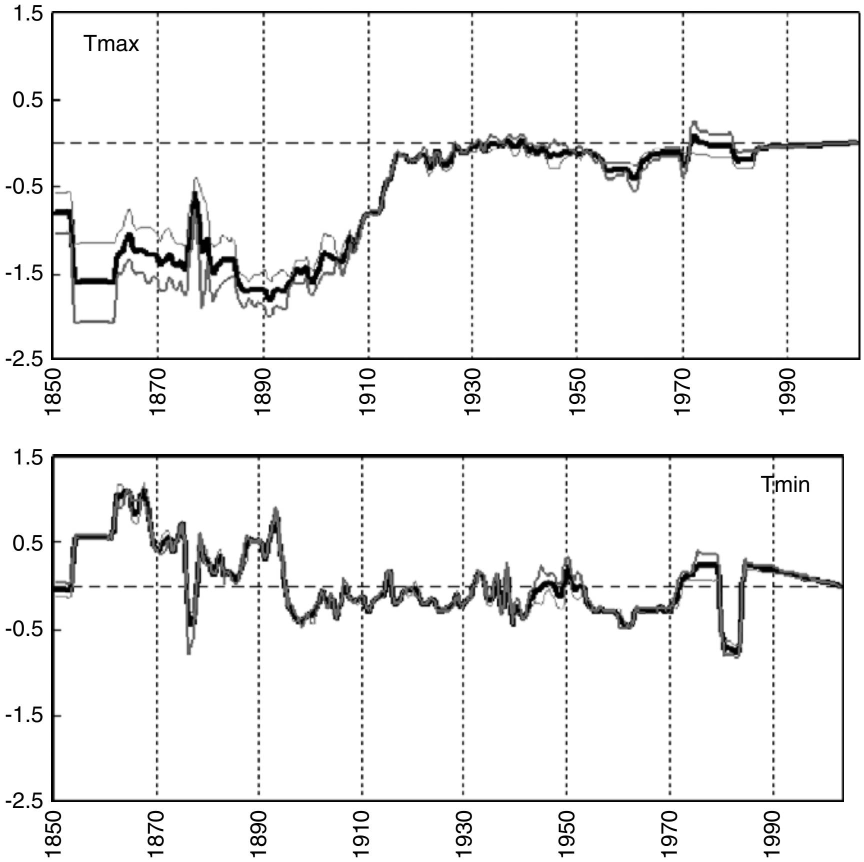

Figure 7. Mean correction factors for $T_{\max}$ (top panel) and $T_{\min}$ (bottom panel) records expressed as the difference between monthly raw and homogenised values and averaged over all single records. Annual (thick black line), winter half-year (October–March, grey thin line), summer half-year (April–September, grey thick line)

where **A** is a tridiagonal 12 × 12 matrix, **M** is a 12 × 1 vector of the monthly correction factors and **T** is a 12 × 1 vector consisting of the target values. The ‘target’ values are assigned to the middle day of each month and finally linearly interpolated to get the daily adjustments. This approach has also been employed by Feng *et al.* (2004) to homogenise daily meteorological data for China.

Two examples illustrate the application of this time-interpolation scheme to SDATS. They are for the Albacete and Soria $T_{\max}$ and $T_{\min}$ records and are shown in top and bottom panels of Figure 8, respectively. An inhomogeneity was detected by the SNHT for Albacete records in 1936, when the station moved from a high school located in the city centre to an airfield situated in the rural surroundings. Monthly $T_{\max}$ adjustments have positive values in all cases, whereas they are negative for the $T_{\min}$ data. The size of the monthly correction factors for $T_{\min}$ are larger than those for $T_{\max}$ ($-0.63\,^{\circ}$C and $+0.25\,^{\circ}$C as annual averages). December and November, as well as February–April, have larger adjustments than the rest of the year for $T_{\min}$ data, while for the $T_{\max}$ record positive monthly correction factors are larger in May to July than for the other months. The direct application of these monthly factors to the daily data is not advisable, because the difference, for instance, between the April and May adjustments for $T_{\max}$ series ($+0.27\,^{\circ}$C and $+0.50\,^{\circ}$C, respectively) might generate an abrupt discontinuity at the end of April and the beginning of May (Figure 8, top graph, grey dashed area). This would not happen if the monthly factors were interpolated to a daily scale as shown on this graph. The daily adjustments (black line) show no abrupt jumps, avoiding any artificial steps between consecutive months. A similar situation occurs for the breakpoint detected at the Soria records in 1942, also due to station relocation (Figure 8, bottom graph). In this regard, differences between the monthly correction factors estimated from SNHT are smoothed when these factors are interpolated to the daily scale.

