AGU PUBLICATIONS

Water Resources Research

RESEARCH ARTICLE

10.1002/2014WR015427

Key Points:

- ETo is sensitive to changes in relative humidity and maximum temperature
- There are spatial gradients in the ETo sensitivity
- Trends in ETo are explained by trends in the aerodynamic component

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Citation:
Vicente-Serrano, S. M., C. Azorin-Molina, A. Sanchez-Lorenzo, J. Revuelto, E. Morán-Tejeda, J. I. López-Moreno, and F. Espejo (2014), Sensitivity of reference evapotranspiration to changes in meteorological parameters in Spain (1961–2011), *Water Resour. Res.*, *50*, 8458–8480, doi:10.1002/2014WR015427.

Received 11 FEB 2014
Accepted 2 OCT 2014
Accepted article online 7 OCT 2014
Published online 4 NOV 2014

Sensitivity of reference evapotranspiration to changes in meteorological parameters in Spain (1961–2011)

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Abstract This study analyzes changes in monthly reference evapotranspiration (ETo) by use of the Penman-Monteith equation and data from 46 meteorological stations in Spain from 1961 to 2011. Over the 51 year study period, there were trends for increasing average ETo during all months and annually at most of the individual meteorological stations. Sensitivity analysis of ETo to changes in meteorological variables was conducted by increasing and decreasing an individual climate variable holding the other variables constant. Sensitivity analysis indicated that relative humidity, wind speed, and maximum temperature had stronger effects on ETo than sunshine duration and minimum temperature. This suggests that aerodynamic component has more importance than radiative component to determine the atmospheric evaporative demand in Spain. The analysis showed a dominant latitudinal spatial gradient in the ETo relative changes across the 46 meteorological observatories, mainly controlled by the increasing available solar energy southward. In addition, the role of different meteorological variables on ETo is influenced by the average climatology at each observatory. ETo trends are mainly explained by the decrease in relative humidity and the increase in maximum temperature since the 1960s, particularly during the summer months. The physical mechanisms that explain ETo sensitivity to the different physical variables and current ETo trends are discussed in detail.

1. Introduction

Reference evapotranspiration (ETo) is an important parameter for characterization of the hydrological cycle, and it is also important for agricultural, environmental, and other studies. Changes in the meteorological components of ETo can affect its values, and this can have climatic and environmental consequences. It is well known that ETo has changed globally in recent decades [*Matsoukas et al*., 2011; *McVicar et al*., 2012]. Moreover, the sign and rate of change in ETo have important regional differences. For example, studies in China [*Zuo et al*., 2012; *Fan and Thomas*, 2013] and Australia [*Donohue et al*., 2010] have indicated negative trends, but studies in India [*Goyal*, 2004; *Darshana et al*., 2013], Iran [*Kousari and Ahani*, 2012; *Tabari et al*., 2012], Florida [*Abtew et al*., 2011], Taiwan [*Yu et al*., 2002], and the Mediterranean region [*Chaouche et al*., 2010; *Espadafor et al*., 2011; *Kitsara et al*., 2013] have indicated positive trends.

The atmospheric evaporative demand is mainly driven by incoming solar radiation, vapor pressure deficit, wind speed, and air temperature. These variables determine two components of ETo: the radiative component (available solar energy) and the aerodynamic component (the drying power of the air, mainly due to wind speed and atmospheric humidity). In general, the ratio of aerodynamic to radiative components is less than 1, and ETo is limited by water vapor transfer in most of the world [*Matsoukas et al*., 2011]. However, the aerodynamic component is important in warm and dry regions [e.g., *Matsoukas et al*., 2011; *McVicar et al*., 2012].

Wang et al. [2012] recently stressed the importance of the aerodynamic component of ETo, and their analysis indicated that this accounted for 86% of the long-term changes in global ETo from 1973 to 2008. However, based on satellite-derived radiation fluxes and reanalysis input for meteorological parameters, *Matsoukas et al*. [2011] showed the opposite pattern: trends in ETo more closely followed trends of energy availability than trends of atmospheric capability for vapor transfer at most locations. Thus, these studies had opposing conclusions regarding the importance of radiative and aerodynamic components in driving changes in ETo. Therefore, further research is needed to resolve this important issue.

Furthermore, the widespread decrease in pan evaporation observed at the global scale [*Peterson et al.*, 1995; *Roderick and Farquhar*, 2004] under a global warming scenario is explained by a complementary hypothesis formulated by *Brutsaert and Parlange* [1998], and supported by *Lawrimore and Peterson* [2000] and *Golubev et al.* [2001]. This hypothesis suggests that soil water content and actual evapotranspiration rates and their influence on the vapor saturation deficit play major roles in ETo variability and changes in water-limited environments. Other studies have provided an alternative hypothesis, in which a decline of incoming solar energy at the global scale drives changes in ETo [*Stanhill and Cohen*, 2001; *Matsoukas et al* 2011; *Roderick and Farquhar*, 2002; *Linacre*, 2004]. Some regional studies support this hypothesis. For example, *Papaioannou et al.* [2011] and *Kitsara et al.* [2013] recently showed a close agreement between changes in ETo and sunshine duration in Greece. The results were similar in Macedonia [*Ambas and Baltas*, 2012] and southwest China [*Fan and Thomas*, 2013]. Finally, a recent hypothesis focused on the aerodynamic component (i.e., changes in wind speed) [*Vautard et al.*, 2010], a parameter that is commonly considered stationary. In particular, *McVicar et al.* [2012] reviewed 148 studies from diverse regions that analyzed wind speed trends and reported that a widespread trend toward reduced wind speed could explain the decrease in global average pan evapotranspiration and ETo.

All these hypotheses have theoretical and empirical support, suggesting that multiple factors may be associated with changes in ETo. For instance, *Brutsaert* [2006] proposed that evapotranspiration changes can be partly attributed to solar irradiance changes and variations in the aerodynamic component. Several studies at the continental and global scales are based on gridded and/or reanalyzed data sets, which contain uncertainties. These studies provide very different results regarding ETo variability and trends [e.g., *Dai*, 2013; *Sheffield et al.*, 2012]. This indicates a need for studies that employ high-quality data to identify the meteorological factors that are most important in explaining changes in ETo at the regional level.

Several studies have analyzed the sensitivity of ETo to its underlying meteorological factors at the regional level [*McCuen*, 1974; *Beven*, 1979; *McKenney and Rosenberg*, 1993; *Irmak et al.*, 2006; *Estevez et al.*, 2009]. The results showed that the most important driving change variables differed among different climatic regions, in that the aerodynamic component was important in some regions [*Liang et al.*, 2008; *Ali et al.*, 2009; *P. Wang et al.*, 2012) but the energy component was also important in other regions [*Saxton*, 1975; *McCuen*, 1974; *Filho et al.*, 2010; *Fan and Thomas*, 2013]. Most of these studies have focused on the theoretical sensitivity of ETo, and determined the expected change in ETo due to changes in different variables under the average local climatic conditions. However, an explanation of the factors that control changes in ETo must consider sensitivity and long-term changes of meteorological parameters.

The present study analyzes the sensitivity of ETo to changes in different meteorological parameters in Spain and the causes of the strong increase in ETo observed in the western part of the Mediterranean region in recent decades [*Chaouche et al.*, 2010; *Espadafor et al.*, 2011; *Vicente-Serrano et al.*, 2014]. The southern Europe/Mediterranean region is one of the most important areas in the world in relation to the impact of climate change processes. Spain has experienced noticeable warming in last decades [*Brunet et al.*, 2007] and change in other meteorological variables [*Vicente-Serrano et al.*, 2014]. It has also experienced a large decrease in surface water availability in recent years [*Lorenzo-Lacruz et al.*, 2012; *García-Ruiz et al.*, 2011] and global climate change is believed to lead to a significant decrease in water resources in the coming decades [*Estrela et al.*, 2012]. In addition, there are complex land use and land cover changes in Spain in the last decades [*Lasanta and Vicente-Serrano*, 2012], including: (i) land abandonment and natural revegetation in mountain areas [e.g., *Gallart and Llorens*, 2003; *Lasanta et al.*, 2005], (ii) creation of a dense net of reservoirs with big reservoirs for irrigation and hydropower production [*García-Ruiz et al.*, 2011], (iii) land transformation to create new irrigated lands in flat areas [*Lasanta*, 2009], and (iv) land degradation in semiarid ecosystems [del *Barrio et al.*, 2010; *Vicente-Serrano et al.*, 2012], which could be relevant to understand current ETo processes. This makes it imperative to assess the effect of different meteorological variables, with implications for projected climate change and land cover scenarios upon future changes in evapotranspiration.

2. Data and Methods

2.1. ETo Calculation

The International Commission for Irrigation (ICID), the Food and Agriculture Organization (FAO) of the United Nations, and the American Society of Civil Engineers (ASCE) have all adopted the Penman-Monteith

(PM) equation [*Allen et al*., 1998; *Walter et al*., 2000] as the standard technique for calculation of ETo from climatic data. The PM method can be used globally and has been widely verified based on lysimeter data from diverse climatic regions [*Allen et al*., 1994; *Ventura et al*., 1999; *Itenfisu et al*., 2000; *López-Urrea et al*., 2006]. *Allen et al*. [1998] simplified the PM equation, developing the FAO-56 PM equation, and defined the reference surface as a hypothetical crop (assumed height of 0.12 m, surface resistance of 70 s m^{-1}, albedo of 0.23) that had evaporation similar to that of an extended surface of green grass of uniform height that was actively growing and adequately watered. The ETo FAO-56 PM is expressed as:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where *ETo* is the reference evapotranspiration (mm d^{-1}), R_n is the net radiation at the crop surface (MJ m^{-2} d^{-1}), *G* is the soil heat flux density (MJ m^{-2} d^{-1}), *T* is the mean air temperature at 2 m height (°C), u_2 is the wind speed at 2 m height (m s^{-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 $°C^{-1}$).

Thus, monthly ETo can be calculated from measurements of the monthly averages of six meteorological parameters: surface pressure, maximum temperature, minimum temperature, relative humidity (which determines vapor pressure deficit), wind speed at a height of 2 m, and daily sunshine duration [*Allen et al*., 1998]. It could be argued that given the nonlinear nature of the PM reference evapotranspiration, some differences could be obtained using monthly averages instead daily meteorological data, for which the method it is more accurate. Nevertheless, we note that using daily data can be more problematic than using monthly records since the quality control and homogenization of daily climate series is more difficult than processing monthly variables. When addressing long-term changes in ETo, it is necessary to balance between the uncertainty in the data forcing (higher for daily than for monthly records) or in the model accuracy (higher for daily than for monthly data). We think that assuming less model accuracy using monthly data are preferable when assessing long-term trends. Moreover, the agreement between calculating monthly ETo from monthly averages of the different variables or from the monthly sum of the ETo daily estimations is very high (Pearson's $r > 0.98$) in different meteorological stations of Spain (results not shown) and using monthly averages instead daily estimations has not important influence on the PM-ETo estimations.

2.2. Data Sets

We used monthly data sets for the six variables cited above, as described in *Vicente-Serrano et al*. [2014], for 46 meteorological stations in Spain from 1961 to 2011. These time series were subjected to careful quality control and homogenization, which is essential to guarantee reliability of the results. *Sanchez-Lorenzo et al*. [2007] provided details of the records for sunshine duration, *Vicente-Serrano et al*. [2014] provided details of the records for relative humidity, surface pressure, maximum temperature, and minimum temperature, and *Azorin-Molina et al*. [2014] provided details of the records for wind speed. These six variables were used to obtain ETo series according to the PM equation above. Following *Jones and Hulme* [1996], a single regional series for the entire mainland of Spain was computed using the areal weighted averages of monthly records for each station based on the recorded data of the six meteorological variables. The weighting factor was the ratio of the surface area at each station to the total area of Spain, based on Thiessen's polygon method.

