Iberia01: A new gridded dataset of daily precipitation and temperatures over Iberia

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Abstract. The present work presents a new observational gridded dataset (referred to as Iberia01) for daily precipitation and temperatures produced using a dense network (thousands) of stations over the Iberian Peninsula for the period 1971-2015 at $0.1°$ regular (and $0.11°$ CORDEX-compliant rotated) resolutions. We analyze mean and extreme indices and compare the results with the E-OBS v17 dataset (using both the standard and ensemble versions, at $0.25°$ and $0.1°$ resolutions, respectively), in order to assess observational uncertainty in this region. We show that Iberia01 produces more realistic precipitation patterns than E-OBS for the mean and extreme indices considered, although both are comparable for temperatures. To assess the differences between these datasets, a new probabilistic intercomparison analysis was performed, using the E-OBS ensemble (v17e) to characterize observational uncertainty and testing whether Iberia01 falls within the observational uncertainty range provided by E-OBS. In general, uncertainty values are large in all the territory, with the exception of a number of kernels where the uncertainty is small, corresponding to the stations used to build the E-OBS grid. For precipitation, significant differences —at a 10% level— between both datasets were found for less than 25% of days over the Iberian Peninsula. For temperature, a very inhomogeneous spatial pattern was obtained, with either a small (in most of the regions) or large fraction of significantly different days, thus indicating sensible regions for observational uncertainty.

Iberia01 is publicly available (Herrera et al., 2019a, DOI: http://dx.doi.org/10.20350/digitalCSIC/8641).

KEY WORDS: *Observational uncertainty; extremes; gridded observations; kriging; thin plate splines; E-OBS*

1 Introduction

The availability of high resolution climate data together with an estimate of its uncertainty (observational uncertainty) is of paramount importance for climate studies, from global (Sun Qiaohong et al., 2018) to regional and local scales (Kidd et al., 2011). The first comprehensive gridded temperature dataset was obtained by Jones et al. (1982). This dataset only covered the Northern Hemisphere and produced monthly

means at $5°$ latitude by $10°$ longitude grid. Later, this grid was extended to cover the entire globe, with a higher spatial resolution (at $0.5°$ resolution, Jones et al., 1986a, b) and currently includes several variables covering Earth's land areas for 1901-2015 (CRU TS4.0, Harris et al., 2014; Trenberth et al., 2014). However, this kind of resolution is too coarse for regional analysis, which typically requires datasets with tens of kilometres spatial resolution and daily to sub-daily temporal data, in order to differentiate climatic sub-regions and extreme events. In

5 Europe, the first high resolution continental observational gridded dataset was produced within the framework of the ENSEMBLES project (E-OBS dataset), for daily precipitation and maximum, minimum and mean temperatures (Klein Tank et al., 2002; Haylock et al., 2008; Klok and Klein Tank, 2009) and sea level pressure (van den Besselaar et al., 2011). With more than 1490 citations in Scopus (as by August 2019), this is the most used climate reference for European climate studies. Yet, in some regions, E-OBS relies on a sparse observational network which limits its ability to correctly represent not only mean values, but also the variance and extremes, particularly over complex topography

10 (Klok and Klein Tank, 2009). The Influence of stations density in the quality of gridded products has been analyzed in the last decades by several authors: Rudolf et al. (1994) was able to significantly reduce the precipitation error, from a maximum of 40% to 20%, by doubling the number of stations within a $2.5°$ grid box; Prein and Gobiet (2017) found that in regions with sparse data the uncertainties associated to mean seasonal precipitation could reach 60%; Beguería et al. (2016) found that, in a high resolution observationally based gridded dataset, the density of the underlying observations determines its spatial variance and thus strongly influences climate variability; Hofstra et al. (2010)

15 concluded that, by randomly changing the number of stations in each grid box, a reduction in the density of stations decreases the variability of both precipitation and temperature with large implications in the representation of extremes. Moreover, large temporal differences in the number of stations within each grid box also adds another source of uncertainty since it can change trends of the time series (Hofstra et al., 2009; Frei, 2014; Beguería et al., 2016). Finally, in an analysis of the sources of uncertainty in observationally based gridded datasets, Herrera et al. (2019b), highlight that the station density represents the major variability factor, irrespective of the interpolation method. The authors

20 analysed several grids for Spain (complex topography) and Poland (smooth topography) and concluded that the influence of station density is more pronounced in Spain than in Poland due to the large spatial variability and complex orography of the first.

The quality of the station observations is an additional source of observational uncertainty for gridded products. These uncertainties may be reduced by applying quality control procedures and homogenising the time series (Herrera et al., 2012). Precipitation time series also commonly suffer from undercatch associated to windy conditions, which usually results in underestimation of the correct precipitation rate

25 (Frei et al., 2003). Yet in complex topography an increased uncertainty may be associated to the use of these types of corrections (Adam et al., 2006). The areal representativeness of a particular station also poses a challenge. Again, in regions with high terrain gradients, like mountains or coastal areas, surface temperatures are affected by local circulations like sea-breeze, up/down slope breeze associated to night-time radiative cooling in the valleys and to differentiated warming/cooling at sunrise/sunset of the slopes (Whiteman, 1982; Whiteman and McKee, 1982; Whiteman, 1990). Frei (2014) proposed a new interpolation method to tackle the latter, in which the thermal vertical profile of

30 the station surrounding area is considered. Yet, Frei (2014) also acknowledges that the best way to reduce this type of uncertainty is through high station density.

Recently, several national high-resolution grids have been compiled for individual European countries from dense observation networks: SAFRAN analysis at 8km grid spacing covering France at an hourly timestep (Durand et al., 1993; Quintana-Seguí et al., 2008; Vidal et al., 2010), and its recently published extension for continental Spain and Balearic Islands (Quintana-Seguí et al., 2017); PTHBV, a 4km daily

35 dataset for Sweden (Johansson, 2000; Johansson and Chen, 2003); the 5km resolution HYRAS for Germany (Rauthe et al., 2013; Frick et al., 2014); seNorge2 a daily dataset with an 1km resolution for Norway (Uboldi et al., 2008; Lussana et al., 2018); TabsD (MeteoSwiss, 2013a) and RhiresD (MeteoSwiss, 2013b) at 2km for Switzerland; CARPATCLIM a $0.1°$ grid covering parts of nine countries along the Carpathian Mountains (Lakatos et al., 2013) and a $0.11°$ grid for Poland (Herrera et al., 2019b).

