Journal of Hydrology 523 (2015) 262–277

Contents lists available at ScienceDirect

Journal of Hydrology

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

Atmospheric evaporative demand observations, estimates and driving factors in Spain (1961–2011)

Cesar Azorin-Molina [a,*], Sergio M. Vicente-Serrano [a], Arturo Sanchez-Lorenzo [a], Tim R. McVicar [b,c], Enrique Morán-Tejeda [a], Jesús Revuelto [a], Ahmed El Kenawy [d,e], Natalia Martín-Hernández [a], Miquel Tomas-Burguera [f]

[a] Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas (IPE-CSIC), Departamento de Procesos Geoambientales y Cambio Global, Zaragoza, Spain
[b] CSIRO Land and Water, Canberra, ACT, Australia
[c] Australian Research Council Centre of Excellence for Climate System Science, Sydney, Australia
[d] Earth System Observations and Modeling Group, WDRC, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia
[e] Department of Geography, Mansoura University, Mansoura, Egypt
[f] Estación Experimental Aula Dei, Consejo Superior de Investigaciones Científicas (EEAD-CSIC), Zaragoza, Spain

ARTICLE INFO

Article history:
Received 7 November 2014
Received in revised form 23 December 2014
Accepted 16 January 2015
Available online 2 February 2015
This manuscript was handled by Geoff Syme, Editor-in-Chief

Keywords:
Piché and Pan observations
Evaporation estimations
Driving factors
Spain

SUMMARY

We analyzed the spatio-temporal evolution of evaporation observations from Piché atmometers (1961–2011; 56 stations) and Pan evaporimeters (1984–2011; 21 stations) across Spain, and compared both measurements with evaporation estimates obtained by four physical models: i.e., Food and Agricultural Organization-56 Penman–Monteith, Food and Agricultural Organization-Pan, PenPan and Penman, based on climate data. In this study we observed a positive and statistically significant correlation between Piché and Pan evaporation measurements during the common period (1984–2011; 19 stations), mainly in summer. When evaporation observations and estimates were compared, we detected positive and statistically significant correlations with the four methods, except for winter. Among the four physical models, the FAO-Pan showed the best fitting to both Piché and Pan evaporation measurements; the PenPan model overestimated evaporation rates; and the FAO-Penman–Monteith and Penman methods underestimated evaporation observations. We also observed a better spatial agreement between Pan evaporation and estimates than that obtained by Piché measurements. Annual and seasonal trends of evaporation estimates show a statistically significant increase for 1961–2011, which do not agree with long-term Piché evaporation trends; e.g. a discontinuity was found around the 1980s. Radiative and aerodynamic driving factors suggest that this discontinuity, and the observed evaporation trends across Spain could be associated with the abrupt increase in air temperature observed during last few decades (i.e., global warming). Further investigations using available Piché evaporation observations for other regions are needed to better understand physical components influencing long-term trends of evaporation.

1. Introduction

Atmospheric evaporative demand (AED) is governed by radiative and aerodynamic components (Penman, 1948; McVicar et al., 2012a). The radiative component is related to the available energy to evaporate water, which depends on solar radiation, land surface albedo, air and surface temperatures and vapour pressure. The aerodynamic component is related to the capacity of the air to store water, which is dependent on (i) air temperature given the Clausius-Clapeyron relationship since water holding capacity of air increases by about 7% per 1 °C of warming, (ii) vapour pressure deficit (VPD) as the difference between the amount of moisture in the air and how much moisture the air can hold when it is saturated, and (iii) wind speed which moves the saturated air and brings unsaturated air to continue evaporating (i.e., if energy and water are available and the incoming air is not saturated).