2.3. Statistical Analysis

Trends in the monthly series of ETo and the six meteorological parameters were calculated using the Mann-Kendall tau rank correlation coefficient [*Kendall*, 1955]. This statistic is more robust than parametric tests, and does not assume normality of data [*Lanzante*, 1996]. The values of tau measure the degree to which a trend is consistently increasing or decreasing. Significant trends were defined as those with *p*-values less than 0.05. An important shortcoming of this method is that the nonparametric tau coefficient only showed the presence of significant trends in the series of ETo, but not the magnitude of change. A small but sustained change can result in a higher coefficient than a bigger but abrupt change. To identify the magnitude of the rates of changes in ETo, we used a regression analysis between the series of time (independent variable) and the ETo series (dependent variable). The results yielded one model for each, and took the form $y = m\,t + b$. The regression constant (b) and the coefficient (m) were calculated using a least-square fit, with the year (t) as the independent variable. The slope of each model (m) indicated the change in ETo (mm d^{-1} of change per year).

Analysis was applied to determine possible spatial structure in the monthly and annual ETo changes. To assess the degree of spatial dependence in ETo changes, we computed semivariance models [*Webster and Oliver*, 2001]. Semivariance allows the detection of scales of variability in spatial data. The semivariance describes the spatial variance as a function of distance between the observatories and semivariance plots are called semivariograms, which are widely used to determine optimum weights in climate interpolation. It is expected that the semivariance value decreases as the pair of data points is separated by a short distance and increases for long distances. This pattern would indicate some spatial structure in ETo changes. No changes in semivariance of ETo between pair of data at different distances would indicate a random spatial structure of the ETo changes. Semivariance analysis was also applied to determine the spatial structure in the influence of the different meteorological variables on observed ETo changes.

In addition, the spatial structure of changes and the spatial distribution of the sensitivity of ETo to the different meteorological variables was correlated to geographic variables and the average climate conditions at each observatory. For this purpose, we used the latitude, longitude, and elevation of each observatory. The average elevation within a radius of 100 km was also considered to determine the possible influence of the average relief surrounding each meteorological observatory. This variable was obtained from a digital terrain model for the whole Spain at a spatial resolution of 1 km. The distance of each observatory to coastlines was obtained by means of a Geographic Information System and also considered in the analysis. Finally, monthly and annual averages (1961–2011) of relative humidity, mean temperature, sunshine duration, and precipitation were also calculated for each observatory to determine whether the strong spatial gradients of these variables in Spain affect the spatial distribution of ETo changes and the sensitivity of the ETo to the different meteorological variables. Precipitation data was obtained from the MOPREDAS data set [*González-Hidalgo et al.*, 2011].

To determine the sensitivity of the ETo to the different meteorological variables, we have used a simple and practical method to assess the impact of a single variable on model output based on a sensitivity curve, in which the absolute change of the dependent variable (ETo) is plotted against the absolute change of independent meteorological variables. This method has been widely employed [e.g., *Paturel et al.*, 1995; *Goyal*, 2004; *Xu et al.*, 2006; *Irmak et al.*, 2006; *Wang et al.*, 2011]. Average values of meteorological variables obtained from the regional series and the series of the different observatories were used to determine how ETo changes in response to variations in each of the meteorological parameters during the warm and cold seasons, assuming stationary conditions for the other variables. This was implemented by calculation of ETo from the FAO-56 PM equation and assuming that all meteorological variables except the variable of interest were constant. For example, increasing or decreasing maximum or minimum temperature, relative humidity is being held fixed, allowing actual vapor pressure to change accordingly. The range of variation of the different variables was selected according to their maximum and minimum values recorded in the 1961–2011 period from the average regional series and the series of the different observatories. The relative importance of the different variables was assessed by means of the calculation of the range of variation of ETo (in mm.) corresponding to 100% of the observed range of variation of each variable.

To assess the importance of the trends in the different meteorological variables to explain the observed trends in ETo between 1961 and 2011, we applied the FAO-56 PM equation to obtain ETo series for the period of 1961–2011 using the observed series of each meteorological variables, with the exception of one variable that was held stationary (using the average from 1961 to 2011). This approach provides five simulated series of ETo for each observatory (one for each meteorological variable considered as stationary for the 1961–2011: relative humidity, maximum and minimum temperature, wind speed, and sunshine duration). From these series, we calculated the magnitude of ETo change at each observatory for each month and annually from 1961 to 2011 and compared these values with actual ETo values to determine the effect of changes in each specific meteorological variable upon the ETo evolution.

3. Results

3.1. Spatial Patterns of Monthly and Annual ETo

Figure 1 is a box plot of the average ETo at the 46 meteorological stations in Spain during each month from 1961 to 2011. There are significant seasonal differences due to natural changes in temperature and solar radiation. From November to February, ETo was less than 50 mm $month^{-1}$ and the variability among stations was small. Maximum ETo was in July, and the variability among stations is greatest in the summer months. The average ETo in July was 193.9 mm, but there are large differences between the maximum (ETo was 280 mm in July 2009 in Toledo, in the centre of the country) and the minimum (ETo was 82.5 mm in July 1983 in San Sebastián, by the bay of Biscay). Taken together, this figure illustrates that 46% of the annual ETo is recorded during the summer months (June–August).

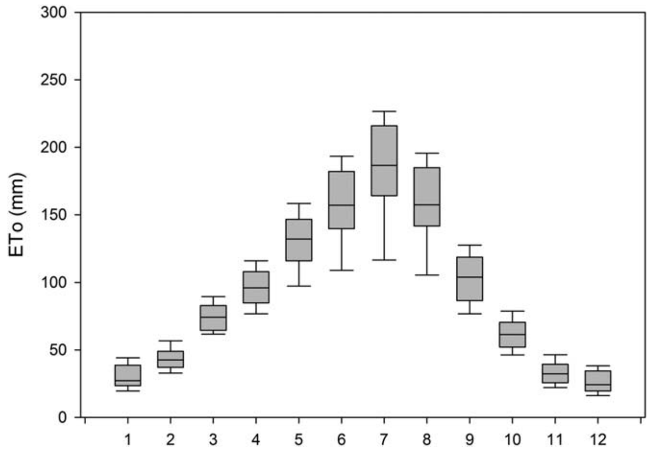

Figure 1. Monthly ETo at 46 observatories from 1961 to 2011. In the box plots here and below, the central line indicates the median, the gray box indicates the upper and lower quartiles, and the vertical lines indicate the 10th percentiles.

Figure 2 shows the spatial differences in the monthly and annual ETo from 1961 to 2011. These results indicate a clear latitudinal gradient during all months, which is more evident at the annual scale. In particular, ETo values in the southwest and central areas were approximately twice as large than those recorded in the north for most of the months. Observatories near the north Atlantic coast showed ETo values less than 120 mm throughout the year, whereas observatories of the central and southwest regions recorded ETo values more than 180 mm from June to August. This pattern is also observed at the annual scale since the southern observatories exceeded in more than 550 mm yr^{-1} in ETo to those located in the northern part of the country.

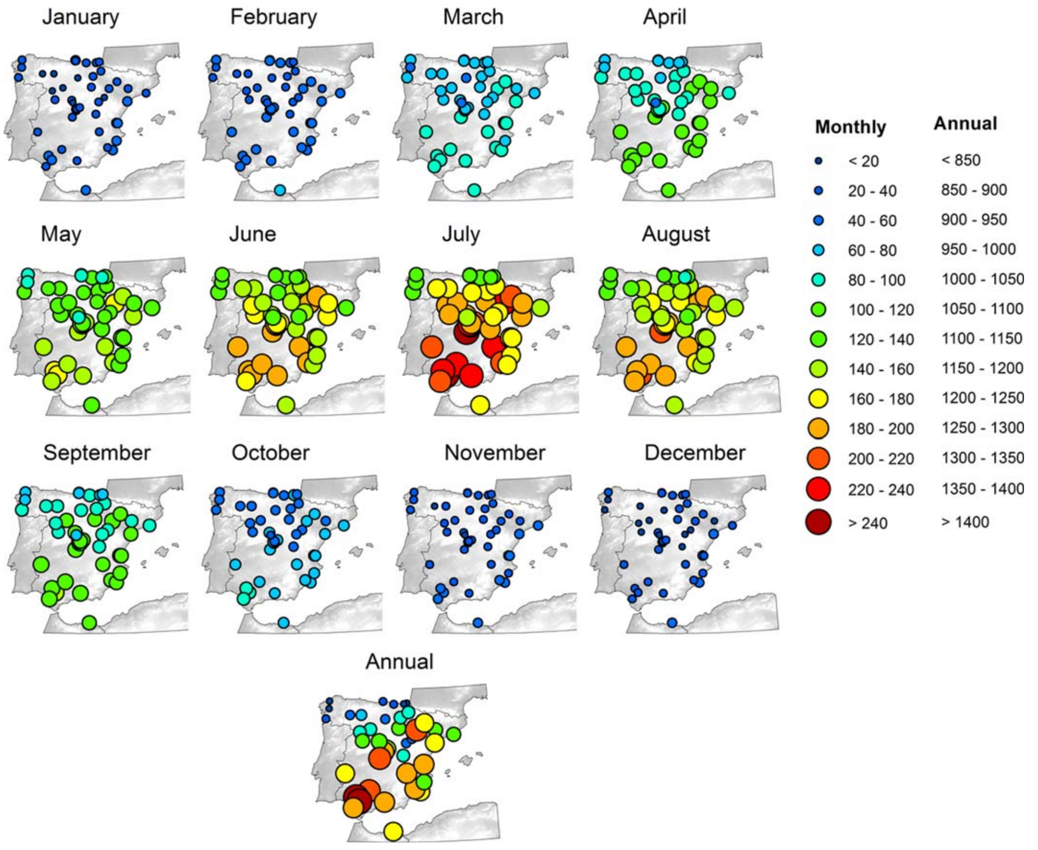

Figure 2. Spatial distribution of average monthly and annual ETo (mm) at 46 observatories from 1961 to 2011.

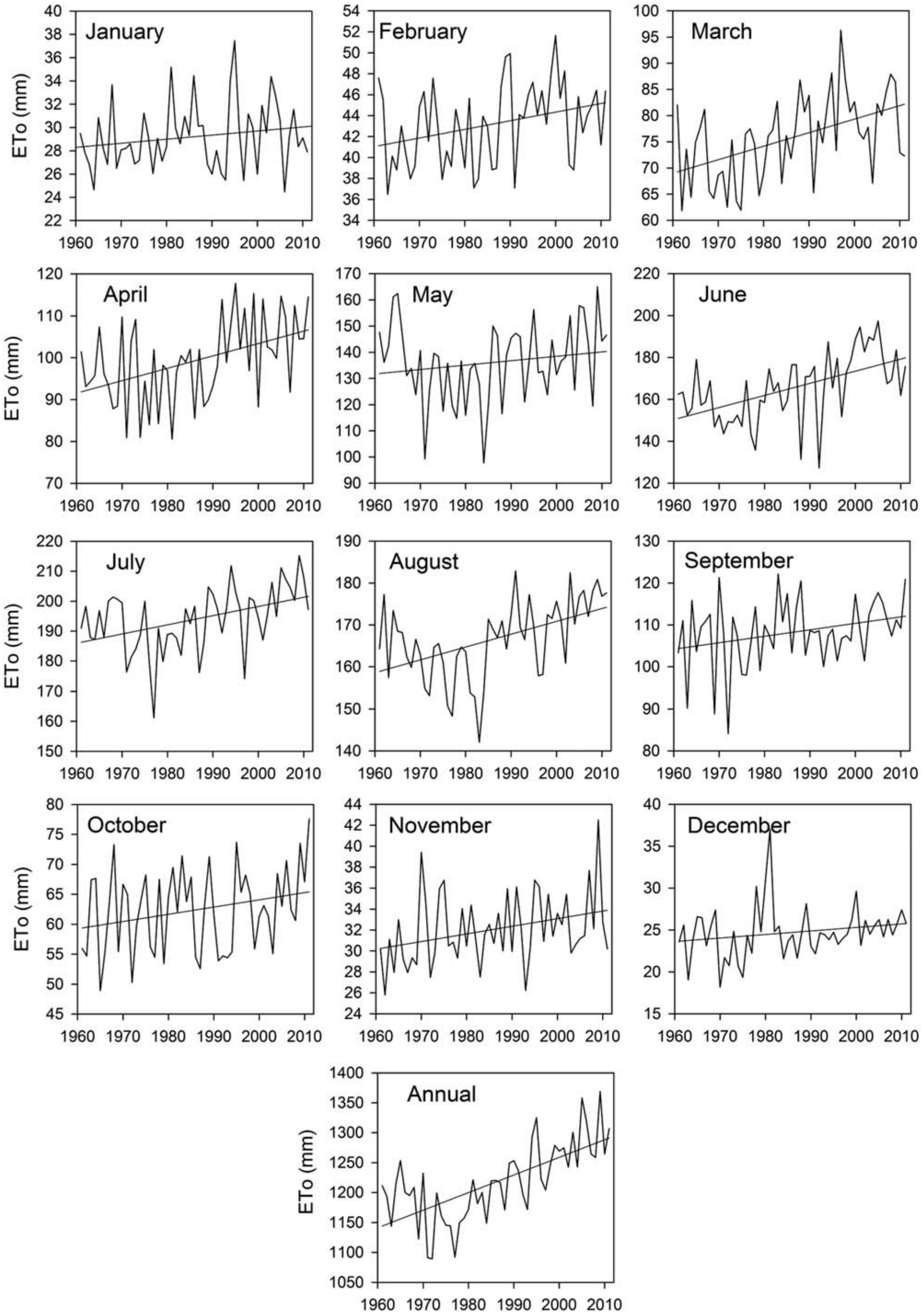

Figure 3. Evolution of monthly and annual ETo from the regional series of Spain from 1961 to 2011.

