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The use of GIS to evaluate and map extreme maximum and minimum temperatures in Spain

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Spanish building legislation has recently changed and now requires an updated and restructured Technical Building Code which is in accordance with European directives. The norm contained in this Code is based on studies of extreme values for climatic elements such as temperature, precipitation and wind. Revised maps of extreme values for climatic elements with a 50-year recurrence interval are required. Here, extreme maximum and minimum temperature maps for Spain are evaluated and mapped by means of geographical information technology. The data are extracted from the historical database held by the Spanish Meteorological Institute. Daily extreme temperatures from 1,181 stations with records going back more than 30 years have been used. The maximum and minimum temperatures are determined as 50-year mean recurrence interval values. To obtain these values, a Gumbel distribution is fitted to the extreme annual values extracted from the database. Spatial interpolation in a regular 5 km × 5 km grid of the annual maximum temperature is made by ordinary kriging. Meanwhile, for the annual minimum temperature a residual kriging has been applied due to its strong dependence on altitude.

Keywords: extreme maximum and minimum temperature, 50-year recurrence interval, Gumbel distribution, GIS

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1. Introduction

Construction is one of the main economic sectors in Spain with implications for society generally and for the cultural value of architectural heritage. However, until the enactment of the Building Legislation Act on 6 May 2000, the sector lacked the regulations to match its economic and social importance. The express aim of the Act is to regulate the basic aspects of the construction process by setting out the obligations and responsibilities of all those involved in the process, as well as the necessary guarantees for its proper implementation. Compliance with these basic requirements will safeguard the quality of buildings and ensure the adequate protection of users' interests (Act 38/1999, 1999). In order to guarantee people's safety, the welfare of society and the protection of the environment, the Building Legislation Act establishes the basic requirements that must be satisfied. In its Second Final Provision, the law authorises the Spanish Government to approve a Technical Building Code, which sets the mandatory standards required to ensure safety and habitability (for more information see the websites of the Spanish Administration http://www.mviv.es and http://www.ietcc.csic.es).

Enhancing building quality is demanded today both at the European and the Spanish level. The Spanish Technical Building Code is intended as a new framework which identifies, arranges and completes existing technical regulations and seeks to facilitate their application and fulfilment in accordance with European regulations. In the European Union a series of directives for the technical harmonisation and standardisation of products has recently been approved. The Construction Products Directive (CPD) 89/106/EEC has fundamentally established the essential requirements which construction works must satisfy. European regulations are regarded as basic documents whose consideration will be mandatory in drawing up the Spanish Technical Building Code. This Code will include the suitably updated and restructured contents of the Basic Building Norms (Act 195/1963, 1963), now more than 30 years old, which it will supersede.

In order to update these norms, a new set of advice, based on studies of extreme values for climatic elements such as temperature, precipitation or wind, for several mean recurrence intervals, are necessary. The maximum snow load on the ground for a recurrence period of 50 years, possibly the most important climatic