DOI: 10.1002/joc

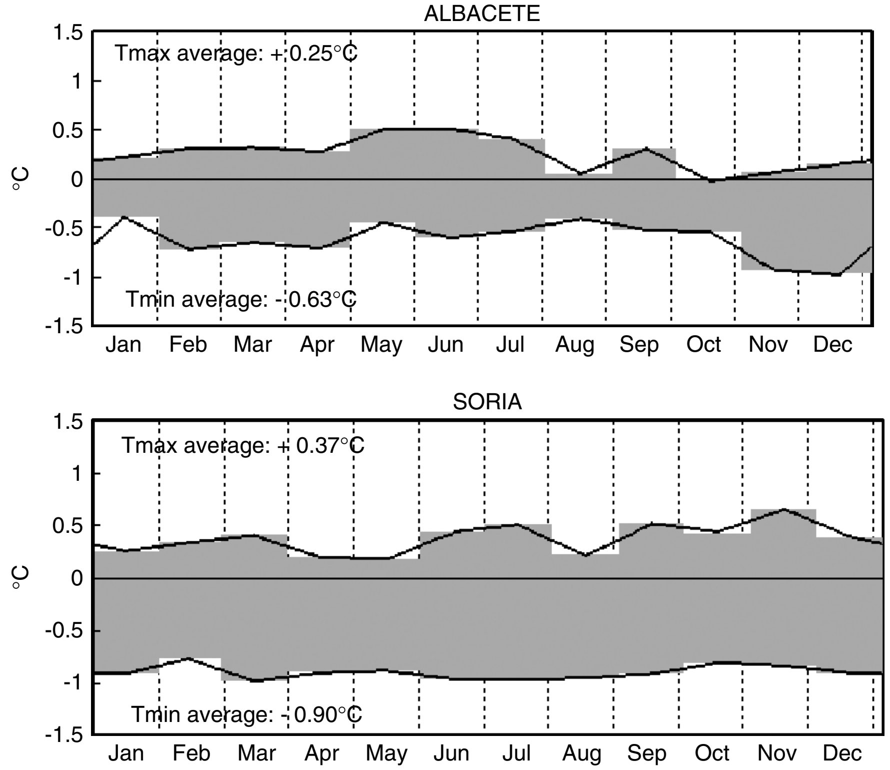

Figure 8. Monthly (in grey) and daily (black line) adjustments of maximum (positive values) and minimum (negative values) temperatures for the inhomogeneity in 1936 at Albacete (top graph) and in 1942 at Soria (bottom graph)

In order to exemplify the impact of our homogenisation, the annual averages of daily raw and adjusted temperature records are compared in Figures 9 and 10, top and bottom panels, respectively, for $T_{\max}$ (Figure 9) and for $T_{\min}$ timeseries (Figure 10). On these plots, all 22 single annually averaged records together with an estimated regional average are given, each smoothed with a 13-year low-pass Gaussian filter. As evident in both figures, the variability of annual anomalies is reduced by homogenisation, particularly for the $T_{\min}$ records (Figure 10, top and bottom panels). The effect of screen bias minimisation on $T_{\max}$ records is also evident in the pre-1910 data (Figure 9, bottom panel) when compared with the original data (Figure 9, top panel), and is particularly clear for the Barcelona (dashed line) and Madrid (dotted line) records from among the 22 sites. In the case of Barcelona, screen adjustment was necessary, but the major inhomogeneity resulted from the move in 1926 from Barcelona University, located in the coastal lowland urban area of Barcelona (∼42 m asl), to Barcelona-Fabra, situated on the Catalonian Littoral Range (∼420 m asl). For Madrid, only screen adjustments account for the most of the reduction applied to the $T_{\max}$ data for the pre-1893 period. The rest of the adjustments are listed at http://www.urv.es/centres/Departaments/geografia/clima/archive.htm.

5. THE CREATION OF THE STS AND AN INITIAL TREND ANALYSIS

The 22 daily adjusted records of maximum, minimum and mean temperatures have been combined to obtain regional time series for the period 1850–2003, which gives a representative series of the long-term temperature evolution over mainland Spain, both regarding the mean and the extreme states of Spanish thermal climate. The STS has been generated by averaging the daily anomalies from individual records and then adding back the base-period mean (1961–1990), according to the Jones and Hulme (1996) method of separating temperature into its two components (the climatology and the anomaly).