3.2. Evolution of the Monthly and Annual ETo

Figure 3 shows the evolution of mean monthly and annual ETo using the Spanish regional series from 1961 to 2011. Regression analysis indicated that all 12 monthly and the annual time series had positive slopes and that these increases were statistically significant in February, March, April, June, July, August, November, and at the annual scale. There was also strong interannual variability of ETo during all months, the range of this interannual variation being maximum in May and June with more than 60 mm. The largest increase in ETo occurred during June (5.78 mm decade^{-1}) and the smallest increase was in January (0.34 mm decade^{-1}) (Table 1). Table 1 also shows the percentage of the 46 stations in which positive and negative trends

Table 1. Change of ETo in the Spain Regional Series From 1961 to 2011 During Each Month and Annually and Percentage of Stations With Positive and Negative Changes of ETo During Each Month[a]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Magnitude of change (mm/decade)	0.34	**0.82**	**2.58**	**2.95**	1.67	**5.78**	**3.07**	**3.06**	1.55	1.20	**0.73**	0.42	**29.4**
Percentage of stations													
Positive ($p < 0.05$)	17.4	34.8	69.6	78.3	37.0	100.0	73.9	80.4	45.7	39.1	28.3	17.4	93.5
Positive (n.s.)	60.9	50.0	23.9	19.6	63.0	0.0	21.7	19.6	45.7	52.2	67.4	69.6	6.5
Negative (n.s.)	21.7	13.0	6.5	2.2	0.0	0.0	4.3	0.0	8.7	8.7	4.3	13.0	0.0
Negative ($p < 0.05$)	0.0	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

[a] Bold numbers indicate significant changes ($p < 0.05$), $p < 0.05$ indicates a significant change, and n.s. indicates no significant change.

were recorded from 1961 to 2011, as determined by the Mann-Kendall tau test. Positive trends were clearly dominant, only recording a statistically significant negative trend for one observatory in February. More stations had negative trends (> 10%) in the winter months than in the spring and summer months (< 5%). Therefore, during the warm seasons, when the greatest ETo values are recorded, there has been a general increase in ETo across Spain from 1961 to 2011. In June (August), 100% (more than 70%) of the stations showed positive and significant trends. Only the 4.3% of the stations (two observatories) had negative coefficients in July. This pattern is also observed at the annual scale, since the 93% of stations showed positive and significant trends and in average for Spain the annual ETo increased by 29.4 mm decade^{-1} between 1961 and 2011.

Further analysis indicated no clear spatial patterns in the absolute magnitude of ETo change (Figure 4). Annually there is also a dominant random pattern. The observatories that record the most important changes are surrounded by others that show a low magnitude of ETo change. However, the relative ETo changes (dividing the absolute changes by the average ETo at each station) show some spatial patterns. During the cold season (October–March), the observatories showing the maximum relative increase are mostly located in the northernmost part of the country, having an influence on the annual changes. On the contrary, in June, the month in which the strongest ETo absolute changes are identified, the main variations are recorded in the South and East. At the annual scale, relative ETo changes only show a significant correlations with latitude and the average sunshine duration (Table 2). Relative changes show positive and significant correlations with latitude in seven months, which means that relative change shows a South-North gradient, with the exception of June, in which the gradient is the opposite, with a negative and statistically significant correlation. This pattern also explains negative correlation between relative changes and the average sunshine duration and mean temperature, given that these variables also show a South (high)-North (low) gradient. Precipitation is negatively correlated with both ETo absolute and relative magnitude of changes in June and July. It means that higher ETo changes during these months are mainly recorded in areas that receive low precipitation amounts, corresponding to less cloud cover and, therefore, resulting in a larger solar radiation at surface.

Semivariograms among pairs of observations at different distances show that absolute and relative changes are spatially random in most months of the year and annually, but semivariance between pairs of observations tend to show lower differences between short than long distances (Figure 5). Nevertheless, the changes show certain spatial structure in some months of the year (e.g. March, June, July, August, September, and October) with a clear increase of the semivariance as the distance between pairs of observatories increases. In these months, the magnitude of change tends to be grouped spatially, as the different maps of Figure 4 suggest.

3.3. Sensitivity Analysis

Sensitivity analysis indicated that the different meteorological parameters had different effects on the ETo according to the average climate conditions in Spain during the cold (e.g., January) and warm (e.g., July) seasons (Figure 6). In particular, the January ETo (Figure 6a) does not show a clear response to variations in the sunshine duration considering the average range of variation of this variable over the whole Spain. ETo is slightly sensitive to minimum temperature, and responds more clearly to variations in maximum temperature and wind speed. In winter the ranges, which allow comparison between the different variables,

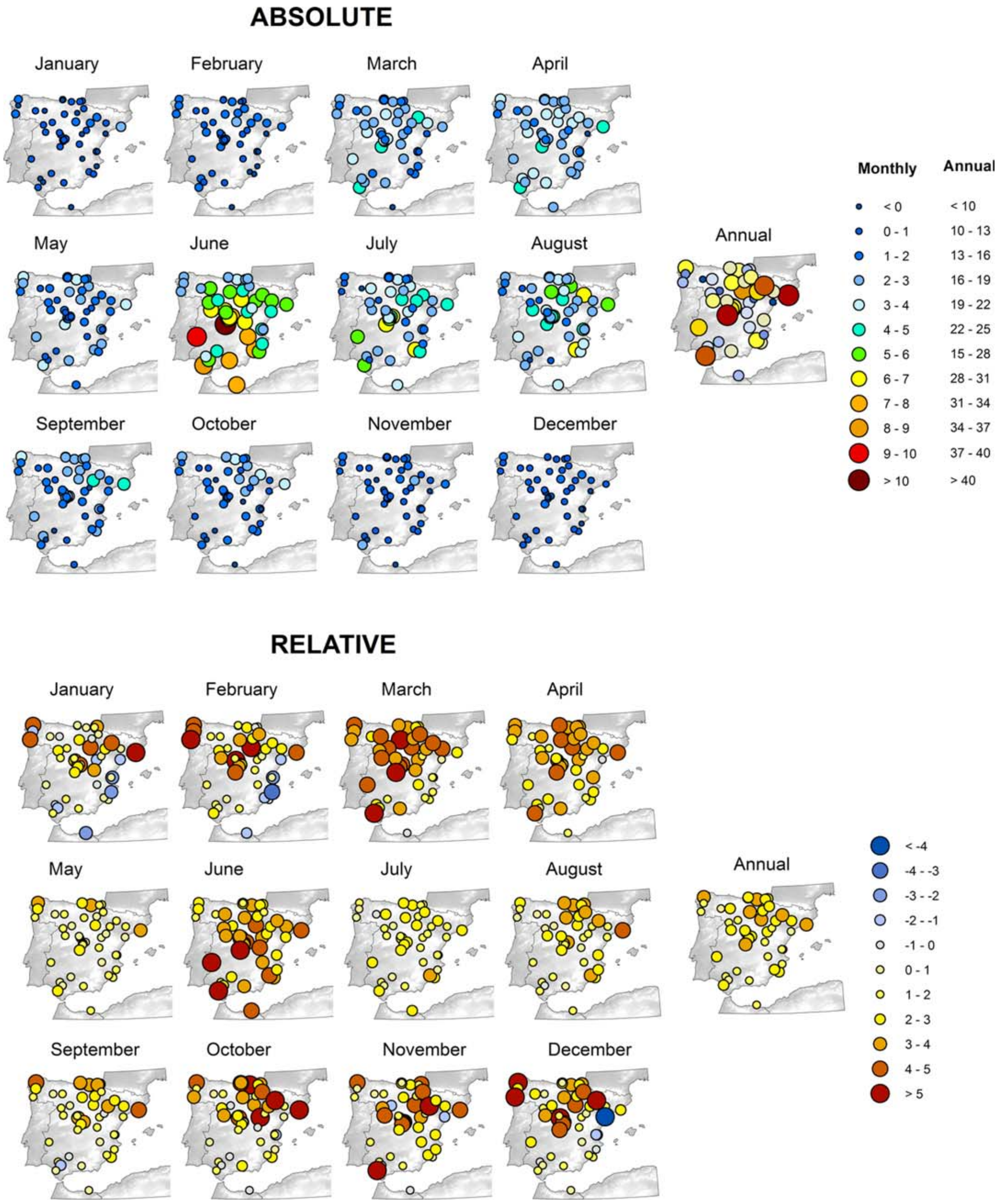

Figure 4. Spatial distribution of monthly and annual changes of ETo at 46 observatories from 1961 to 2011. The change is given in absolute ETo change (mm decade^{-1}) and in relative units (% decade^{-1}).

independently of the different units, show a higher influence of relative humidity than the rest of variables. The July ETo (Figure 6b) shows some sensitivity differences in comparison to January. The values are higher due to the higher range of variability of the ETo in summer. ETo variations show higher response to the variability of maximum temperature followed by relative humidity. Range of average wind speed and sunshine duration in summer is low (from 2.9 to 3.8 m s^{-1} and from 9.6 to 12 h, respectively), which could explain the low sensitivity of ETo to the observed range of variation for these two meteorological variables, in comparison to relative humidity and maximum temperature.