Observations show that AED has contrasting trends among regions and periods as a consequence of the evolution of the different climate factors that control this variable (e.g., Hidalgo et al., 2005; Cong et al., 2009; Liu et al., 2011; McVicar et al., 2012b). Some studies suggest that the observed changes in AED are related to changes in the VPD, mainly in semi-arid regions (Wang et al., 2012). While others show that the effect of climate warming on

* Corresponding author at: Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas (IPE-CSIC), Departamento de Procesos Geoambientales y Cambio Global, Avda. Montañana 1005, 50059 Zaragoza, Spain.
E-mail address: cazorin@ipe.csic.es (C. Azorin-Molina).

http://dx.doi.org/10.1016/j.jhydrol.2015.01.046
0022-1694/

AED is minimal, and the evolution of other meteorological variables (primarily solar radiation and wind speed) are more important to explain the observed changes (Roderick and Farquhar, 2002; Jhajharia et al., 2006; Jhajharia et al., 2009a; Roderick et al., 2007; McVicar et al., 2012b).

Despite observed climate warming, numerous studies assessing observed Pan evaporation (E_{Pan}) trends have shown a general decrease in E_{Pan} has been widely reported (e.g., Peterson et al., 1995; Roderick and Farquhar, 2004; McVicar et al., 2012b, their Table 5). Different hypotheses have been formulated to explain the E_{Pan} decrease under global warming, including decreased solar radiation (Stanhill and Cohen, 2001; Roderick and Farquhar, 2002; Matsoukas et al., 2011), a widespread decline in near-surface wind speed (McVicar et al., 2012b) or both together (Jhajharia et al., 2009a). Brutsaert (2006) and McVicar et al. (2012a) stressed that current AED trends are likely not linked to a individual process, yet are more likely attributed to simultaneous changes in the primary meteorological variables governing the evaporation process: solar irradiance, air temperature, relative humidity and wind speed.

There is strong scientific and social interest to know how AED is changing given the current climate change scenario (including global warming), given the far-reaching hydrological, agricultural and environmental implications. Nevertheless, there are few studies that have compared trends in Evaporation (E) observations (using E_{Pan} measurements) and estimations (by means of physical models that use data of VPD, air temperature, solar radiation and wind speed) (e.g., Chattopadhyay and Hulme, 1997; Hobbins et al., 2004; Abtew et al., 2011; Johnson and Sharma, 2007 and Johnson and Sharma, 2010). These types of studies are highly relevant since the agreement between observations and physical estimates provides more robustness when determining evaporation variability and trends. Moreover, they can provide knowledge on how changes in the primary meteorological variables may affect AED trends in the current climate change scenario.

The Mediterranean region is one of the hotspot areas of the world in relation to climate change processes and their impact on water resources availability. For instance, a consistent decrease in water resources has been identified in recent decades (García-Ruiz et al., 2011). This has been primarily related to decreasing precipitation and increasing temperature trends across the Mediterranean region. Nevertheless, the analysis of the relationship between increasing air temperature and AED processes in the region has been poorly assessed and no AED observations have been analyzed, with the exception of Turkey (Topaloğlu et al., 2012; Yeşilirmak, 2013), Israel (Cohen et al., 2002) and Greece (Papaioannou et al., 2011). To date, there are no studies assessing AED trends using observations in the western Mediterranean basin.

In this study, we analyse the evolution of AED observations and estimations across Spain from 1961 to 2011. In this region, AED is highly relevant for agriculture, forestry and water resources (e.g., Austin et al., 1998; Estrela et al., 2012). Moreover, air temperature over this region has increased 2 °C in the last five decades (Brunet et al., 2007; Vicente-Serrano et al., 2014a), relative humidity and cloud cover have experienced a strong decrease during the same period (Vicente-Serrano et al., 2014a; Sanchez-Lorenzo et al., 2012), whereas wind speed (Azorin-Molina et al., 2014) and solar radiation (Sanchez-Lorenzo et al., 2007) have not shown a clear trend. Different ecological studies have hypothesized that increased AED is in the root of the decline in forest growth (Carnicer et al., 2011), and the increase of degradation processes in vulnerable semi-arid areas (Vicente-Serrano et al., 2012). The objectives of this study are threefold: (i) to determine the spatial relationship between the AED observed and estimated by four physical models based on climate information; (ii) to assess the temporal relationship and consistency between AED observations by different instruments and estimations for 1961–2011; and (iii) to quantify the influence of variability of the primary meteorological variables (i.e., air temperature, relative humidity, wind speed and solar radiation) on the AED evolution in Spain.

