Answer to Referee 1

The paper by Tomas-Burguera et al. develops a process to gap fill, homogenize, and grid historical climate data to be used to calculate a weekly 1.1 km gridded estimate of reference evapotranspiration using the modified Penman-Monteith equation. The data is made available in netCDF format via an online repository and the authors provide an online visualization and extraction tool. An overview of the review is provided here with specific comments embedded in the attached annotated manuscript. I was able to access the data via the link provided in the paper and downloaded the evapotranspiration (ETo) data. It was relatively easy to access the data using MATLAB netCDF tools and the data that I accessed seemed to be usable. The link to the visualization tool provided also worked quite well for viewing and querying the data although I did not use the online tool for downloading.

Overall, the organization of the paper is acceptable and the data and methodology description were understandable. However, the language and paragraph structure needs a lot of work before this paper can be published. I think several key points are confused by language and sentence structure. There are a few key points that I would like to see addressed:

Authors: We would like to thank the reviewer for his valuable comments and his efforts helping the authors to improve this paper.

The use of language has been carefully revised in order to improve the paper, and we addressed all the suggested points, both the three key points as well as all the points in the supplementary file.

1) Please add a paragraph in the introduction to explain what "reference evapotranspiration" actually is and why it is considered a standardized method (with references). I think this is a key point that justifies your methodology and validates your dataset and deserves more than a brief mention.

Authors: We added the following sentences to introduce the concept of reference evapotranspiration:

'Reference evapotranspiration (ET_o) is a theoretical variable describing the evapotranspiration that would occur from a well-watered reference surface under specific meteorological conditions (Allen et al. 1998). Because well-watered conditions and a reference crop are assumed, both spatial and temporal ET_o variability depends solely on the variability of the meteorological conditions. Hence, ET_o is an accepted proxy for the atmospheric evaporative demand (AED), which is a key variable for understanding both water and energy terrestrial balances and, therefore, relevant to a variety of disciplines, including climatology, hydrology, and agronomy (Espadafor et al. 2011).'

2) I think that your justification for using FAO-PM for calculating ETo should be stronger and better organized in the Introduction and following this, should be discussed in greater detail in the Discussions and conclusions section.

Authors: We added a sentence in the Introduction to justify the use of FAO-PM, by adding some references to authors who validated the use of FAO-PM against lysimiters data.
We also added a paragraph in the Discussions and conclusions section (see answer to point 3).

'The main advantage of this method is that it is physically based. It has also been tested against lysimeters data obtaining reliable results (Jensen et al. 2000,Itenfisu et al. 2000, Berengena y Gavilan 2005, Trajkovic, 2007).'

New references:

Berengena, J. and Gavilán, P: Reference evapotranspiration estimation in a highly advective semiarid environment, Journal of Irrigation and Drainage Engineering, 131, 147-163

Itenfisu, D., Elliot, R, Allen, R and Walter, I.: Comparison of reference evapotranspiration calculations across a range of climates, in: Proceedings of the 4th National Irrigation Symposium, pp. 216-227, St Joseph. asae edn., 2000

Jensen, M., Burman, R. and Allen, R: Evapotranspiration and irrigation water requirements, in: ASCE manual No. 70, p.332, New York, asce edn, 1990

Trajkovic, S.: Hargreaves versus Penman-Monteith, Journal of Irrigation and Drainage Engineering, 133, 38-42

3) It is my understanding that even though FAO-PM is the recommended methodology for estimating ETo, it does have some issues and limitations. I would like to see this addressed more in the Discussions and conclusions section, especially in regards to climate conditions in Spain and how those limitations may impact your data.

Authors: A paragraph discussing possible effects of using PM has been added to the discussion section:

'Calculating ETo using PM assumed a well-watered reference surface, which can differ significantly from the actual conditions present in a semiarid region, as is the case across most of our study area. A scarcity of soil moisture can decrease the air humidity and increase the air temperature compared with well-watered conditions due to the effects of the land$-$atmosphere continuum. Both changes, which especially affect the aerodynamic component of ETo, may have a noticeable effect on ETo, meaning that an overestimation can occur under semiarid conditions (Bouchet 1961, Allen et al. 1998). Such an overestimation would be higher during the warm season when these conditions prevail. The possible overestimation due to the use of PM in a semiarid environment should be considered by potential users of this database.'

Find here the answer to all the *Specific Comments*

Reviewer (R): Page 1. Line 15.- I believe "Budyko" should be capitalized and I think that it should be "the Budyko curve"

Authors (A): We agree. We changed the use of '*budyko*' for '*the Budyko curve*'

R: P1L20.- Could you add a paragraph to explain what "reference evaporation" actually is and why it is considered a standard (with references). I think this is a key point for justifying the validity of your data.

A: We added the following two sentences to introduce the concept of reference evapotranspiration:

'Reference evapotranspiration (ET_o) is a theoretical variable describing the evapotranspiration that would occur from a well-watered reference surface under specific meteorological conditions (Allen et al. 1998). Because well-watered conditions and a reference crop are

assumed, both spatial and temporal ET_o variability depends solely on the variability of the meteorological conditions. Hence, ET_o is an accepted proxy for the atmospheric evaporative demand (AED), which is a key variable for understanding both water and energy terrestrial balances and, therefore, relevant to a variety of disciplines, including climatology, hydrology, and agronomy (Espadafor et al. 2011).'

We also added some references to authors who validated the results of ET_o against lysimeter data:

'The main advantage of this method is that it is physically based. It has also been tested against lysimeters data obtaining reliable results (Jensen et al. 2000,Itenfisu et al. 2000, Berengena y Gavilan 2005, Trajkovic, 2007).'

New references:
Berengena, J. and Gavilán, P: Reference evapotranspiration estimation in a highly advective semiarid environment, Journal of Irrigation and Drainage Engineering, 131, 147-163

Itenfisu, D., Elliot, R, Allen, R and Walter, I.: Comparison of reference evapotranspiration calculations across a range of climates, in: Proceedings of the 4th National Irrigation Symposium, pp. 216-227, St Joseph. asae edn., 2000

Jensen, M., Burman, R. and Allen, R: Evapotranspiration and irrigation water requirements, in: ASCE manual No. 70, p.332, New York, asce edn, 1990

Trajkovic, S.: Hargreaves versus Penman-Monteith, Journal of Irrigation and Drainage Engineering, 133, 38-42

R: P2L4.- I like "especially" better since it is more formal. Suggest changing throughout.

A: We changed '*specially*' for '*especially*' throughout the text.

R: P2L6.- The transition into this paragraph is awkward and repetitive. Merge this with the previous paragraph.

A: See answer to the next question.

P2L8.- The reviewer doesn't like the use of "… difficult the generation …"

A: We merged both paragraphs and we changed the whole redaction:

'Although the maximum and minimum air temperature are commonly collected at weather observatories, observations of the other variables are scarce, especially if long time series are required for climate studies (Vanderlinden et al. 2004, McVicar et al. 2007, Irmak et al. 2012, Vicente-Serrano et al. 2014a) or to generate ET_o grids. The other significant problem facing the generation of ET_o climate grids is the changing number of observations, which can introduce non-climatic changes in variance (Beguería et al. 2016).

R: P2L11. Methods of what?

A: We changed the expression *'use of less demanding methods'* for *'use of methods for calculating ET_o requiring fewer climatic variables, commonly known as "less demanding methods"'*

R: P2L12. Again, methods of what?

A: In order to clarify, we changed the sentence.
'The use of methods for calculating ETo requiring only temperature data'

R. P2L15. This sentence is a bit confusing. Try rewording it

A: We changed the sentence '*Nevertheless, this strategy is not recommended as methods not using data for all climatic variables are not able to deal with the variability and/or trends of missing variables and they could lead to erroneous conclusions ()*' for:

'*One of the major drawbacks of these methods is that variability and trends in the estimated ET_o values depends only on temperature, regardless of the importance of the other variables ()*'

R. P2L20 I think you need a sentence or two here or above explaining what FAO-56 is, with references. You then, in the next sentence tell the reader that the method should be avoided but the reader may not know what they are avoiding. Clarify this.

A: We added some sentences in the introduction to explain what reference evapotranspiration is and why FAO-56 is a recommended method. In this specific line, we also added the following words: '*in the FAO-56 document, which is the FAO document describing the guidelines for computing ETo, ...*'

R. P2L23. Which problems, why are they similar?

A: The sentence reads now:

'First, they use stationary relationships between variables that were empirically derived, which can be problematic in the context of climate change since these relationships may also change. This is in fact the same problem that affects the less demanding methods, which also rely on empirically derived relationships (Tomas-Burguera et al. 2017).'

R. P2L24. Clarify why this is a problem

A: we added *'limiting the number of locations from which ETo can be obtained*'

R. P2L32. These next two paragraphs seem disjointed and make for bad flow. They seem to be attached to the "Estimation of missing data" section but should be separate. Also, please re-read these paragraphs for grammar and English.

A: We added a white line to avoid confusion. We re-wrote and joined the two paragraphs, and now they are*:*
'The changing number of observations available over time is another relevant problem affecting the generation of ET_o climate grids. To avoid negative effects, usually only the longest climate time series are used to generate climate grids using geostatistical methods, such as universal kriging (UK). Obviously, this strategy diminishes the number of usable climatic observations'

R. P3L12. IC is defined above but I don't think PM is defined.

A: We added the definition of PM in page 2, Line 20. *'... Penman-Monteith (PM) is calculated.'*

R. P3L16. Minor thing but it would sound better if you used a different word here.

A: We changed '*implemented*' for '*designed*'.

R. P4L15. A couple more sentences here on how you detected bad values would be appreciated. Range detection? Unrealistic jumps? Nearest neighbour?

A: We added some sentences to better explain the quality control:

'The quality of the data were assessed by implementing an automated daily quality control in R. Daily data were tested against two types of controls:codification errors and out-of-range values. The presence of duplicate data or n consecutive days having the exact same values in different observatories were the two most relevant codification errors detected. Out-of-range values mainly detected out-of-physical-range-values and out-of-climate-range values. More details can be found in (Tomas-Burguera et al. 2016)

R. P4L17. These two sentences are clumsy and should be part of the previous paragraph.

A: We changed the sentences in order to clarify the content:

The temporal aggregation of daily data into weekly data was then executed. For all variables, weekly time series were obtained by calculating the mean value of the daily data. Weeks presenting more than one day without data were considered to have no data. This is an adaptation of the WMO rules for monthly data (WMO, 1989)'

R. P5L3. Were there any gap size limits used in this process?

A: All the weather stations available were used in the gap filling process. The last step of the process is a data selection according to the number of original data. In the original version of the manuscript, the data selection was explained in the following paragraph. We mixed the two paragraphs and reword some sentences in order to clarify the process regarding the gap size limits:

'All weather stations available were used in the gap filling process. The last step of the process involved data selection and depended on the amount of original data available. For temperature, only time series accounting for more than 25 years of the original data were used. For the rest of variables, this period was reduced to 15 years due to the low availability of long records (Figure 3) Up to three gap filling loops were implemented for less frequent variables (sunshine duration, dew point temperature, and wind speed). Various steps in the gap filling procedure took advantage of non-overlapping data. This configuration was used previously to generate other databases over Spain (Gonzalez-Hidalgo et al. 2015).