The sensitivity of ETo to the different meteorological variables changes according to the local climate conditions (Figure 7). For changes in absolute and ranges in January, there are not noticeable spatial differences in the sensitivity of the ETo to the different meteorological variables, although sunshine duration shows higher influence in southern than in northern areas as a consequence of the latitude and the higher cloud coverage in northern areas. In July, the absolute maps show a Northeast-Southwest gradient for relative

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Table 2. Pearson's r Correlation Coefficients Between the Spatial Distribution of Absolute and Relative Changes in the Monthly and Annual ETo and the Spatial Distribution of Different Geographic and Topographic Variables and the Monthly or Annual Average Climate Conditions[a]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Absolute													
Relative humidity	0.19	**0.30**	−0.14	−0.12	0.21	−**0.48**	−**0.34**	−0.05	0.22	0.25	0.00	0.11	−0.13
Sunshine duration	−**0.36**	−**0.39**	0.06	0.13	−0.23	**0.55**	0.33	0.01	−0.27	−**0.33**	−0.11	−**0.31**	0.03
Mean temperature	−0.22	−**0.32**	−**0.31**	0.05	0.11	**0.39**	0.25	0.06	−0.18	−0.16	−0.04	−0.04	−0.07
Latitude	**0.30**	**0.43**	0.10	0.00	0.16	−**0.45**	−0.14	0.08	**0.34**	**0.49**	0.09	0.19	0.10
Longitude	−0.04	−**0.37**	−**0.30**	−0.02	0.10	0.01	0.22	**0.43**	0.23	0.22	0.07	−0.23	0.11
Distribution of sea	0.20	**0.38**	**0.50**	0.14	−0.26	**0.53**	**0.37**	0.07	0.02	−0.09	0.05	0.01	**0.30**
Elevation	0.12	**0.34**	0.25	−0.03	−**0.30**	0.26	0.10	−0.13	−0.06	0.04	−0.12	0.06	0.09
Elevation_100	0.09	0.27	**0.29**	−0.02	−**0.30**	0.20	0.03	−0.10	−0.10	−0.01	−0.13	−0.02	0.04
Precipitation	0.12	0.11	−0.15	−**0.28**	0.12	−**0.59**	−**0.47**	−0.22	0.05	0.17	−0.13	0.25	−0.25
Relative													
Relative humidity	0.24	**0.38**	0.06	0.20	**0.45**	−**0.29**	−0.14	0.20	0.41	**0.34**	0.08	0.25	0.19
Sunshine duration	−**0.39**	−**0.45**	−0.13	−0.21	−**0.49**	**0.36**	0.05	−**0.33**	−**0.49**	−**0.43**	−0.19	−**0.43**	−**0.30**
Mean temperature	−0.26	−**0.36**	−**0.46**	−0.19	−0.04	0.21	0.08	−0.12	−0.26	−0.25	−0.13	−0.16	−0.25
Latitude	**0.30**	**0.47**	**0.28**	**0.29**	**0.35**	−**0.34**	0.02	0.27	**0.46**	**0.58**	0.19	0.31	**0.37**
Longitude	−0.07	−**0.38**	−**0.38**	−0.10	0.00	0.01	0.27	**0.41**	0.14	0.15	0.03	−0.27	0.03
Distribution of sea	0.26	**0.39**	**0.49**	0.08	−**0.37**	**0.46**	0.17	−0.18	−0.12	−0.06	0.19	0.12	0.17
Elevation	0.21	**0.47**	0.42	0.16	−**0.30**	0.36	0.04	−0.25	−0.08	0.15	0.05	0.24	0.15
Elevation_100	0.16	**0.34**	**0.44**	0.12	−0.31	0.23	−0.07	−0.21	−0.15	0.07	0.06	0.14	0.08
Precipitation	0.15	0.15	0.01	−0.03	**0.34**	−**0.49**	−**0.30**	0.04	0.23	0.25	−0.12	0.31	0.02

[a] Significant correlations are in bold ($p < 0.05$).

humidity, minimum temperature, and wind speed, whereas for sunshine duration the Northwest-Southeast spatial gradient identified in January is also recorded. Sensitivity of ETo to absolute changes in sunshine duration and maximum temperature shows a significant correlation with latitude, average sunshine duration, average relative humidity, and precipitation (Table 3). The semivariogram of the sensitivity of ETo to absolute changes in the meteorological variables shows a clear spatial structure for summer maximum temperature, wind speed, and sunshine duration (Figure 8). The patterns identified from ETo sensitivity to absolute variations of the meteorological variables are not so evident when the influence on ranges is assessed. Nevertheless, sensitivity to range variations of sunshine duration shows the opposite pattern that absolute variations, and in the northern areas, ETo is more sensitive to sunshine variations.

3.4. Trends in ETo in Response to Trends in the Meteorological Variables

To examine the effect of changes in the meteorological parameters on the increase of ETo for Spain, we compared the observed magnitude of change of ETo at the 46 observatories during each month and annually over the 51 year study period, and simulated the change assuming each of the five meteorological variables used in the FAO-56 PM equation was constant. Figure 9 shows the results expressed as monthly and annual box plots. Thus, in January the observed regional change of ETo at the 46 observatories was 0.31 mm decade^{-1} (Table 4). Holding any of the five meteorological variables stationary during January would have caused some changes in ETo. In particular, an assumption of stationary relative humidity would have led to a negative change of −0.08 mm decade^{-1} and an assumption of stationary maximum temperature would have led to a change of 0.15 mm decade^{-1}. Holding the minimum temperature or sunshine duration stationary had minimal effects, but holding wind speed stationary would have increased ETo to 0.48 mm decade^{-1}. The same general pattern occurred during the other 11 months and annually, in that the magnitude of change in ETo would have been much lower if relative humidity and maximum temperature were stationary, but the other variables had smaller effects. The results for June were particularly notable, because the observed regional increase in ETo was 5.2 mm decade^{-1}, but holding relative humidity or maximum temperature stationary would have changed this to 3.2 and 3.3 mm decade^{-1}, respectively. Comparison of the different months indicated seasonal effects of wind speed and sunshine duration. In winter, holding wind speed stationary increased ETo, but in August and September it decreased ETo. The role of sunshine duration was even more variable, in that holding this constant during March, April, and June reduced ETo, but holding it constant in May increased ETo. Taken together, these results indicate that changes of ETo in Spain from 1961 to 2011 were highly sensitive to changes in relative humidity and maximum temperature, but less sensitive to changes in the other meteorological variables. Annually the

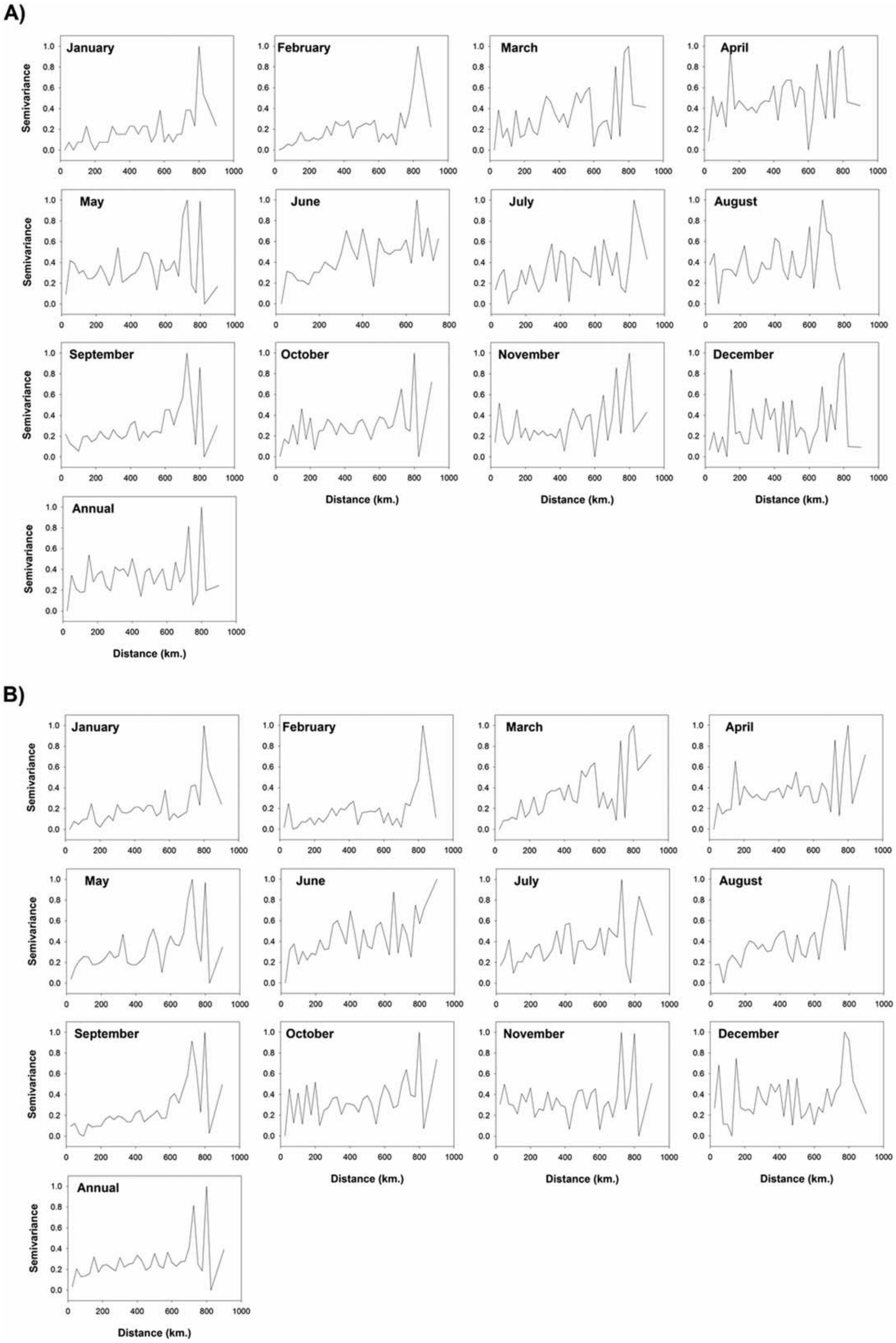

Figure 5. Semivariance of the absolute (a) and relative (x 1000) (b) magnitude of change of monthly and annual ETo between the whole set of observatory pairs separated at different distances. Semivariances are in normalized units from 0 to 1.

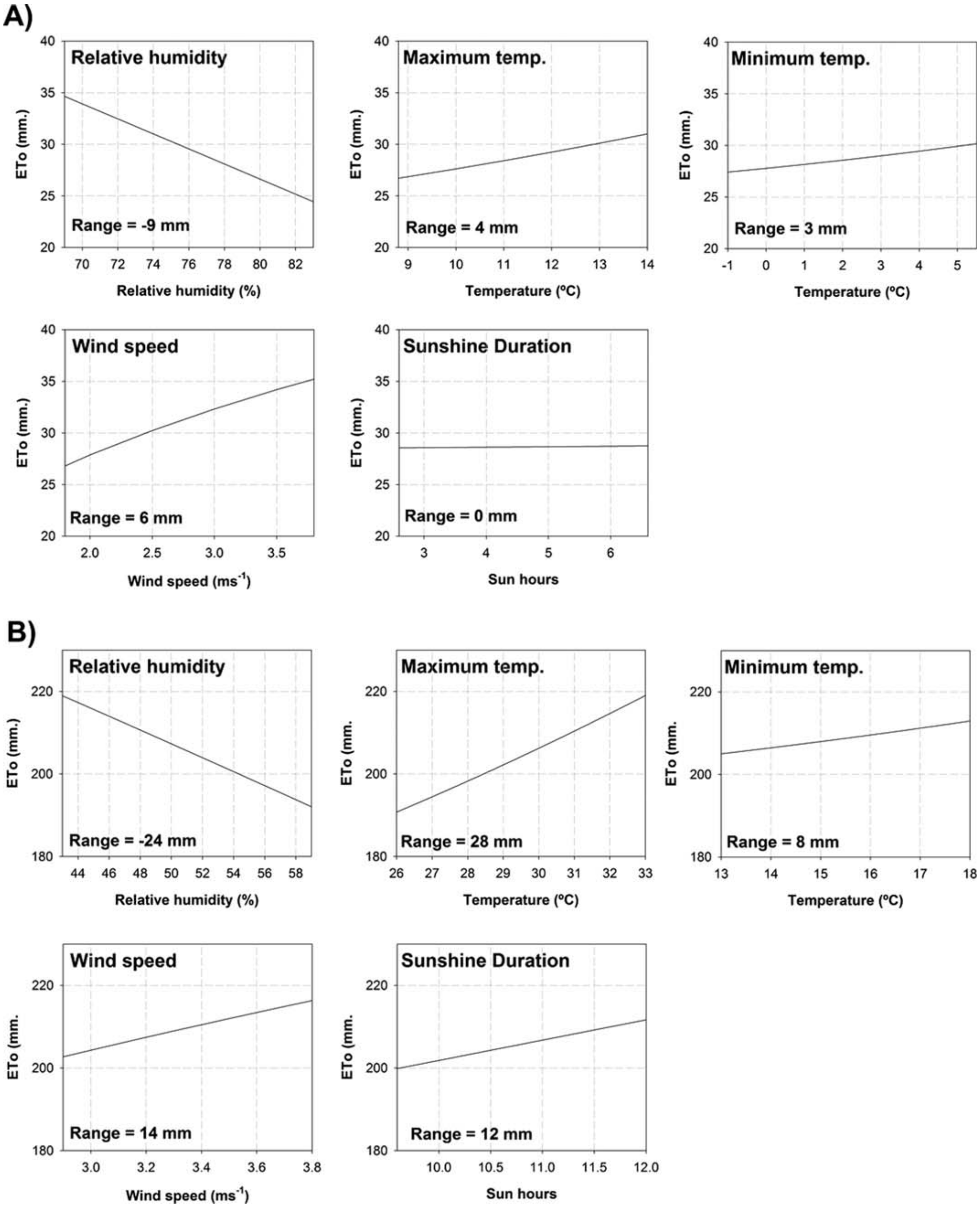

Figure 6. Effect of changes in each of five meteorological variables on variations in ETo during January (a) and July (b) from 1961 to 2011 according to the range of climate variability observed in Spain. The variables oscillate between maximum and minimum monthly observations recorded in the Spanish regional series. The ranges are comparable between the different variables. They are changes in ETo (in mm.) corresponding to 100% of the observed range of each variable.

observed average change of ETo was 23.4 mm decade^{-1}, but holding relative humidity and maximum temperature constant would have led to a lower change (12.1 and 14.7 mm decade^{-1}, respectively). Temporal series of ETo simulated with relative humidity and maximum temperature held constant show a clear difference with observed ETo, mainly from 1990 to 2011 (Figure 10).