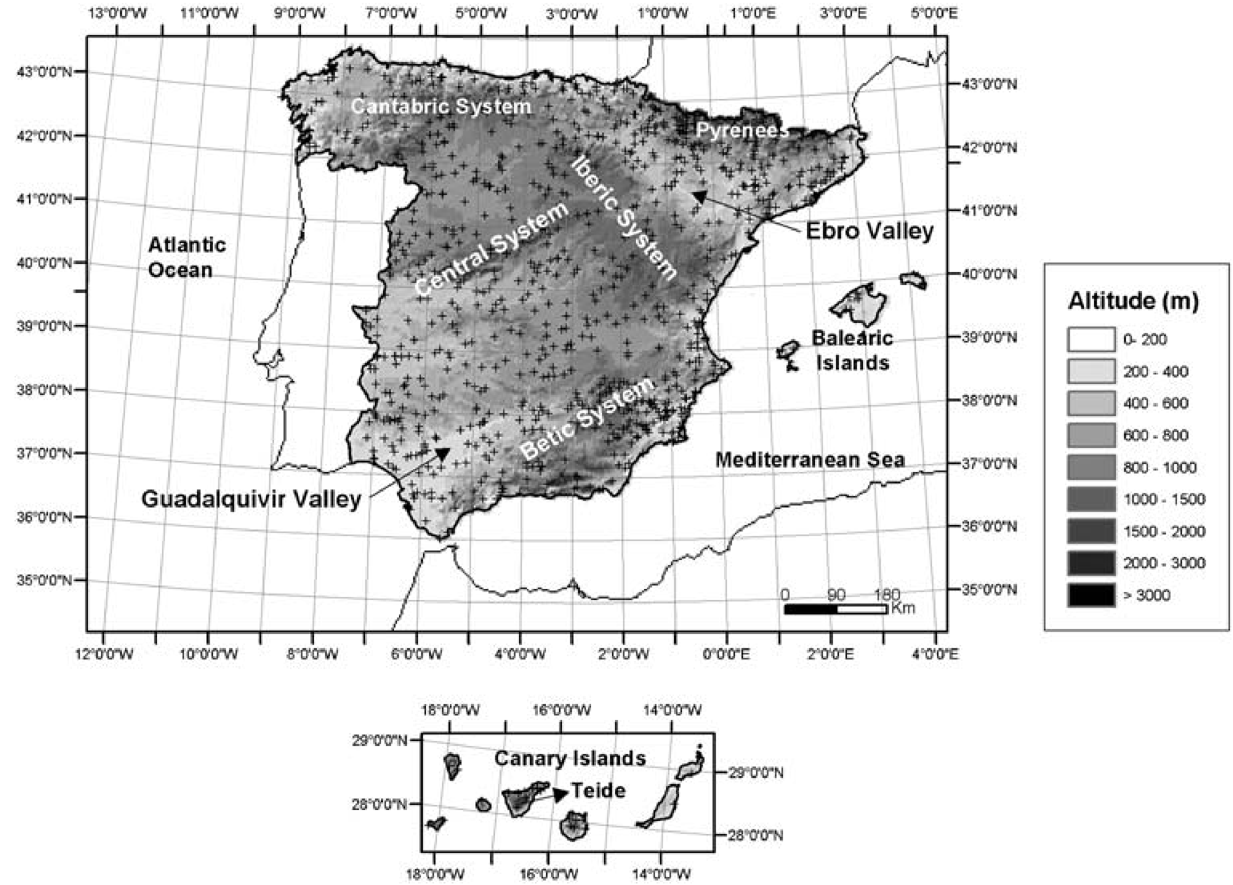

Figure 1. *Distribution of the stations in Spain for which there are temperature measurements +. Places cited in the text are also indicated.*

parameter for building design (Schmidlin et al. 1992), has been already obtained and mapped and has been included in the Technical Building Code (Luna et al. 2005). Now, revised maps of extreme values of temperature for a 50-year recurrence interval are also required (ISO-4355, 1981). The main purpose of this work is to derive these extreme values of temperature in Spain so that they can be included in the Technical Building Code. To do this, a Geographical Information System (GIS; ESRI® ArcMap 8.3 Software) has been used on account of its suitability for analysing and handling the spatial data. Digital maps are produced in easier and cheaper ways and data can be represented on a wide range of spatial scales. Maps of maximum and minimum temperature values for a 50-year recurrence interval for Spain are presented in this work at scale of 1:1,200,000. The results will be transferred to the Spanish Administration responsible for the Code in the digital format obtained from the GIS software; in this way, the results will be available for all members of the construction sector.

2. Data

The temperature data were extracted from the historical climatic database of the Spanish Meteorological Institute (INM). This database contains observations from both the temperature and the synoptic/complete observatory networks. The dataset was initially constituted from 1,181 time series of both maximum and minimum daily temperatures. The time series have records of different lengths but all of them cover at least 30 years. The spatial distribution of the time series is displayed in Figure 1.

From the daily maximum and minimum temperature series, time series of monthly extreme values have been constructed. A quality control process involving missing data, processing of outliers and homogenisation has been applied to the monthly extreme temperature time series, independently for each series. First, missing data have been estimated by the correlation method using neighbourhood stations with overlapping periods. The outliers are usually removed by trimming extreme values using a threshold value. However, in the present work, outliers could be very important as an extreme value holds the information of an extreme event and therefore it would not be desirable to eliminate them. The threshold value is defined as the upper quartile plus three times the interquartile range (Trenberth & Paolino 1980). The values that were identified as outliers have been investigated individually in order to determine whether or not they were erroneous. If they were erroneous, they were corrected or deleted and treated as missing values. If they were correct, the value was held. The problem is that outliers increase the bias for the homogenisation test used later (Afifi & Clark 1990).

The homogeneity of the monthly time series has been tested by applying the Standard Normal Homogeneity Test (Alexandersson 1986; Alexandersson & Moberg 1997). This resulted in 16% of the series being removed due to inhomogeneities or non-corrected missing data, leaving only 994 time series that were irregularly distributed around the country. From these monthly time series, the time series of annual maximum and minimum temperature are extracted for each station. In the next section, the extreme values for a 50-year mean recurrence interval will be estimated.

