Global and Planetary Change 121 (2014) 26–40

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

Reference evapotranspiration variability and trends in Spain, 1961–2011

Sergio M. Vicente-Serrano [a,*], Cesar Azorin-Molina [a], Arturo Sanchez-Lorenzo [a,b], Jesús Revuelto [a], Juan I. López-Moreno [a], José C. González-Hidalgo [c], Enrique Moran-Tejeda [a], Francisco Espejo [d]

[a] Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas (IPE-CSIC), Campus de Aula Dei, P.O. Box 13034, E-50059, Zaragoza, Spain
[b] Department of Physics, University of Girona, Spain
[c] Universidad de Zaragoza, Zaragoza, Spain
[d] Agencia Estatal de Meteorologia (AEMET), Madrid, Spain

ARTICLE INFO

Article history:
Received 27 January 2014
Received in revised form 30 May 2014
Accepted 30 June 2014
Available online 8 July 2014

Keywords:
reference evapotranspiration
Penman–Monteith
climate change
global warming
Mediterranean region
drought

ABSTRACT

In this study we analyzed the spatial distribution, temporal variability and trends in reference evapotranspiration (ET_0) in Spain from 1961 to 2011. Twelve methods were analyzed to quantify ET_0 from quality controlled and homogeneous series of various meteorological variables measured at 46 meteorological stations. Some of the models used are temperature based (e.g., Thornthwaite, Hargreaves, Linacre), whereas others are more complex and require more meteorological variables for calculation (e.g., Priestley–Taylor, Papadakis, FAO–Blaney–Criddle). The Penman–Monteith equation was used as a reference to quantify ET_0, and for comparison among the other methods applied in the study. No major differences in the spatial distribution of the average ET_0 were evident among the various methods. At annual and seasonal scales some of the ET_0 methods requiring only temperature data for calculation provided better results than more complex methods requiring more variables. Among them the Hargreaves (HG) equation provided the best results, at both the annual and seasonal scales. The analysis of the temporal variability and trends in the magnitude of ET_0 indicated that all methods show a marked increase in ET_0 at the seasonal and annual time scales. Nevertheless, results obtained suggested substantial uncertainties among the methods assessed to determine ET_0 changes, due to differences in temporal variability of the resulting time series, but mainly for the differences in the magnitude of change of ET_0 and its spatial distribution. This suggests that ET_0 trends obtained by means of methods that only require temperature data for ET_0 calculations should be evaluated carefully under the current global warming scenario.

1. Introduction

Evapotranspiration (ET) is an essential component of both climate and hydrological cycles, and has significant agricultural, ecological and hydrological implications. ET uses approximately three fifths of the available annual solar radiation globally received at the Earth's surface (Wang and Dickinson, 2012; Wild et al., 2013). In addition to the energy balance, ET is also a major component of the water cycle, as it accounts for approximately two thirds of the precipitation falling on land (Baumgarter and Reichel, 1975). ET is important in several atmospheric processes, as it determines the supply of water to the atmosphere from the oceans and terrestrial areas. It affects the magnitude and spatial distribution of global temperature and pressure fields (Shukla and Mintz, 1982), and it may affect the occurrence of heat waves (Seneviratne et al., 2006) and precipitation processes (Zveryaev and Allan, 2010).

The concepts of actual evaporation (ET_a) and reference evaporation (ET_0) are defined as follows: the ET_a is the quantity of water that is transferred as water vapor to the atmosphere from an evaporating surface (Wiesner, 1970) under real conditions (e.g. water availability, vegetation type, physiological mechanisms, climate), whereas ET_0 represents the atmospheric evaporative demand (AED) of a reference surface (generally a grass crop having specific characteristics), and it is assumed that water supply from the land is unlimited (Allen et al., 1998). The only factors affecting ET_0 are climatic parameters, given some reference crop and associated parameters, e.g., albedo and vegetation height. Consequently, ET_0 is a climatic parameter and can be computed from weather data. ET_0 expresses the evaporating power of the atmosphere at a specific location and time of the year and it allows for spatial and temporal comparisons, independent of different land cover types and temporal coverage changes (Katerji and Rana, 2011). ET_a will be less than or equal to ET_0, but never greater. Equally, ET_0 cannot be measured directly using meteorological instruments, as it depends on a number of meteorological variables (net radiation, air temperature, surface pressure, wind speed and relative humidity).

In recent decades paradoxical processes have been detected related to the evolution of the AED. Despite the observed recent climate warming, a general decrease in pan evaporation has been reported (Peterson et al., 1995; Roderick and Farquar, 2004), which could be explained by decreased solar radiation (e.g., Matsoukas et al., 2011; Roderick and

---

* Corresponding author.
E-mail address: svicen@ipe.csic.es (S.M. Vicente-Serrano).

http://dx.doi.org/10.1016/j.gloplacha.2014.06.005

Farquhar, 2002) and/or wind speed decrease (McVicar et al., 2012a,b). Nevertheless, Brutsaert and Parlange (1998) offered theoretical explanations why a trend of decrease in pan evaporation is not necessarily an indication of decreasing ET_0 and ET_a. Moreover, recent studies have suggested major limitations in the use of pan ET measurements to assess current AED trends (Fu et al., 2009; Abtew et al., 2011).

ET_0 is currently considered to be a reliable parameter for assessing long-term trends of the AED (Katerji and Rana, 2011), as it only depends on the meteorological conditions and has a clear physical meaning, and the meteorological variables necessary to calculate ET_0 are available worldwide and have been measured for many years. Although ET_0 may not correspond to accurate ET_a estimates, which depend largely on water availability, soil characteristics and vegetation properties, assessing ET_0 trends is of great interest because it is a measure of aridity conditions and crop requirements, and has major implications for land desertification and food production.