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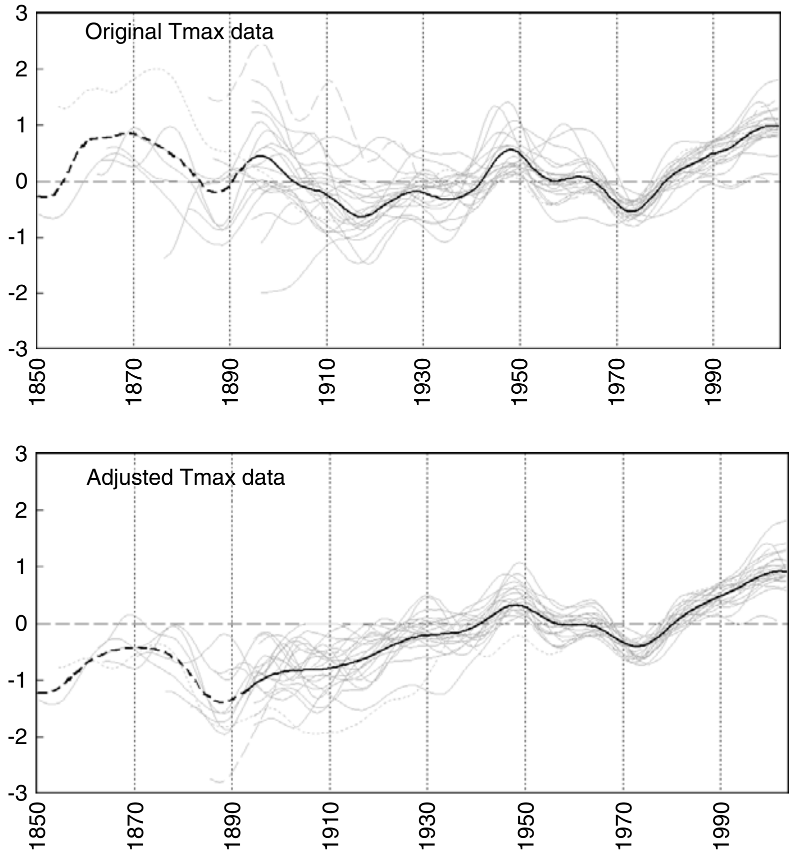

Figure 9. Original (top) and homogenised (bottom) annual variations (1850–2003) of the 22 Spanish daily maximum temperature records (thin grey lines) and their corresponding mean (thick black line) expressed as anomalies from 1961 to 1990 and smoothed with a 13-year Gaussian filter. The heavy solid line has been converted into a heavy dashed line prior to 1893 for stressing the decay of the number of records for this initial period. Dashed line (dotted line) is Barcelona (Madrid) station. See text for details

Here we present the first results of a trend analysis performed both on the 22 daily adjusted maximum and minimum temperature single records of the SDATS over the common period 1903–2003 and the corresponding regional (mainland Spain) averaged time series over the longer period 1850–2003. This analysis has been performed on an annual basis by adapting Sen's (1968) estimator of the slope. Our application of this method is similar to that undertaken by Zhang *et al.* (2000) in a study of annual temperature and precipitation change over Canada, and in extreme wave heights over Northern Hemisphere oceans (Wang and Swail, 2001). The 95% confidence intervals of the trend coefficients have also been estimated from tabulated values (Kendall, 1955).

Figure 11 shows annual trends (in °C/decade) for each individual record placed at their approximate geographical location for both $T_{\max}$ (left) and $T_{\min}$ (right) series for the period of 1903–2003, when all 22 daily records are available. All coefficients are found to be highly significant (at 0.01 level) both for $T_{\max}$ and $T_{\min}$ series showing moderate to high rates of change in all records. However, it can be appreciated that the majority of the $T_{\max}$ records indicates larger coefficients than those estimated for $T_{\min}$, except for Zaragoza and Sevilla where the $T_{\min}$ trend have slightly larger coefficients than their respective $T_{\max}$ trends.

Moreover, in Table XI annual and seasonal trends estimated for the regional STS time series of $T_{\max}$ and $T_{\min}$ for 1850–2003 together with their 95% confidence intervals are given. All estimated regional trends are also statistically significant at the 0.01 level. Again daytime temperatures indicate larger rates of positive change over mainland Spain as a whole when compared with $T_{\min}$ series over this period. For the $T_{\max}$ annual series, increases in daytime temperatures have been mainly contributed by larger increases in winter and spring, although autumn and summer also present highly significant coefficients. The seasonal trends of the $T_{\min}$ regional series indicate winter as the season with the largest contribution to the annual values, while the