3. Extreme values of temperature for a 50-year mean recurrence interval

The extreme temperature values that were obtained and mapped are determined as 50-year mean recurrence interval values. In order to obtain these values, a statistical Gumbel distribution function (Gumbel 1958) was fitted to the annual maximum and minimum temperature time series extracted from the database. This distribution has been used because it is appropriate for annual extreme values of hydrological and meteorological variables (Brown & Katz 1995; Lana & Burgueño 1996; Kieffer & Bois 1997; Koutosoyiannis 2003).

The Gumbel distribution is defined as

$$F(x) = \exp\left[-\exp\left(-\frac{x - x_0}{\alpha}\right)\right] \quad (1)$$

where x is the variable to be fitted, and x_0 and α the parameters of the distribution (Gumbel 1958). A reduced variable y can be obtained from

$$y = \frac{x - x_0}{\alpha} = -\ln(-\ln F(x)) \quad (2)$$

From the values of x, the observed annual temperature series, and the values y from the Gumbel distribution, the parameters α and x_0 are fitted with the least squares method as

$$\alpha = \frac{s_x}{s_y} \quad (3)$$

$$x_0 = \overline{x} - \frac{s_x}{s_y}\overline{y} \quad (4)$$

where s_x and s_y are the standard deviation of x and y, respectively, and $\overline{x}$ and $\overline{y}$ the mean values of x and y, respectively.

The annual maximum and minimum temperature values have been fitted to a Gumbel distribution. From these theoretical distributions, the values, which correspond to a probability value of 0.2, are calculated. This annual probability corresponds to a 50-year mean recurrence period, this being the average interval of time within which the magnitude of x will be equalled or exceeded once (Chow 1964). The obtained maximum and minimum temperature values that have a probability of 0.2 of being observed on average every 50 years are calculated from the fitted Gumbel distributions. These data need to be known by civil engineers in order to measure the physical and engineering properties of materials used in construction (for example, the thermal dilation coefficients of concrete, asphalt, steel and cement) and they constitute the climatic parameters that will be mapped in the next section.

4. Interpolation of extreme maximum and minimum temperatures

In order to map the annual maximum and minimum temperature, the values obtained by the Gumbel distribution must not be interpolated directly owing to the possible dependence of temperature on altitude. A digital terrain model (DTM) provided by the Spanish Geographical Institute was used to obtain the altitude data needed to find the relationship between the extreme values of temperature and altitude. The DTM was constructed by digitalising a 1:1,000,000 scale map. The altitude data were obtained in each node of a 1 km grid square. The Earth model used is the international ellipsoid and Universal Transverse Mercator (UTM) Projection. The map of the relief of Spain, based on an interpolation of the DTM, is shown in all maps presented in this work as a reference framework (for simplicity, the corresponding legend is only displayed in Figure 2).

In the *Atlas Nacional de España* (IGN 2004), the dependence of climatic parameters with topography was studied, and it was shown that the functions which relate climatic and geographical parameters are different depending on the zone. Seven zones of similar climatic behaviour were defined (see Figure 2) and it can be observed that they are related to the geographical distribution of the main mountain systems, valleys and plains.

For mapping all climatic elements or parameters in the *Atlas Nacional de España*, several functions relating extreme temperature values and physiographic parameters were tested. These functions were linear, polynomial, exponential and potential, and the physiographic parameters used were altitude, latitude, longitude and distance from the sea. For extreme minimum temperature, the linear relationship was the best function which related the temperature with altitude: the other parameters were not significant in the regression model. In the summer months, when extreme values of annual maximum temperature are reached, westerly winds almost disappear from the lower layers of the atmosphere over the Iberian Peninsula and Balearic Islands. In these months conditions are similar to sub-tropical dry weather and the little observed precipitation is of convective origin. The observed extreme annual maximum temperatures are

