# AN ASSESSMENT OF LONG – TERM TEMPERATURE VARIABILITY IN THE SIERRA DE GUADARRAMA

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**RESUMEN**
Este trabajo proporciona un primer análisis de la variabilidad de la temperatura a escalas interanuales y decadales en la Sierra de Guadarrama (SG), un área protegida de alta montaña del Sistema Central en la Península Ibérica. Se utilizan datos observacionales de estaciones situadas en la zona y una simulación regional de alta resolución (1km) del modelo Weather Research and Forecasting (WRF) para analizar la variabilidad de la temperatura durante el periodo 2000–2015. La comparación entre ambos conjuntos de datos permite evaluar el grado de realismo con el que las simulaciones representan la variabilidad observada. Los resultados muestran que el modelo tiene tendencia a infraestimar los valores medios y las anomalías de las temperaturas observacionales en las estaciones de mayor altitud. Se observa un gradiente vertical de temperatura media de -3.95$°C/km$, que es sobreestimado por el modelo (-6.52$°C/km$).La variabilidad de las anomalías térmicas aumenta con la altitud para las observaciones y, en menor medida, para las simulaciones.
Se evalúa el valor añadido que ofrece WRF frente al uso del reanálisis ERA Interim, que proporciona las condiciones iniciales y de contorno a la simulación regional. Se observa un menor sesgo de las temperaturas que proporciona el modelo regional en comparación con el reanálisis.
Se lleva a cabo un Análisis de Componentes Principales (PCA) sobre el campo de anomalías de temperatura de WRF para la evaluación de su variabilidad. Este análisis proporciona un primer modo muy dominante que explica el 94% de la varianza total y cuya componente principal muestra una gran correlación con las anomalías observacionales. La variabilidad de la temperatura en la SG muestra una gran relación con la temperatura en el interior de la Península Ibérica y con una gran parte del suroeste de Europa. El patrón de regresión entre la temperatura proporcionada por la simulación y la que procede del reanálisis permite obtener una estimación de la variabilidad de la temperatura en la SG en los últimos 40 años.

**Palabras clave**: temperatura, montaña, observaciones, WRF, reanálisis.

**ABSTRACT**
This work provides a first assessment of temperature variability at interannual and decadal timescales in the Sierra de Guadarrama (SG), a high mountain protected area of the Central System in the Iberian Peninsula. Observational data from stations located in the area and simulated data from a high-resolution configuration (1 km) of the Weather Research and Forecasting (WRF) model, fed from ERA Interim inputs, are used in order to analyse the temperature variability in the period 2000 - 2015. The comparison between both datasets allows for the evaluation of the realism of the model simulations. Results show that the model tends to underestimate observational mean temperatures and anomalies at high altitude stations. A linear mean temperature vertical gradient of -3.95$°C/km$ is observed and overestimated by the model (-6.52$°C/km$).The variability of temperature anomalies for both the observations and, to a lesser extent, the simulations increases with height.
The added value that WRF offers against the use of ERA Interim is evaluated. Results show that WRF provides a better performance than the reanalysis, as it shows smaller biases with the observational temperature anomalies.
A Principal Component Analysis (PCA) is performed over the temperature anomalies field of WRF for the assessment of its variability. This analysis provides a very dominant first mode that explains the 94% of the total variance and whose PC shows a large correlation with the observational anomalies. Temperature variability in the SG shows a large relationship with temperature in the midland Iberian Peninsula and broadly over south-western Europe. The regression patterns between WRF and the reanalysis are calculated in order to obtain an estimate of the temperature variability over the SG during the last 40 years.

**Key words**: temperature, mountain, observations, WRF, reanalysis.

## 1. INTRODUCTION

Mountains are areas that treasure natural and cultural heritage. They offer a useful space for research and educational activities, as well as for leisure. Also, they provide natural resources needed by society. Winter snow is a source of water for spring and summer. This water is used both for consumption and for the generation of hydroelectric energy and the sustainability of crops. They are greatly important in biological diversity, since they serve as home for a large number of species, both animals and plants. Thus, it is increasingly necessary to have a deeper knowledge of high mountain climates that can be used to help manage of ecosystems, risks and other environmentally related activities.

Mountain climates are characterized by complex terrains that produce very large temperature gradients (Beniston, 2005). Their steep orography, along with the location of the mountains, the proximity to the sea and the interaction with the atmospheric flow, can have an influence and change their climate (Barry, 2008). However, during the last four decades, mountains have been greatly affected by climate change and they have as well experienced the recent warming. This warming can result in an increase of extreme events, such as heat waves, landsides, droughts or heavy precipitation, as well as in a retreat of ice and snow cover and a decrease of albedo (Kohler et al., 2014). Acquiring meteorological observations over a high mountain environment is, therefore, a task of great importance.

Nevertheless, the work of obtaining meteorological observations and longer term climatological records in high altitude environments represents a challenge. The remoteness of the meteorological stations hampers the continued maintenance and exposes them to different kind of risks, including the exposure to extreme meteorological conditions that may lead to a malfunctioning of the station or, even, to system failures (Durán, 2015a). Due to the lack of observational data over mountain regions, the use of model simulations becomes an alternative for studying these environments. The biggest problem presented by the models is the difficulty to simulate the complex orography of high mountain areas, since the linearization of the model equations is a challenge in complex terrains. The simulation of the terrain can potentially be improved by increasing the spatial resolution in the model, although this is often not the case due to large-scale biases or to local scale representation errors (Jimenez et al, 2010).