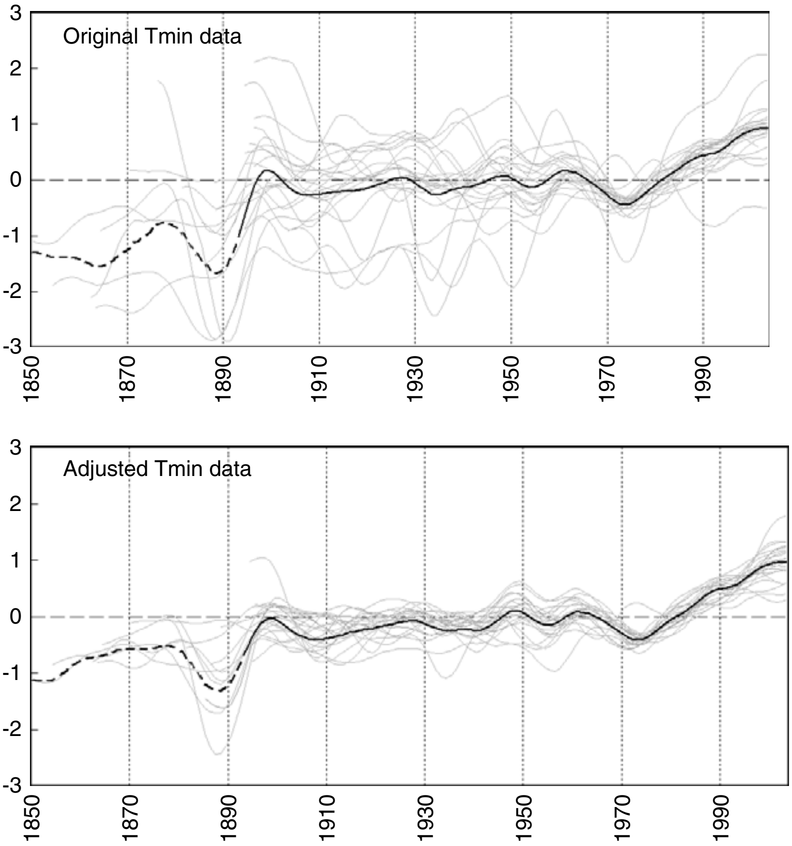

Figure 10. As in Figure 9, but for minimum temperatures

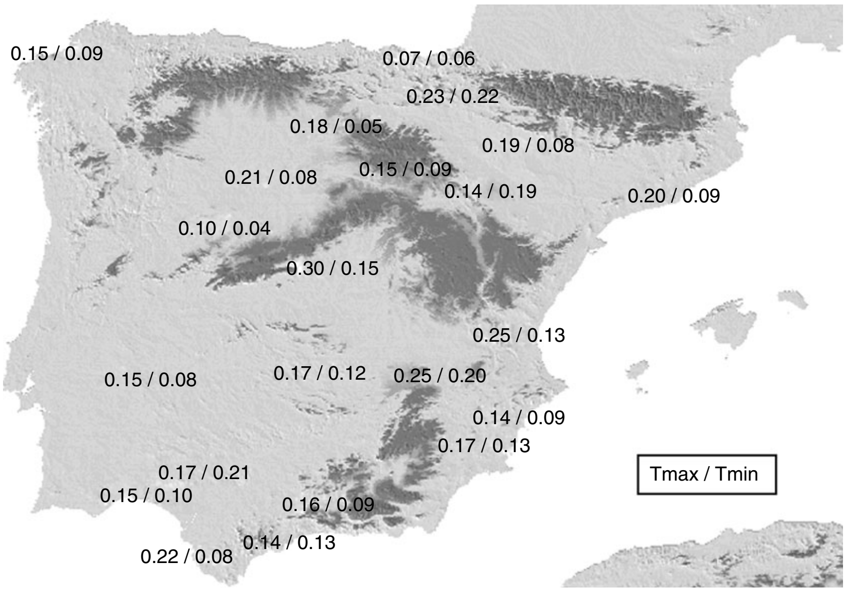

Figure 11. Map of annual trends (in °C/decade) of the 22 Spanish daily maximum and minimum temperature time series calculated for the 1903–2003 period plotted approximately at their respective locations (see Figure 1 for locations). All coefficients are statistically significant at the 0.01 level

Table XI. Annual and seasonal temperature change in the regional STS curves estimated by a linear trend, and in brackets the associated 95% confidence intervals (in °C/decade), for the regional time series of maximum and minimum temperatures calculated over the 1850–2003. Bold indicates significance at the 1% confidence level

Variable	Periods	Decadal coefficient (°C)	95% confidence intervals
T_{max}	Winter	**0.14**	(0.10/0.18)
	Spring	**0.13**	(0.08/0.19)
	Summer	**0.10**	(0.05/0.15)
	Autumn	**0.11**	(0.07/0.15)
	Annual	**0.12**	(0.08/0.16)
T_{min}	Winter	**0.12**	(0.08/0.16)
	Spring	**0.08**	(0.04/0.11)
	Summer	**0.08**	(0.05/0.11)
	Autumn	**0.09**	(0.05/0.13)
	Annual	**0.10**	(0.06/0.12)

rest of seasons indicate smaller, but similar rates of change. Despite the different periods and the different Spanish sub-regions analysed, our results are in good agreement with those reported by Abaurrea *et al.* (2001) over the middle Ebro River Basin, Brunet *et al.* (2001b) over northeastern Spain, Galán *et al.* (2001) over the Spanish Southern Plateau and Horcas *et al.* (2001) over southeastern Spain, as well as in excellent agreement with the findings reported by Brunetti *et al.* (2006) over Italy, by Böhm *et al.* (2001) and Auer *et al.* (2006) over the Greater Alpine Region and by Begert *et al.* (2005) over Switzerland.