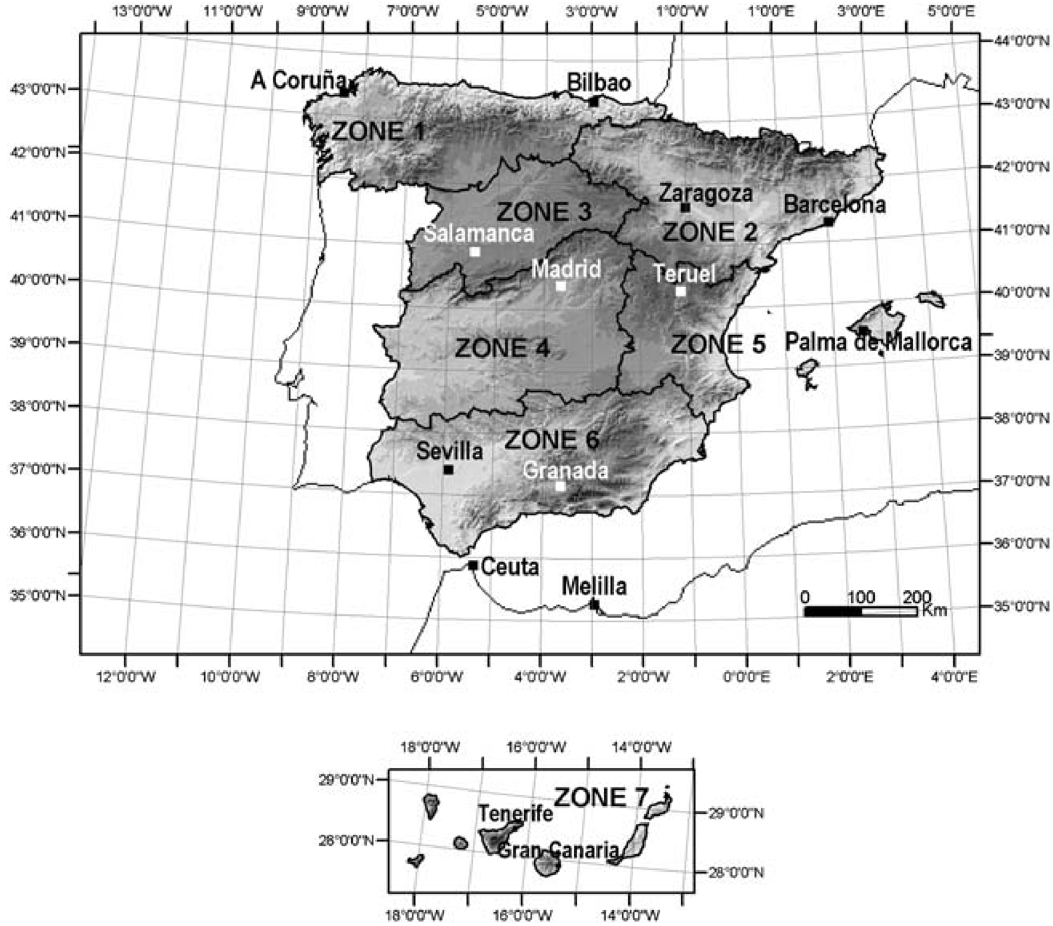

Figure 2. *The seven homogeneous climatic zones. The Balearic Islands are in Zone 5 and the Canary Islands in Zone 7. Altitude is given in metres.*

related to the presence of heat waves, characterised by classical synoptic patterns of high pressure (Font-Tullot 2000). For this reason, the extreme annual maximum temperature does not show a significant dependence on any physiographic parameter, so the 50-year mean recurrence interval extreme values obtained from the Gumbel distribution are interpolated by ordinary kriging.

The linear function for extreme minimum temperature has the form:

$$T_{\min} = \alpha + \beta A \qquad (5)$$

where T_{min} is the minimum temperature value for a 50-year return-period and A is the altitude. The parameters α and β of this linear equation were obtained by the least squares method: a regression line was computed to fit the data. For each zone, the obtained linear functions and the 95% upper and lower confidence level functions are displayed in Table 1 and Figure 3. All correlation coefficients are significant at the 95% level and the functions fit reasonably well, as can be observed in Figure 3.

The spatial interpolation method used has been ordinary kriging for the annual maximum temperature and residual kriging for annual minimum temperature. By means of the functions displayed in Table 1, the 50-year return period minimum temperature values related with altitude are calculated for all stations. A residual is obtained, defined as the difference between minimum temperatures obtained from fitting the Gumbel distribution and minimum temperatures obtained from these linear functions. Residuals were calculated for all stations and then interpolated for the whole of Spain by an ordinary kriging technique implemented in GIS software in a regular 5 km × 5 km grid. The minimum temperature values for the 50-year

Table 1. *Functions of the extreme minimum temperature (T_{min} in °C) with altitude (A, in m), for the seven climatic zones. r is the correlation coefficient and N is the number of stations for the seven zones.*