In the Iberian Peninsula, Herrera (2011) and Herrera et al. (2012) built a precipitation regular grid for continental Spain and Balearic Islands based on 2756 stations (Spain02) following the methodology used in E-OBS. The same methodology was also applied by Belo-Pereira et al. (2011) for continental Portugal using more than 400 stations (PT02). Both datasets had consistent grids (with $0.2°$ resolution) and time periods (1950-2003) and were combined to build a gridded precipitation dataset of opportunity for the Iberian peninsula (IB02). However, this is not an homogeneous product for the Iberian peninsula due to the discrepancies existing between the two datasets near the borders, particularly in the northern mountains. Recently, Herrera et al. (2015) updated the Spanish grid including precipitation and temperatures (daily maximum, mean and minimum) and enhancing the spatial resolution to $0.1°$ (regular); moreover, they also provided results on a $0.11°$ rotated grid (CORDEX compliant) for the purpose of Regional Climate Model (RCM) evaluation. The lack of temperature for PT02 (and IB02) hinders a comprehensive analysis of the large inter-annual and spatial variability, characteristic of the Iberian climate (Esteban-Parra et al., 1998; Muñoz-Díaz and Rodrigo, 2004; Cardoso et al., 2013). These problems could be solved building an Iberian grid, using observational station data from both countries.

In this paper, we develop an Iberian wide daily regular grid at $0.1°$ resolution, for precipitation and temperatures (maximum, mean and minimum) as well as a $0.11°$ rotated grid (EURO-CORDEX compliant) suitable for model evaluation purposes. This grid is based on a high density network of stations across continental Portugal and Spain and Balearic Islands, with a reasonably stable number of stations for the period 1971-2015. This represents the first gridded dataset of daily precipitation and temperatures for Iberia as a whole, and can be considered an update of the PT02 and IB02 datasets. Here, we also introduce the elevation as covariate in the interpolation process, which was missing in the initial PT02 and Spain02. The resulting dataset is compared against the most recent version of E-OBS (v17.0, referred to as v17), which includes a new ensemble version (v17e) to assess observational uncertainty and allows for a new probabilistic intercomparisson of these datasets.

The paper is structured as follows. In Section 2 a description of the data and methods considered in this work is presented. The main results are described (Sec. 3). Finally, the main conclusions from the analysis are detailed in Section 4.

2   Data and Methods

2.1   Observation Network and Quality Control

The present work is based on a dense network of thousands of stations from the Spanish Meteorological Agency (AEMET), the Portuguese Institute for Sea and Atmosphere (IPMA) and the Portuguese Environmental Agency (APA). To keep consistency with previous datasets, the final network was obtained applying the same quality control used to build *Spain02* (see Herrera, 2011; Herrera et al., 2012, for a detailed description), which requires stations with at least 15 (40) years in the period 1951-2015 with less than 10% yearly missing precipitation (temperature) data. The resulting observational network includes 3486 and 275 stations for precipitation and temperature, respectively, as shown in Figure 1(a-b). Note that detailed metadata for each station, including geographical and data availability information, is provided as part of the dataset in the same repository. Figure 1(c) shows the data availability on a yearly basis, exhibiting a clear decline of the number of stations in the last two decades, mainly for precipitation. Therefore, the resulting gridded product is not suitable for historical trend analysis, since biased results could be obtained as a result of the changing number of stations. Moreover, during the period 2009-2014 there are very few precipitation stations in Portugal and, therefore, results should be interpreted with caution in this period. Therefore, we recommend using the reference climate period 1971-2000 for this dataset. Overall, the spatial distribution of the stations is quite homogeneous over the Iberian Peninsula with a good representation of the orographical gradients, specially for the case of precipitation (see the first column of Fig. 1).

Therefore, the elevation was included as a covariate in the interpolation process (at a monthly scale) to model and reflect these gradients (see Sec. 2.4).
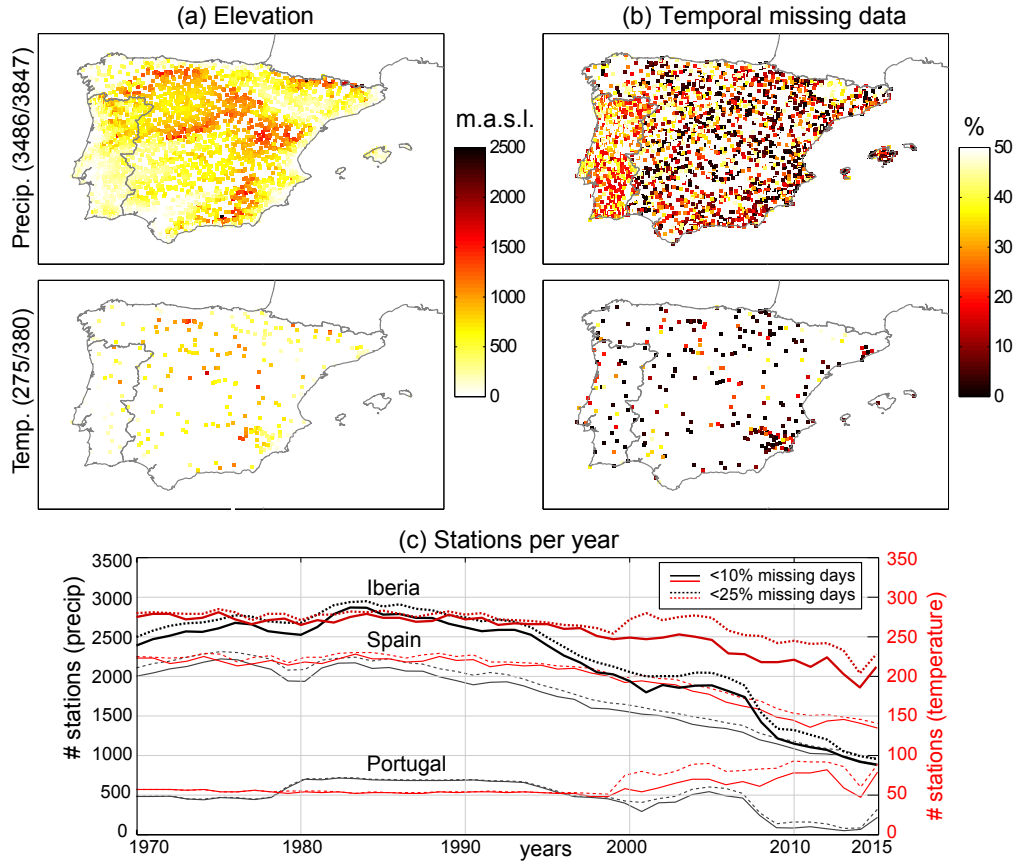

Figure 1. (a) Elevation and (b) data availability (percentage of missing days) in the period 1971-2015 for precipitation (top) and temperature (bottom) for the observational networks considered for the interpolation. The numbers on the left of the figure reflect the initial and final number of stations used, once the quality control is applied. (c) Number of stations —considering the Iberian Peninsula, Spain or Portugal— per year for different thresholds of annual missing data for precipitation (black) and temperature (red).