2. Meteorological datasets

We used daily time series of near-surface meteorological variables observed at 56 meteorological stations from the Spanish State Meteorological Agency (AEMET), including: (i) AED observations from (a) Class-A Pan evaporimeters, and (b) Piché atmometers; and (ii) meteorological data such as atmospheric pressure, relative humidity, wind speed, air temperature and sunshine duration, to estimate E using four physical models (see Section 3.1).

Among the different approaches to directly measure E (e.g., lysimeters, eddy covariance towers, etc.; McMahon et al., 2013), pan evaporation is the most widely used instrument (Roderick et al., 2009; Fu et al., 2009; Stanhill, 2002). Class-A Pan evaporimeters are circular cylinders of 120 cm diameter and 25 cm depth, mounted on an open wooden platform. The pan is filled with water to 20 cm depth, and the daily evaporation rate, adjusted for precipitation, is measured manually. The USA Class-A evaporator is the most widely used pan (for more details see Roderick et al., 2009), and has been used at AEMET's first-order meteorological stations since 1984.

Much less used is the Piché atmometer (Papaioannou et al., 1996), which consists of a 3 cm diameter disc of filter paper held by a metal clip to the bottom of an inverted graduated cylindrical tube of 1.5 cm in diameter, which supplies deionized water to the disc. The water is evaporated from the surface of the filter paper and daily measurements of the volume of water remaining in the graduated tube allow to compute evaporation (in mm). In Spain, the Piché atmometer is located inside Stevenson screens together with other meteorological instruments. Observations of Piché ($E_{\mathrm{Piché}}$) and Pan (E_{Pan}) evaporation were obtained from Sanchez-Lorenzo et al. (2014): $E_{\mathrm{Piché}}$ are observed at 56 stations for 1961–2011, and E_{Pan} are observed at 21 stations for 1984–2011. Both $E_{\mathrm{Piché}}$ and E_{Pan} series were carefully quality controlled and homogenized (for details see Sanchez-Lorenzo et al., 2014). $E_{\mathrm{Piché}}$ and E_{Pan} were simultaneously observed at 19 locations for the common period 1984–2011.

Only AEMET's first-order meteorological stations (approximately $\sim$100) measure all the required variables to estimate AED. Using these records and after applying a homogenization protocol, high quality controlled and homogeneous time series were created by Sanchez-Lorenzo et al. (2007) of monthly sunshine duration for the Iberian Peninsula since 1900; Vicente-Serrano et al. (2014a) of monthly relative humidity (also maximum and minimum air temperature and atmospheric pressure) across Spain since the 1960s; and Azorin-Molina et al. (2014) of monthly near-surface (10-m height) wind speed dataset for Spain and Portugal since 1961. We updated (until 2011 in case of sunshine duration) and used these reliable datasets to estimate AED in Spain.

Fig. 1 shows the location of the stations used and the availability of data at each station. In 32 out of 56 stations with $E_{\mathrm{Piché}}$ and in 12 out of 21 stations with E_{Pan} there were also meteorological data to compare between evaporation observations (E_{Obs}) and evaporation estimates (E_{Est}). Only in 10 first-order meteorological stations were $E_{\mathrm{Piché}}$, E_{Pan} and the required meteorological data simultaneously observed.

3. Methods

3.1. Atmospheric evaporative demand methods

There are different models to estimate AED using meteorological data (see McMahon et al., 2013). We used four physical models corresponding to different modifications of the method proposed