	Function	*r*	*N*
ZONE 1	$T_{min} = -7.30 - 0.013$ A	0.86	138
ZONE 2	$T_{min} = -11.22 - 0.008$ A	0.75	242
ZONE 3	$T_{min} = -10.51 - 0.008$ A	0.65	91
ZONE 4	$T_{min} = -5.91 - 0.010$ A	0.68	158
ZONE 5	$T_{min} = -5.47 - 0.015$ A	0.90	94
ZONE 6	$T_{min} = -6.14 - 0.008$ A	0.70	246
ZONE 7	$T_{min} = 6.37 - 0.008$ A	0.92	25

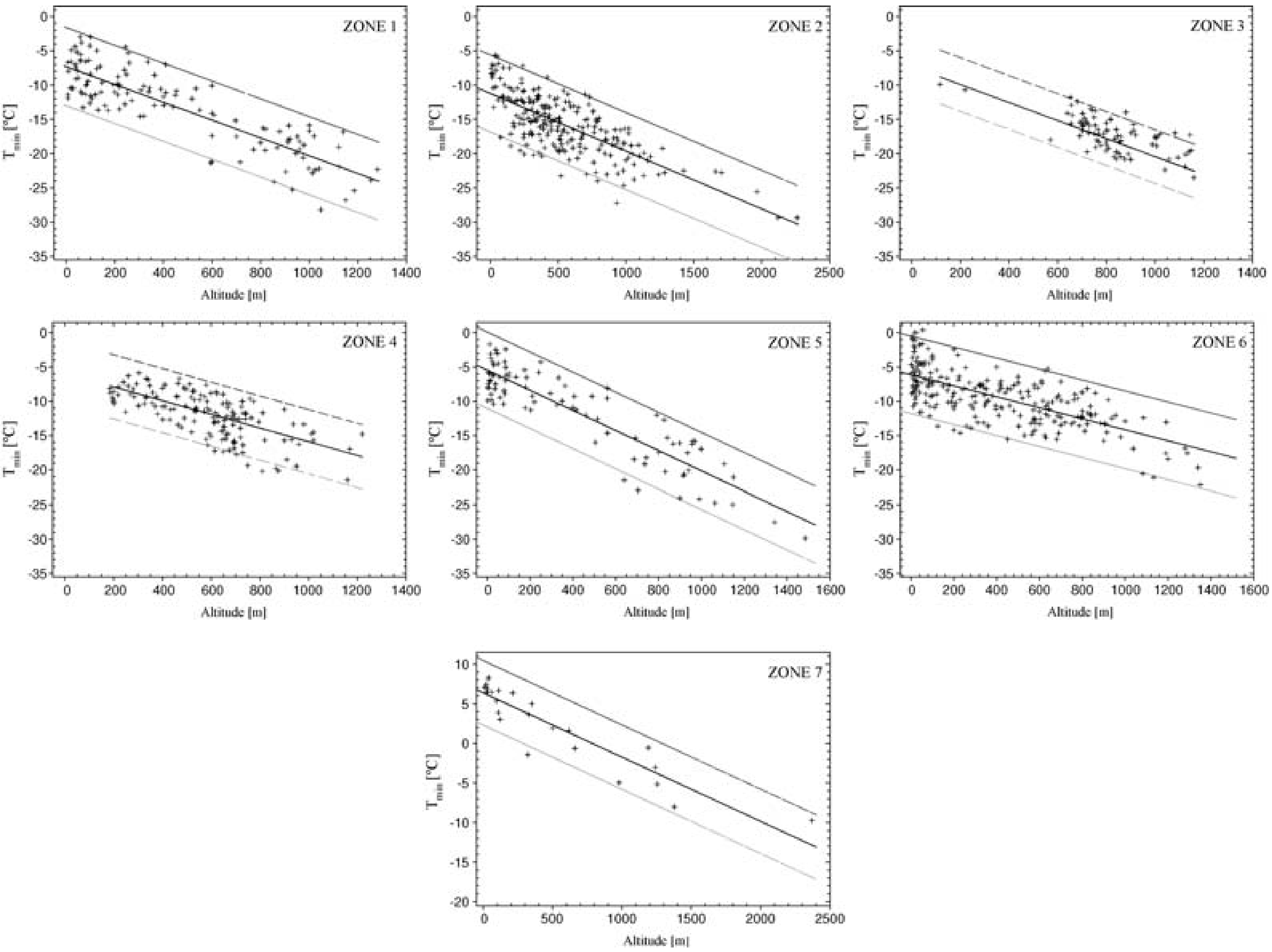

Figure 3. *Linear functions (black line) and both 95% upper (dark grey line) and lower (light grey line) confidence level functions relating the extreme minimum temperature values (points) with altitude for the seven climatic zones.*

mean recurrence interval were obtained by adding the interpolated residual field to the minimum temperature values determined by the linear function in all grid points. These calculations were made by means of geographical information technology, resulting in the map shown in Figure 4a.