R. P5L13. It would be good to have a sentence or two about this process so that the reader doesn't have to pull the reference to get the idea.

A: We added two sentences to explain the basis of the method:

'This method used as a basis the comparison of the time series to be homogenized, the candidate series, and a reference time series. Reference time series were obtained using the same process used to obtain the gap filling reference time series.'

R. P5L19. This doesn't need to be its own paragraph.

A: Done.

R. P5L29. Redundant.

A: Deleted.

R. P5L29. If this is done before the interpolation, why do you discuss it afterward? Out of order.

A: Obtaining the semi-variogram is the first step of the interpolation process. In order to clarify, we rewrote the sentence:

'As a first step in the interpolation process, a semi-variogram model was generated. This model was unique for each time step and each climatic variable'

R. P5L32. You changed this to UK above. Be consistent.

A: Done.

R. P6L1. Reword.

A: We deleted the expression 'At this point' and we merged it with the previous sentence.

R. P6L11. Attach to previous paragraph.

A: Done.

R. P6L21. What is the advantage and/or utility for splitting the components?

A: We added an example of one specific situation in which having data of the two components separately can benefit the user:

'A variability and trend analysis could benefit from the availability of the two components. For example, wind stilling and solar brightening have opposite effects in ET_o, but studying the two components separately facilitates the study of the impacts of each one on ET_o.'

R: P6L23. This is already stated before.

A: Deleted.

R: P7L17.

A: We changed '*reaching*' for '*yielding'*.

R: P8L4. Doesn't need to be a new paragraph. Reword these sentences to remove the redundancy.

A: Done. The new paragraph reads:

During the last part of the period (2010-2014), a high number of AWS were installed. A sharp increase in the available RH and W data was observed during this period, compared with the data available from weather stations used to generate the original database (Table 2).The values of these observations and the values of the climate grids were compared directly to obtain the relative humidity and wind speed over the 2010-2014 period using the new stations as an independent dataset.

R: P8L8. Gap Filling section. To me, the order of the paragraphs in this section is reversed. You should first present the results and then discuss why you see them.

A: We moved the first paragraph to the end of the section.

R: P8L10. Important why?

A: We changed '*important*' for '*large*'.

R: P8L14. Implications?

A: We changed some sentences in order to clarify this point:

'The wind speed provided the lowest amount of filled data. It was difficult to obtain highly correlated time series to fill in the gaps, which had two major effects in the process: i) the probability of obtaining a reference time series from the neighbors was decreased; and ii) the reconstruction was poor when the reference time series could be obtained. The low correlation of the wind speed time series was a consequence of i) the high spatial and temporal variability of this variable and ii) the low number of observations available.

R: P8L16. Reword or just remove 'Evidently'.

A: Removed.

R: P8L19. …shows an r2 for the adjustment of … Also, you start calling the gap filling exercise here an "adjustment". It's a bit of a leap in semantics so if you are going to call it an "adjustment", you should probably lead into this in the previous sentences.

A: Changed:

'Which showed an r2 of only …'

Also, we changed the word 'adjustment' for other expressions in the three cases in which we used this word.

R: P8L19. Have ME and PBIAS been defined anywhere?

A: DONE
'*Mean Error (ME) and Percent Bias (PBIAS)*'

R: P8L21. Reverse the number and the acronym for this to make more sense, complete throughout

A: Done.

R: P8L24. Speculation as to why?

We hypothesize that the variance increase in gap-filled wind time series is due to the right-skewed nature of this variable. The gap-filling method that we used undergoes standardization of the data to avoid biases when a reference series is computed from neighbor observatories. This method has been tested and works very well with temperature data and other similar variables such as dew point temperature. However, it is possible that in the case of wind speed, which has a right-skewed distribution, the method does not work as expected and generates a slight expansion of the variance. This is an issue that would need further research, though.

R: P8L27. Reword this entire sentence.

A: Done. The text now reads:

'For wind speed, the most recent decade showed slightly higher R^2 value than the first decades of the period.'

R: P8L30. Do you mean the quantity of data? You should say that.

A: Done. The text now reads:

'*The percentage of data affected by the homogenization process exceeded…'*

R: P9L4. This whole paragraph is confusing. Reword and be less vague.

A: Done. The new text reads:

'The temporal evolution of the quantity of data detected as inhomogeneous was analyzed (Figure 4), revealing a temporal trend with maximum values at the start of the study period and minimum values at the end. The most likely explanation for this observation is the use of more recent conditions as the standard conditions.'

R: P9L7. Consideration??

A: We changed the sentence:

'*Another effect of this assumption is the…*'

R: P9L9. This sentence needs some work.

A: We changed the sentence, which now reads:

'The maximum and minimum temperature, which displayed a positive trend in Spain over the study period (DelRio et al. 2012, Gonzalez-Hidalgo et al. 2016), suggested that higher values occurred in the present than in the past.A positive bias was observed in the homogenized data over the first decades. Unlike the maximum and minimum temperature, the wind speed, which displayed a negative trend (Azorin-Molina et al. 2014), was affected by a negative bias during the first decades of the study period.'

R: P10L4. Reaching the recent decades greater values of R2 ???

A: We changed the sentence:

'A temporal analysis of the R^2 values obtained from the spatial validation of the maximum and minimum temperature (Fig. 8) showed slightly better statistics (i. e., closer to one) in recent decades'

R: P10L22. Discussion and conclusions. In your discussion and conclusions section, you discuss limitations in the data for calculating ETo from the gridded climate data but you didn't really discuss any limitations of using PM ETo in applications. I would like to see a paragraph in this section that contains a discussion of any limitations to the ETo database as derived from PM.

A: A paragraph discussing possible effects of using PM has been added to the discussion section:

'Calculating ETo using PM assumed a well-watered reference surface, which can differ significantly from the actual conditions present in a semiarid region, as is the case across most of our study area. A scarcity of soil moisture can decrease the air humidity and increase the air temperature compared with well-watered conditions due to the effects of the land$-$atmosphere continuum. Both changes, which especially affect the aerodynamic component of ETo, may have

a noticeable effect on ETo, meaning that an overestimation can occur under semiarid conditions (Bouchet 1961, Allen et al. 1998). Such an overestimation would be higher during the warm season when these conditions prevail. The possible overestimation due to the use of PM in a semiarid environment should be considered by potential users of this database.'

R: P10L26. This would be more appropriate in the Introduction rather than in the Discussion section.

A: It has been moved to the introduction.

R: P11L4. '… based in first interpolate' ??

A: We changed the sentence:

'The PM-IC strategy, which consisted of interpolating climatic variables prior to calculating ETo'

R: P11L8. Misused. Not sure if this is the right word.

A: We changed '*misused*' for '*not used*'.

R: P11L11. Reword.

A: We changed the sentence:

'As 80% of the ETo variability was related to the variability in temperature and radiation (Mendicino and Senatore, 2013; Samani, 2000), using as many temperature observations as possible was important for ensuring the quality of the obtained results.'

R: P12L5. Reword this second part of this sentence.

A: We changed the sentence:

'This dataset was first developed as an input to generate, in combination with the precipitation data, grids of drought indices over the study area (Vicente-Serrano et al. 2017). Due to the relevance of ETo and the high number of possible uses of these data, the ETo climate grid is now being made available to other research groups.'

R: P12L8. I think this should be joined to the previous paragraph in order to make sense.

A: Done.

R: P12L14. Reword these sentences.

A: We reword the previous sentences. Now:

More accurate models of ETo is also useful for rainfed agriculture. Hence, the whole agricultural sector could benefit from this dataset.

R: P12L17. This sentence is very hard to read.

A: The new sentence reads:

'This database could also be used for regional (or global) climate model assessment in the context of climate change studies.'

R. FIG 5.- The lines would be better with color.

A: We added colors to the figure.

R. FIG 8.- These are a little hard to read. How about adding some colour to the plots?

A: We added colors to the figure.

R. Table 1 and 2. Seems like Table 1 and Table 2 could be combined.

A: We have combined both tables into one.

R. Table 3. It would be useful and common practice to define the column headers in the caption.

A: Done.

R. Table 4. Table number format not consistent with other tables.

A: We have checked and homogeneized the number formats in the tables.

R. Table 5. Same comment as for Table 3.

A: Done.

Answer to Referee 2

This study presents a strategy to calculate a weekly 1.1 km gridded estimate of reference evapotranspiration using the modified Penman-Monteith equation. The study provides a good justification for first interpolating the climatic variables and then calculate ETo, rather than first calculating ETo and then interpolating the obtained values. The link to the data provided worked as I could download the evapotranspiration data. Honestly though I have not evaluated the data or assessed the visualisation tool. I would rather comment on the structure and content of the paper. Generally I found the structure of the paper to be acceptable. I managed to follow the paper fairly well. One concern is that there are many problems with the grammar and spelling, which detracts from the potential positive impact of the paper. Some specific problems are: 1. The use of tense: the paper switches between past and present tense 2. Commas: There are many places in the text where commas are needed 3. Spelling mistakes: The authors need to run a spell check of the document 4. General bad use of English in a few places.

Authors: We would like to thank the reviewer for his valuable comments and his efforts in helping the authors to improve this paper.

The use of language has been carefully revised in order to improve the quality of the paper.

Some specific queries I have in relation to the methodology are:

1. Page 4 line 20: Could the description of converting daily values to weekly be clearer? Specifically this description needs to be clearer: 'Trying to adapt the WMO rules for monthly data (WMO, 1989) to weekly data, those weeks with at least two missing values are considered to have no value.'

Authors: After reading again the sentence, we agree with the reviewer that this explanation required an improvement. The sentence reads now:

'*The temporal aggregation of daily data into weekly data was then executed. For all variables, weekly time series were obtained by calculating the mean value of the daily data. Weeks presenting more than one day without data were considered to have no data. This is an adaptation of the WMO rules for monthly data (WMO, 1989)'*

2. Page 5 line 30: The selection of nearby stations for gap filling depended on three criteria: 1) overlapping period > 7 years; 2) closer than 100 km; 3) R2 > 0.6. Could I suggest an additional criterion: that of the station being at a similar elevation

We know that weather stations being close but located at different elevation can show relevant climatic differences, affecting the ability of these observations to be used in a gap filling process. The use of the correlation coefficient in the selection of nearby stations already prevents the use of weather stations showing a contrasting climatology due to differences in elevation.

Moreover, the used gap filling method uses and standardization approach, preventing the differences in the mean values and/or variance to be transferred from one weather station to another, which is one of the risks of not using an elevation criterion.

Reference crop evapotranspiration database in Spain (1961-2014)

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Abstract.

Obtaining climate grids ~~for~~ describing distinct variables is ~~of high importance to develop~~ important for developing better climate studies~~, but also to offer usable~~. These grids are also useful products for other researchers and ~~to~~ end users. ~~As a measure of~~ The atmospheric evaporative demand (AED) ~~,~~ may be measured in terms of the reference evapotranspiration (ET_o)~~is~~ , a key variable for understanding ~~both~~ water and energy terrestrial balances ~~, being important for~~ and an important variable in climatology, hydrology, and agronomy. ~~In spite of~~ Despite its importance, the calculation of ET_o is not ~~very common~~commonly undertaken, mainly because ~~data~~ datasets consisting of a high number of climate variables are required, and some of ~~them~~ the required variables are not commonly available.