This study is focused on the Sierra de Guadarrama, a mountain range located in the Iberian Peninsula Central System with a southwest – northeast orientation that represents a natural borderline that divides the Central Plateau. The Sierra de Guadarrama experiences a large difference between the summer and winter temperatures that are influenced by atmospheric flows that originate both in the Atlantic Ocean and in the Mediterranean Sea (Durán et al., 2013). The present work will provide a first approximation of the temperature variability and the climatology in that area by using a high-resolution configuration of the WRF model, the ERA Interim reanalysis and observational data from meteorological stations located in the Sierra de Guadarrama National Park (SGNP). The skill of the model will be evaluated by comparing the instrumental to the WRF simulations and the reanalysis data. This will allow for an evaluation of the high resolution model relative to the reanalysis fields that provide the boundary conditions. The reanalysis will be used as well to estimate local climate variability during the last decades. An analysis based on Principal Components (PC) and Empirical Orthogonal Functions (EOF) will be carried out to provide a first characterization of the temperature variability.

This text is structured as follows: in Section 2, all datasets, observations, simulations and reanalysis, will be described; the methodology is described in Section 3; results are presented in Section 4 and a discussion of results is included in Section 5.

## 2. DATA

The WRF model (Skamarock et al., 2005) was spatially configured for this study in four domains (Figure 1) at different grid spacings down to the finest horizontal resolution of 1 km. The outermost domain, D1 is configured with a horizontal resolution of 27 km, the second domain, D2, with 9 km, D3, 3 km and, last, the innermost domain, D4, presents a resolution of 1 km, covering the SGNP and a large area of the provinces of Madrid and Segovia. Such a high spatial resolution was selected in order to represent the orography as realistically as possible without having to resort to turbulent kinetic energy parameterizations (Gibbs et al, 2011). Note that, while increasing the resolution to 1 km provides a high resemblance of surface physics with reality, it does not guarantee a better performance than slightly lower model resolutions (Jiménez et al., 2010). The WRF model was initialized as a cold start at 0 hours every day and was run for 48 hours, using a temporal step of 120 seconds, storing every hour output. The first 24 hours were discarded as model spin-up, so as to obtain as stable a simulation as possible, and the outputs for the following 24 hours were retained. This process was repeated until a complete simulation, spanning the years 2000-2015, was obtained. ERA-Interim (Berrisford et al., 2011; Dee et al., 2011) reanalysis data were used as boundary conditions.

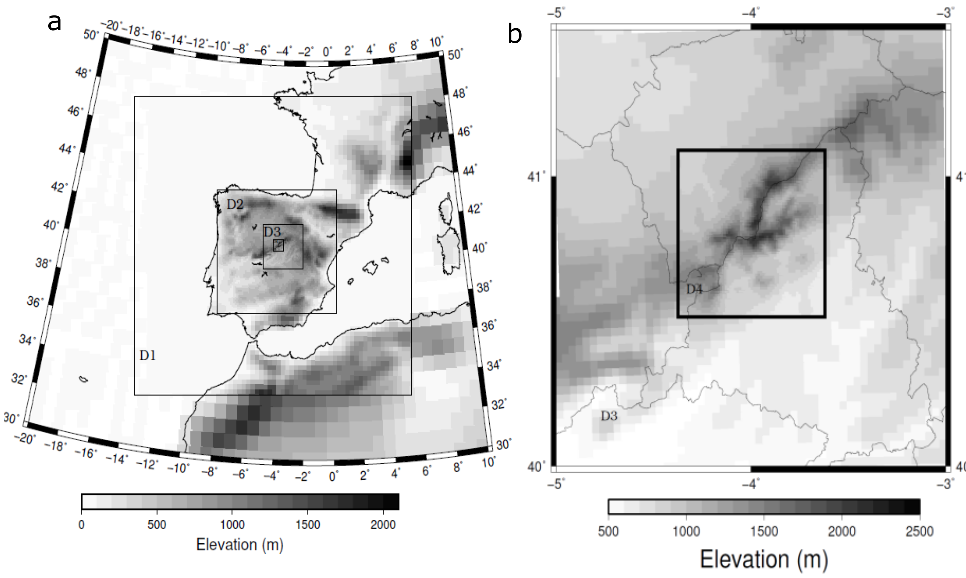


***Figure 1.*** *Configuration of the WRF domains. a) Domains D1 through D4. b) An enlargement of domains D3 and D4. Grey shadings depict orographical height with the resolution of the boundary reanalysis fields (outer borders) and the increasing resolution of the WRF domains.*

For the purpose of the present study, the simulated temperature from domain D4 has been used with a daily temporal resolution. In addition, to ease comparisons with the observations, the data of the closest WRF grid points in D4 to the observational stations have been selected and treated as separate stations. The information of the horizontal coordinates and height of the closest WRF grid points to the stations (denoted by *WRF**) can be found on Table 1.