Figure 4b shows the map obtained from the ordinary kriging interpolation of the 50-year mean recurrence interval minimum temperature obtained from the Gumbel distribution. It is clear that Figure 4a is more realistic, showing lower values in the mountain areas (Figure 1); these regions are not clear in Figure 4b. The poor resolution in mountain regions, observed in Figure 4b, could be due to the lack of observational data in regions above 1100 m. Also it is noticeable that the minimum temperature can be observed in a zone near Teruel with temperatures lower than −30 °C. This area, situated in the Iberic System, is the coldest area of Spain and typically presents temperatures colder than other places situated in higher mountains to the north (Pyrenees) or the south (Betic System) (see Figure 1 for these locations). In Figure 4a it can be observed that minimum temperature values of −10 °C occur in the centre of Tenerife (Canary Islands) where Teide volcano (3718 m) is situated; these are more realistic values than those observed in Figure 4b.

The extreme maximum temperature is displayed in Figure 5. The higher maximum temperatures can be generally noted in the southwest, with certain particularities. The Guadalquivir Valley is the hottest area with secondary maxima being observed in the Ebro Valley in the northeast, and in the inner part of the southeast Mediterranean coast. These zones have been identified in previous climatic studies of Spain (Linés 1970; Font-Tullot 2000).

5. Discussion and conclusion

To meet the requirements of the norm contained in the new Spanish Technical Building Code, a study of extreme maximum and minimum temperature values has been presented. The extreme annual maximum and minimum temperatures were obtained as the 50-year return-period maximum values fitting the data to the Gumbel distribution. The spatial interpolation methods used have been ordinary kriging for annual maximum temperature data and residual kriging for annual minimum temperature data. The annual minimum temperature is strongly dependent on the parameter of altitude, while the annual maximum temperature shows no significant dependence on this.