To ~~solve~~ address this problem, a strategy based on the spatial interpolation of climate variables ~~previous to~~ prior to the calculation of ET_o using FAO-56 ~~Penman-Monteith~~ Penman−Monteith was followed to obtain an ET_o database for Continental Spain and the Balearic Islands covering the ~~1961-2014~~ 1961−2014 period at a spatial resolution of 1.1 km and at a weekly temporal resolution. In this database, values for the radiative and aerodynamic components as well as the estimated uncertainty related ~~with~~ to ET_o ~~are~~ were also provided.

This database is available ~~to download in~~ for download in the Network Common Data Form (~~netcdf~~netCDF) at http://dx.doi.org/10.20350 (Tomas-Burguera et al., 2019)~~, and a~~. A map visualization tool (http://speto.csic.es) is ~~also~~ available to help users ~~to download data of~~ download the data corresponding to one specific point in comma-separated values (csv) format.

A relevant number of research ~~ares~~ areas could take advantage of this database. Providing only some examples: i) ~~the study of budyko~~ studies of the Budyko curve, which relates rainfall data ~~with~~ to the evapotranspiration and AED at the watershed scale; ii) ~~the calculation~~ calculations of drought indices using AED data, such as SPEI or PDSI; iii) agroclimatic studies related ~~with irrigation requirement~~to irrigation requirements; iv) validation of ~~Climate Models~~ climate models water and energy balance; v) ~~the study~~ studies of the impacts of climate change in terms of the AED.

1 Introduction

As a measure of Reference evapotranspiration (ET_o) is a theoretical variable describing the evapotranspiration that would occur from a well-watered reference surface under specific meteorological conditions (Allen et al., 1998). Because well-watered conditions and a reference crop are assumed, both spatial and temporal ET_o variability depends solely on the variability of the meteorological conditions. Hence, ET_o is an accepted proxy for the atmospheric evaporative demand (AED), reference evapotranspiration (ET_o) which is a key variable for understanding both water and energy terrestrial balances , being important for and, therefore, relevant to a variety of disciplines, including climatology, hydrology, and agronomy (Espadafor et al., 2011). To compute ET_o, the Food and Agriculture Organization of the United Nations (FAO) recommends the use of using a modified version of Penman-Monteith (Allen et al., 1998), requiring data of Penman−Monteith (Allen et al., 1998). The main advantage of this method is that it is physically based. It has also been tested against lysimeters data obtaining reliable results (Jensen et al., 1990; Itenfisu et al., 2000; Berengena and Gavilán, 2005; Trajkovic, 2007). On the other hand, its main problem is its high data requirement, as data corresponding to the maximum and minimum air temperature, air humidity, wind speed, and solar radiation . While are needed. Although the maximum and minimum air temperature are commonly collected at weather observatories, the observation of the rest of variables is scarce, specially observations of the other variables are scarce, especially if long time series are required for climate studies (McVicar et al., 2007; Irmak et al., 2012).

Main problems affecting (Vanderlinden et al., 2004; McVicar et al., 2007; Irmak et al., 2012; Vicente-Serrano et al., 2014) or to generate ET_o grids. The other significant problem facing the generation of ET_o climate grids are related to climate data availability: a) some of the variables needed to compute ET_o are not commonly available (Vanderlinden et al., 2004; Vicente-Serrano et al., and b) changes in observation network difficult the generation of climate grids as the use of a is the changing number of observationscan introduce non climatic , which can introduce non-climatic changes in variance (Beguería et al., 2016).

When In the event that some of the variables are not commonly available, possible solutions that available, two types of approaches have been used to allow ET_o calculation can be classifiedin two groupscalculations to be classified: i) use of methods for calculating ET_o requiring fewer climatic variables, commonly known as "less demanding methods", and ii) estimation of missing data previous prior to ET_o calculation.

i) Less demanding methods

The use of less demanding methods methods for calculating ET_o requiring only temperature data, such as the Thornthwaite (Thornthwaite, 1948) or Hargreaves and Samani (1985)Hargreaves Hargreaves and Samani (1985) approaches, are still common, is still very common, specially especially because temperature is commonly available, and temperature and solar radiation accounts for 80 % of the ET_o variability (Mendicino and Senatore, 2013; Samani, 2000). Nevertheless, this strategy is not recommended as methods not using data for all climatic variables are not able to deal with the variability and/or trends of missing variables and they could lead to erroneous conclusions One of the major drawbacks of these methods is that variability and trends in the estimated ET_o values depend only on temperature, regardless of the importance of the other variables (Irmak et al., 2012; Mcvicar et al., 2012; Sheffield et al., 2012; Tomas-Burguera et al., 2017).

ii) Estimation of missing data

~~The estimation~~ Estimations of missing data ~~previous~~ prior to ET_o calculation can also be divided in two possibilities: i) ~~the use of FAO-56 recommendations~~ use of the recommendations described in the FAO-56 document, which is the FAO document describing the guidelines for computing ET_o, and ii) ~~the~~ use of nearby weather ~~stations~~ station data. Whenever data ~~of~~ corresponding to the non-observed ~~variable exist~~ variables has been collected at nearby locations, the use of FAO-56 recommendations should be avoided ~~because: a)~~ for two reasons. First, they use stationary relationships between variables ~~, leading to similar problems than those detected for~~ that were empirically derived, which can be problematic in the context of climate change since these relationships may also change. This is in fact the same problem that affects the less demanding methods~~(Tomas-Burguera et al., 2017) and b) data of temperature is always required~~, which also rely on empirically derived relationships (Tomas-Burguera et al., 2017). Second, temperature data are always required, limiting the number of locations from which ET_o can be obtained.

The use of nearby weather ~~stations~~ station data to estimate missing data takes advantage of spatial interpolation methods, and it is the only ~~of the above~~ approach among the above-mentioned methods that ~~estimate the~~ estimates missing data using information ~~of~~ about the same variable. This strategy, usually known as Interpolate-then-Calculate (IC), has two main steps. First, the missing variables are estimated using a spatial interpolation method~~and then, Penman-Monteith~~ , and second, the Penman−Monteith (PM) is calculated. This method was tested in various regions, such as Greece, China, and Great Britain (Mardikis et al., 2005; McVicar et al., 2007; Robinson et al., 2017). Tomas-Burguera et al. (2017), in the Iberian Peninsula, compared the performance of this method with the performances of some of the aforementioned solutions, concluding that ~~IC strategy was the one obtaining~~ the IC strategy yielded better results.

~~The other problem related with data availability is that climatic networks changes over time, affecting the number of available observations .~~

~~In Spain, relevant changes affected the availability of wind speed and relative humidity data during last decades, as the installation of a high number of automatic weather stations (AWS) 10 years ago implied a sharply increase in data availability of these relevant variables for~~

The changing number of observations available over time is another relevant problem affecting the generation of ET_o ~~calculation. Nevertheless, and as it was mentioned before, it is important to use a constant number of observations through time when a climate grid wants to be generated by using a geostatistical method, such as universal kriging. That means that~~ climate grids. To avoid negative effects, usually only the longest climate time series ~~should be~~ are used to generate ~~the climate grids , diminishing~~ climate grids using geostatistical methods, such as universal kriging (UK). Obviously, this strategy diminishes the number of ~~weather observationsthat can be used. In order to extend the number of observations, it is common to use a gap filling procedure, which estimate the missing data from one specific weather station using as a reference the data from nearby well-correlated time series~~usable climatic observations.

~~This research is focused on the generation of~~ The problems mentioned above usually restrict the availability of high spatial resolution climate data sets of ET_o, especially if they are developed using the Penman−Monteith equation. During the last several years, a ET_o climate grid at a 1 km spatial resolution over Great Britain was presented Robinson et al. (2017) . Haslinger and Bartsch (2016) presented a climate grid at a 1 km spatial resolution over Austria, but their grid was based on the Hargreaves equation.

A method focused on overcoming the above-mentioned problems related to data availability was designed to generate a climate grid of ET_o for over Continental Spain and the Balearic Islands with a spatial resolution of 1.1 km covering the 1961-2014 1961−2014 period with a weekly temporal resolution. The followed methodology, which mainly consists in the combination This method took advantage of two estimation processes to overcome the above mentioned problems previous to prior to ET_o calculationis presented in this paper. A gap fillingprocedure was : i) gap filling, used to obtain a subset of the complete time series for over the period of interest for each one of the climatic variables, and a spatial interpolationmethodology was implemented ii) spatial interpolation, used to generate climate grids of each one of the required climate variablesprevious to the calculation of ET_o, meaning . After spatial interpolation, ET_o was calculated using climate grids as its source of data. This means that a PM-IC scheme was implemented. Quality used. In addition to the estimation processes, quality control and homogenization steps were also implemented. The validation of gap filling, homogenization and interpolation steps are presented trying to detect possible spatial or temporal effects that could affect to ET_o obtained values.

Although it is not commonly implementednecessary. Although not commonly used, an uncertainty propagation scheme was also implementeddesigned, considering the two estimation processes (gap filling and interpolation) as the unique sources of uncertainty. The method and validation of the gap filling, homogenization, and interpolation steps are presented in detail in this paper.

2 Data sources

The original dataset contains data of contained data corresponding to the daily maximum temperature (Tmax), minimum temperature (Tmin), wind speed (W), relative humidity (RH), and sunshine duration (SD), and was provided by AEMET for the whole across the whole region of Spain. Sunshine duration is was used to estimate the radiation data as the number of weather stations collecting radiation data is very lowand Sanchez-Lorenzo et al. (2013) obtained a good adjustment between these two variableswas very low, and Sanchez-Lorenzo et al. (2013) assessed this method to obtain satisfactory results.

The number of observations available (Table 1) depends depended on the variable. More than 4000 weather stations are available both for collected the maximum and minimum temperature. Less Fewer than 1000 weather stations are available for the others variables, being less collected the other variables, and fewer than 300 for collected the sunshine duration. The number of selected weather stations is was always much lower than the available ones, as only the longest time series were selected.

These weather stations did not collect data throughout the entire period. Figure 1 shows, for each variable and each year, provides the number of weather observations available for the 1961-2014 each variable and each year for the 1961−2014 period. Temperature data show showed the highest number of observations, always higher than 500, reaching 2000 observations available in the mid 90'swith a posterior decrease. Relative , followed by a subsequent decrease. The relative humidity and wind speed ~~show~~ showed a low number of observations during the study period. Nevertheless, in the mid 2000's, ~~when~~ the installation of a ~~high~~ large number of automatic weather stations (AWS) ~~took place, a sharply increase in~~ sharply increased the availability of these two climatic variables~~is detected. Sunshine duration measurements are~~ . The sunshine duration measurements remained constant throughout the ~~whole period~~entire period.

Some geographic variables were ~~also~~ used in the interpolation process. The Digital Elevation Model (DEM) was obtained from the IGN (Instituto Geográfico Nacional), and other variables, such as distance to the sea, were derived from the DEM.