| | Sierra de Guadarrama National Park (SGNP) | | | | | |
|---|---|---|---|---|---|---|
| | **ONTALVA (ONT)** | **CABEZA MEDIANA (CBM)** | **ZABALA (ZBL)** | **COTOS (CTS)** | **ALAMEDA (ALM)** | **NAVACERRADA (NVC)** |
| **Longitude (deg)** | -3.893 | -3.908 | -3.958 | -3.961 | -3.844 | -4.004 |
| **Latitude (deg)** | 40.872 | 40.844 | 40.837 | 40.825 | 40.915 | 40.789 |
| **Height (m)** | 1188 | 1682 | 2057 | 1873 | 1115 | 1858 |
| | **WRF*** | | | | | |
| **Longitude (deg)** | -3.890 | -3.914 | -3.963 | -3.962 | -3.842 | -3.998 |
| **Latitude (deg)** | 40.870 | 40.841 | 40.840 | 40.822 | 40.917 | 40.784 |
| **Height** | 1186 | 1487 | 2092 | 1788 | 1084 | 1986 |
| | **ERA Interim (ERAIT)** | | | | | |
| **Longitude (deg)** | -3.750 | -3.750 | -3.750 | -3.750 | -3.750 | -3.750 |
| **Latitude (deg)** | 40.500 | 40.500 | 40.500 | 40.500 | 41.250 | 40.500 |

**Table1.** Horizontal coordinates and heights of the stations used in this work. On the top, SGNP stations. At the bottom, the WRF grid points that are closest to the SGNP stations are shown.

ERA Interim temperatures over Europe and the North Atlantic were used to assess the relationship of the Sierra de Guadarrama with larger spatial scales. The spatial resolution of ERA Interim (ERAIT) is, approximately, 80 km, which is much coarser than the grid of the exterior domain of the WRF simulation, D1 (Figure 1). Therefore, the closest grid points to the SGNP stations are located outside domain D4 (Figure 1; Table 1). Also, all observational sites are represented by only two different grid points in the reanalysis due to its coarser resolution. The ERA Interim data have been used here to evaluate the added value of the WRF model experiments.

Daily temperature observations are available for 6 sites (Table 1). The data for Navacerrada (NVC; since 1946) were provided by the Spanish National Meteorological Agency (AEMet). The SGNP provided the temperature information for the other 5 sites: Ontalva (ONT; data availability since 2008), Cabeza Mediana

(CBM; since 2000), Zabala Shelter (ZBL; since 2000), Cotos (CTS; since 2005) and Alameda del Valle (ALM; since 2009).

## 3. METHODOLOGY

As a first step, the temperature data from the WRF model, the ERAIT reanalysis and the observations have been compared. The daily temperature annual cycles were calculated for every station and every dataset. These cycles were estimated by calculating the temperature average for every day of the year and by low pass-filtering it after (using first a 61-days moving average in order to discard the intra-monthly variability). In this way, a smoothed annual cycle is obtained. From these annual cycles, the daily temperature anomalies were calculated by subtracting them from the raw data. This comparison was performed over the period 2009 – 2014, since this is the common period in which every SGNP station has available data. From the resulting daily temperature anomalies, the frequency distribution (box-whiskers plot) and the regional averages were obtained and used to compare models and observations.

The relative performance of the WRF model in comparison to the use of the ERAIT reanalysis data was assessed by the use of Taylor Diagrams (Taylor, 2001). These diagrams allow for two datasets to be compared through their correlations, their Root Mean Square Error (RMSE) and their standard deviations. In this way, it is possible to know if the high resolution simulation constitutes an added value in the area of the SGNP with respect to the reanalysis data. This analysis was performed over the daily temperature anomalies during the winter (December, January and February; DJF) and summer (June, July and August, JJA) seasons, spanning the years 2000 to 2015.

For the study of the variability of the daily temperature anomalies, Principal Component Analysis (PCA) was chosen (Preisendorfer, 1988; Zwiers and von Storch, 1995). This method tries to find patterns of covariance or correlation dependence in the data by searching for linear combinations of the variables that explain maximum variance. This means that EOFs can be interpreted as variability modes of a climate field, while PCs explain how those variability modes vary in time. The PCA method was applied to the WRF simulated daily temperature anomalies in the domain D4 for the period 2000 – 2015 and the first three PCs and EOFs were calculated. The PCs were also used for the calculation of the regression coefficients with the observed daily temperature anomalies for the period 2000 – 2015 in order to assess the consistency between the simulations and the observations. For the analysis of the behaviour of the daily temperature anomalies on a larger scale, the correlations between the PCs in the D4 WRF domain and the daily temperature anomalies from the rest of WRF domains were calculated for the same period.

Furthermore, the monthly temperature means were calculated from the daily data and regression patterns were calculated between the ERAIT monthly temperature anomalies and the regional average of WRF simulations during the DJF and JJA seasons during the period 2000 – 2015, covering a wide region over Europe and the

North Atlantic Ocean. This allows for exploring teleconnections at continental spatial scales. Finally, based on the regression patterns between the monthly temperature anomalies from ERAIT and the WRF regional average of the anomalies, the whole period of availability from the ERAIT temperature field was used to estimate the regional average of the temperature variability in the Sierra de Guadarrama during the DJF and JJA seasons from 1979 to 2015.