The differences between observed monthly and annual 1961–2011 ETo changes and those obtained assuming each of the five meteorological variables constant show some spatial differences (Figure 11). In the cold season (November–April), the spatial differences between observed ETo and simulated ETo for each one of the different variables are small given low ETo rates. Nevertheless, in February the differences between the observed and simulated ETo changes with the relative humidity constant show values higher than 2 mm decade^{-1}, especially in eastern areas. In March, some spatial patterns emerge from simulated series of

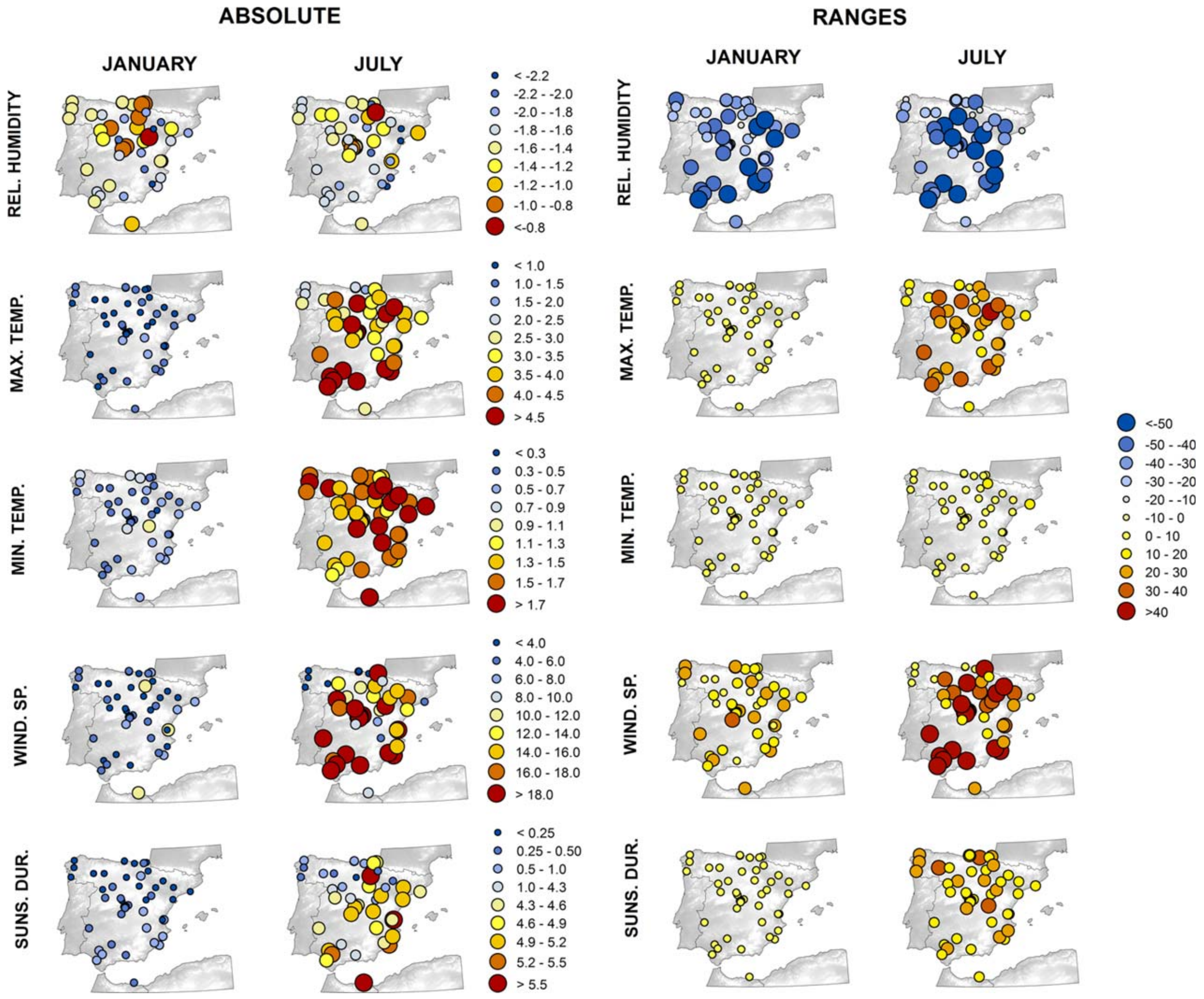

Figure 7. Spatial distribution of the effect of changes in each of five meteorological variables on variations in ETo during January and July. The absolute values are change of ETo (in mm.) corresponding to changes of one unit in the different variables (% for relative humidity, °C for temperature, ms^{-1} for wind speed and hours for sunshine duration). The ranges are changes in ETo (in mm.) corresponding to 100% of the observed range of each variable.

relative humidity (North-South gradient) and sunshine duration (Southeast-Northwest gradient). Important spatial differences are found in summer months, mainly for relative humidity and maximum temperature. In June, the differences between observed ETo changes and simulated ETo changes holding relative humidity constant show high magnitudes in the South of Spain and a clear South-North gradient. Nevertheless, the most frequent pattern is the spatial homogeneity in the difference between observed and simulated changes holding the different variables constant.

Next, we examined monthly changes of the five meteorological parameters used to calculate ETo. Figure 12 shows box plots of these results. The 12 bars in each plot represent the medians and distributions of changes at the 46 observatories for a single parameter during all 12 months. Changes in relative humidity and temperature were important, especially during June, the month with the greatest observed increase of ETo. For relative humidity, the changes were greater than 1% per decade for 6 months (mostly the warm seasons) and annually (Table 5), this change was statistically significant for nine months (all months except May, October, and November) and annually, and this general pattern occurred at all of the 46 stations.

We determined the total number of stations that displayed positive or negative trends for relative humidity, maximum temperature, minimum temperature, wind speed, and sunshine duration (Figure 13). For relative humidity (top), more than 90% of the observed changes were negative trends (orange or yellow), and

Table 3. Pearson's r Correlation Coefficients Between the Spatial Distribution of the Effect of the Absolute and Relative Changes in the Different Meteorological Variables on the ETo (shown in Figure 6) and the Spatial Distribution of Different Geographic Variables and the Average Monthly Climate Conditions at Each Observatory[a]

	Longitude	Latitude	Elevation	Elevation_100	Distribution of Sea	Sunshine Duration	Relative Humidity	Precipitation	Mean Temperature.
Absolute									
Relative Humidity (Jan)	−0.11	0.15	0.04	−0.03	0.08	−0.24	0.00	0.16	**−0.29**
Relative Humidity (Jul)	−0.18	0.16	0.14	0.18	0.26	−0.13	0.17	0.11	−0.20
T. max. (Jan)	0.22	−0.26	**−0.39**	**−0.41**	**−0.31**	0.11	0.02	−0.10	**0.75**
T. max. (Jul)	0.14	**−0.53**	0.10	0.16	**0.28**	**0.79**	**−0.73**	**−0.65**	0.15
T. min. (Jan)	0.04	−0.01	−0.31	−0.31	**−0.30**	−0.19	**0.30**	0.15	**0.52**
T. min. (Jul)	0.27	0.09	0.05	0.04	−0.11	0.00	**0.38**	0.03	**0.32**
Wind speed (Jan)	0.26	−0.23	**−0.43**	**−0.46**	**−0.34**	0.13	−0.19	−0.17	**0.68**
Wind speed (Jul)	0.10	**−0.56**	0.01	0.01	**0.31**	**0.73**	**−0.93**	**−0.68**	0.12
Sunshine duration (Jan)	0.13	**−0.69**	−0.07	−0.07	0.00	**0.72**	**−0.44**	**−0.46**	**0.60**
Sunshine duration (Jul)	**0.34**	**−0.55**	**−0.29**	**−0.33**	−0.12	**0.47**	**−0.41**	**−0.40**	**0.70**
Relative									
Relative humidity (Jan)	−0.15	**0.42**	**0.35**	**0.40**	0.24	**−0.41**	0.27	0.15	**−0.45**
Relative humidity (Jul)	−0.05	**0.33**	−0.14	−0.16	−0.06	**−0.32**	**0.38**	0.26	0.10
Temperature max. (Jan)	**0.36**	0.14	**−0.32**	**−0.29**	−0.17	−0.20	0.07	−0.01	0.23
Temperature max. (Jul)	0.09	**−0.30**	0.25	0.15	**0.35**	0.55	**−0.65**	−0.52	−0.24
Temperature min. (Jan)	0.20	**−0.29**	**−0.34**	**−0.35**	−0.17	0.11	−0.05	−0.03	**0.43**
Temperature min. (July)	**0.30**	0.16	0.16	0.12	0.17	−0.03	0.03	−0.16	−0.09
Wind speed (Jan)	0.13	−0.11	**−0.43**	**−0.44**	−0.21	0.00	−0.12	−0.12	**0.61**
Wind speed (Jul)	0.00	**−0.53**	0.06	−0.04	0.22	**0.66**	**−0.73**	**−0.54**	0.08
Sunshine duration (Jan)	0.09	**−0.69**	−0.15	−0.18	−0.05	**0.70**	**−0.48**	**−0.40**	**0.59**
Sunshine duration (Jul)	−0.22	**0.32**	0.04	0.13	−0.14	**−0.50**	**0.64**	**0.58**	−0.01

[a] Significant correlations are in bold ($p < 0.05$).

significant negative trends (orange) were predominant during five months (April, June, July, August, September). For maximum and minimum temperature, most of the observed changes were positive trends (blue or green). Moreover, maximum temperature was much more important than minimum temperature, and there were more significant increases of both (blue) during the warm seasons. The smaller number of positive trends for minimum temperature than maximum temperature reinforces the lower sensitivity of ETo to changes in minimum temperature than maximum temperature (Figure 6). The negative trends in the wind speed data (orange or yellow) indicate that ETo was affected by this variable, although wind speed did not have an important role in explaining the observed variance in ETo because there were only modest changes in wind speed in Spain from 1961 to 2011. In other words, except from November to March when negative trends predominated, there was a balance of observatories with positive trends (blue or green) and negative trends (yellow or orange). Sunshine duration had more often significant changes than wind speed in some months. Nevertheless, at the regional scale very few of these changes were statistically significant (blue or orange). The maximum was again in June, with 28.3% of positive and significant trends. Sunshine duration had more positive than negative trends in all months, but May and August had some stations with significantly negative trends.