3 Methodology

The general scheme used to generate the ET_o database ~~has~~ involved two main steps: i) generation of climatic grids, and ii) estimation of ET_o (Figure 2). The generation of the climatic grids ~~can be divided in:~~ could be divided into a) daily quality control, b) ~~daily to weekly~~ daily-to-weekly data conversion, c) gap filling, d) data selection, e) homogenization, and f) interpolation, and all of these steps ~~are~~ were implemented individually for each climatic variable. The estimation of ET_o ~~consists in~~ consisted of the calculation of ET_o ~~by~~ using the FAO-56 ~~Penman-Monteith equation using the climatic grids as the source of data~~ Penman−Monteith equation over the climatic grid data sources.

On the other hand, the uncertainty ~~of~~ in ET_o was ~~also~~ estimated using a ~~two steps~~ two-step process: i) uncertainty estimation of ~~climatic grids~~ the climatic grids, and ii) uncertainty propagation from the climatic grids to ET_o. The uncertainty estimation of ~~climatic grids refers to~~ the climatic grids estimated the uncertainty of each climatic grid after the interpolation process and ~~it takes into account~~ considered the uncertainty related ~~both with~~ to the gap filling process and ~~with~~ the interpolation process. ~~The uncertainty~~ Uncertainty propagation refers to the technique ~~that estimates the uncertainty of~~ used to estimate the uncertainty in ET_o values by combining the uncertainty ~~of~~ in each climatic variable with the Jacobian of the ~~Penman-Monteith~~ Penman−Monteith equation.

The quality of the data were assessed by implementing an automated daily quality control ~~was implemented in Rand, for each variable, all data available was evaluated at time. The tests at daily time scale are based on the detection of erroneous codificated and abnormal values(Tomas-Burguera et al., 2016).~~

~~Then, daily data was converted to weekly data~~in R. Daily data were tested against two types of controls: codification errors and out-of-range values. The presence of duplicate data or n consecutive days having the exact same values in different observatories were the two most relevant codification errors detected. Out-of-range values mainly detected out-of-physical-range-values and out-of-climate-range values. ~~Trying to adapt~~ More details can be found in Tomas-Burguera et al. (2016). The temporal aggregation of daily data into weekly data was then executed. For all variables, weekly time series were obtained by calculating the mean value of the daily data. Weeks presenting more than one day without data were considered to have no data. This is an adaptation of the WMO rules for monthly data (WMO, 1989) ~~to weekly data, those weeks with at least two missing values are considered to have no value.~~

Some comparison problems between distinct years ~~emerge when~~ emerged if a time scale of 7 days ~~is~~ were used, mainly because the number of days in a year is not divisible ~~per~~ by 7. ~~Trying to combine the weekly time scale with comparability~~

~~between distinc~~ In an attempt to combine weekly timescales to preserve comparability between years, each month was divided ~~in~~ into 4 periods (days 1-8, 9-15, 16-22, 23-end). ~~From now on~~For the remainder of this discussion, the use of ~~word weeks in this paper~~ the word week(s) refers to this definition of a sub-monthly period.

After this step, the relative humidity data ~~was~~ were transformed into dewpoint temperature (T_d) using ~~also~~ the temperature data. ~~After some tests with gap~~ Gap filling and interpolation ~~, it was noticed that working with~~ tests revealed that T_d was easier ~~than working with~~ to work with than RH. ~~As~~ The T_d data ~~adjust~~ adjusted better to a ~~gaussian~~ Gaussian distribution than RH data; therefore, working with T_d data ~~is preferrable in~~ was preferable for most of the implemented steps.

3.1 Gap filling

~~Trying to obtain~~ In an effort to obtain a complete time series of distinct climate variables, a gap filling procedure based on the estimation of missing data ~~by~~ using nearby weather ~~stations' data~~station data, designed by (Beguería et al., 2019), was implemented. The standard error of the estimated data was ~~also~~ obtained and used as a measure of the uncertainty of the process.

The ~~selecion of used~~ selection of nearby weather stations ~~is relevant for~~ was relevant to the process, and a selection based on three steps was implemented: i) overlapping ~~period higher~~ periods longer than 7 years; ii) location closer than 100 km, and iii) values of R^2 higher than 0.6.

The ~~used procedure uses standardization of values previous to the gap filling ,~~ procedure used standardized values prior to gap filling in order to avoid problems related ~~with~~ to differences in the mean values and/or ~~in the variance~~ variances between weather stations.

~~The gap filling was implemented individually for each climatic variable and more than one (3) gap filling loop was implemented for less frequent variables (sunshine duration, dewpoint temperature and wind speed). The use of various steps in the gap filling procedure was implemented to take advantage of non-overlapping data , and it was used previously to generate other databases in Spain (Gonzalez-Hidalgo et al., 2015).~~

~~A high number of complete time series for each variable was obtained after this process, but only time series containing a high percentage of original data was selected to be used in the interpolation process~~All weather stations available were used in the gap filling process. The last step of the process involved data selection and depended on the amount of original data available. For temperature, only time series accounting for more than 25 years of the original data were used. For the rest of variables, this period was reduced to 15 years ~~,~~ due to the low availability of long records (Figure 3). Up to three gap filling loops were implemented for less frequent variables (sunshine duration, dew point temperature, and wind speed). Various steps in the gap filling procedure took advantage of non-overlapping data. This configuration was used previously to generate other databases over Spain (Gonzalez-Hidalgo et al., 2015).

3.2 Homogenization

~~To test the~~ The homogeneity of the obtained time series after the gap filling process ~~we used~~ was tested using the Standard Normal Homogeneity Test (SNHT) (Alexandersson, 1986). This method used as a basis the comparison of the time series to be homogenized, the candidate series, and a reference time series. Reference time series were obtained using the same process used to obtain the gap filling reference time series.

The test was implemented at the monthly time scale after the conversion of time series to ~~this~~ time scales, mainly because homogeneity tests, in general, are more robust when they are used with monthly data than with sub-monthly ~~. In order to obtain weekly~~ data. Weekly homogeneous time series ~~, once~~ were obtained by transforming the monthly parameters ~~are obtained we transformed~~ to weekly parameters.

The ~~homogenization of the climate series~~ climate series homogeneity was tested after ~~the gap filling due~~ gap filling to: i) ~~it is possible to~~ detect inhomogeneities introduced by the gap filling process, and ii) ~~the process is more reliable when time series have~~ determine if the process was more reliable if the time series had no gaps.

Present observations were assumed to be ~~the~~ standard, meaning that ~~in case of detecting any inhomogeneity, the correction was made~~ any inhomogeneities were corrected to adjust the values of the past to the present values.

3.3 Interpolation

Kriging is a geostatistical method widely used in Climatology to generate interpolated surfaces for many variables (Aalto et al., 2013; Hofstra et al., 2008). Kriging is, in fact, a set of different methods~~such as~~, for example, ordinary kriging (OK) or Universal Kriging (UK). The main difference between OK and UK is that the former assumes the presence of a spatial constant mean, ~~while~~ whereas the latter assumes that the spatial mean is a function that can depend on geographical factors (Cressie, 1993). The ~~last assumption is preferrable in Climatology , at~~ latter assumption is preferable in Climatology because climate variables commonly ~~varies depending~~ depend on geographical factors, such as latitude, longitude, or elevation (Aalto et al., 2013). In this paper, climate grids for each ~~varieable~~ variable were generated individually ~~by~~ using UK to predict a value at each grid point ~~of interest~~ for each time step.

~~One interpolation process was executed for each variable and for each time step . Previous to the interpolation , a semivariogram~~ As a first step in the interpolation process, a semi-variogram model was generated~~, being~~. This model was unique for each time step and each climatic variable. This process was implemented using the gstat package in R (Pebesma, 2004; Gräler et al., 2016).

Using ~~universal kriging~~ UK a variance of the prediction was also obtained, and this value was used ~~as an estimator of~~ to estimate the uncertainty. One of the advantages of using the gstat package is that an uncertainty associated with observed data can be provided. ~~At this point, we~~ We decided to use the quantification of the uncertainty obtained from the gap filling process, which is the previous estimation process.

3.4 $\mathrm{ET_o}$ calculation

Predicted values of distinct climate variables were used to calculate $\mathrm{ET_o}$ ~~by~~ using the FAO-PM equation (Allen et al., 1998).

$$\mathrm{ET_o} = \frac{0.408\,\Delta\,(R_n - G) + \gamma\,(\frac{900}{T+273})\,U_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,U_2)}, \tag{1}$$

where R_n is the net radiation at the crop surface ($MJ\ m^{-2} day^{-1}$), G is the soil heat flux density ($MJ\ m^{-2} day^{-1}$), T is the mean air temperature at 2 m (°C), U_2 is the wind speed at 2 m (ms^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), $e_s - e_a$ is the saturation vapor pressure deficit (kPa), Δ is the slope of the vapor pressure curve ($kPa\ °C^{-1}$), and γ is the psychrometric constant ($kPa\ °C^{-1}$). The value 0.408 is was used to convert from $MJ\ m^{-2} day^{-1}$ units to $kg\ m^{-2} day^{-1}$ (alternatively: $mm\ day^{-1}$).

Following Following the recommendations of Allen et al. (1998), we fixed G to 0, as we estimated ET_o for over a time period lower of fewer than 10 days.

The main advantage advantages of this equation is are that it is physically-based and it physically based and accounts for both the radiative and aerodynamic components of evapotranspiration, being the former . The former is related to the available energy energy available for evaporation and the latter is related to the capacity of the air to store the vapor from evapotranspiration (Azorin-Molina et al., 2015). While Although the radiative component is was strongly related to the solar radiation , hence presenting and presented a high seasonality in the study region due to its latitude, the aerodynamic component is was more variable throughout the yearas it is , as it was influenced by the vapor pressure deficit but also by as well as the wind speed. If Splitting Eq. (1) is splitted in the summation into the sum of its two parts , one part could be interpreted as yielded the radiative component (ET_{oRa}) and the other part as the aerodynamic component (ET_{oAe}).

$$
\begin{aligned}
ET_{oRa} &= \frac{0.408\,\Delta\,(R_n - G)}{\Delta + \gamma\,(1 + 0.34\,U_2)} \\
ET_{oAe} &= \frac{\gamma\,(\frac{900}{T+273})\,U_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + 0.34\,U_2)}
\end{aligned}
\qquad (2)
$$

This dataset contains data contained data describing each of the two componentsET_{oRa}, ET_{oAe} and of the final value of , ET_{oRa} and ET_{oAe}, as well as their summation, which is ET_o.

3.5 ET_o uncertainty estimation

A variability and trend analysis benefitted from the availability of the two components. For example, wind stilling and solar brightening have opposite effects in ET_ouncertaitny estimation has two main steps: i) uncertainty estimation of climatic grids and ii) uncertainty propagation from climatic grids to , but studying the two components separately facilitates the study of the impacts of each one on ET_o.

3.5 ET_o uncertainty estimation

Due to the complexity of the process of uncertainty estimation of process involved in estimating the uncertainty in ET_o, the uncertainty in this first version of the dataset the uncertainty estimation is only provided was estimated only for the final value of ET_o , but and not for its two components (ET_{oRa} and ET_{oAe}).