## 4. RESULTS

The mean annual temperatures from observations, WRF model and ERAIT reanalysis are shown in Figure 2a. This map provides a basic climatological description of the temperature in the Sierra de Guadarrama, where orography is dominant, so the coldest temperatures are found at the highest altitudes. The regional averages (squares in Figure 2a) show that observations and the WRF simulation are very similar at this spatial scale, whilst the reanalysis shows a warmer bias. The local values of observed mean temperatures are in agreement with the simulated spatial distribution. The temperature dependency with height is evident too in Figure 2b, where the linearity

a )
b )

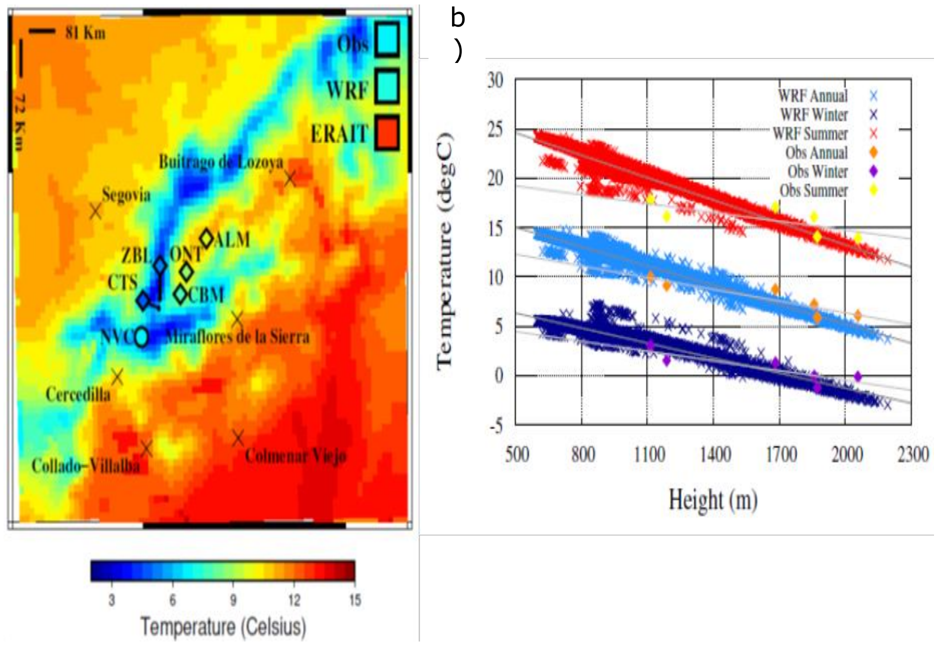


***Figure 2.****a) Mean temperature in the period 2009 – 2015 for the simulated and observed data: WFR simulation values are represented by the shaded scale; diamonds represent the values of the SGNP network; the circle is the Navacerrada station and the crosses indicate reference locations of nearby towns. b) The distribution of vertical temperature gradients: for the observations (WRF model), annual temperatures are shown in orange (light-blue), DJF temperatures in purple (dark-blue) and JJA temperatures in yellow (red). Linear fit for every dataset is shown: dark-grey for the simulations and light-grey for the observations.*

of the vertical gradient for WRF and the observations is noticeable, with a value of -6.52°C/$km$ for the annual period in the simulations (light-blue crosses in Figure 2b) and -3.95°C/$km$ in the observations (orange diamonds in Figure 2b). Thus, observed temperatures at high altitude stations are underestimated by the model

Figure 3 shows a description of the annual cycles for every site and dataset. The annual cycles of the simulated and observed temperatures in both Figure 3a,b are very close to each other. Meanwhile, the reanalysis annual cycle at Alameda (Figure 3a) is also very close to the observational and simulated ones, although it is different at Navacerrada with a systematic bias of about 5ºC (Figure 3b). At the rest of the stations, a situation similar to the one at Navacerrada happens (Figure 3c), with the ERAIT annual cycle showing warmer temperatures. This is due to the fact that every station, except for Alameda is associated with the same ERAIT grid point. As for the WRF annual cycles, it shows colder temperatures at high altitude stations (Zabala and Navacerrada) and warmer temperatures at the stations located in the valley (Ontalva and Alameda), as in Figure 2b.