2.2 E-OBS Gridded Datasets (v17 and v17e)

E-OBS (Haylock et al., 2008) is the reference gridded dataset of daily precipitation and temperatures in Europe and has been previously used to analyze the observational uncertainty in the context of the evaluation of regional climate models (see, e.g. Kotlarski et al., 2019). In this study, we use both the standard (v17, $0.2°$ resolution) and the ensemble (v17e, $0.1°$ resolution; Cornes et al., 2018) versions of E-OBS v17 as benchmark for comparison purposes. In addition to the estimated daily value for each gridbox, the ensembles grid also provides a measure of daily uncertainty, characterized by the standard deviation of the ensemble. E-OBS v17 is used for the sake of comparison with Iberia01 (see Fig. 2) and the E-OBS v17e (the ensemble) is used to assess the observational uncertainty provided by this dataset, and test whether Iberia01

does not differ significantly from the ensemble (i.e. it falls within the observational uncertainty range) with a certain confidence (90%) day by day. For this purpose, the E-OBS ensemble mean (μ) and spread (σ) are used to define a normal distribution $N(\mu, \sigma)$ characterizing observational uncertainty for each grid box and day, and the corresponding Iberia01 values are classified as either inside or outside (values outside the P5-P95 percentile range) the uncertainty range for each grid box and day. Note that outsider values indicate significant differences

5   between both datasets (as characterized by the E-OBS ensemble).

2.3   Weather Indices

To analyze the mean and extreme regimes of precipitation and temperature we use the indicators shown in Table 1. In particular, the 50-year return value for each grid-box was used to characterize the extreme regimes (for the period 1971-2015) obtained by adjusting a Generalized Extreme Value (GEV) distribution to the series of annual maximum of daily values (see Herrera et al., 2015, for a detailed description). In

10   the case of precipitation, both wet-day frequency and rainfall intensity have been considered to properly characterize the mean regime.

Table 1. Precipitation and temperature indices used in this study.

ID	Indicator	Units
pr	Mean daily precipitation amount	mm/day
RR1	Wet-day ($pr > 1mm$) frequency	%
RV50Yp	50-years return value of daily precipitation	mm/day
tas	Mean daily 2-meter air temperature	deg. Celsius
RV50Yt	50-years return value of the mean daily 2-meter air temperature	deg. Celsius

2.4   Gridding Method

The Iberia01 daily gridded dataset for precipitation and temperatures was built using the previously described observational network and applying the area-averaged 3-dimensional (AA-3D) interpolation method described in previous studies (Herrera, 2011; Herrera et al., 2012, 2015). This interpolation method is an area-averaged method based on ordinary kriging (OK; Krige, 1951; Matheron, 1962) and

15   3-dimensional thin plate splines (3D-TPS; Craven and Wahba, 1979; Wahba, 1990; Hutchinson, 1998a, b) in a two-step process:

- first, the 3D-TPS is applied to the monthly value considering the elevation given by the Global Digital Elevation Model (GTOPO30, see section on code and data availability) as covariate;
- second, the daily anomaly is interpolated by applying OK;
- as a result, both the daily anomaly and monthly value are combined to obtain the interpolated daily values

20   To ensure the area-averaged representativity of the final values, the initial interpolation is done over an auxiliary $0.01°$ resolution grid and, then, the interpolated results are upscaled (averaged) to the target resolutions, in our case a regular version of $0.10°$ spatial resolution ($10km$ approx.) and a rotated version matching the grids considered in the EURO-CORDEX project ($0.11°$ and $0.44°$). In this work we only describe for simplicity the regular version of $0.10°$ spatial resolution, although the other datasets are also provided (these datasets will be used in a future paper to evaluate the performance of EURO-CORDEX models over Iberia).

Taking into account the two-step interpolation procedure followed to develop the area-average representative gridded dataset, a natural doubt surges about the possible application of the auxiliary very-high resolution grid (1 km) to build a grid at a resolution higher than 10 km. For instance, the new RCM convective permitting simulations performed in the framework of the CORDEX Flagship Pilot Studies (FPS) reach a resolution of $2 - 3$ km and, thus, high resolution grids are needed for the evaluation of these projects (Giorgi et al., 2009; Jacob et al., 2014). Some previous works warn against the development of high-resolution grids with few (or none) stations per gridbox (Herrera et al., 2019b). Therefore, we limited the resolution of Iberia01 to $0.10°$ and do not provide higher resolution intermediate products. As an illustrative example to illustrate the effective resolution of the datasets, we consider a convective high-resolution extreme precipitation event occurred on 4-5 November 1997, and characterized by heavy precipitation over most of the Iberian Peninsula. This event had great socioeconomic impacts in Portugal (Ramos and Reis, 2002) and Spain (Lorente et al., 2008), and was ranked as the second greatest extreme precipitation event of the Iberian Peninsula (Ramos et al., 2015). We use this event as an illustrative case study the effective resolution of a potential 3 km gridded version of Iberia01, as compared with the standard 10 km resolution.

3 Results

Figure 2 shows the climatologies (mean annual values) of the indices shown in Table 1 for Iberia01 $(0.1°)$ and E-OBS (v17, $0.2°$ and v17e, $0.1°$). The three datasets provide similar results in the case of temperature, with the main differences being located in the South, around the Guadalquivir and Guadiana basins, where the maximum values are attained. In addition, the climatology of observational uncertainty (calculated as the temporal mean of the daily standard deviations of the ensemble values) is also provided for the ensemble version of E-OBS, showing a value around $2.5°$ in all the territory, with the exception of a number of kernels where the uncertainty is very small, corresponding to the stations used to build the E-OBS grid. Note that the observational uncertainty pattern is different in Spain and Portugal, with more clear kernels in the first case; this could be due to the different temporal coverage of both networks, with an increase of uncertainty due to days with no observation. Therefore, the uncertainty conveys relevant information on the station network used to build the grid.

In the case of precipitation, E-OBS cannot reproduce neither the mean spatial pattern (pr) nor the intensity of the 50-year return value (RV50Yp). E-OBS underestimates mean precipitation by 15% (mean relative bias, for E-OBSv17 and v17e, as obtained from the spatial mean numbers in Figure 2), particularly in the Central System range of the Iberian Peninsula, and 50-year return values by 40 - 44% (mean relative bias, for E-OBSv17 - v17e, respectively), with some very high biases in some Southern and Mediterranean regions. The case of wet-day frequency is different, since all datasets show a clear overestimation, with Iberia01 showing a more orographic pattern than E-OBS. In this case, the higher resolution of E-OBS v17e provides further spatial detail as compared to the standard v17 one, which is not evident for precipitation intensity. Moreover, the E-OBS observational uncertainty is of similar magnitude to the mean value (also with kernels of small uncertainty corresponding to stations) reflecting a large uncertainty for this variable.

Figure 3 shows the percentage of significantly different days for each gridbox, variable and season. For precipitation (first row), only Iberia01 wet-days were used in order to minimize the effect of the different wet-day frequencies. The differences for this variable exhibit a homogeneous spatial pattern over the Peninsula with values around 10% in general; this is due to the large uncertainty of the daily E-OBS ensemble spread (see Fig. 2). Regarding the temperatures, most of the spatial pattern presents values close to zero, reflecting the similarity between both datasets for these variables. However, some local differences are found particularly for the mean (second row) and maximum (third row) temperatures, with the greatest values reached in the Pyrenean and Central ranges and the south coast of the Iberian Peninsula, in agreement with the differences shown in Figure 2. In this case, the ensemble uncertainty is in agreement with the differences between these two datasets found in Figure 2.