4. Discussion

This study analyzed the sensitivity of the ETo in Spain (as determined by the FAO-56 PM equation) to changes in the different meteorological parameters used for its calculation by analysis of data from 46 meteorological stations from 1961 to 2011. In this study, we have used monthly homogenized records of relative humidity, air temperature, wind speed, and sunshine duration. Given the nonlinear nature of Penman-Monteith ETo, the time resolution (monthly) of the data sets used could have some influence in the obtained results. Nevertheless, obtaining high-quality and homogeneous time series of the necessary variables for calculating ETo on finer time scales (e.g., daily) is highly problematic, whereas testing and correcting homogeneity using monthly records is reliable. Then, when addressing long-term changes in ETo, it is necessary to balance between the uncertainty in the data forcing (higher for daily than for monthly records) or in the model accuracy (higher for daily than for monthly data). Temporal homogeneity of climate data sets is more critical than model uncertainty associated with the time resolution. Thus, the influence of the later is expected to be minimum given the strong relationship between the monthly ETo sum

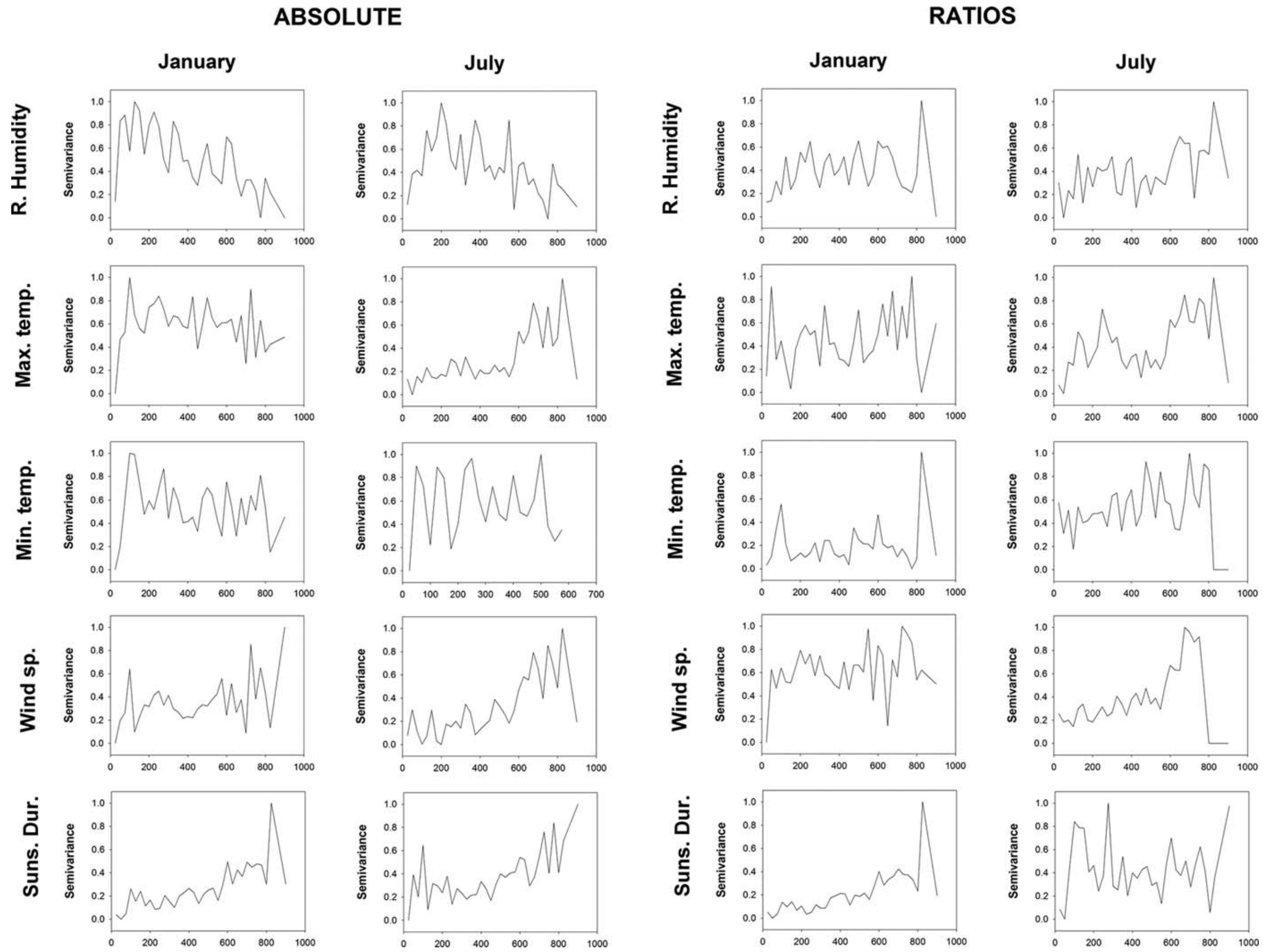

Figure 8. Semivariance of the absolute and relative sensitivity of ETo to changes in the meteorological variables during January and July (as in Figure 7) in the whole set of observatory pairs separated at different distances. Semivariances are in normalized units from 0 to 1.

from daily measurements and the calculations from the average of monthly climate variables in some stations of Spain (results not shown).

Previous studies reported a strong increase of ETo in recent decades in the western Mediterranean region [*Chaouche et al*., 2010; *Espadafor et al*., 2011; *Vicente-Serrano et al*., 2014]. The results presented here indicated that ETo increased throughout the year in Spain, and that the changes were greater during the warm seasons (June, July, and August) at most of the 46 observatories. The spatial patterns in ETo change are complex and highly random in most of the months of the year and also annually. Nevertheless, latitude seems to control relative ETo in the annual mean, as well as during the cold season. The strong spatial diversity of climate variables in Spain, along with the spatial diversity in the magnitude of changes of the different variables involved in the estimation of ETo [e.g., *Azorin-Molina et al*., 2014; *Vicente-Serrano et al*., 2014; *Sanchez-Lorenzo et al*., 2007; *Brunet et al*., 2007], may explain the complex observed spatial patterns. ETo is obtained using four different variables: relative humidity, temperature, wind speed, and sunshine duration, which show strong spatial variations in Spain due to the complex topographical features, land cover, etc. In the past 50 years, Spain has suffered major land cover changes. The creation of new irrigated lands [*García-Ruiz et al*., 2011] and the strong forest growth recorded in mountain ecosystems, as a consequence of the rural depopulation and the land abandonment [*García-Ruiz and Lasanta-Martínez*, 1990; *Lasanta et al*., 2005], may have locally affected the evolution of some of the climate variables (mainly relative humidity

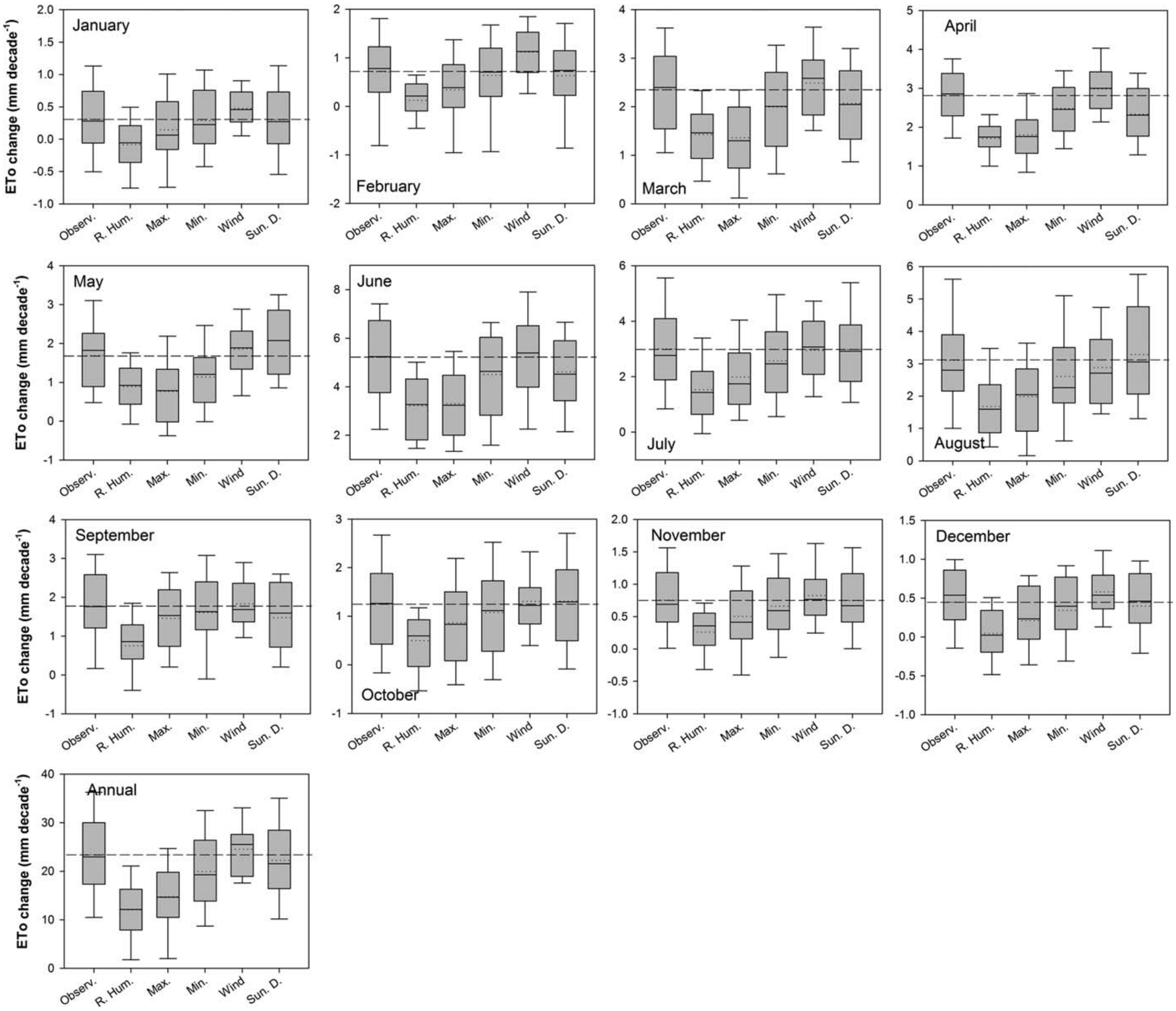

Figure 9. Magnitude of the change in ETo at the different stations (Observersations) and the simulated value with each meteorological parameter held constant during each month and annually. The dashed horizontal line represents the average observed change. The bottom and top of the box are the first and third quartiles, and the band inside the box is the median. Dotted line inside the box is the Spain regional mean.

and wind speed) used in the Penman-Monteith ETo model, explaining the complex spatial patterns observed in the ETo changes.

Our analysis of the changes in ETo due to changes in the meteorological parameters used for its calculation clearly showed that ETo was most sensitive to relative humidity, wind speed, and maximum temperature variations. ETo had a strong sensitivity to relative humidity along the whole year, while maximum temperature had a much stronger effect in the warm season. Our analysis of data by use of sensitivity curves showed that winter ETo was almost insensitive to variations in daily sunshine duration, according to the average range of variability of this variable in Spain. These patterns are not exclusive to regions with Mediterranean climates, such as Spain. For example, *Wang et al.* [2012] performed a global study of the evolution of pan evaporation estimates from 1973 to 2008 using data from 1300 stations throughout the world and showed that the vapor pressure deficit contributed more to the monthly variability of pan evaporation than other factors (e.g., incoming radiation, wind speed, and temperature). Regional studies of areas with very different environments have also stressed the importance of changes in relative humidity and vapor

Table 4. Observed Magnitude of Change (mm. decade^{-1}) in the Regional ETo Series From 1961 to 2011 and the Simulated Value With Each Meteorological Parameter Held Constant During Each Month and Annually

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Observed	0.31	0.72	2.35	2.81	1.67	5.21	3.00	3.10	1.76	1.25	0.75	0.45	23.4
Relative humidity	−0.08	0.12	1.43	1.71	0.89	3.22	1.53	1.68	0.75	0.50	0.26	0.04	12.06
Maximum temperature	0.15	0.34	1.36	1.80	0.77	3.30	1.99	1.99	1.46	0.87	0.50	0.21	14.73
Minimum temperature	0.29	0.64	2.00	2.48	1.14	4.51	2.57	2.61	1.61	1.08	0.66	0.34	19.92
Wind speed	0.48	1.12	2.49	2.98	1.85	5.22	2.95	2.88	1.83	1.31	0.83	0.58	24.52
Sunshine duration	0.30	0.63	2.07	2.33	2.08	4.61	2.99	3.29	1.48	1.31	0.75	0.40	22.23

pressure deficit on ETo. For example, *Kwon and Choi* [2011] used data in Korea to analyze the sensitivity of the PM equation to errors in the meteorological parameters used for its calculation, and showed that vapor pressure was the most important variable, wind speed was the second most important, and incoming radiation was the third most important. *Zuo et al.* [2012] used data from the Wei river basin in China and reported that relative humidity was the most important variable in driving changes of ETo, followed by wind speed, air temperature, and solar radiation. They also showed that 10% of the increase in relative humidity accounted for about 30% of the observed decrease in ETo. Other studies in China have also reported that relative humidity had the greatest effect on ETo in the Yangtze River basin [*Gong et al*. 2006], the Yellow River basin [*W. Wang et al*. 2012c], the Haihe River basin [*Wang et al*., 2011], and the west Songnen Plain [*Liang et al*. 2008]. *Abtew et al*. [2011] studied evapotranspiration in South Florida (USA) and reported that the decline in humidity and the increase in vapor pressure deficit from 1992 to 2009 drove most of the observed increase in ETo. *Irmak et al*. [2006] analyzed the response of the FAO-56 PM equation to changes in the variables used for its calculation in regions with different climatic conditions in the USA. Their results indicated that ET was generally most sensitive to vapor pressure deficit at all studied locations. They also showed that after vapor pressure deficit, ETo was most sensitive to wind speed in semiarid regions and to solar radiation in humid regions.