Various studies have analyzed global ET_0 trends based on interpolated gridded datasets (e.g. Dai, 2011; Sheffield et al., 2012) and reanalysis data (Matsoukas et al., 2011), but the results have differed markedly, depending on the datasets and methods used to estimate ET_0. Regional and local studies based on observational datasets have shown a variety of results in different regions of the world. In some cases the trends in ET_0 have been negative, including those in the Yangtze River (Xu et al., 2006), the Yellow River (Ma et al., 2012) and the Tibetan Plateau (Zhang et al., 2007) in China. Other studies have shown positive trends in ET_0, including those in central India (Darshana et al., 2012), Iran (Kousari and Ahani, 2012; Tabari et al., 2012) and Florida (Abtew et al., 2011). Moreover, in some areas (e.g. Australia) there has been large spatial variability in the evolution of ET_0 during recent decades (Donohue et al., 2010).

One of the most important areas worldwide in relation to the impact of climate change processes is the Mediterranean region, because of its high spatial and temporal variability in precipitation (Lionello, 2012). Various empirical studies have shown that water availability has decreased in this area in recent decades (García-Ruiz et al., 2011). Hypotheses to explain this decrease are related to not only land cover changes and human management, but also climate change processes to which ET is strongly connected.

Although there is a number of agronomic studies estimating AED with the purpose of improving the selection of more appropriate crops and irrigation practices (i.e., water saving) in the Mediterranean region, some of them using evaporation observations from lysimeters for validation (e.g., Steduto et al., 2003; Lorite et al., 2012), there are very few studies that have analyzed temporal variability and trends of ET_0 in the last decades (See Table 1 for a general review). Among these, Espadafor et al. (2011) analyzed ET_0 trends from 1960 to 2005 at eight stations in southern Spain, and showed a general increase in ET_0. Papaioaunou et al. (2011) showed a general increase in ET_0 in Greece since the early 1980s, mainly driven by the evolution of global radiation, whereas Platineau et al. (2012) used the same calculation method to show a general increase in ET_0 in Romania, resulting from an increase in temperature. Palumbo et al. (2011) analyzed the trends in ET_0 in southern Italy; they found an increase of 14 mm/decade between 1957 and 2008, which has increased the water requirements of the main cultivated crops by 7 mm/decade. Vergni and Todisco (2011) analyzed the evolution of ET_0 in central Italy, and found a dominant positive trend between 1951 and 2008. In the studies noted above, ET_0 was calculated using a variety of formulae, which makes it difficult to compare the magnitudes of change reported, and to assess the robustness of the observed trends. Moreover, some of the studies are applying empirical methods to estimate ET_0 only using temperature records. Limitations of the use of this type of formulation are obvious in climate change studies since an increase in temperature will translate to increased AED (Roderick et al., 2009), when this is a synthesis of two (radiative and aerodynamic) components not only determined by the evolution of temperature but also of changes in solar radiation, wind speed and relative humidity (Penman, 1948). For these reasons, studies that compare the reliability of temperature-based methods and robust physical estimates based on both radiative and aerodynamic components to estimate the AED evolution are of high priority in this region.

In this study we analyzed trends in ET_0 in Spain from 1960 to 2011. Some of the methods for calculating ET_0 were based on temperature records, while others involved several meteorological variables (e.g. relative humidity, wind speed, radiation). The objectives were: i) to compare average estimates of ET_0 obtained using the various methods; ii) to determine the magnitude and spatial patterns of ET_0 variability; and iii) to evaluate the reliability of the different methods for assessing ET_0 trends. Overall, this is the first study covering the complete Spanish territory and, to our knowledge, including a complete comparison of methods based on quality controlled and homogenized datasets of different climate variables across the Mediterranean basin.

2. Methods

2.1. ET_0 methods

The International Commission for Irrigation (ICID), the Food and Agriculture Organization of the United Nations (FAO), and the American Society of Civil Engineers (ASCE) have adopted the Penman–Monteith (PM) method (Allen et al., 1998) as the standard method for computing ET_0 from climate data. The PM method is widely used because it is predominantly a physically-based approach that can be used globally, and has been widely tested using the lysimeter data obtained under a broad range of climate conditions (e.g. Itenfisu et al., 2000).

The main drawback of the PM method is the relatively large amount of data involved, as it requires data on solar radiation, temperature, wind speed and relative humidity. For this reason, numerous other methods have been developed to calculate ET_0 using less data. In this study we used the PM method as a reference, and 11 other methods commonly used worldwide that require much less information. Some of them are recommended when there is low availability of data (e.g., Hargreaves; Allen et al., 1998) whereas others are of high use for agricultural purposes and irrigation management (e.g., Blaney–Criddle, Priestley–Taylor). They do not cover the complete methods existing to obtain ET_0, but they are a representative sample and it included the most used methods. We distinguished between the temperature-based methods and those requiring additional meteorological variables.

2.1.1. The reference FAO–56 Penman–Monteith (PM; Allen et al., 1998) equation

The FAO PM method was developed by defining the reference crop as a hypothetical crop with an assumed height of 0.12 m, a surface resistance of 70 s m^{-1} and an albedo of 0.23. This closely approximates the evaporation expected from an extensive surface of actively growing and adequately watered green grass of uniform height (Allen et al., 1998), and is defined by the equation:

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

where ET_0 is the reference evapotranspiration (mm day^{-1}), R_n is the net radiation at the crop surface (MJm^{-2} day^{-1}), G is the soil heat flux density (MJ m^{-2} day^{-1}), T is the mean air temperature at a height of 2 m (°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 vapor pressure