However, slightly different results are seen in a recent contribution (Staudt *et al.*, 2005 based on the PhD thesis of Staudt, 2004), which analysed on a monthly basis about 27 Spanish temperature records for 1869–2002. These results highlight the slightly higher T_{min} trends in comparison with T_{max} records for different Spanish sub-regions. Although in this work spurious urban trends were explicitly corrected, the authors did not consider the bias incorporated in the longest record related to time-changing thermometric exposures.

The differential diurnal warming of mainland Spain, evident through the larger increases of daytime compared to nighttime temperatures, contrasts with that detected on global and hemispherical scales (Folland *et al.*, 2001), where larger positive changes during nighttimes indicates a reduced DTR. Over Spain, this exploratory and initial analysis shows higher rates of change for T_{max} than for T_{min}, indicating an increase in DTR, which has to be explored further. This is evident for both the majority of the individual series and the regional averaged time series.

6. CONCLUSIONS

The new dataset of Spanish Daily Adjusted Temperature Series (SDATS), composed of 22 records of daily maximum, minimum and derived daily mean temperatures was generated for the 1850–2003 period covering mainland Spain. Its development required arduous data and metadata searches, as well as much digitisation of paper records. Raw data were subjected to strict QC checks, and for the very first time an empirical approach to minimise screen bias was undertaken and applied to the quality-controlled monthly values of daily maximum temperatures.

The homogenisation procedure employed, in combination with the analysis of the station history, has allowed us to conduct an improved homogeneity assessment on a monthly basis, which proved that all long Spanish records used are inhomogeneous and require adjustments. The employment of SNHT has enabled the calculation of monthly correction factors, which have been transferred to the daily scale using a time-interpolation scheme that preserves monthly means and does not yield artificial discontinuities at the calendar month boundaries.

Trend analysis has shown a highly significant increase in temperatures over mainland Spain, as seen either through analysis of the individual adjusted records or using the regional average series. Larger rates of positive change have been found for daytime than for nighttime temperatures, in contrast to those observed at global, hemispherical and continental scales.

Finally, the adjusted daily data will be made available for scientific purposes through requests to oscar.saladie@urv.net via the following web site: http://www.urv.net/centres/Departaments/geografia/clima/currentresearch.htm

ACKNOWLEDGEMENTS

We thank Carlos Almarza from the SDC (Climatological Branch) of the INM (Spanish Met Office) for the provision of much of the raw data. Rob Allan and Tara Ansell helped the authors locate valuable sources of daily Spanish data for the 19th century in the UK Met Office Archives. Manolo Bañón from the Territorial Centre of INM at Murcia assisted in the provision of digitised raw data from Murcia station. The ROASF staff helped us with updating recent (1996–2003) daily data. Francisco García from the Territorial Centre of INM at La Coruña helped us in locating substantial metadata. Finally, Mariano Barriendos provided daily temperature data for the last third of the 19th century for Barcelona. This work was supported by the EU EMULATE project (EVK2-CT-2002-00161) and the Spanish SCREEN project (CICYT: REN2002-0091/CLI).

REFERENCES

AAOAM (Asociación de Amigos del Observatorio Astronómico de Madrid). 1992. *Doscientos años del observatorio astronómico de Madrid*. AAOAM: Madrid, 187.

Abaurrea J, Asín J, Erdozain O, Fernández E. 2001. Climate variability analysis of temperature series in the medium Ebro River Basin. In *Detecting and Modelling Regional Climate Change*, Brunet M, López D (eds). Springer: Berlin, 109–118.

Aguilar E, Brunet M, Saladié O, Sigró J, López D. 2002. Hacia una aplicación óptima del standard normal homogeneity test para la homogeneización de series de temperatura. In *La Información Climática Como Herramienta de Gestión Ambiental*, VII Reunión Nacional de Climatología, Grupo de Climatología de la AGE, Cuadrat JM, Vicente SM, SAZ MA (eds). Universidad de Zaragoza: Zaragoza, 17–33.

Aguilar E, Auer I, Brunet M, Peterson TC, Wieringa J. 2003. Guidelines on climate metadata and homogenization. WCDMP-No. 53, WMO-TD No. 1186. World Meteorological Organization: Geneve.

Aguilar E, López JM, Brunet M, Saladié O, Sigró J, López D. 1999. Control de calidad y proceso de homogeneización de series térmicas catalanas. In *La Climatología Española en Los Albores del Siglo XXI*, Raso Nadal JM, Martin-Vide J (eds). Publicaciones de la A.E.C.: Barcelona, 15–23, Serie A, 1.

Alexandersson H, Moberg A. 1997. Homogenization of Swedish temperature data. Part I: homogeneity test for linear trends. *International Journal of Climatology* **17**: 25–34.

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Klein Tank A, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A, Ambenje P, Rupa Kumar K, Revadekar J, Griffiths G, Vincent L, Stephenson D, Burn J, Aguilar E, Brunet M, Taylor M, New M, Zhai P, Rusticucci M, Vazquez-Aguirre JL. 2006. Global observed changes in daily climate extremes of temperature and precipitation. *Journal of Geophysical Research–Atmospheres* **V III**: DO5109, doi: 10.1029/2005JD006290, 2006.