3.5.1 Uncertainty estimation of in the climatic grids

~~When climate grids are generated many uncertainty~~ Climate grid generation involves many sources of data ~~exist (uncertainty~~uncertainty, including uncertainty related to the observation, ~~uncertainty related to~~ interpolation process, ~~...)~~ and other sources (Haylock et al., 2008). In this paper~~we assumed~~ , we assumed that uncertainty was only related to the estimation processes, i.e., gap filling and interpolation. Moreover, we considered the uncertainty of each climatic grid at each time step ~~is~~ to be equal to the uncertainty after the interpolation process.

Uncertainty estimation ~~of~~ over the gap filling process was based on the number of weather observations used to estimate the missing data and the covariance between these data points. Less covariance between data was associated with more uncertainty. ~~The less covariance between the data , the more uncertaintywe considered.~~

~~In the interpolation process it was assumed that~~ The interpolation process assumed that any uncertainty was equal to the variance of the prediction, i.e., the variance of the kriging. ~~To propagate the uncertainty estimated in~~ The uncertainty estimated over the gap filling process was propagated to the interpolation process ~~,~~ using the gstat package in R~~was used, as it is possible to provide the uncertainty~~ , as the uncertainties related to the observational data ~~that will be~~ used in the interpolation process was available.

3.5.2 Uncertainty propagation

The uncertainty propagation ~~allow~~ allowed us to obtain the uncertainty ~~of predicted~~ associated with the predicted values of ET_o (R) ~~by~~ using the posterior variance of the climate grids and the Jacobian of the FAO-PM.

$$R = J_{ETo} Q (J_{ETo})^T, \tag{3}$$

where $J_{_{ETo}}$ is the Jacobian of ET_o, and Q is the covariance matrix of ~~variables, in which we considered (for simplicity) independence between variables, reaching to~~ the variables. For simplicity, the variables were considered to be independent, yielding a diagonal matrix with ~~only~~ variance positions distinct ~~to~~ from 0.

The Jacobian ~~has~~ assumed the following form ~~, and it~~ and was analytically derived.

$$J_{_{ETo}} = \begin{bmatrix} \frac{dET_o}{dT_{max}} & \frac{dET_o}{dT_{min}} & \frac{dET_o}{dTd} & \frac{dET_o}{dW} & \frac{dET_o}{dSD}. \end{bmatrix}$$

~~and the covariance matrix as.~~ The covariance matrix could be expressed as

$$\mathbf{Q} = \begin{bmatrix} \sigma^2_{T_{max}} & 0 & 0 & 0 & 0 \\ 0 & \sigma^2_{T_{min}} & 0 & 0 & 0 \\ 0 & 0 & \sigma^2_{T_d} & 0 & 0 \\ 0 & 0 & 0 & \sigma^2_{W} & 0 \\ 0 & 0 & 0 & 0 & \sigma^2_{SD}, \end{bmatrix}$$

where σ^2 is the variance of the kriging of each of the climatic variables. In fact, as Q is a diagonal matrix, the R calculation ~~can~~ could be rewritten as:

$$R = \left(\frac{\partial ET_o}{\partial T_{max}}\right)^2 * \sigma^2_{T_{max}} + \left(\frac{\partial ET_o}{\partial T_{min}}\right)^2 * \sigma^2_{T_{min}} + \left(\frac{\partial ET_o}{\partial T_d}\right)^2 * \sigma^2_{T_d} + \left(\frac{\partial ET_o}{\partial W}\right)^2 * \sigma^2_{W} + \left(\frac{\partial ET_o}{\partial SD}\right)^2 * \sigma^2_{SD}. \quad (4)$$

3.6 Using ~~2010-2014~~ 2010−2014 data to validate the air humidity and wind speed grids

~~In~~ During the last part of the period (2010−2014), a high number of AWS were installed~~, and available data for the period 2010-2014 show a sharp increase for~~. A sharp increase in the available RH and W ~~when~~ data was observed during this period, compared with the ~~available weather stations~~ data available from weather stations used to generate the original database (Table ~~??).~~

~~As the climatic grid have a spatial resolution of 1.1 a direct comparison of the estimation of climatic grid against the observed value was implemented. For the 2010-2014 period this methodology was followed to evaluate the quality of~~ 1). The values of these observations and the values of the climate grids were compared directly to obtain the relative humidity and wind speed ~~estimations of the climatic grid.~~ over the 2010−2014 period using the new stations as an independent dataset.

4 Validation

4.1 Gap filling

~~As the number of original data changes over time, the number of filled data also shows a temporal evolution. Figure 5 represents this temporal evolution, with a higher number of filled data during the first years of the period , with an important decline throughout the time. Nevertheless, for maximum and minimum temperature, the number of filled data increased again during the last years because a slow decline in the number of observation and the disappearance of some of the weather stations with longer records. Wind speed is the variable showing a lower percentage of filled data. Due to the high variability, both spatial and temporal, and the low number of observations available of this variable, it was difficult to obtain highly correlated time series to fill the gaps.~~

~~To verify the~~ The performance of the gap filling ~~a comparison between~~ step was verified by comparing the original data and estimated data~~was developed. Evidently~~. Obviously, this comparison was only possible for periods having original data.

~~In Table 2 some statistics of the process are provided~~Table 2 lists certain statistics associated with the verification process. In general, ~~the adjustment in terms~~ satisfactory values of R^2 ~~is quite good~~were achieved, with values higher than 0.9 for all variables except for the wind speed, which ~~shows an adjustment~~ showed an R^2 of only 0.53. Evaluation of ~~ME and PBIAS show~~ Mean Error (ME) and Percent Bias (PBIAS) showed no bias for the maximum and minimum temperature, a small negative bias for the dewpoint temperature (ME of -0.01 ~~of ME and -0.15 of PBIAS) and for~~ and PBIAS of -0.15) and the sunshine duration (ME of -0.01 ~~of ME and -0.23 of PBIAS~~and PBIAS of -0.23), and a positive bias for the wind speed (ME of 0.08 ~~of ME and 0.64 of PBIAS). Ratio of~~ and PBIAS of 0.64). The ratio of the mean values and ~~ratio of standard deviation show~~

the ratio of the standard deviation showed values close to 1 for all variables. ~~Wind speed shows a ratio of standard deviation~~ The wind speed displayed a standard deviation ratio of 1.05, meaning that the temporal variability of the gap filling data ~~is~~ was slightly higher than the temporal variability of the original data.

~~In Figure 4~~ Figure 4 evaluates the possible existence of temporal differences in the performance of the gap filling process ~~was evaluated by~~ using decadal values of R^2. In general, all ~~the analyzed periods show a similar performance~~analyzed periods showed similar performances. For wind speed, ~~it seems that~~ the most recent ~~period show a small better performance than the rest~~ decade showed slightly higher R^2 values than the first decades of the period.

As the number of original data changed over time, the number of filled data also showed a temporal evolution. Figure 5 indicates this temporal evolution, with a higher number of filled data during the first years of the period ~~, but being for all the periods the variable showing the lower performance~~and a large decline over time. The number of filled data corresponding to the maximum and minimum temperature increased again during the last several years because of a slow decline in the number of observations and the disappearance of some of the weather stations with longer records.

The wind speed provided the lowest amount of filled data. It was difficult to obtain highly correlated time series to fill in the gaps, which had two major effects in the process: i) the probability of obtaining a reference time series from the neighbors was decreased; and ii) the reconstruction was poor when the reference time series could be obtained. The low correlation of the wind speed time series was a consequence of i) the high spatial and temporal variability of this variable and ii) the low number of observations available.

4.2 Homogenization

~~Statistics~~ The percentage of data affected by ~~homogenization process show a percentage higher than~~ the homogenization process exceeded 10 % for all variables except for the wind speed (Table 3). For all ~~the~~ variables, the percentage of homogenized ~~is higher for~~ data was higher for the filled data than for the original data, ~~showing~~ indicating the importance of implementing ~~the~~ a homogenization process after ~~the~~ gap filling. Two factors could explain this effect: i) ~~as~~ because the original data was not homogenized ~~previous~~ prior to the gap filling, the ~~existence~~ presence of inhomogeneities in ~~original data propagates to homogenized data~~ the original data propagated to the homogenized data, and ii) ~~the possible introduction of inhomogeneities~~ inhomogeneities may have been introduced by the gap filling procedure.

The ~~homogenization process affected specially the first decades of the study period, showing for all the variables a clear decline through time reaching values close to 0 during last years~~ temporal evolution of the quantity of data detected as inhomogeneous was analyzed (Figure 5), revealing a temporal trend with maximum values at the start of the study period ~~(Figure 5). This result is related with the fact that in this homogenization process, the~~ and minimum values at the end. The most likely explanation for this observation is the use of more recent conditions ~~were considered the standard ones~~as the standard conditions.

~~A possible~~ Another effect of this ~~consideration~~ assumption is the propagation of the current conditions to the past, which was evaluated by comparing the spatial mean values of ~~homogenized and previous to homogenization~~ the homogenized and prior-to-homogenization time series. ~~The Figure 6 shows the presence of~~ Figure 6 highlights this effect in the implemented homogenization process~~, as variables affected by a well-known positive trend, ~~. The maximum and minimum temperature~~(del Río et al., 2012; Gonzalez-Hidalgo et al., 2016), show a positive bias in homogenized data during ~~, which displayed a positive trend in Spain over the study period (del Río et al., 2012; Gonzalez-Hidalgo et al., 2016), suggested that higher values occurred in the present than in the past. A positive bias was observed in the homogenized data over the first decades~~, and~~ . Unlike the maximum and minimum temperature, the wind speed, ~~variable affected by~~ which displayed a negative trend (Azorin-Molina et al., 2014), ~~shows~~ was affected by a negative bias during the first decades of the study period.

~~To investigate the effect of homogenization process in~~ The effect of the homogenization process on ET$_o$ ~~,~~ was evaluated using a similar procedure~~was followed~~ , which involved calculating the mean regional values of ET$_o$ before and after ~~the~~ homogenization of the climatic variables. These regional values were obtained by calculating first a mean regional value of ~~climatic variables and then~~ the climatic variables, followed by calculating the ET$_o$ ~~by using the Penman-Monteith~~ using the Penman−Monteith equation.

No important differences were detected ~~when~~ in a comparison of the two time series of ET$_o$ ~~were compared~~ (Fig. 7). This result is relevant, as it shows that the ~~non-desired~~ undesirable detrending introduced by the homogenization process ~~have no effects for~~ did not affect the spatial mean values of ET$_o$.

4.3 Interpolation validation

~~To validate the interpolation process ,~~ The interpolation process was validated by executing a leave-one-out-cross-validation (LOO-CV) process~~was executed~~ , and validation statistics were calculated to evaluate the ~~perfomance~~ performance of the interpolation predicting both the temporal variability and the spatial variability. ~~A~~ The LOO-CV process ~~consists in the repetition of~~ consisted of repeating the interpolation process ~~n-times (being n~~ n times (n being the number of observations available) using each time n-1 observations and using the predicted value at ~~non used~~ the unused observatory as a way to evaluate the quality of the interpolation.