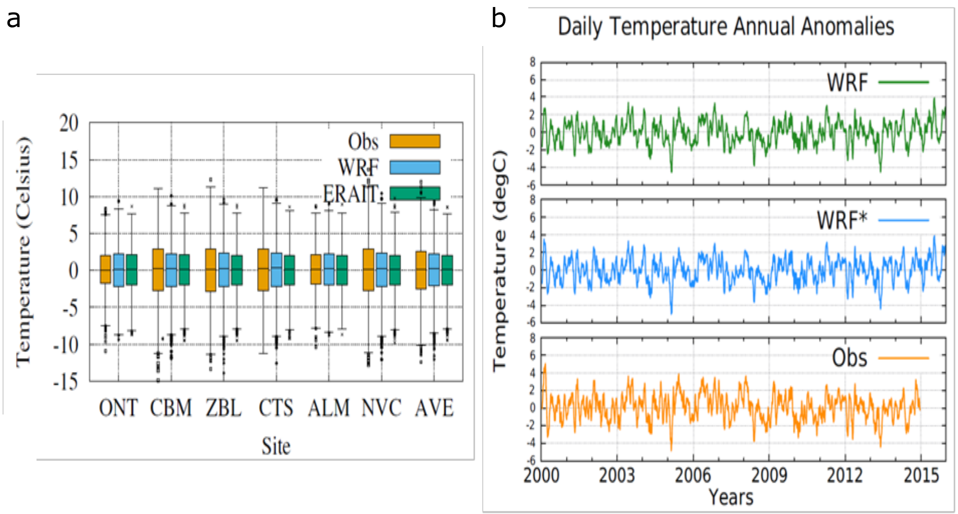


***Figure 4.****a) Frequency distribution of the daily temperature anomalies for the annual case. Green box-whiskers correspond to the ERAIT data, blue to WRF outputs and orange to the observations. b) Spatial average of the daily temperature annual anomalies for the average of the complete D4 field (green), the simulated data at the closest grid points to the stations (blue) and the observed series (orange).*

The daily frequency distribution of the observed and simulated temperature anomalies is represented in Figure 4a. It can be appreciated that, while WRF is able to reproduce better the extreme events, ERAIT fails in capturing the most extreme variability, especially at high altitude stations. Figure 4b shows the similarity of the regional averages after filtering out the annual cycle. For the WRF model, the averages of both the complete field (WRF) and the average using the points co-located to the observational sites (WRF*) are shown. Correlations are above 0.9 ($p < 0.05$). This suggests that the six points capture adequately the temporal variability of the SG.

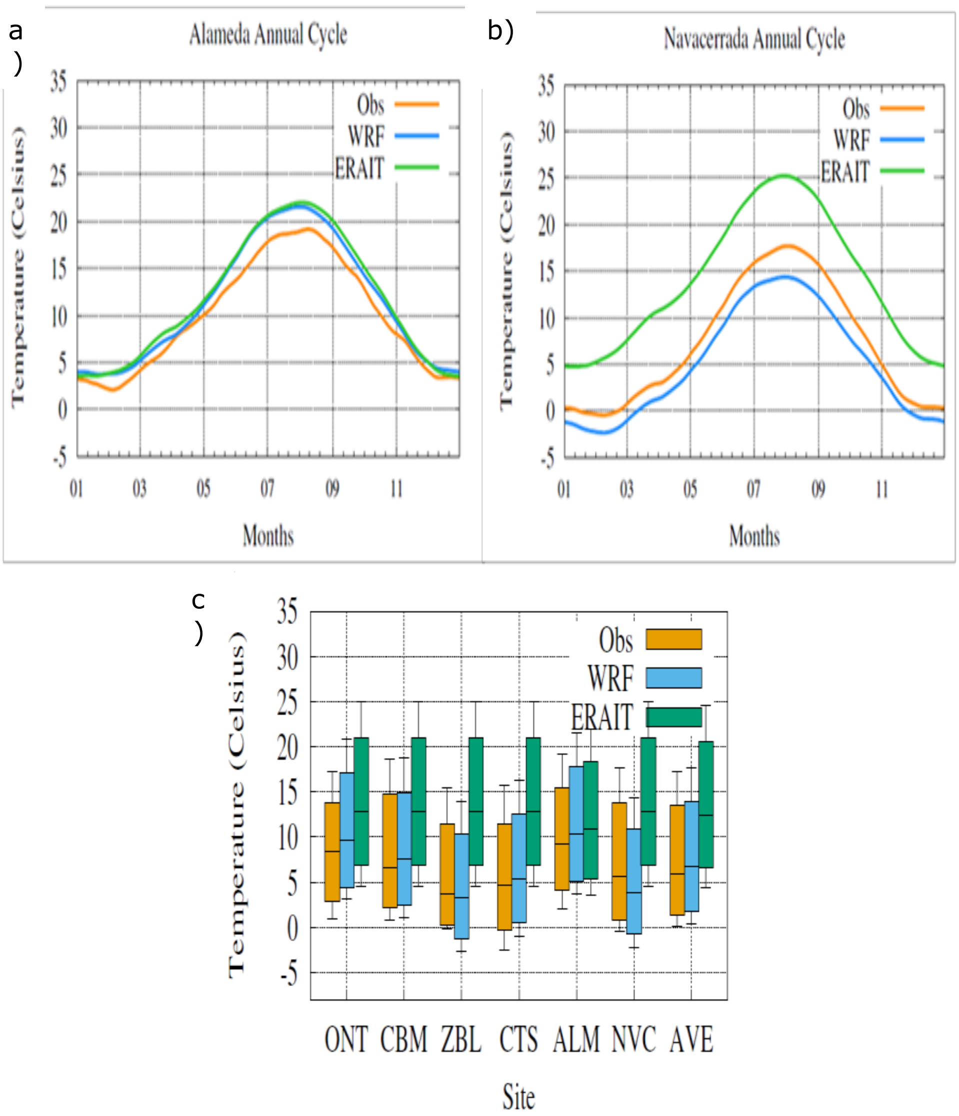


***Figure 3.*** *(a) Alameda and (b) Navacerrada daily annual cycles. Green lines correspond to the ERAIT data, blue lines to the WRF model outputs and orange to the observations. (c) Statistical distribution of the temperature annual cycles for all the locations and the regional average of each dataset.*