Almarza C, López JA, Flores C. 1996. *Homogeneidad y variabilidad de Los Registros Históricos de Precipitación de España*. Ministerio de Medio de medio Ambiente, Direccíon General del Instituto Nacional de Meteorologıa: Madrid.

Andersson T, Mattisson I. 1991. *A Field Test of Thermometer Screens*, SMHI RMK No. 62. Swedish Meteorological Institute: Norköping, 40.

Angot A. 1903. *Instructions Météorologiques*, 4ème edn. Gauthier Villars, Imp Libraire: Paris.

Auer I, Böhm R, Jurkovic A, Orlik A, Potzmann R, Schöner W, Ungersböck M, Brunetti M, Nanni T, Maugeri M, Briffa K, Jones PD, Efthymiadis D, Mestre O, Moisselin J-M, Begert M, Brazdil R, Bochnicek O, Cegnar T, Gajic-Capka M, Zaninovic K, Majstorovic Z, Szalai S, Szentimrey T, Mercalli L. 2005. A new instrumental precipitation dataset for the greater Alpine region for the period 1800–2002. *International Journal of Climatology* **25**: 139–166.

Auer I, Böhm R, Jurkovic A, Orlik A, Potzmann R, Schöner W, Ungersböck M, Brunetti M, Nanni T, Maugeri M, Briffa K, Jones PD, Efthymiadis D, Mestre O, Moisselin J-M, Begert M, Brazdil R, Bochnicek O, Cegnar T, Gajic-Capka M, Zaninovic K, Majstorovic Z, Szalai S, Szentimrey T, Mercalli L. 2006. HISTALP–Historical instrumental climatological surface time series of the greater Alpine region. *International Journal of Climatology* submitted.

Barriendos M, Martin-Vide J, Peña JC, Rodriguez R. 2002. Daily meteorological observations in Cádiz–San Fernando. Analysis of the documentary sources and the instrumental data content (1786–1996). *Climatic Change* **53**: 151–170.

Begert M, Schlegel T, Kirchhofer W. 2005. Homogeneous temperature and precipitation series of Switzerland from 1864 to 2000. *International Journal of Climatology* **25**: 65–80.

Böhm R, Auer I, Brunetti M, Maugeri M, Nanni T, Schöner W. 2001. Regional temperature variability in the European Alps: 1760–1998 from homogenized instrumental time series. *International Journal of Climatology* **21**: 1779–1801.

Brunet M, Aguilar E, Saladié O, Sigró J, López D. 2001a. The variations and trends of the surface air temperature in the Northeastern of Spain from middle nineteenth century onwards. In *Detecting and Modelling Regional Climate Change*, Brunet M, López D (eds). Springer: Berlin, 81–93.

Brunet M, Aguilar E, Saladié O, Sigró J, López D. 2001b. A Differential response of Northeastern Spain to asymmetric trends in diurnal warming detected on a global scale. In *Detecting and Modelling Regional Climate Change*, Brunet M, López D (eds). Springer: Berlin, 95–107.

Brunet M, Bañón M, García F, Aguilar E, Saladié O, Sigró J, Asín J, López D. 2004. Una aproximación experimental tendente a la minimización del sesgo artificial asociado al tipo de garita meteorológica mediante la observación dual de la temperatura del aire. *La Meteorología y el Clima Atlánticos*. Publicaciones de la Asociación Española de Meteorología: Badajoz; 93–103.

Brunetti M, Maugeri M, Monti F, Nanni T. 2004. Changes in daily precipitation frequency and distribution in Italy over the last 120 years. *Journal of Geophysical Research* **109**: D05102, DOI:10.1029/2003JD004296.

Brunetti M, Maugeri M, Monti F, Nanni T. 2006. Temperature and precipitation variability in Italy in the last two centuries from homogenised instrumental time series. *International Journal of Climatology* **26**: 345–381.

Camuffo D, Jones PD. 2002. *Improved Understanding of Past Climatic Variability from Early Daily European Instrumental Sources*. Kluwer Academia Publishers: Dordrecht, Boston, London.

Della-Marta P, Wanner H. 2006. A method of homogenizing the extremes and mean of daily temperature measurements. *Journal of Climate* Submitted.

Della-Marta P, Moberg A, Luterbacher J, Wanner H. 2005. A potential new method of homogenising daily temperature data. *Geophysical Research Abstracts* EGU05-A-07940, 1607-7962/gra/EGU05-A-07940.

Eischeid JK, Pasteris PA, Diaz HF, Plantico MR, Lott NJ. 2000. Creating a serially complete, national daily time series of temperature and precipitation for the western United States. *Journal of Applied Meteorology* **39**: 1580–1591.