The dominant semiarid climate in most of Spain may explain the lower sensitivity of ETo to variations in sunshine duration (which is closely related to solar radiation in Spain, see *Vicente-Serrano et al*., [2014]), since in warm and dry regions the radiative component of the ETo has lower importance than aerodynamic component [*Irmak et al*., 2006; *Teuling et al*., 2009; *Matsoukas et al*., 2011]. ETo has showed more sensitivity to the aerodynamic component (composed by relative humidity, temperature, and wind speed) in Spain. In particular, analyses clearly showed that changes in relative humidity and maximum temperature explained most of the observed changes of ETo in recent decades. This is because according to the range of variation of the different meteorological variables in Spain, the FAO-56 PM equation is highly sensitive to changes in relative humidity, maximum temperature, and because there have been strong decreases (increase) of relative humidity (maximum temperature) in Spain in recent decades.

In fact, there were trends for decreasing relative humidity during all months at most of the 46 stations. This explains why our simulations of ETo with the assumption of stationary relative humidity from 1961 to 2011 resulted in much smaller changes in ETo during all months. However, we cannot neglect the influence of

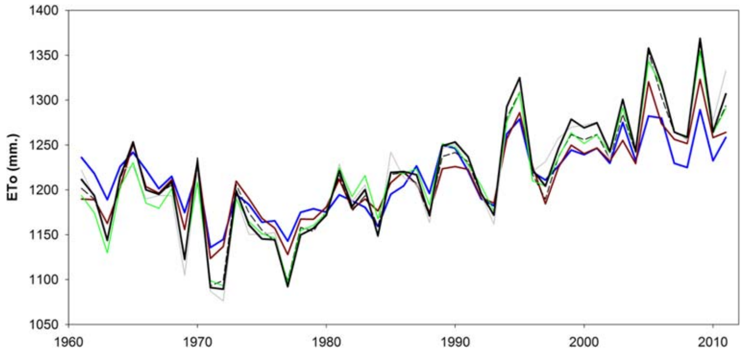

Figure 10. Evolution of the observed regional annual ETo (in black) from 1961 to 2011 and those simulated with each meteorological variable held constant: blue: relative humidity, dark red: maximum temperature, green: minimum temperature, gray: wind speed, dashed: sunshine duration.

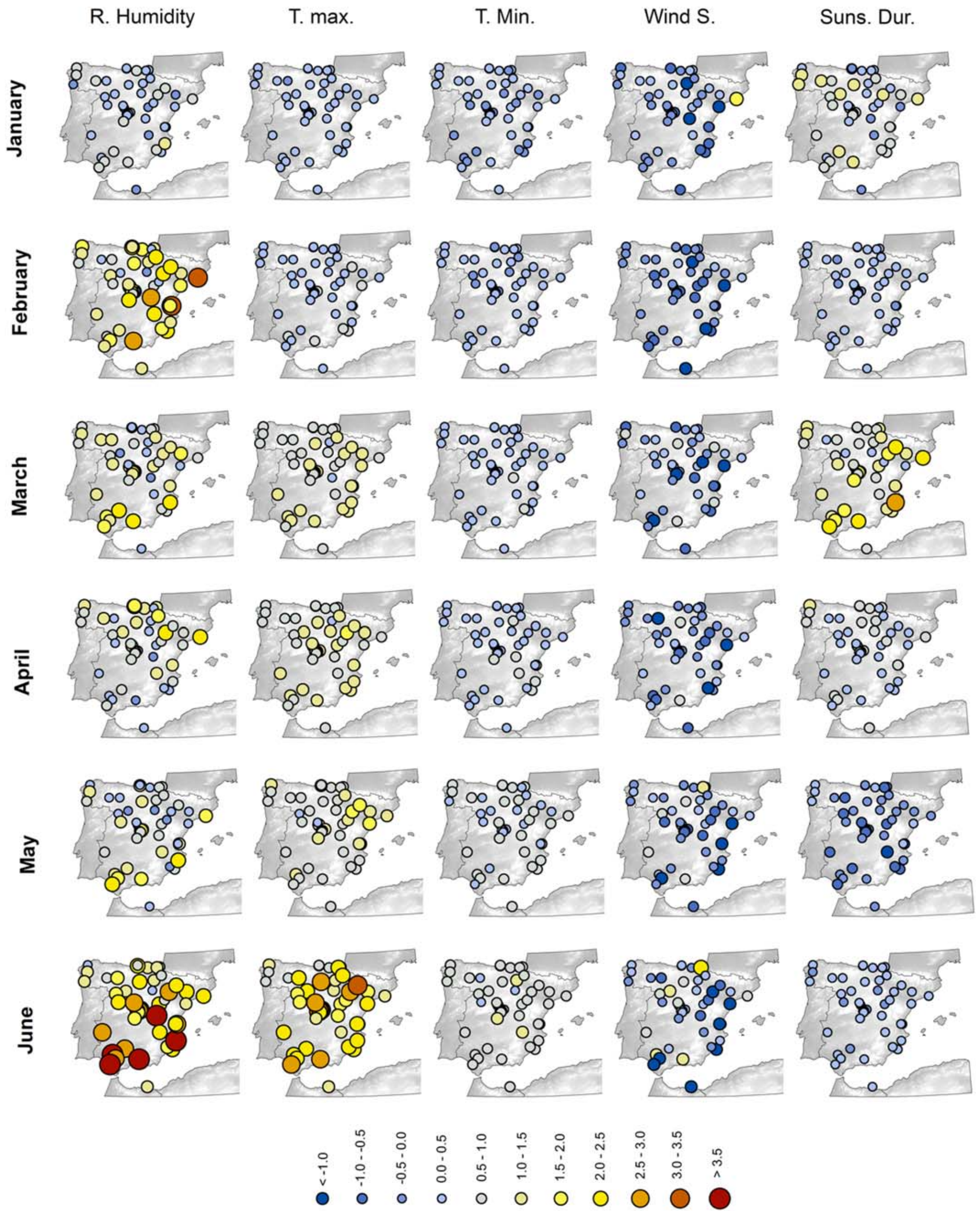

Figure 11. Spatial distribution of the differences between observed monthly and annual magnitude of change in ETo (in mm.) and the simulated monthly and annual magnitudes of change with the meteorological variables held constant. Spatial distribution of the differences between the observed monthly and annual magnitude of change of ETo (in mm.) in the different observatories and the simulated monthly and annual magnitudes of change with the different variables held constant.

temperature changes, mainly maximum temperature, in explaining the observed changes of ETo in Spain. We have showed that ETo shows low sensitivity to minimum temperature, in agreement with the results of *Irmak et al.* [2006] throughout United States. Although in the estimation of some of the terms of the FAO-56 PM equation the mean temperature is used instead of the maximum temperature, we showed that maximum temperature has greater influence than minimum temperature. Evapotranspiration daily cycles are determined by the available energy, and the maximum energy (solar radiation) is commonly recorded at the time of the day in which maximum temperature is measured and it is affecting ETo rates; whereas during the night, when minimum temperature is recorded, evapotranspiration is much lower. This would explain why in winter, when low ETo rates are recorded and temperature is also low, the difference in ETo sensitivity to maximum and minimum temperature is much lower than in summer.

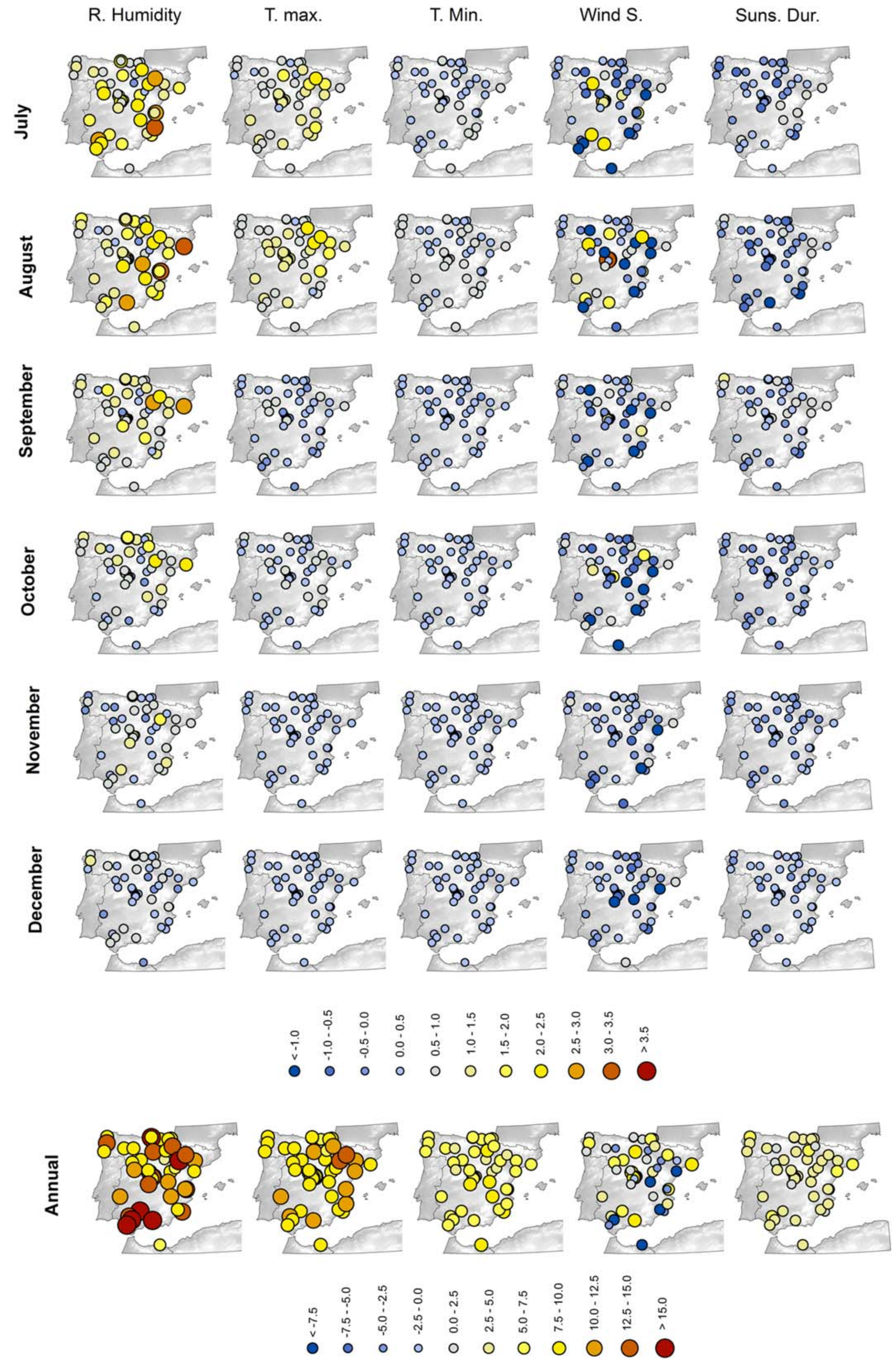

Figure 11. (continued)

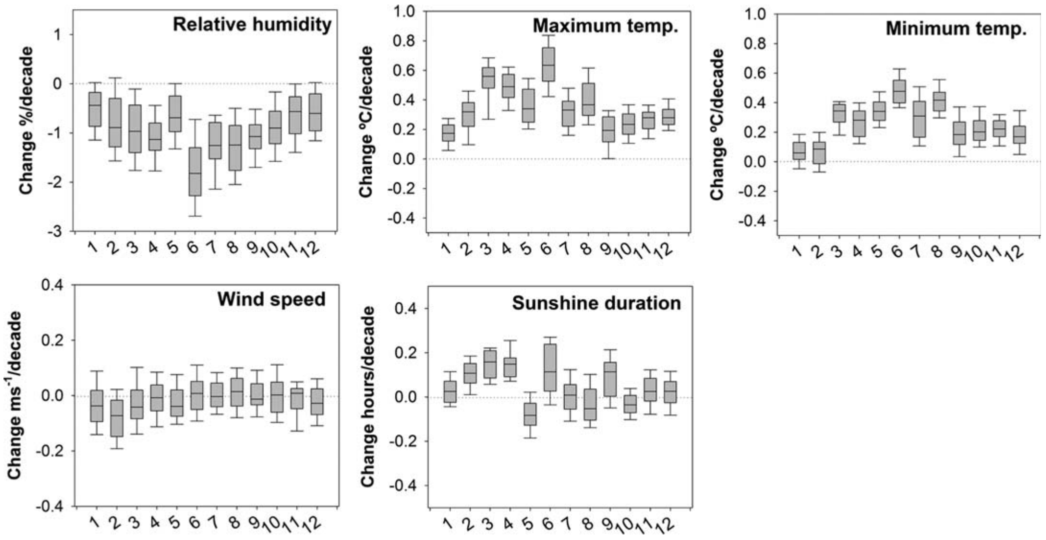

Figure 12. Monthly magnitude of change of the different meteorological variables from 1961 to 2011 at the 46 observatories.