The temporal variability was evaluated by calculating the temporal statistics individually for each observatory and then computing the mean of all observatories. ~~However, the~~ The spatial variability was evaluated by calculating the statistics at each time step using information ~~of~~ comprising all observatories and then computing the mean of all time steps. The problem with the LOO-CV method is that validation ~~can~~ could only be estimated at ~~places were observations used in~~ a given point if observations used during the interpolation process ~~exist~~existed.

Another option ~~to validate~~ for validating the interpolation process ~~consists in the comparison of non-used observational data for the 2010-2014~~ consisted of comparing the unused observational data over the 2010−2014 period (when a high number of wind speed and relative humidity observations ~~exist~~existed) against the interpolated values.

4.3.1 Spatial and temporal validation using LOO-CV

~~Statistics referring to the ability of~~ The ability of the interpolation process to predict the spatial and the temporal variability of ~~climatic grids appears~~ the climatic grids is summarized in Table 4. In general, temporal validation ~~shows~~ showed better statistics than spatial validation. In terms of R^2 all the All variables, except for the wind speed, show showed R^2 values greater than 0.9 for the temporal validation and close to 0.8 for the spatial validation.

According to ME and PBIAS, the only variable showing that indicated the presence of a bias , for both validations , is bias in both validations was the wind speed, with a PBIAS reaching which yielded a PBIAS of 12.31 for the temporal validation.

A temporal analysis of the R^2 of values obtained from the spatial validation (Fig. 8) show some differences between decades of of the maximum and minimum temperature , reaching the recent decadesgreater values of R^2 (Fig. 8) showed slightly better statistics (i. e., closer to one) in recent decades. Nevertheless, the most relevant detected effect is was the presence of seasonality in the R^2 of the dewpoint temperature, showing which indicated lower values during summer than in during winter. A higher spatial variability of in the air humidity in summer months due to the contrast between the high air humidity at in the coastal areas and the low air humidity at continental areas could be the reason of the presence of in the continental areas may be the source of the lower values during summer.

4.3.2 2010-2014 2010−2014 validation

When 2010-2014 Validating the interpolation performance over the 2010−2014 independent time series of the wind speed and relative humidity was used to validate the performance of interpolation, the revealed that the two most relevant detected problems are an were the overestimation of the wind speed during winter months at in the northeastern region of the Iberian Peninsula and an overestimation of dewpoint temperature at the overestimation of the dewpoint temperature in the inner region of the Iberian Peninsula during the summer months at the same time that an underestimation was detected at in the maritime region. These two effects can be are visualized in Figure 9, in which the mean error which shows the mean errors for January and for July for the two variableswere represented.

4.3.3 Uncertainty validation

Data of 2010-2014 from the 2010−2014 period could also be used to validate the uncertainty estimation of the climatic grids. First, the Mean Absolute Error (MAE) was calculated by comparing the independent weather stations station data against the climatic grid data. Then, the obtained values of the MAE were compared against the uncertainty values of the climatic grids.

The mean spatial values of MAE and the MAE and the uncertainty are represented in the Figure 10. In general, the uncertainty of climatic grids is the climatic grids was well estimated, specially for especially for the wind speed and for sunshine duration, variables showing as these variables showed similar values of the MAE and uncertainty. The rest of the variablesother variables, (T_{max}, T_{min}, and T_d)show , showed slightly higher values of uncertainty than the MAE values but always with similar temporal oscillations.

5 Discussion and conclusions

We proposed a methodology to obtain a 1961-2014 method for obtaining a 1961−2014 ET_o climate grid in across Spain based on Penman-Monteith equation. While the Penman−Monteith equation. Whereas previous studies of ET_o and AED climatology

~~exist in Spain~~ in Spain have been developed (Azorin-Molina et al., 2015; Sanchez-Lorenzo et al., 2014; Vicente-Serrano et al., 2014), this is the first suitable ET_o database for use in climate studies covering ~~all the~~ the full study area with a high spatial resolution and ~~for~~ over a long time period. ~~High spatial resolution climate data sets of ET_o are not usually available, specially if they are developed using Penman-Monteith equation. During last years, ET_o climate grid at 1 of spatial resolution was presented in Great Britain Robinson et al. (2017). Haslinger and Bartsch (2016) presented also a climate grid at 1 of spatial resolution for Austria, but based on the Hargreaves equation.~~

As the number of weather stations collecting all variables required to calculate ET_o ~~is~~ was very low, the proposed methodology ~~takes~~ took advantage of two estimation processes~~,~~ : gap filling and spatial interpolation. The ~~performance of each one of these two steps was carefully studied trying to detect~~ performances of the processes were carefully studied to detect the possible negative impacts ~~in~~ on the generation of the ET_o database. In general, no relevant problems were detected for most of the climatic variables~~but for wind speed , which is the variable showing the~~ . The wind speed displayed the worst performance in each of the estimation processes ~~,~~ due to its high spatial and temporal variability.

The PM-IC strategy, which ~~is based in first interpolate the climatic variables and then calculate~~ consisted of interpolating climatic variables prior to calculating ET_o, was previously used ~~in~~ to model other regions (Mardikis et al., 2005; McVicar et al., 2007) and was determined to be the best method ~~to estimate~~ for estimating ET_o in ~~scenarios~~ the event of missing data in Spain (Tomas-Burguera et al., 2017). Another strategy, known as PM-CI, ~~which is based in first calculate~~ calculated ET_o ~~and then interpolate the obtained values, could also be used~~prior to interpolation and was also appropriate for use. The main advantage of the PM-CI ~~against~~ over PM-IC ~~is~~ strategy was that only one interpolation ~~is required, but the main disadvantage is that a lot of data is misused~~was required. The main disadvantage was that much of the available data was not used. In the case of Spain, the use of the PM-CI ~~would restrict~~ strategy would have restricted the calculation of ET_o to nearly 50 weather stations, which is the number of weather stations used in previous studies (Vicente-Serrano et al., 2014). On the other hand, the use of the PM-IC ~~allow~~ strategy allowed the use of more data, ~~specially~~ especially of temperature data, ~~reaching~~ from more than 1000 weather stations. ~~Considering that according to (Mendicino and Senatore, 2013; Samani, 2000),~~ As 80 % of the ET_o variability ~~is related with~~ was related to the variability in temperature and radiation ~~, this is relevant~~(Mendicino and Senatore, 2013; Samani, 2000) , using as many temperature observations as possible was important for ensuring the quality of the obtained results.

A comparison against an independent subset of climatic data ~~for the 2010-2014~~ collected over the 2010−2014 period showed the presence of a positive bias ~~for wind speed in winter in~~ in the wind speed during winter over the northeastern region of the Iberian Peninsula. ~~This overestimation of~~ The overestimation of the wind speed in this region ~~can~~ could be explained by the fact that a low number of observations ~~are~~ were used in that region, and most of the ~~used observations are~~ observations used were located in places affected by tramontana events. Fortunately, the higher bias ~~is~~ was detected in winter, when ET_o values ~~are~~ were lower and the importance of this variable for some uses (e.g. irrigation schedule) ~~is~~ was also lower. Two factors ~~seem~~ appeared to be relevant for wind speed estimation problems: i) the high spatial variability of ~~wind speed Luo et al. (2008)~~ the wind speed (Luo et al., 2008) and ii) the fact that ~~wind speed is~~ the wind speed was not normally distributed~~, while both~~ . Both the gap filling and interpolation processes ~~perform better with normally adjusted~~ tend to perform better when applied to normally distributed data.

These comparisons also detected some problems related ~~with dewpoint temperature predicted values in summer. Inverse bias are detected between~~ to the dewpoint temperature values predicted during summer. An inverse bias was detected between the inland and maritime regions. ~~In~~ During the summer months, the humidity contrast between the inland and maritime regions ~~is~~ was high in the Iberian Peninsula, as maritime regions ~~present~~ experienced a higher humidity due to the ~~contribution of~~ contributions of the sea breezes. The detected overestimation of ~~dewpoint temperature in summer in continental regions leads~~ the dewpoint temperature during the summer across the continental regions led to an underestimation of the vapor pressure deficit and also to an underestimation of ET_o. ~~Because of this effect , it is probable that some underestimation of~~ This effect suggested that the ET_o values ~~is produced in~~ were underestimated to some degree across the continental regions of Spain, ~~while~~ whereas the maritime regions ~~could be~~ may have been affected by an overestimation.

The performance of the homogenization process was ~~also testeddetecting~~ tested, and changes in the spatial mean values of the first decades were detected in some of the climatic variables. ~~While~~ Although the maximum and minimum ~~temperature are~~ temperatures were affected by an increase in their spatial mean, ~~wind speed is~~ the wind speed was affected by a decrease in the spatial mean. Due to counteracting effects, the ET_o mean spatial value ~~is~~ was not affected by this problem.

Considering that each estimation process ~~is affected by an uncertainty, a methodology to obtain the uncertainty of~~ was affected by uncertainty, the uncertainty in ET_o after applying the two estimation processes was ~~also implemented~~obtained. For simplicity, ~~independence between climatic variables was considered~~ the climatic variables were considered to be independent in the final step of the uncertainty estimation, which ~~is~~ involved the propagation of the uncertainty of each climatic variable through the ~~Penman-Monteith~~ Penman–Monteith equation.

~~While~~ Haylock et al. (2008) pointed out that the variance of the kriging, which in this paper was used ~~as~~ to estimate the uncertainty of each climatic grid, is not a true estimation of the uncertainty~~, the~~ ; however, an evaluation of the ~~estimation of the uncertainty for~~ uncertainty estimations of each variable showed a good ~~accordance between~~ agreement between the MAE values and the estimated uncertainty values. Unfortunately, the uncertainty of ET_o ~~cannot be verified as~~ could not be verified because an independent subset of observatories ~~collecting all variables~~ that collected all variables was required to calculate ET_o but was not available.

This dataset was ~~firstly developed~~ first developed as an input to generate, in combination with ~~precipitaation data, drought climate grids for~~ the precipitation data, grids of drought indices over the study area (Vicente-Serrano et al., 2017)~~, but finally this~~ . Due to the relevance of ET_o ~~climate grid is made available due to the~~ and the high number of possible uses of ~~this data~~these data, the ET_o climate grid is now being made available to other research groups. As with drought studies, in some cases, the interest ~~is~~ was focused on the combined ~~anaysis~~ analysis of ET_o and the precipitation data.

This could be the case ~~of hydrological studies ,~~ for hydrological studies in which the AED data ~~is relevant to~~ can explain some of the most important processes taking place in a catchment. ~~Better estimations of ET_o should also lead to obtain~~ The combined analysis may provide better estimations of water balance and aridity indices. ~~As the presented dataset covers~~ The present dataset covered a long period ~~,~~ of time, thereby enabling studies of the temporal evolution of these indices~~could be studied~~.

Irrigated agriculture is another interested sector in these studiessector interested in these data, as the water balance is important both for irrigation planning and also for irrigation schedule. Due to the for irrigation scheduling. The development of modern irrigation systems , irrigation is a relevant economic activity at some regions in has rendered irrigation a significant economic activity in some regions of Spain, such as the Ebro basin (Vidal-Macua et al., 2018), which reinforces reinforcing the importance of the presented dataset in the region. But not only the irrgated agriculture is interested in the study dataset in that region. More accurate models of ET$_o$. In generalis also useful for rainfed agriculture. Hence, the whole agricultural sector is interested in a better knowledge of ET$_o$ and/or ET$_c$ (obtained multiplying ET$_o$ by a crop coefficient - Kc) could benefit from this dataset.