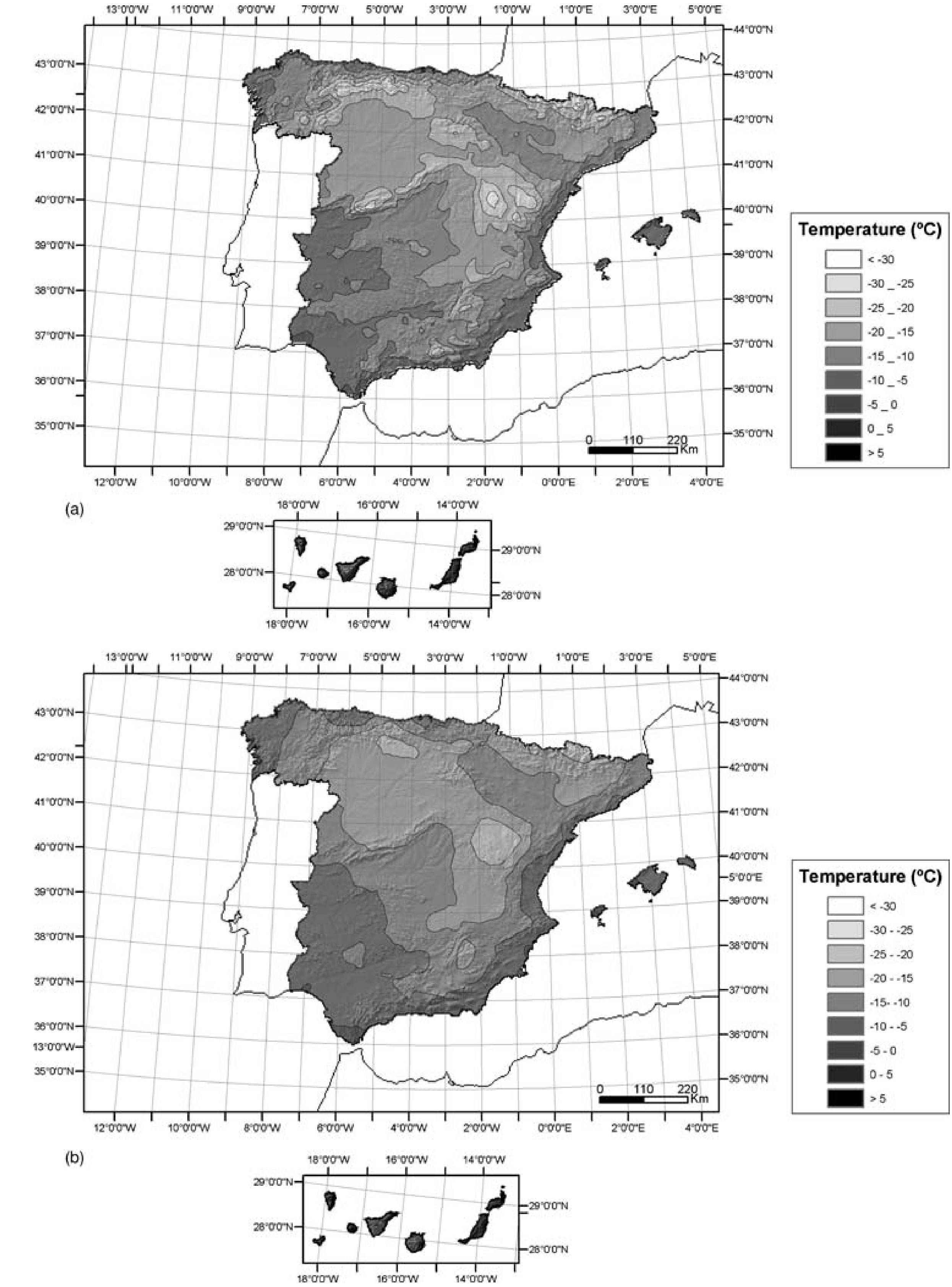

Figure 4. *Map of annual minimum temperature values for a 50-year recurrence interval obtained from: (a) residual kriging, and (b) ordinary kriging.*

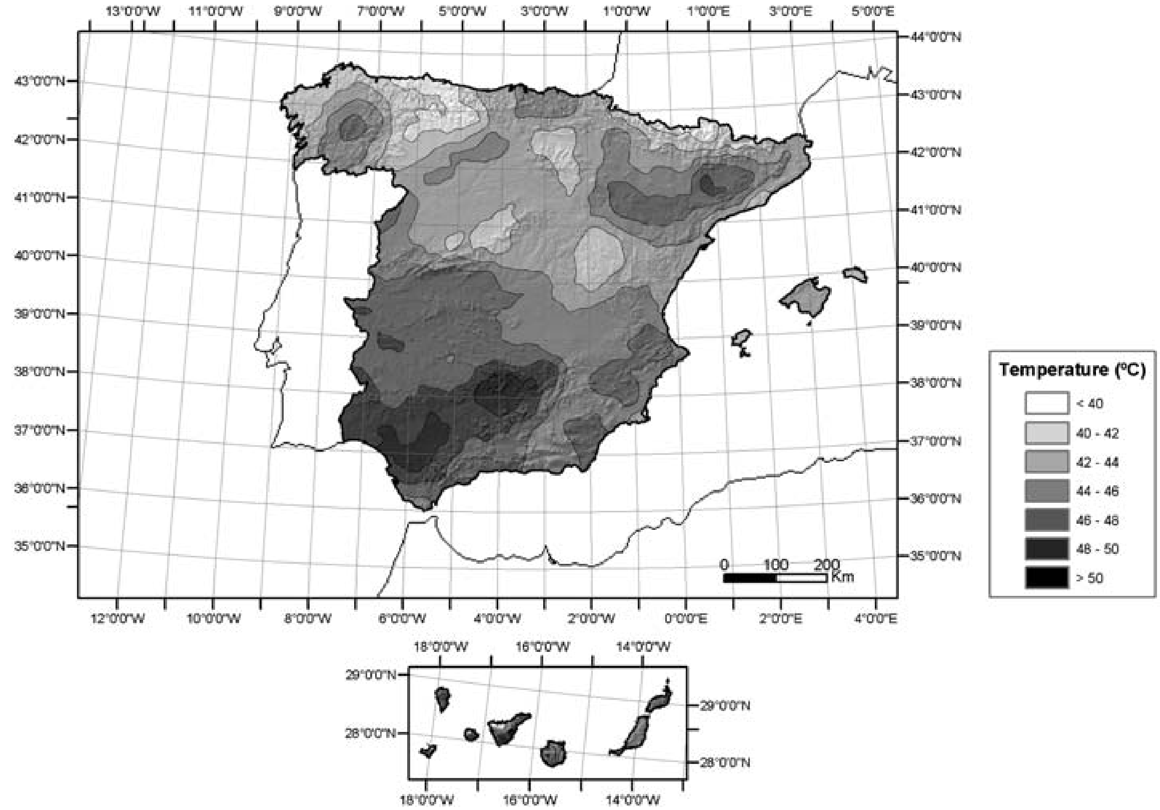

Figure 5. *Map of annual maximum temperature values for a 50-year recurrence interval obtained from ordinary kriging.*