Finally, we consider an illustrative extreme event occurred the 4-5 November 1997 to illustrate the effective resolution of the different datasets (including potentially new higher resolution products). To this aim, compare the resulting values of the $0.1°$ grid with a higher resolution $0.03°$ one developed using the auxiliary $0.01°$ grid generated in the interpolation process. Figure 4 show the results obtained for the extreme event indicating that an increment of the Iberia01 resolution beyond 10 km has no clear impact in the effective resolution of the 5 precipitation pattern. In particular, in spite of the apparent improvement of both versions of Iberia01 w.r.t. E-OBS v17e, there are only slight differences between both versions of Iberia01 when compared with observations.

4 Conclusions and Discussion

In this work a new gridded dataset for the Iberian Peninsula and the Balearic Islands based on a quality-controlled and dense station network has been described and compared with E-OBS v17, considering both the standard and the ensemble version of this product, to reflect and 10 analyze the observational uncertainty related with both datasets.

It is shown that Iberia01 is able to reproduce the spatial pattern and intensity of both the mean and extreme regimes of precipitation and temperature, in terms of the weather indices defined in Table 1, including extreme events as the illustrative case study occurred the 4-5 November 1997 shown in the Figure 4. However, E-OBS v17 tends to underestimate the extremes and soften the spatial pattern of precipitation, in agreement with previous studies (Herrera et al., 2012). In the case of temperature, both datasets exhibit similar spatial 15 patterns with the main differences appearing in the Guadalquivir and Guadiana basins, and the Pyrenean range.

We have also used the ensemble version of E-OBS, E-OBS v17e to define observational uncertainty, and analyzed whether Iberia01 does differ significantly from the ensemble (i.e. it falls outside the observational uncertainty range). In this case, we conclude that both datasets are significantly different. In general, uncertainty values are large in all Iberia, with the exception of a number of kernels where the uncertainty is small, corresponding to the stations used to build the E-OBS grid. For precipitation, significant differences —at a 10% level— between 20 both datasets were found for less than 25% of days over the Iberian Peninsula. For temperature, a very inhomogeneous spatial pattern was obtained, with either a small (in most of the regions) or large fraction of significantly different days, thus indicating sensible regions for observational uncertainty.

The complex orography and the influence of both the Atlantic Ocean and the Mediterranean Sea modulate the precipitation over the Iberian Peninsula. This leads to particular regimes, as the cold drop in the east coast, that a continental adjustment of the interpolation 25 model is not able to reproduce, particularly when a low-dense observational network is considered. In this sense, the large increase of rain gauges considered in Iberia01, when compared with E-OBS, give rise to a much improved precipitation rendering. In the case of temperature, although the observational network considered is similar in both cases, the pattern tends to be more orographic in E-OBS v17 due to the continental adjustment of the interpolation method that overrates this component avoiding regional behaviors. In addition, the contribution of the observational network considered in France also has a clear effect on the interpolated value over the Pyrenees and the northeast of the 30 Iberian Peninsula.