Feng S, Hu Q, Qian W. 2004. Quality control of daily meteorological data in China, 1951–2000: a new dataset. *International Journal of Climatology* **24**: 853–870.

Folland CK, Karl TR, Christy JR, Clarke RA, Gruza GV, Jouzel J, Mann ME, Oerlemans J, Salinger MJ, Wang SW. 2001. Observed climate variability and change. In *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of Intergovernmental Panel on Climate Change*, Houghton JT, Ding Y, Griggs DJ, Noguer M, van der Linden PJ, Dai X, Maskell K, Johnson CA (eds). Cambridge University Press: Cambridge, 99–182.

Galán E, Cañada R, Fernández F, Cervera B. 2001. Annual temperature evolution in the southern plateau of Spain from the construction of regional climatic time series. In *Detecting and Modelling Regional Climate Change*, Brunet M, López D (eds). Springer: Berlin, 119–131.

González FJ. 1992. *El observatorio de San Fernando (1831–1924).* Serv. Publ. Ministerio de Defensa: Madrid.

Horcas R, Rasilla D, Fernández F. 2001. Temperature variations and trends in the Segura River Basin. An exploratory analysis. In *Detecting and Modelling Regional Climate Change*, Brunet M, López D (eds). Springer: Berlin, 133–142.

ICM (Instituto Central Meteorológica) 1891. *Resumen de las Observaciones Meteorológicas Efectuadas en la Peninsula algunas de sus Islas Adyacentes*. Imprenta de Rafael Marco Y Viñas, Madrid.

ICM (Instituto Central Meteorológico) 1893. *Treinta años de Observaciones Meteorológicas: Exposición y Resumen de Las Efectuadas en el Observatorio de Madrid Desde el 1° de Enero de 1860 al 31 de Diciembre de 1889*. Establecimiento Tipográfico de los Sucesores de Cuesta: Madrid.

Jones PD, Hulme M. 1996. Calculating regional climatic time series for temperature and precipitation: methods and illustrations. *International Journal of Climatology* **16**: 361–377.

Jones PD, Moberg A. 2003. A hemispheric and large-scale surface air temperature variations: an extensive revision and update to 2001. *Journal of Climate* **16**: 206–223.

Jones PD, New M, Parker DE, Martin S, Rigor IG. 1999. Surface air temperature and its changes over the past 150 years. *Reviews of Geophysics* **37**: 173–199.

Jones PD, Raper SCB, Bradley RS, Diaz HF, Kelly PM, Wigley TML. 1986. Northern Hemisphere surface air temperature variations: 1851–1984. *Journal of Climate and Applied Meteorology* **25**: 161–179.

Jones PD, Groisman PY, Coughlan M, Plummer N, Wang WC, Karl TR. 1990. Assessment of urbanization effects in time series of surface air temperature over land. *Nature* **347**: 169–172.

Jones PD, Osborn TJ, Briffa KR, Folland CK, Horton B, Alexander LV, Parker DE, Rayner NA. 2001. Adjusting for sampling density in grid-box land and ocean surface temperature time series. *Journal of Geophysical Research* **106**: 3371–3380.

Karl TR, Diaz HF, Kukla GJ. 1988. Urbanization: its detection and effect in the United States climate record. *Journal of Climate* **1**: 1099–1123.

Kendall MG. 1955. *Rank Correlation Methods*. Charles Griffin and C: London.

Klein Tank A, Können GP. 2003. Trends in indices of daily temperature and precipitation extremes in Europe. *Journal of Climate* **16**: 3665–3680.

Klein Tank AMG, Wikngaard JB, Können GP, Böhm R, Demarée G, Gocheva A, Mileta M, Pashiardis S, Hejkrlik L, Kern-Hansen C, Heino R, Bessemoulin P, Müller-Westermeier G, Tzanakou M, Salía S, Pálsdóttir T, Fitzgerald D, Rubin S, Capaldo M, Maugeri M, Leitass A, Bukantis A, Aberfeld R, Van Encelen AFV, Forland E, Mietus M, Coelho F, Mares C, Razuvaev V, Nieplova E, Cegnar T, López JA, Dahlström B, Moberg A, Kirchhofer W, Ceylan A, Pachaliuk O, Alexander LV, Petrovic P. 2002. Daily dataset of 20th-century surface air temperature and precipitation series for the European climate assessment. *International Journal of Climatology* **22**: 1441–1453.

Luna MY, Almarza C. 2004. Interpolation of 1961–2002 daily climatic data in Spain. In *Proceedings of International Meeting on Spatial Interpolation in Climatology and Meteorology*, Budapest.

Manley G. 1974. Central England temperatures: monthly means 1659 to 1973. *Quarterly Journal of the Royal Meteorological Society* **100**: 389–405.

Martín-Vide J, Olcina J. 2001. *Climas y tiempos de España*. Alianza Editorial: Madrid.