The quality control and the statistical fitting to a Gumbel distribution function of both the maximum and minimum temperature time series have been carried out with a FORTRAN programme. The results of these calculations have been transferred to the climatic database of the Spanish Meteorological Institute. The GIS software used by the Spanish Meteorological Institute operates online with the climatic database and makes it possible to carry out all the spatial analyses presented in this work relatively quickly. This means that access to data is immediate and the response times for cartographic operations are reduced. The Spatial Analyst module contained in the GIS software was used for all spatial calculations and interpolations. The digital maps obtained constitute both a direct climatological application of a Geographical Information System and an administrative application that will be including in the Technical Building Code. This Code will be published not only on paper (as maps) but also digitally. Using this information, the members of the Spanish Construction Economic Sector can consult and identify the extreme temperature values that they need in order to improve the quality of building materials in the construction of facilities and structures. By doing this, the vulnerability of structures to climate, and hence the risks of structural failure, can be reduced.

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References

Act 195/1963 (1963) Acciones en la edificación. Norma MV (101–1962). *Boletín Oficial del Estado Español*, 17 January: 4578–4599.

Act 38/1999 (1999) Building Legislation. *Boletín Oficial del Estado Español*, 6 November 1999.

Afifi, A. A. & Clark, V. (1990) *Computer-Aided Multivariate Analysis*. 2nd edn. New York: Van Nostrand Reinhold, 500 pp.

Alexandersson, H. (1986) A homogeneity test applied to precipitation data. *J. Climatol.* **6**: 661–675.

Alexandersson, H. & Moberg, A. (1997) Homogenization of Swedish temperature data. Part I: Homogeneity test for linear trends. *Int. J. Climatol.* **17**: 25–34.

Brown, B. G. & Katz, R. W. (1995) Regional analysis of temperature extremes: spatial analog for climate change? *J. Climate* **8**: 108–119.

Chow, V. T. (1964) *Handbook of Applied Hydrology*. New York: McGraw-Hill, 1460 pp.

Font-Tullot, I. (2000) *Climatología de España y Portugal*. 2nd edn, Salamanca: Universidad de Salamanca, Spain. 422 pp.

Gumbel, E. J. (1958) *Statistics of Extremes*. New York: Columbia University Press, 375 pp.

IGN (2004) Fascículo de climatología, *Atlas Nacional de España*. 2nd edn, Madrid: Instituto Geográfico Nacional, 36 pp.

ISO-4355 (1981) Norme Internationale: bases du calcul des constructions-Détermination de la charge de neige sur les toitures. Première édition 1981-08-15. Organisation Internationale de Normalisation.

Kieffer, A. & Bois, P. (1997) Variability of the statistical characteristics of extreme rainfall values in the French Alps. *Revue des Sciences de l'Eau*, **10**: 199–216.

Koutosoyiannis, D. (2003) On the appropriateness of the Gumbel distribution for modelling extreme rainfall. Proceedings of the ESF LESC Exploratory Workshop held at Bologna.

Lana, X. & Burgueño, A. (1996) Extreme winter minimum temperatures in Catalonia (north-east Spain): expected values and their spatial distribution. *Int. J. Climatol.* **16**: 1365–1378.

Linés, A. (1970) The climate of the Iberian Peninsula. In: C. C. Wallén (ed.), *World Survey of Climatology, Volume* **5***: Climates of Northern and Western Europe*. Amsterdam: Elsevier Co.: 195–239.

Luna, M. Y., Morata, A., Chazarra, A. & Almarza, C. (2005) Mapping of snow loads on the ground in Spain. *Geographical Information Systems and Remote Sensing: Environmental Applications*. Proceedings of the International Symposium held at Volos, Greece, 7–9 November 2003.

Trenberth, K. E. & Paolino, D. A. (1980) The Northern Hemisphere sea-level pressure data set: trends, errors and discontinuities. *Mon. Wea. Rev.* **108**: 856–872.

Schmidlin, T. W., Edgell, D. J. & Delaney, M. A. (1992) Design ground snow loads for Ohio. *J. Appl. Meteorol.* **31**: 622–627.