Note that the interpolation method, independently of the target resolution, is calibrated to reproduce the spatial dependence of the mean field of the target variable, which is usually greater than the grid resolution ($1°$ approximately in this case). Therefore, the effective resolution of purely interpolated gridded products is limited by this spatial value, which define the size of the kernels used for the interpolation process. As a result, in order to properly evaluate the convecting permitting CORDEX simulations, other approaches like regional reanalysis (e.g. 35 Häggmark et al., 2000) or methods combining interpolation and analysis as the proposed by Quintana-Seguí et al. (2017) and Peral et al. (2017), among others, should be used.
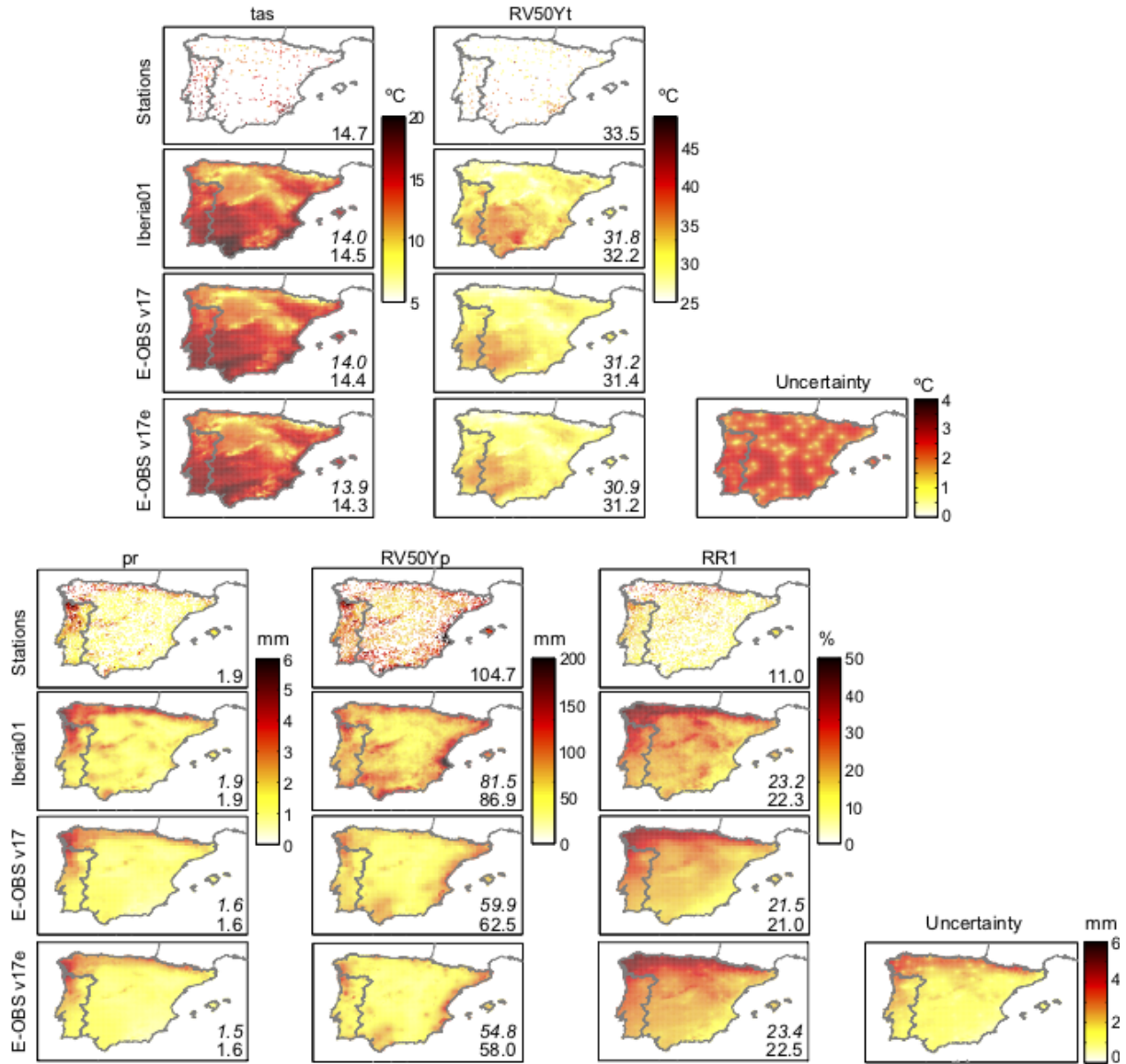
Figure 2. Climatology of the different temperature (top) and precipitation (bottom) indices defined in Table 1, from the stations (local values), Iberia01 (0.1° resolution), E-OBS v17 (0.2°) and E-OBS v17e (0.1°), in rows. The climatologies have been obtained averaging the annual values of the indices (tas, pr and RR1); in the case of the 50-years return value the index is representative of the whole period. For the ensemble E-OBS version (v17e), the climatology of daily standard deviations of the ensemble values is also shown (characterizing E-OBS observational uncertainty). The numbers shown in each panel correspond to the spatial mean values, calculated for gridded datasets averaging over all gridboxes (top, in italics) or over the gridboxes nearest to the stations (bottom), to provide a fair comparison with the station mean values in the top panels (in particular these numbers are used to assess the biases of the different gridded datasets).
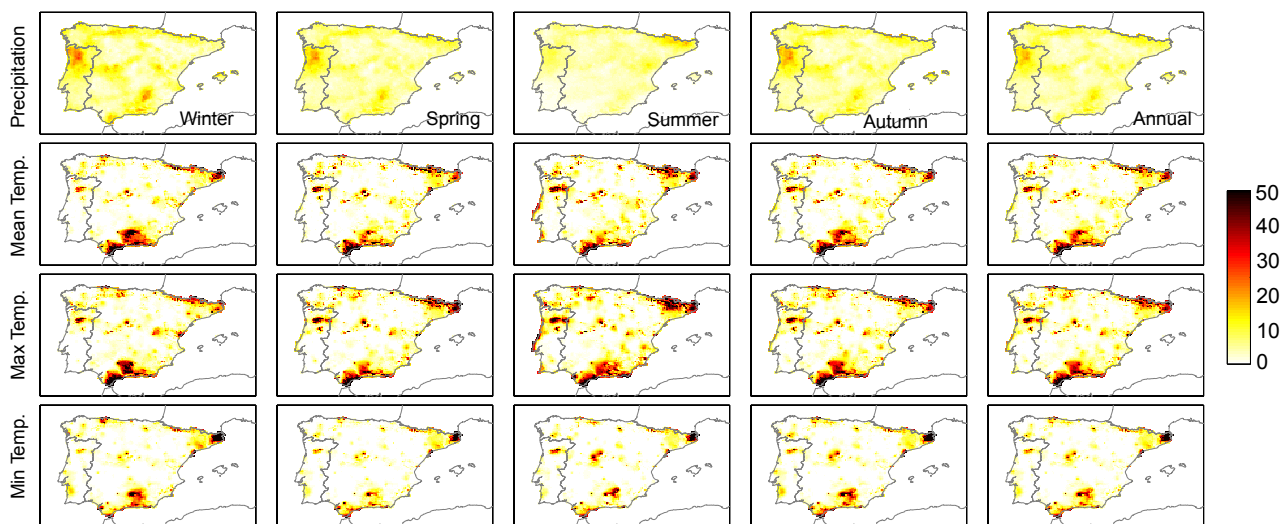
Figure 3. Percentage of significantly different days between Iberia01 and E-OBS v17e for each gridbox, variable and season, defined as the Iberia01 daily values outside the the $P5 - P95$ percentile interval of the normal distribution given by the E-OBS ensemble, in the period 1970-2015 for wet-days (first row), and mean (second row), maximum (third row) and (fourth row) minimum temperatures.
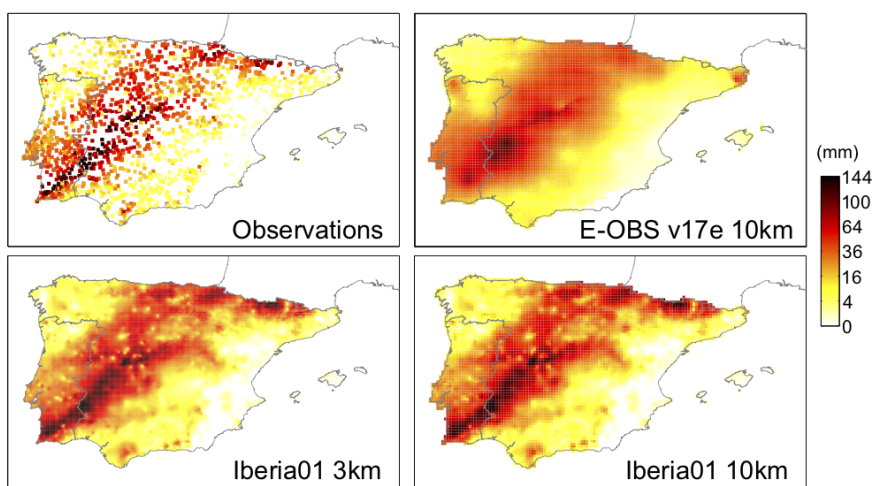

Figure 4. Daily precipitation of the 4-5 November 1997 observed and represented by E-OBS v17e and Iberia01 (10 km), and higher resolution 3 km version of Iberia01.

5 Code and data availability

All the datasets used in this work are publicly available. On the one hand, the Iberia01 dataset is publicly available through the DIGITAL.CSIC open science service (Herrera et al., 2019a, DOI: http://dx.doi.org/10.20350/digitalCSIC/8641). Moreover, a THREDDS remote access to this dataset is available from the Santander Climate Data Service, via the User Data Gateway (instructions at http://meteo.unican.es/udg-wiki). On the other hand, the E-OBS v17 dataset is remotely available through the KNMI's THREDDS server http://opendap.knmi.nl/knmi/thredds/e-obs/e-obs-catalog.html and the ensemble version E-OBS v17e is available through the Copernicus' Climate Change Service http://surfobs.climate.copernicus.eu. Elevation data is taken from the Global 30 Arc-Second Elevation (GTOPO30) DOI: 10.5066/F7DF6PQS.

The R code needed to partially reproduce the results of this paper (for the remotely accessible datasets Iberia01 and E-OBS v17) is publicly available at https://github.com/SantanderMetGroup/notebooks, building on the remote data services above described and on the `climate4R` R framework (Iturbide et al., 2019).

Author contributions. Herrera S., Gutiérrez J.M. and Soares P.M. conceived the study; Gutiérrez J.M., Soares P.M., Cardoso R.M., Espíritu-Santo F. and Viterbo P, obtained and processed the Spanish and Portuguese observational datasets; Herrera S. implemented the code to make the interpolation and the analysis, and built the dataset and figures of the paper; Herrera S., Soares P.M., Gutiérrez J.M. and Cardoso R.M. wrote the manuscript and all the authors revised the results.

References

Adam, J. C., Clark, E. A., Lettenmaier, D. P., and Wood, E. F.: Correction of Global Precipitation Products for Orographic Effects, Journal of Climate, 19, 15–38, https://doi.org/10.1175/JCLI3604.1, https://doi.org/10.1175/JCLI3604.1, 2006.