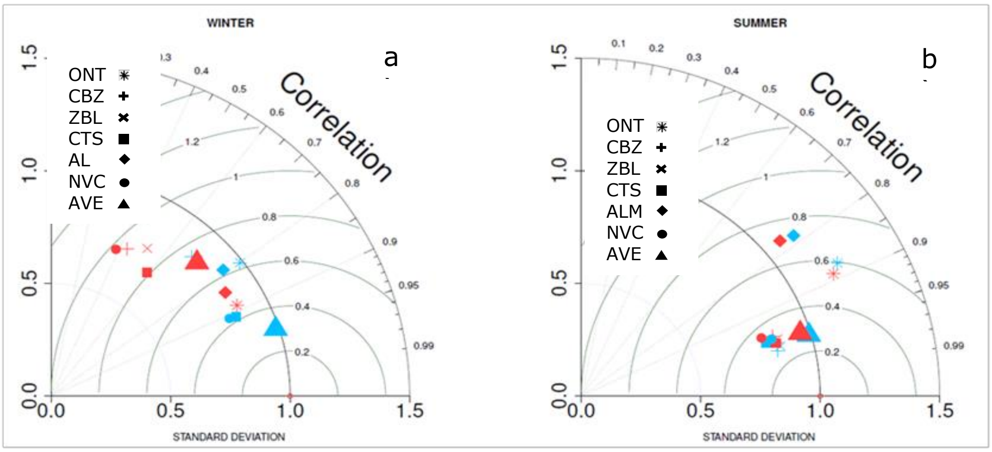


***Figure 5.****Taylor diagrams of the daily temperature anomalies for the DJF (a) and the JJA (b). Blue symbols represent the WRF outputs and red the ERAIT*

According to the Taylor Diagrams in Figure 5, WRF introduces an improvement in the accuracy of temperature anomalies over the ERAIT results, especially during the DJF season (Figure 5a), with higher correlations, lower RMSEs and closer to 1.0 standard deviations. During the JJA season (Figure 4b), the WRF model shows a slightly better performance in the regional average (triangles in Figure 4) and most of the stations, but at Cotos (squares in Figure 4) and Alameda (diamonds in Figure 4), ERAIT is slightly better. Thus, improvements are significant only in DJF.

The daily temperature anomalies in the annual case (Figure 6a,b). The EOF1 pattern shows that temperatures are milder over the plateau and more extreme in the mountains, especially at the north-western side. The regression coefficients of PC1 and observations are comparable to the EOF values and indicate consistency. As for the PC1, it explains to a large extent the overall temperature variability over the area. This is consistent with the similarity between the WRF and WRF* averages in Figure 4a.The second mode (Figure 6c,d) explains the 3% of the variance, showing clearly two different variability areas over the northwest and the southeast. Even if this mode explains a small percentage of the variability, it accounts for a significant part of the variability in some valleys and for some extreme situations.

The third EOF (Figure 6e,f) displays a large orographical influence, although it explains only 1% of the variance. This implies that this mode contributes to explain the variability of the highest altitude locations in the SG and, therefore, its contribution to the temperature anomalies of the entire domain is barely significant.