Maugeri M, Brunetti M, Monti F, Nanni T. 2004. Sea-level pressure variability in the po plain (1765–2000) from homogenised daily secular records. *International Journal of Climatology* **24**: 437–455.

Mitchell JM Jr. 1953. On the cause of instrumentally observed secular temperature trends. *Journal of Meteorology* **10**: 244–261.

Moberg A, Jones PD, Barriendos M, Bergström M, Camuffo D, Cocheo C, Davies TD, Demarée G, Martín-Vide J, Maugeri M, Rodríguez R, Verhoeve T. 2000. Day-to-day temperature variability trends in 160 to 275-year long European instrumental records. *Journal of Geophysical Research* **105 D18**: 22849–22868.

NCDC. 2002. *Data Documentation for Data Set 9101, Global Daily Climatology Network*, version 1.0, 26. (available online http://www.ncdc.noaa.gov/oa/climate/climateinventories.html.

Nicholls N, Tapp R, Burrows K, Richards D. 1996. Historical thermometer exposures in Australia. *International Journal of Climatology* **16**: 705–710.

Nordli PO, Alexandersson H, Frich P, Forland EJ, Heino R, Jónsson T, Tuomenvirta H, Tveito OE. 1997. The effect of radiation screens on Nordic times series of mean temperature. *International Journal of Climatology* **17**: 1667–1681.

Parker DE. 1994. Effects of changing exposure of thermometers at land stations. *International Journal of Climatology* **14**: 1–31.

Parker DE, Legg TP, Folland CK. 1992. A new daily central England temperature series, 1772–1991. *International Journal of Climatology* **12**: 317–342.

Peterson TC, Easterling DR. 1994. Creation of homogeneous composite climatological reference series. *International Journal of Climatology* **14**: 671–679.

Peterson TC, Vose R. 1997. An overview of the global historical climatology network temperature data base. *Bulletin of the American Meteorological Society* **78**: 2869–2872.

Peterson TC, Daan H, Jones PD. 1997. Initial selection of a GCOS surface network. *Bulletin of the American Meteorological Society* **78**: 2837–2849.

Portman DA. 1993. Identifying and correcting urban bias in regional time series: surface temperature in China's northern plains. *Journal of Climate* **6**: 2298–2308.

Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP, Kent EC, Kaplan A. 2003. Globally complete analyses of sea surface temperature, sea ice and night marine air temperature, 1871–2000. *Journal of Geophysical Research* **108**: 4407.

Rico Sinobas M. 1857. *Resumen de Los Trabajos Meteorológicos Correspondientes al año 1854 Verificados en el Real Observatorio de Madrid*. Imprenta de Eusebio Aguado: Madrid.

Sánchez Pascua F. 1985. *El Instituto de Segunda Enseñanza de Badajoz en el siglo XIX (1845–1900).Orígenes, Tratamiento Estadístico del Alumnado y Bibliometría de Los Profesores*. Diputación Provincial de Badajoz: Badajoz.

Sen PK. 1968. Estimates of the regression coefficient based on Kendall's tau. *Journal of the American Statistical Association* **63**: 1379–1389.

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

Staudt M. 2004. Detección de cambios térmicos en la Península Ibérica con datos homogéneos regionales, Ph.D., University of Granada, Spain.

Staudt M, Esteban-Parra MJ, Castro-Díez Y. 2005. Evolution and changes in Spanish monthly maximum and minimum temperatures with homogenized data. *Geophysical Research Abstracts* **7**: 06754.

Trewin BC. 1999. *The development of a high quality daily temperature data set for Australia, and implications for the observed frequency of extreme temperatures*. In *Meteorology and Oceanography at the New Millennium: AMOS 1999. Proceedings of the Sixth National Australian Meteorological and Oceanographic Society Congress*: Canberra, 1999.

Trewin BC. 2001. Extreme temperature events in Australia, Ph.D. thesis, School of Earth Sciences, University of Melbourne, Australia.

Vincent LA, Gullet DW. 1999. Canadian historical and homogeneous temperature datasets for climate change analyses. *International Journal of Climatology* **19**: 1375–1388.

Vincent LA, Zhang X, Bonsal BR, Hogg WD. 2002. Homogenization of daily temperatures over Canada. *Journal of Climate* **15**: 1322–1334.

Vose RS, Schmolyer RL, Steurer PM, Peterson TC, Heim R, Karl TR, Eischeid J. 1992. *The Global Historical Climatology Network: Long-Term Monthly Temperature, Precipitation, Sea Level Pressure and Station Pressure Data*, ORNL/CDIAC-53, NDP-041, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory: Oak Ridge, TN.

Wang XL, Swail VR. 2001. Changes of extreme wave heights in Northern Hemisphere oceans and related atmospheric circulation regimes. *Journal of Climate* **14**(10): 2204–2221.

Zhang X, Vincent LA, Hogg WD, Niitsoo A. 2000. Temperature and precipitation trends in Canada during the 20th century. *Atmosphere and Ocean* **38**: 395–429.