20 Beguería, S., Vicente-Serrano, S. M., Tomás-Burguera, M., and Maneta, M.: Bias in the variance of gridded data sets leads to misleading conclusions about changes in climate variability, International Journal of Climatology, 36, 3413–3422, https://doi.org/10.1002/joc.4561, https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/joc.4561, 2016.

Belo-Pereira, M., Dutra, E., and Viterbo, P.: Evaluation of global precipitation data sets over the Iberian Peninsula, Journal of Geophysical Research: Atmospheres, 116, n/a–n/a, https://doi.org/10.1029/2010JD015481, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2010JD015481, d20101, 2011.

Cardoso, R., Soares, P., Miranda, P., and Belo-Pereira, M.: WRF high resolution simulation of Iberian mean and extreme precipitation
5 climate, International Journal of Climatology, 33, 2591–2608, https://doi.org/10.1002/joc.3616, https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/joc.3616, 2013.

Cornes, R. C., van der Schrier, G., van den Besselaar, E. J. M., and Jones, P. D.: An Ensemble Version of the E-OBS Temperature and Precipitation Data Sets, Journal of Geophysical Research: Atmospheres, 123, 9391–9409, https://doi.org/10.1029/2017JD028200, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2017JD028200, 2018.

10 Craven, P. and Wahba, G.: Smoothing noisy data with spline functions, Numerische Mathematik, 31, 377–403, 1979.

Durand, Y., Brun, E., Merindol, L., Guyomarc'h, G., Lesaffre, B., and Martin, E.: A meteorological estimation of relevant parameters for snow models, Annals of Glaciology, 18, 65–71, https://doi.org/10.3189/S0260305500011277, 1993.

Esteban-Parra, M., Rodrigo, F., and Castro-Diez, Y.: Spatial and temporal patterns of precipitation in Spain for the period 1880–1992, International Journal of Climatology, 18, 1557–1574, https://doi.org/10.1002/(SICI)1097-0088(19981130)18:14<1557::AID-
15 JOC328>3.0.CO;2-J, https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/%28SICI%291097-0088%2819981130%2918%3A14%3C1557%3A%3AAID-JOC328%3E3.0.CO%3B2-J, 1998.

Frei, C.: Interpolation of temperature in a mountainous region using nonlinear profiles and non-Euclidean distances, International Journal of Climatology, 34, 1585–1605, https://doi.org/10.1002/joc.3786, https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/joc.3786, 2014.

Frei, C., Christensen, J. H., Déqué, M., Jacob, D., Jones, R. G., and Vidale, P. L.: Daily precipitation statistics in regional
20 climate models: Evaluation and intercomparison for the European Alps, Journal of Geophysical Research: Atmospheres, 108, https://doi.org/10.1029/2002JD002287, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2002JD002287, 2003.

Frick, C., Steiner, H., Mazurkiewicz, A., Riediger, U., Rauthe, M., Reich, T., and Gratzki, A.: Central European high-resolution gridded daily data sets (HYRAS): Mean temperature and relative humidity, Meteorologische Zeitschrift, 23, 15–32, https://doi.org/10.1127/0941-2948/2014/0560, http://dx.doi.org/10.1127/0941-2948/2014/0560, 2014.

25 Giorgi, F., Jones, C., and Asrar, G. R.: Addressing climate information needs at the regional level: the CORDEX framework, World Meteorological Organization (WMO) Bulletin, 58, 175, 2009.

Häggmark, L., Ivarsson, K.-I., Gollvik, S., and Olofsson, P.-O.: Mesan, an operational mesoscale analysis system, Tellus A: Dynamic Meteorology and Oceanography, 52, 2–20, https://doi.org/10.3402/tellusa.v52i1.12250, https://doi.org/10.3402/tellusa.v52i1.12250, 2000.

Harris, I., Jones, P., Osborn, T., and Lister, D.: Updated high-resolution grids of monthly climatic observations – the CRU TS3.10 Dataset, In-
30 ternational Journal of Climatology, 34, 623–642, https://doi.org/10.1002/joc.3711, https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/joc.3711, 2014.

Haylock, M., Hofstra, N., Klein-Tank, A., Klok, E. J., Jones, P., and New, M.: A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006, Journal of Geophysical Research, 113, D20 119, https://doi.org/10.1029/2008JD010201, 2008.

35   Herrera, S.: PhD thesis: Desarrollo, Validación Y Aplicaciones de Spain02: Una Rejilla de Alta Resolución de Observaciones Interpoladas Para Precipitación Y Temperatura en España. In Spanish, Ph.D. thesis, Universidad de Cantabria, 5 September 2011. Available at http://www.meteo.unican.es/tesis/herrera, 2011.

Herrera, S., Gutiérrez, J. M., Ancell, R., Pons, M. R., Frías, M., and J., F.: Development and analysis of a 50–year high–resolution daily gridded precipitation dataset over Spain (Spain02), International Journal of Climatology, 36, 74–85, https://doi.org/10.1002/joc.2256, 2012.

Herrera, S., Fernández, J., and M., G. J.: Update of the Spain02 gridded observational dataset for EURO-CORDEX evaluation: assessing

5   the effect of the interpolation methodology, International Journal of Climatology, 36, 900–908, https://doi.org/10.1002/joc.4391, https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/joc.4391, 2015.

Herrera, S., Cardoso, R. M., Soares, P. M. M., Espírito-Santo, F., Viterbo, P., and Gutiérrez, J. M.: Iberia01: Daily gridded (0.1° resolution) dataset of precipitation and temperatures over the Iberian Peninsula, https://doi.org/http://dx.doi.org/10.20350/digitalCSIC/8641, 2019a.

Herrera, S., Kotlarski, S., Soares, P. M. M., Cardoso, R. M., Jaczewski, A., Gutiérrez, J. M., and Maraun, D.: Uncertainty in gridded precipita-

10   tion products: Influence of station density, interpolation method and grid resolution, International Journal of Climatology, 39, 3717–3729, https://doi.org/10.1002/joc.5878, 2019b.

Hofstra, N., Haylock, M., New, M., and Jones, P.: Testing E-OBS European high-resolution gridded data set of daily precipitation and surface temperature, Journal of Geophysical Research, 114, D21 101, https://doi.org/10.1029/2009JD011799, 2009.

Hofstra, N., New, M., and McSweeney, C.: The influence of interpolation and station network density on the distributions and trends of

15   climate variables in gridded daily data, Climate Dynamics, 35, 841–858, https://doi.org/10.1007/s00382-009-0698-1, 2010.

Hutchinson, M.: Interpolation of rainfall data with thin plate smoothing splines ?- Part I: two dimensional smoothing of data with short range correlation, Journal of Geographic Information and Decision Analysis, 2(2), 139–151, 1998a.

Hutchinson, M.: Interpolation of rainfall data with thin plate smoothing splines ?- Part II: analysis of topographic dependence., Journal of Geographic Information and Decision Analysis, 2(2), 152–167, 1998b.