For climatology, this datasetcould also This dataset could be interpreted as the first available AED climate grid in across Spain, which is quite relevant to develop the development of spatial and temporal studies to climatology studies that could confirm the previously detected positive trends of this variable in certain variables across the study area. This database could also be used to study the ability of distinct climate models (regional for regional (or global) to resolve the energy and water balance for an observed period, which is relevant for climate model assessment in the context of climate change studies, as a comparison of analysis and /or historical experiments against observational data is necessary whenever climate models are evaluated for projected scenarios. .

Calculating ET$_o$ using PM assumed a well-watered reference surface, which can differ significantly from the actual conditions present in a semiarid region, as is the case across most of our study area. A scarcity of soil moisture can decrease the air humidity and increase the air temperature compared with well-watered conditions due to the effects of the land−atmosphere continuum. Both changes, which especially affect the aerodynamic component of ET$_o$, may have a noticeable effect on ET$_o$, meaning that an overestimation can occur under semiarid conditions (Bouchet, 1963; Allen et al., 1998). Such an overestimation would be higher during the warm season when these conditions prevail. The possible overestimation due to the use of PM in a semiarid environment should be considered by potential users of this database.

6 Data availability

The four files generated in this dataset (weekly values of reference evapotranspiration, uncertainty estimation of the weekly values of reference evapotranspiration, aerodynamic component values of the weekly reference evapotranspiration, and the radiative component values of the weekly reference evapotranspiration) can be accessed and downloaded via two different sources.

>From Digital CSIC, which is a long-term repository managed by the Spanish Research Council (CSIC), users can download the files in netCDF format through http://dx.doi.org/10.20350/digitalCSIC/8615 (Tomas-Burguera et al., 2019)

The data can also be accessed at the web page http://speto.csic.es, which is a map visualization tool. Users can visualize the data generated at different time steps, download the complete netcdf files, or download a complete time series for a chosen point as a comma-separated value (csv) file. As the spatial resolution of the data is 1.1 km over continental Spain and the

Balearic Islands, the total number of grid points is slightly higher than 400,000. The weekly temporal resolution yielded 2592 different weekly maps for each of the four available files.

Author contributions. Miquel Tomas-Burguera, in collaboration with Sergio M. Vicente-Serrano and Santiago Beguería, conceived the research. Miquel Tomas-Burguera developed the quality control algorithms applied to the data, contributed to the computation of ET_o, developed the data validation algorithms, and prepared the manuscript. Santiago Beguería developed methods for data reconstruction and climate mapping. Fergus Reig and Borja Latorre processed the data and developed the web portal infrastructure.

Competing interests. The authors declare no conflict of interest.

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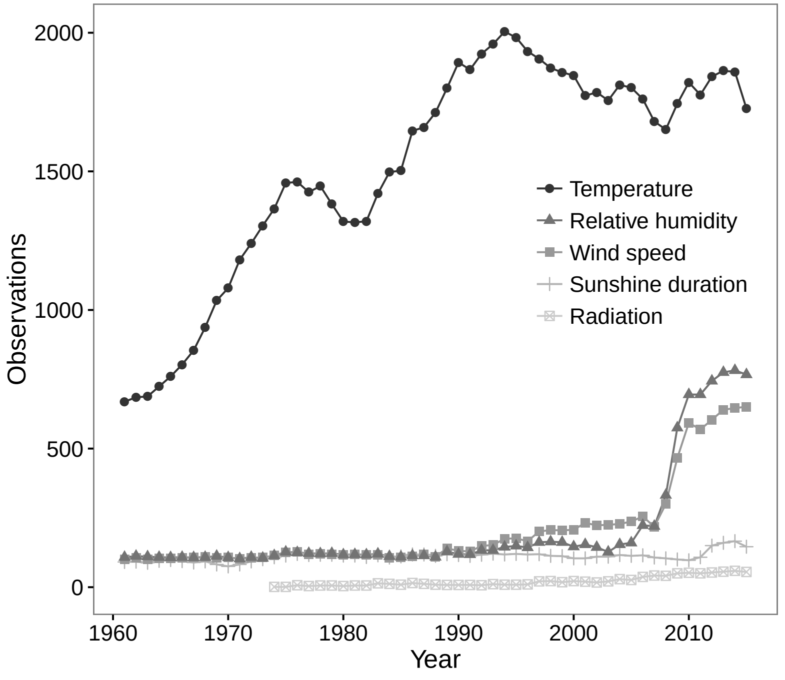

Figure 1. Temporal evolution of the data availability.

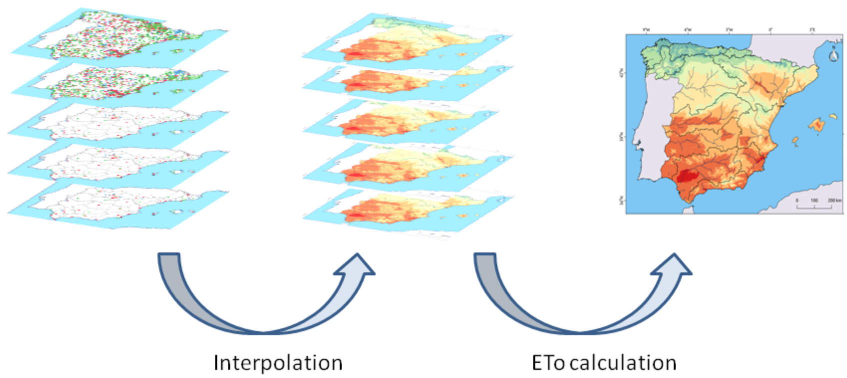

Figure 2. Main steps involved in generating the ~~generation of~~ ET_o database. First, we ~~interpolate~~ interpolated each climatic variable~~and~~ , then ~~we calculate~~ calculated ET_o.

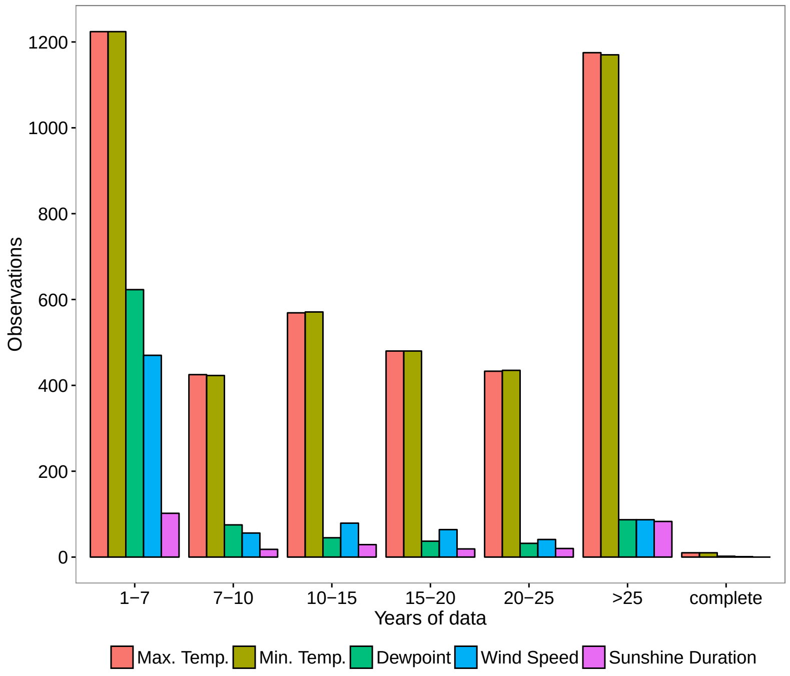

Figure 3. Number of available observations grouped by ~~variables~~ variable and by years of data available.

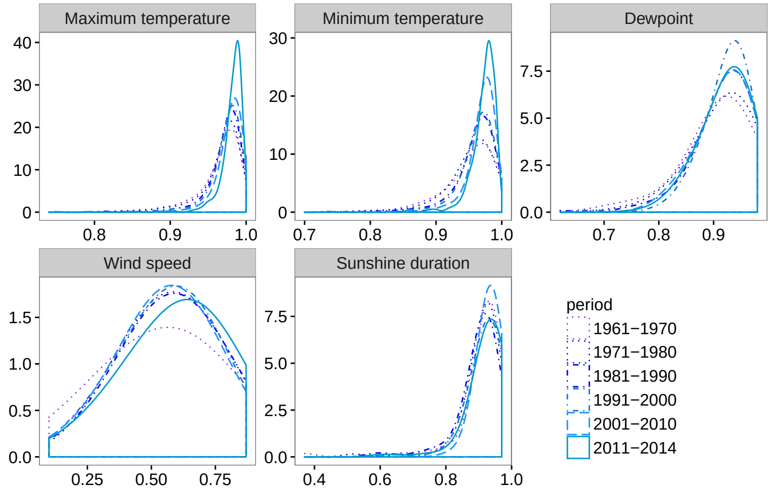

Figure 4. Kernel density of the gap filling R^2, grouped by decadal periods.

Figure 5. Temporal evolution of the number of filled data for the different climatic variables. The temporal evolution of the homogenized data is also shown.

~~Kernel density of gap filling R^2 grouped by decadal periods.~~

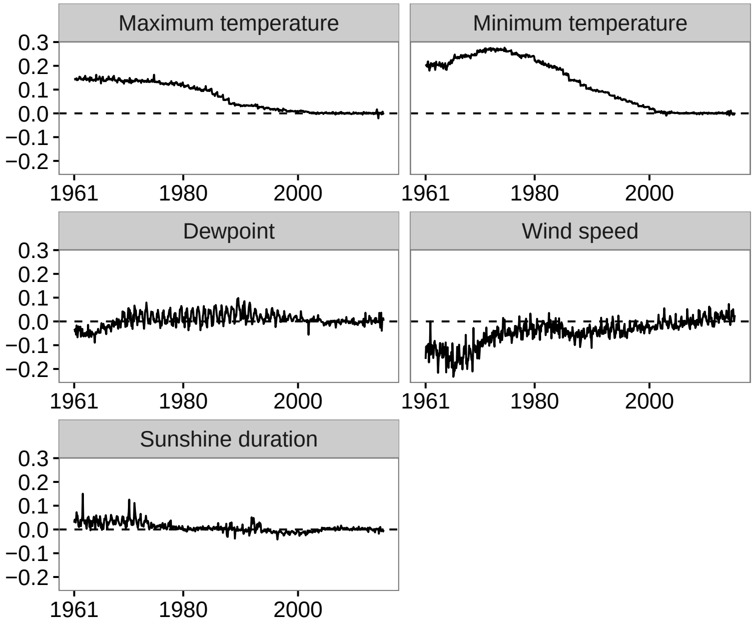

Figure 6. Temporal evolution of the differences between the mean regional values before and after ~~the~~ homogenization.