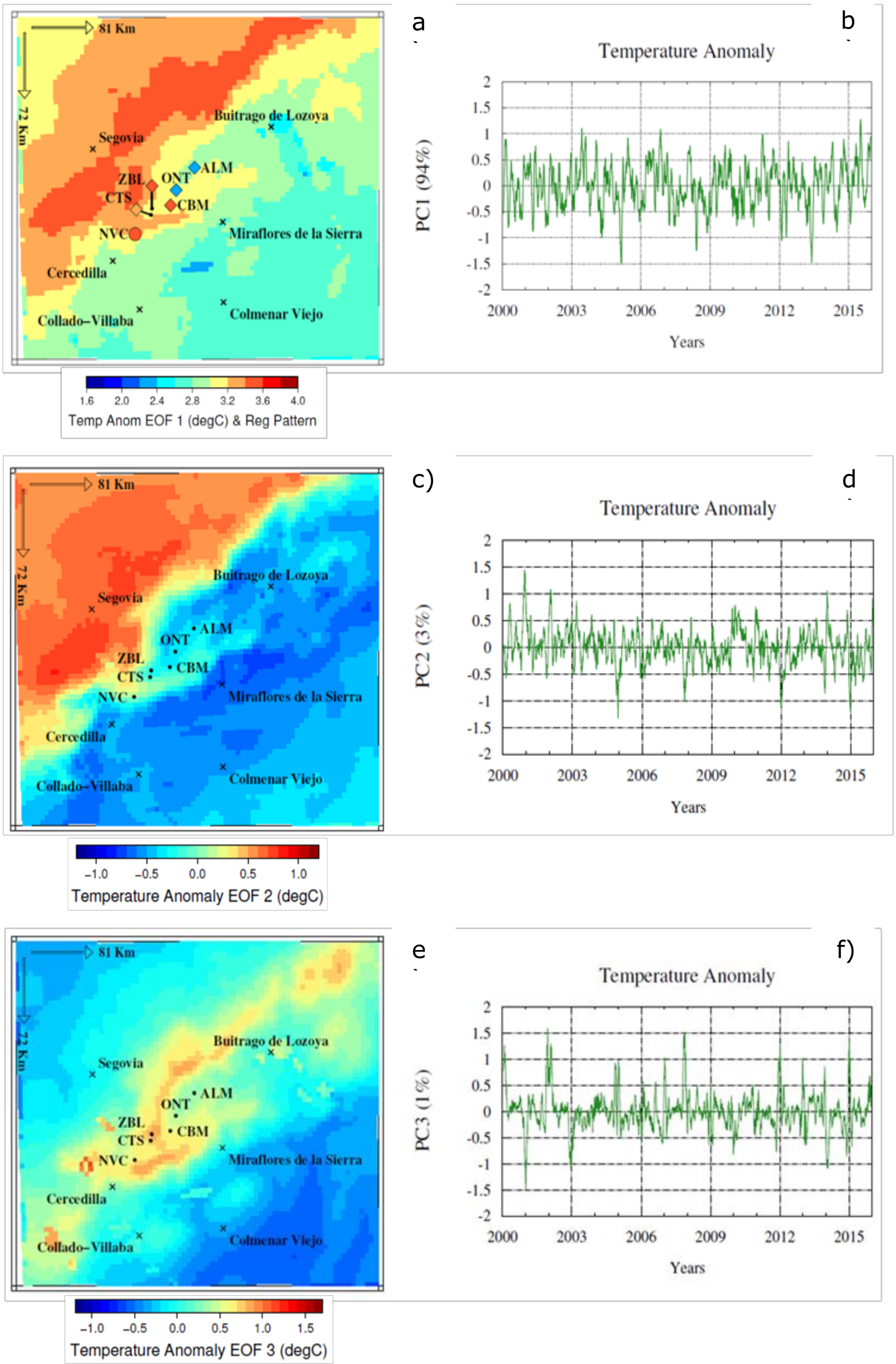


***Figure 6.****Maps (left) and time series (right) from the PC. Coloured symbols on the map represent the regression coefficients between the observed time series and the PCs. Crosses are reference locations of nearby towns. The PC time series have been filtered using a 31-days moving average. See text for explained variances.*

The correlations between the temperature PCs within the WRF domain D4 and the daily temperature anomalies from the rest of the domains within the simulations show very high values in the case of PC1 (Figure 7a). The overall pattern shows the continental character of this mode with values decreasing over the ocean. The correlation with PC2 (Figure 7b) keeps the contrast between the northwest and the southeast, with higher values over the basins of the main rivers in the Iberian Peninsula. Figure 7c shows, as expected from Figure 6, the influence of the main mountain ranges within the peninsula extended to the larger domains of the simulation. The highest correlations can be found over the Pyrenees, the Alps or the Central System.