20   Iturbide, M., Bedia, J., Herrera, S., Baño-Medina, J., Fernández, J., Frías, M. D., Manzanas, R., San-Martín, D., Cimadevilla, E., Cofiño, A. S., and Gutiérrez, J. M.: The R-based climate4R open framework for reproducible climate data access and post-processing, Environmental Modelling & Software, 111, 42–54, https://doi.org/10.1016/j.envsoft.2018.09.009, http://www.sciencedirect.com/science/article/pii/S1364815218303049, 2019.

Jacob, D., Petersen, J., Eggert, B., Alias, A., Christensen, O., Bouwer, L., Braun, A., Colette, A., D?qu?, M., Georgievski, G., Georgopoulou,

25   E., Gobiet, A., Menut, L., Nikulin, G., Haensler, A., Hempelmann, N., Jones, C., Keuler, K., Kovats, S., Kr?ner, N., Kotlarski, S., Kriegsmann, A., Martin, E., van Meijgaard, E., Moseley, C., Pfeifer, S., Preuschmann, S., Radermacher, C., Radtke, K., Rechid, D., Rounsevell, M., Samuelsson, P., Somot, S., Soussana, J.-F., Teichmann, C., Valentini, R., Vautard, R., Weber, B., and Yiou, P.: EURO-CORDEX: new high-resolution climate change projections for European impact research, Regional Environmental Change, 14, 563–578, https://doi.org/10.1007/s10113-013-0499-2, http://dx.doi.org/10.1007/s10113-013-0499-2, 2014.

30   Johansson, B.: Areal Precipitation and Temperature in the Swedish Mountains: An Evaluation from a Hydrological Perspective, Hydrology Research, 31, 207, https://doi.org/10.2166/nh.2000.0013, http://dx.doi.org/10.2166/nh.2000.0013, 2000.

Johansson, B. and Chen, D.: The influence of wind and topography on precipitation distribution in Sweden: statistical analysis and modelling, International Journal of Climatology, 23, 1523–1535, https://doi.org/10.1002/joc.951, https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/joc.951, 2003.

35 Jones, P. D., Wigley, T. M. L., and Kelly, P. M.: Variations in Surface Air Temperatures: Part 1. Northern Hemisphere, 1881–1980, Monthly Weather Review, 110, 59–70, https://doi.org/10.1175/1520-0493(1982)110<0059:VISATP>2.0.CO;2, https://doi.org/10.1175/1520-0493(1982)110<0059:VISATP>2.0.CO;2, 1982.

Jones, P. D., Raper, S. C. B., Bradley, R. S., Diaz, H. F., Kellyo, P. M., and Wigley, T. M. L.: Northern Hemisphere Surface Air Temperature Variations: 1851–1984, Journal of Climate and Applied Meteorology, 25, 161–179, https://doi.org/10.1175/1520-0450(1986)025<0161:NHSATV>2.0.CO;2, https://doi.org/10.1175/1520-0450(1986)025<0161:NHSATV>2.0.CO;2, 1986a.

Jones, P. D., Raper, S. C. B., and Wigley, T. M. L.: Southern Hemisphere Surface Air Temperature Variations: 1851–1984, Journal of
5 Climate and Applied Meteorology, 25, 1213–1230, https://doi.org/10.1175/1520-0450(1986)025<1213:SHSATV>2.0.CO;2, https://doi.org/10.1175/1520-0450(1986)025<1213:SHSATV>2.0.CO;2, 1986b.

Kidd, C., Bauer, P., Turk, J., Huffman, G. J., Joyce, R., Hsu, K.-L., and Braithwaite, D.: Intercomparison of High-Resolution Precipitation Products over Northwest Europe, 13, 67–83, https://doi.org/10.1175/JHM-D-11-042.1, 2011.

Klein Tank, A. M. G., Wijngaard, J. B., Können, G. P., Böhm, R., Demarée, G., Gocheva, A., Mileta, M., Pashiardis, S., Hejkrlik, L.,
10 Kern-Hansen, C., Heino, R., Bessemoulin, P., Müller-Westermeier, G., Tzanakou, M., Szalai, S., Pálsdóttir, T., Fitzgerald, D., Rubin, S., Capaldo, M., Maugeri, M., Leitass, A., Bukantis, A., Aberfeld, R., van Engelen, A. F. V., Forland, E., Mietus, M., Coelho, F., Mares, C., Razuvaev, V., Nieplova, E., Cegnar, T., Antonio López, J., Dahlström, B., Moberg, A., Kirchhofer, W., Ceylan, A., Pachaliuk, O., Alexander, L. V., and Petrovic, P.: Daily dataset of 20th-century surface air temperature and precipitation series for the European Climate Assessment, International Journal of Climatology, 22, 1441–1453, https://doi.org/10.1002/joc.773, https://rmets.onlinelibrary.wiley.com/
15 doi/abs/10.1002/joc.773, 2002.

Klok, E. J. and Klein Tank, A. M. G.: Updated and extended European dataset of daily climate observations, International Journal of Climatology, 29, 1182–1191, https://doi.org/10.1002/joc.1779, https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/joc.1779, 2009.

Kotlarski, S., Szabó, P., Herrera, S., Räty, O., Keuler, K., Soares, P. M., Cardoso, R. M., Bosshard, T., Pagé, C., Boberg, F., Gutiérrez, J. M., Isotta, F. A., Jaczewski, A., Kreienkamp, F., Liniger, M. A., Lussana, C., and K., P.-K.: Observational uncertainty and regional climate
20 model evaluation: A pan-European perspective, International Journal of Climatology, 39, 3730–3749, https://doi.org/10.1002/joc.5249, 2019.

Krige, D. G.: A statistical approach to some basic mine valuation problems on the Witwatersrand, Journal of the Chemical, Metallurgical and Mining Society of South Africa, 52 (6), 119–139, 1951.

Lakatos, M., Szentimrey, T., Bihari, Z., and S., S.: Creation of a homogenized climate database for the Carpathian region by applying the
25 MASH procedure and the preliminary analysis of the data., Quarterly Journal of the Hungarian Meteorological Service, 117, 143–158, 2013.

Lorente, P., Hernández, E., Queralt, S., and Ribera, P.: The flood event that affected Badajoz in November 1997, Advances in Geosciences, 16, 73–80, https://www.adv-geosci.net/16/73/2008/adgeo-16-73-2008.pdf, 2008.

Lussana, C., Saloranta, T., Skaugen, T., Magnusson, J., Tveito, O. E., and Andersen, J.: seNorge2 daily precipitation, an observational gridded
30 dataset over Norway from 1957 to the present day, Earth System Science Data, 10, 235–249, https://doi.org/10.5194/essd-10-235-2018, https://www.earth-syst-sci-data.net/10/235/2018/, 2018.

Matheron, G.: Traité de Géostatistique appliquée, vol. Tome 1??2, Editions Technip, Paris, France, 1962.