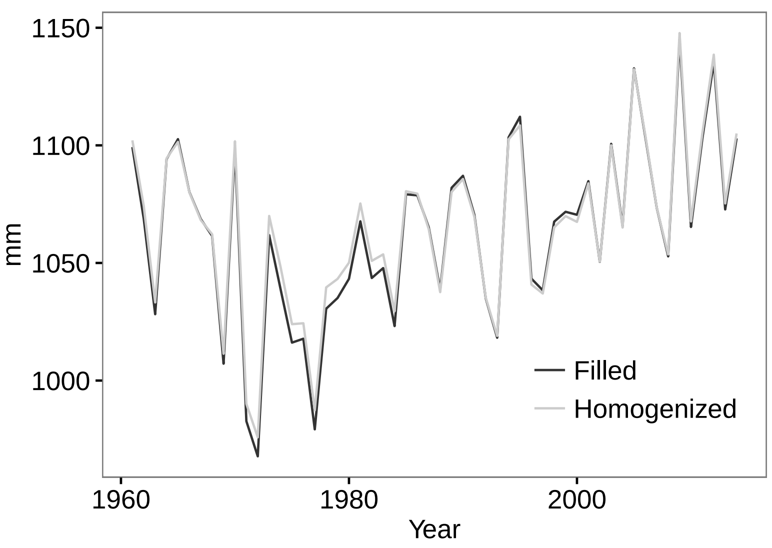

Figure 7. Temporal evolution of the mean regional values of ET_o ~~between mean regional values~~ before (Filled) and after (Homogenized) ~~the~~ homogenization.

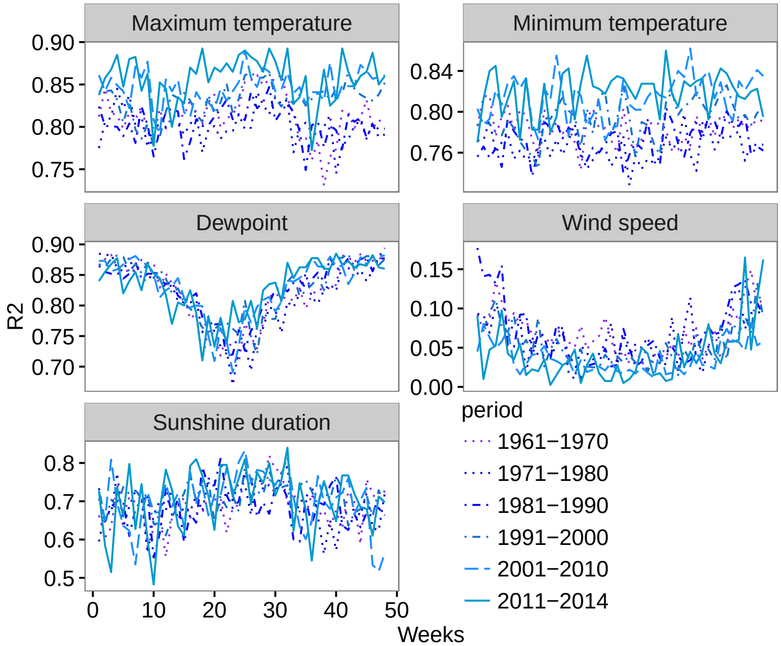

Figure 8. Spatial validation of the interpolation in terms of R^2, grouped by decadal periods.

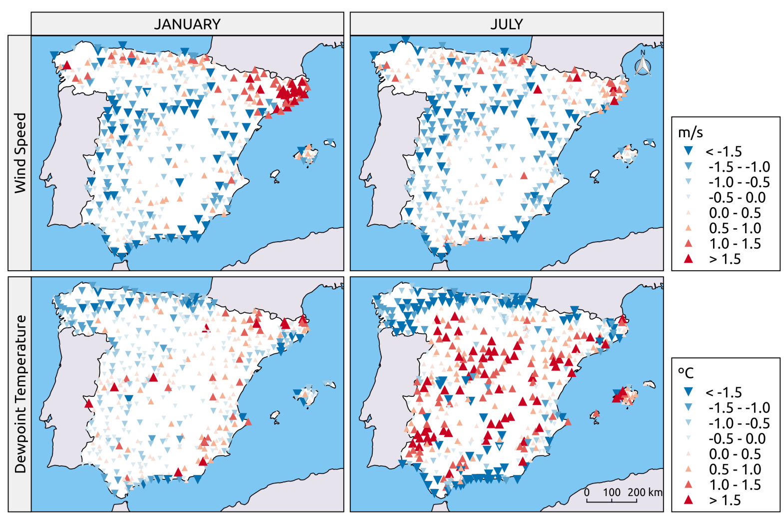

Figure 9. Spatial validation of the dewpoint and wind speed climatic grids ~~by~~ using a subset of independent observations ~~for~~ over the ~~2010-2014~~ 2010–2014 period, in terms of the Mean Error.

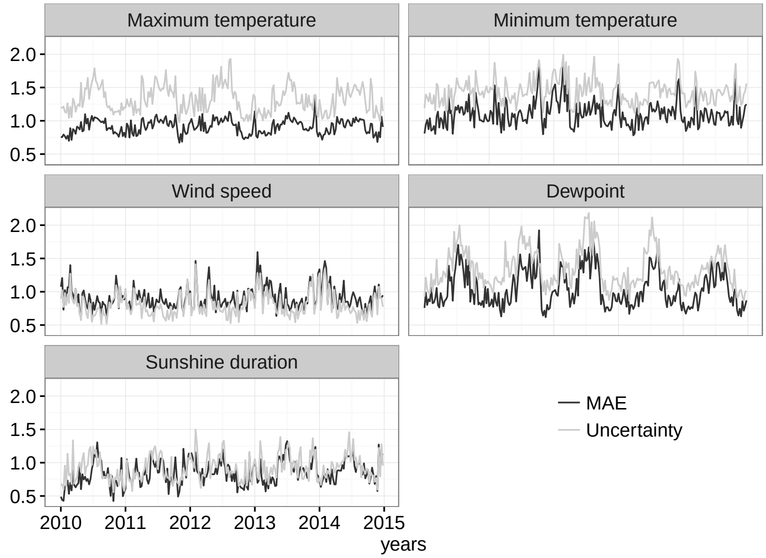

Figure 10. Temporal evolution of the MAE and uncertainty of the interpolation at a subset of independent observations ~~for~~ over the ~~2010-2014~~ 2010–2014 period.

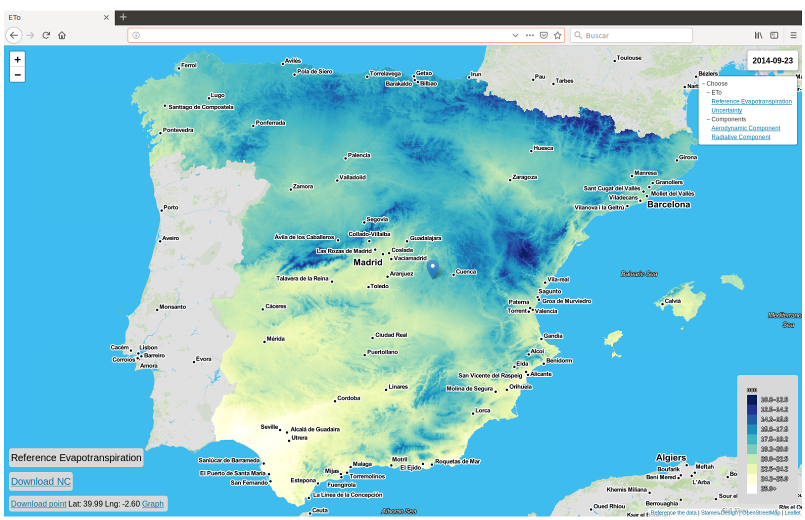

Figure 11. Example of the data visualitzation ~~in~~ tool available at the web page http://speto.csic.es.

Table 1. Number of weather stations per variable.

	Available		
Variable	~~Available~~ All period	2010-2014	Selected
Maximum temperature	4306	1186	1246
Minimum temperature	4303	1195	1217
Relative humidity	899	648	164
Wind speed	797	583	67
Sunshine duration	271	80	92

~~Comparison of the number of weather stations used to generate the climate dataset and the number of observations available during 2010-2014 period. Variable Original database 2010-2014 Maximum temperature 1246 1186 Minimum temperature 1217 1195 Relative humidity 164 648Wind speed 67 583Sunshine duration 92 80~~

Table 2. Gap filling ~~performance~~statistics. Values for the following validation statistics are provided: i) Mean Absolute Error (MAE), ii) Coefficient of determination R^2, iii) Mean Error (ME), iv) Percent Bias (PBIAS), v) ratio of Mean values (rM), and vi) ratio of Standard Deviation (rSD).

Variable	MAE	R^2	ME	PBIAS	rM	rSD
Maximum temperature (℃)	0.92	0.97	0.00	0.00	0.99	1.00
Minimum temperature (℃)	0.83	0.95	0.00	0.00	0.99	1.00
Dewpoint temperature (℃)	1.04	0.91	-0.01	-0.15	0.99	1.00
Sunshine duration (h)	0.63	0.91	-0.01	-0.23	0.99	1.00
Wind speed (kmh^{-1})	2.32	0.53	0.08	0.64	1.00	1.05

Table 3. Percentage of data affected by inhomogeneities.

	Weekly data	Original data	Filled data
Maximum temperature (℃)	~~14,8~~ 14.8	~~13,7~~ 13.7	~~17~~ 17.0
Minimum temperature (℃)	~~16,7~~ 16.7	~~14,8~~ 14.8	~~20,3~~ 20.3
Dewpoint temperature (℃)	~~14,1~~ 14.1	~~11,2~~ 11.2	~~18,2~~ 18.2
Wind speed (ms^{-1})	~~3,1~~ 3.1	~~1,8~~ 1.8	~~8,9~~ 8.9
Sunshine duration (h)	~~10,1~~ 10.1	~~7,2~~ 7.2	~~16,8~~ 16.8

Table 4. Spatial and temporal validation of the interpolation process. Values for the following validation statistics are provided: i) Mean Absolute Error (MAE), ii) Coefficient of determination R^2, iii) Mean Error (ME), iv) Percent Bias (PBIAS), v) ratio of Mean values (rM), and vi) ratio of Standard Deviation (rSD).

Variable	Validation	MAE	R^2	ME	PBIAS	rM	rSD
Maximum temperature (℃)	Temporal	1.02	0.98	-0.02	0.00	0.99	0.99
	Spatial	1.02	0.82	-0.02	0.00	0.99	0.92
Minimum temperature (℃)	Temporal	1.11	0.97	0.03	0.01	1.00	0.98
	Spatial	1.11	0.78	0.04	0.00	1.00	0.89
Dewpoint temperature (℃)	Temporal	1.01	0.95	0.05	0.02	1.00	0.98
	Spatial	1.02	0.82	0.06	0.00	0.99	0.89
Sunshine duration (h)	Temporal	0.65	0.93	0.00	0.48	1.00	0.97
	Spatial	0.64	0.70	0.00	0.12	1.00	0.85
Wind speed (ms^{-1})	Temporal	0.75	0.54	0.05	12.31	1.12	0.87
	Spatial	0.75	0.06	0.06	2.44	1.02	0.46