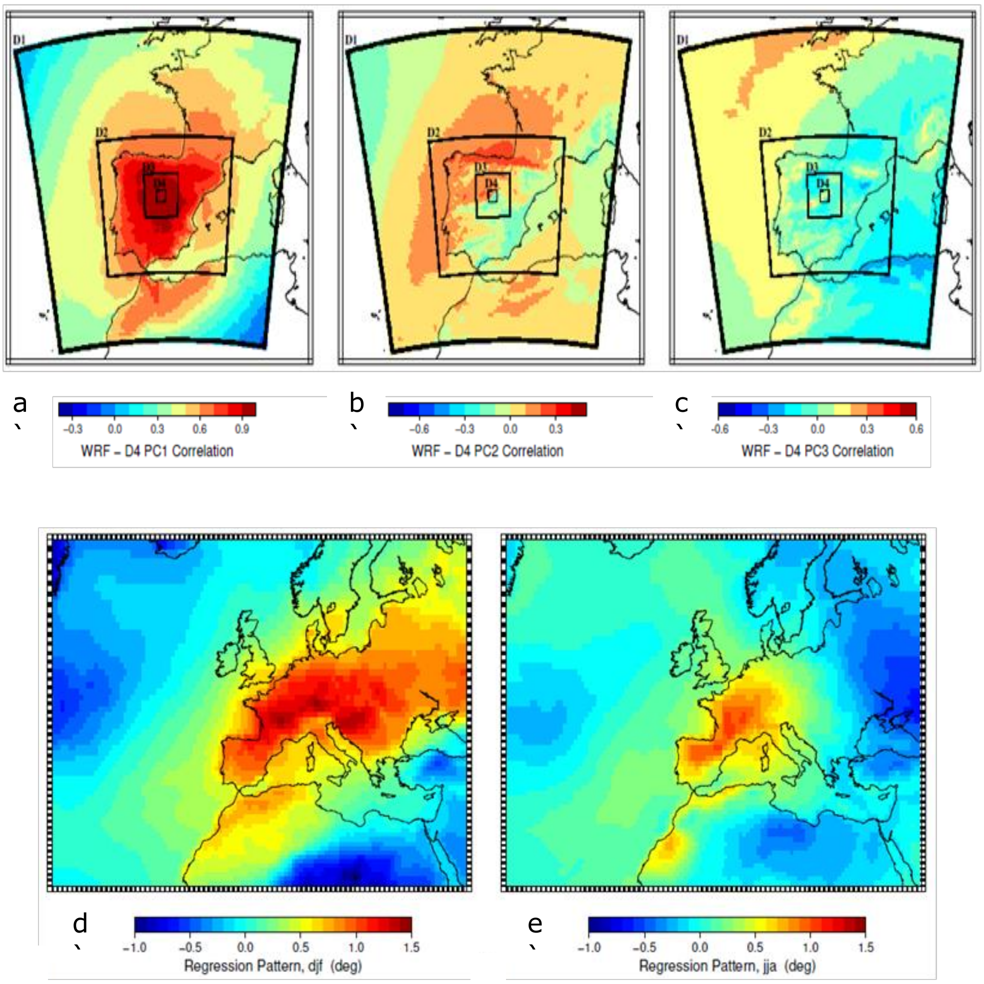


***Figure 7.****Top: Correlation maps between PC1 (a), PC2 (b) and PC3 (c) calculated over the WRF simulated daily temperature anomalies for the annual case over the D4 domain and over domains D1 to D4. Bottom: Regression patterns between ERAIT monthly anomalies and the regional average of the WRF*

The regression pattern between the ERAIT monthly anomalies and the regional average of the WRF anomalies are shown in Figure 7d,e. Note that the regional average is virtually identical to PC1 (correlation about 0.9). Here, a continental pattern can be seen again, where the highest correlations can be found over areas at larger distances from the ocean in central Europe, especially during the winter.

Finally, from these regression patterns, the ERAIT monthly anomalies have been reconstructed and compared to the WRF anomalies in the D4 domain and with the anomalies in Navacerrada, since this station has available temperature records since 1946 (Figure 8). The reconstruction uses only the period 1979-2015 since that is the period of availability of the ERAIT. It can be noticed that the ERAIT anomalies are in agreement with both the WRF model and the observed anomalies in Navacerrada in the long-term for the DJF season. The Navacerrada anomalies present a wider range due to their local character in comparison to the regional downscaled estimates of ERAIT. No significant long-term trends are shown by any of the two records.

## 5. CONCLUSIONS AND DISCUSSION

Two main targets have been addressed in this study. On the one hand, the performance of a high resolution regional simulation with the WRF model in reproducing the temperature variability over the complex terrain of the Sierra de Guadarrama was evaluated, allowing the comparison with the reanalysis temperature field that provides the initial and boundary conditions. On the other hand, the temperature variability was analysed over the same area as well as its relationship with temperatures at a larger scale.

Overall, the high-resolution WRF model improves the bias of ERAIT and shows a more realistic simulation than the reanalysis when representing thermal anomalies. In addition to this, WRF proves to be very consistent to the observations, although it

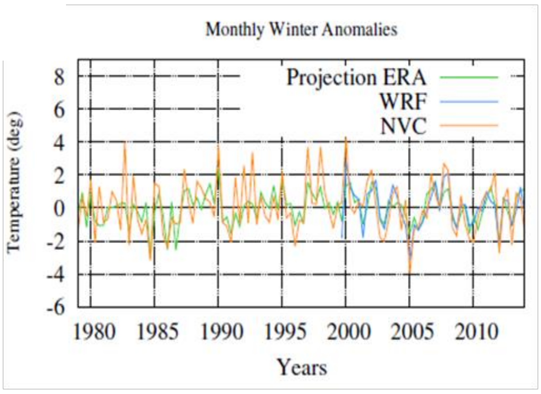


***Figure 8.*** *Estimation of the monthly temperature anomalies for the complete ERAIT temperature field (green). The monthly mean anomalies from the D4 WRF domain (blue) and the Navacerrada station observations (orange) for DJF are also shown for comparison.*

shows some underestimation of the observed variability over the SGNP. Nonetheless, regional averages showed that the simulated data co-located to the observational sites, few as they are, are representative of the temperature over the Sierra de Guadarrama. This implies that the observational temperatures from the stations represent a good estimate of the variability over the region as well.

From the PCA, the first EOF represents most of the variability in the Sierra de Guadarrama and explains the majority of the temperature anomalies in the period 2000 – 2015. The pattern found in the basis of the WRF simulated temperatures resembles as well that obtained if the ERAIT anomalies are used instead. The estimation is consistent with the variability of the Navacerrada observations during the period 2000 – 2015, although, prior to year 2000, it seems to be underestimated.

The second EOF, though it explains a relatively small amount of the variance, could, presumably, explain some of the influence of zonal air fluxes over the area, since a pattern separating north-western and south-eastern areas emerges with this mode. As for the third EOF, with a comparatively small percentage of variance, it shows orographical influences with special emphasis on very high mountain areas, which could be assumed to be related to radiative cooling.

Finally, the temperature anomalies reconstruction from ERAIT, seeing as it resembles the anomalies at Navacerrada, can provide an overview of the temperature variability in the Sierra de Guadarrama for the DJF season during the last quarter of the 20$^{th}$ century and the beginning of the 21$^{st}$. Future studies will try to extend this analysis back to the 20$^{th}$ century by the use of different reanalysis products.

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