Monteith and Unsworth [1990] stated that ETo is little affected by temperature if the vapor pressure deficit is held constant. However, with relative humidity held constant rather than vapor pressure deficit, our sensitivity analysis indicated that ETo is highly sensitive to maximum temperature variations in summer, and that maximum temperature was the second most important variable in explaining the observed changes of ETo. *Irmak et al*. [2006] also showed strong influence of relative humidity and maximum temperature on ETo variations in U. S. and they explained that since saturation vapor pressure is an exponential function of temperature and ETo is a linear function of the vapor pressure deficit, a fairly large increase in ETo is expected for an increase in temperature in arid and semiarid environments. Other regional studies in this kind of environments have also stressed the sensitivity of ETo to changes in temperature. For example, in the arid region of Rajasthan (India), *Goyal* [2004] showed that ETo increased by 14.8% with a 20% increase in temperature, and that increased solar radiation (11%), wind speed (7%), and vapor pressure (−4.31%) had weaker effects. Also in India, *Mahmood* [1997] reported a 5% increase in ETo for each 1°C increase, and a 4.6% decrease for each 1°C decrease. *Donohue et al*. [2010] showed that temperature changes in Australia had a large effect on changes in ETo (1.5 mm yr^{-1}), but that the average decrease of ETo from 1981 to 2006 were due to the negative effects of wind speed (−1.3 mm yr^{-1}), solar radiation (−0.6), and vapor pressure deficit (−0.4). Moreover, the high sensitivity of ETo to the maximum temperature found, in average, in Spain is lower in the most humid regions of the country than in semiarid sites, where actual vapor pressure may be closely comparable to the vapor pressure deficit. Thus, the strong correlation between the spatial distribution of ETo sensitivity to maximum temperature and the average annual precipitation and relative humidity in summer ($r = -0.52$ and -0.65, respectively) reinforces this pattern. The relative sensitivity of ETo to changes in relative humidity is also dependent on the temperature conditions, and the sensitivity of ETo to relative humidity will be larger at low temperature, explaining why winter ETo sensitivity to relative humidity show a spatial gradient, which is negatively correlated with mean temperature ($r = -0.45$) and sunshine duration ($r = -0.41$).

Therefore, we showed that temperature and relative humidity played a major role in explaining changes in ETo during the spring and summer. In Spain, we cannot completely separate the effects of relative humidity

Table 5. Magnitude of Change (decade^{-1}) in the Regional Series of Each Meteorological Parameter From 1961 to 2011[a]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Relative humidity	**−0.57**	**−0.89**	**−1.09**	**−1.25**	−0.74	**−2.05**	**−1.35**	**−1.30**	**−1.03**	−0.80	−0.66	**−0.54**	**−1.02**
Temperature maximum	0.17	**0.32**	**0.56**	**0.49**	**0.34**	**0.66**	**0.33**	**0.39**	0.17	0.23	**0.26**	**0.29**	**0.35**
Temperature minimum	0.04	0.04	**0.31**	**0.25**	**0.33**	**0.47**	**0.30**	**0.42**	0.19	0.23	0.21	0.20	**0.25**
Wind speed	−0.03	−0.08	−0.02	0.00	−0.03	0.01	−0.00	0.01	−0.00	0.01	−0.02	−0.02	−0.01
Sunshine duration	0.03	0.10	0.15	0.13	−0.10	0.13	0.00	−0.06	0.08	−0.04	0.03	0.00	0.04

[a] Each number is given in the units in which the parameter is measured. Bold values indicate statistical significance. RH in % Temp in °C, wind speed in m s^{-1} and Sunshine duration in hours.

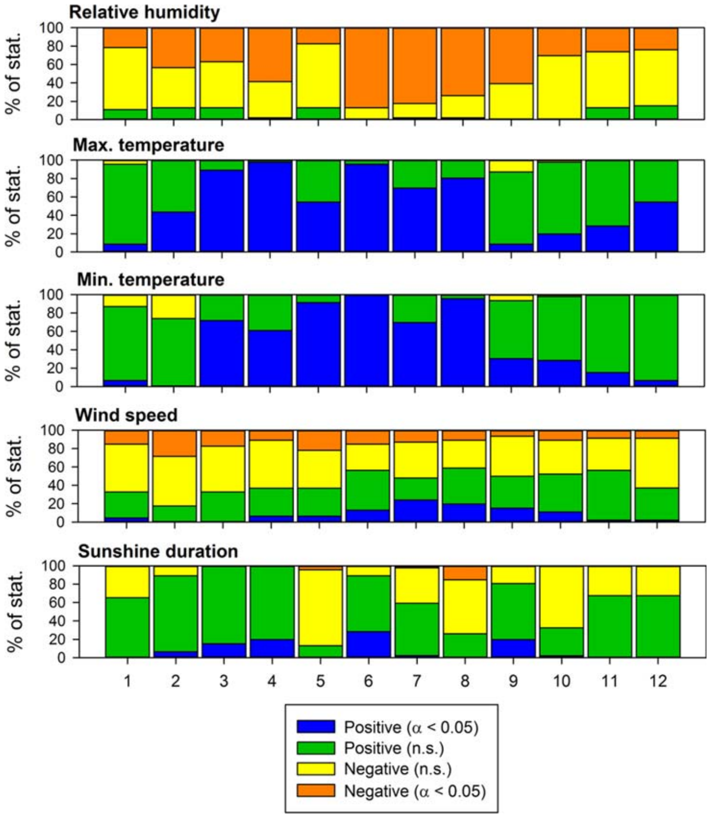

Figure 13. Percentage of stations with positive trends (blue or green) and negative trends (yellow or orange) for relative humidity, maximum and minimum temperature, wind speed, and sunshine duration at the 46 meteorological stations. Blue and orange indicate statistically significant trends ($\alpha < 0.05$).

and temperature in explaining changes of ETo, because the observed changes of relative humidity are strongly linked to the strong warming process, with increased droughts [*Vicente-Serrano,* 2013] and reduced soil moisture leading to decreased water potentially available to the atmosphere and dramatically lower relative humidity. *Vicente-Serrano et al*. [2014] reported that the generalized decrease of relative humidity in Spain from 1961 to 2011 may be explained by the constrained supply of water vapor from terrestrial and oceanic areas. Thus, there has been an increase in the water holding capacity of the atmosphere as a consequence of warming during recent decades, but no accompanying increase in the surface water vapor content. This stresses the importance of the complementary hypothesis [*Brutsaert and Parlange*, 1998], which says that in semiarid regions under water stress, warming may increase the vapor pressure deficit and this cannot be compensated by increased water supply to the atmosphere from the soil and other sources [see *Vicente-Serrano et al*., 2014], thereby leading to increased ETo and an even more arid climate. In Spain, this pattern would reinforce by the significant precipitation decrease observed between 1961 and 2011 (-18.7 mm decade^{-1}, *Vicente-Serrano et al*., 2014].

Finally, we would like to stress that although the results of the sensitivity analyses showed that ETo was highly sensitive to wind speed in Spain, wind speed showed only a secondary role in explaining the observed increases in ETo. Other regional studies have also reported a high sensitivity of ETo to wind speed [*Zhang et al*., 2007; *Yin et al*., 2010; *Liu et al*., 2010; *Wang et al*., 2011; *Han et al*., 2012; *Kousari and Ahani*, 2012]. *McVicar et al*. [2012] performed a global analysis of the role of wind speed on ETo. They concluded that ETo was highly sensitive to wind speed and suggested that the widespread decline in measured near-surface wind speed (termed "global stilling") contributed to ETo decreases at the global scale, or at least compensated for the expected increases driven by increased vapor pressure deficit [*Wang et al*., 2012]. Nevertheless, we did not observe this pattern in Spain. Although there was observed a weak decrease in wind speed in winter [*Azorin-Molina et al*., 2014], this did not compensate for the ETo increase that was driven by decreasing relative humidity and increasing temperature. Wind speed has not showed a clear and significant tendency in Spain during the warm season in the last five decades, and this explains why modeling with stationary rather than observed wind speed values had only a small effect on ETo.

Therefore, the observed changes of ETo in Spain have been mainly driven by warming processes and reduced water supply to the atmosphere, which have strongly decreased relative humidity. Our observed increase of ETo and the increasing climatic aridity in Spain from 1961 to 2011 have negative consequences for hydrology [*Lorenzo-Lacruz et al*., 2012; *Estrela et al*., 2012] and the environment in general [*Andreu et al*., 2007; *Carnicer et al*., 2011; *Vicente-Serrano et al*., 2012].

5. Summary and Conclusions

In this study, we have analyzed the evolution of spatial patterns of reference crop evapotranspiration (ETo) in Spain between 1961 and 2011 by means of the FAO-56 Penman-Monteith equation and the sensitivity of the ETo to changes in the different meteorological variables involved in the calculations and their recent trends. The main results of this study are:

1. There is a large increase in ETo at the monthly and annual scales. The average annual magnitude of change throughout Spain is 29.4 mm decade^{-1}.
2. Spatial patterns of the ETo change are complex and mostly random but there is certain South-North gradient, with higher relative changes recorded in the north.
3. ETo is more sensitive to changes in relative humidity and maximum temperature than wind speed, sunshine duration, and minimum temperature according to the range of variation of these variables in Spain.
4. There are spatial gradients in the sensitivity of the ETo to changes in the different meteorological variables controlled by the latitude and the average sunshine duration.
5. Observed trends in ETo are mostly explained by recent trends in the variables that determine the aerodynamic component. Relative humidity and maximum temperature changes show a clear decrease and increase, respectively, throughout the entire country and they have mainly influenced the observed ETo changes.

Acknowledgments
We would like to thank the Spanish Meteorological State Agency (AEMET) for providing the database used in this study. This work has been supported by the research project CGL2011-27574-CO2-02 financed by the Spanish Commission of Science and Technology and FEDER, and “Demonstration and validation of innovative methodology for regional climate change adaptation in the Mediterranean area (LIFE MEDACC)” financed by the LIFE programme of the European Commission. Cesar Azorin-Molina was granted by the postdoctoral JAE-DOC043 (CSIC) and JCI-2011-10263 (Spanish Ministry of Science and Innovation) grants. Arturo Sanchez-Lorenzo was supported by a postdoctoral fellowship from the “Secretaria per a Universitats i Recerca del Departament d’Economia i Coneixement, de la Generalitat de Catalunya i del programa Cofund de les Accions Marie Curie del 7è Programa marc d’R+D de la Unió Europea” (2011 BP-B 00078). The authors wish to acknowledge the editor and three anonymous reviewers for their detailed and helpful comments to the original manuscript.

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