MeteoSwiss: Documentation of MeteoSwiss Grid-Data Products: Daily Mean, Minimum and Maximum Temperature: TabsD, TminD, TmaxD, Tech. rep., Federal Office of Meteorology and Climatology MeteoSwiss, Federal Department of Home Affairs FDHA, Switzerland, https://www.meteoswiss.admin.ch/content/dam/meteoswiss/de/service-und-publikationen/produkt/raeumliche-daten-temperatur/doc/ProdDoc_TabsD.pdf, 2013a.

MeteoSwiss: Documentation of MeteoSwiss Grid-Data Products: Daily Precipitation (final analysis): RhiresD, Tech. rep., Federal Office of Meteorology and Climatology MeteoSwiss, Federal Department of Home Affairs FDHA, Switzerland, https://www.meteoswiss.admin.ch/content/dam/meteoswiss/de/service-und-publikationen/produkt/raeumliche-daten-niederschlag/doc/ProdDoc_RhiresD.pdf, 2013b.

Muñoz-Díaz, D. and Rodrigo, F.: Spatio-temporal patterns of seasonal rainfall in Spain (1912-2000) using cluster and principal component analysis: comparison, Annales Geophysicae, 22, 1435–1448, https://doi.org/10.5194/angeo-22-1435-2004, 2004.

Peral, C., Navascués, B., and Ramos, P.: Serie de precipitación diaria en rejilla con fines climáticos., Nota técnica de AEMET 24/2017, Ministerio de Agricultura y Pesca, Alimentación y Medio Ambiente - Agencia Estatal de Meteorología, C/ Leonardo Prieto Castro, 8, 28040 Madrid, http://www.aemet.es/, available at http://www.aemet.es/documentos/es/conocermas/recursos_en_linea/publicaciones_y_estudios/publicaciones/NT_24_AEMET/NT_24_AEMET.pdf;InSpanish, 2017.

Prein, A. F. and Gobiet, A.: Impacts of uncertainties in European gridded precipitation observations on regional climate analysis, International Journal of Climatology, 37, 305–327, https://doi.org/10.1002/joc.4706, https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/joc.4706, 2017.

Quintana-Seguí, P., Le Moigne, P., Durand, Y., Martin, E., Habets, F., Baillon, M., Canellas, C., Franchisteguy, L., and Morel, S.: Analysis of Near-Surface Atmospheric Variables: Validation of the SAFRAN Analysis over France, Journal of Applied Meteorology and Climatology, 47, 92–107, https://doi.org/10.1175/2007JAMC1636.1, https://doi.org/10.1175/2007JAMC1636.1, 2008.

Quintana-Seguí, P., Turco, M., Herrera, S., and Miguez-Macho, G.: Validation of a new SAFRAN-based gridded precipitation product for Spain and comparisons to Spain02 and ERA-Interim, Hydrology and Earth System Sciences, 21, 2187–2201, https://doi.org/10.5194/hess-21-2187-2017, https://www.hydrol-earth-syst-sci.net/21/2187/2017/, 2017.

Ramos, A. M., Trigo, R., Liberato, M. L., and Tomé, R.: Daily Precipitation Extreme Events in the Iberian Peninsula and Its Association with Atmospheric Rivers, Journal of Hydrometeorology, 16, 579–597, https://doi.org/10.1175/JHM-D-14-0103.1, https://doi.org/10.1175/JHM-D-14-0103.1, 2015.

Ramos, C. and Reis, E.: Floods in southern Portugal: their physical and human causes, impacts and human response, Mitigation and Adaptation Strategies for Global Change, 7, 267–284, https://doi.org/10.1023/A:1024475529524, https://doi.org/10.1023/A:1024475529524, 2002.

Rauthe, M., Steiner, H., Riediger, U., Mazurkiewicz, A., and Gratzki, A.: A Central European precipitation climatology ? Part I: Generation and validation of a high-resolution gridded daily data set (HYRAS), Meteorologische Zeitschrift, 22, 235–256, https://doi.org/10.1127/0941-2948/2013/0436, http://dx.doi.org/10.1127/0941-2948/2013/0436, 2013.

Rudolf, B., Hauschild, H., Rueth, W., and Schneider, U.: Terrestrial Precipitation Analysis: Operational Method and Required Density of Point Measurements, in: Global Precipitations and Climate Change, edited by Desbois, M. and Désalmand, F., pp. 173–186, Springer Berlin Heidelberg, Berlin, Heidelberg, 1994.

Sun Qiaohong, Miao Chiyuan, Duan Qingyun, Ashouri Hamed, Sorooshian Soroosh, and Hsu Kuo?Lin: A Review of Global Precipitation Data Sets: Data Sources, Estimation, and Intercomparisons, 56, 79–107, https://doi.org/10.1002/2017RG000574, 2018.

Trenberth, K. E., Dai, A., van der Schrier, G., Jones, P. D., Barichivich, J., Briffa, K. R., and Sheffield, J.: Global warming and changes in drought, Nature Climate Change, 4, https://doi.org/10.1038/nclimate2067, https://doi.org/10.1038/nclimate2067, 2014.

Uboldi, F., Lussana, C., and Salvati, M.: Three-dimensional spatial interpolation of surface meteorological observations from high-resolution local networks, Meteorological Applications, 15, 331–345, https://doi.org/10.1002/met.76, https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/met.76, 2008.

van den Besselaar, E. J. M., Haylock, M. R., van der Schrier, G., and Klein Tank, A. M. G.: A European daily high-resolution observational gridded data set of sea level pressure, Journal of Geophysical Research: Atmospheres, 116, https://doi.org/10.1029/2010JD015468, https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2010JD015468, 2011.

Vidal, J.-P., Martin, E., Franchisteguy, L., Baillon, M., and Soubeyroux, J.-M.: A 50-year high-resolution atmospheric reanalysis over France with the Safran system, International Journal of Climatology, 30, 1627–1644, https://doi.org/10.1002/joc.2003, https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/joc.2003, 2010.

Wahba, G.: Spline models for Observational Data, in: CBMS-NSF Regional Conference Series in Applied Mathematics. Philadelphia: Society for Industrial and Applied Mathematics., 1990.

Whiteman, C. D.: Breakup of Temperature Inversions in Deep Mountain Valleys: Part I. Observations, Journal of Applied Meteorology, 21, 270–289, https://doi.org/10.1175/1520-0450(1982)021<0270:BOTIID>2.0.CO;2, https://doi.org/10.1175/1520-0450(1982)021<0270:BOTIID>2.0.CO;2, 1982.

Whiteman, C. D.: Observations of Thermally Developed Wind Systems in Mountainous Terrain, pp. 5–42, American Meteorological Society, Boston, MA, https://doi.org/10.1007/978-1-935704-25-6_2, https://doi.org/10.1007/978-1-935704-25-6_2, 1990.

Whiteman, C. D. and McKee, T. B.: Breakup of Temperature Inversions in Deep Mountain Valleys: Part II. Thermodynamic Model, Journal of Applied Meteorology, 21, 290–302, https://doi.org/10.1175/1520-0450(1982)021<0290:BOTIID>2.0.CO;2, https://doi.org/10.1175/1520-0450(1982)021<0290:BOTIID>2.0.CO;2, 1982.